

The Impact of the EU CBAM on Financing Costs of China's High-Carbon Export-Oriented Manufacturing Industry

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Abstract. Against the backdrop of the global carbon neutrality drive and the full rollout of the EU Carbon Border Adjustment Mechanism (CBAM), CBAM has emerged as a major exogenous policy shock shaping the operation and financing of China's high-carbon export manufacturing sector. This paper selects panel data of A-share listed firms across six high-carbon export manufacturing industries from 2020 to 2025, constructs a multi-sector general equilibrium model to depict the dual mechanism through which CBAM affects financing costs, and conducts empirical analysis using a two-way fixed effects model, stepwise mediation effect model, grouped regression and multiple robustness tests. The findings show that, overall, rising CBAM policy intensity significantly reduces corporate debt financing costs, as the long-term dividend of policy-driven transformation outweighs the short-term cost shock. In terms of transmission channels, profitability and financing constraints exert significant partial mediation effects: CBAM compels enterprises to improve production efficiency and profitability, while easing external financing constraints, which ultimately drives down financing costs. Heterogeneity results indicate that this effect is more pronounced among large enterprises, firms in highly concentrated industries, and samples with high R&D investment. The core conclusions remain valid after multiple robustness tests including variable winsorization, sample adjustment and model replacement. Based on the findings, this paper puts forward targeted suggestions at the enterprise, financial institution and government levels, to provide references for Chinese high-carbon export enterprises to cope with CBAM shocks, optimize financing structure and advance low-carbon transformation.

Keywords: EU Carbon Border Adjustment Mechanism (CBAM), high-carbon export manufacturing industry, financing cost, low-carbon innovation, financing constraint

1. Introduction

The global climate governance process keeps accelerating, and "carbon neutrality" has become a shared consensus across countries. As a front-runner in global climate policy, the European Union officially launched the Carbon Border Adjustment Mechanism (CBAM) in 2023, imposing carbon tariffs on imports of six high-carbon products: steel, cement, primary aluminum, basic chemicals, paper and glass [1]. The mechanism aims to prevent carbon leakage and push forward low-carbon

transformation of the global industrial chain. It follows a phased implementation schedule: a transition period from 2023 to 2025, followed by full enforcement starting in 2026. Free carbon allowances will be cut year by year, and carbon constraints will keep tightening.

China is one of the EU's largest import sources of high-carbon products. The six high-carbon manufacturing industries mentioned above, as major exporters to the EU, are directly exposed to CBAM policy shocks. The impact is twofold: on one hand, CBAM raises the carbon cost of corporate exports [2], squeezes profit margins and increases operational uncertainty; on the other hand, strict carbon constraints will force high-carbon enterprises to phase out backward production capacity, increase investment in green technological upgrading and R&D, improve ESG compliance systems, and drive the transformation and upgrading of production and operation models [3].

Debt financing cost is a key pain point for high-carbon export enterprises when dealing with external shocks. At present, domestic listed manufacturing firms generally disclose debt cost information incompletely, so financial expenses have become a reasonable proxy for measuring overall financing costs [4]. At the critical juncture when CBAM shifts from the transition period to full implementation, clarifying its dual impact on the financing costs of high-carbon export enterprises and identifying the internal transmission path not only meets the practical needs of industrial transformation under the "dual carbon" goal, but also carries practical value for enterprise risk management, credit pricing of financial institutions and government industrial regulation.

Existing studies mostly focus on simulating the impact of CBAM on export scale, trade competitiveness and macroeconomic performance [2, 5, 6], while research on the mechanism at the micro enterprise financing level is relatively weak. In particular, there is a lack of joint tests on the dual mediation channels of profitability and financing constraints, and heterogeneity dimensions such as enterprise size, industry characteristics and R&D level have not been fully discussed. This is also the practical motivation for this research.

2. Literature review and hypothesis development

2.1. Domestic and foreign literature review

As a cross-border carbon policy to address carbon leakage and align with the EU ETS, the EU Carbon Border Adjustment Mechanism (CBAM) has been a hot research topic for scholars at home and abroad since its legislation. Early foreign studies mainly used computable general equilibrium models to simulate the impact of CBAM on global trade and national macroeconomies. It is widely agreed that CBAM will push up the export cost of high-carbon products in developing countries and curb export volume, but will drive global carbon emission reduction in the long run. Studies by institutions such as the IMF and Bruegel point out that the impact of CBAM varies significantly across industries, with energy-intensive sectors like steel and primary aluminum hit the hardest [7-9].

Domestic scholars conduct in-depth research in light of China's national conditions. Some focus on the macro trade and industrial level, holding that CBAM will reshape China-EU trade patterns, raise the export threshold for China's high-carbon products, and put more pressure on coastal export-oriented industries [2, 10]. Others focus on micro enterprise behavior, finding that CBAM's carbon constraints push enterprises to carry out green technological transformation, increase R&D input and improve ESG compliance [11-13]. However, most existing domestic literature stays at the stage of theoretical analysis and scenario simulation, and empirical research on corporate financial indicators, especially financing costs, is relatively scarce. This is also the key breakthrough direction of this paper.

Against the background of the "dual carbon" policy, a large body of literature confirms that carbon constraint policies force enterprises to optimize production and eliminate inefficient capacity, thus lifting return on total assets. Meanwhile, the combination of green policies and green credit can effectively ease enterprises' external financing constraints [14, 15]. Some studies further use mediation effect models to verify that carbon policies affect enterprise investment, performance and other indicators through profitability and financing constraints [16, 17]. Yet few studies link CBAM, a cross-border carbon policy, with financing costs and test two parallel mediation paths at the same time. In addition, existing discussions on heterogeneity are relatively limited. This paper conducts grouped tests by enterprise size, industry concentration and R&D level to further expand the boundary of mechanism analysis.

2.2. Hypothesis development

Based on the above literature, this paper explores whether the net effect of CBAM on financing costs of high-carbon manufacturing enterprises is positive (i.e., CBAM pushes up financing costs) or negative (i.e., CBAM drives down financing costs by forcing low-carbon transformation). Accordingly, Hypothesis H1 is proposed: EU CBAM policy shocks significantly reduce the financing costs of enterprises in China's high-carbon export manufacturing industry.

Scholars including Zhan Shaocheng found through constructing a CGE model for the steel industry and numerical simulation that low-carbon transformation can help China's steel industry improve emission reduction performance and narrow the output decline [7]. Based on this finding, this paper deduces the impact path of CBAM policy and puts forward the following hypotheses: H2a: CBAM forces enterprises to phase out high-energy-consuming and inefficient production capacity, so as to improve production efficiency and raise return on total assets. This sends positive profit signals to creditors and lowers debt costs. H2b: CBAM policy pushes enterprises to upgrade technology and reduce operational risks, thus alleviating financing constraints, lowering financial institutions' credit risk pricing, and ultimately reducing debt costs.

3. Theoretical model construction

3.1. Axioms and assumptions of the economic environment

This model strictly follows the MWG microeconomic axiom system and sets the following standard assumptions:

(1) Household sector preference axioms and utility specification

The preferences of the representative household satisfy completeness, transitivity, continuity, strong monotonicity and strict convexity. The utility function takes the form of an intertemporal CES utility function:

$$U = \sum_{t=0}^{\infty} \beta^t u(C_t, L_t) = \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma}}{1-\sigma} - \frac{L_t^{1+\eta}}{1+\eta} \right) \quad (1)$$

Where $\beta \in (0,1)$ is the household's subjective time discount factor, $\sigma > 0$ is the coefficient of relative risk aversion, $\eta > 0$ is the inverse of the Frisch elasticity of labor supply; C_t is total household consumption in period t , and L_t is household labor supply in period t .

The representative household's income comes from wage income, interest income from capital supply, enterprise profit dividends and government transfer payments. Its expenditures include

consumption and savings (savings are converted into capital supply in the next period). The budget constraint is:

$$P_t C_t + S_t = W_t L_t + R_{t-1} K_{t-1} + \Pi_t + T_t \quad (2)$$

Where P_t is the general price level of consumer goods, W_t is the nominal wage rate, R_{t-1} is the enterprise's financing cost in period $t - 1$; K_{t-1} is the capital stock supplied by households in period $t - 1$, which follows the capital accumulation equation $K_t = (1 - \delta)K_{t-1} + S_t$, with $\delta \in (0,1)$ being the capital depreciation rate; Π_t is total profit dividends received by households from enterprises, and T_t is the government's net transfer payments to households.

(2) Production sector technology axioms and multi-layer nested production structure

The production sector is divided into three parts: ① High-carbon export sector H (N_H sectors in total, corresponding to the six high-carbon industries directly hit by CBAM policy shocks [1]); ② Upstream supporting sector U (N_U sectors in total, which provide intermediate inputs for high-carbon export manufacturing and are indirectly affected by CBAM shocks); ③ Non-high-carbon sector L (N_L sectors in total, serving as the control group). The production set of each sector satisfies standard axioms: non-empty, closed and convex, free disposal, no free lunch, and constant returns to scale. Enterprises in the production sector can reduce carbon intensity through low-carbon R&D and energy substitution to hedge against CBAM carbon tariff costs.

Based on the above production technology axioms, each sector j adopts a standard multi-layer CES production function with a Leontief intermediate input structure, which fully matches the accounting framework of China's input-output table. The specific form is:

$$Q_{j,t} = \min\left(\frac{VA_{j,t}}{1 - \sum_{k=1}^N a_{kj}}, \frac{X_{1j,t}}{a_{1j}}, \frac{X_{2j,t}}{a_{2j}}, \dots, \frac{X_{Nj,t}}{a_{Nj}}\right) \quad (3)$$

Where $Q_{j,t}$ is the total output of sector j in period t , $VA_{j,t}$ is the value added of sector j , $X_{kj,t}$ is the quantity of intermediate inputs supplied by sector k to sector j ; a_{kj} is the direct consumption coefficient, satisfying $\sum_{k=1}^N a_{kj} < 1$.

Value added $VA_{j,t}$ takes the CES form, nesting labor, capital and energy as production factors, and incorporates carbon emission factors. The specific form is:

$$VA_{j,t} = Z_{j,t} \left[\alpha_j L_{j,t}^{\frac{\varepsilon_j - 1}{\varepsilon_j}} + (1 - \alpha_j) \left(\gamma_j K_{j,t}^{\frac{\nu_j - 1}{\nu_j}} + (1 - \gamma_j) E_{j,t}^{\frac{\nu_j - 1}{\nu_j}} \right)^{\frac{\nu_j}{\nu_j - 1} \cdot \frac{\varepsilon_j - 1}{\varepsilon_j}} \right]^{\frac{\varepsilon_j}{\varepsilon_j - 1}} \quad (4)$$

Where $Z_{j,t}$ is total factor productivity (TFP) of sector j , $\alpha_j \in (0,1)$ is the labor income share, $\gamma_j \in (0,1)$ is the share of capital in the capital-energy composite; $\varepsilon_j > 0$ is the elasticity of substitution between labor and the capital-energy composite, $\nu_j > 0$ is the elasticity of substitution between capital and energy; $L_{j,t}$, $K_{j,t}$, $E_{j,t}$ are labor, capital and fossil energy input of sector j , respectively.

Total carbon emissions of sector j are expressed as $CE_{j,t} = \theta_j E_{j,t}$, where $\theta_j > 0$ represents carbon emissions per unit of fossil energy consumed.

In addition, it is assumed that the representative enterprise in each sector is a price taker in a perfectly competitive market, aiming to maximize current profit. The profit function is:

$$\Pi_{j,t} = P_{j,t} Q_{j,t} - W_t L_{j,t} - R_t K_{j,t} - P_{E,t} E_{j,t} - \sum_{k=1}^N P_{k,t} X_{kj,t} \quad (5)$$

$$-\tau_{j,t} \cdot EX_{j,t} \cdot \max(0, e_{j,t} - e_{EU})$$

Where $P_{j,t}$ is the ex-factory price of sector j 's products, $P_{E,t}$ is the price of fossil energy; $EX_{j,t}$ is the export volume of sector j to the EU market, $\tau_{j,t}$ is the core parameter of CBAM policy, i.e., the real-time carbon price in the EU carbon market (euro per tonne of CO₂). When $\tau_{j,t} = 0$, it corresponds to the baseline scenario without CBAM shocks; $e_{j,t}$ is the embodied carbon emission per unit of export products of sector j , $\bar{e}_{EU}$ is the free allowance carbon emission cap for comparable EU products. When $e_{j,t} > \bar{e}_{EU}$, enterprises have to pay CBAM carbon tariffs on the excess emissions.

(3) Financial intermediation and endogenous financing costs

Assume there is one representative perfectly competitive financial intermediary in the economy. It absorbs household savings and grants loans to production enterprises. The financial market is imperfect with information asymmetry: financial intermediaries cannot fully observe enterprises' default risk, and can only set loan interest rates based on enterprises' expected profit levels.

An enterprise's default probability is endogenously determined by its expected net profit. When net profit falls below a threshold, the enterprise defaults and fails to repay the principal and interest of the loan. The default probability function is:

$$p_{j,t} = \Phi\left(\frac{\Pi - E_t \Pi_{j,t}}{\sigma_{\Pi}}\right) \quad (6)$$

Where $p_{j,t} \in [0, 1]$ is the enterprise's default probability in period t , $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution, satisfying $\Phi'(\cdot) = \phi(\cdot) > 0$, meaning default probability rises monotonically as expected net profit falls; $E_t \Pi_{j,t}$ is the enterprise's expected net profit in period t , σ_{Π} is the volatility of net profit, measuring operational risk.

The representative financial intermediary is risk-neutral, and its expected profit is zero under perfect competition. It chooses the loan interest rate so that the expected return on loans equals the funding cost of absorbing savings (the risk-free rate):

$$(1 - p_{j,t})(1 + R_{j,t}) + p_{j,t} \cdot \xi = 1 + R_{f,t} \quad (7)$$

Where $\xi \in [0, 1]$ is the loan recovery rate after default, i.e., the proportion of principal the financial intermediary can recover when the enterprise defaults.

(4) Government, foreign sector and market clearing

The government runs a balanced budget: its revenue comes from domestic taxes, and expenditures include transfer payments to households and public consumption:

$$T_t + G_t = Tax_t \quad (8)$$

Where G_t is government public consumption, Tax_t is government tax revenue. In this model, the government does not proactively implement fiscal policies or levy domestic carbon taxes. It only acts as a balance sheet entity in general equilibrium to avoid interference from other policies.

The foreign sector is divided into the EU market and other international markets. China's export demand function to the EU takes the CES form and follows the Armington trade assumption:

$$EX_{j,t} = EX_{j,0} \left(\frac{P_{j,t}(1 + \tau_{j,t}(e_{j,t} - \bar{e}_{EU}))}{P_{EU,t}} \right)^{-\mu_j} \quad (9)$$

Where $EX_{j,0}$ is the scale parameter of export demand, $\mu_j > 1$ is the price elasticity of export demand, $P_{EU,t}$ is the price level of comparable products in the EU market.

All markets in the economy are perfectly competitive with fully flexible prices, and all markets clear in each period, corresponding to the Arrow-Debreu general equilibrium market clearing conditions in MWG Chapter 16.

3.2. Baseline general equilibrium without CBAM shocks

Based on the above assumptions, this section constructs a baseline Arrow-Debreu general equilibrium model without CBAM shocks ($\tau_{j,t} = 0$), derives the optimal decisions of each agent, proves the existence and welfare properties of the equilibrium, and provides a benchmark for subsequent policy shock analysis. All analysis strictly follows the general equilibrium paradigm in MWG Chapters 15–16.

3.2.1. Optimal decisions of each agent

(1) Optimal decisions of the household sector

The representative household's optimization problem is to maximize the intertemporal utility function subject to the budget constraint and capital accumulation equation. We solve it using dynamic programming and construct the Bellman equation:

$$V(K_{t-1}) = \frac{C_t^{1-\sigma}}{1-\sigma} - \frac{L_t^{1+\eta}}{1+\eta} + \beta V(K_t) \quad (10)$$

Subject to:

$$P_t C_t + K_t = W_t L_t + (1 + R_{t-1} - \delta)K_{t-1} + \Pi_t + T_t \quad (11)$$

Taking first-order conditions with respect to control variables C_t, L_t and state variable K_t , and applying the envelope theorem, we obtain the core Euler equation and labor supply equation for household optimal decisions:

•Euler equation for consumption:

$$C_t^{-\sigma} = \beta E_t[C_{t+1}^{-\sigma} \cdot \frac{P_t}{P_{t+1}} \cdot (1 + R_t - \delta)] \quad (12)$$

This is the core condition for household intertemporal consumption decisions. It shows that households optimally trade off current and future consumption such that the marginal utility of current consumption equals the discounted marginal utility of future consumption, fully consistent with the first-order condition for utility maximization in MWG Chapter 4.

•Labor supply equation:

$$L_t^\eta = C_t^{-\sigma} \cdot \frac{W_t}{P_t} \quad (13)$$

This equation describes the household's optimal labor supply decision: the marginal disutility of labor equals the marginal utility of consumption multiplied by the real wage rate, i.e., the optimal trade-off between leisure and consumption.

•Capital supply function:Combining the Euler equation and capital accumulation equation, the household's capital supply function can be derived as:

$$K_t^s = K_t^s(R_t, W_t, P_t, E_t C_{t+1}) \quad (14)$$

This function satisfies $\partial K_t^s / \partial R_t > 0$, meaning capital supply increases monotonically with the interest rate and the capital supply curve slopes upward, providing the supply-side foundation for capital market equilibrium analysis.

(2) Optimal decisions of enterprises

Without CBAM shocks, $\tau_{j,t} = 0$, and the enterprise's profit function simplifies to:

$$\Pi_{j,t} = P_{j,t} Q_{j,t} - W_t L_{j,t} - R_t K_{j,t} - P_{E,t} E_{j,t} - \sum_{k=1}^N P_{k,t} X_{kj,t} \quad (15)$$

Given the properties of the Leontief production function, the enterprise's optimal intermediate input decision is:

$$X_{kj,t} = a_{kj} Q_{j,t}, \forall k, j \quad (16)$$

That is, intermediate inputs are proportional to total output, fully matching the direct consumption coefficients in the input-output table.

Substituting the intermediate input decision into the profit function, the enterprise's profit maximization problem reduces to factor input decisions at the value-added level. Taking first-order conditions with respect to labor $L_{j,t}$, capital $K_{j,t}$ and energy $E_{j,t}$, we obtain the factor demand functions:

•Labor demand equation:

$$\frac{\partial \Pi_{j,t}}{\partial L_{j,t}} = 0 \implies P_{j,t} \cdot \frac{\partial V A_{j,t}}{\partial L_{j,t}} = W_t \quad (17)$$

That is, the marginal revenue product of labor equals the nominal wage rate, which is the standard condition for enterprise labor demand in perfect competition.

•Capital demand equation:

$$\frac{\partial \Pi_{j,t}}{\partial K_{j,t}} = 0 \implies P_{j,t} \cdot \frac{\partial V A_{j,t}}{\partial K_{j,t}} = R_t \quad (18)$$

That is, the marginal revenue product of capital equals the capital interest rate (the enterprise's financing cost). This equation is the core condition for enterprise capital demand, satisfying $\partial K_{j,t}^d / \partial R_t < 0$. In other words, capital demand falls monotonically as the interest rate rises, and the capital demand curve slopes downward, providing the demand-side foundation for capital market equilibrium analysis.

•Energy demand equation:

$$\frac{\partial \Pi_{j,t}}{\partial E_{j,t}} = 0 \implies P_{j,t} \cdot \frac{\partial V A_{j,t}}{\partial E_{j,t}} = P_{E,t} \quad (19)$$

That is, the marginal revenue product of energy equals the energy price. This equation also determines the enterprise's carbon emissions and is the core transmission node for subsequent CBAM shock analysis.

(3) Optimal decisions of financial intermediation and baseline financing costs

Without CBAM shocks, the enterprise's expected net profit is $E_t \Pi_{j,t}^0$ and the corresponding default probability is $p_{j,t}^0$. Based on the zero-profit condition of financial intermediation, the enterprise's financing cost in the baseline scenario is derived as:

$$R_{j,t}^0 = \frac{1+R_{f,t}-p_{j,t}^0 \cdot \xi}{1-p_{j,t}^0} - 1 \quad (20)$$

Taking a first-order Taylor expansion, when the default probability $p_{j,t}^0$ is small, financing costs can be decomposed as:

$$R_{j,t}^0 \approx R_{f,t} + p_{j,t}^0 \cdot (1 - \xi) \quad (21)$$

This decomposition is one of the core conclusions of the model: an enterprise's financing cost equals the risk-free rate plus an endogenous risk premium, which is positively related to the enterprise's default probability and loss given default $(1 - \xi)$.

3.2.2. Definition of baseline equilibrium

(1) Baseline Arrow-Debreu general equilibrium

In the baseline scenario without CBAM shocks, an Arrow-Debreu general equilibrium is defined as a set of price vectors $P_t^*, W_t^*, R_t^*, P_{E,t}^*, R_{f,t}^*$ and a set of resource allocation vectors $C_t^*, L_t^*, K_t^*, Q_{j,t}^*, L_{j,t}^*, K_{j,t}^*, E_{j,t}^*, X_{kj,t}^*$, which satisfy utility maximization, profit maximization, financial market equilibrium, market clearing and budget balance.

(2) Equilibrium existence and welfare theorems

- Existence of equilibrium: Based on the above assumptions and Brouwer's fixed-point theorem, excess demand is continuous, homogeneous of degree zero, satisfies Walras' law and boundary conditions. There exists at least one Arrow-Debreu general equilibrium in the economy, i.e., there exists a price vector $p^* \in \Delta$ such that excess demand for goods $z(p^*) \leq 0$, and for any good m with $z_m(p^*) < 0$, we have $p_m^* = 0$ (free good).

- First Welfare Theorem: Under the above assumptions and in the absence of externalities, the baseline equilibrium is Pareto optimal, and the marginal product of capital is equalized across sectors:

$$\frac{\partial VA_{j,t}}{\partial K_{j,t}} = \frac{\partial VA_{k,t}}{\partial K_{k,t}} = \frac{R_t^*}{P_t^*} \quad (22)$$

3.3. Modified equilibrium model with CBAM and carbon externalities

This section depicts the cross-border negative externality of carbon emissions, introduces CBAM as a cross-border Pigouvian tax into the model, revises agents' decisions and equilibrium conditions in the baseline model, and derives equilibrium properties under CBAM shocks, providing a theoretical framework for subsequent financing cost analysis.

3.3.1. Cross-border negative carbon externality

Carbon emissions from China's high-carbon export manufacturing industry generate cross-border negative externalities: CO₂ emitted during production harms EU residents' welfare and production efficiency through the global climate system. This corresponds to the "negative production externality" defined in MWG Chapter 11, i.e., producers' decisions impose unpriced harm on third parties' welfare.

Specifically, the utility function of the representative EU household is negatively affected by China's total carbon emissions:

$$U_{EU} = u(C_{EU}, L_{EU}) - D(\sum_{j \in H} CE_{j,t}) \quad (23)$$

Where $D(\cdot)$ is the carbon damage function, satisfying $D'(\cdot) > 0$ and $D''(\cdot) > 0$, meaning marginal damage rises monotonically with carbon emissions.

In the baseline equilibrium, Chinese high-carbon export enterprises do not internalize this cross-border externality in their production decisions. Their private marginal cost is lower than the social marginal cost, leading to overproduction and over-emission of high-carbon products, while also forcing low-carbon transformation. The baseline equilibrium is no longer Pareto optimal, which provides the theoretical rationale for CBAM.

3.3.2. Mathematical characterization of CBAM policy

This model strictly follows official EU CBAM rules and characterizes CBAM as a specific cross-border Pigouvian tax levied on Chinese high-carbon exports to the EU. The specific form is:

For a high-carbon export sector $j \in H$, the CBAM tax per unit of export product is:

$$T_{CBAM,j,t} = \tau_t \cdot \max\{0, e_{j,t} - \bar{e}_{EU,j}\} \quad (24)$$

Where τ_t is the EU carbon price in period t , acting as both a cost shock parameter and a low-carbon transformation incentive: a higher carbon price means stronger incentives for transformation. When $\tau_t = 0$, it corresponds to the baseline scenario without CBAM; when $\tau_t > 0$, it corresponds to the CBAM implementation scenario. $e_{j,t}$ is the embodied carbon per unit of export product of Chinese sector j , calculated as $e_{j,t} = CE_{j,t}/Q_{j,t} \cdot \sum_{k=1}^N b_{kj}$, where b_{kj} are elements of the Leontief inverse matrix, capturing full-chain embodied carbon per unit of export. $\bar{e}_{EU,j}$ is the free allowance emission cap for comparable EU products, i.e., the free emission quota per unit of output available to EU firms. When $e_{j,t} > \bar{e}_{EU,j}$, Chinese enterprises pay CBAM tariffs on excess emissions. This setting fully aligns with the "common but differentiated responsibilities" principle of EU CBAM.

Incorporating CBAM taxes into the profit function, the profit function of high-carbon export enterprises is revised as:

$$\begin{aligned} \Pi_{j,t} = & P_{j,t}Q_{j,t} - W_tL_{j,t} - R_tK_{j,t} - P_{E,t}E_{j,t} - \sum_{k=1}^N P_{k,t}X_{kj,t} \\ & - \tau_t \cdot \max\{0, e_{j,t} - \bar{e}_{EU,j}\} \cdot EX_{j,t} \end{aligned} \quad (25)$$

CBAM carbon tariffs increase current costs, but they also push enterprises to cut energy use, increase low-carbon investment, optimize production structure, and improve long-term profitability and operational stability.

3.3.3. Revised optimal decisions under CBAM shocks

(1) Revised optimal decisions of high-carbon export enterprises

The introduction of CBAM essentially raises the marginal cost of exports, leading to systematic changes in enterprises' optimal decisions. Taking first-order conditions of the revised profit function, we obtain the revised conditions for optimal export and factor input decisions:

First-order condition for export demand:

$$\frac{\partial \Pi_{j,t}}{\partial EX_{j,t}} = 0 \implies P_{j,t} = \tau_t \cdot \max\{0, e_{j,t} - \bar{e}_{EU,j}\} + MC_{j,t} \quad (26)$$

Where $MC_{j,t}$ is the enterprise's marginal cost of production. This equation shows that CBAM directly raises the marginal cost of exports, forcing enterprises to carry out energy-saving upgrades and fuel switching. In the long run, marginal costs will decline, offsetting the short-term carbon tariff shock.

(2) Revised first-order condition for capital demand

$$P_{j,t} \cdot \frac{\partial VA_{j,t}}{\partial K_{j,t}} - \tau_t \cdot \frac{\partial e_{j,t}}{\partial K_{j,t}} \cdot EX_{j,t} = R_t \quad (27)$$

This is the core revised condition of the model. It shows that CBAM affects enterprise capital demand through three channels: First, CBAM raises enterprises' marginal cost and reduces optimal output scale, thus lowering capital demand (scale effect). Second, if capital and energy are substitutes ($\nu_j > 1$), more capital input reduces energy consumption, thus cutting carbon intensity and CBAM tax burdens. CBAM therefore incentivizes higher capital input (substitution effect). Third, CBAM encourages low-carbon fixed asset investment and green equipment upgrading, generating a transformation investment effect that boosts demand for high-quality capital and improves long-term profitability and risk resilience.

For high-carbon export enterprises, the scale effect dominates the substitution effect, so the net effect of CBAM shocks is lower capital demand, shifting the capital demand curve downward and to the left.

(3) Revised first-order condition for energy demand and carbon emissions

$$P_{j,t} \cdot \frac{\partial VA_{j,t}}{\partial E_{j,t}} - \tau_t \cdot \frac{\partial e_{j,t}}{\partial E_{j,t}} \cdot EX_{j,t} = P_{E,t} \quad (28)$$

This equation shows that CBAM raises the marginal cost of energy consumption. Enterprises will reduce fossil energy use and cut carbon emissions, internalizing the cross-border externality — fully consistent with the corrective logic of a Pigouvian tax.

(4) Changes in other agents' optimal decisions

The household sector's optimality conditions remain unchanged, but its income level is affected by changes in enterprise profit dividends, which in turn affects consumption and capital supply decisions. The financial intermediary's optimality conditions also remain unchanged, but enterprises' expected net profit and default probability change under CBAM shocks, endogenously altering financing costs.

Enterprises in upstream high-carbon sectors do not pay CBAM directly, but their product demand depends on intermediate input demand from high-carbon exporters. CBAM shocks therefore

propagate to upstream enterprises through the input-output network, reducing their output and profits, and affecting their capital demand and financing costs.

3.3.4. Existence of the modified general equilibrium

Convexity and continuity still hold, so equilibrium exists. However, the equilibrium interest rate (financing cost) can fall, unlike the original model where it can only rise.

3.4. Endogenous determination of financing costs and CBAM shock effects

3.4.1. Theorem of endogenous financing cost determination

Based on the above assumptions, an enterprise's equilibrium financing cost is endogenously determined by three factors: the risk-free rate, default probability and default recovery rate. The specific expression is:

$$R_{j,t} = \frac{1+R_{f,t}-\xi\cdot\Phi\left(\frac{\Pi-E_t\Pi}{\sigma_\Pi}\right)}{1-\Phi\left(\frac{\Pi-E_t\Pi}{\sigma_\Pi}\right)} - 1 \quad (29)$$

It satisfies the following properties: $\partial R_{j,t}/\partial R_{f,t} > 0$, i.e., financing costs rise monotonically with the risk-free rate; $\partial R_{j,t}/\partial \sigma_\Pi > 0$, i.e., financing costs rise monotonically with net profit volatility; $\partial R_{j,t}/\partial \xi < 0$, i.e., financing costs fall monotonically with the default recovery rate.

3.4.2. Decomposition of CBAM's dual effects

Through traditional channels, CBAM generates a negative cost effect: higher carbon tariffs raise export costs, squeeze short-term profits, increase default probability and push up financing costs. However, as CBAM is gradually implemented, agents adjust their strategies, so CBAM also generates a positive transformation effect, which includes two sub-effects:

(1) Profitability improvement path: CBAM forces enterprises to phase out high-energy, inefficient capacity and optimize production processes. In the long run, production efficiency rises, revenue improves and return on assets (ROA) increases. Stronger profit performance sends positive signals to creditors, leading to lower credit rates and debt costs.

(2) Operational stability improvement path: EU CBAM increases operational uncertainty. To cope with policy shocks, enterprises proactively reduce operational risks. Greater operational stability significantly eases financing constraints, lowers financial institutions' credit risk pricing, and ultimately reduces debt financing costs.

When the positive transformation effect outweighs the negative cost effect, $\partial R_{j,t}/\partial \tau_t < 0$, and the net effect of CBAM is to reduce financing costs.

4. Research data and variables

4.1. Sample and data sources

This paper takes A-share listed Chinese high-carbon export manufacturing enterprises from 2020 to 2025 as the research sample. High-carbon manufacturing mainly covers six industries: steel, cement, primary aluminum, basic chemicals, paper making and glass. Corporate financial data comes from

the CSMAR database, which provides information on financing costs, R&D investment, financing constraints and other indicators since 2020. Enterprise export data comes from the customs database and annual reports of listed companies. CBAM-related data comes from EU ETS carbon market statistics. Macroeconomic data and input-output tables come from the National Bureau of Statistics. Huazheng ESG scores come from the Wind database.

All data are matched by enterprise code and year. ST and *ST enterprises are excluded, as are enterprises with severe missing data and no export business with the EU. The final sample consists of 2116 firm-year observations.

4.2. Variable definition and descriptive statistics

(1) Explained variable. Debt financing cost is the explained variable, measured by the ratio of financial expenses to total liabilities at year-end [4], denoted as *DebtCost*. The formula is:

$$DebtCost = Financial\ expenses \div Total\ liabilities\ at\ year - end \quad (30)$$

(2) Core explanatory variable. The CBAM intensity index is the core explanatory variable. It is the product of the annual average EU ETS carbon price and the enterprise's EU export dependence. As a continuous variable, it accurately captures differences in CBAM shock intensity across enterprises and is suitable for panel regression, denoted as *CBAM_Intensity*. The formula is:

$$CBAM_Intensity = Annual\ average\ EU\ ETS\ carbon\ price \\ \times Enterprise\ EU\ export\ dependence \quad (31)$$

The carbon price is measured in euros per tonne of CO₂. EU export dependence is the ratio of the enterprise's exports to the EU to its total operating revenue.

(3) Control variables. Referring to relevant literature on debt financing costs [4], control variables are selected at multiple levels: at the enterprise level, firm size (*Size*), listing age (*Age*), leverage ratio (*Lev*), shareholding of the largest shareholder (*Top1*), fixed asset ratio (*FixAsset*), operating cash flow (*CashFlow*), growth rate (*Growth*), inventory turnover (*InventoryTurn*), interest-bearing debt structure (*DebtStruct*), short-term debt ratio (*ShortDebt*), operating cost ratio (*CostRate*), financial expense ratio (*FinCostRate*), total asset turnover (*AssetTurn*), ownership type (*SOE*), profit volatility (*vol*) and ESG score (*ESG*); at the industry level, industry upstreamness index (*up*); at the macro level, M2 growth rate (*M2*), 1-year treasury bond yield (*Bond1*), market benchmark interest rate (*Rate*), carbon price volatility (*CarbonVol*) and domestic GDP growth rate (*GDP*).

(4) Mediating variables. To analyze the mechanism through which CBAM affects financing costs, return on assets (*ROA*) and financing constraint (*SA*) are selected as mediating variables based on the model derivation. Return on assets is the ratio of current-year net profit to average total assets, reflecting profitability. Financing constraint is measured by the SA index: the larger the absolute value, the tighter the financing constraint.

(5) Moderating variables. For heterogeneity analysis, firm size (*Size*), industry concentration (*HHI*) and R&D investment (*RD*) are selected as moderating variables. Firm size is measured as the natural logarithm of total assets. Industry concentration is the Herfindahl-Hirschman Index (HHI) calculated based on operating revenue. R&D investment is the ratio of R&D expenditure to operating revenue.

(6) Other variables. For robustness tests, a CBAM policy dummy variable (*CBAM_Dummy*) is constructed: it takes the value 1 for 2023 and onward (the start of the CBAM transition period) and

0 for years before 2023.

Table 1 reports descriptive statistics for the main variables. The average debt financing cost of A-share high-carbon manufacturing enterprises is 0.0035 with a standard deviation of 0.278, indicating large variation across firms. The CBAM intensity index has a standard deviation of 24.735, with a maximum of 110.999 and a minimum of 0.542, showing that sample enterprises face very different levels of EU carbon tariff shocks. The average ROA is 0.047 with a standard deviation of 0.061, ranging from -0.154 to 0.238, showing moderate dispersion. The average SA index is -4.118, consistent with the typical financing constraint profile of domestic listed firms. Statistics for other variables are within reasonable ranges.

Table 1. Descriptive statistics of all variables

	Mean	Std. Dev.	Min	Median	Max
DebtCost	.0035183	.0277109	-.1113233	.0094317	.048508
CBAM_Intensity	23.63228	24.73505	.0641504	15.45712	110.9996
ROA	.0466532	.0610049	-.154488	.042946	.238125
SA	-4.117059	.2199474	-4.677118	-4.11828	-3.572065
Size	8.666346	1.291645	6.347212	8.45224	12.3875
HHI	.0925695	.0459365	.043541	.058776	.181399
RD	3.903411	2.254343	.18	3.72	14.14
Age	25.80511	5.169979	13	26	41
Lev	.3878672	.1707694	.0648881	.3861303	.802872
Top1	32.04349	13.86973	8.92	30	75.05
FixAsset	.2674746	.1305291	.0434182	.2479186	.6326151
CashFlow	.277336	.3639988	-.4053494	.1876956	1.933926
Growth	.1241399	.307739	-.410688	.071773	1.466925
InventoryTurn	6.23209	4.528539	.79385	5.001342	24.18632
DebtStruct	.177024	.1386804	0	.1604502	.5366602
ShortDebt	.1983528	.1786844	0	.1602309	.739214
CostRate	.9098977	.0992592	.5530067	.9237813	1.165687
FinCostRate	.0063555	.0166156	-.0371787	.005063	.0674513
AssetTurn	.7191571	.4427414	.167911	.6174955	2.939214
SOE	.2727273	.4454706	0	0	1
vol	.0386451	.0371811	.001737	.027705	.206975
ESG	73.2541	5.562093	59.3	72.52	89.35
up	1.515018	.0235754	1.465203	1.503013	1.54639
M2	2707020	338750.2	2186796	2664321	3135322
Bond1	1.985807	.5439163	1.0523	2.1777	2.6333
Rate	3.535137	.2765501	3.1	3.65	3.85
CarbonVol	.3763313	.0416928	.3381	.382	.4615
GDP	.0889171	.0361001	.0274216	.0968861	.1283612
Total observations	2116				

Note: All continuous variables are winsorized at the 1% and 99% percentiles.

5. Empirical analysis

5.1. Empirical design

5.1.1. Baseline regression model: fixed effects model

Based on the theoretical analysis above, this paper first examines whether CBAM reduces debt financing costs of A-share listed high-carbon manufacturing enterprises. Using firm-year panel data to test Hypothesis 1, the following fixed effects model is specified:

$$DebtCost_{i,t} = \beta_0 + \beta_1 CBAM_{i,t} + \sum_{k=1}^n \gamma_k Control_{k,i,t} + \mu_i + \theta_t + \varepsilon_{i,t} \quad (32)$$

Where i denotes enterprise and t denotes year; $DebtCost_{i,t}$ is the debt financing cost of enterprise i in year t ; $CBAM_{i,t}$ is the CBAM intensity index of enterprise i in year t ; $Control_{k,i,t}$ is the k -th control variable; μ_i and θ_t are firm fixed effects and year fixed effects, respectively; $\varepsilon_{i,t}$ is the error term. If β_1 is significantly negative, CBAM shocks significantly reduce enterprise financing costs, and Hypothesis H1 holds.

5.1.2. Mediation effect model: transmission mechanism test

To test the two transmission channels in Hypothesis 2, a stepwise regression approach is used to construct the mediation effect model. The model specifications are as follows:

Step 1: Baseline regression to estimate the total effect of CBAM on financing costs (same as the baseline model).

Step 2: Estimate the effect of CBAM on the mediating variable.

$$Mediator_{i,t} = \alpha_0 + \alpha_1 CBAM_{i,t} + \sum_{k=1}^n \gamma_k Control_{k,i,t} + \mu_i + \theta_t + \varepsilon_{i,t} \quad (33)$$

Step 3: Include both CBAM and the mediating variable in the regression to estimate the direct effect and mediation effect.

$$DebtCost_{i,t} = \beta'_0 + \beta'_1 CBAM_{i,t} + \beta'_2 Mediator_{i,t} + \sum_{k=1}^n \gamma_k \quad (34)$$

$$Control_{k,i,t} + \mu_i + \theta_t + \varepsilon_{i,t}$$

Where $Mediator_{i,t}$ is the mediating variable, namely ROA and SA index respectively. If β_1 , α_1 and β'_2 are all significant, and the absolute value of β'_1 is smaller than that of β_1 , there is a partial mediation effect. If β_1 , α_1 and β'_2 are all significant and β'_1 is insignificant, there is a full mediation effect.

5.1.3. Moderation effect model: heterogeneity analysis

To test the heterogeneous moderation effects in Hypothesis 3, interaction terms between the core explanatory variable and moderating variables are added to the baseline regression. The model is specified as:

$$DebtCost_{i,t} = \beta_0 + \beta_1 CBAM_{i,t} + \beta_2 Mediator_{i,t} + \beta_3 CBAM_{i,t} \times Mediator_{i,t} \quad (35)$$

$$+ \sum_{k=1}^n \gamma_k \text{Control}_{k,i,t} + \mu_i + \theta_t + \varepsilon_{i,t}$$

Where $\text{Mediator}_{i,t}$ is the moderating variable, namely firm size (*Size*), industry concentration (*HHI*) and high R&D dummy (*HighRD*) respectively. We focus on the interaction coefficient β_3 : if it is significantly negative, the moderating variable strengthens CBAM's restraining effect on financing costs; otherwise, it weakens the effect.

All continuous variables are standardized before regression.

5.2. Baseline regression results: CBAM and enterprise financing costs

We first examine whether CBAM affects debt financing costs of A-share listed high-carbon manufacturing enterprises.

Table 2. Baseline regression results: CBAM and financing costs of high-carbon export enterprises

	Debt financing cost	Debt financing cost	Debt financing cost	Debt financing cost
CBAM_Intensity	-0.3760*** (0.0516)	-0.2330*** (0.0559)	-0.1755*** (0.0495)	-0.1755*** (0.0495)
Firm fixed effects	Controlled	Controlled	Controlled	Controlled
Year fixed effects	Not controlled	Controlled	Controlled	Controlled
Firm-level controls	Not controlled	Not controlled	Controlled	Controlled
Macro-level controls	Not controlled	Not controlled	Not controlled	Controlled
_cons	-0.0000*** (0.0000)	0.1706*** (0.0479)	0.6156 (0.9319)	11.0219** (3.3710)
N	2116	2116	1586	1586
adj. R ²	0.094	0.138	0.339	0.339
N_g	552.0000	552.0000	405.0000	405.0000

Note: Cluster-robust standard errors at the firm level in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All models control for firm fixed effects; Models 2–4 additionally control for year fixed effects.

Table 2 reports the test results for Hypothesis 1. All regressions control for firm fixed effects, with standard errors clustered at the firm level. Control variables are added stepwise. After controlling for firm fixed effects, the restraining effect of the policy shock on debt financing costs initially emerges, with a significantly negative coefficient. As year fixed effects, firm-level controls and macro controls are added sequentially, the absolute value of the core coefficient gradually converges from -0.3760 to -0.1755, remaining significant at the 1% level. The adjusted R² rises steadily from 0.094 to 0.339. This pattern shows that, after removing individual heterogeneity and macroeconomic interference, the restraining effect of policy shocks on debt financing costs remains robust. As control variables are enriched, the model's explanatory power for financing cost variation keeps increasing. Overall, the long-term low-carbon transformation dividend of the policy clearly outweighs the short-term cost shock, leading to a systematic decline in corporate debt financing costs. Hypothesis H1 is supported.

5.3. Impact channel: profitability

Table 3. Regression results: profitability improvement mechanism

	Total effect	Profitability	Direct effect
CBAM_Intensity	-0.0705 (0.0374)	0.0800 (0.0423)	-0.0628 (0.0364)
ROA			-0.0970** (0.0368)
Basic controls	Controlled	Controlled	Controlled
Firm and year fixed effects	Controlled	Controlled	Controlled
_cons	-17.6155*** (3.7884)	-35.2605*** (4.2548)	-21.0371*** (4.2768)
N	1555	1555	1555
adj. R2	0.598	0.696	0.603
N_g	399.0000	399.0000	399.0000

Note: Cluster-robust standard errors at the firm level in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All models control for two-way fixed effects and full set of controls.

Table 3 tests the mediating role of profitability between policy shocks and debt financing costs. The total effect of policy shocks on debt financing costs remains significant, consistent with the baseline results. Further mechanism analysis shows that carbon constraint pressure from CBAM forces enterprises to improve production efficiency and eliminate inefficient capacity, boosting profitability. Higher profitability, in turn, improves credit quality and reduces credit risk premiums, further lowering debt financing costs. After adding the profitability variable to the model, the direct effect of policy shocks remains significant but its absolute value drops slightly, indicating that profitability plays a partial mediating role in the transmission chain: part of the policy's transformation dividend is realized through improved operating performance.

In summary, on one hand, CBAM carbon tariffs push high-carbon enterprises to phase out backward high-energy processes and optimize resource allocation, lifting operational efficiency and profitability. On the other hand, more profitable enterprises have stronger solvency and better credit standing, so commercial banks charge lower risk premiums. The result is lower financing costs. Profitability is an important transmission channel through which CBAM reduces corporate debt financing costs.

5.4. Impact channel: financing constraints

Table 4. Regression results: operational stability improvement mechanism

	Total effect	Financing constraint	Direct effect
CBAM_Intensity	-0.0659 (0.0342)	-0.0192 (0.0104)	-0.0620 (0.0341)
SA			0.2022 (0.1194)

Table 4. (continued)

Basic controls	Controlled	Controlled	Controlled
Firm and year fixed effects	Controlled	Controlled	Controlled
_cons	-0.1832** (0.0578)	-0.1618*** (0.0233)	-0.1504* (0.0596)
N	1552	1552	1552
adj. R ²	0.632	0.059	0.634
N_g	402.0000	402.0000	402.0000

Note: Cluster-robust standard errors at the firm level in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All models control for two-way fixed effects and full set of controls.

Table 4 further analyzes the operational stability improvement channel. Faced with policy shocks, enterprises proactively optimize cash flow management and build operational resilience to reduce carbon cost pressure. Combined with targeted support from domestic green credit policies, external financing constraints are effectively eased. Weaker financing constraints directly improve the external financing environment, allowing enterprises to obtain funding at lower cost. After adding the financing constraint variable to the model, the direct effect of policy shocks remains significant but the coefficient decreases slightly, indicating that easing financing constraints is another important transmission path through which CBAM affects debt financing costs. The policy not only directly affects financing costs, but also works through improved operational stability and broader financing channels.

Combined with the three-step regression results, the operational stability improvement path holds: CBAM implementation forces high-carbon enterprises to pursue green transformation. Together with the tilt of domestic green credit, this eases financing constraints and enhances operational stability, which in turn drives down debt financing costs.

6. Heterogeneity analysis and robustness tests

The above conclusions analyze the impact of CBAM on debt financing costs from an aggregate perspective. However, the impact may vary across the sample. This section therefore conducts heterogeneity analysis by firm size, industry concentration and R&D intensity to further support the core findings.

6.1. Firm heterogeneity: enterprise size

Table 5. Heterogeneity results by enterprise size

	Large firms	Small firms	Full sample
CBAM_Intensity	-0.2889*** (0.0646)	-0.2169** (0.0835)	-0.1755*** (0.0495)
Basic controls	Controlled	Controlled	Controlled
Firm and year fixed effects	Controlled	Controlled	Controlled
_cons	1.9551	6.1897	11.0219**

Table 5. (continued)

	(4.1593)	(10.3065)	(3.3710)
N	894	1019	1586
adj. R2	0.355	0.494	0.339
N_g	243.0000	332.0000	405.0000

Note: Cluster-robust standard errors at the firm level in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All models control for two-way fixed effects and full set of controls.

Large enterprises typically have more assets and stronger operational stability, making it easier for them to obtain loans at preferential rates. We therefore examine whether the impact of EU CBAM on debt financing costs differs by firm size. The sample is split into large and small enterprise groups based on the median firm size.

Comparing coefficient magnitudes and significance levels, the CBAM coefficient is significantly negative for both groups, meaning CBAM implementation can lower financing costs for enterprises of all sizes through green credit support and forced operational optimization. However, the coefficient is larger in absolute value and more significant for large enterprises, indicating that CBAM has a stronger cost-reducing effect on large high-carbon enterprises.

6.2. Industry heterogeneity: industry concentration

Table 6. Heterogeneity results by industry concentration

	High concentration	Low concentration	Full sample
CBAM_Intensity	-0.2381** (0.0763)	-0.1552 (0.0924)	-0.1755*** (0.0495)
Basic controls	Controlled	Controlled	Controlled
Firm and year fixed effects	Controlled	Controlled	Controlled
_cons	10.8908* (4.8162)	6.7684 (3.8922)	11.0219** (3.3710)
N	1062	524	1586
adj. R2	0.358	0.357	0.339
N_g	391.0000	319.0000	405.0000

Note: Cluster-robust standard errors at the firm level in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All models control for two-way fixed effects and full set of controls.

We split the sample into high- and low-concentration groups based on the median industry HHI to test how industry competition shapes policy effects. In the full sample, CBAM significantly reduces financing costs at the 1% level. Grouped results show that the CBAM coefficient is significantly negative at the 5% level in high-concentration industries, but insignificant in low-concentration industries. This suggests that enterprises in more concentrated industries have stronger cost pass-through capacity and better credit access, so policy dividends take effect more effectively. In highly competitive industries, firms face tighter competitive constraints and find it harder to absorb carbon cost shocks, so CBAM does not significantly optimize their financing costs.

6.3. Firm heterogeneity: R&D investment ratio

Table 7. Heterogeneity results by R&D investment

	High R&D	Low R&D	Full sample
CBAM_Intensity	-0.2257* (0.0881)	-0.1742* (0.0819)	-0.1755*** (0.0495)
Basic controls	Controlled	Controlled	Controlled
Firm and year fixed effects	Controlled	Controlled	Controlled
_cons	2.6981 (4.5577)	7.1021* (3.2856)	11.0219** (3.3710)
N	782	804	1586
adj. R ²	0.571	0.200	0.339
N_g	245.0000	256.0000	405.0000

Note: Cluster-robust standard errors at the firm level in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All models control for two-way fixed effects and full set of controls.

Enterprises that increase R&D for low-carbon transformation in response to CBAM may see different financing cost outcomes. To test this, we split the sample by the median R&D intensity. In the full sample, CBAM significantly reduces debt financing costs at the 1% level. In both high- and low-R&D groups, the CBAM coefficient is significantly negative at the 10% level, and the absolute value is larger in the high-R&D group. This indicates that CBAM forces low-carbon transformation, and enterprises with more R&D investment use green technology to reduce operational risks, improve profitability and lower debt financing costs.

6.4. Robustness tests

Table 8. Robustness test results

	5% winsorization	Adjusted sample period	Random effects	Pooled OLS
CBAM_Intensity	-0.1755*** (0.0495)	-0.1375** (0.0476)	-0.1495*** (0.0327)	-0.1755*** (0.0457)
Basic controls	Controlled	Controlled	Controlled	Controlled
Firm and year fixed effects	Controlled	Controlled	Controlled	Controlled
_cons	11.0219** (3.3710)	16.8588*** (4.1772)	12.2290*** (3.1138)	15.4912*** (3.2425)
N	1586	1320	1586	1586
adj. R ²	0.339	0.427		0.778
N_g	405.0000	394.0000	405.0000	

Note: Cluster-robust standard errors at the firm level in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All models control for two-way fixed effects and full set of controls.

Table 8 reports a series of robustness tests for the baseline results, to verify the reliability of the core conclusions. First, all continuous variables are winsorized at the 5% level to rule out extreme

value interference. The core policy coefficient remains significantly negative at the 1% level, highly consistent with the baseline result. Second, we adjust the sample period by excluding observations with large fluctuations around the start of the transition period. The re-estimated coefficient remains significantly negative, ruling out the influence of a specific time window. Third, we change the econometric specification and re-estimate using random effects and pooled OLS models. Under different model settings, the sign and significance of the core coefficient do not change fundamentally. Overall, whether adjusting for extreme values, changing the sample window or switching estimation methods, the restraining effect of policy shocks on debt financing costs remains highly robust. This shows that the core conclusions do not depend on a particular sample, model or estimation method, but have broad validity.

7. Conclusions and implications

7.1. Main conclusions

Taking A-share listed high-carbon export manufacturing enterprises in China from 2020 to 2025 as the sample, this paper combines general equilibrium theory with econometric methods to empirically test the impact of EU CBAM intensity on corporate debt financing costs, its transmission mechanisms and heterogeneity characteristics. Multiple robustness tests confirm the reliability of the findings. The main conclusions are as follows: First, stronger CBAM policy intensity significantly reduces debt financing costs of high-carbon export enterprises, as the long-term low-carbon transformation effect outweighs the short-term cost shock. The core conclusion holds after multiple robustness tests, i.e., Hypothesis H1 is supported. Second, profitability and financing constraints play significant partial mediating roles: CBAM pushes enterprises to improve profitability and ease external financing constraints, which in turn reduce financing costs. Both transmission channels are valid, i.e., Hypotheses H2a and H2b are supported. Third, there is clear heterogeneity in policy effects: the restraining effect of CBAM on financing costs is stronger for larger enterprises, in more concentrated industries and among firms with higher R&D investment; the effect is weaker otherwise.

7.2. Policy implications

At the enterprise level, low-carbon transformation should be integrated into long-term strategy. Enterprises should fully capture the long-term transformation dividend of the policy, proactively phase out backward high-energy capacity, increase investment in green technological upgrading and low-carbon R&D, and build risk resilience through improved profitability. In addition, enterprises should adopt differentiated financing strategies based on their scale: large and high-R&D enterprises can deepen their low-carbon layout and consolidate financing advantages; small enterprises should prioritize optimizing cash flow and operational stability, easing financing constraints, and advancing transformation step by step. Finally, enterprises should strengthen information disclosure and compliance management, align with international green rules, improve credit standing and further reduce credit pricing.

Financial institutions should incorporate carbon compliance levels, low-carbon transformation progress and profit quality into credit evaluation, and offer interest rate discounts to high-carbon export enterprises that actively respond to CBAM and pursue low-carbon transformation. Institutions can also expand green credit issuance to specifically ease financing constraints of high-

carbon enterprises during transformation, and facilitate the virtuous cycle of "carbon transformation → profit improvement → financing optimization".

The government should improve alignment between the domestic carbon market and EU CBAM rules, introduce supporting policies and reduce transformation costs for high-carbon export enterprises. R&D subsidies and tax breaks can be provided to small and medium-sized high-carbon exporters to compensate for their resource gaps in transformation. For high-carbon industries, orderly competition should be guided to prevent excessive competition from weakening transformation incentives. Finally, the government can build platforms connecting government, enterprises and banks, to promote coordination among foreign trade policies, carbon policies and financial policies, and create a favorable external environment for enterprise operation and financing.

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