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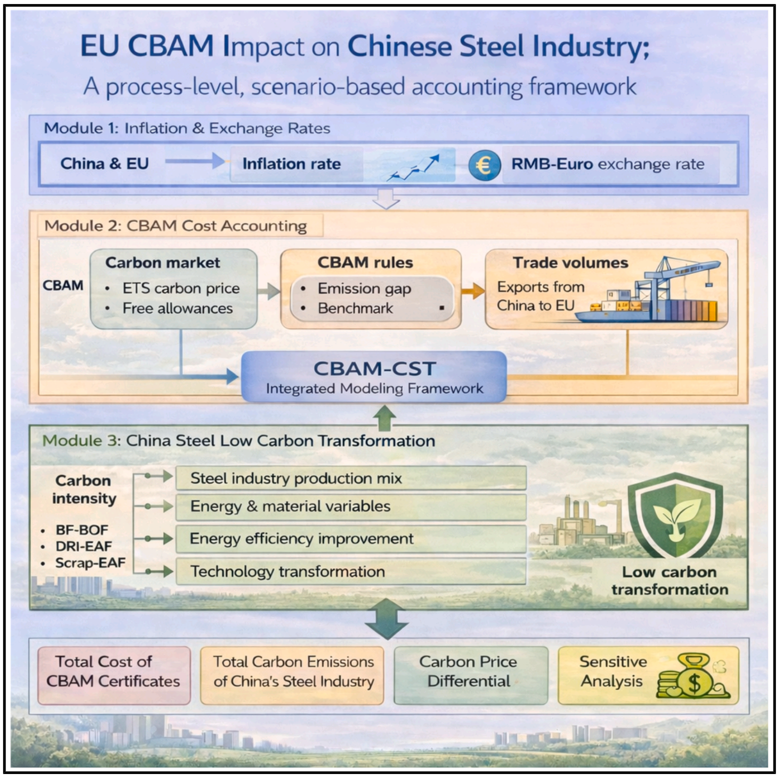
Quantifying the long-term impact of carbon border adjustment mechanism on Chinese steel industry

Graphical abstract



Highlights

- A dynamic model simulates long-term CBAM impacts on China's steel industry
- Multiple scenarios assess CBAM cost drivers under different decarbonization paths
- EU ETS carbon price is the primary determinant of CBAM certificate costs
- Low-carbon technologies significantly reduce CBAM burden on steel exports

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In brief

Environmental policy; global carbon cycle

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Quantifying the long-term impact of carbon border adjustment mechanism on Chinese steel industry

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SUMMARY

Mitigating climate change has become a global consensus, yet uneven carbon prices and fragmented policies raise concerns about carbon leakage and trade competitiveness. The European Union's carbon border adjustment mechanism (CBAM) levies charges on imported goods based on embedded emissions. This study develops a process-level accounting framework to assess the long-term impacts of CBAM on China's steel industry. Linking production routes, emission intensities, and carbon pricing, we estimate certificate costs of 0.29–12.3 billion CNY by 2050 across scenarios. Sensitivity analysis identifies the EU emissions trading system price as the primary driver, while low-carbon technologies such as direct reduced iron (DRI) and electric arc furnace (EAF) routes significantly reduce the burden. Inclusion of steel in China's national carbon market could offset up to 11.44% of blast furnace-basic oxygen furnace (BF-BOF) and 18.78% of DRI-EAF costs. The findings highlight the importance of internationally comparable carbon accounting and reinvesting CBAM revenues into green innovation in developing economies.

INTRODUCTION

Addressing carbon leakage resulting from discrepancies in climate policies has become an urgent challenge for global decarbonization.[1] In this context, the european commission proposed the carbon border adjustment mechanism (CBAM) in July 2021 as part of its "Fit for 55" package, with the regulation officially adopted in October 2023.[2] CBAM is designed to extend the EU's internal carbon pricing regime to imports by levying carbon-related charges on goods based on their embedded emissions, thereby aligning the treatment of foreign producers with that of EU firms covered by the emissions trading system (ETS).[3] While empirical evidence suggests that observed carbon leakage has historically been limited due to efficiency improvements and transitional safeguards,[4,5] persistent disparities in carbon prices and fragmented international coordination continue to generate competitiveness concerns and relocation risks.[6,7] Against this backdrop, the EU's CBAM is presented by the european commission as a mechanism intended to address residual carbon leakage, ensure fair competition, and align the treatment of imports with the EU's domestic carbon pricing framework.[8–11] By targeting a set of emission-intensive and trade-exposed sectors including steel, cement, aluminum, fertilizer, electricity, and hydrogen products,[12] CBAM aims to reshape global trade incentives while advancing climate policy objectives.

Among the CBAM-covered sectors, steel is of particular relevance due to its high carbon intensity, large trade volumes, and central role in industrial decarbonization. Steel production accounts for a substantial share of global industrial emissions and represents a major component of CBAM-exposed trade flow.[13] China is the world's largest steel producer, accounting for more than half of global crude steel output, and remains a significant exporter to the EU market. China accounted for approximately 54% of global crude steel production in 2022,[14] with 6.47 million tons exported to the EU, representing over half the total value of CBAM-covered Chinese exports.[15] As a traded product with pronounced differences in production routes and carbon intensity between China and the EU—particularly the dominance of blast furnace-basic oxygen furnace (BF-BOF) routes in China versus higher electric arc furnaces (EAF) shares in Europe—steel is especially sensitive to CBAM-induced carbon cost adjustments. These characteristics make the sector a critical test case for assessing how border carbon pricing interacts with technology choice, cost pass-through, and competitiveness.[16–18] Under China's dual-carbon targets of peaking emissions by 2030 and achieving carbon neutrality by 2060, understanding how CBAM affects the steel sector's long-term decarbonization pathway is therefore essential for aligning industrial transformation with evolving international climate policy constraints.

The rapidly growing CBAM literature encompasses diverse perspectives, including policy design, legal legitimacy,[19] macroeconomic implications,[20] and trade equity concerns.[21–23] The mechanism implicitly requires global convergence in carbon pricing, which could impose substantial compliance costs

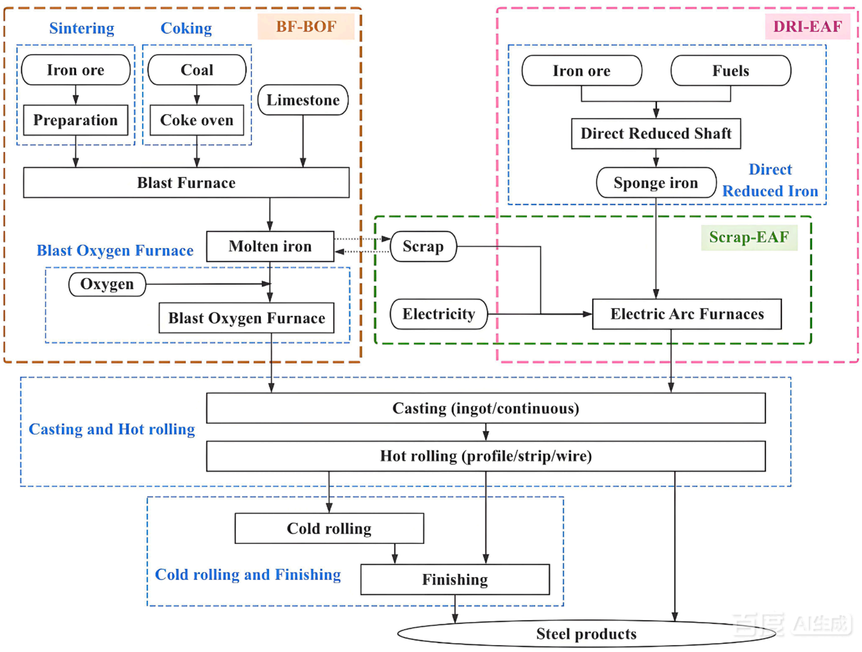

Figure 1. Predominant routes of steel production

This figure illustrates the three main steel production processes including the BF-BOF, DRI-EAF, and Scrap-EAF route. Arrows indicate the material flow between stages. The BF-BOF, route is outlined with an orange dashed box and primarily uses iron ore, coal, and limestone as raw materials, undergoing sintering, coking, and blast furnace reduction, followed by steelmaking in the basic oxygen furnace. The DRI-EAF route is outlined with a pink dashed box and produces sponge iron through the reduction of iron ore using fuels in a direct reduction shaft, which is then melted in electric arc furnaces. The Scrap-EAF route is shown with a green dashed box and uses scrap steel as input, which is melted using electricity in electric arc furnaces. All routes converge at the downstream stages of casting, hot rolling, cold rolling, and finishing, ultimately producing a variety of steel products.

on energy-intensive industries in countries with developing carbon markets.[24,25] There remains ongoing debate on whether CBAM is an environmental safeguard or a disguised trade barrier.[26] For the steel sector, recent studies have begun exploring CBAM's distributional and technological effects, such as induced scrap recycling,[27,28] production cost increases,[29,30] and competitiveness risks for exporters from developing economies.[31] However, most existing research remains top-down and short-term,[32] typically relying on computable general equilibrium (CGE) or static trade models that capture aggregate impacts but overlook process-level heterogeneity,[33] dynamic emission pathways, and feedback between EU carbon pricing and domestic decarbonization.[34] Few studies systematically quantify how CBAM interacts with long-term technology adoption—particularly hydrogen metallurgy, electrification, and carbon capture—within China's steel industry.

To address these gaps, this study integrates the technical details of CBAM implementation with China's steel-sector transformation pathways under decarbonization goals. We adopt a bottom-up process-level scenario-based model, the carbon border adjustment mechanism—China steel transformation (CBAM-CST), that links production routes, emission intensities, carbon prices and trade flows through 2050. The CBAM-CST model functions as both a quantitative assessment tool and a policy-support framework for industry stakeholders and policymakers by supporting multi-scenario simulations and parameter customization as well as potential Sino-EU dialogues on CBAM. Moreover, its modular design offers a transferable methodology foundation for evaluating CBAM's implications in other carbon-intensive sectors, thereby extending the analytical frontier of climate policy and international trade research. Detailed model descriptions, including policy scenario settings, and data sources are provided in the STAR Methods, with supplementary model architecture shown in Method S3.

RESULTS

Typical steel production processes and key elements of CBAM regulations

China's steel industry primarily relies on three major production routes, each characterized by distinct raw materials, technologies, and carbon emission profiles, as illustrated in Figure 1. The BF-BOF process is the currently dominant route in China, accounting for approximately 90% of national steel output in 2021. This route primarily depends on iron ore, coal, and limestone and involves multiple energy-intensive stages, including sintering, coking, blast furnace ironmaking, basic oxygen steelmaking, continuous casting, and rolling. Due to its long and multi-stage configuration, it is often referred to as the "long process".[35] Detailed process flows and emission boundaries for this route are provided in Method S2. The BF-BOF route is also the most carbon-intensive, with an average emission of approximately 2.3 tCO_2 per tonne of steel.[36]

The second major route is the EAF process, which comprises two subtypes depending on feedstock: the scrap-based EAF (Scrap-EAF) and the direct reduced iron- EAF (DRI-EAF) The Scrap-EAF route utilizes recycled scrap steel as the primary input and currently contributes about 10% of China's steel output, with a comparatively low carbon intensity of 0.6 tCO_2 per tonne.[36] In contrast, the DRI-EAF route, though less common in China, relies on DRI produced via natural gas or hydrogen reduction, exhibiting a moderate carbon intensity of approximately 1.4 tCO2 per tonne.[36] Detailed process flows and emission boundaries for EAF-based production are shown in Method S2.

Table 1. Steel products covered by CBAM

Product category	Production process
Sinter ore	/
Alloys (ferromanganese, ferrosilicon, ferrochrome)	/
Pig iron	Blast furnace route
	Smelting reduction
Direct reduced iron (DRI)	/
Crude steel	Basic oxygen furnace (BOF) route
	Electric arc furnace (EAF) route
Steel products	BF-BOF route
	DRI-EAF route
	Scrap-EAF route

Product categories and corresponding production processes are classified according to Regulation (EU) 2023/956 and the European Commission's CBAM implementation guidance (2024). The listed products represent the main categories of iron and steel goods subject to CBAM coverage, organized by their predominant production routes. The BF-BOF, DRI-EAF, and Scrap-EAF routes correspond to integrated, hydrogen-based, and scrap-based processes, respectively.

Given the technological and emission heterogeneity among China's steel production routes, this study adopts the number of CBAM certificates required for steel products exported from China to the EU as the key quantitative indicator to evaluate the impact of the mechanism. The CBAM is implemented in two stages: a transitional phases (from October 1, 2023 to December 31, 2025), during which EU importers must report the embedded carbon emissions of imported goods but are not required to purchase certificates, and a definitive regime starting on January 1, 2026, when importers must purchase certificates covering the excess embedded emissions of imported goods. Each certificate representing one tonne of CO_2 equivalent, and the required number of certificates depends mainly on the carbon intensity of the exported products, export volumes, the EU ETS carbon price, and any carbon costs already paid in the exporting country. Additional policy details, including transitional free allocations and adjustment mechanisms, are provided in the STAR Methods.

Steel products covered by CBAM are listed in Method S1 following regulation (EU 2023/956)[37] and are classified using combined nomenclature (CN) codes. In total, 41 four-digit CN codes are included, comprising 28 from chapter 72 (e.g., pig iron and piegel iron) and 13 from chapter 73 (e.g., seamless tubes and hollow profiles). Following the European Commission (2024) CBAM implementation guidance, steel products are grouped into ten categories based on production processes, as shown in Table 1. In 2022, China exported 6.47 million tonnes of CBAM-covered steel products to the EU.[15] Among these, BF-BOF products accounted for 5.76 million tonnes (89.04%), while DRI-EAF and Scrap-EAF exports totaled 6,600 tonnes and 633,200 tonnes, respectively. Upstream intermediate products such as sinter ore, ferroalloys, pig iron, DRI, and crude steel accounted for about 70,000 tonnes. This distribution mirrors the dominance of the BF-BOF route in China's steel exports to the EU and the limited penetration of lower-carbon production pathways, underlining the need to assess CBAM's effects from a process-specific perspective.

Changes in carbon intensity of Chinese steel products covered by CBAM

Based on the established research framework and accounting methodology (see STAR Methods), Figure 2 presents the contribution of different energy sources to carbon emissions from Chinese steel production across three technological routes—BF-BOF, DRI-EAF, and Scrap-EAF—under three policy scenarios (BAU, DCS, and NES, see Method S3 for scenario settings). Each panel in Figure 2 corresponds to one production route under a given scenario, depicting how the shares of coking coal, natural gas, biomass, electricity, heat, hydrogen, and process-related emissions evolves from 2020 to 2050. The results indicate that the BF-BOF route remains predominantly coal-dependent in all scenarios, although the share of coal declines moderately under DCS and NES. In contrast, the DRI-EAF route exhibits a clear shift from electricity toward hydrogen use, achieving substantial emissions reductions in low-carbon scenarios. The Scrap-EAF route, which already features a low-emission profile, benefits most from power sector decarbonization, reaching nearly zero emissions by 2050 under the NES scenario. It should be noted, however, that the substitution between primary (BF-BOF) and secondary (EAF/scrap-based) steelmaking is constrained by scrap availability, product quality requirements, and the long lifetimes of existing blast-furnace assets. Therefore, scenarios assuming accelerated scrap utilization should be interpreted as upper-bound potentials rather than fully attainable short-term outcomes. These results highlight the pivotal role of clean energy carriers, particularly electricity and hydrogen, in driving the decarbonization of China's steel industry.

Figure 3 illustrates the long-term evolution of carbon intensity for Chinese steel products from 2020 to 2050, accounting for both direct and indirect emissions. across production routes. Overall, carbon intensity declines over time across all routes, though the magnitude of reduction differs by energy mix and policy scenario. For the BF-BOF route, which relies heavily on coal, carbon intensity decreases only slightly—from 2.08 t CO_2/t in 2020 to 1.94 t CO_2/t in 2050—under BAU, reflecting its structural fossil-fuel dependence. Under the net-zero scenario, however, the introduction of clean electricity and hydrogen metallurgy achieves a deeper reduction to 0.90 t CO_2/t, consistent with the rising share of hydrogen (from 2% to 9.97%), and electricity (from 20% to 50%) in the energy mix. The DRI-EAF route demonstrates greater decarbonization potential with carbon intensity falling from 1.69 t CO_2/t to 1.00 t CO_2/t under BAU and reaching 0.02 tons CO_2/t under the net-zero pathway, primarily due to hydrogen-based direct reduction and renewable electricity integration. Meanwhile, the Scrap-EAF route, inherently low in emissions, decreases from 0.55 t CO_2/t in 2020 to 0.09 t CO_2/t in 2050, reflecting its high energy efficiency and compatibility with a fully decarbonized power grid.

Total CBAM certificates for Chinese steel products

This study applies a multi-scenario modeling framework (Method S3) to estimate the potential range of CBAM certificates

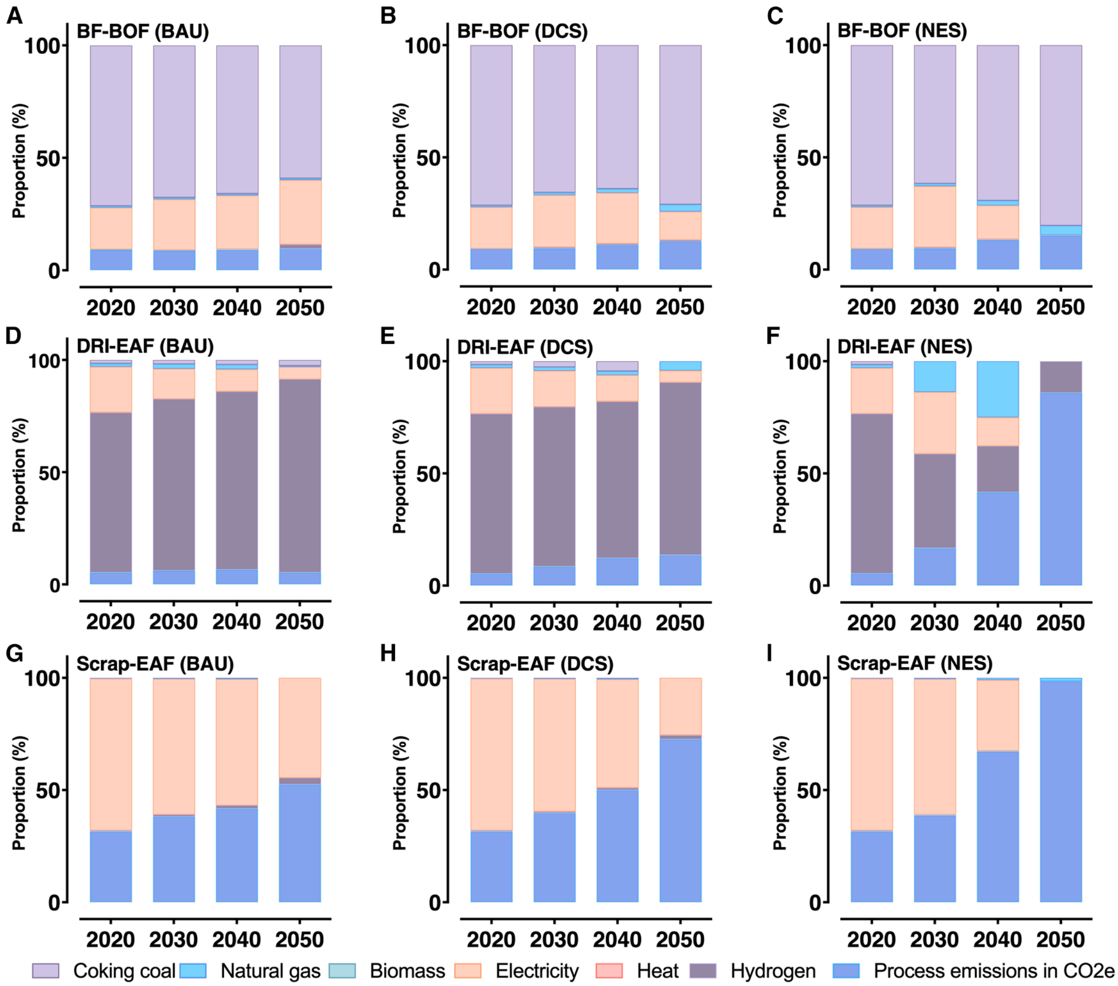

Figure 2. Carbon emissions by energy sources across different steel production routes in China

This figure illustrates the contribution of various energy sources to carbon emissions from Chinese steel production across three technological routes. (A–C) show results for the BF-BOF route, (D–F) for the DRI-EAF route, and (G–I) for the Scrap-EAF route, under the BAU, DCS, and NES scenarios, respectively. Colored bars indicate the proportional contributions of various energy sources, including coking coal, natural gas, biomass, electricity, heat, hydrogen, and process emissions to total carbon emissions. The horizontal axis represents years, while the vertical axis denotes the share of total emissions attributable to each source.

fee associated with Chinese steel product exports to the EU, as shown in Figure 4. The estimated range represents the upper and lower bounds of possible CBAM obligations, reflecting uncertainties in policy evolution, market responses, and technological progress, thereby capturing both optimistic and pessimistic outcomes. In the baseline specification, Chinese steel export volumes to the EU follow a stable, historically calibrated logarithmic trajectory, while alternative projections based on linear and power-exponential models are examined in Method S7.2. Under the BAU scenario, beginning in 2026, the annual CBAM certificates for Chinese steel exports to the EU are projected at approximately 290 million CNY, equivalent to 2.16% of the total export value of China's steel industry. By 2050, these figure rises sharply to 12.3 billion CNY, indicating a substantial escalation of the carbon cost burden over time. Notably, the projected 2050 CBAM cost nearly equals the total export value of China's steel exports to the EU in 2022, underscoring the magnitude of the challenge. In dynamics terms, CBAM certificates fee under BAU is expected to grow at an average annual rate of 35% between 2026 and 2035, driven primarily by the progressive phase-out of free allowances in the EU ETS, before slowing to around average 7% per year after 2035.

To assess the influence of key parameters on CBAM outcomes, we further conducted single-factor and two-factors sensitivity analyses, as illustrated in Figure 5. Under high EU-ETS carbon price scenarios, the total CBAM certificates cost could reach 22.96 billion CNY by 2050 (see Figure 5A), far exceeding BAU estimates. Conversely, accelerated adoption of low-carbon technologies within China's steel sector significantly reduces CBAM costs across all scenarios. In the most optimistic scenario, total CBAM fee fall to as low as 2.96 billion CNY by 2050 (see Figure 5A). However, Figure 5B shows that even with aggressive decarbonization, persistently high EU-ETS carbon price can still result in higher CBAM costs than those

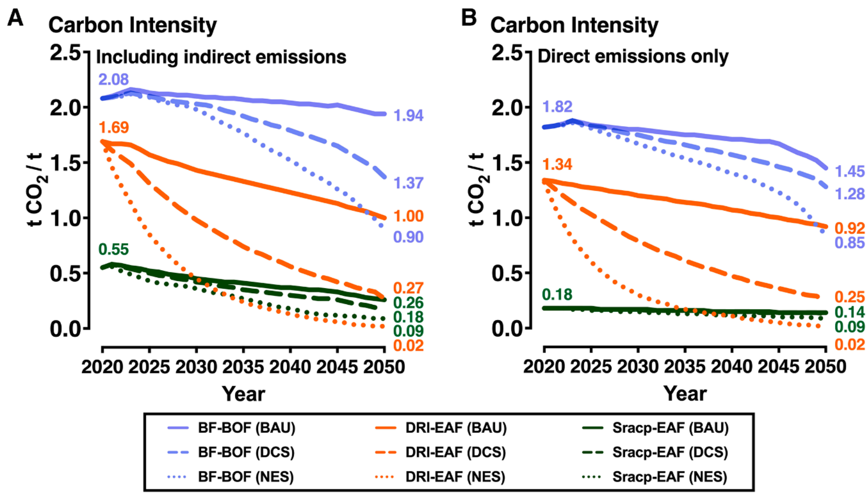

Figure 3. Carbon intensity trajectories of Chinese steel products by production route

(A) Includes both direct and indirect emissions, while (B) considers only direct emissions. The purple, orange, and green lines represent steel products produced via the BF-BOF, DRI-EAF, and Scrap-EAF routes, respectively. Solid, dashed, and dotted lines correspond to the BAU, DCS, and NES scenarios.

under the BAU baseline. This suggests that external carbon price dynamics in the EU exert a stronger influence on export costs than domestic emission reduction efforts alone. Figures 5C–5K further illustrate that while multiple factors affect CBAM obligations, the EU ETS carbon price remains the dominant driver, whereas China's relatively low domestic carbon price has only a marginal mitigating effect.

Changes in CBAM certificates for the Chinese steel industry after integration into the Chinese carbon market

Chinese steel industry is expected to complete its first compliance cycle under the national carbon market by 2025 (see STAR Methods). Against this backdrop, we evaluate how the inclusion of the steel sector in China's domestic carbon market may influence its CBAM certificate obligations, as illustrated in Figure 6. Starting in 2026, Chinese steel exporters will begin incurring carbon costs through the domestic market, which could offset part of their CBAM obligations if recognized by the EU on a one-to-one equivalence basis. Under the BAU scenario, steel products produced via the BF-BOF route are projected to pay 5.63% of their total CBAM certificate fee through China's carbon market by 2050. When indirect emissions (e.g., electricity use) are included, this share rises to 11.44%. Under a high carbon price scenario, it could reach 41.18%. These variations primarily reflect differences in the price level and coverage scope of China's carbon market. As domestic carbon prices increase or regulatory coverage expands, a larger portion of CBAM is effectively internalized within China. This finding underscores that the overall carbon cost burden of Chinese steel exports is shaped not only by EU climate policies but also by the design and evolution of China's carbon market. For the DRI-EAF route, the share of CBAM certificates fee offset through China's carbon market is projected at 2.84% by 2050, rising to 18.78% when indirect emissions are included. Interestingly, under a scenario of sharply rising domestic carbon prices, this proportion declines to 8.51%, reflecting the lower carbon intensity and higher energy efficiency of the DRI-EAF process, particularly when powered by hydrogen and renewable electricity. By 2050, hydrogen-based metallurgy is expected to account for roughly 90% of the DRI-EAF energy mix, reducing carbon intensity and strengthening the competitiveness of low-carbon steel exports. These results highlight that energy structure transformation and technological upgrading are essential to mitigating both domestic and international carbon cost exposures under mechanisms such as CBAM.

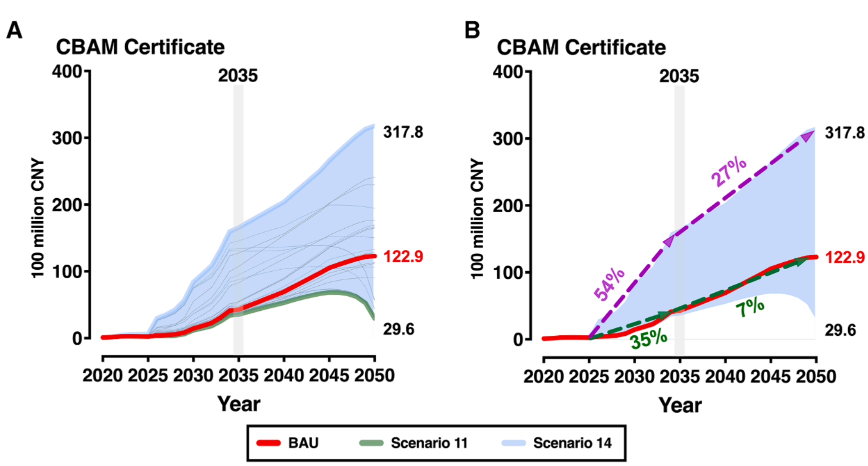

Figure 4. Projected range and growth of CBAM certificate costs for Chinese steel exports to the EU

(A) Displays the expected CBAM certificate cost range under different scenarios, with the red line representing the BAU scenario. The shaded area reflects the upper and lower bounds of the range, with high ETS carbon price (scenario 11) as the upper limit and net-zero carbon intensity for Chinese steel products (scenario 14) as the lower limit.

(B) Compares the average annual growth rates of CBAM certificate costs during the periods 2025–2035 and 2035–2050. The purple dashed line corresponds to scenario 11, while the green dashed line represents the BAU scenario.

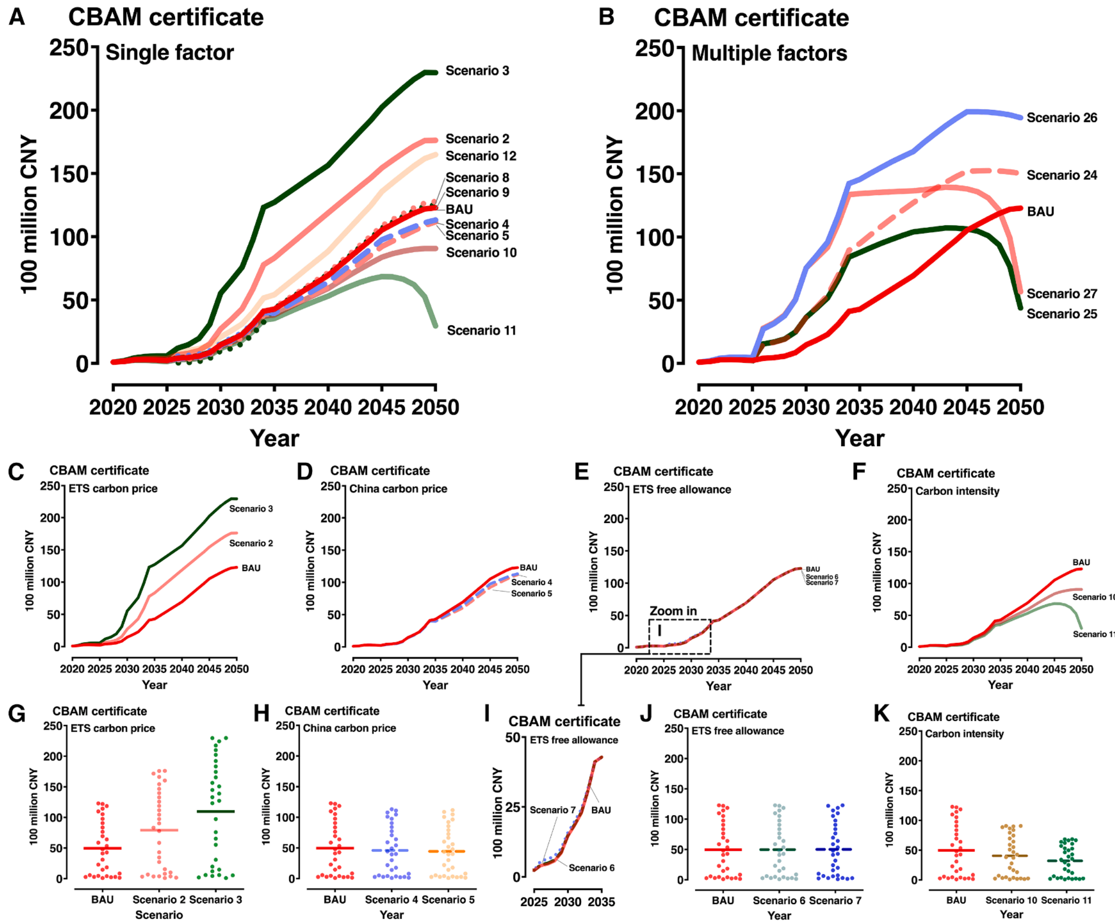

Figure 5. Effects of single factor changes and multi-factor combinations on CBAM certificate for Chinese steel exports to the EU

(A) Shows the effects of varying individual key factors, while (B) presents the combined effects of multiple factors adjustments.

(C–F) Illustrate how changes in the EU ETS carbon price, Chinese domestic carbon price, ETS free allocation benchmarks, and carbon intensity of Chinese steel products influences total CBAM certificates fee under the BAU, DCS, and NES scenarios. Colored lines represent different scenario pathways (see corresponding relationships in Table S4).

(G, H, J, and K) depict annual variations as scatterplots, with horizontal lines indicating average certificates fee for 2020–2050.

(I) provides a magnified view of the sensitivity to ETS free allocation changes during 2025–2035.

Effects of electricity decarbonization and hydrogen utilization on CBAM certificates

To further evaluate how domestic mitigation efforts can alleviate the CBAM cost burden on China's steel industry, this study simulates two critical decarbonization pathways: electricity system decarbonization and hydrogen utilization. These pathways represent complementary approaches for reducing both direct and indirect carbon emissions in steel production. The simulation results are presented in Figure 7, showing the effects on total CBAM certificates fee and the carbon intensity of the three main production routes (BF-BOF, DRI-EAF, and Scrap-EAF).

Figures 7A–7D show the impact of electricity system decarbonization, parameterized by China's average electricity emission factor, which declines from 0.58 t CO_2/MWh in 2020 to 0.20 t CO_2/MWh under the BAU scenario and 0.01 t CO_2/MWh under full decarbonization by 2050 (MEE, 2025). Deeper grid decarbonization leads to substantial reductions in total CBAM certificates fee (see Figure 7A), particularly for electricity-intensive routes. Panel B–D indicate only modest improvements for the coal-based BF-BOF route due to its limited electricity use, in contrast to pronounced carbon intensity reductions for DRI-EAF and Scrap-EAF routes. For instance, the carbon intensity of DRI-EAF steel declines from 1.69 t CO_2 per ton in 2020 to 0.95 t CO_2 per ton by 2050 under the full decarbonization scenario. Panels E–H focus on hydrogen utilization with two key parameters: the hydrogen emission factor and hydrogen penetration rate in steel production. The hydrogen emission factor decreases from 3.09 t CO_2 per ton H_2 in 2020 to 2.00 t CO_2 per ton H_2 under BAU, and 0.50 t CO_2 per ton H_2 under the green hydrogen scenario by 2050.

Panel E shows that wider deployment of hydrogen moderately reduces CBAM costs, while the reduction is smaller than that of grid decarbonization, given the current limited hydrogen-based exports volume. Panels G highlights that hydrogen adoption substantially lowers the carbon intensity of the DRI-EAF process, particularly when hydrogen replaces coal or natural gas as the

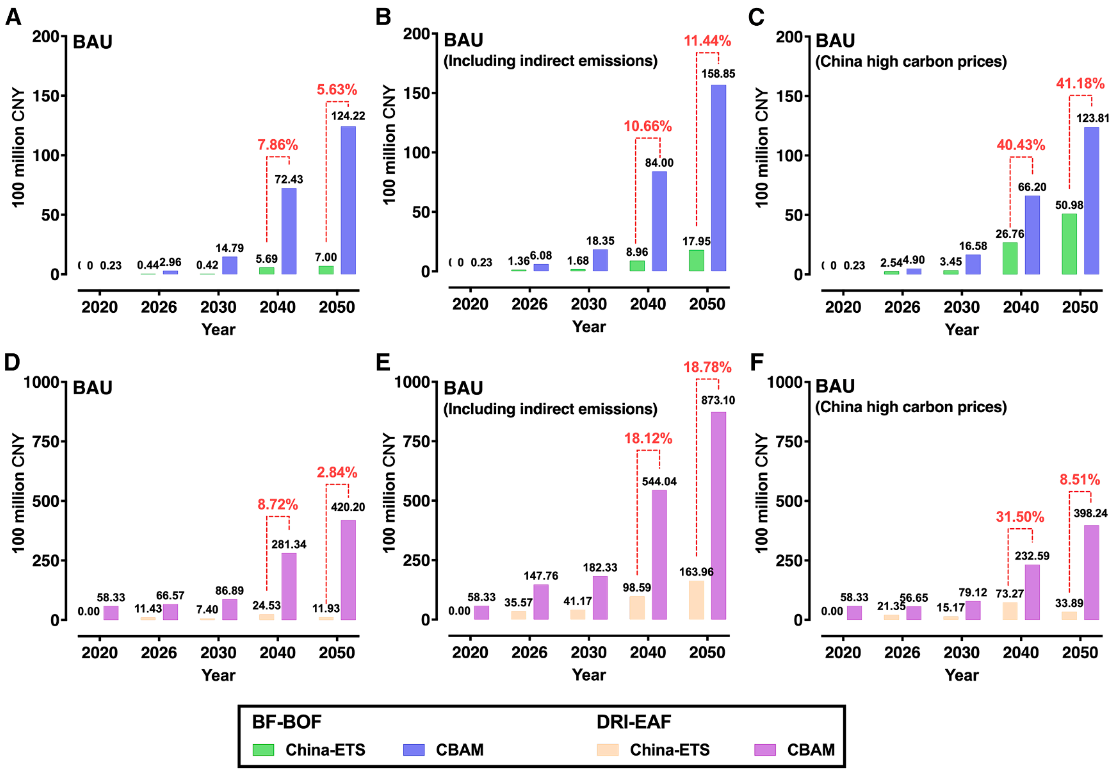

Figure 6. Changes in CBAM certificates for Chinese steel industry after integration into the domestic carbon market

(A–C) present CBAM certificates fee and corresponding domestic carbon market payments for the BF-BOF route under three scenarios: BAU, inclusion of indirect emissions, and high domestic carbon price scenario.

(D–F) show the same analysis for the DRI-EAF route. Each bar represents total CBAM certificates fee, divided into payments to the EU and the China's carbon market. The percentage values above the red dashed lines indicate the share of CBAM costs offset by domestic carbon market payments in each scenario.

reducing agent. Under the green hydrogen scenario, DRI-EAF carbon intensity drops to 0.15 t CO_2 per ton by 2050, compared with 1.00 t CO_2 per ton under BAU. Overall, these results emphasize the pivotal role of electricity decarbonization and green hydrogen in reducing steel carbon intensity and mitigating CBAM exposure.

DISCUSSION

This study quantifies the long-term impacts of the EU CBAM on Chinese steel industry by developing a dynamic, process-level accounting framework that links production technologies, carbon price systems, and energy transition pathways. Unlike prior studies that analyze these dimensions separately or over limited time frames, our model integrates the co-evolution of energy structure transitions, technological innovation, and policy instruments such as emissions trading and carbon taxation. The flexibility of our framework also allows for parameter customization according to specific production contexts, thereby enhancing both the accuracy and applicability of CBAM cost simulations across different steelmaking routes.

To ensure the robustness of these results, a comprehensive series of uncertainty and sensitivity analyses were performed (see Method S7). These include tests of partial recognition of domestic carbon payments, alternative trade-projection models, parameter sensitivity scenarios for EU carbon-price trajectories, hydrogen and scrap utilization rates, export-structure adjustments, and competitiveness extensions incorporating carbon cost pass-through. We note that higher CBAM cost pass-through shifts the burden from exporters to EU buyers, lowering exporters' direct risk but raising import prices, which can reduce EU demand and market share. Collectively, these analyses confirm that the model's core findings are robust across a wide range of parameter and policy assumptions.

Our findings indicate that CBAM imposes a substantial cost burden for exporters in countries without robust carbon pricing mechanisms, highlighting the opportunity cost of delayed climate action. The results reaffirm CBAM's dual role in mitigating carbon leakage and maintaining the competitiveness of EU industries under the EU ETS. Among all determinants, the EU-ETS carbon price exerts the strongest influence on CBAM costs. However, the large and persistent carbon price disparity between China and the EU significantly constrains China's ability to offset CBAM certificates through domestic carbon pricing. This imbalance raises broader concerns from developing countries. Differences in developmental stages, industrial structures, and implicit regulatory costs mean that nominal carbon prices cannot fully reflect each country's actual decarbonization efforts. Consequently, CBAM risks disproportionately transferring adjustment costs to emerging economies.

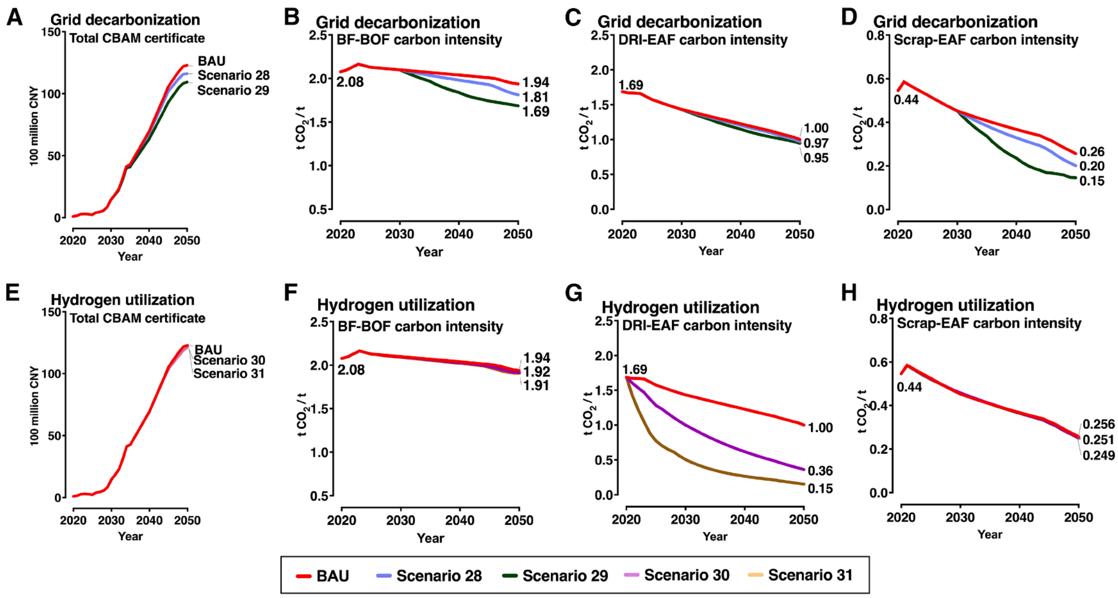

Figure 7. Impact of grid decarbonization and hydrogen utilization on CBAM certificates and carbon intensity of Chinese steel products

This figure presents the simulated impacts of two decarbonization strategies—electricity system decarbonization (A–D) and hydrogen utilization (E–H)—on total CBAM certificates fee (A and E) and carbon intensity (B–D and F–H) of for steel products produced via BF-BOF, DRI-EAF, and Scrap-EAF routes. Colored lines represent different scenario settings. The red line indicates the baseline scenario. The blue and green lines represent scenarios correspond to decarbonization and net-zero pathways for electricity, and purple and brown lines depict analogous pathways for hydrogen development.

The results also highlight that technological innovation and structural transformation are the most effective strategies for mitigating CBAM exposure. Energy efficiency improvement, product upgrading, and increased adoption of electric arc furnace technologies can substantially lower carbon intensity. While the BF–BOF route remains dominant, expanding the share of EAF-based production, especially scrap-based short processes, could yield significant carbon savings. For example, achieving an EAF share above 30% by 2030 could reduce crude steel output emissions by more than 70% relative to the BAU pathway. In the short term, efficiency retrofits and process optimization remain the main levers for emission reduction, but in the medium to long term, the structural shift toward low-carbon steelmaking will determine the sector's competitiveness in a CBAM-regulated trade environment.

China's inclusion of the steel sector in its national carbon market further incentivizes domestic mitigation. Our results suggest that by 2050, 5.63%–11.44% of CBAM costs for BF-BOF products and 2.84%–18.78% for DRI-EAF products could be offset through domestic carbon payments, depending on levels of carbon price and coverage scope. This reflects the growing potential of China's ETS to internalize part of the CBAM cost domestically, stimulating technological upgrading and encouraging firms to invest in low-carbon production. Complementary pathways, such as grid decarbonization and hydrogen utilization, are shown to further reduce CBAM exposure. While power-sector decarbonization yields immediate and sizable reductions, particularly for electricity-intensive routes, hydrogen utilization provides a longer-term pathway for deep emission cuts in BF-BOF and DRI-EAF routes. Their combined deployment will be critical to maintaining China's steel competitiveness in a tightening global climate regime.

At the global scale, the design and implementation of CBAM must balance environmental effectiveness with trade fairness. While the mechanism aims to level the playing field and discourage carbon leakage, its application may inadvertently distort trade and investment patterns if regional policy asymmetries persist. Without improvements in technology and productivity, CBAM could undermine competitiveness of carbon-intensive exporters. Countries have responded to CBAM with a range of positions and countermeasures, from legal challenges to the development of parallel pricing systems. Recent developments reflect growing geopolitical complexity. Russia filed a formal WTO complaint against the EU's CBAM, while countries such as India and South Africa have begun introducing domestic responses, including national carbon pricing and border adjustment measures. These trends underscore the importance of international coordination, particularly the mutual recognition of carbon pricing schemes and harmonization of emission accounting methodologies, will be essential for ensuring that CBAM functions as a climate cooperation instrument rather than a trade barrier.

Conclusions

Outlook

This study develops an integrated, process-level, and scenario-based framework to assess the long-term impacts of the EU carbon border adjustment mechanism (CBAM) on China's steel industry. The analysis combines production process modeling, carbon pricing mechanisms, and technology transition pathways to provide a transparent representation of carbon cost dynamics under multiple policy scenarios. The results quantify how

CBAM-related costs evolve across varying trajectories of carbon pricing, technological change, and market integration. The EU ETS carbon price emerges as the primary driver of CBAM obligations, while the expansion of China's domestic carbon market offers potential to internalize part of these costs and strengthen industrial decarbonization incentives. The findings also highlight the importance of technological transformation—particularly the scaling-up of electric arc furnace production, adoption of hydrogen-based metallurgy, and decarbonization of the electricity system—and of international coordination on carbon accounting and policy alignment. Together, these elements can help balance competitiveness and climate goals, advancing a more equitable and effective global transition toward low-carbon industrial systems.

Policy implications

This study provides several policy directions for balancing industrial competitiveness with global decarbonization goals. (1) Enhance data transparency and mutual recognition between carbon markets to ensure accurate crediting of domestic emission reductions under CBAM. (2) Accelerate industrial decarbonization by expanding the share of EAF and DRI–EAF production, supported by hydrogen and renewable electricity. (3) Establish global standards for carbon accounting and benchmarking to harmonize emission calculations and improve comparability across jurisdictions. (4) Promote equitable revenue recycling, directing a portion of CBAM revenues toward green-technology development in developing economies to foster international legitimacy and inclusiveness.

Limitations of the study

There are several limitations to the present study that could inspire future research. First, the model relies on aggregate emission factors rather than firm-level microdata, which may underestimate intra-industry heterogeneity. Incorporating detailed firm-level emission and cost data in future research would improve precision and allow more granular policy evaluation. Second, while the framework captures long-term technology pathways through scenario-based adjustments, it does not explicitly model dynamic firm-level behavioral mechanisms, such as endogenous production, investment, and consumption decisions over time. Investment behavior and carbon cost pass-through dynamics are therefore represented in a simplified manner, which may influence competitiveness outcomes under CBAM. As a result, the estimated impacts should be interpreted as conditional on exogenously specified pathways rather than fully endogenous market adjustments. Third, non-EU market reallocation mechanisms, such as export substitution and regional trade shifts, are not explicitly modeled and should be explored through multi-region or general equilibrium simulations. Additionally, the model uses national average electricity prices as a baseline, without capturing regional tariff variations or preferential industrial pricing policies, thereby reflecting average national conditions rather than localized differences. Finally, the inflation and exchange-rate module is retained to enable macroeconomic scenario testing, which is essential for long-term projections. The baseline adopts fixed reference values for stability, but the framework can be dynamically extended once reliable macroeconomic forecasts become available.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Dr. Kevin Mo (kevinzmo@outlook.com).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- Data: All core input datasets, and output files used in this study have been deposited at GitHub (https://github.com/iGDP-coder/CBAM-iGDP) and are publicly available as of the date of publication.
- Code: Original code used for simulations and data processing has been deposited at GitHub https://github.com/iGDP-coder/iGDP-CBAM-code and is publicly accessible as of the date of publication.
- Additional information: CBAM-related regulatory documents and supplementary configuration files in this paper will be shared by the lead contact upon request.

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AUTHOR CONTRIBUTIONS

K.M., X.L. and B.L. designed the study; X.L. and B.L. completed data processing and visualization; X.L., J.H., B.L., and K.M. completed econometric model related work; B.L., X.L., J.Y., and N.N. wrote the first draft; B.L., Z.W., X.L., and K.M. contributed to the interpretation of the results.

DECLARATION OF INTERESTS

The authors declare no conflict of interest.

STAR★METHODS

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SUPPLEMENTAL INFORMATION

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Data		
CBAM-CST data	CBAM-CST model	https://github.com/iGDP-coder/CBAM-iGDP
Code		
China–EU steel trade volume forecasting	Predictive model	https://gibhub.com/iGDP-coder/iGDP-CBAM-code
Additional information		
CBAM regulation	European Commission	https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en
Software	Python Version 3.5.7	https://www.python.org/

METHOD DETAILS

CBAM overview

Given the technological and emission heterogeneity among China's steel production routes, this study uses the number of CBAM certificates required for steel products exported from China to the EU as the core quantitative indicator to assess CBAM's potential impact. The Carbon Border Adjustment Mechanism (CBAM) operates in two phases: a transitional phase (October 1, 2023–December 31, 2025) and a definitive regime starting on January 1, 2026. During the transitional phase, EU importers are obligated to report embedded carbon emissions of imported goods on a quarterly basis but are not yet required to purchase CBAM certificates. From 2026 onward, importers must purchase certificates corresponding to the excess embedded emissions of imported products, with each certificate representing one tonne of CO_2 equivalent. The number of certificates required depends on four primary factors: (1) the carbon intensity of the exported product, (2) the export volume, (3) the weekly average EU ETS carbon price, and (4) any carbon costs already paid in the exporting country through carbon markets or taxes. CBAM allows deductions for verified domestic carbon payments under national schemes. This ensures that exporters in countries with active carbon pricing mechanisms can offset part of their CBAM obligations. In the early implementation stage, transitional free emission allowances are introduced for certain embedded emissions, easing compliance pressures, and promoting fair competition among trading partners.

Accounting boundaries

The carbon emission accounting scope defined under the CBAM regulation differs from conventional "cradle-to-grave" life cycle assessment frameworks, as it focuses solely on emissions generated during the production phase of covered goods. Specifically, CBAM excludes emissions from upstream raw material transportation and downstream activities such as product distribution, consumption, and end-of-life treatment. However, the accounting boundary includes both direct and indirect emissions that occur during the manufacturing of the exported products. Direct emissions refer to greenhouse gases released from the production processes themselves. These encompass emissions from the combustion of fossil fuels used for energy or heat generation and emissions associated with industrial processes, such as the reduction of iron ore using coke or natural gas, the thermal decomposition of carbonate-based raw materials, the oxidation of carbon-containing inputs like scrap materials, ferroalloys, and electrodes. In cases where heat supplied by adjacent facilities or district heating systems, the associated emissions are also classified as direct. Furthermore, when electricity is self-generated on-site, the combustion emissions from power generation are considered part of the direct emissions of the production facility. Indirect emissions primarily arise from the consumption of purchased electricity during the production process, and they also include the embedded emissions in carbon-intensive materials used in the production of complex steel products. While these emissions do not occur directly within the production facility, they are essential components of the product's carbon footprint and are included within the CBAM scope. Importantly, CBAM accounting also considers the carbon content retained in intermediate and final steel products, such as pig iron, crude steel, DRI, and ferroalloys, as well as residual carbon present in by-products and waste materials like slag. These embedded forms of carbon are included to ensure a more accurate representation of the carbon footprint associated with the exported product.

In terms of emission source categories, the accounting framework incorporates emissions from fossil fuel combustion (e.g., from sintering machines, coke ovens, industrial boilers, and blast furnaces), process-related emissions from the chemical transformation of raw materials, indirect emissions from purchased electricity, and the embedded carbon content in solid carbon-containing inputs. A detailed mapping of these emission sources for each production process is presented in Table S3. This production-focused accounting boundary, consistent with CBAM regulations, is designed to ensure consistency in cross-border carbon cost assessments and to promote comparability among products from different countries.

Model framework

This study develops a carbon border adjustment mechanism-China steel transformation (CBAM-CST) accounting model to simulate the operational mechanism of the EU CBAM and evaluate its long-term impact on Chinese steel industry under multiple decarbonization scenarios. The model incorporates multiple parameters and dynamic policy settings to reflect realistic economic and regulatory environments. It integrates scenarios analysis (see Method S3) to assess CBAM effects under different decarbonization pathways and consists of three interconnected modules: (1) the inflation and exchange rate module, (2) the CBAM cost calculation module, and (3) the China steel low-carbon transition module. The overall model framework is illustrated in Figure S3, and detailed specific parameter configurations are provided in Tables S5 and S6 and Methods S4–S6.

(1) Inflation and exchange rate module. This module captures the impact of macroeconomic fluctuations on CBAM certificates fee by modeling inflation in China and the EU, as well as the CNY-EUR exchange rate. It enables dynamic policy simulations to estimate how macroeconomic influence export competitiveness and emission reduction incentives.
(2) CBAM certificates cost calculation module. This module provides a transparent accounting framework aligned with official CBAM regulations. It incorporates key elements such as EU ETS carbon prices, free allowance benchmarks, and export volumes to compute certificate obligations for Chinese steel exports. This module quantifies direct financial impacts under alternative carbon-price and policy trajectories.
(3) China steel low-carbon transformation module. This module focuses on domestic decarbonization pathways, modeling shifts in energy structure, process-level carbon intensity, and the deployment of low-carbon technologies such as hydrogen metallurgy and power-grid decarbonization. It produces time-series outputs for total emissions, carbon intensity, reduction costs, and carbon expenditures paid under China's national carbon market, enabling integrated evaluation of domestic and border-adjustment carbon pricing.

The CBAM-CST framework links these modules to generate multi-dimensional outputs, including total CBAM certificates, certificates fee per ton of steel, and sector-wide emission trajectories. Default parameter settings are derived from current policy data, while users can adjust assumptions such as carbon-price trajectories, exchange rates, and technology adoption rates to test scenario sensitivities. The model can also incorporate firm-level emission data, allowing individualized estimation of CBAM obligations and mitigation strategies.

All input data, assumptions, and sources are summarized in Tables S5 and S6. Variables such as energy consumption intensity, grid emission factors, and technology shares are exogenously specified for the baseline but are endogenously linked through scenario-bundled parameter design. For example, scenarios with higher carbon prices are paired with faster green hydrogen deployment, accelerated grid decarbonization, and a steeper phase-outs of free allowances. This design ensures consistency among technological, economic, and policy components, capturing the interdependent mechanisms that jointly determine CBAM-related carbon cost outcomes.

Scenario setting

This study covers the period from 2020 to 2050 and define three policy pathways: business-*as*-usual pathways (BAU), decarbonization pathways (DCS), and net-zero emissions pathways (NES). Each pathway represents a distinct climate policy environment and decarbonization trajectories. Under BAU, all existing energy and climate policies implemented before 2020 remain in place with no additional measures or new energy infrastructure deployments beyond those already planned. CBAM parameters assume free allocation benchmarks decline annually by 0.2% or 1.6%, with these free allocations gradually phased out over time (see Table S9). The DCS pathway introduces stronger mitigation measures to stabilize atmospheric CO_2 concentrations around 450 ppm, accelerating decarbonization relative to BAU. Free allocation benchmarks decline at 0.2% or 2.0% annually until they are fully eliminated. The NES pathway envisions achieving net-zero CO_2 emissions by 2050, supported by globally coordinated energy policies. Solar and wind power are projected to dominate electricity generation—reaching nearly 70% by 2050—while the steel industry achieves zero direct emissions. Correspondingly, CBAM free allocation benchmarks decline more rapidly, by 0.5% or 2.5% annually, until fully phased out.

This study examines the interaction between the EU CBAM and China's steel-sector decarbonization using a scenario framework grounded in the CBAM-CST model. As illustrated in Figure S3, the model comprises three integrated sub-modules and 37 key parameters that collectively define the simulation space. A scenario construction mechanism (see Figure S4) was developed to explore the dynamic linkages between CBAM policy settings and emission-reduction trajectories. Each parameter is assigned three standardized values corresponding to distinct climate policy pathways: BAU reflecting current policy trends, DCS representing strengthened mitigation efforts, and NES aligned with carbon-neutrality goals. Coordinated configuration of these parameters enables flexible generation of internally consistent simulation cases. Although 3^{37} parameter combinations are theoretically possible, only feasible and coherent scenarios are retained after applying systemic constraint logic and technical dependencies (e.g., power-sector decarbonization only when indirect emissions are included). The study focuses on four analytical themes: 1) changes in carbon intensity of CBAM-regulated steel products, 2) estimation of CBAM certificates fee ranges for Chinese steel exports to the EU, 3) effects of integrating the steel sector into China's carbon market, and 4) mitigation potential of grid decarbonization and hydrogen-based steelmaking. This scenario framework allows a comprehensive assessment of how policy configurations and parameter uncertainties jointly shape the carbon competitiveness of Chinese steel exports under CBAM.

Carbon intensity of steel products

This study estimates the carbon intensity of steel products produced through three major technological routes, namely BF-BOF, DRI-EAF, and Scrap-EAF. Carbon intensity is defined as the ratio of total carbon emissions to steel output, expressed in tonnes of CO_2 equivalent per tonne of steel. In accordance with the methodology specified in the EU CBAM Regulation ((EU) 2023/956), total emissions are calculated using the mass-balance approach, which aggregates emissions from (i) fuel combustion, (ii) industrial production processes, and (iii) net consumption of electricity, heat, and hydrogen. The implicit carbon removal associated with carbon-sequestering products is deducted to obtain the net emission value. The specific direct embedded emissions per tonne of steel product category g in year t are calculated using the following equation [1]:

$$ASEE_{t,g} = \sum \left(E_{i,t,g} \times F_{i,t,g}\right) + PRE_{t,g} - SE_{t,g} \quad \text{(Equation 1)}$$

where $ASEE_{t,g}$ denotes the actual specific embedded emissions for one tonne of steel product type g in year t. $E_{i,t,g}$ represents the consumption of energy type i per tonne of steel product g in year t (tce/t steel). $F_{i,t,g}$ denotes the carbon emission factor of energy type i (tCO_2/tce). $PRE_{t,g}$ refers to the process-related emissions generated during physical or chemical transformations of input materials other than fuel combustion, and $SE_{t,g}$ represents the carbon embedded in the final product, corresponding to the amount of carbon retained in the steel output rather than emitted to the atmosphere. Following the Ministry of Ecology and Environment of China (2023), the carbon fixation intensity of crude steel products is assumed to be 0.248 tCO_2 per tonne of crude steel.

For each production route—BF–BOF, DRI–EAF, and Scrap–EAF—energy consumption is determined by the steel output and the energy intensity associated with each process stage, taking into account differences in process configuration and energy mix. Specifically, emissions from fuel combustion are calculated based on the consumption of fossil fuels such as coking coal, natural gas, and biomass, while emissions from indirect energy use are derived from the consumption of electricity, heat, and hydrogen. For each process, total energy consumption is obtained by multiplying the process-specific steel output by its energy intensity, after which the share of each energy carrier in the total energy mix is applied to allocate consumption among different fuels and secondary energy sources. This disaggregated, process-level approach ensures that emission estimates accurately reflect the heterogeneity in energy structures, technological efficiencies, and fuel substitution patterns across different steelmaking routes and production processes (see Method S3).

CBAM certificates calculation

According to the EU CBAM regulation, authorized EU declarants are required to surrender a number of CBAM certificates corresponding to the embedded carbon emissions of imported goods. Specifically, the number of certificates to be surrendered is determined by the amount of imported CBAM-covered goods and their actual specific embedded emissions, reduced by (i) the specific emissions covered by free allowances under the EU ETS and (ii) where applicable, the specific emissions already covered by an effective carbon price paid in the country of origin. In the case of steel products, EU importers must therefore purchase CBAM certificates to account for the embedded carbon emissions of imports. The total cost of these certificates depends on the carbon intensity of the imported goods, the prevailing EU carbon price, the volume of imports, and any domestic carbon costs already incurred in the exporting country through existing carbon markets or taxes. In addition, CBAM allows for a transitional free allocation of emission allowances, which is gradually phased out in accordance with the EU policy schedule, reflecting the evolving alignment between different jurisdictions' carbon pricing systems—particularly between the EU and China.

In this study, the total CBAM certificates fee for Chinese steel exports is calculated following the intermediate CBAM legislative document CBAM P9_TA(2022)0248 and the updated formula presented in the EU document "Carbon Border Adjustment Mechanism (CBAM) Questions and Answers," last updated on 17 December 2024. The calculation is based on a process-level accounting framework that quantifies the difference between a product's actual embedded emissions and the portion already covered by an effective domestic carbon price, as summarized by the following equation:

$$N_{t,g} = \left\{\left[ASEE_{t,g} - \left(CB_{t,g} \times FA_t\right)\right] - \left[\frac{CPA_{t,g} \times ASEE_{t,g}}{PCC_t}\right]\right\} \times AoG_{t,g} \quad \text{(Equation 2)}$$

$$CBAM_{t,g} = N_{t,g} \times PCC_t \quad \text{(Equation 3)}$$

where $N_{t,g}$ represents the number of CBAM certificates required for one tonne of steel product type g in year t, while $ASEE_{t,g}$ denotes the actual specific embedded emissions of that product, measured as tonnes of CO_2 emitted per tonne of goods. $CB_{t,g}$ refers to the CBAM benchmark value, indicating the emission-intensity threshold used for free allocation under the CBAM system, and FA_t represents the annual reduction factor applied to this benchmark in year t. The variable $CPA_{t,g}$ corresponds to the specific emissions already paid for under a domestic carbon price in the exporting country, expressed in CNY per tonne of CO_2. PCC_t denotes the price of CBAM certificates, equivalent to the prevailing EU ETS carbon price in year t, which is converted from euros to CNY using the corresponding annual exchange rate and expressed in CNY per tonne of CO_2. $AoG_{t,g}$ represents the amount of goods, that is, the export volume of steel product type g from China to the EU in year t. Finally, $CBAM_{t,g}$ denotes the CBAM certificates fee payable for one tonne of product type g in year t, expressed in CNY and subsequently converted into U.S. dollars for inter-scenario comparison. All monetary values are converted at the annual average exchange rate of the corresponding year, based on data from the People's Bank of China and the European Central Bank.

Inclusion of the steel industry in China's carbon emissions trading market

China officially launched its national carbon emissions trading market in July 2021, initially covering the power generation sector. After successfully completing two compliance cycles (2019–2020 and 2021–2022), the system has become the largest in the world in terms of covered greenhouse gas emissions. Regulatory assessments indicate that conditions are now in place to expand coverage to high emission industries such as cement, steel, and electrolytic aluminum. The Chinese government has announced plans to incorporate these sectors into the national carbon market starting in 2024, which will extend market coverage to nearly 60% of China's total greenhouse gas emissions. The inclusion will follow a two-phase implementation plan the 2024–2026 and the 2027 onward. During the "Implementation Phase" (2024–2026), carbon control will focus on intensity-based targets, with free allowances allocations linked to production volumes and no hard cap on total emissions. The "Deepening Phase" (from 2027) will adopt benchmark-based allocation, gradually tightening allowance standards to drive further emission reductions and efficiency improvements.

Integrating the steel industry into China's has direct implications for CBAM-related carbon costs. Once included, steel producers must purchase carbon allowances for domestic compliance, meaning part of their carbon costs will be paid at the production stage. According to CBAM regulations, verified carbon costs already paid in the exporting country can be deducted from the total CBAM obligation, thereby reducing the effective burden on Chinese exports. As China's carbon price gradually converge with the EU ETS, this offsetting effect will strengthen. In addition, the carbon market inclusion is expected to accelerate low-carbon transformation within the steel industry by promoting energy efficiency and technologies such as hydrogen-based metallurgy. Lowering the carbon intensity of steel directly reduces the number of CBAM certificates required, thus decreasing total compliance costs. Furthermore, participation in the national carbon market will enhance the standardization and transparency of emission accounting, reducing transaction costs, improving data credibility, and increasing the global competitiveness of Chinese steel under carbon-constrained trade conditions.

QUANTIFICATION AND STATISTICAL ANALYSIS

All quantitative estimates are computed deterministically using the official CBAM accounting formulas, based on arithmetic operations applied to scenario-specific emissions, benchmarks, carbon prices, and trade volumes. Future China–EU steel trade volumes are projected using logarithmic (baseline), linear, and power-exponential regressions. Uncertainty is characterized using 95% prediction intervals, shown as shaded areas in the figures.