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How will CBAM affect the decarbonisation of steel industry in China? A system dynamics approach

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ABSTRACT

EU's Carbon Border Adjustment Mechanism (CBAM) has been promulgated. The steel industry is included in CBAM, which will undoubtedly affect the export trade of China's steel manufacturers to the EU. It is necessary to analyse the impact of CBAM on China's steel industry quantitatively. By establishing a system dynamics model that can simulate the operation mechanism of the steel supply chain in China, we have clarified the impacts of CBAM on the China's steel export and carbon reduction. Moreover, we have reasonably set up scenarios that represent the possible decarbonisation paths of China's steel industry and evaluated the implementation effect of each policy in these scenarios. The analysis shows that CBAM will lead to a decrease of 32% in export volume and a loss of 58% in export profits for China's steel exporters. The environmental benefits of CBAM are limited. Due to the low trade exposure, CBAM is unable to promote a large-scale carbon reduction in the China's steel industry. Although CBAM will bring great pressure to steel exporters, a comprehensive policy of adopting more emission reduction measures can greatly improve the carbon reduction efficiency, effectively reduce the negative impact of CBAM, and maintain the stability of steel exports.

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Steel supply chain; decarbonisation; CBAM

1. Introduction

The steel industry is a critical basic industry in the modernisation of society and plays an important role in the national economy. Since 1996, China has held the position of the world's largest steel producer. According to the World Steel Association (WSA) latest statistics yearbook (WSA 2022), China still maintains the highest share of crude steel production in 2022, accounting for about 54% of global production. There is no doubt that China will continue to play the most important role in the global steel industry in the future (Zhang et al. 2023). The steel industry is a representative industry with high energy consumption and carbon emissions. In China, steel manufacturers contribute 13% of national energy consumption and 15% of carbon emissions (National Bureau of Statistics of China 2020). Therefore, achieving carbon reduction in the steel supply chain (SSC) is critical to China's carbon neutrality.

Currently, there are three main steel production routes in the world. The first one is called blast furnace-basic oxygen furnace steelmaking (BF-BOF). This method is mainly based on iron ore and uses blast furnace and basic oxygen furnace for production. BF-BOF undergoes a complex energy conversion process, therefore it is also known as a long process (Mousa et al. 2016). In 2021, 90% of steel production in China follows the BF-BOF route (WSA 2022). The average carbon intensity of BF-BOF is 2.3 tCO_2/t steel (ETC and RMI 2021). The second type of steel production, mainly using an electric arc furnace, includes Scrap-EAF with scrap as raw material and DRI-EAF with DRI as raw material. Among them, Scrap-EAF accounts for about 10% of China's steel production (WSA 2022), and its carbon intensity is about 0.6 t/t (ETC and RMI 2021). The proportion of DRI-EAF in China is extremely small and its carbon intensity is approximately 1.4 t/t (ETC and RMI 2021).

Currently, the SSC in China is shown in Figure 1 (Modified by Geyer et al. 2007).

The raw material suppliers import iron ores from overseas and deliver them to the crude steel manufacturers. Crude steel manufacturers process iron ores into crude steels and export a small part of crude steels to overseas customers. Most crude steels continue to be transferred to general product manufacturers as intermediate products. Through fabrication and manufacturing, crude steels are processed into steel products, which are sold

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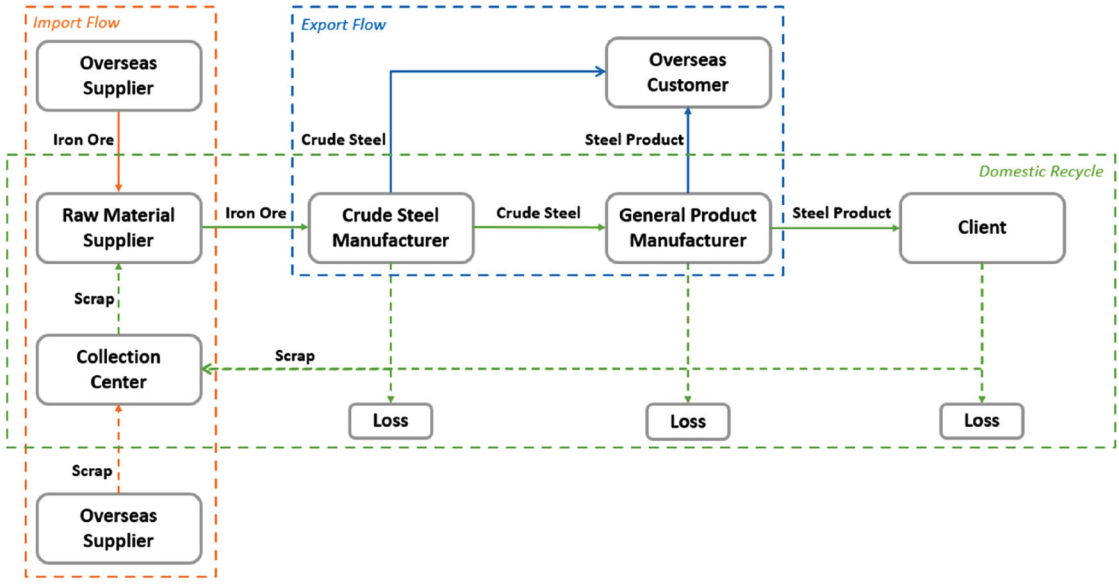


Figure 1. Diagram of the steel supply chain in China.

to domestic customers and overseas consumers, respectively. Part of the scraps generated from production or processing will be recycled to the collection centre for reprocessing, and the others will be discarded as a loss.

As the leader in the current global carbon emission reduction plan, the carbon emission trading system (ETS) established by the European Union (EU) is the most representative carbon market in the world. However, due to differences in motivations for reducing carbon emission between countries, there is an increasing risk of carbon leakage, which means that highly polluting industries can shift from developed countries to developing countries and carbon emissions from strongly constrained regions to weakly constrained regions, thus curbing global carbon emission reduction achievements (Mörsdorf 2022). In July 2021, the European Commission called for a series of measures to accelerate carbon emission reduction. The Carbon Border Adjustment Mechanism (CBAM) was formally proposed to prevent carbon leakage among these measures. In April 2023, the European Council voted to approve CBAM, marking this policy has been officially put on the agenda. According to the proposal, the EU will impose carbon border taxes on imported products from non-EU regions. At present, CBAM covers five sectors: electricity, steel, aluminium, cement, and fertilisers. The experimental period of CBAM is 2023-2025, and it will be officially implemented in 2026. The EU hopes to further accelerate its carbon reduction plan by reducing the free allowance of EU-ETS internally and implementing CBAM externally. In addition, CBAM will also protect the price competitiveness of EU's energy-intensive industries in the competition with imported products that have not yet paid carbon costs, ensuring both bear the same carbon costs (Morgan 2000).

As one of China's largest trade partners, the implementation of CBAM will undoubtedly have an impact on relevant sectors in China. For China–EU trade, the steel sector has the highest proportion among the five industries covered by CBAM, reaching about 60%. The aluminium sector accounts for approximately 38% and others are less than 2% (UN Comtrade Database). Obviously, steel will be the industry most affected by CBAM. Stakeholders generally believe that CBAM will crack down on China's steel export to the EU, while forcing China's SSC to accelerate decarbonisation. Therefore, this article will focus on the Chinese steel industry and aims to address the following two research questions (RQ):

RQ1. As a unilateral policy with attributes of both international climate instruments and trade protectionism, what impact will CBAM have on export and decarbonisation of SSC in China?

RQ2. Considering the current trend of decarbonisation in China, what strategies should the stakeholders of SSC adopt to better cope with CBAM?

To answer these questions, this article has established a system dynamics model to simulate the operation of the SSC in China. Based on this model, we analyse the impact of CBAM and compare the implementation effects of various decarbonisation measures to obtain the relatively optimal solution to address the CBAM. These analyses can provide decision-makers with practical guidance in assessing the impact of CBAM and developing response strategies. In addition, this article can provide valuable insights for steel manufacturers in

achieving the decarbonisation of steelmaking, helping them to better adapt to stricter climate regulations in the future.

The paper is structured as follows. Section 2 provides a review of existing research on carbon border taxes. Section 3 proposes a system dynamics model to simulate China's SSC and completes a model test. Section 4 presents model simulations and analyses the simulation results. Finally, we conclude the entire paper and propose the corresponding policy implications.

2. Literature review

Although the European Commission has repeatedly claimed that it is only a climate tool, CBAM, as a unilateral trade policy simultaneously, will undoubtedly have a comprehensive impact on environmental, economic, and social welfare. Therefore, scholars have discussed the potential impact of carbon border taxes, mainly from aspects of environmental benefits and economic impacts.

For the environmental benefits, many scholars' studies have shown that carbon border taxes can indeed inhibit the occurrence of carbon leakage, whereas it cannot eliminate this risk completely (Clora, Yu, and Corong 2023). Its environmental benefits are relatively limited, in general. A major review comes from Branger and Quirion (2014), who conducted a meta-analysis of 310 simulations from 25 different studies to assess the inhibitory effect of carbon border taxes on carbon leakage and show how key variables and modelling assumptions affect carbon leakage rates. Their results show that in the absence of CBAM, the leakage rate is between 5% to 25% (14% on average). While the implementation of CBAM reduces the leakage rate by 6% on average, failing to eliminate carbon leakage to zero. Zhong and Pei (2022) extended this review, showing that studies between 2013 and 2020 basically confirmed Branger's conclusion (Antimiani et al. 2016; Böhringer et al. 2017; Böhringer, Schneider, and Asane-Otoo 2021; Fouré, Guimbard, and Monjon 2016). Overall, since CBAM cannot cut off the leakage channel from the fossil fuel price, it can only partially reduce but not eliminate the carbon leakage (Al Khourdajie and Finus 2020; Mörsdorf 2022). The legal risks and uncertainties in the external environment implied in the design of CBAM may further weaken its environmental benefits. The CBAM may be regarded as contravening the 'common but differentiated responsibility and respective capabilities' of the United Nations Framework Convention on Climate Change (UNFCCC) and may be challenged at the WTO due to violating the 'special and differential treatment' granted to developing countries (Bellora and Fontagné 2023).

For the aspect of economic and social welfare, researchers believe that carbon border taxes may disturb the order of global trade, impede the economic growth of the target countries (Larch and Wanner 2017), and reconstruct the international competitiveness of relevant industries (Evans et al. 2021; Zhong and Pei 2022), exacerbating inequality (Perdana and Vielle 2022). The study conducted by Dong and Whalley (2011) showed that carbon border taxes had little effect on preventing carbon leakage, but constituted a trade barrier that hindered the free circulation of global trade. Ghosh et al. (2012) state that CBAM would lead to reduced efficiency and countries with higher dependence on fossil fuels, such as China, would suffer serious adverse effects. Kasterine and Vanzetti (2010) simulated the results of the EU's imposition of CBAM on the agricultural, showed that if the EU imposed taxes at 100 USD/ton of CO_2, the loss of agricultural exports of developing countries would be about 1.4 billion USD. Brandi (2013) focusses on the ethical implications of CBAM. From the perspective of development ethics, CBAM hurt developing countries that depend on commodities restricted by the tax for their exports, while limiting market access for them and reducing trade development potential; from the perspective of climate ethics, CBAM undermine procedural and distributive justice and ignore the damage they cause at the consumption level. Böhringer, Carbone, and Rutherford (2018) argued that CBAM shifts the economic burden of climate policy from developed countries to developing countries. In other words, developing countries would suffer the main economic losses from the implementation of CBAM, while developed countries would be the main beneficiaries.

Due to the possible unfairness caused by CBAM, other countries may adopt corresponding response measures. Researchers have conducted some discussions on this topic. The first type of response measures can be summarised as obtaining exemptions from CBAM by increasing the domestic carbon tax, since the CBAM will deduct the carbon tax that was already paid. Dong, Ishikawa, and Hagiwara (2015) proposed that China implement an export carbon tax to address CBAM, but the results indicate that this will cause more competitive losses to domestic carbon-intensive industries. Zhu et al. (2020) explored the feasibility of China imposing a high carbon tax as developed countries, and found that this would result in a significant decrease in GDP and social welfare. This type of strategy overlooks the differences in social development and climate transition stages between developing and developed countries, resulting in severe economic burdens. The second type of response measures advocates addressing the negative impact of CBAM through international cooperation.

Clora, Yu, and Corong (2023) evaluated the results of retaliation or cooperation taken by other countries and found that retaliation would make the situation worse, while cooperation would yield greater environmental benefits. Sun et al. (2023) also stated that, compared to CBAM, achieving climate neutrality needs to be carried out within the framework of international cooperation. However, achieving international cooperation is often difficult to achieve, since it requires coordinating the interests of multiple representatives and going through lengthy debates and compromises. People lack sufficient capacity to force all countries to participate in climate neutrality together (Bellora and Fontagné 2023). In fact, this is one of the motivations for the EU to propose CBAM. For comparison, achieving decarbonisation in supply chain production is undoubtedly a more rational choice. The taxation method of CBAM determines that it is more friendly to low-carbon exporters. Therefore, compared to the response measures proposed in the existing literature, the strategies discussed in this article to seek decarbonisation in SSC have higher feasibility and effectiveness.

Regarding the methodology, the commonly used model in existing literature on CBAM is the computable general equilibrium (CGE) model (Zhong and Pei 2022). The CGE model and the SD approach are both simulation models. Their respective characteristics make them suitable for different research topics (Tang et al. 2020). The CGE model is a more macroscopic approach. It can consider the connections between various regions and sectors, thereby comprehensively analysing the behaviour in the economic system. Therefore, the CGE model is suitable for more macro topics. Mörsdorf (2022) used the CGE model to study the impact of CBAM on global carbon leakage. Perdana and Vielle (2022) discussed the comprehensive impact of CBAM on least developed countries based on the CGE model; Bellora and Fontagné (2023) used the CGE model to analyse the impact of different CBAM designs on the economy and environment of different regions worldwide.

The research topic considered in this article is more micro. We mainly explore the impact of CBAM on China's steel sector, thereby the SD approach is undoubtedly more suitable. The advantage of SD approach is that it can capture the interaction and feedback mechanisms between variables, making it effective in modelling complex systems such as supply chain system, which is not possessed by the CGE model. In fact, the SD approach has been widely applied in the analysis of supply chain system (Gu and Gao 2012; Kong, Liu, and Chen 2023; Mehrjoo and Pasek 2016; Mohammadi et al. 2022; Mula et al. 2013; Olivares-Aguila and ElMaraghy 2021) and energy conservation and carbon reduction in the steel sector (Ansari and Seifi 2012; Norbert, Kim, and Griffay 2020). Based on the SD approach, we can effectively simulate the operating mechanism of SSC, and thus reasonably evaluate the impact of CBAM as an exogenous shock on the system. Therefore, this article chose the SD approach considering the pertinence and relevance of the research topic.

In sum, we contribute to literature on CBAM in the following aspects. Firstly, although scholars have fully discussed the impact mechanism of CBAM, most studies analyse factors such as carbon leakage, GDP, and welfare from the perspective of the nation. Few researchers analyse the impact of CBAM from the perspective of the industry level, especially the steel industry, which will be the sector most affected by the upcoming CBAM. Secondly, the response strategies proposed in existing literature have been questioned in terms of feasibility. The strategy of pursuing decarbonisation of SSC to address CBAM discussed in this article fully considers the trend of China's pursuit of decarbonisation in the steel sector, thereby has greater effectiveness and practical significance. Finally, the SD approach used in this article is not only more suitable for our research questions, but also complements the diversity of methodology in the topic of CBAM. This research paradigm can be applied to the analysis of other sectors affected by CBAM, providing researchers with new research ideas.

3. Methodology

In order to effectively evaluate the impact of CBAM on the SSC of China, we first need to simulate the operation of the SSC. In the SSC system, the behaviour often changes in a non-linear form, and constantly interacts with the feedback of information. Considering these, system dynamics approach is a useful technique in such complex systems. System dynamics (SD) was proposed by Jay Wright Forrester in the 1960s (Forrester 1961) as a method for delving deeper into dynamic complexity problems. In SD, the system introduces a series of variables that interact to form a unified whole (Ghaffarzadegan, Lyneis, and Richardson 2011). By describing the interactions and information feedback of various variables in the system, the SD method can effectively analyse the behaviour patterns of complex systems and evaluate their impacts from a holistic perspective (Xiao et al. 2020). Based on these characteristics, SD enables people to have a more comprehensive understanding of the entire system and develop suitable strategies (Ye et al. 2021).

The main modelling steps of SD include two stages: constructing a causal-loops diagram (CLD) and a stock-flow diagram (SFD). The CLD describes the logical

relationship of the system, explaining how each variable affects other variables and produces interactions throughout the system. The SFD is a quantitative feature of the SD model, which supplements the quantity equations based on causal relationships constructed in CLD, thereby quantifying the interactions between various variables. Finally, people can validate the effectiveness and rationality of the proposed SD model through methods such as behavioural reproduction testing and extreme condition testing (Mohammadi et al. 2022), then conduct scenario simulations based on the SD model to solve the problem.

3.1. Research framework of system dynamics analysis

This article proposes an SD model (named SSC-CBAM) to simulate the operation mechanism of SSC and evaluate the potential impact of CBAM on China's steel sector. Then, by simulating possible decarbonisation scenarios of China's SSC, the implementation effects of different decarbonisation routes were evaluated and their response capabilities to CBAM were compared.

The specific steps of our study are shown in Figure 2. We first accomplish the mechanism analysis of the SSC system and extracted the important variables for SD modelling (main mechanism logical nodes of the system are shown in ovals and important variables are shown in square boxes). The operation mechanism of the SSC mainly includes material flow and information feedback. The material flow includes the input of raw materials to the production of steel products to the sales of products. The costs and revenues generated from material flow will act as feedback on the supply chain, resulting in a closed loop of the entire system. In next, the important variables extracted from the system will be used for SD modelling: We depict the causal relationship of variables through CLD, then we supplement the quantitative analysis of the model through SFD. Finally, after passing model verification, we perform scenario simulations to obtain the corresponding results. It should be noted that due to the availability of high-quality data, and from the perspective of the relevance and simplicity of the model design, the system analysis carried out in this article mainly includes the operation of China's SSC in the domestic market and exports to the EU market. The analysis of other markets outside the EU is not included within the boundary.

3.2. Causal loop diagram (conceptual modelling)

The basic logic of the SSC system runs from the import of raw materials to the production of steel products to the sale of steel products. Each step is interlinked and is further influenced by other factors. The factors in all steps combine to form a complex supply chain feedback system. To illustrate the problem more precisely and concisely, we have extracted the key factors to form our CLD. As shown in Figure 3, the variables at the bottom of the figure depict the material flow of the SSC, while the cost and profit-related variables above them represent information feedback in the system.

For the material flow of SSC, the first is the supply of iron ores, which will provide the raw materials for the steel production chain. More raw materials mean more production capacity. Domestic sales are influenced by the production of steel products and the domestic economy (GDP). More productions increase the available for sale to meet the demand for steel products as

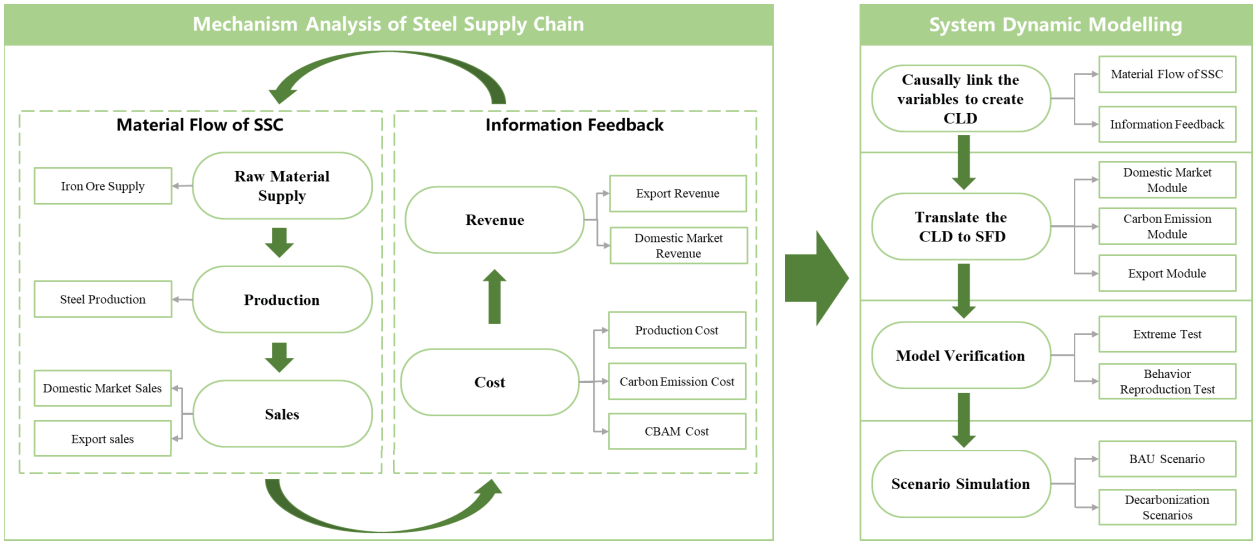


Figure 2. System dynamics analysis flowchart.

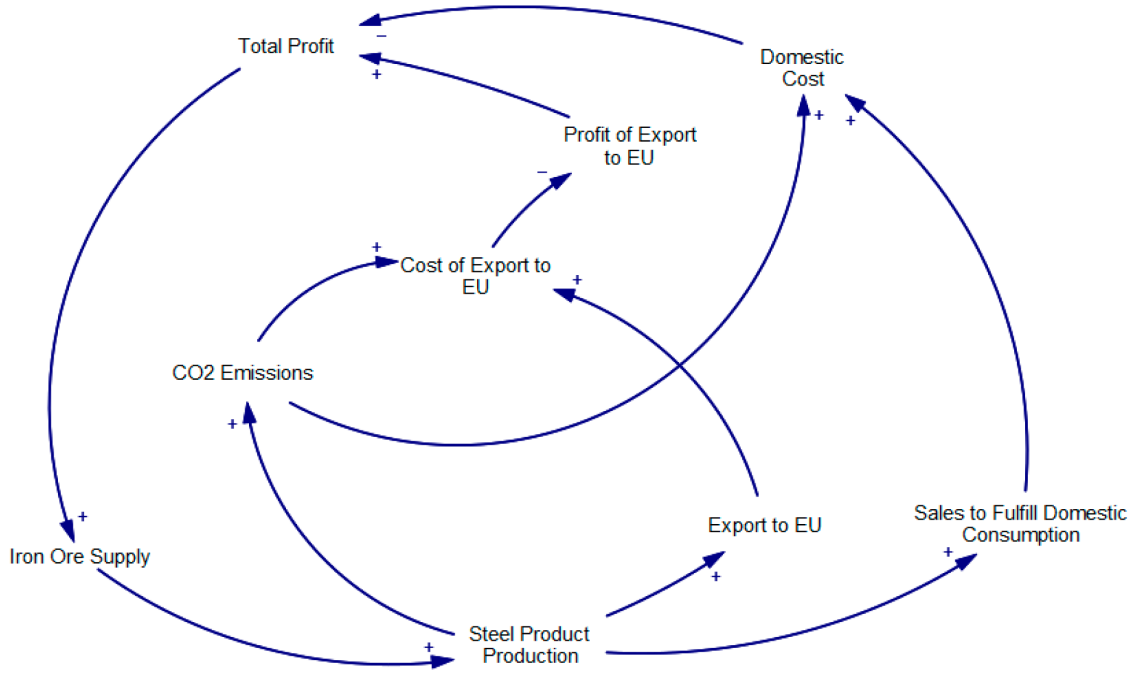


Figure 3. Causal loop diagram of steel supply chain.

the domestic economy grows. Most of steel products are used to meet domestic demand, and the remainder is exported to the EU. For the information feedback part, production and sales are transmitted to the cost-profit part of SSC through their respective price elasticities, thus determining profitability, which further affects the import capacity of raw materials and forms a feedback loop. For instance, overproduction leads to lower prices, so that the rate of return on sales is compressed. Additionally, more production means more carbon emissions cost, which continues to squeeze supply chain margins. These will make the supply chain less able to import raw materials. Then, a shortage of production due to a lack of imports of upstream raw materials will result in the domestic demand not being met, leading to a gradual price recovery and improved supply chain profitability. Next, manufacturers can effectively increase their ability to import raw materials upstream of the supply chain, compensating for the current lack of production to meet demand and restoring supply and demand back in balance. Finally, the entire SSC forms a complete system through the interaction and feedback mechanisms between the various factors.

3.3. Scenario discussion

This study enumerates possible decarbonisation measures of SSC according to reality and then sets up policy scenarios containing different measures.

Measure 1: The steel industry will be included in the national carbon market. In December 2017, the National Development and Reform Commission (NDRC) of China issued the construction plan for the national carbon emission trading market, which explained the construction plan of China's carbon market. However, the first phase of China's carbon trading system launched in 2021 has reduced the coverage of industries from seven energy-intensive sectors, including the steel, non-ferrous metal sectors, etc., to only the power sector. The steel sector will be included in the carbon trading system in the second phase. In addition, the relevant research indicates that following the idea that 'enterprises with low marginal emission reduction costs should reduce emissions first', steel sector ranks second among all industries that should be included in the carbon market coverage (Wang et al. 2023). Gradually expanding the coverage of the national carbon emission trading system is an effective way to realise the low carbonisation of the steel industry and an important way to keep the carbon tax and other related revenues in the country (Zhang et al. 2023). Consequently, measure 1 will be set to include the steel industry in the ETS.

Measure 2: Structural optimisation of steel production route. Currently, the BF-BOF steelmaking route is used mainly in China, accounting for about 90%, while Scrap-EAF only accounts for about 10% (WSA 2022). Because the carbon intensity of BF-BOF is much higher than that of the EAF route, the overall carbon intensity of China's steel industry has been among the highest position in the world for a long period. The development of Scrap-EAF to optimise steelmaking routes has always attracted the attention of policy makers (NDRC 2015; NEA 2016).

An et al. (2018) analysed the emission reduction potential of China's steel sector from the perspective of costs, showing that increasing the share of Scrap-EAF is feasible. Wang et al. (2022) and Ren et al. (2021) also state that the main emission reduction method for China's steelmaking is to increase the proportion of Scrap-EAF. Therefore, measure 2 is to optimise the steel production structure by improving the Scrap-EAF share.

Measure 3: Applying Carbon Capture Technology. Carbon capture, utilisation, and storage (CCUS) is considered one of the most potential approaches to meet the energy needs of the economy and simultaneously meet the CO_2 emission reduction targets. CCUS has attracted increasing attention as a solution that can achieve additional large-scale carbon reductions (IPCC 2018). As a carbon-intensive industry, the key path to reducing SSC's carbon emission is to accelerate the decarbonisation of production. However, the current production route based on EAF has been quite efficient, and the carbon emission level in production has been close to the theoretical limit (Gazzani, Romano, and Manzolini 2015). Therefore, CCUS appears to be a possible option for the continued decarbonisation of the steel industry (GCI 2017). In addition, CCUS technology does not involve the steelmaking process. By appropriately setting collection points in integrated steel plants, CCUS can be applied together with other solutions to further improve decarbonisation efficiency (Yao et al. 2021). The research conducted by scholars of both technical and economic feasibility (Kuramochi et al. 2011; Leeson et al. 2017) has also confirmed the rationality of applying CCUS to decarbonisation in steelmaking (Quader et al. 2015; Rootzén and Johnsson 2016). Therefore, measure 3 is considered as the adoption of CCUS technology in the steel industry.

After comprehensive consideration of the feasibility and emission reduction capabilities of implementing various measures, scenarios are set as shown in Table 1. In each scenario, we will assess the mitigation effect of different policies on CBAM shocks and obtain a better response policy.

Table 1. Scenario description.

Scenario	Description
Business as usual (BAU)	BAU means that the steel supply chain will follow the current state without any additional policy intervention, considered as a benchmark.
Policy 1	Policy 1 will be set as the steel industry takes Measure 1, which means the steel industry will be included in the national carbon trading system.
Policy 2	Policy 2 is considered as the steel supply chain adopts Measure1 plus Measure2, that is, the steel industry will join the ETS and increase the proportion of Scrap-EAF.
Policy 3	Policy 3 will integrate all the emission reduction measures mentioned above, including joining ETS, increasing the Scrap-EAF ratio, and deploying CCUS in steel plants.

3.4. SFD (mathematical modelling)

Based on the previous analysis, we have drawn an SFD to supplement the quantitative analysis features in the SD model. The main parameters and relationship equations are defined based on actual data from 2005 to 2021. Data are from the World Steel Association, China Iron & Steel Association, UN Comtrade Database, and Wind Database. The principal equations of the SD model are listed in the appendix.

SFD mainly includes three modules: Domestic Market Module, Export Module, and Carbon Emission Module, which correspond to the domestic market, export to the EU market, and carbon emissions of SSC, respectively. The modules are interconnected through various variables. For example, the connection between the domestic market module and the export module was achieved through variables such as 'Steel Production' and 'Export Profit'. The connection between the carbon emission module and the domestic market module was achieved through variables such as 'Steel Production' and 'Carbon Emission Costs'. Each module is linked to form a complex system SSC-CBAM.

The variables in SFD are divided into main variables and scenario control variables. The former represents the operation of the SSC without additional decarbonisation policies, while the latter controls the switching of different scenarios for subsequent decarbonisation scenario simulation analysis. As shown in Figure 4, the main variables in the SFD are linked by blue arrows, while the scenario control variables, which used to switch scenarios in the system, are connected by other coloured arrows (pink arrows for Policy 1 scenario, green arrows for Policy 2 scenario, and orange arrows for Policy 3 scenario).

In the Domestic Market Module, the material flow is constructed by the supply chain consisting of raw material supply, steel production, and sales to the domestic market. Cost and profit-related variables comprise the information feedback. In the material flow section, the import capacity of iron ore is mainly influenced by the profitability of SSC, which determines the reinvestment capacity of supply chain's operation. Then, iron ores are processed into steel products. Variables such as iron ore utilisation rate and production capacity utilisation rate will influence the production level. Steel products are mainly sold to meet domestic demand, while the remaining will be exported (Yu et al. 2023). Domestic steel demand is mainly influenced by domestic GDP. In the information feedback section, the variables of cost and profit supplement the feedback mechanism of material flow in the model. The production and demand in the material flow are transmitted to the various costs and profits in the information feedback section through their

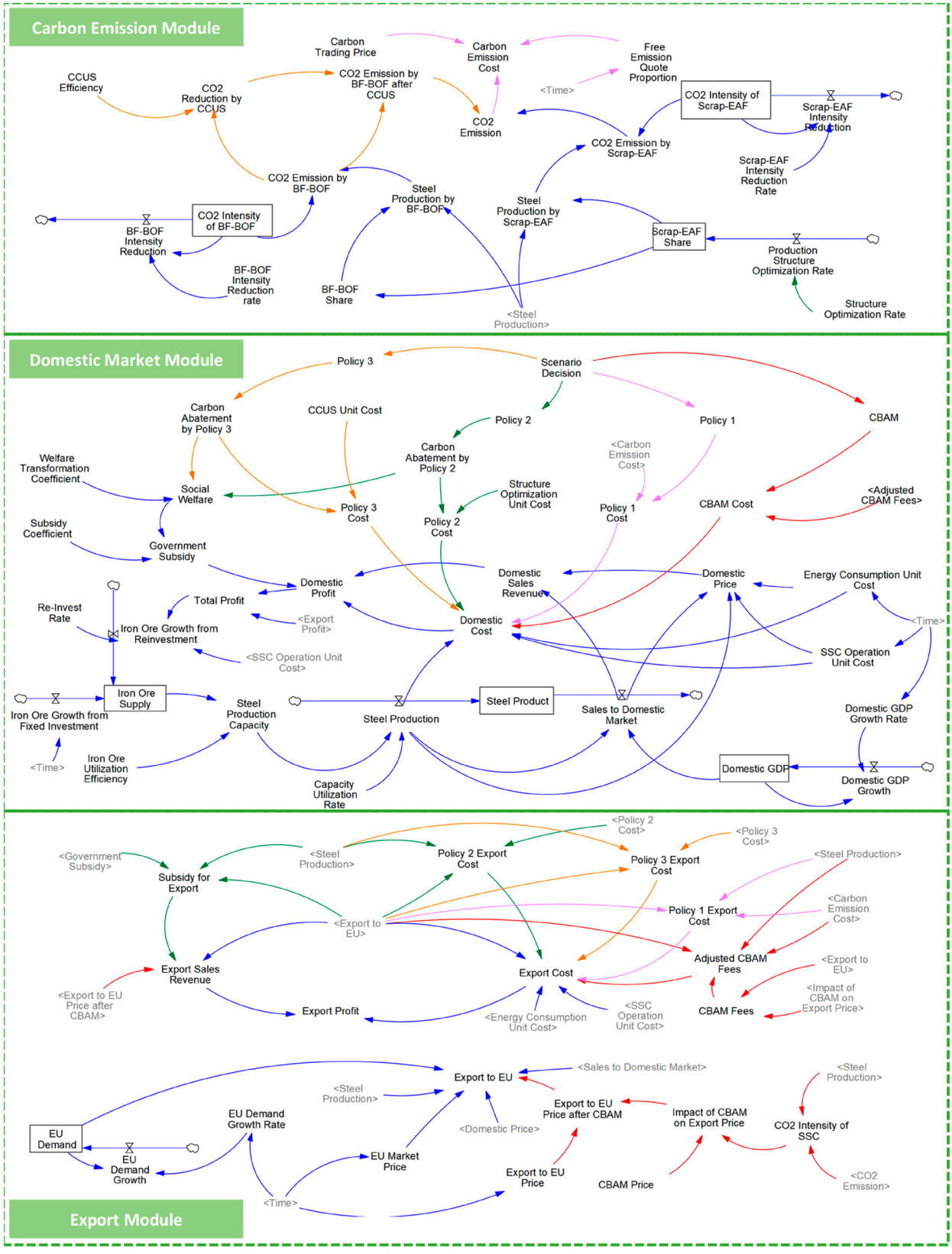


Figure 4. SFD of SSC-CBAM system.

respective price elasticity, and the costs and profits affect the supply chain operation ability so that feedback to the material flow section. Therefore, the feedback mechanism is achieved through the price mechanism. Price, which is endogenous in the model, is mainly determined by production, demand, and SSC operating costs. When steel production exceeds demand, the price will fall and vice versa. In addition, an increase in SSC's operating cost will also lead to an increase in price. The cost of SSC mainly includes cost variables like SSC operating costs and energy consumption costs. The profitability of SSC is mainly determined by the variables related to sales and the endogenous price. At last, the profitability of SSC will affect the reinvestment capacity, thereby altering the material flow of the system.

Similar analysis was also conducted in the Export Module. The variable Exports to the EU are jointly influenced by steel production, sales to domestic market, domestic price, EU market price, EU demand, and export price. As mentioned earlier, the difference between steel production and sales to domestic market determines the share available for export, and the price difference between the EU market price and the export price of China's SSC also affects the export propensity. When the export price is lower than the EU market price, China's steel products exported to the EU have a competitive price advantage, so the exports will increase accordingly and vice versa. The other variables linked by red arrows represent the impact mechanism of CBAM, which increases the export price from China to the EU through the imposition of tariffs. This will result in a loss of price advantage of export prices over EU market prices. Then, this will further damage exports, increase costs and decrease profits in the export chain, and create feedback effects throughout the system.

In the Carbon Emission Module, the carbon emission of SSC is mainly determined by the steel production and the corresponding carbon intensity of different steelmaking routes. BF-BOF with higher carbon intensity accounts for most of the production share, while Scrap-EAF with lower carbon intensity accounts for a small portion. Moreover, we have set carbon reduction coefficients for each production routes to simulate technological progress (Xuan and Yue 2016). It is worth noting that since CBAM currently only considers direct carbon emissions of production but does not consider indirect carbon emissions or even the complete carbon footprint of steel products, the Carbon Emission Module mainly considers direct carbon emissions during the steelmaking.

At last, the policy decision variables control the switching of scenarios in the system. Different policy choices have changed the profits and carbon emissions of the SSC, which will further spread to the material flow and affect the entire system. For example, in the case of Policy 3, SSC will join the ETS, adopt more Scrap-EAF for steelmaking, and adopt CCUS for carbon capture (variables related to Policy 3 are connected by orange arrows). As can be seen, Policy 3 will cause a series of variables in the system to change. Joining ETS, implementing more Scarp EAF, and deploying CCUS will incur execution costs. However, the carbon reduction effects they bring will reduce the costs of carbon emissions in SSC and receive subsidies from the government to support the transformation of decarbonisation. Lastly, these additional costs and benefits will affect the profitability of SSC and further propagate to the entire system.

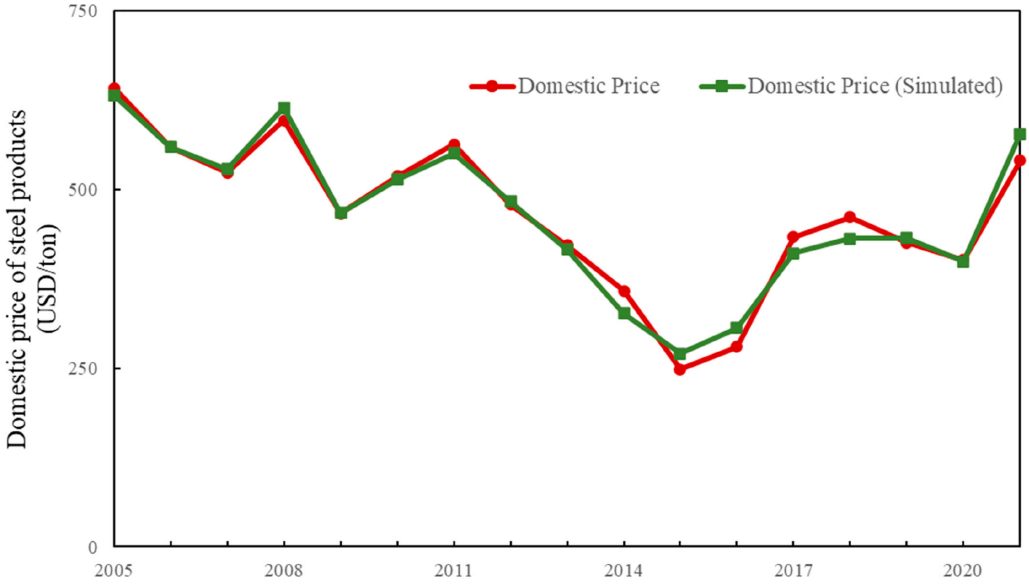
In brief, we quantitatively describe the interrelationships and feedback effects of various variables in the SSC-CBAM system through SFD. Based on this model, we can analyse the impact of CBAM on China's steel sector. Furthermore, by switching scenarios, we can evaluate the mitigating effects of different decarbonisation trends on CBAM.

3.5. Model verification

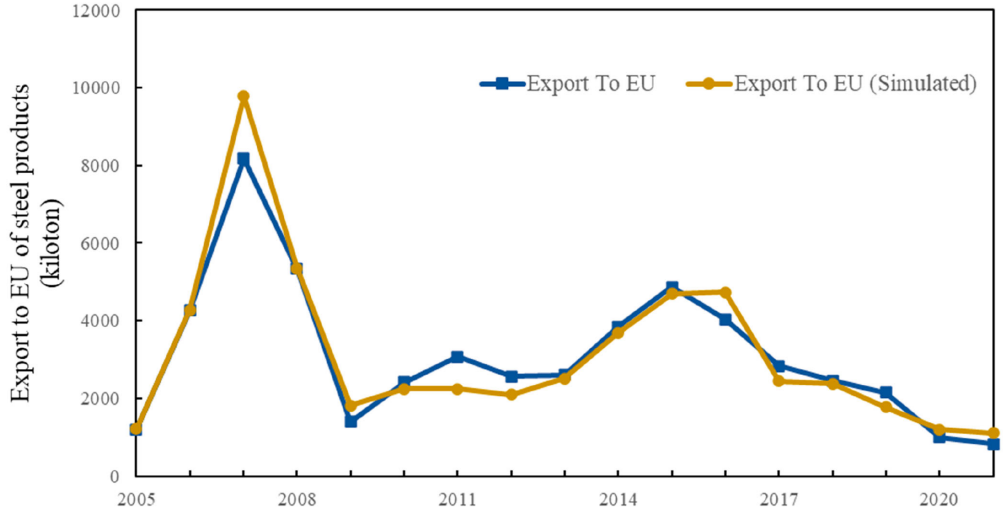
Model verification is an important step before the application of SD models, which can evaluate the rationality of models for described scenarios and enhance the reliability of simulation results. SD model validation methods mainly include structural integrity testing, behaviour reproduction testing, extreme condition testing, etc. Although the verification approaches depend on model application and purpose, the latter two methods are the most common consistency tests (Mohammadi et al. 2022). Behavioural reproduction test evaluates whether the SD model can simulate reality by comparing its results with real historical data. Extreme condition testing aims to verify whether the model can behave consistently with real-world analysis under extreme conditions. For example, if the production capacity is equal to almost zero, its direct production should also be close to zero.

First, according to the actual status of China's steel industry, the causal relationship and the feedback effect among all variables are analysed. After inspection, it is ensured that the relationship between variables conforms to the logic, and the relationship described by the equation is consistent with reality. Furthermore, the inspection of the units of each variable was completed to ensure that the dimension remained at the same level. Therefore, the SD model passed the structural integrity check and the dimensional consistency check.

Then, to verify the validity of the SD model, we compare the simulated value with real data. We choose domestic price and export to the EU of steel products as



(a) Comparison of real and simulated values of domestic price.



(b) Comparison of real and simulated values of export to EU of steel products.

Figure 5. Behaviour reproduction test.

test variables because they have involved the most variables. As shown in Figure 5, the simulation results fit the actual data well. Furthermore, the error levels of other relevant variables are within 15%, indicating that the model is valid.

Finally, we tested whether the model could exhibit the expected behaviour when some parameters were set to extreme values. We choose the variable of production capacity utilisation rate for the test, and set it to 10^{-20}, which is close to 0 (because the relevant variable is set as the denominator in the relationship equations, it cannot be set to 0 directly). It is expected that in this case, the steel production will be close to 0. Due to the lack of steel production and sales, carbon emissions and profits should also approach zero. In addition, due to the absence of steel production, the demand for steel required by domestic economic development cannot be met, so the price of steel products should be close to extremely high. As shown in Figure 6, the results of the model test are consistent with the expected behaviour, so the SD model passes the extreme conditions test.

4. Model simulation and results discussion

4.1. Scenario settings

Based on the discussion of possible decarbonisation scenarios in section 3.3, we have designed each scenario

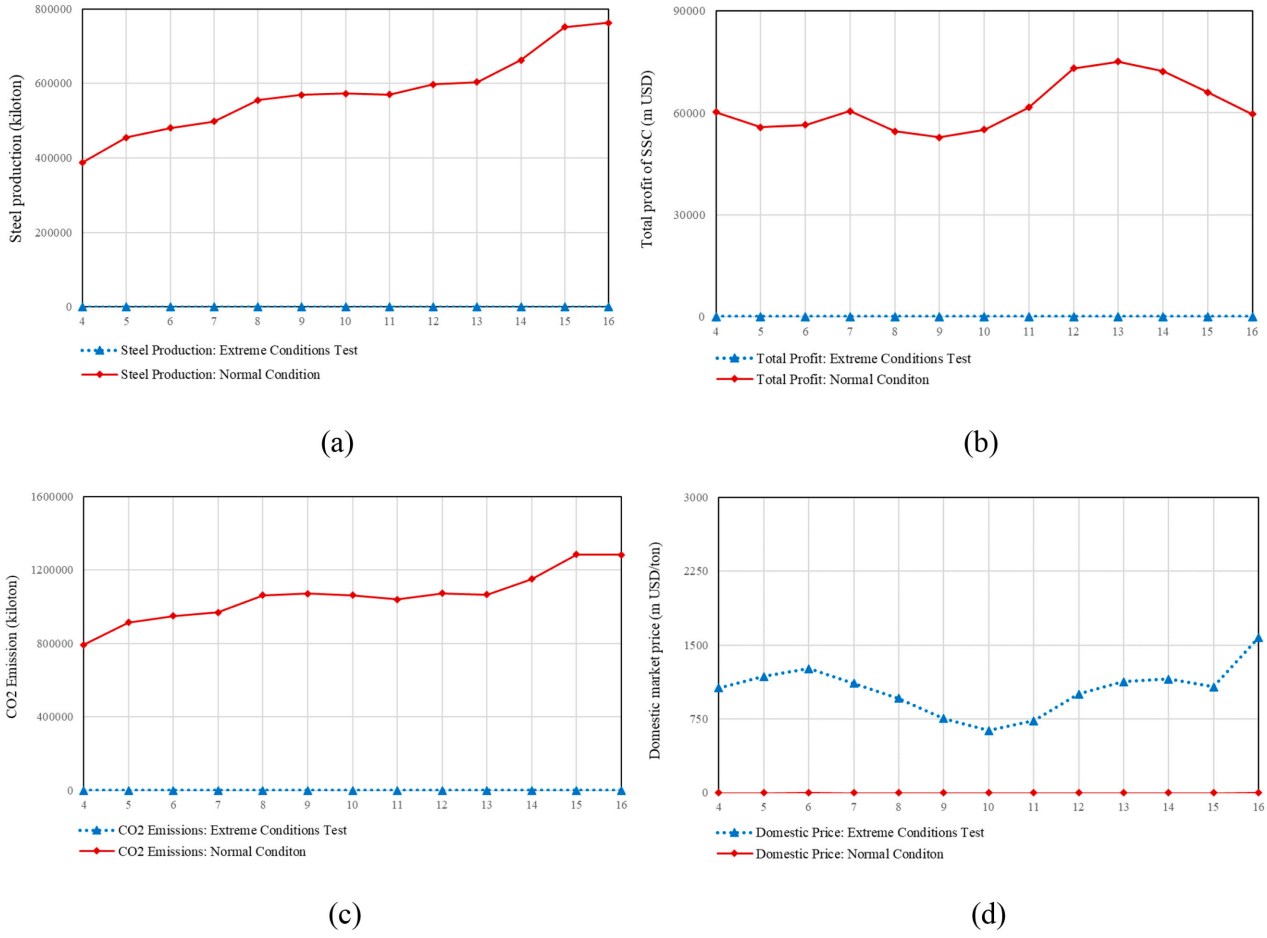


Figure 6. Extreme condition test.

reasonably. In scenario Policy 1, we include the steel industry in China's ETS, and the carbon price is set at 8 USD/tCO_2 based on the average price of China's ETS in 2022. In Policy 1, the change of SSC is the carbon cost borne by being included in the carbon market. Scenario Policy 2 will further optimise the production structure of SSC, gradually increasing the share of Scrap-EAF, thereby achieving a low-carbon transformation of SSC's production structure. In Policy 2, steel companies not only need to pay for carbon emission costs, but also need to take on the cost of upgrading production structure. Meanwhile, they will receive financial subsidies from the government, which can reduce the resistance of the cost side in the decarbonisation of the SSC. In scenario Policy 3, manufacturers will further deploy CCUS to gain additional carbon reduction capabilities, so they will front the additional cost of CCUS. Correspondingly, the carbon reduction brought by CCUS also benefits manufacturers, mainly including government green subsidies and a reduction in carbon emission costs. The specific parameter settings for each scenario are summarised in Table 2.

Table 2. Scenario settings.

Scenario	Carbon Price (USD/ton)	Production Structure	Carbon Capture Technology	Subsidies
Business as usual (BAU)	0	90% BF-BOF and 10% EAF	No	No
Policy 1	8	90% BF-BOF and 10% EAF	No	No
Policy 2	8	Gradually transitioning to 75% BF-BOF, 25% EAF	No	Yes
Policy 3	8	Gradually transitioning to 75% BF-BOF, 25% EAF	Yes	Yes

4.2. The impact of CBAM in BAU scenario

Firstly, we would like to focus on the impact of CBAM on the SSC in the BAU scenario. The direct impact of CBAM on exports is to increase the additional cost of carbon emission. The cost of CBAM is determined by the anchoring price of CBAM (CBAM anchors the EU carbon market price, therefore is set at 80 USD according to the average carbon price of EU-ETS in 2022) and

the carbon intensity. In fact, since CBAM price is exogenous to SSC, the degree of influence of CBAM mainly depends on the carbon intensity of SSC. When the carbon intensity of SSC is high (especially in developing countries like China), exporters need to pay more CBAM fees, resulting in higher export prices and greater loss of price competitiveness in the EU market.

According to the simulation results, the impact of CBAM on China's SSC is mainly concentrated in exports. It will result in a decrease of approximately 32% in steel exports from China to the EU and a loss of 58% in export profits. Meanwhile, the effectiveness of CBAM as a climate tool is relatively limited, since the total carbon emission of China's SSC has not significantly decreased.

Figure 7 shows the impact of CBAM on key variables in the system such as steel product exports, export profits, total profits of SSC, and total carbon emission. Compared to the situation without implementation of CBAM, steel exports under CBAM have decreased significantly. This is because without CBAM, China's steel products had lower production costs compared to local manufacturers in the EU and were in an advantage position of price competition. Due to the CBAM, China's export prices have to increase to compensate for tariff losses, losing their price competitiveness in the EU market. Meanwhile, despite the increase in export prices, export profits are still damaged, mainly due to the combined effect of the increase in cost and the decrease in export volume. Furthermore, considering the environmental benefits of CBAM, we found that it has a limited effect on promoting decarbonisation in China's steel industry. There was no significant change in the total carbon emissions level of SSC in China after the execution of CBAM. The reason is that compared to the domestic market, the proportion of exports to the EU is small. It can be seen in Figure 7(c) that the impact of CBAM on the total profit of China's SSC is inconsequential, and it is unable to promote emission reduction in energy-intensive industries through the carbon tariff. The environmental benefits of CBAM are constrained by the trade exposure of different countries (Perdana and Vielle 2022). This also indicates that the idea of forcing the low-carbon transformation of China's steel industry through the CBAM is unrealistic. CBAM cannot force energy-intensive industries in countries with low trade exposure to pursue a massive decarbonisation through a pricing mechanism like national ETS.

4.3. Changes of SSC in different decarbonisation scenarios

In this section, we will simulate the decarbonisation scenarios to discuss the changes in SSC under different degrees of carbon reduction, preparing for further

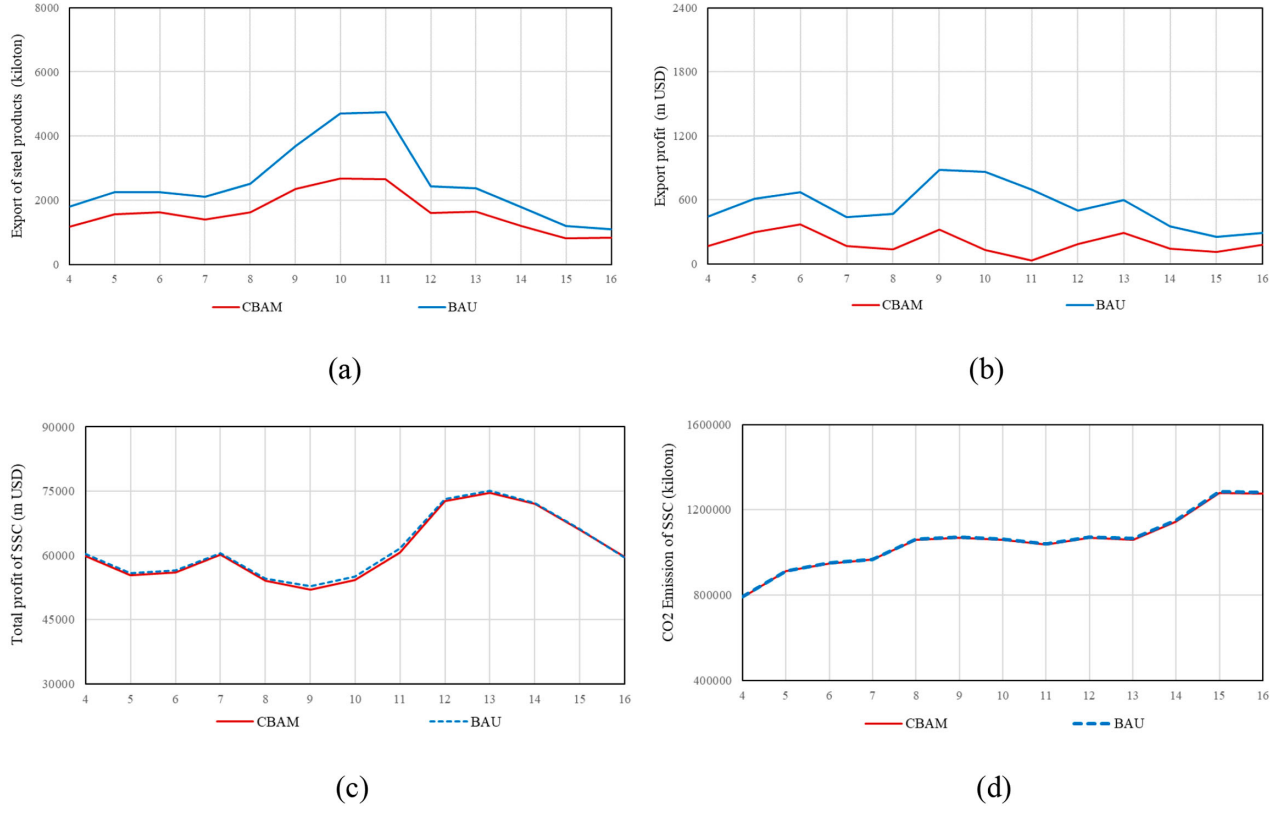


Figure 7. Impacts of CBAM in BAU scenario.

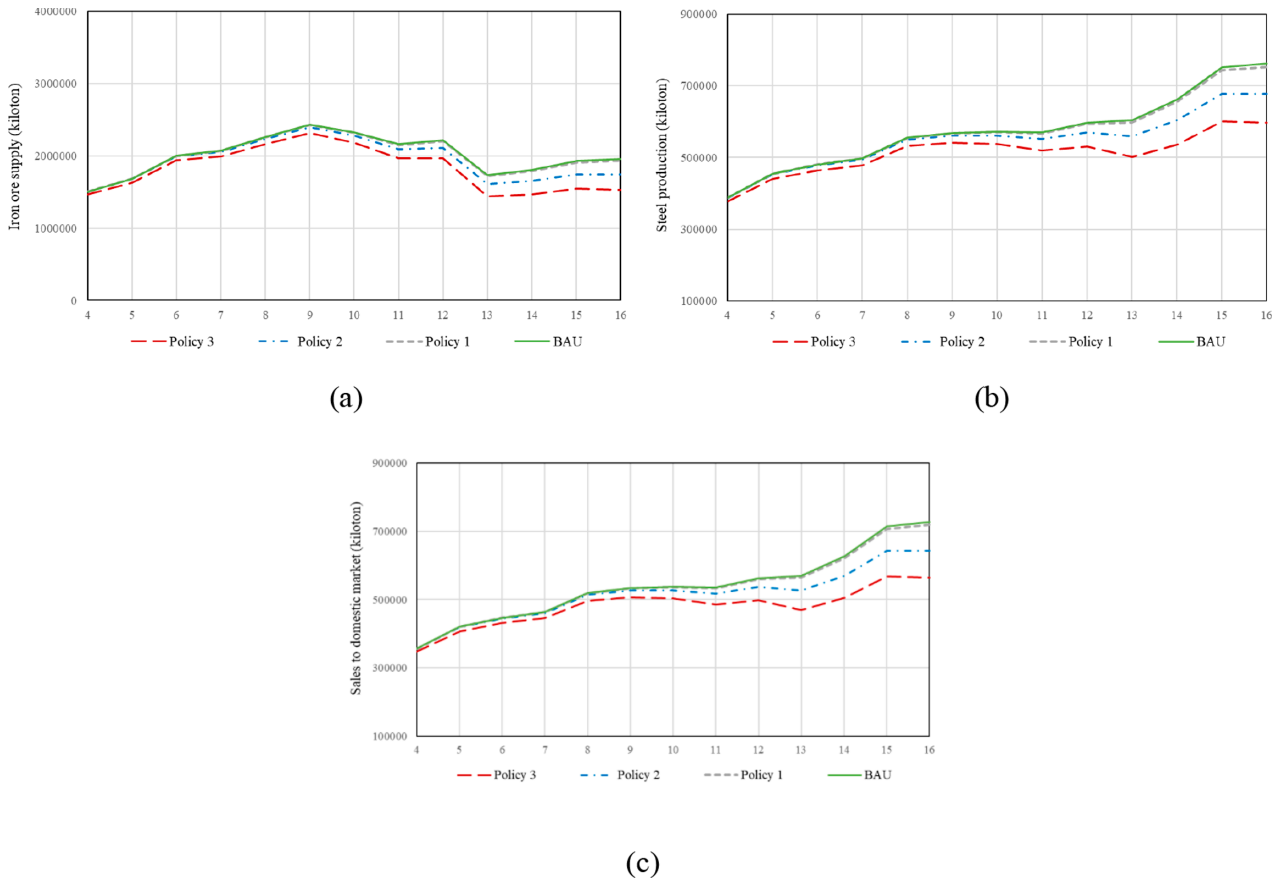


Figure 8. Material flow of SSC in different scenarios.

discussions on the response effects of different policies on CBAM.

4.3.1. Changes in material flow of SSC

Firstly, we focus on the material flow of the SSC in different scenarios, as shown in Figure 8. For scenario Policy 1, the material flow is weakly affected, and the status of the 'raw material supply to steel production to sales' chain remains almost unchanged compared to the BAU scenario. This is mainly due to the current low carbon market prices in China, so there are insufficient pressures for SSC brought by carbon prices. For scenario Policy 2, the material flow of SSC has been squeezed by about 4%, resulting in a decrease in SSC activity. Production and sales decreased by 3.68% and 3.81%, respectively. The reason for this phenomenon is that the BF-BOF which with higher energy-intensity has been upgraded to a cleaner Scrap-EAF, eliminating some outdated highly polluting production capacity. In scenario Policy 3, decarbonisation measures not only include joining the ETS and upgrading production structure, but also further acquiring carbon reduction capabilities through the deployment of CCUS. In this scenario, the 'raw material supply to steel production to sales' chain has experienced a more significant decline compared to the previous scenario. The production and sales of SSC decreased by 9.17% and 9.47%, respectively. In a more aggressive decarbonisation policy scenario, the space of manufacturers with high pollution has been squeezed even higher, which will eliminate most of its inefficient production capacity. The overproduction situation in China's steel industry has been cooled.

4.3.2. Changes in profitability of SSC

Next, we will discuss the impact of different decarbonisation policies on the cost and profit of SSC. Figure 9 shows the changes in the relevant variables under each scenario.

In scenario Policy 1, SSC's profit level remains basically at its original level, with a decrease of only 2.5%. It can be observed that Policy 1 has a relatively limited impact on SSC, with minimal losses of SSC's profit and almost no additional carbon reduction subsidies received. In scenario Policy 2, SSC's profit level suffered some shocks. The cost of SSC increased by about 8%, and the sales revenue decreased by about 3%. The profit margin of unit steel production decreased from 130 USD/ton (in the BAU scenario) to 110 USD/ton. Considering the

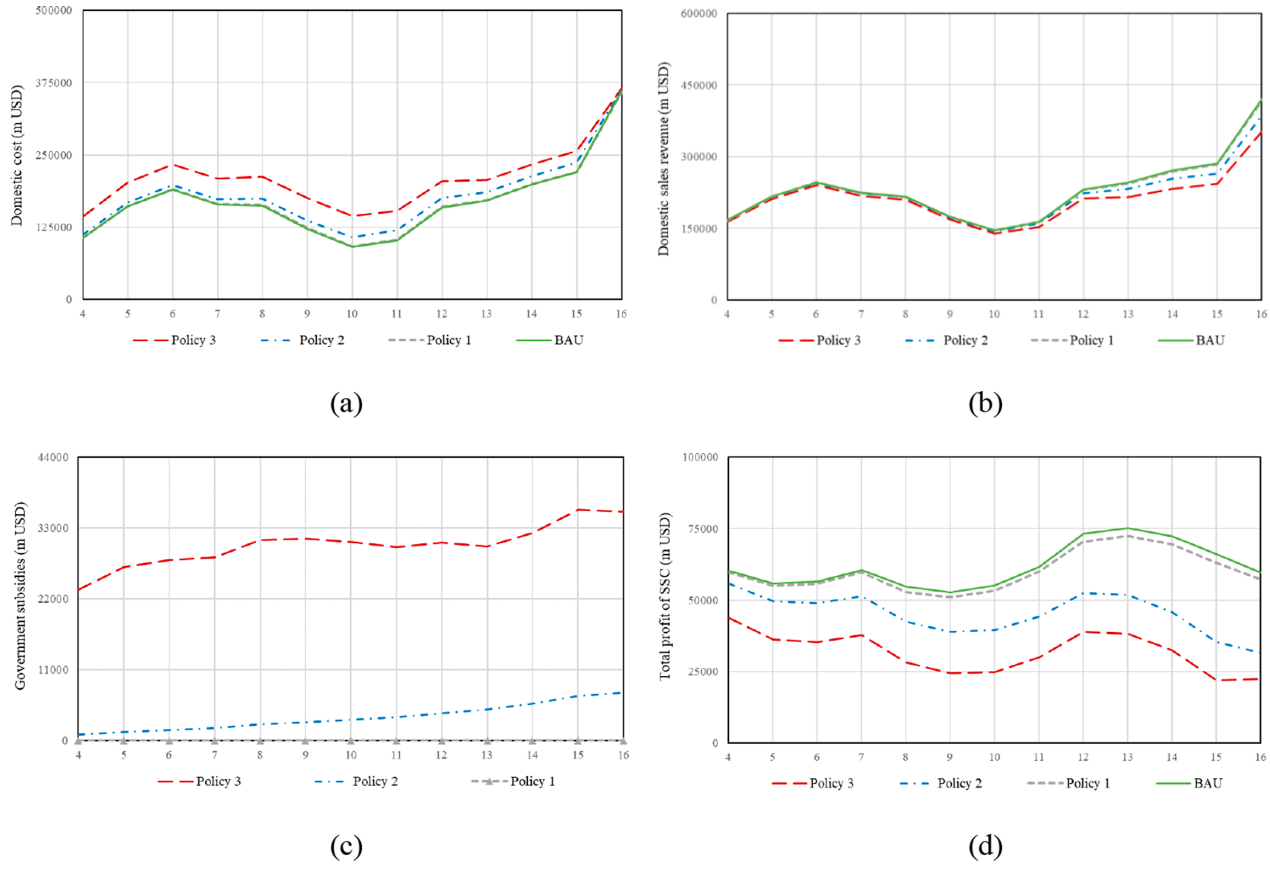


Figure 9. Profitability of SSC in different scenarios.

reduction in production caused by the elimination of some high-polluting production capacity, the net profit level of SSC decreased by about 24% compared to BAU. It can be found that the low carbon upgrading of the production route in SSC has cost pressures, and the elimination of high-polluting production capacity has also lost some of the profit space, indicating that corresponding government subsidies are necessary. Benefiting from the government subsidies and the reduction of carbon emission costs, the cost pressure of Policy 2 has been alleviated. In scenario Policy 3, despite steel producers receiving the most government subsidies, profits still significantly decreased. The main pressure comes from the cost side, with supply chain costs increasing by about 29% and sales revenue decreasing by about 7%. The profit margin of unit steel production has further decreased from 110 USD/ton to 87 USD/ton. Meanwhile, the more aggressive pollution production capacity elimination has also led to a loss of approximately 45% in the total net profit of SSC compared to BAU. Therefore, we believe that the high execution costs of Policy 3 will bring enormous pressure to the operation of SSC. This result indicates that before implementing large-scale emission reduction policies, the steel sector needs to complete comprehensive preparations and have a certain level of resilience. The government not only needs to provide financial support, but also needs to actively guide consumers to choose to purchase low-carbon products.

4.3.3. Changes in carbon emission of SSC

Finally, we will see the changes in carbon emissions of SSC in each scenario to evaluate their environmental benefits, as shown in Figure 10.

In the conservative decarbonisation scenario, Policy 1, the carbon emission decreases little compared to the BAU scenario. SSC fronts much more carbon emission costs than other decarbonisation scenarios due to higher carbon emissions. As mentioned earlier, the reason for this phenomenon is the carbon trading price set by the model is the current Chinese carbon price. The China's ETS is in its initial stage, and the market mechanism still needs to be improved. The carbon price is at a low level, making it difficult to play its role in effectively providing a decarbonisation motivation for steel producers to eliminate high polluted capacity. For scenario Policy 2, there has been a certain level of decrease in carbon emission of SSC. The carbon emission has decreased by about 11% compared to BAU, and the carbon payment cost has been saved by about 9% compared to Policy 1. Due to the upgrading of industrial structure, some manufacturers with high emission were eliminated, resulting in the SSC

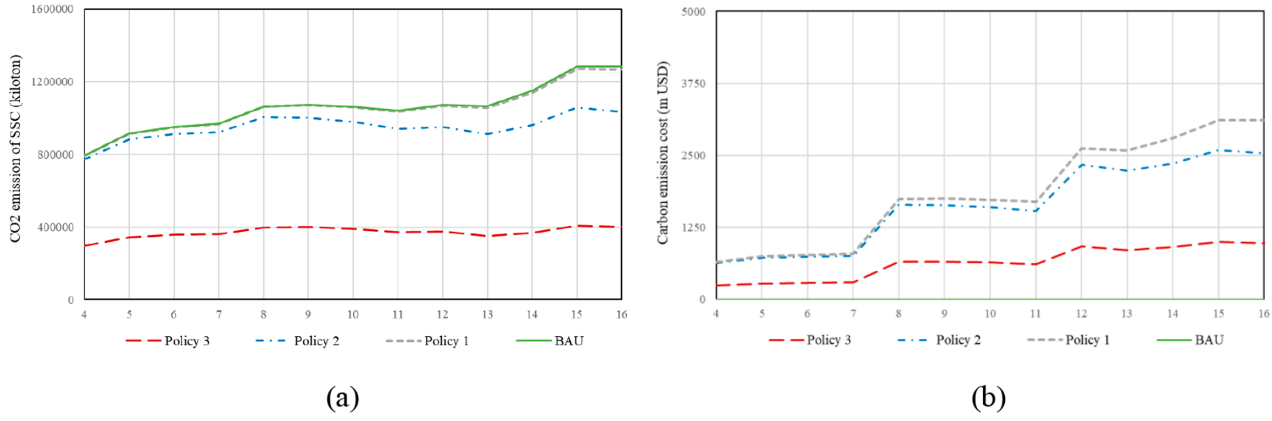


Figure 10. Carbon emission changes of SSC in different scenarios.

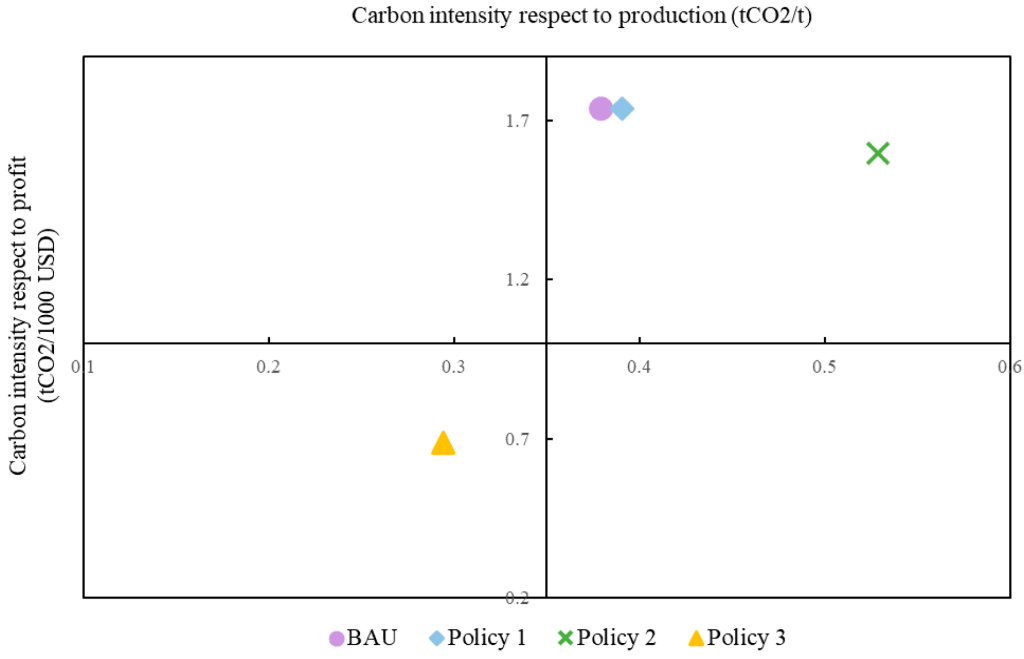


Figure 11. Assessment of environmental benefits for different scenarios.

shift towards cleanliness. The most radical decarbonisation scenario, Policy 3, will result in a greater reduction in carbon emission of SSC. The emission reduction reached about 63% compared to BAU, and the carbon emission cost decreased by about 70% compared to Policy 1, which achieves the highest emission reduction target. It can be observed that compared to previous scenarios, although Policy 3 adopts the most comprehensive decarbonisation measures, the marginal emission reduction cost shows a decreasing trend due to the carbon payment cost savings brought by large-scale emission reduction and the existence of the most sufficient government subsidies.

Figure 11 summarises the emission reduction effects under different scenarios, with the Y-axis representing the carbon emission per unit of steel production (unit: tCO_2/t) and the X-axis representing the carbon emission per unit of profit (unit: $tCO_2/1000$ USD).

The indicator 'carbon intensity respect to production' in *Y*-axis measures the carbon emission control effect of SSC output, that is, the cleanliness level of SSC production. Policy 3 has the smallest carbon intensity respect to production, indicating that its carbon reduction effect is significantly better than other decarbonisation scenarios on SSC. Policy 3 is only about 0.69, which is less than half of BAU. Policy 2 is about 1.6. In Policy 1, joining the ETS does not directly affect the production behaviour of SSC, and the carbon price is at a low level, the price mechanism is limited. Therefore, the improvement effect of Policy 1 on the carbon intensity of steel production is very weak.

The indicator 'carbon intensity respect to profit' on the *X*-axis represents the carbon emission control ability of

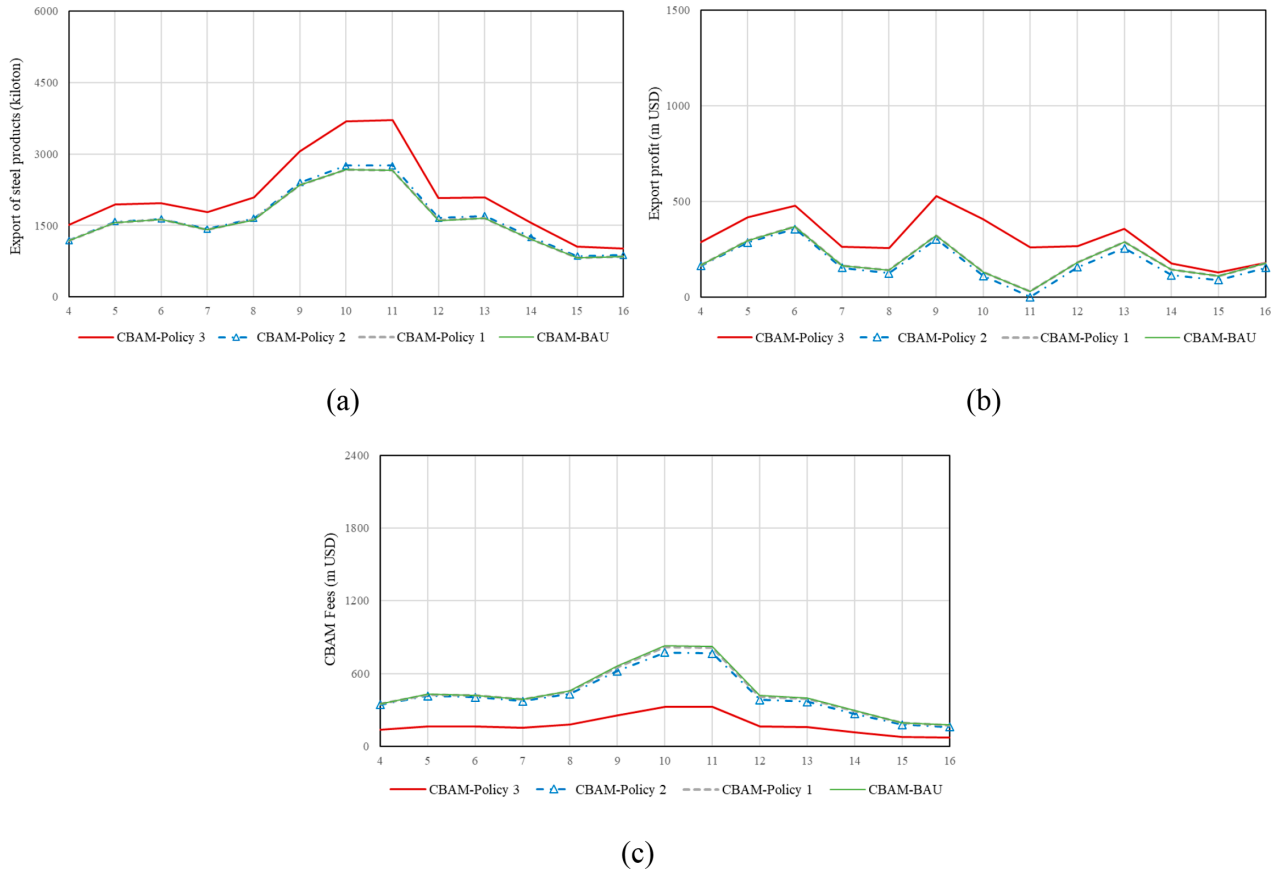


Figure 12. Changes in the impacts of CBAM in different scenarios.

SSC when obtaining profits. Policy 3, which still has the best performance, is about 0.29; Policy 1 and Policy 2 performed poorly on this indicator, with 0.39 and 0.53, respectively. These results show that although Policy 3 has lower net profits than other scenarios, its contribution to carbon reduction is outstanding. In other words, the profit loss of SSC in Policy 3 may be worthwhile, as it eliminates outdated capacity in the steel industry and obtains additional carbon reduction capabilities through the deployment of CCUS. Policy 3 has traded for the low-carbon upgrade of the entire industry at the cost of losing profits from high-polluting manufacturers. In contrast, the carbon emissions per profit of Policy 1 and Policy 2 are even higher than BAU, indicating that their contribution to carbon reduction is insufficient. Therefore, SSC should adopt more aggressive strategies to achieve a higher emissions reduction and lower marginal emission reduction costs.

4.4. The mitigation effect of different policies on CBAM

Based on the analysis in Section 4.2, CBAM will undoubtedly have negative impacts on SSC. In this section, we hope to pay attention to the changes in the impacts of CBAM on SSC under different decarbonisation scenarios, to help us know which strategies can minimise these negative impacts. Figure 12 shows the impacts of CBAM on steel exports and the changes in CBAM fees under different decarbonisation scenarios.

We found that compared to BAU, the impacts on SSC's exports from CBAM in scenario Policy 1 did not show a significant difference. This is mainly because the policy of only considering the inclusion of the steel industry within the scope of ETS did not directly reduce the carbon intensity of SSC production, but rather hoped to use the carbon price mechanism to encourage steel producers to reduce emissions. However, due to the current low carbon prices in China, SSC will not have a strong momentum to actively decarbonise. Therefore, a conservative decarbonisation scenario Policy 1 will not have a positive emission reduction effect on the SSC. Meanwhile, although there is a deduction mechanism in CBAM, which means that if the relevant imported products have already paid the carbon cost in their own region, the EU will exempt this part of the cost to avoid double taxation, China's carbon price (about $8) is insignificant for the EU carbon price (about $80), thereby the SSC of

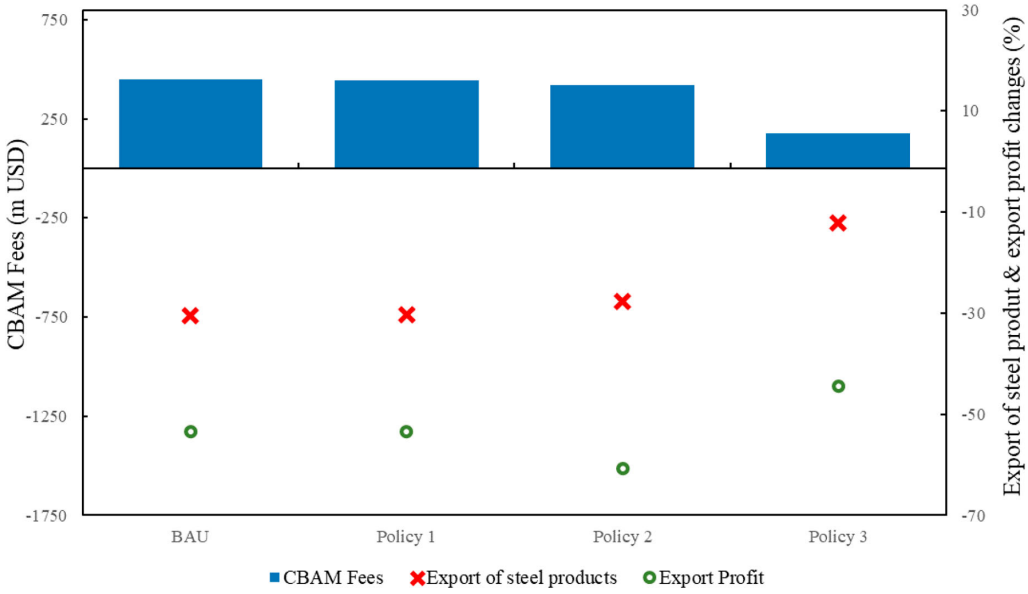


Figure 13. Summary of the impacts of CBAM in different scenarios.

China will not enjoy much CBAM credits. China's existing carbon market is still incomplete. If only using carbon market tools to cope with the impact of CBAM, the effect is insufficient. The performance of scenario Policy 2 in mitigating CBAM impacts is also insignificant. Due to the better carbon reduction effect of this scenario, the steel export volume losses are slightly lower than Policy 1, and SSC needs to pay less CBAM fees. However, we found that the performance of Policy 2 is not even as good as Policy 1 for the export profits of SSC, mainly due to the higher costs incurred by SSC in upgrading its production structure in this scenario. Accordingly, it is difficult to conclude that the implementation effect of Policy 2 is superior to Policy 1 in dealing with CBAM. In scenario Policy 3, the impact of CBAM on SSC exports has been alleviated, and the effect is significantly better than other policy options. The decrease in steel export volume and the loss of export profits in the Policy 3 are minimal. Moreover, the CBAM fees that need to be paid for exports are much less than those of other scenarios. This indicates that compared to all other scenarios, Policy 3, which adopts comprehensive measures, is the best solution to address CBAM.

Figure 13 summarises the relevant indicators, showing that Policy 3 is the best strategy to address the negative impacts of CBAM compared to other scenarios. First, for the steel export loss caused by CBAM (represented by red crosses in the figure, presented on the secondary axis), the degree of mitigation in Policy 3 is significant. The export loss in Policy 1 is approximately 30%, which is close to BAU. The export loss in Policy 2 and Policy 3 is 27.8% and 12.2%, respectively, showing Policy 3 performance better in this indicator. For the loss of export profits (represented by green circles, presented on the secondary axis), Policy 3 also had the lowest profit loss, which is about 44%. Policy 2 suffered the highest profit loss, which is nearly 60%. At last, for the CBAM fees (represented by blue bar charts, presented on the main axis), Policy 3 still has the best protection effect for SSC, with a CBAM cost of only 175 million USD, which is about 60% less than the BAU. The CBAM fees for Policy 1 and Policy 2 are 444 million USD and 421 million USD, respectively, which are much higher than Policy 3. To sum up, we can believe that Policy 3 is the best solution to address CBAM, and mobilising various resources to reduce carbon emissions is the most effective approach when conditions allow.

5. Conclusions

This article proposes an SD model to simulate the operation of SSC in China. Then, we introduce CBAM as an exogenous shock into the model and analyse its potential impact. Next, several scenarios were reasonably set based on the decarbonisation trends in the real world, and SSC under different scenarios were evaluated from the perspectives of profitability and carbon emission control. Finally, we analysed the mitigation effects of these scenarios that contain different decarbonisation measures on the negative impact of CBAM.

The results show that the implementation of CBAM will hurt SSC's export from China to the EU. CBAM will lead to an increase in export prices by about 34%, thereby losing price advantages, which will further result in a decrease of about 32% in the export of steel products and a decrease of about 58% in export profits. However, the

impact of CBAM on the decarbonisation of China's steel industry will be limited. The total carbon emission of the steel sector in China has not significantly decreased due to CBAM, as it has a low trade exposure to the EU. This indicates that CBAM perhaps has insufficient effectiveness in playing its role as a climate tool, which is its original design intentions: to provide additional motivation for countries to accelerate the global emission reduction. CBAM only focusses on carbon-intensive products, and its environmental benefits are constrained by factors such as trade exposure of different countries. For huge markets like China, it is unrealistic to accelerate decarbonisation solely through CBAM.

Scenario Policy 3, which includes joining the ETS, adopting more Scrap-EAF in production routes, and deploying CCUS, provides the best performance among all scenarios. Although Policy 3 has the highest execution costs, the sacrifice of some profits may be worthwhile as its excellent carbon reduction effect significantly promotes the decarbonisation of SSC. The result that it is greatly superior to other scenarios in indicator of carbon intensity of profit confirms this viewpoint. Considering the increasingly ambitious decarbonisation policies nowadays and changes in consumer preferences that gradually lean towards low-carbon products, the carbon costs will continue to increase in future, so this choice will more fit the future trends. In addition, Policy 3 is also the best solution to mitigate the negative impacts of CBAM, maintaining the relative stability of China's steel exports. Compared to the BAU, Policy 3 reduced export losses of SSC by about 18%, export profit losses by about 9%, and CBAM fees by about 60%. This performance is optimal compared to other decarbonisation scenarios. Benefiting from the most positive carbon reduction efforts, the SSC receives the most CBAM credit.

Based on these discussions, we would like to propose the following policy implications. China's steel sector should adopt proactive strategies to address CBAM by promoting decarbonisation of SSC. The simulation results indicate that proactive carbon reduction policies can effectively reduce the negative impact of CBAM by about 60%. China needs to further strengthen its carbon market and expand its coverage to promote the effectiveness of carbon prices. By including the steel sector into domestic ETS, part of CBAM fees can be retained domestically to support the steel's green development, and manufacturers could obtain more motivation for reducing carbon emissions and receive more exemptions from carbon tariffs. Meanwhile, the government should provide assistance to decarbonisation of SSC to overcome its huge costs. By upgrading production routes and developing decarbonisation technology, China's steel industry can reduce its carbon intensity essentially, to avoid massive export losses due to CBAM. In addition, regulatory authorities should strengthen export supervision, restrict the disorderly export of low value-added products, and encourage manufacturers with green competitiveness to participate in international trade.

The limitations of this article and corresponding research prospects mainly include the following aspects. Firstly, due to the availability of data, this article only considers two markets of China and the EU, without considering the possible interactions between other markets (such as the United States, ASEAN, and other important trading partners). If CBAM increases the export costs of other markets more than China, China's steel exports may instead gain a relative competitive advantage. Therefore, future research can consider further incorporating third-party markets to obtain more comprehensive evaluations. Secondly, the CBAM price is anchored to EU-ETS, thereby fluctuations in EU carbon prices may affect CBAM analysis. At present, the continuous rise and instability of the EU carbon price have made it difficult to predict. Therefore, the CBAM price set in this article is based on the current EU carbon price. In the future, will further reduction of free allowance in EU significantly increase carbon prices, or will emerging decarbonisation technologies reduce market demand to stabilise carbon prices? New research can incorporate analysis of these issues. Thirdly, the carbon emissions of SSC evaluated in this article only include direct carbon emissions, which is consistent with the current CBAM rules. However, CBAM may expand its coverage to indirect carbon emissions in the future (Clora, Yu, and Corong 2023). Therefore, future research can be combined with the assessment of the carbon footprint of SSC, which refers to the total carbon emissions from the entire lifecycle of steel products, including the extraction and processing of raw materials, logistics and transportation, steelmaking, and disposal, as well as the indirect carbon emissions generated by electricity during this process, to obtain more interesting results.

Disclosure statement

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Data availability statement

The data that support the findings of this study are available from the corresponding author Lu-Tao Zhao upon reasonable request.

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Appendix

The principal equations of the SSC-CBAM system are listed as follows

Domestic recycle module

(1) Iron Ore Supply = INTEG(Iron Ore Growth from Fixed Investment + Iron Ore Growth from Reinvestment, 671965)
(2) Iron Ore Growth from Fixed Investment = ([(0,0)-(16,1000000)], (0,166490), (1,114992), (2,107157), (3,241355), (4,121240), (5,282537), (6,39509.9), (7,137789), (8,132824), (9,−157271), (10,−256630), (11,−47094.4), (12,−579176), (13,−28066), (14,41154.8), (15,−33537.3), (16,−2200.91))
(3) Iron Ore Growth from Reinvestment = Total Profit∗Reinvest Rate/SSC Operation Unit Cost
(4) Steel Production Capacity = Iron Ore Supply∗ Iron Ore Utilisation Efficiency
(5) Steel Production = Capacity Utilisation Rate∗ Steel Production Capacity
(6) Sales to Domestic Market = EXP(−0.678 + 1.03634∗LN(Steel Production) + 0.01∗LN(Domestic GDP))
(7) Steel Product = INTEG(Production – Domestic Consumption)
(8) Domestic GDP = INTEG(Domestic GDP Growth, 187319)
(9) Domestic GDP Growth = Domestic GDP∗Domestic GDP Growth Rate
(10) Domestic GDP Growth Rate = ([(0,0)-(16,10)], (0,0.174932), (1,0.1956), (2,0.136222), (3,0.11918), (4,0.165321), (5,0.143539), (6,0.0951763), (7,0.0923907), (8,0.0832058), (9,0.0746042), (10,0.0813707), (11,0.116934), (12,0.101611), (13,0.0616658), (14,0.020405), (15,0.143968), (16,0.0509878))
(11) Energy Consumption Unit Cost = ([(0,0)-(16,1e + 06)], (0,1551.47), (1,1400.02), (2,1230.2), (3,1494.28), (4,1168.8), (5,1322.58), (6,1494.98), (7,1303.03), (8,1074.71), (9,780.413), (10,641.066), (11,796.328), (12,1293.9), (13,1414.87), (14,1381.22), (15,1250), (16,2143.64))
(12) SSC Operation Unit Cost = ([(0,0)-(16,1e + 06)], (0,638.811), (1,605.196), (2,922.623), (3,1164.45), (4,679.991), (5,1055.83), (6,1160.73), (7,909.866), (8,884.57), (9,658.342), (10,419.445), (11,411.144), (12,489.154), (13,488.752), (14,639.084), (15,714.378), (16,1037.72))
(13) Domestic Price = EXP(7.22 - 0.81∗LN(Steel Production) + 0.47∗LN
(Sales to Domestic Market) + 0.16∗LN(SSC Operation Unit Cost) + 0.57∗LN(Energy Consumption Unit Cost))
(14) Domestic Cost = Production∗(Energy Consumption Unit Cost + SSC Operation Unit Cost) + Cost of Policies +
CBAM Cost
(15) Domestic Sales Revenue = Domestic Price∗Sales to Domestic Market
(16) Domestic Profit = (Domestic Sales Revenue – Domestic Cost) + Government Subsidy
(17) Total Profit = Domestic Profit + Export Profit
(18) Social Welfare = Carbon Abatement by Policies∗Welfare Transformation Coefficient
(19) Government Subsidy = Social Welfare∗Subsidy Coefficient

Export module

(1) Export to EU = EXP(−31.66 + 50.84∗LN(Steel Production) – 49.62∗LN(Sales to Domestic Market) – 1.35∗LN(Export to EU Price after CBAM) – 1.41∗LN(Domestic Price) + 1.58∗LN(EU Market Price) + 2.49402∗LN(EU Demand))
(2) EU Demand = INTEG(EU Demand Growth, 155763)
(3) EU Demand Growth = EU Demand∗EU Demand Growth Rate
(4) EU Demand Growth Rate = ([(0,0)-(16,10)], (0,0.148122), (1,0.0670227), (2,−0.0837199), (3,−0.350702), (4,0.215245), (5,0.068093), (6,−0.114703), (7,0.0185188), (8,0.0426902), (9,0.0368928), (10,0.0287561), (11,0.0302023), (12,0.0301765), (13,−0.058447), (14,−0.116226), (15,0.178966), (16,0.1))
(5) CO_2 Intensity of SSC = CO_2 Emission/Steel Production

(6) Impact of CBAM on Export Price = CBAM Price∗CO_2 Intensity of SSC
(7) Export to EU Price = ([(0,0)-(16,10)], (0,4507.68), (1, 3790.61), (2,4378.76), (3,6086.96), (4,3509.12), (5, 4206.59), (6,4668.1), (7,3613.35), (8,3212.16), (9,3048.59), (10,2293.64), (11,2195.56), (12,3150.19), (13,3593.49), (14,3354.01), (15,3381.59), (16,4940.86))
(8) Export to EU Price after CBAM = Export to EU Price + Impact of CBAM on Export Price
(9) CBAM Fees = Export to EU∗Impact of CBAM on Export Price
(10) Adjusted CBAM Fees = IF THEN ELSE((CBAM Fees – (Export to EU/Steel Production)∗Carbon Emission Cost) > 0, CBAM Fees – (Export to EU/Steel Production)∗Carbon Emission Cost, 0)
(11) EU Market Price = ([(0,0)-(16,10)], (0,1685.17), (1, 2615.02), (2,4825.69), (3,5986.7), (4,3163.2), (5,3770.92), (6,4208.06), (7,3646.04), (8,3347.88), (9,3190.5), (10, 2379.37), (11,2518.17), (12,2955.68), (13,3359.73), (14, 3051.36), (15,2861.86), (16,4219.79))
(12) Export Sales Revenue = Export to EU Price after CBAM∗
Export to EU + Subsidy for Export
(13) Export Cost = Export to EU∗(Energy Consumption Unit Cost + SSC Operation Unit Cost) + Policies Export Cost + Adjusted CBAM Fees
(14) Export Profit = Export Sales Revenue – Export Cost

Carbon emission module

(1) Scrap-EAF Share = INTEG(Proportion Adjustment, 0.1)
(2) Production Structure Optimisation Rate = IF THEN ELSE(Policy 2 = 1, 0.01, 0)
(3) Steel Production by Scrap-EAF = Steel Production∗Scrap-EAF Share
(4) BF-BOF Share = 1 – Scrap-EAF Share
(5) Steel Production by BF-BOF = Steel Production∗BF-BOF Share
(6) Scrap-EAF Intensity Reduction = 0.018∗CO_2 Intensity of Scrap-EAF
(7) CO_2 Intensity of Scrap-EAF = INTEG(0 – Scrap-EAF Intensity Reduction, 1.067)
(8) CO_2 Emission by Scrap-EAF = Steel Production by Scrap-EAF∗CO_2 Intensity of Scrap-EAF
(9) BF-BOF Intensity Reduction = 0.016∗CO_2 Intensity of BF-BOF
(10) CO_2 Intensity of BF-BOF = INTEG(0 – BF-BOF Intensity Reduction, 2.304)
(11) CO_2 Emission by BF-BOF = Steel Production by BF-BOF∗CO_2 Intensity of BF-BOF
(12) CO_2 Emission = CO_2 Emission by BF-BOF + CO_2 Emission by Scrap-EAF