THE INDIRECT IMPACTS OF CARBON FUTURES ON SHIPPING:

A CASE STUDY FROM STEEL INDUSTRY

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The Indirect Impacts of Carbon Futures on Shipping:

A Case Study from Steel Industry

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CERTIFICATE OF ORIGINALITY

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Abstract

Emissions Trading Scheme (ETS) is a market-based approach under Kyoto Protocol for efficient reduction of greenhouse gas emissions. Many regional ETSs have been implemented, and some regions have established futures markets for emission allowance, namely "carbon futures", to enable the manufacturers to hedge the risk of price fluctuation. In addition to risk management and speculation, manufacturers can also use carbon futures in their production planning to improve economic efficiency. This will affect the production process, as well as the transportation demand for raw material.

Taking steel industry as a case study, this research establishes a two-period short-term model to explore the possibility of using carbon futures to re-adjust the steel production and raw material inventory, to maximize the total profit in two periods. The indirect impact of carbon futures on shipping volume and freight market is researched. This research also analyses the relationship of steel price with that of the raw materials including iron ore and coke, and freight rate for simulation. The results show that when the carbon futures price is high enough, steel plants will produce more in period one for sale in period two. This increases the emission and shipping volume in period one. When futures price is low enough, steel plants will balance their raw material inventory to minimize the overall freight cost. The impact of carbon futures base on shipping is asymmetric.

This research fills in the research gap of indirect impact of ETS on shipping. It optimizes the production plan of steel industry when there is carbon futures market. It also provides a reference for shipping companies to adjust shipping capacity based on carbon futures in the short term.

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Content

Figure Content

Table content

Chapter 1

1. Introduction

1.1. Introduction of Emission Trading Scheme (ETS) and carbon futures

To ensure the sustainable development of the global economy, the contracting parties to the Kyoto Protocol have agreed to adopt cooperative mechanisms to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (*Kyoto Protocol*, 1998; UnitedNations, 1992). These targets are expressed as levels of allowed emissions, or assigned amounts, over the period 2008-2012. Emissions Trading Scheme (ETS) is a market-based instrument in this protocol for efficient allocation of emission reduction requirement at the national or regional level. Under such scheme, government sets the emission cap for the whole country. Entities in the country can obtain emission allowances from the government through auction or free allocation. They can also sell surplus emission allowances to others that need emission allowance privately or through emission allowance markets. ETS helps to maximize economic efficiency in emission control (ICAP, 2021a; WorldBank&ICAP, 2021).

Many countries or regions have established or are preparing to set up ETSs, including the European Union, the United Kingdom, South Korea, Japan, China, California. Industries covered by the ETSs include power generation, steel, cement, and paper. International civil aviation also sets ETS called Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (Efthymiou & Papatheodorou, 2019). The EU Emissions Trading Market is by far the largest, with a cumulative turnover of 201 billion euros by the end of 2020.

In recent years, in EU, Korean, China and other countries, the adjustments in the allocation of emission allowance as well as the changes in the economy resulted in imbalances between supply and demand of emission allowances, which caused sharp fluctuation in the emission allowance price (Bertrand, 2014; Demailly & Quirion, 2008; Li, Wu, & Li, 2018; Lu, Ma, Huang, & Azimi, 2020). Take the EU ETS as an example, in 2008, emission allowance price plummeted due to the ban of emission allowance banking. Later, the depressed manufacturing activities during the European debt crisis resulted in oversupply of emission allowance. Emission allowance price maintained low for a long time. In 2020, with tighter emissions control policies, and the economic recovery after the shock of COVID-19 pandemic, the price of emission allowances soared from €16 in April 2020 to €58 in June 2021 (EuropeanCommission, 2020), and increased to over €90 in 2022. With an expected tighter emission policies, the price of emission allowance will rise further in the future. The expenses on emission allowance will become an important expense for high-emission companies (Bank, 2020; Demailly & Quirion, 2008).

The soaring of emission trading volume in the past few years (WorldBank&ICAP, 2021) and the increasing needs of financial contracts to hedge the price risk of emission allowances provide the foundation for emission allowance financial products, such as futures, options, and bonds. Emission allowance futures, normally called carbon futures, provides contracts to pricing and trade future emission allowance, assists participates to hedge the price risk in emission cost and manage their emission allowance in advance (Balcılar, Demirer, Hammoudeh, & Nguyen, 2016; WorldBank&ICAP, 2021). The EU ETS, Regional Greenhouse Gas Initiative (RGGI), California Cap-and-Trade Program, and the United Kingdom ETS have established carbon futures markets, while other ETSs are still investigating the feasibility. China and South Korea have announced the launch of carbon futures markets in the future (ICAP, 2021b; Y. Shi, S. R. Paramati, & Ren, 2019).

1.2.Literature review on the impacts of ETSs on shipping

Academic research on the impact of ETS on shipping is limited. At the beginning, most discussions are on the possible impacts of ETS on shipping from perspectives such as legislation, economy, and emissions (Kågeson, 2007; Miola, Marra, & Ciuffo, 2011; Nikolakaki, 2013; Yubing Shi, 2016). Concerns about the uncertainty of ETS's policy, the difficulty of legislation, the possibility of carbon leakage and other issues are mentioned in these studies. Later, research starts to address these concerns by constructing models and simulations, most research explores the impacts of ETS on shipping from the apects of shipping revenue, strategy, and/or emissions reduction. Results show that ETS can lead to a more energy efficient shipping industry (K. Wang, Fu, & Luo, 2015; Zhong, Hu, & Yip, 2019; Zhu, Li, Lin, Shi, & Yang, 2020).

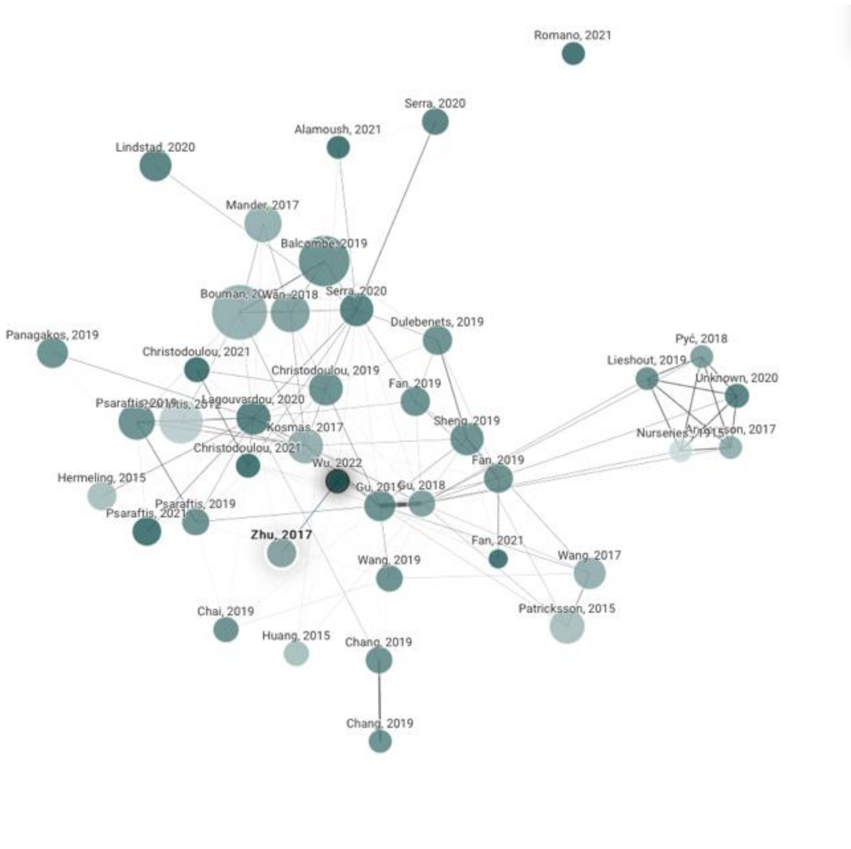


Figure 1 Network of academic research on the impact of ETS on shipping

As a pioneer research on ETS in shipping industry, Kågeson (Kågeson, 2007) discussed the proposal for open ETS for shipping industry, including the allocation of emission allowance, the use of revenue, and potential risks. Miola et al. (Miola et al., 2011) conducted a comparative analysis of open ETS for shipping with other alternatives such as bunker levy and the Maritime Sector Credit Mechanism (MSCM) from economic, legal, technical, and political aspects. Nikolakaki (Nikolakaki, 2013) reviewed the policies on economic incentives submitted by different regions to address GHG emissions from international shipping. Shi (Yubing Shi, 2016) also summarized market-based measures for emission reduction in shipping industry including ETS, and proposed recommendations on the legislative framework. Research suggests that the regional ETS may cause carbon leakage and competitiveness concerns, while others discussed other challenges such as regulatory costs, acceptance, and regional policy coordination.

While reviewing the existing literature on emission reduction in international shipping, based on economic principles, Luo (Luo, 2013) discussed the impact of emission reduction measures, especially open ETS, on shipping according to the nature of shipping as both a service provider in the global supply chain and a consumer for services that support shipping industry. The impacts on the world trade pattern, net exporters and the market concentration of the shipping industry are also discussed. Franc and Sutto (Franc & Sutto, 2014) constructed different scenarios - different scopes and linkages of ETS markets, recalculated the operating costs for shipping companies. The results show that under different scenario, there is a significant difference effect. The study also lists potential strategies for shipping companies in ETS - applying emission reduction technologies, regulating speed, increasing vessel capacity, changes in the spatial organization of shipping networks. Koesler et al. (Koesler, Achtnicht, & Köhler, 2015) conducted a case study to assess the impact of ship operators' organizational and operational factors within Maritime Emission Trading

Scheme (METS) using expert interviews. It suggests that shipping companies are optimistic about the potential performance of METS.

Wang et al (K. Wang et al., 2015) established a analytical model to explore the impact of open or closed (maritime only) ETS on shipping. They found that the ship speed would reduce in both open and closed scenarios. Since then, most of the research in this area has been based on operational research models. Zhong et al (Zhong et al., 2019) proposed optimal emission reduction strategy for container terminal to minimize related costs while meeting the emission reduction requirements by establishing a nonlinear optimization model. They found that policymakers should achieve greater emission reductions by reducing the percentage of free allowances and/or increasing the price of emission allowance. Wang et al (W. Wang, Ren, Bian, & Jia, 2019) discussed the design of low-carbon shipping logistics network under market demand and emission price uncertainty. Artificial bee colony algorithm is used to solve the model. The study finds that moderate fluctuations in demand could reduce the total cost of the logistics network. Wang et al (X. Wang, Norstad, Fagerholt, & Christiansen, 2019) developed an operation model from the perspective of tramp vessel operators. The model explores how the bunker levy scheme and the open ETS affect operational decisions and their economic and environmental consequences. Zhu et al (Zhu et al., 2020) established a stochastic programming model for the fleet composition problem, investigated the potential impact of an open ETS on the fleet composition strategy and CO_2 emission levels of individual container ship operators. The research shows that using METS, emissions could be reduced by 1.54% to 3.38%. METS could motivate operators to use energy efficiency technologies, deploy more energy-saving and emission-reducing ships. The efficiency of METS is better when conventional fuel prices are high. Zhou and Luo (Zhou & Luo) evaluated the incentive under different emission allocation methods in ETS for shipowners to adopt emission reduction measures using optimization and simulation methods. The results show that the benchmarking allocation method provides greater incentives for shipowners to adopt decarbonization technologies than the grandfathering allocation method. When emission allowance price is low, shipowners prefer energy efficiency measures; Only when low-carbon energy prices are low and/or emissions prices are very high, they would adopt low-carbon energy such as hydrogen.

However, existing research also identified some difficulties on the effectiveness of ETS. Gu et al (Gu, Wallace, & Wang, 2019) developed an optimization model to study the impact of (global or regional) METS on fleet composition and deployment and the corresponding CO_2 emissions. The computational research shows that the application of METS does not actually reduce CO_2 emissions in the short term. The decrease in CO_2 emissions will only be observable when low carbon fuel prices are low, emissions allowance price is high, or ETS coverage is large. Wu et al (Wu, Li, Xiao, & Yuen, 2022) conducted a literature review to summarize and categorize research on the drivers, challenges and impacts of ETS in the shipping industry. It concluded that the research on the impact of ETS on the shipping industry in recent years is mainly divided into: (1) environmental impact and economic impact; (2) optimal emission reduction strategy. These studies are mainly focused on the direct impact of ETS on shipping, including shipping cost, fuel usage, choice of emission reduction technology, fleet deployment.

There is no research to explore the indirect impact of ETS on the shipping industry. As shipping demand is derived demand, the impact of other industries' decision may have larger impacts on the emission reduction in shipping than the shipping industry itself. Studying the impact on shipping industry from the decision of other industry may be a better way to keep the consistency in the whole logistics system. Therefore, it is important to consider the indirect impact in the emission reduction strategy in shipping.

1.3.The indirect impacts of ETS on shipping

As emission allowance price increases, producers adjust their production plans to maximize profit by re-schedule raw materials purchase and manufacturing activities (Ansari & Seifi, 2012; Gay, Simkins, & Turac, 2009; Gong & Zhou, 2013; Leach & Madhavan, 1992). For some materials that can be stored for a long time, such as crude oil, coal and iron ore, their price fluctuations can be closely related to inventory. For example, an expected increase in future crude oil price may lead to inventory expansion in importing countries. Accordingly, increase in shipping demand can push up freight rates as shipping capacity cannot be expanded in the short term (Gavriilidis, Kambouroudis, Tsakou, & Tsouknidis, 2018; W. Shi, Yang, & Li, 2013; Siddiqui & Basu, 2020; Y. Zhang, 2018). Mutual impact between the fluctuation of other raw material price (e.g. grain, iron ore, coal) and its freight rate is also verified by studies (Bangar Raju, Bavise, Chauhan, & Ramalingeswar Rao, 2020; Gavriilidis et al., 2018; Yang, Zhang, Luo, & Li, 2020; Y. Zhang, 2018).

As iron ore and coal are the irreplaceable raw materials for steel production, their imports account for more than 50% of the major bulk shipping. Thus, shipping freight rate will be affected by the production plan of steel. In addition, the steel industry is included in most ETSs, and it contributes nearly 10% of global greenhouse gas emission. Therefore, in this study, we bridge the gap by using steel industry as a medium to explore the possible indirect impact of carbon futures, an important feature in the ETS, on the shipping industry.

1.4.Background

1.4.1. Background of crude steel production

Crude steel is mainly made via two routes - Blast Furnace-Basic Oxygen Furnace (BF-BOF) route and the Electric Arc Furnace (EAF) route - often referred as the 'primary' and 'secondary' paths.

BF-BOF produces iron from iron ore through a basic oxygen converter into steel. Blast furnace operates continuously for more than ten years. In the production process, iron ore, coke and flux are injected from the top of the furnace in the first step. Hot air (1000 ~ 1300 degrees Celsius), spray oil, coal or natural gas and other fuels are injected from the lower blast furnace tuyere. As iron ore is a compound of iron and oxygen, at high temperatures, coke and the carbon in the jet will turn into carbon monoxide after burning, which takes the oxygen out of the iron ore. Through the reaction, iron ore turn into iron, and will be released from the blast furnace. The gangue in iron ore, ash from coke and jet will turned to slag with limestone and other fluxes. The slag will be released from the bottom. The residual gas will be removed from the top of the furnace and used as industrial gas after dust removal. Modern blast furnaces can also use the high pressure at the top of the furnace to generate electricity.

The second step is to change the molten iron into steel in basic oxygen furnace, also known as a converter. In the converter, oxygen is injected into molten iron to burn unwanted elements in iron. Generally, air is directly used as the source of oxygen. Air will be pumped into the molten iron to oxidize impurities such as silicon and manganese. In this process, a large amount of heat is generated, which enable the furnace to reach a desired temperature. Therefore, this process does not need additional fuels. Certain amount of quicklime should be added to form stable calcium phosphate and calcium sulfide, which become slag. When this process is over, iron is changed into steel. Then the molten steel will be released and casted into solid slabs or ingots, which can be processed into bar, wire, or flat strip products after several rolling processes. Other additional operations such as tempering, coating can enhance the properties and functions of steel.

EAF produces steel mostly from scraps collected for recycling. Compared with BF-BOF, EAF is limited by the availability of electricity and scrap. The main raw material of EAF is scrap steel, solidified iron or sponge iron can also be smelted. The key components of arc furnace include graphite electrode. The heat to melt the metal comes from the arc when the electrode contacts with the metal. Temperatures of the arc can be as high as 3,500℃, while required temperature to melt the metal is about 1,800℃. EAF can produce a variety of steels, from the metals used in basic products such as rebar, to stainless steels and high-alloy special steels. EAF has the advantages of flexibility and small capacity. Further process steps, such as casting and rolling, are similar to the BF-BOF route. As the main energy source is electricity, emission from EAF mainly depends on the carbon intensity of the electricity used. The working flows of BF-BOF and EAF are shown in Figure 2 and Figure 3.

Figure 2 Blast Furnace-Basic Oxygen Furnace (BF-BOF) production route (Source: Eurofer)

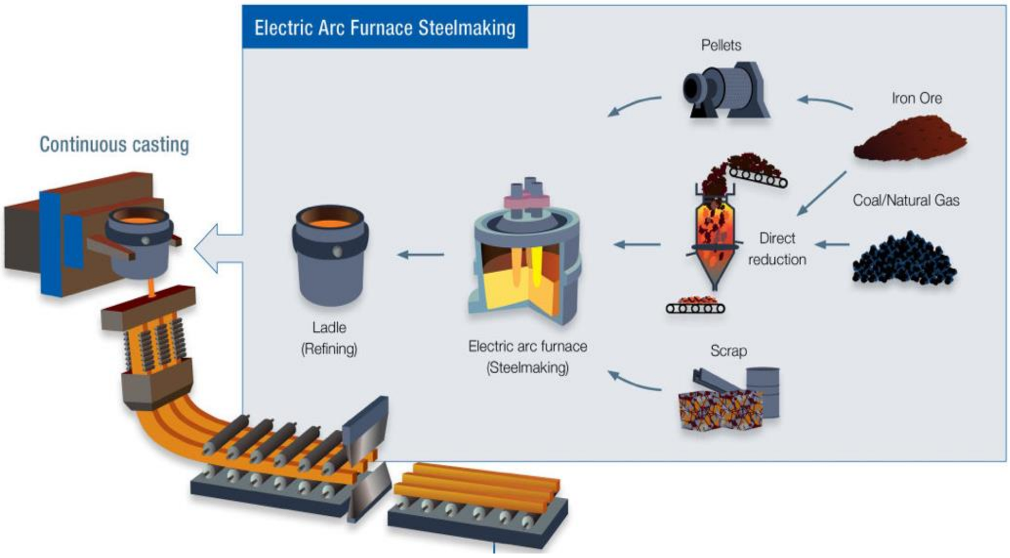


Figure 3 Electric Arc Furnace (EAF) production route (Source: Eurofer)

Table 1 lists the crude steel production capacities in the top 10 production areas in 2019. As the largest crude steel producer, China accounts for more than half of the global crude steel output. This is followed by 28 European countries, India, and Japan. Compared to EAF route, BF-BOF route is a major problem for emission because it uses most of the coke and generates emissions that cannot be reduced by using low-carbon energy sources. China has the largest proportion (90%) of crude steel made by BF-BOF route, followed by 80% in Japan and 75% in Brazil. In 2019, about 65% of the world's crude steel is produced through the BF-BOF route, of which about 74% is produced by China. The United States have the largest proportion (65%) of crude steel made by EAF route. Developed regions have higher proportion of steel production in EAF route, because they had a period of high demand for steel in the past, which leave them a large volume of scrapped steels. National or regional ETSs have been established in the top 7 steel production areas except for India and Russia, and they all included the steel industry.

Table 1 Crude steel production capacities by process in top 10 production areas

Area	Emission Trading Scheme	Total output in million tons)	BF-BOF in million tons (%)	EAF in million tons (%)
China	Y	996.3	896.7 (90%)	99.6 (10%)
EU28, Inc. UK	Y	158.8	95.3(60%)	63.5(40%)
India	N	111.2	72.3(65%)	38.9(35%)
Japan	Y	99.3	79.4(80%)	19.9(20%)
United States	Y	87.8	30.7(35%)	57.1(65%)
Russia	N	71.9	43.1(60%)	28.8(40%)
South Korea	Y	71.4	46.4(65%)	25.0(35%)
Turkey	N	33.7	10.1(30%)	23.6(70%)
Brazil	N	32.2	24.2(75%)	8.1(25%)
Iran	N	25.6	NA	NA
Global	N	1868.3	1214.4(65%)	653.9(35%)

Source: World Steel Association, IEA, OECD

1.4.2. Emission allowance allocation for steel industry

Currently, the allocation of emission allowance varies from region to region (Antimiani, Costantini, Martini, Salvatici, & Tommasino, 2013; Jiang, Ye, & Ma, 2014; Kuik & Hofkes, 2010). There are two ways to allocate emission allowances - free allocation and auction.

If the emissions policy of a country raises its production costs, other countries with a looser policy may have a trading advantage. If demand for products remains the same, production may move offshore to the countries with lower requirements, and global emissions will not be reduced (Branger, Quirion, & Chevallier, 2016). This is called carbon leakage. For those industries which have high risk in carbon leakage, to avoid these industries move to other areas without ETS, they get more free emission allowances from the governments (WorldBank&ICAP, 2021). As steel industry has high-energy intensity and high-emission and it is also important for the society (Wen-Bin, 2019), it is necessary to avoid carbon leakage and prevent the relocation of steel factories. In this regard, the free allocations percentages for steel plants are often more than 95% (EuropeanComission, 2018; ICAP, 2021b).

There are two methods to calculate the emission allowances (ICAP, 2021b).

- The first one is called Grandfather method where the allowances equal to the arithmetic average of total emissions in the past one or a few years. This considers the large differences in final products which results in different emission intensity. Grandfather method performs very well in total emission control, but it limits the expansion of the scale of industry, which may lead to reduced output and slow down the economic development. This method is used for steel industry in most regions include cities in China, such as Tianjin, Beijing, Guangdong, and Hubei. Several world's top steel producers, such as China Baowu Group and Shougang Group, are in these regions.
- The second one is called Benchmarking, allowances allocated by its carbon intensity and total output. The carbon emission intensity follows the best performer in the in the industry or comes from the historical emission intensity of the specific steel plant. In Benchmarking

method, output data is derived from historical or current output. The specific allocation method is shown in Table 2.

Table 2 Summarizes of emission allowance allocation methods by calculation methods

Allocation method	Total Emission Allowance from government		Free Allocation Percentage	Cap Adjusted Factor	Free Emission Allowance E^f	Adopted Area
Grandfather	$\frac{\Sigma_0^N E}{N}$		A_f	A_C	$\frac{\Sigma_0^N E}{N} \cdot A_f \cdot A_C$	Chongqing, Guangdong*, Hubei, Tianjin, Beijing
Allocation method	Carbon Intensity	Production	Free Allocation Percentage	Cap Adjusted Factor	Free Emission Allowance E^f	Adopted Area
Benchmark	$\frac{\Sigma_0^N I}{N}$	y_t	A_f	A_C	$\frac{\Sigma_0^N I}{N} \cdot y_t \cdot A_f \cdot A_C$	Fujian, Guangdong*, Shanghai
	I_G	$\frac{\Sigma_0^N y}{N}$	A_f	A_C	$I_G \cdot \frac{\Sigma_0^N y}{N} \cdot A_f \cdot A_C$	EU28, South Korea,
	I_G	y_t	A_f	A_C	$I_G \cdot y_t \cdot A_f \cdot A_C$	California, Guangdong*

Source: Organized by the author, data collected from Carbon Association

Note:

E: total emission;

N: number of years used for data collection;

A_f*: free allocation percentage;*

A_C*: cap adjusted factor for specific industry;*

E^f *:free emission allowance.*

**For Guangdong, the Carbon Intensity method is used for power plant, benchmark method is used for iron and steel, and Grandfather method is used for steel rolling or flatting.*

1.4.3. Breakdown of material, cost and emission in crude steel production

To understand the steel industry, industry reports, papers as well as markets reports related to the cost and emission of crude steel production are reviewed. Steel production costs of China, EU, Japan, Korea, India, Turkey, and other countries are collected (He & Wang, 2017; Medarac, Moya, & Somers, 2020), providing varying production costs in different areas. Emission factors in different areas varies in the same range, and standard emission factors are provided by World Steel Association, IEA, and IPCC. Breakdowns of crude steel production cost and emission for two production routes are provided in Table 3 and Table 4.

Table 3 Material inputs, cost, and emission in steel production from BF-BOF route

Material	Unit	Quantity	Unit Price	Cost (USD)	Emission Factor of Input	Emission
Iron Ore(CFR)	t	1.509	170	256.53(51%)	0.037	0.06(3%)
Coke (FOB)	t	0.86	115	98.90(20%)	2.06	1.77（82%）
Steel Scrap	t	0.148	371	54.91(11%)	0.172	0.03(1%)
Industrial gases	m^3	162	0.12	19.44(4%)	0	0(0%)
Ferroalloys	t	0.009	1588	14.29(3%)	0.1	0(0%)
Fluxes etc	t	0.531	49.98	26.54(5%)	0.44	0.23(11%)
Refractories	t	0.004	1314	5.26(1%)	NA	NA
Other cost	NA	1	20.22	20.22(4%)	NA	NA
By-product credits	NA	1	-8.96	-8.96(-2%)	NA	NA
Thermal energy net	GJ	-6.417	8.32	-53.39(-11%)	NA	NA
Electricity	MWh	0.138	106.97	14.76(3%)	0.504	0.07(3%)
Labour	hours	0.605	41.97	25.39(5%)	NA	NA
Capital Charges	NA	1	29.89	29.89(6%)	NA	NA
Total	\	\	\	503.78(100%)	\	2.16(100%)

Source: Calculated and organized by the author; data from World Steel Association, Steelonthenet, IEA, IPCC.

According to Table 3, the cost function of steel can be estimated as follows:

$$Q_{steel} = 1.51Q_{iron\ ore} + 0.86Q_{coke} + 0.15Q_{scrap} + Q_{others} \quad (1.)$$

Q_i is the quantity of the different input, where $i \in [iron\ ore, coke, scrap, others]$. Industrial gases, ferroalloys, labor, etc. are grouped in ‘others’.

Table 4 Material inputs, cost and emission in steel production from EAF route

Material	Unit	Quantity	Unit Price	Cost (USD)	Emission Factor of Input	Emission
Steel Scrap	t	1.117	371	414.41(74%)	0.172	0.19(36%)
Pig Iron	t	0	406	0(0%)	0.172	0(0%)
Industrial gases	m^3	56	0.11	6.16(1%)	0.001518	0.09(16%)
Ferroalloys	t	0.021	1588	33.35(6%)	0.1	0(0%)
Fluxes etc	t	0.068	149.98	10.20(2%)	0.44	0.03(6%)
Refractories	t	0.001	1314	1.31(0%)	NA	NA
Electrodes	t	0.001	4000	4.00(1%)	3.663	0(1%)
Other cost	NA	1	19.62	19.62(3%)	NA	NA
Net thermal energy	GJ	-0.068	8.32	-0.57(0%)	NA	NA
Electricity	MWh	0.444	102.61	45.56(8%)	0.504	0.22(42%)
Labour	hours	0.291	41.97	12.21(2%)	NA	NA
Capital Charges	NA	1	17.31	17.31(3%)	NA	NA
Total	\	\	\	563.56(100%)	\	0.54(100%)

Source: Calculated and organized by the author; data from World Steel Association, Steelonthenet, IEA, IPCC.

The prices of raw materials are updated in June 2021, and the emission intensity of each material is extracted from the Emission Calculation Guide published by World Steel Association (WorldsteelAssociation, 2021a). It should be noted that in Table 3, by-product credits only applies in areas such as EU. Heat recovery technology is assumed to be used, this technology can recover the heat from coke in oxygen converter and used as heating source. However, in most traditional steel mills, the technology is not applied, and the heating energy comes from electricity. In summary:

- Coal consumption by steel industry rose from 16.4% to 32.5% from 1971 to 2018 according to the International Energy Agency (IEA, 2021).
- More than 70% of the steel production cost in BF-BOF path comes from iron ore and coke, and more than 80% of its emissions come from the combustion of coal. In total, for each ton of crude steel produced, about 2 tons of CO_2 will be generated.
- More than 70% of the cost of crude steel produced through EAF path comes from scrap steel purchase, and more than 75% of its emissions come from scrap steel and electricity. In total, each ton of crude steel releases about 0.5 tons of CO_2.

From Table 3, iron ore and coke are the most important raw materials in the BF-BOF route. It can be estimated that for each ton of steel produced in EU by BF-BOF path, the emission fee should increase by 100-250 USD to satisfy the zero-emission requirement of ETS according to emission allowance price in EU ETS in 2022. This is not a negligible part of the total production cost.

Most of the raw materials used in the steel production is tranported by vessels. Table 5 summarizes the import volume of iron ore and coal by the major countries with ETS in 2019. They accounted for 92% of the total seaborne iron ore trade and 53% of the total seaborne coal trade. China imported 72% of iron ore, Japan and Europe followed. China also imported most of coal, accounted for 20%, followed by Japan at 14% and South Korea at 10%.

Table 5 Seaborn Iron Ore and Coal trade in 2019 (Areas with ETSs)

Iron			Coal		
Area	million tons	% of global Iron Ore Import	Area	million tons	% of global Coal Import
China	1047	0.719093407	China	258	0.200622084
Japan	120	0.082417582	Japan	180	0.139968896
Europe	109	0.074862637	South Korea	135	0.104976672
South Korea	75	0.051510989	EU28(Inc. UK)	110	0.085536547
% of World	NA	0.927884615	% of World	NA	0.531104199
World	1456	NA	World	1286	NA

Source: Clarkson Shipping Intelligence Network (CSIN), IEA, OECD

It can be found that regions with the largest seaborne trade of iron ore and coal are also the main production areas of iron and steel. As the most important carrier of iron ore and coal, shipping is closely related to the production of steel industry. In the following chapters, the research conducts a detailed analysis of the raw materials required for steel production - coking coal and iron ore, in conjunction with the shipping market.

1.4.4. Global coking coal trade

Coal is mainly divided into two types according to their usage. The first is thermal coal, which is used to generate power for power generation, propulsion, boiler combustion. The second one is coking coal, used to produce coke, also called metallurgical coal. According to IEA report (IEA, 2020), the global coal trade volume increased year by year from 2017 to 2019. In 2019, the global coal trade was 1.43 billion tons, up 2.3% from 2018. Among them, thermal coal trade was about 1.1 billion tons, accounted for about 77.7%. In the consumption thermal coal in China, the biggest user is thermal power generation, which accounts for more than one third of the total thermal coal. The second is general industrial boilers, which accounts for about 30%, with the annual consumption about 300 million tons. Daily life consumption accounts for about 20% with annual consumption about 200 million tons. Building materials account for more than 10%, with annual consumption about 100 million tons. The thermal coal used in melting metal is mainly sintering and blast furnace injection. It consumes less than 1% of the thermal coal, with annual consumption less than 10 million tons.

Coking coal trade accounted for about 22%. Coking coal is either bituminous coal or sub-bituminous coal. Compared with thermal coal, it has strong caking and coking properties, and is indispensable for coke production. Usually, it needs about 1.33 tons of coking coal to produce 1 ton of coke (IEA, 2021). More than 90% of the world's coke production is used for blast furnace ironmaking. Coke has become one of the necessary raw materials for modern blast furnace ironmaking technology and an important upstream raw material for the iron and steel industry.

Compared with coal, coke has less harmful impurities such as phosphorus and sulfur. When these impurities enter molten iron during combustion, they will affect the quality of subsequent steel. Therefore, most of the blast furnace ironmaking uses coke, not coal or coking coal. Coke is not only a fuel but also a raw material in blast furnaces. Coal can replace coke as heating source. Therefore, a small amount of coal is also injected during the production process. However, it cannot totally replace coke. There is no alternative solution at present.

Among all industries that use coke as the input, only the steel industry has a continuous increase in the proportion of coke. Take China as an example, the proportion increased from 73.95% in 2000 to 85.00% in 2007; while that in the other industries from 26% to 15%.

Figure 4 and Figure 5 present the major coking coal exporters and importers. The main exporters of coking coal are Australia, the United States, Canada, and Russia. Australia's coking coal exports are three times that of the second-ranked United States. The main importers of coking coal are China, Japan, India, South Korea and the 28 EU countries, with an average annual import of 30-50 million tons. Almost all the major importers of coking coal are major producers of steel.

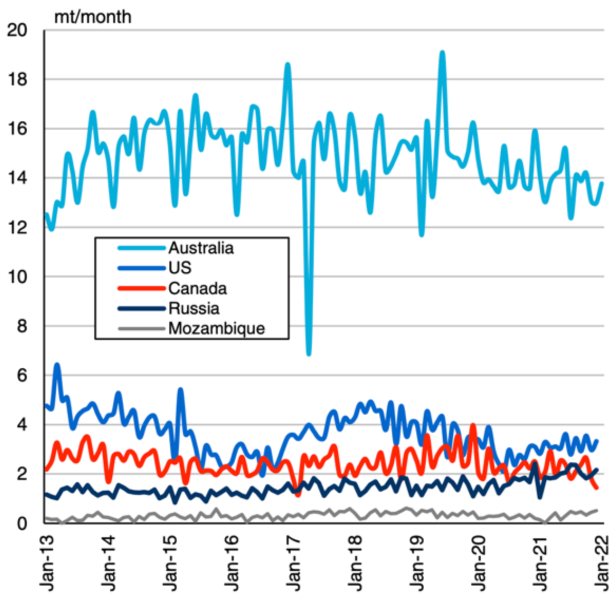


Figure 4 Major seaborne coking coal exporters (Source: CSIN)

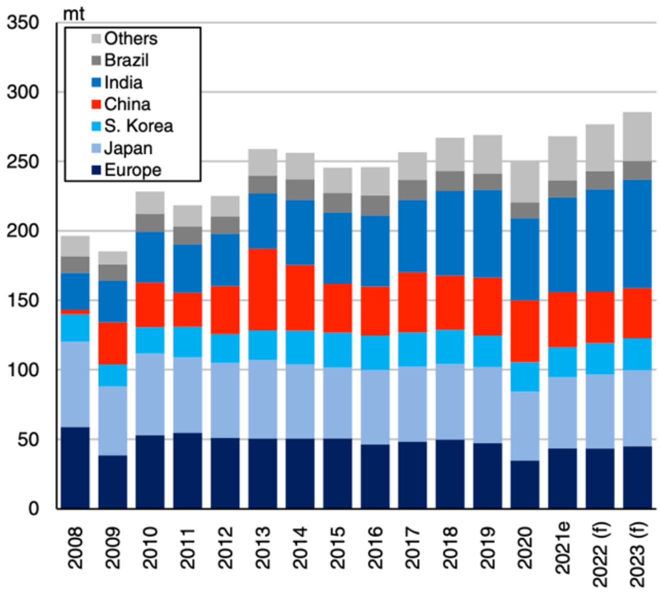


Figure 5 Major seaborne coking coal importers (Source: CSIN)

The demand for coking coal in international trade is mainly derived from steel industry, which depends on the global economic situation and the operating conditions of the steel market. According to IEA's data, from 2017 to 2019, the output of coking coal remained basically the same, which was about 1.007 billion tons in 2019, accounted for about 12.7% of the total coal. Australia is the world's largest exporter in coking coal. Australian coking coal makes up approximately 65% of the global production. Its coal industry is highly concentrated, and the six largest coal companies accounted for nearly 50% of Australia's total output. Therefore, on the supply side, the market is dominated by Australian exporters. Other countries are the United States (about 12-15%), Canada (about 10%) and Russia (about 7-8%). Mongolia, exporting coal to China by road, has also been one of the major exporters since 2015 (IEA, 2022).

The importers of coking coal are mainly concentrated in the Asia-Pacific region. As a major steel producer, China has 156.96 billion tons of coking coal reserves, accounting for 20% to 25% of China's total coal reserves (Bai et al., 2017). Domestic coking coal accounts for 80% of the total supply and imported coking coal accounts for 20%. The local supply is not sufficient, so imports are required to meet domestic demand. The inventory of imported coking coal is concentrated in Qinhuangdao Port, Guangzhou Port, Jingtang Port (GACC, 2022). To ensure the supply of coke, large steel plants generally have their own production lines. One third of China's coke production capacity is in steel plants, and the other two thirds are independent coking plants, which sell coke products to steel plants or other metallurgical enterprises.

Japan's domestic coal production is very limited. Its demand is almost entirely relied on imports, both for thermal coal in power generation and coking coal for producing crude steel (Samuels, 2019). From 2000 to 2017, the annual import of coking coal was between 40 million and 50 million tons, accounting for 20% to 30% of total coal imports. Japan imports coking coal from very few sources. The top three suppliers are Australia, Indonesia and the America, accounted for over 90% of total coking coal imports, of which more than 50% are from Australia (IEA, 2021).

Although India is also one of the main producers of coal, coking coal is extremely scarce. Coking coal imports account for about 50% of total coking coal consumption in India, and the import ratio is increasing every year. In 2021, India has replaced China as the world's largest coking coal importer. It imported 56.27 million tons of coking coal in 2021, a 7% increase from 2020. This is due to the rapid development of India's steel industry in last year, and the domestic coking coal output is too low to meet the demand. Indian steel mills are highly dependent on Australian coking coal. In 2021, India imported 50 million tons of coking coal from Australia, which accounted for more than 80% of the total imports (Argus, 2022). In addition, India also imports coking coal from the United States, Canada, Mozambique, Indonesia, Russia and other countries.

EU has also long relied on imports of coking coal. From 2014 to 2017, 27 coal mines in Germany, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia, and the United Kingdom were closed. This reduced the production from 30 million tons to 15 million tons, and the self-sufficiency rate dropped to about 30% (IEA, 2021). EU mainly import coking coal from the America and Australia, which accounted for more than 50% of the total import. In addition, EU also imports coking coal from Colombia, Russia, and some other places. Overall, EU’s coking coal imports are increasingly reliant on the America.

Coal shortages in two geographically distant markets, Asia (Pacific Basin) and Western Europe (Atlantic Basin), are supplied mainly from Australia and North America. Therefore, most of the trade (almost 90% of them) are seaborne (ShippingIntelligence, 2022). Land transportation is generally used in the Commonwealth of Independent States, European and North Asian countries (mainly Mongolia and China) to northern and central European countries. Australia is the largest coking coal exporter in the seaborne market, accounting for more than 50% of global coking coal export. It mainly exports to the entire Pacific region. Major global seaborne trade routes include Australia East to Northeast Asia (including China, Japan and South Korea), Indonesia to Northeast Asia and the Atlantic region, South Africa to Europe and Asia, the United States to Northeast Asia (through the Pacific), Canada to Europe and Asian routes and China to Northeast Asia. China has about 30 ports along its coastline. These ports are important for shipping seaborne coking coal to China and coal from northwestern China to southeastern China. The three major coal ports are Qinhuangdao, Huanghua and Tianjin. These three ports account for more than 70% of coal shipments. Russia exports coal through the ports of Murmansk, Vanino, Vostochny and Ust-Rugo.

Recent developments in Ukraine and Russia are having significant impacts on coking coal markets. Russia exported around 24 million tons of coking coal by sea in 2021 (9% of global seaborne trade volumes), mostly to China, Japan, Korea and Vietnam, and also exports some additional volumes by land into both Asia and Europe (Argus, 2022).

1.4.5. Comparison of coking coke price and voyage rate of coal

This study selects and presents the freight rates of several main routes for seaborne coal. According to the data, the longer the route, the higher the freight rate. The freight rate from Hay Point, Australia, to Rotterdam port is almost twice the freight rate to Qingdao port. Freight rates are higher for smaller vessel sizes, the freight rates for Panamax vessels are higher than those for Capsize vessels. The trends of freight rates on several routes follow largely the same pattern.

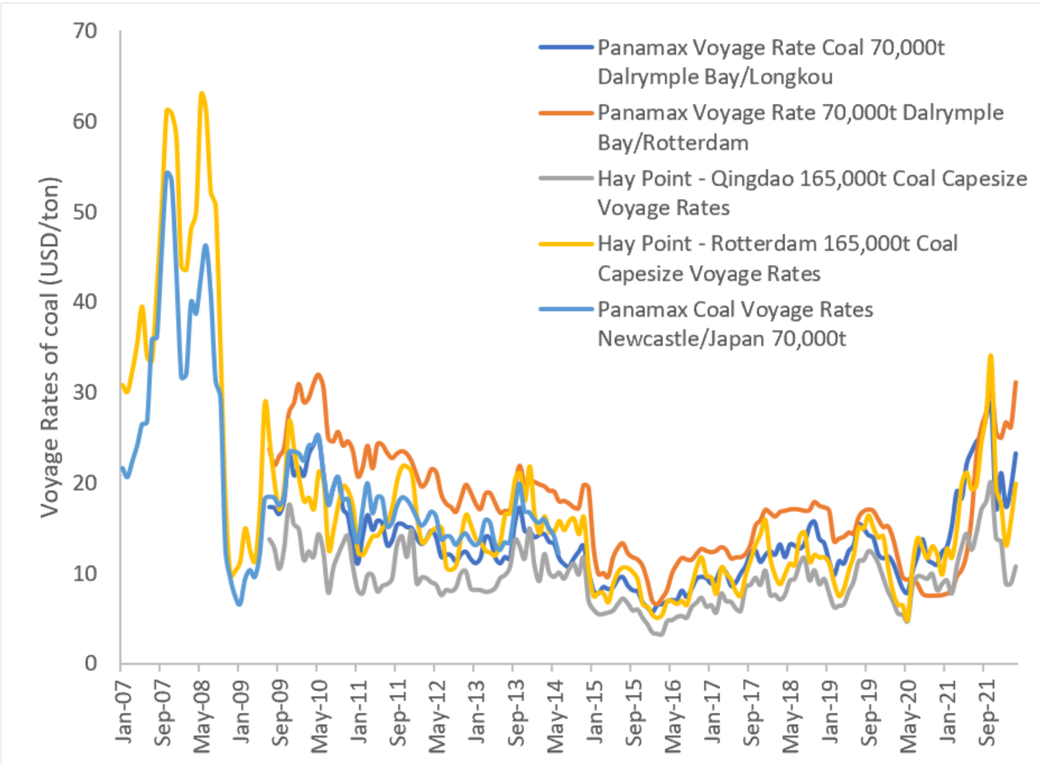


Figure 6 Voyage Rates of Coal 2007-2022 (Source: CSIN)

As coking coal is the main raw material for coke production, the price of coke and coking coal is closely related. There are two pricing categories for coking coal: long-term contracts and spot sales. Coking coal is sold mainly in long-term contracts, with prices fixed over a 12-month period. Large coal mining companies usually sign long-term contracts with coking or steel mills. Long-term prices are generally lower than spot prices, but price can be negotiated if the market changed significantly. Only a fraction of the volume (complementary buying) is traded on the spot market (Ozga-Blaschke, 2021).

In recent years, Australia's coking coal exports accounted for about 60% of the world exports. Therefore, Australian coking coal prices can be used to represent the world price. The FOB price for Australian coking coal from East Coast is take as an example. Since 2006, coking coal prices have experienced 3 short cycles:

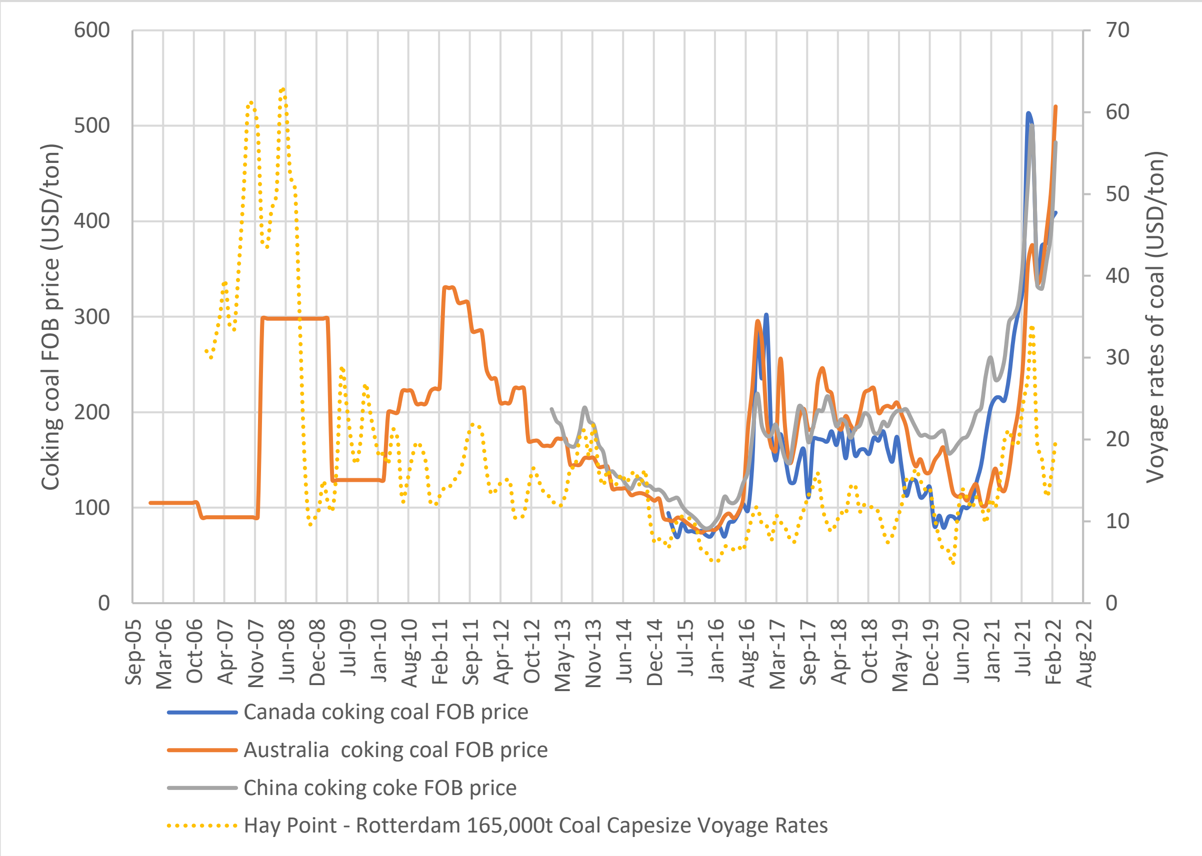


Figure 7 Coking coal FOB price and voyage rate (Source: Bloomberg, IEA, Mysteel, CSIN)

The first period - 2006-2009: the low point was 95 USD/ton for coking coal and freight rate was 30USD/ton in October 2006, and the high point was 300 USD/ton in October 2008 while the freight rate was 60USD/ton. Freight rate costs about 20%-30%of the CIF price of coking coal. In this stage, global commodity was in a bull market, and the economies of various countries are in a boom cycle. Coupled with low commodity inventory, commodity prices rose rapidly across the board. On the one hand, the demand for coking coal rose rapidly due to the growth of steel output in China and India; on the other hand, the shortage of supply side also exacerbated the price increase.

The second period (2009 – 2015): the low point was 167 USD/ton for coking coal and 10USD/ton for freight rate in June 2009, and the high point was 335 USD/ton for coking coal and 20 USD/ton for freight rate in January 2011. Freight rate costs about 5%-10% of the CIF price of coking coal. After the financial crisis, the global economy gradually improved, and countries fixed Asset investment accelerated, and global liquidity was generally ample. At the beginning of 2011, the price of Australian coking coal began to fall. On the one hand, Australia's production recovered from the flood in 2011, and the output increased year-on-year; on the other hand, demand was sluggish, the global steel industry was sluggish, and the United States and Europe promoted clean energy. The annual growth rate of global coking coal consumption remains low.

The third round - 2015 to 2021: the low point was 73 USD/ton for coking coal and 5 USD/ton for freight rate in November 2015, and the high point was 374USD/ton for coking coal and 35USD/ton for freight rate in 2021. Freight rate costs about one-tenth of the arrival price of coking coal. Compared with the first and second rounds, the share of freight rate in the arrival price has decreased, which may be caused by the excess shipping capacity. As for the coking coal, on the supply side, global coal mines have gradually reduced their production capacity after coal prices have fallen. In addition, China has implemented supply-side reforms, the short-term shutdown of Australian railways and coal mine production problems have led to supply contraction. On the demand side, China’s supply contraction has led to high coking coal prices resulting in import demand increase. India's revitalization of infrastructure has stimulated demand for imported coking coal, and the recovery of European and American economies after Covid-19 has comprehensively led to a stabilization and soar of international coking coal prices.

From the description, it can be concluded that there are two main factors for the fluctuation of coking coal price. First, the factors affect the supply side, such as weather that may reduce coking coal output and increase its price. Second, the factors affect the demand side, including steel industry's high demand for raw materials that may increase its price. The contribution of freight rate to coking coal CIF price has declined gradually from 20% in 2006 to about 10% in 2021.

1.4.6. Global iron ore trade

As one of the raw materials used in steel production, iron ore is usually imported by ships, there are many bulk carriers providing iron ore transport services on fixed routes. Specifically, almost 90% of the world's iron ore trade is exchanged between the top 4 importing and 4 exporting countries using seaborne trade. The main exporting countries are Australia and Brazil, each account for about 57% and 24% of the total world exports in 2019.

On the supply side, the world's top five iron ore reserves (Ukraine, Russia, Brazil, China, and Australia) account for 78.5% of global reserves, and mine iron reserves are mainly concentrated in Brazil, Russia and Australia. Brazil and Australia have led the world in iron ore exports since 2012. In the international iron ore market, the world's three largest iron ore producers and exporters-Brazil's Vale and Australia's Rio Tinto and BHP Billiton control more than 70% of the world's iron ore production and trade volume. It has created an oligopoly in the iron ore market (Xu & Guo, 2022). Companhia Vale Do Rio Doce (CVRD) is the world's largest iron ore producer and exporter and the largest mining company on the American continent. Now, CVRD 's iron ore production accounts for 80% of Brazil's total national production. Its iron ore resources are concentrated in the "Iron Four Corners" area and the state of Barra in northern Brazil. CVRD owns Tingbopebe iron ore, Capannima iron ore, Carajas iron ore, etc., and has about 4 billion tons of iron ore reserves. For Australia, BHP Billiton is the world's largest mining group company. Its mines are in the Pilbara region of Western Australia, namely Newman, Yandy and Goldworth.

The total proven reserves of the three mining areas are about 2.9 billion tons, and the annual production of iron ore is 100 million tons. In the southern part of Yari, there is also an undeveloped mining area, with reserves of 4.5 billion tons. RioTinto is the world's second largest mining group, successfully acquired Australia's Northern Mining Company in 2000, becoming a global leader in the exploration, mining and processing of mineral resources. Australia's second largest iron ore production company-Hamersley Iron Ore Co., Ltd is controlled by RioTinto. With five production mines in the Pilbara region of Western Australia (ie Tom Price Iron Mine, Parabudu Iron Mine, Chana Iron Mine, Malandu Iron Mine and Bnockman Second Mining Area), the proven reserves are about 2.1 billion tons, and the company's annual iron ore production capacity is 55 million tons.

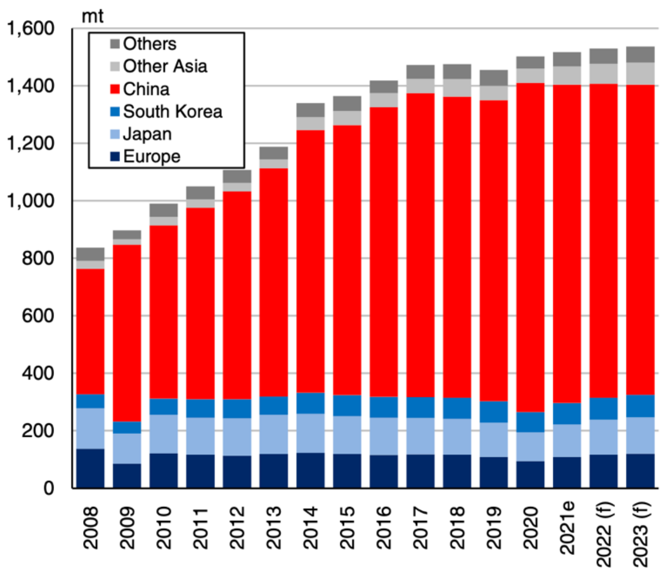


Figure 8 Major Seaborne Iron Ore Importers 2006-2023 (Source: CSIN)

On the demand side, Figure 8 shows the imports of iron ore by sea from 2008 to 2022. Since 2008, the import of iron ore has increased every year, and the growth rate has slowed down after 2015. China is the world's largest importer of iron ore, and the import volume of iron ore has been rising in recent years. According to the statistics from Mysteel, the total import of iron ore in 45 ports in

China continues to rise. The total estimated iron ore imports can be over 160 million tons (Mysteel, 2022). Domestic production of iron ore in China is also on the rise. The National Bureau of Statistics (NBS) disclosed that China's iron ore production in 2021 amounted to 981 million tons, a 9.4% from last year (NBS, 2022). China imports iron ore only from a few countries, nearly 80% from Australia and Brazil. Among them, 60% are from Australia. In 2019, the domestic production of iron ore reaches 241 million tons, while the import accounts 1069 million tons (WorldsteelAssociation, 2021b). China's iron ore import share exceeds 80%.

Japan has limited natural resources, and almost 100% of its iron ore are imported. They usually use a long-term purchase guarantee agreement (Samuels, 2019). Through investment in the development of overseas iron ore resources, stable imported resources are obtained. In 2019, Japan imported 1.2 million tons of iron ore, mainly from Australia and Brazil (IEA, 2021).

Compared with other mining areas in the world, the overall scale of EU mines is relatively small. Germany, France, the United Kingdom, Poland, Sweden and Spain have some iron ore resource reserves, which has also become the development advantage of the early steel industry in these countries. Currently, only Sweden, Germany and Austria mine iron ore, and the global share of iron ore production is only about 1%. From 2009 to 2018, the EU's iron ore production remained at 30 million tons, which was far below the needs of steel production and rely on imports from American countries, the Commonwealth of Independent States and other regions. In 2019. The total output of the EU was 33 million tons, and the import was 135 million tons, with an import rate of 80% (IEA, 2021; WorldsteelAssociation, 2021b).

In conclusion, the iron ore in major steel producing areas depends mainly on imports from Australia, Brazil, North America and other places. The iron ore is shipped mainly in Capsize ships to China, Japan, South Korea, Europe, and other industrialized countries that produced large quantities of steel (Yang et al., 2020).

In terms of shipping routes, Brazilian iron ore reserve is concentrated in Minas Gerais and Pará. The main export ports are Itaqui Port, Tubarão Port and Sepetiba Port; Itaqui Port is located in Maranhao State, in recent years, the export volume of Itaqui iron ore has gradually surpassed that of Tubarão, becoming the largest iron ore shipping port in Brazil; Tubarão is located in the state of Espirito Santo, and is one of the fastest iron ore loading and unloading terminals in the world. The port of Sepetiba is close to the port of Tubarão. Almost all iron ore in Brazil is transported by capesize ships, and the BCI (Baltic Capsize Index) used two iron ore shipping routes from Brazil - Tubarão to Rotterdam(C2) and Tubarão-Qingdao (C3):

Australia is the country with the largest iron ore reserves and production in the world. The Pilbara region in the northern part of Western Australia is the main producing area. The main export ports are located at the Northwest Coast, including Port Hedland, Port Dampier and Port Alcott. Australia's iron ore transportation is dominated by capsize as well. The BCI index includes one Australian iron ore route - Australia West-Qingdao route (C5).

The distance of the C5 route is about 3,600 nautical miles, and it takes about 15 days. Distance and sailing time About 1/3 of C3, the freight level is usually 2/5 of C3. In addition to the above traditional routes, there are some new routes to transport iron ore and coal. The new routes C14, C15 and C16 focus on China iron ore and coal trades.

- Route C14: Round voyage via Brazil, redelivery China-Japan range, carrying 180,000 million tons iron ore per voyage.

- Route C16: Departure from Australia or Indonesia or US West Coast or South Africa or Brazil, deliver in North China-South Japan range, redeliver in UK-Cont-Med within Skaw-Passero range, carrying 180,000 million tons iron ore per voyage.

- Route C17: From Saldanha Bay to Qingdao, carrying 170,000 million tons iron ore per voyage.

1.4.7. Comparison of iron ore price and voyage rate of iron ore

Freight rates for these main routes mentioned above are shown in Figure 9. The voyage cost for longer routes (e.g., from Brazil to China) higher than that of shorter routes (Canada to Europe), but almost all routes maintain a similar trend.

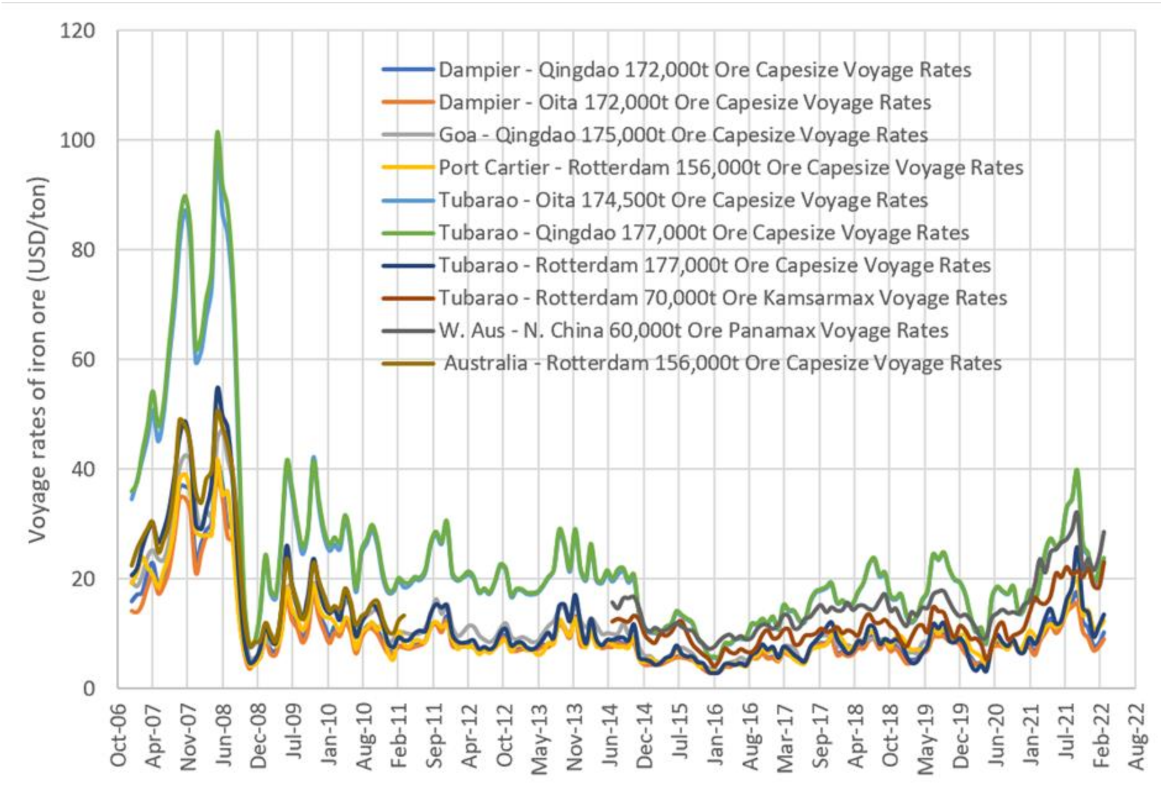


Figure 9 Voyage rates of iron ore 2006-2022 (Source: CSIN)

Since these shipping routes are different and the sailing time is relatively long, it is difficult to quickly adjust the capacity in one specific route in the short term. As the shipping market is competitive, the steel plant's sudden demand for iron ore has a direct impact on freight rates on these routes in the short term. Due to the small elasticity of short-term capacity supply, the freight rate depends on the transportation demand, that is, the change in trade volume. The iron ore freight rate shows a certain seasonality: April-September is the peak season, and October-March of the following year runs to low season. The seasonal effect of the supply side is not obvious. Only the demand side of iron ore is affected by holidays and seasonal heating in the crude steel production, and there is a slight sign of off-season in October-February. Due to the obvious effect of heating season, the ironmaking capacity is idle, and after the heating season ends, the ironmaking capacity will increase significantly, which will directly drive the demand for the shipping.

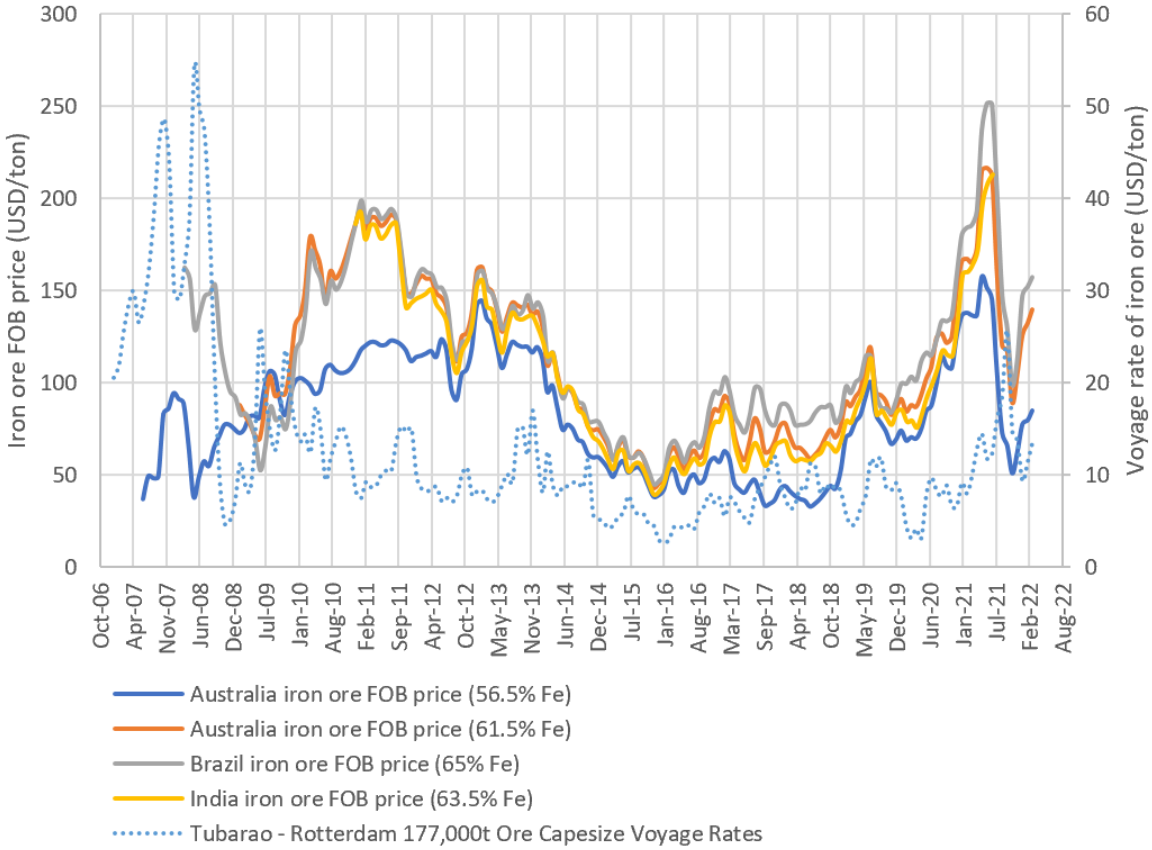


Figure 10 Iron ore FOB price and voyage rate 2007-2022 (Source: Xiben, CSIN)

Figure 10 shows FOB prices of iron ore in Australia, Brazil, and India from 2006 to 2022. The higher the quality of iron ore, the higher the price, and their fluctuation patterns are basically the same. The price evolution of iron ore is roughly the same as that of coking coal, with price peaks at 2011, 2016, and 2022. The factors for the fluctuation of iron-ore price are similar to those of coke. There are also some differences compared with coking coal. For example, in 2013, there was a peak in iron ore prices due to the delay delivery by the three major iron ore companies with bad weather condition. In 2019, iron ore price reached a new peak due to the dam failure of Vale in Brazil, which led to a significant shortage in iron ore supply and price increase. Although the changes in demand for iron ore and coking coal are basically the same, the price changes of the two in the same period will be different due to the differences in supply.

Different from coking coal and iron ore price cycles, the freight market has a longer cycle. This is because the shipbuilding lag is as long as 2-3 years, and the lifespan of ships is as long as 10-20 years. Shipping capacity is hard to adjusted to the rapid changes in demand. In 2001, China joined the WTO and entered a rapid growth period. Chinese manufacturing drove the growth of demand in steel. Capesize market entered a rising cycle, and the freight rate reached its peak at as high as 55 USD per ton in 2008. The increase in shipbuilding orders during this period led to an increase in ship capacity after 2-3 years. At that time, the price of iron ore was less than 130 USD per ton. Freight rate accounted for more than 30% of the iron ore CIF price.

At the end of 2008, the global economy was hit hard by the financial crisis. The demand for iron ore and coke decreased. Due to the continuous increase in capacity, shipping industry entered into a stage of overcapacity. Shipping market turned a downward trend until 2016. During this period, freight rates fluctuated in the range of 5 USD per ton to 15 USD per ton, however, iron ore prices went through a new cycle during the same period, falling again from a high of 200 USD per ton to 50 USD per ton. Freight cost accounts for 5% to 20% of the CIF price of iron ore during 2009 to 2016.

After 2016, with the new cycle in the bulk carrier market, the freight rate gradually rose to 30 USD per ton in 2021, while the iron ore price also increased from 100USD to 200USD per ton in the same period. Freight cost accounts for about 10% of the CIF price of iron ore.

1.4.8. Summary of the freight rate and iron ore and coal price

According to the proportions of arrival prices of iron ore and coal, the freight rate shall be a nonnegligible part in crude steel production planning. It can be concluded that the trend of freight rate still has some difference compared with that of iron ore or coal price. Therefore, freight rate is an important variable cost to consider in crude steel production.

To sum up, the prices of coke and iron ore and the freight rate are affected mainly by the raw material demand of steel industry, but the price fluctuations of the three are different because the suppliers are not the same, or the supply and demand cannot be balanced all the time. The international coke supply is mainly provided by Australia, where local production and weather are important factors in its supply. In addition to Australia, Brazil is also the main supplier of iron ore, the local production and weather also affect the supply of iron ore. In addition, iron ore supply is monopolized, and the bargaining power of the buyers is weak. The supply and demand of the freight market is difficult to balance quickly due to the low flexibility of shipping capacity.

Chapter 2

2. Statistical analysis of steel prices

For steel producers, the price changes in these three markets have direct impacts on the production cost of steel, and then affect the profitability of steel plant. However, there is no existing research on the contribution of raw material price and freight rate to steel prices. In the related research, Crompton and Lesourd (Crompton & Lesourd, 2008) constructed and verified the linear relationship between fixed ratio inputs and total cost by combining panel data with generalized Leontief production function. The costs in this study include iron ore, coking coal, electricity, and capitals using data from Australian steel producers. However, transportation costs were not considered. Tsioumas and Papadimitriou (Tsioumas & Papadimitriou, 2016) confirmed the bidirectional relationship between iron ore and coal price and BCI index by using cointegration analysis, Granger causality test and impulse response analysis, but the article did not verify the relationship between steel price and freight rate.

To test the composition of steel price, this research statistically validated the composition of iron ore prices, coking coal prices, and freight charges in steel prices.

2.1.Modelling the Steel Price

According to Table 3 in Chapter 1, the input quantity of iron ore and coking coal for steel production is basically fixed, so are the shipping demand for iron ore and coking coal. This input ratio will not change with the scale of production. They are not substitutes for each other, and there are no substitutes for them. Such production function was first proposed by Wassily Leontief

(Leontief, 1947) based on the fixed proportion of raw materials used in steel production. Using such production function, steel production cost can be expressed as a fixed proportion of iron ore price, coking coal price, freight price, labor cost and other raw materials and capital cost. To estimate the model, this study considers iron ore price, coking coal price, and freight rate on the composition of steel price. Other fixed-proportion inputs, e.g, limestone, electricity, labor, are not included as they only account for a small portion of the total cost. Other inputs in steel production, such as operation costs, depreciation of assets, distribution intermediaries are treated as fixed cost, and will be grouped in the constant.

Considering the main steel production regions and the suppliers of raw materials, this research analyzes the relationship between steel prices and the prices of factor inputs in three different regions- China, Japan, and Northern Europe, using monthly average prices from 2013 to 2022 in USD. To make the data more comparable, the steel price takes local FOB price of cold-rolled coils, FOB price of fine iron ore with iron content of 65% in Brazil, and capsize voyage rate from Tubarao, Brazil. Considering the coking coal for steel production are from different regions, China adopts the FOB price of Chinese coking coal, Japan uses that from Australian, and Northern Europe uses that from Canada. The scatter plots of the price of each input and steel price are presented as below.

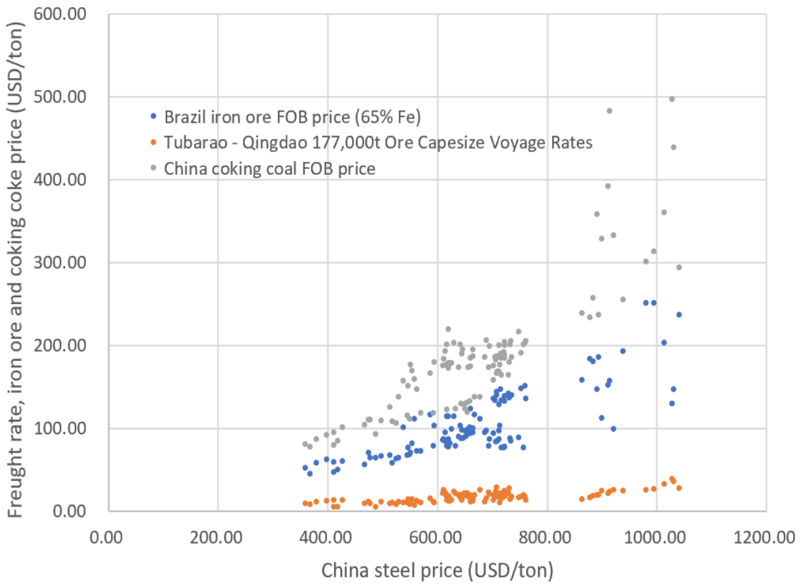


Figure 11 Scatter plots of the price of each input and China steel price

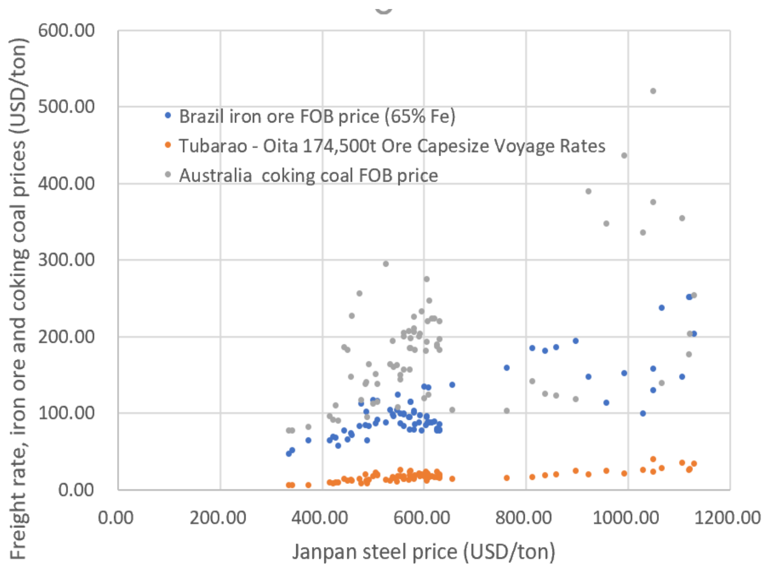


Figure 12 Scatter plots of the price of each input and Japan steel price

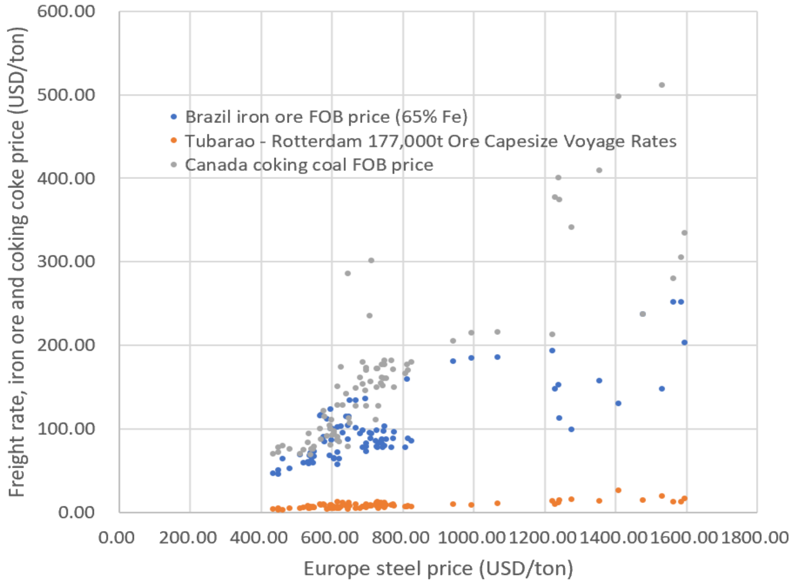


Figure 13 Scatter plots of the price of each input and Europe steel price

According to the figures above, in China, Japan, and Northern Europe, steel prices and inputs all show a linear relationship. The correlation test was carried out on these combinations, and the results showed that there was a significant correlation between inputs and steel price. Considering the freight rates of coking coal and iron ore are both dry bulk freight and are highly correlated, to avoid collinearity, iron ore freight rate is selected as the representative of freight rate. Data used in the statistical analysis has been described in Chapter 1.

This research uses a linear regression analysis to analyze the statistical relationship between multiple input prices and steel prices. In linear regression, the ordinary least square method is used to obtain statistical relationship.

The statistical model is:

$$P_{steel} = C + k_1 P_{iron\ ore} + k_2 P_{coal} + k_3 P_{freight\ rate} + \varepsilon \quad (2.)$$

P_{steel} is the unit steel price,

$P_{iron\ ore}$ is the unit iron ore price,

P_{coal} is the unit coking coal price,

$P_{freight\ rate}$ is the freight rate,

C is the intercept，

k_i is the coefficient to be estimated.

ε is the residual.

According to Table 6 - Material inputs, cost, and emission in steel production from BF-BOF route in Chapter 1, the coefficient k_i should be estimated as the input-output ratio, corresponding to about 1.5 for iron ore and 1.1 for coking coal, and the total freight of iron ore and coal is about 2.6.

2.2.Regression analysis of steel price and input prices

Monthly average data was used, and the impact of the pandemic on the imbalance between supply and demand in the steel supply chain is considered. Due to the slower supply of raw materials, steel market experienced a sharp increase in demand during the shock. Steel prices in China, Japan and Europe have experienced different sharp fluctuations. The study compared data over time：

1) Statistical results before-COVID-19 - data as of January 2019; 2) Statistical results including COVID-19 - data as of March 2022. The regression results of steel prices and input prices are shown in Table 6.

Table 7 Regression of steel price and inputs price

Before Covid-19						
	China		Japan		Europe	
R-Square	0.78002		0.70730		0.58909	
Significance F	0.00000		0.00000		0.00000	
	Coefficients	P-value	Coefficients	P-value	Coefficients	P-value
Iron ore price	1.21059	0.00000	1.10500	0.06420	1.45147	0.04777
Freight rate	3.50797	0.00013	6.53158	0.00012	7.92963	0.07883
Coking coal price	1.44661	0.01354	0.65707	0.00006	0.98054	0.00003
Intercept	227.62786	0.00000	227.14715	0.00000	343.59966	0.00000
Included observations	83		49		58	

Include Covid-19						
	China		Japan		Europe	
R-Square	0.88262		0.91021		0.89906	
Significance F	0.00000		0.00000		0.00000	
	Coefficients	P-value	Coefficients	P-value	Coefficients	P-value
Iron ore price	1.37214	0.00000	2.82086	0.00000	2.90648	0.00000
Freight rate	3.67543	0.00158	8.15543	0.00000	9.78283	0.02603
Coking coal price	1.05793	0.00000	0.83735	0.00000	1.49450	0.00000
Intercept	268.10480	0.00000	32.98479	0.16869	140.18190	0.00000
Included observations	108		75		84	

2.2.1. China

In steel production, about 80% of the iron ore in China is imported from Australia and Brazil. Considering that the import from Brazil is relatively stable, the FOB price of iron ore with 65% iron content in Brazil is selected, and the data is from Xiben Information (XibenInfomation, 2022). China imports less than 20% of coking coal. Therefore, the price of domestic coking coal is selected, which is from Mysteel (Mysteel, 2022). The monthly average prices are from May 2013 to March 2022, 108 data points are observed.

The regression result before Covid-19 shows the model can explain 78% of the data variation and 88% of the data variation include Covid-19. Combined with the fixed-proportion production function for steel production, the regression coefficient of iron ore price to steel price before Covid-19 is about 1.21 and 1.37 include Covid-19, which means that if the FOB price of iron ore from Brazil increases one dollar, the price of China's cold-rolled coil can increase 1.21 USD begore Covid-19 and 1.37 USD includes Covid-19. In general, from table 3, about 1.5 tons of iron ore are required to produce one ton of crude steel. This means the estimated coefficient is slightly lower than the input-output ratio. The estimated coefficient of iron ore freight rate is about 3.5 before Covid-19 and 3.7 includes Covid-19. This coefficient is greater than the transportation volume of inputs required to produce one ton of steel, Capsize's freight rate from the origin to the large port is used. In practice, the freight rate from the large port to the smaller port close to the factory should also be considered. In addition, there are other materials such as thermal coal, scrap, and other materials that need to be transported by sea, and their voyage rates varies. The slight increase in the correlation coefficients suggests that iron ore price and freight rate volatility increased steel price volatility after the pandemic began. The estimated coefficient for coking coal is about 1.45 before Covid-19 and 1.06 includes Covid-19. As it takes about 1 tons of coking coal to produce one ton of steel, the estimated coefficient is almost the same as the input-output ratio include Covid-19. Compared with the coking coal coefficient in Japan and Europe, the coking coal coefficient in China decreased when include the pandemic. Considering that the pandemic led to an increase in the dependence of local coking coal, the local coking coal fluctuation was directly related to local steel price fluctuation. The intercept is 227.6 before Covid-19 and 268.1 include Covid-19, which is very significant as well. It suggests that the intermediate cost per ton of cold rolled coil from production to sale is roughly 227 USD before Covid-19 and increased to 268 USD include Covid-19.

2.2.2. Japan

The data for the output-input price relationship are selected in the similar way. The import rate of iron ore is almost 100%, mainly from Brazil and Australia. In the statistical analysis, the FOB price of iron ore with 65% iron content in Brazil is selected, and the data is from Xiben Information.

Japan's coking coal is also entirely imported from Australia and the Americas. Therefore, the FOB price of Australian coking coal is selected. The data is obtained from Bloomberg and IEA. Monthly average prices from January 2016 to March 2022 are applied with a total of 75 data observation points.

The result shows 71% of the data variation can be explained by the regression model and 91% includes Covid-19. The estimates are all very significant. The iron ore coefficient is 1.2 before Covid-19, which is slightly lower than the input-output ratio of iron ore to steel because a portion of Japanese steel production is scrap instead of iron ore. Japan also uses natural gas in its steel production. The coefficient of coking coal is 0.66, which also lower than the same as the input-output ratio of coking coal to steel. The coefficient of iron ore freight rate is about 6.5. The coefficient is much bigger than the transportation volume of inputs required to produce one ton of steel and it is twice that of China, considering that Japan needs to transport 100% of coking coal and other raw materials by ship and may use smaller ships with higher freight rates than Capsize because the demand is much smaller. This result shows that freight have a greater impact on steel price changes in Japan than in China. It is worth noting that results including COVID-19 show that the coefficients for iron ore, coking coal and freight rates have all increased, with the iron ore coefficient doubling. This suggests that steel prices have been more volatile than raw material prices as a result of the pandemic, and compare to coking coal and freight, iron ore volatility relative to steel volatility is smaller. This may because of more plentiful storage of iron ore and longer-term contracts.

Before COVID-19, the intercept of Japan was almost the same as that of China, both of which were 227 USD, but after the inclusion of the pandemic data, the intercept was reduced to 33 USD and was not significant, which may be caused by the sharp fluctuations of steel prices since the pandemic.

2.2.3. North Europe

In North Europe, more than 80% of the iron ore are imported, which are mainly from Brazil. In the statistical analysis, the FOB price of iron ore with 65% iron content in Brazil is selected (Xiben). About 70% of their coking coal is imported, mainly from America. Therefore, the FOB price of Canada coking coal is selected from Bloomberg and MySteel. Monthly average prices from April 2015 to March 2022 are applied. 84 data points are observed.

The result shows about 60% of the data variation can be explained by the regression model before the pandemic. The iron ore coefficient is about 1.5, which is equal to the input-output ratio of iron ore to steel. The coefficient of coking coal is about 1, which is basically the same as the input-output ratio of coking coal to steel as well. The coefficient is greater than the transportation volume of inputs required to produce one ton of steel than that of Japan. The intercept is 343 USD, it suggests that the intermediate cost per ton of cold rolled coil from production to sale is roughly 343 USD since the steel price is higher in Europe.. The coefficient of iron ore freight rate is about 7.9. Consider that large dry bulk ports in Europe, such as Rotterdam, are longer distances from ports near European steel plants, the coastal freight rate may be higher, freight rate have a greater impact on steel price in Europe than in Japan and China. Similarly, sharp fluctuations in steel prices during the pandemic led to an increase in the coefficients containing pandemic data and a decrease in the intercept term.

2.3.Conclusion of statistical model

The above regression results suggest that the statistical model proposed in this research is significant and effective for the price of steel produced in different regions. Although the influence of input price changes on local steel price changes is slightly different in each region due to the inconsistent import dependence of iron ore and coking coal, the coefficient of each input price is basically consistent with the input-output ratio of input to steel especially before the pandemic. In addition, through the regression results, it can be found that the fluctuations in steel prices is greater than raw material price fluctuations during the pandemic. It is worth noting that the iron ore price fluctuation is smaller than price fluctuations of coking coal and the freight rate. In the future study, detailed data will be used for further study of the causes of this phenomenon.

In terms of academic contribution, as mentioned in section 2.1, this statistic studies the linear coefficient between input including freight and steel price, which fills the research gap. Statistical results confirmed that the impact of freight on steel prices is significant, and it is worth noting that in different regions, the coefficient of freight rate is different. The coefficient of Japan and Northern Europe is more than twice that of China. It is possible that smaller shipping volumes and longer coastlines lead to higher freight rates. Besides, different from China, Japan and Europe export most of their steel products, further exploration of bidirectional causality between steel price and freight rate may also be considered in future research.

The regression in this chapter proves that multiple linear equation can describe steel production cost well. Therefore, in the model construction in the next chapter, multiple linear equation is used to describe steel production cost and profit function is estimated accordingly. In addition, emission allowance price will be introduced as a cost to complete the construction of the optimization model in Chapter 3.

In addition, the regression results in this chapter help to revise the coefficient of input raw materials in the cost of steel, which will be used in the model simulation in Chapter 4 to make the simulation results closer to reality and more reliable. At the same time, the regression results also indicate that the pandemic caused fluctuations in the prices of steel and raw materials, making the coefficient deviate from the input-output ratio - the coefficients before the pandemic. Compared with Japan and Europe, China's coefficients are more stable, therefore, they are adopted in the simulation in Chapter 4.

Chapter 3

3. Modelling the carbon futures of ETS on shipping

3.1.Hedging and production strategy for steel plant

The uncertainty on profitability grows with the time from raw material purchase to the sale of crude steel. To stabilize the profits, steel mills hedge steel and raw materials in the futures market. Hedging is the purchase or sale of commodity futures contract with a same quantity as the spot market but in the opposite direction (Garbade & Silber, 1983; Peck, 1976). The actual loss caused by price decrease in spot market can be compensated in the futures market by selling or buying the futures contract. Once the times for raw material purchase and products delivery can be estimated, futures contracts can be selected accordingly. Unit prices of raw materials and products can be secured at the moment that futures contracts finalized. Sellers or buyers can adjust their production plan accordingly. This have been used in industries of steel, energy, agriculture, shipping and so on (Alizadeh, Kavussanos, & Menachof, 2006; Chang, McAleer, & Zuo, 2017; Elumalai, Rangasamy, & Sharma, 2009; Gay et al., 2009; KAVUSSANOS & NOMIKOS, 2003; Martin, 2019). Steel plant can generate its marginal cost curve and decide the best production to maximize its profit in this period.

This model considers a two-period optimization model where the steel producer to set up a raw material inventory, steel production and sales plan in period one to maximize the total profit in two periods. It is considered as a short-term model because it does not consider that the steel plant can plan again in period 2 for the next two periods. Such long-term model can be considered in future research.

In the two-period model, with anticipated price or cost change in the second period, the production planner can make use of these information to adjust the level of production and/or raw material inventory to maximize profit. Under the current emission reduction policy, if ETS is available and there is futures market for the emission allowance, then it is possible to fixed the price of the emission allowance. If the futures price of emission allowance is high, the planner can produce more in the first period, to save the cost in the second period.

Emission allowance price has been proved affecting the production plan of the steel plant (Chen & Hu, 2018). Compared with the iron ore, coal and crude steel futures markets, carbon futures markets only exists in a few main steel production areas. Research also shows carbon futures performance well in forecasting the trend of emission allowance spot market (Ji, Zou, He, & Zhu, 2019; L. Zhang, Zhang, Xiong, & Su, 2017) and carbon futures can be used to manage risk of emission allowance (Balcılar et al., 2016). Although the setting of carbon futures markets in the rest areas with ETSs is unknown, during the reduction of carbon emission cap, the emission allowance cost will certainly become one of the important elements in the production plan of steel producers. It is important to study the possible impacts of steel production planning on shipping and emission control. Therefore, in this paper, to modelling the impact of carbon futures to shipping industry, a two-period short-term equilibrium model need to be established to help the decision-maker in considering the emission reduction policies.

In this model, iron ore and coke prices are treated as exogenous, to simplify the model and keep focus on the emission reduction policy. Other raw materials, such as thermal coal, limestone and oxygen, are not significant inputs in steel production. Therefore, their costs are neglected.

To focus on the impact of carbon futures markets, 3 scenarios are set as below.

- Without ETS: This used as a benchmark scenario, providing a base for comparison for the other two scenarios.
- ETS without carbon futures: steel plant estimates the cost of future price of the emission allowance based on the current price.
- ETS with carbon futures: steel mill uses the futures market to hedge their emissions allowance for use in future periods.

3.2. Cost model for steel production

To simplify the analysis, the total cost (tc) of steel is assumed to include only four parts:

$$tc = c^m + c^f + c^e + c^c \quad (3.)$$

Where:

c^m is the total cost of raw materials;

c^f is the total shipping cost of raw material;

c^e is the total cost of emission allowance;

c^c is the total capital cost.

For c^m, the prices of raw materials in the second period are set to be the same as that in the first period. The steel production is assumed to be follow the Leontief production function, as the combination of iron ore, coal, electricity, limestone and other materials are relatively fixed (Ansari & Seifi, 2012; Crompton & Lesourd, 2008). Using y to denote the steel output, x^i the total quantity of raw material i ($i \in \{ir, co, ot\}$, ir: iron ore; co: coal; ot: others), and a^i as the quantity of input per unit output(Greer, 2012; Pollak， & Wales), the production function can be expressed as:

$$y \leq min\left(\frac{x^i}{a^i}\right) \tag{4.}$$

c^m can be written as:

$$c^m = p^{ir}x^{ir} + p^{co}x^{co} + p^{ot}x^{ot} \tag{5.}$$

Where p^i is the unit price of each raw material.

The data in Figure 14 presents the global bulk trade from 2013 to 2020. Three main commodities, namely iron ore, coal, and grains, account for more than half of the total trade volume, and their proportions are relatively stable. Among them, iron ore accounts for nearly one-third of the dry bulk trading volume. Coal accounts for nearly 20%, of which the split of coking coal and thermal coal is 20 to 80. They are mainly used for steel production and carried by Capesize vessels. To study the impact of demand change on the freight rate when shipping supply cannot be expanded in short-term, a linear supply is assumed to model the relationship between the freight rate and dry bulk shipping demand.

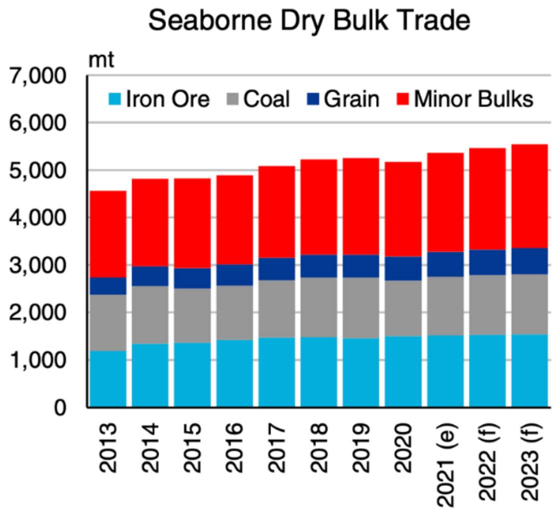


Figure 14 Global seaborn dry bulk trade (Source: CSIN)

Denoting freight rate as p^{fr} (unit: mile-ton) and the supply function are the same for the two periods, then the freight cost can be written as:

$$c^f = \beta^{fr}\left(x^{ir} + x^{co}\right) \tag{6.}$$

$$p^{fr} = \alpha^{fr} + \beta^{fr}(x^{ir} + x^{co}) \tag{7.}$$

Where $\alpha^{fr}$is the intercept, β^{fr} is the sensitivity of freight rate with supply change. Therefore,

$$\alpha^{fr} > 0 \tag{8.}$$

$$\beta^{fr} > 0 \tag{9.}$$

Steel plants are required to surrender the emission allowance according to their total emissions in an emission allowance clearing year. If they used more than the allowance quantity, they have purchase additional allowance from the ETS market. In most ETS, emission allowances are valid only for current year. Therefore, strategic behavior in saving the allowance for later use is not considered. Emission banking can be explored in the future study. The steel industry accounts for about 10% of emissions in most ETSs, while the power generation industry accounts for more than 60%, so steel producers do not have market power for emissions allowance. Therefore, assume the equilibrium price of emission allowance is exogeneous and emission requirement per ton steel output is e, the cost on the emission would be:

$$c^e = eyp^{em} \tag{10.}$$

Then, the total cost for producing y units of steel is:

$$tc = p^{ir}x^{ir} + p^{co}x^{co} + p^{ot}x^{ot} + p^{fr}(x^{ir} + x^{co}) + p^{em}ye + c^c \tag{11.}$$

3.3.Profit model for steel production

In this study, we assume that the initial emission allowances are allocated using the most popular allocation methods for steel industry, *Grandfathering rule*, as mentioned in section 1.4.2. This allocation method ensures the allocated allowance is not related to the emission in the current and future periods. For the steel plant, the free allocation can be treated as a source of revenue. Using E^f to denote the quantity of free allocated emission allowances, the profit equation can be written as:

$$\pi = p^{st}y + p^{em}E^f - tc \tag{12.}$$

which can be expanded as below by replacing Eq.3 according to the cost model,

$$\pi = p^{st}y + p^{em}(E^f - ye) - [p^{ir}x^{ir} + p^{co}x^{co} + p^{ot}x^{ot} + p^{fr}(x^{ir} + x^{co})] + c^c \tag{13.}$$

Assume the demand of the steel from this steel plant can be expressed as a linear demand function:

$$p^{st} = \alpha^{st} - \beta^{st} y \tag{14.}$$

where $\alpha^{st} > 0$ is the intercept and $\beta^{st} > 0$ is the sensitivity of steel price.

3.4.Two-period optimization model

If only one period is considered, to maximize the profit, the decision variables of the steel mill are steel production and raw material purchase. However, in the two-period optimization model, to maximize the total profit of the two period, the steel mill needs to consider the optimal steel production and raw material purchase of each period. For example, if the allowance price in period 1 is low, the steel mill should produce more in this period, to take the cost advantage. This requires more raw materials, which may push up the freight rates. Therefore, there is a tradeoff between the benefits from the low emission cost, and the cost increases in freight transportation.

As shown in Fig. 15, subscripts are introduced into the notations in the above equations to mark the parameters in different period.

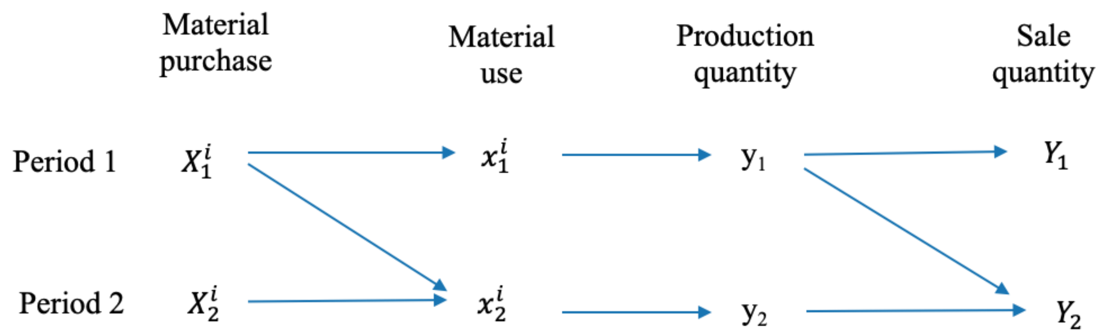


Figure 15 Parameters in Two-stage optimization model

X_1^i and X_2^i present the materials purchased in period 1 and period 2, superscript i stands for ir, co, ot, which are iron ore, coking coal and other inputs. Since the raw materials are used in different periods, the raw materials used in period 1 are marked as x_1^i; the raw materials used in period 2 are marked as x_2^i. $X_1^i - x_1^i \geq 0$ is the part of raw material purchased in period 1 and used in period 2, it is defined as material inventory in this research.

Y_1 and Y_2 represent the products sold in period 1 and period 2. Subjected to their production time, the products produced in two periods are denoted as y_1 and y_2, and $y_1 - Y_1 \geq 0$ is the output produced in period 1 and sold in period 2. According to the Leontief production function,

$$y_1 = \frac{x_1^i}{a^i} \tag{15.}$$

To focus on the impact of carbon futures, the model sets three different scenarios and assumes that there are no arbitrage opportunities in product or raw material markets, i.e., for the iron ore and coking coal, the present value of price in period 2 is equal to the price in period 1. In steel market, the two periods use the same demand function (Eq. 14). The supply functions for the shipping market are also the same in the two periods (Eq. 7). The emission factor e and the capital cost c^c are constant. p^{in} is the inventory cost, which is the same for both raw material and steel. The problem of the planer is then to maximize the total profit, i.e.,

$$\underset{X_1, X_2, y_1, y_2, Y_1, Y_2}{\text{Max}} \quad \Pi = \tag{16.}$$

$$\sum_{n=1}^{2}\left[(\alpha^{st}-\beta^{st}Y_{\mathrm{n}})Y_{\mathrm{n}}+\left(E_{\mathrm{n}}^{f}-ey_{\mathrm{n}}\right)p_{\mathrm{n}}^{em}\right]-\sum_{i\in[ir,co,ot]}\left(p^{i}\sum_{n=1}^{2}X_{n}^{i}\right)$$
$$-\sum_{n=1}^{2}\left[\left(\alpha^{fr}+\beta^{fr}\sum_{i\in[ir,co]}X_{n}^{i}\right)\sum_{i\in[ir,co]}X_{n}^{i}\right]$$
$$-\,p^{in}\left[\sum_{i\in[ir,co]}(X_{1}^{i}-x_{1}^{i})+(\mathrm{y}_{1}-Y_{1})\right]]-2c^{c}$$

s.t.

$$\sum_{n=1}^{2}X_{n}^{i}=\sum_{n=1}^{2}x_{n}^{i} \tag{17.}$$

$$x_{n}^{i}=a^{i}y_{n} \tag{18.}$$

$$\sum_{n=1}^{2}y_{n}^{i}=\sum_{n=1}^{2}Y_{n}^{i} \tag{19.}$$

Three scenarios are designed to compare the impact of carbon futures as below:

- Scenario 1: Without ETS

In this scenario, it is assumed that there is no policy on emission control and there is no emission allowance trading. Thus, $p^{em}=0$. The production plan is just to maximize the total profit in two periods:

- Scenario 2: With the absence of carbon futures, steel mill estimates the cost of future permits

In scenario 2, emission allowance can be traded in ETS. However, there is no carbon futures market. it is assumed that the emission allowance prices of the two period are equal, i.e., $p_2^{em} = p_1^{em}$.

- Scenario 3: With carbon futures, steel mill can use emission futures to hedge

In scenario 3, steel producers use emission futures to hedge the emission price in the second period. Then, the planner can decide whether it is worthy to produce more in the current period to reduce the impact of future price increase in emission allowance. The planner can also decide if it is necessary to import more raw material for use in the second period.

Therefore, the problem is how to adjust the production level in each period y_1 and y_2, and the percentage of the raw material required for period 2 to be purchased in period 1, b $(0 \leq b < 1)$, and the friction of output in period one to be sold in period 2, c $(0 \leq c < 1)$. $b = 1$ and $c = 1$ is not possible as there should be always something to buy and sell at period 2.

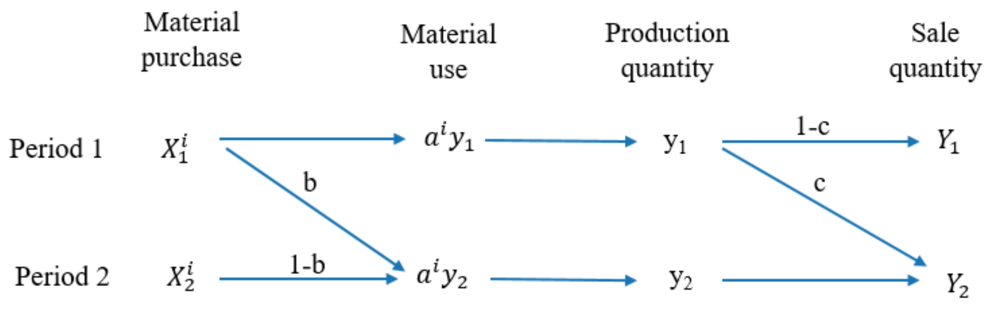


Figure 16 Illustration of raw material purchase to product sale in two periods

Expand the Eq. 16 according to the conditions above,

$$\underset{b,c,y_1,y_2}{\text{Max}} \quad \Pi = \tag{20.}$$

$$\sum_{n=1}^{2}\left[\left(\alpha^{st}-\beta^{st}Y_{\mathrm{n}}\right)Y_{\mathrm{n}}+\left(E_{\mathrm{n}}^{f}-ey_{\mathrm{n}}\right)p_{\mathrm{n}}^{em}\right]-\sum_{i\in[ir,co,ot]}\left(p^{i}\sum_{n=1}^{2}X_{n}^{i}\right)$$
$$-\sum_{n=1}^{2}\left[\left(\alpha^{fr}+\beta^{fr}\sum_{i\in[ir,co]}X_{n}^{i}\right)\sum_{i\in[ir,co]}X_{n}^{i}\right]$$
$$-p^{in}\left[\sum_{i\in[ir,co]}(X_{1}^{i}-x_{1}^{i})+\left(\mathrm{y}_{1}-Y_{1}\right)\right]]-2c^{c}$$

$s.t.$

$$\sum_{n=1}^{2}X_{n}^{i}=\sum_{n=1}^{2}x_{n}^{i} \tag{21.}$$

$$x_{n}^{i}=a^{i}y_{n} \tag{22.}$$

$$\sum_{n=1}^{2}y_{n}^{i}=\sum_{n=1}^{2}Y_{n}^{i} \tag{23.}$$

$$\left(1-b\right)x_{2}^{i}=X_{2}^{i} \tag{24.}$$

$$bx_{2}^{i}+x_{1}^{i}=X_{1}^{i} \tag{25.}$$

$$(1-c)y_{1}=Y_{1} \tag{26.}$$

$$cy_{1}+y_{2}=Y_{2} \tag{27.}$$

It can be inferred from Fig 16 and Eq.20 that in the two-period optimization model, the decision variables of steel production are b, c, y_1, y_2. The total profit can be optimized with these four variables. Take the partial derivative of the profit function:

$$\frac{\partial \Pi(\cdot)}{\partial b} = -\beta^{fr}\left[2\left(\mathrm{a}^{ir}+\mathrm{a}^{co}\right)^2(y_1+\mathrm{b}y_2)y_2 - 2\left(\mathrm{a}^{ir}+\mathrm{a}^{co}\right)^2(1-b){y_2}^2\right] - p^{in}\left(\mathrm{a}^{ir}+\mathrm{a}^{co}\right)y_2$$

$$= y_2 \sum_{i\in[ir,co]} x_2^i \cdot \left\{2\beta^{fr}\left[\sum_{i\in[ir,co]}(X_n^i - X_1^i)\right] - p^{in}\right\} \tag{28.}$$

$$\frac{\partial \Pi(\cdot)}{\partial c} = [2\beta^{st}(1-c)y_1 - 2\beta^{st}(\mathrm{c}y_1+y_2)]y_1 - p^{in}y_1$$

$$= y_1 \cdot \left[(\alpha^{st} - 2\beta^{st}Y_2) - (\alpha^{st} - 2\beta^{st}Y_1) - p^{in}\right] \tag{29.}$$

$$\frac{\partial \Pi(\cdot)}{\partial y_1} = \tag{30.}$$

$$-2\beta^{st}(1-c)^2y_1 - 2\beta^{st}c(y_1c+y_2) - ep_1^{em} - p^{ir}a^{ir} - p^{co}a^{co} - p^{ot} - \alpha^{fr}\left(\mathrm{a}^{ir}+\mathrm{a}^{co}\right)$$

$$- 2\beta^{fr}\left(\mathrm{a}^{ir}+\mathrm{a}^{co}\right)^2(y_1+\mathrm{b}y_2) - p^{in}c$$

$$= -2\beta^{st}Y_1(1-c) - 2\beta^{st}Y_2c - ep_1^{em}$$

$$- p^i \sum_{i\in[ir,co,ot]} a^i - \left(\alpha^{fr} + 2\beta^{fr}\sum_{i\in[ir,co]} X_1^i\right)\sum_{i\in[ir,co]} a^i - p^{in}c$$

$$\frac{\partial \Pi(\cdot)}{\partial y_2} = \tag{31.}$$

$$-2\beta^{st}(y_1c+y_2) + \alpha^{st} - ep_2^{em} - p^{ir}a^{ir} - p^{co}a^{co} - p^{ot} - \alpha^{fr}\left(\mathrm{a}^{ir}+\mathrm{a}^{co}\right)$$

$$- 2\beta^{fr}[\left(\mathrm{a}^{ir}+\mathrm{a}^{co}\right)^2(y_1+\mathrm{b}y_2)b + \left(\mathrm{a}^{ir}+\mathrm{a}^{co}\right)^2(1-b)^2y_2] - p^{in}\left(\mathrm{a}^{ir}+\mathrm{a}^{co}\right)b$$

$$= -2\beta^{st}Y_2 - ep_2^{em}$$

$$- p^i \sum_{i\in[ir,co,ot]} a^i - \{\alpha^{fr} + 2\beta^{fr}\sum_{i\in[ir,co]}[X_1^i b + X_2(1$$

$$- b)]\}\sum_{i\in[ir,co]} a^i - p^{in}b\sum_{i\in[ir,co]} a^i$$

The sign of the partial derivative, $\frac{\partial \Pi(\cdot)}{\partial b}$, depends on the difference between marginal freight rate of period 2 with that in period 1 and the inventory cost. If the marginal freight rate of period 2 exceeds the marginal freight rate of period 1 and the inventory cost, it is positive, then b should equal to 1, which is not possible according to definition. If it is negative, $b = 0$. It is better to purchase all the raw material at the same period when it is required. This is because the inventory cost and the marginal impact of freight rate in period 1 is too high, it is not a good idea to purchase anything for use in the second period.

The sign of $\frac{\partial \Pi(\cdot)}{\partial c}$ depends on the difference in marginal revenue of the two periods and the inventory cost. If marginal revenue in period 2 is larger than that in period 1 and inventory cost, the sign is positive, then $c = 1$ which is not possible according to definition. If the sign is negative, the still mill only need to produce the output to satisfy its customers for the same period.

3.5. Carbon futures impact on shipping volume

3.5.1. Situation 1: No raw material inventory, no product inventory

When the partial derivatives $\frac{\partial \Pi(\cdot)}{\partial b} < 0$, $\frac{\partial \Pi(\cdot)}{\partial c} < 0$, the total profit decreases with b and c. Therefore, $b = c = 0$, there will be no inventory for both raw material or product. Then, the Figure 16 can be simplified as Figure 17 below.

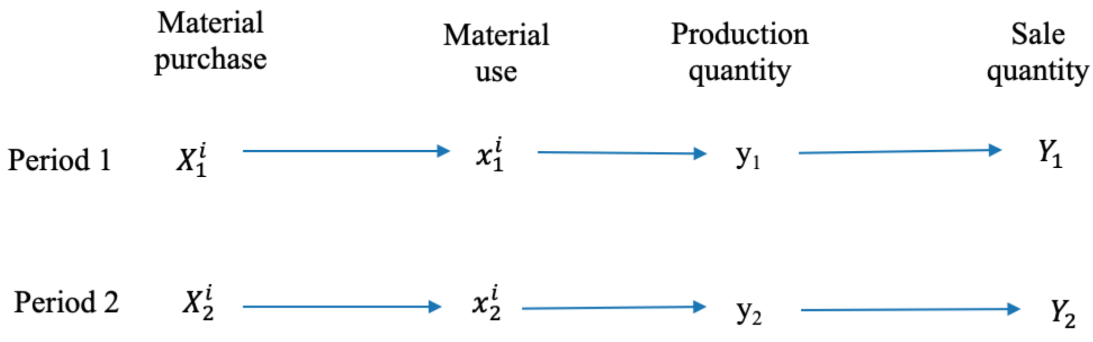


Figure 17 No raw material inventory and no product inventory

The condition for no inventory in both raw material and products is:

$$-\frac{p^{in}\beta^{fr}\left(a^{ir}+a^{co}\right)^2}{\beta^{st}}-p^{in} \leq ep_1^{em}-ep_2^{em} \leq p^{in}\left(a^{ir}+a^{co}\right)+\frac{\beta^{st}p^{in}}{\beta^{fr}(a^{ir}+a^{co})} \qquad (32.)$$

The left inequality is derived from the condition $\frac{\partial \Pi(\cdot)}{\partial c} < 0$, indicating when the condition for the inventory of raw material, while the right one is from the $\frac{\partial \Pi(\cdot)}{\partial b} < 0$. Since there is no inventory, the two-period optimization is the same as optimizing the two periods separately.

The optimal production in period 1 and 2 are:

$$y_1{}^* = \frac{\alpha^{st}-ep_1^{em}-p^{ot}-p^{ir}a^{ir}-p^{co}a^{co}-\alpha^{fr}\left(a^{ir}+a^{co}\right)}{2\beta^{fr}(a^{ir}+a^{co})^2+2\beta^{st}} \qquad (33.)$$

$$y_2{}^* = \frac{\alpha^{st}-ep_2^{em}-p^{ot}-p^{ir}a^{ir}-p^{co}a^{co}-\alpha^{fr}\left(a^{ir}+a^{co}\right)}{2\beta^{fr}(a^{ir}+a^{co})^2+2\beta^{st}} \qquad (34.)$$

The corresponding shipping volume in two periods are：

$$q_1^* = \left(a^{ir}+a^{co}\right)y_1{}^* \qquad (35.)$$

$$q_2^* = \left(a^{ir}+a^{co}\right)y_2{}^* \qquad (36.)$$

In addition, the difference between the shipping volumes is：

$$q_1^* - q_2^* = -\frac{\left(a^{ir} + a^{co}\right)(ep_1^{em} - ep_2^{em})}{2\beta^{fr}(a^{ir} + a^{co})^2 + 2\beta^{st}} \tag{37.}$$

From this, if the emission cost of a period is higher, the shipping volume can be lower.

3.5.2. Situation 2: No raw material inventory, product inventory

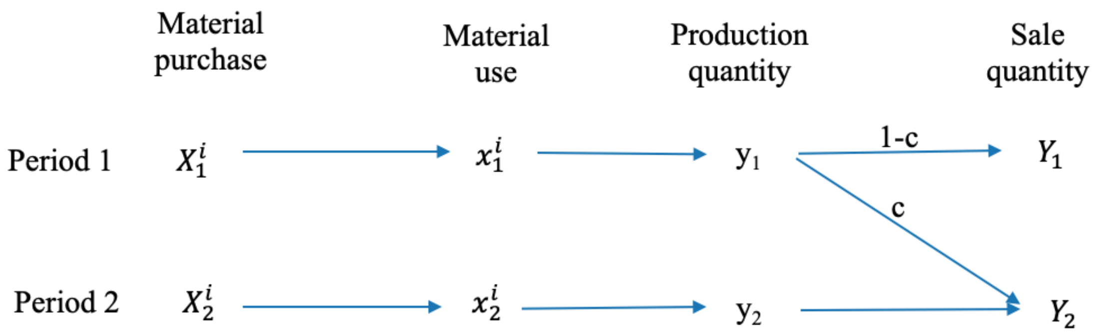


Figure 18 No raw material inventory, product inventory

When the partial derivatives $\frac{\partial \Pi(\cdot)}{\partial b} < 0$ and $\frac{\partial \Pi(\cdot)}{\partial c} = 0$, no inventory in raw material, yes for steel product. The illustrative process of from raw material purchase to the selling of the steel is shown in Figure 18. The condition for this to happen is listed below:

$$ep_1^{em} - ep_2^{em} < p^{in}\left(a^{ir} + a^{co}\right) + \frac{\beta^{st} p^{in}}{\beta^{fr}\left(a^{ir}+a^{co}\right)} \tag{38.}$$

$$ep_1^{em} - ep_2^{em} < -p^{in} - \frac{p^{in}\beta^{fr}\left(a^{ir} + a^{co}\right)^2}{\beta^{st}} \tag{39.}$$

$$ep_1^{em} - ep_2^{em} < -p^{in} \tag{40.}$$

The first inequality is derived from $\frac{\partial \Pi(\cdot)}{\partial b} < 0$. The conditions Eq.39 and Eq.40 are deformed from the condition $0 < c < 1$. Eq.39 is from $c > 0$, and Eq.40 is from $c < 1$. These two inequalities are related. When Eq 39 is satisfied, Eq.38 and Eq.40 is satisfied as well.

The optimal production in period 1 and 2 are, respectively：

$$y_1{}^* = \frac{1}{4\beta^{fr}(a^{ir}+a^{co})^2(\beta^{fr}(a^{ir}+a^{co})^2+\beta^{st})} \tag{41.}$$

$$\left\{-\left(a^{ir}+a^{co}\right)^2\beta^{fr}\left[2\left(\alpha^{fr}+p^{ir}\right)a^{ir}+2(\alpha^{fr}+p^{co})a^{co}+2ep_1^{em}-2\alpha^{st}+2p^{ot}+p^{in}\right] - \beta^{st}\left[p^{in}+ep_1^{em}-ep_2^{em}\right]\right\}$$

$$y_2{}^* = \frac{1}{4\beta^{fr}(a^{ir}+a^{co})^2(\beta^{fr}(a^{ir}+a^{co})^2+\beta^{st})} \tag{42.}$$

$$\left\{-\left(a^{ir}+a^{co}\right)^2\beta^{fr}\left[2\left(\alpha^{fr}+p^{ir}\right)a^{ir}+2(\alpha^{fr}+p^{co})a^{co}+2ep_2^{em}-2\alpha^{st}+2p^{ot}-p^{in}\right] + \beta^{st}\left[p^{in}+ep_1^{em}-ep_2^{em}\right]\right\}$$

$$y_1{}^* - y_2{}^* = -\frac{(ep_1^{em}-ep_2^{em})+p^{in}}{2\beta^{fr}(a^{ir}+a^{co})^2} \tag{43.}$$

The corresponding shipping volume in period 1 and 2 are：

$$q_1^* = \left(a^{ir}+a^{co}\right)y_1{}^* \tag{44.}$$

$$q_2^* = \left(a^{ir}+a^{co}\right)y_2{}^* \tag{45.}$$

In addition, the difference between the shipping volumes in the 2 periods is：

$$q_1^* - q_2^* = -\frac{(ep_1^{em}-ep_2^{em})+p^{in}}{2\beta^{fr}(a^{ir}+a^{co})} \tag{46.}$$

This result indicates the volume of raw material purchase in the two period is inversely related with the relationship of the emission cost in these periods. If the price of emission permit is high in the second period, the planner should purchase more in the first period and produce more, to save the high emission cost later.

3.5.3. Situation 3: Raw material inventory, no product inventory

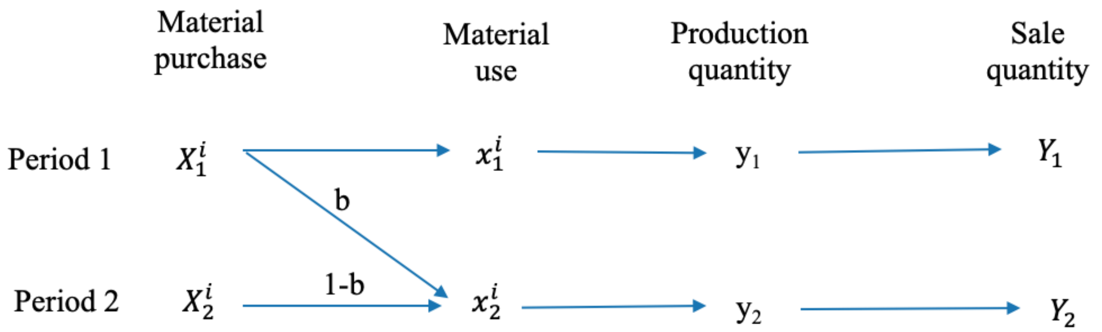


Figure 19 Raw material inventory, no product inventory

When the partial derivatives of total profit $\frac{\partial \Pi(\cdot)}{\partial c} < 0, \frac{\partial \Pi(\cdot)}{\partial b} = 0$, the total profit decreases with c. Therefore, $c = 0$, there will be no product inventory, but there will be some raw material inventories. The condition as below:

$$ep_1^{em} - ep_2^{em} > -\frac{p^{in}\beta^{fr}\left(a^{ir}+a^{co}\right)^2}{\beta^{st}} - p^{in} \quad (47.)$$

$$ep_1^{em} - ep_2^{em} > p^{in}\left(a^{ir} + a^{co}\right) + \frac{\beta^{st}p^{in}}{\beta^{fr}\left(a^{ir} + a^{co}\right)} \quad (48.)$$

$$ep_1^{em} - ep_2^{em} > p^{in}\left(a^{ir} + a^{co}\right) - p^{in} \quad (49.)$$

The first inequality is derived from the condition $\frac{\partial \Pi(\cdot)}{\partial c} < 0$, while the second and third one is derived from $0 < b < 1$. From Eq.48, the right-hand side is positive, indicating the future emission price have to be lower to make raw material inventory possible. From Eq.49, the right-hand side is the difference in the inventory cost between raw material and steel product. It says if the difference in inventory cost is lower than emission cost, then inventory of raw material is better than produce more in period 1. When Eq 48 is satisfied, Eq.47 and Eq.49 is satisfied as well.

The optimal production quantities in two periods are:

$$y_1{}^* = \frac{1}{4\beta^{fr}(a^{ir}+a^{co})^2\beta^{st} + 4{\beta^{st}}^2} \{(a^{ir}+a^{co})^2\beta^{fr}[p^{in}(a^{ir}+a^{co}) - ep_1^{em} + ep_2^{em}] - 2\beta^{st}\left[\left(\alpha^{fr} - \frac{p^{in}}{2} + p^{ir}\right)a^{ir} + \left(\alpha^{fr} - \frac{p^{in}}{2} + p^{co}\right)a^{co} + ep_1^{em} + p^{ot} - \alpha^{st}\right]\} \tag{50.}$$

$$y_2{}^* = \frac{1}{4\beta^{fr}(a^{ir}+a^{co})^2\beta^{st} + 4{\beta^{st}}^2} \{-(a^{ir}+a^{co})^2\beta^{fr}[p^{in}(a^{ir}+a^{co}) - ep_1^{em} + ep_2^{em}] - 2\beta^{st}[\left(\alpha^{fr} + \frac{p^{in}}{2} + p^{ir}\right)a^{ir} + \left(\alpha^{fr} + \frac{p^{in}}{2} + p^{co}\right)a^{co} + ep_2^{em} + p^{ot} - \alpha^{st}]\} \tag{51.}$$

The corresponding shipping volume in two periods are:

$$q_1^* = (a^{ir}+a^{co})(y_1{}^* + b^* y_2{}^*) \tag{52.}$$

$$q_2^* = (a^{ir}+a^{co})(1-b^*)y_2{}^* \tag{53.}$$

In addition, the difference between the shipping volumes in the 2 periods is：

$$q_1^* - q_2^* = -\frac{p^{in}}{2\beta^{fr}} \tag{54.}$$

It is worth noting that, in this case, the difference between the shipping volumes in period 1 and period 2 is fixed and does not change with the difference in emission allowance price in the two periods.

Chapter 4

4. Simulation

4.1.Model settings

This chapter provides the simulation result of the model. Data used in simulation is listed in the table below:

Table 8 Data used in simulation

Description		Parameter	Value	Unit
Steel	demand function constant	α^{st}	830	USD/ton
	demand function elasticity	β^{st}	0.11	USD/million ton per month
Iron ore	iron ore coefficient	a^{ir}	1.4	USD/ton
	iron ore price	p^{ir}	100	USD/ton
Coking coal	coking coal coefficient	a^{co}	1.1	USD/ton
	coking coal price	p^{co}	200	USD/ton
Other inputs	other inputs	p^{ot}	268	USD/ton
Emission allowance	emission factor	e	2.1	ton CO2e/ton steel
	emission allowance price 1	p_1^{em}	20	USD/ton CO2e
	emission allowance price 2	p_2^{em}	20±10	USD/ton CO2e
Freight rate	freight rate constant	α^{fr}	-19	USD/ton
	freight rate elasticity	β^{fr}	0.18	USD/million ton per month
Inventory fee	inventory fee	p^{in}	1	USD/ton

The research conducted a simulation for the Chinese steel market. The steel demand function is derived from empirical research on China's steel price and its demand from 1981 to 2007

(Menggang, 2011). The coefficients of iron ore and coking coal and the prices of other inputs are derived from the regression analysis in Chapter 2. Iron ore and coking coal prices are taken from average prices for the period 2010-2020. The emission factor is consistent with the emission factor of steel production issued by Worldsteel (WorldsteelAssociation, 2021a). The current price of emission allowance is 20USD/ton, which is consistent with the medium-scenario in the IPCC report. In this scenario, 20USD is the average emission reduction cost of the industry without economic losses (Edenhofer et al., 2014). For the supply function of freight rate, due to the lack of existed empirical studies or reports, this study uses the voyage rate of Capesize from Brazil to China and iron ore import volume during 2015-2017 to estimate the supply function. Inventory fee is in line with the average dry bulk storage fee at several large ports in China (GACC, 2022).

When there is a carbon futures market, if the expected future demand for emission allowance is higher than the supply, people will buy carbon futures, which will push up the carbon futures price. For example, in 2021, the market expects a gradual recovery of industrial production from Covid-19, and the increase in the demand for emission allowance causes futures prices to increase. When the expected supply is higher, carbon futures will move in opposite direction. For example, during the financial crisis and the European debt crisis, industrial production capacity declined, many emission allowances were not used. The changes in market expectation may also be due to policy changes, such as modifying the cap of emission allowance and introducing a mechanism to withdraw emission allowances. Regional confrontations can also have a huge impact on the price of emission allowance. For example, the conflict between Russia and Ukraine in 2022 leads to the concern over the cut-off of natural gas supply in Europe, indirectly cause the decline of carbon futures prices. These economic, policy, and political influences may present opportunities as well as significant risks to steel production. Steel producers can estimate the price of emission allowance for the next period according to the carbon futures market or hedge the emission allowance through the futures market, and then adjust the production plan to maximize profits.

In this study, we name the difference between the spot price of current period and futures price as the "basis" which is the spot price minus the future price. According to the historical price difference between EU carbon futures and its spot market, the basis can fluctuate about 2-5 euros. Therefore, the study sets the futures basis from -10 USD to 10 USD. A negative number indicate that the future price is higher than the spot price. In the simulation of steel production, raw material transportation, freight and freight revenue in the 2 period are different basis. The results are shown next.

4.2.Impacts of carbon futures on steel production and emission

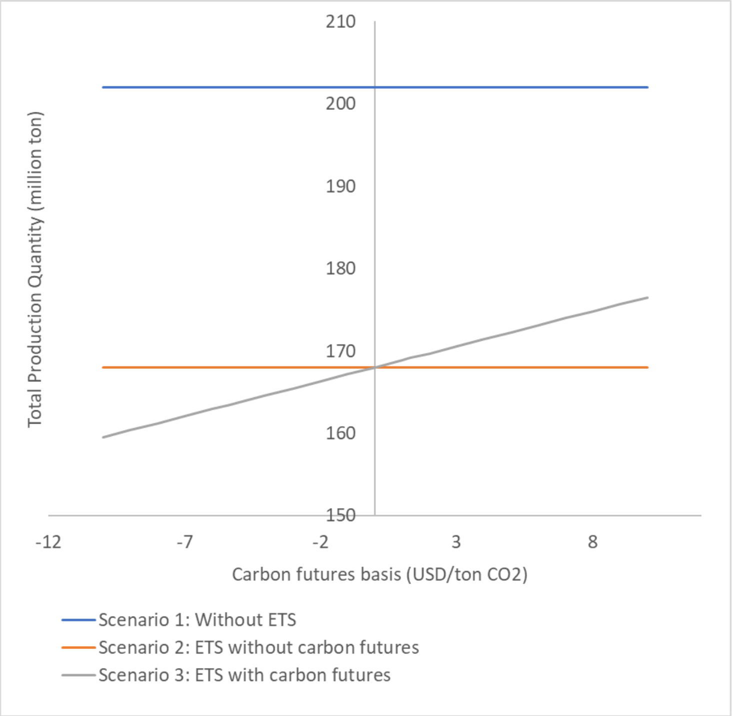


Figure 20 Total production under different carbon futures basis

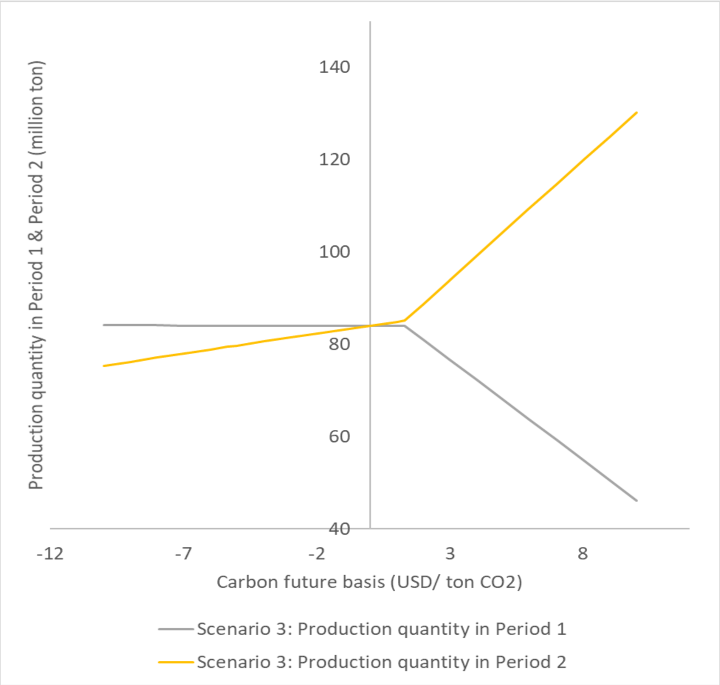


Figure 21 Production for each period under different carbon futures basis

Figure 20 presents the total production under different carbon futures basis. The total production in Scenario 1 is higher than that in Scenario 3, which reflects that the introduction of ETS has a depressing effect on steel production in short term. Comparing Scenario 2 and Scenario 3, we can see that the carbon futures market will have an impact on steel production. As the carbon futures price decreases, from left to right, the total steel production increases gradually in Scenario 3. Figure 21 presents the production for each period when there is a carbon futures market. When the basis is lower than the threshold, the production difference expands but not to a large extent, because more product inventory will lead to greater transportation demand in period 1, the gradually rising marginal cost of freight rate restricts the increase in product inventory. When the positive basis exceeds the threshold, the production difference expands. Due to raw material inventories, more production in period 2 is no longer affected by the increase in the marginal cost of freight, but the elasticity of demand for steel constrains the increase in period 2 production.

Since the demand elasticity of steel is smaller than the elasticity of freight demand in this simulation, the output difference on the right side is larger. The production in period 1 decreases as the basis increases, and the production in period 2 increases as the basis increases. It suggests that a higher spot price (or low futures price) of emission allowance can significantly decreases the production in the current period, because producers can take the advantage of the lower futures price to produce more steels in period 2.

From the linear relationship between production and emissions, although high carbon futures prices can promote both production and emissions in period 1, the effect is not significant as its inhibitory effects on period 2 and total emissions.

4.3. Carbon futures impact on shipping volume and freight rate

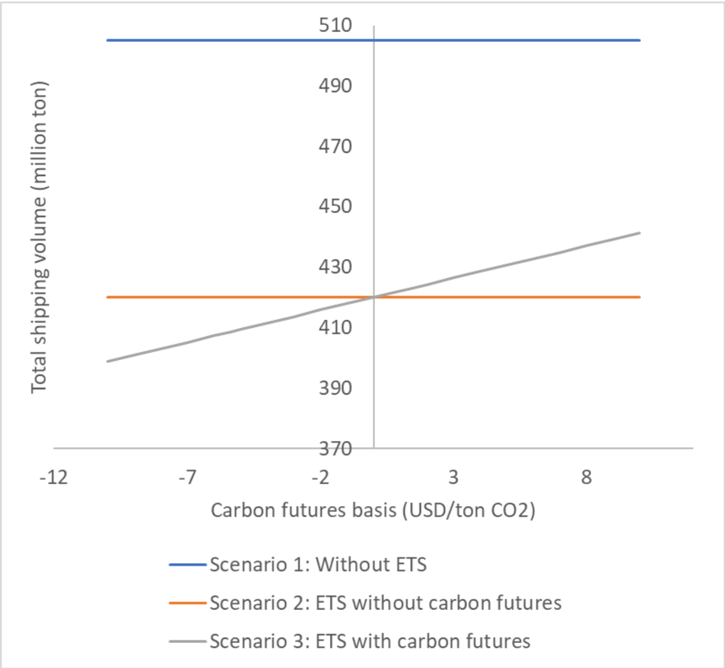


Figure 22 Total shipping volume under different carbon futures basis

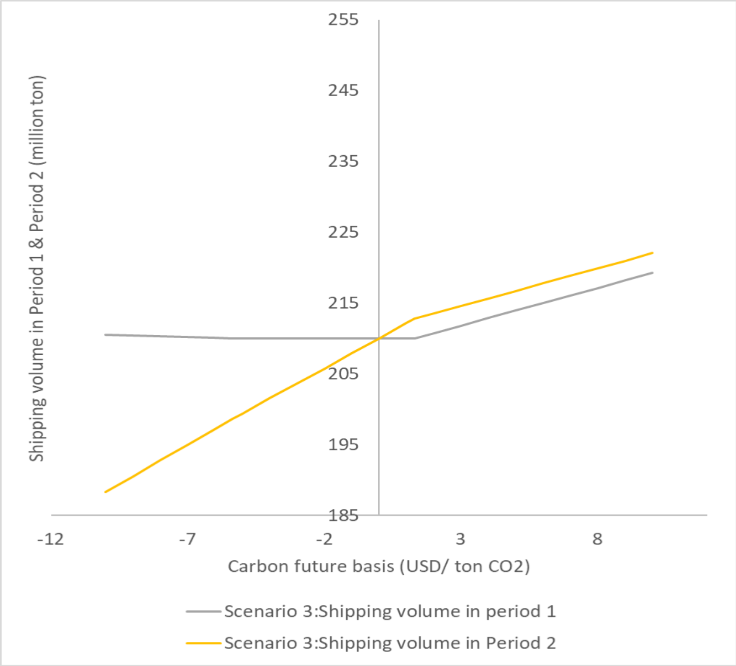


Figure 23 Shipping volume for each period under different carbon futures basis

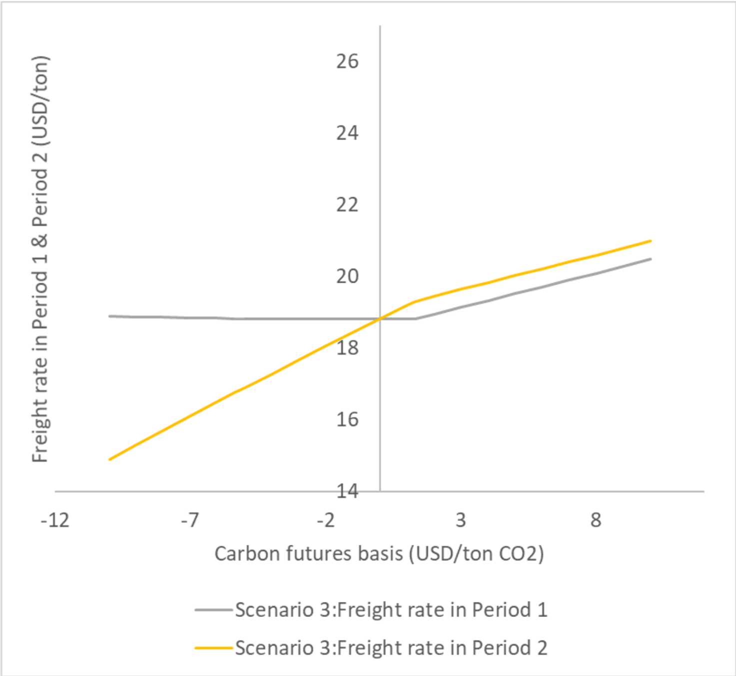


Figure 24 Freight rate for each period under different carbon futures basis

According to the steel production plan, the total raw material shipments are simulated in the Figure 22. With the carbon futures price is much bigger than the spot price (on the most left side), the shipping volume in first period is much higher than that in the second period, indicating the shifting of steel production from period two to period one, can avoid the high emission cost in period 2. The shipments of raw material in each period and their freight rates are simulated in Figure 23 and Figure 24. The freight rate in period 1 is also much higher than that in period 2 in Figure 24. With the decrease of futures price, the incentive for producing more in the period 1 decreases, which narrows the gap between the shipping volumes and freight rates between the two periods. When the future price is equal to the spot rate (the basis =0), the shipping volume and freight rates of the two periods are the same. If the futures price is much lower, the shipping volume and freight rate in period 2 can be higher than that in period 1, as more products can be produced in this period when emission cost is low.

To sum up, the carbon futures price can have negative impacts on total shipping volume. It is worth noting that the impact of negative and positive carbon futures basis on the shipping market is asymmetric. From left to right, when the basis is lower than the threshold, the reduction in the futures price can narrow the gap between the two periods. After that, further decrease of carbon futures price can increase the volume and freight rate of both periods, as it can reduce the steel production cost and increase the output level.

4.4.Carbon futures impact on shipping revenue

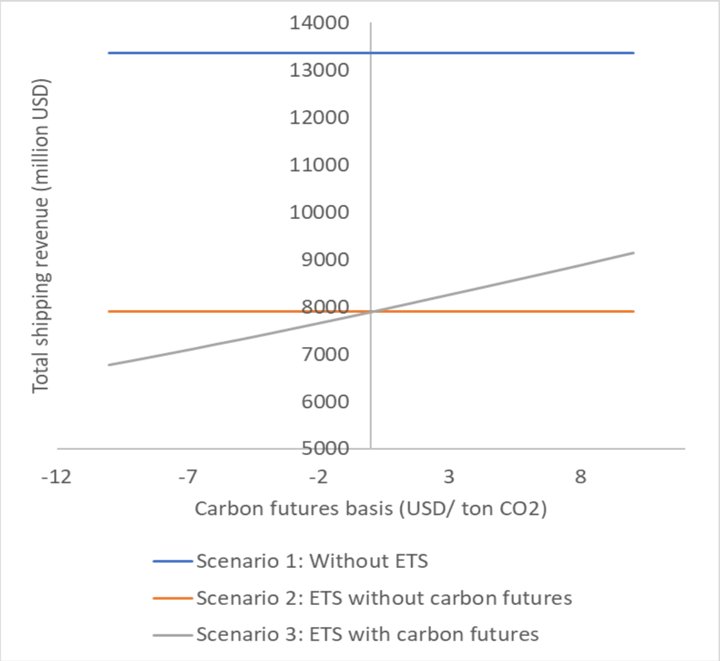


Figure 25 Total shipping revenue under different carbon futures basis

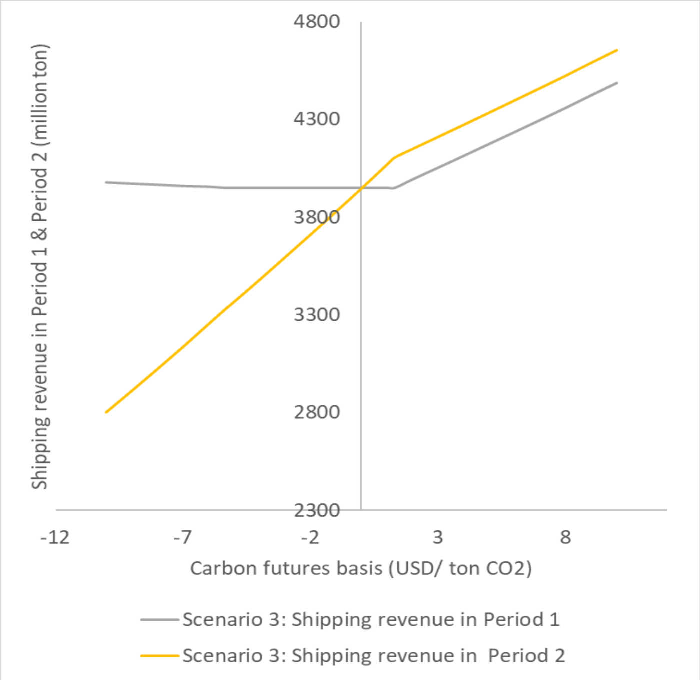


Figure 26 Shipping revenue for each period under different carbon future basis

According to Figure 25 and 26, the change of revenue of dry bulk shipping with the basis of carbon future is consistent with that in shipping volume and freight rate. When the futures price is really high, the decrease of carbon future can narrow the gap between the two period. When the basis is over the threshold, the further increase of the basis will increase the shipments in both periods. Therefore, the revenue will increase in both periods.

Chapter 5

5. Conclusions and Suggestions for future research

As steel industry is a major user of iron ore and coal, it is a major contributor to the global CO_2 emission, and also a major customer for the world dry bulk shipping services. Therefore, this study taking steel industry for a case study, (1) analyses the relationship of steel price with that of the raw materials including iron ore and coke, and bulk freight rate; (2) establishes a two-period short-term model to explore the indirect impacts of carbon futures on production planning of steel plant and its impact on shipping volume and freight rate.

In Chapter 2, a regression analysis is applied to analyze the steel prices of China, Japan and Europe with their respective raw material prices and freight rate. The regression model verifies that there is a very significant linear relationship between iron ore price, coking coal price, freight price and steel price. The coefficient of coking coal is very close to the input and output ratio in steel production especially before Covid-19. The fluctuation in steel price is greater than raw material price fluctuation during the pandemic. It is worth noting that the iron ore price fluctuation is smaller than price fluctuations of coking coal and the freight rate. In the future study, detailed data can be used for further study of the causes.

In terms of academic contribution, this statistic studies the linear coefficient between input including freight and steel price, which fills the research gap. Statistical results confirmed that the impact of freight on steel prices is significant, and it is worth noting that in different regions, the coefficient of freight rate is different. The coefficient of Japan and Northern Europe is more than twice that of China. It is possible that smaller shipping volumes and longer coastal shipping result in higher freight rates. In future research, the statistical model can be improved to considering mutual impacts of steel production countries and time-series properties of the data.

In Chapter 3, a two-period short-term model is established to study the possible impact of carbon futures on the production plan of the steel plants from raw material purchasing to the final sales of the steel products. The objective of the planner is to maximize the total profit of the two periods for given market demand of the steel and market supply of the dry bulk shipping fleet, by determining the best production quantity of the two period, and the quantity of inventory of raw material and steel product. The results show that when the market demand of steel remains unchanged, high carbon futures prices can limit the total steel production, and correspondingly, reducing the emissions from steel production. Maintaining high carbon futures prices will benefit the steel industry's transition to low carbon. For policy makers, according to the conclusion of the model, by moderately relaxing and tightening the policies on emission allowance for the steel industry, can help the steel industry to achieve a balance between supply and demand and emission reduction.

In terms of academic contribution, this study bridges the research gap of indirect impact of ETS on shipping. The results show that if the dry bulk shipping supply remains fixed in the short term, high carbon futures prices will reduce shipping volume and shipping freight rate. When the carbon futures price is high enough, producers will produce more in period one for sale in period two. This can increase shipping demand and freight rate in period 1 and reducing shipping volume and freight rate in period 2. In practice, shipping companies may consider using the information from carbon futures to conduct cross-variety hedging on freight rate or adjust the sailing speed and capacity to cope with the reduced shipping demand in period 2. When futures price is low enough, producers will balance the raw material inventory to minimize the overall freight cost. As the price of carbon futures decreases, the shipping volume and freight revenue in both periods can increase simultaneously. When the basis fluctuates within a certain range, carbon futures have no effect on the shipping volume and shipping revenue in period 1. It is also worth noting that the model results suggest that the impact of carbon futures basis on shipping is asymmetric. This model optimizes the production plan of the steel industry when there is carbon futures market. In summary, it provides a reference for shipping companies to adjust shipping capacity based on carbon futures in the short term.

Although the model is based on the steel industry as an example, it is also applicable to some other industries, such as paper making, coal and natural gas-based power generation, and other metal melting industries. It also has some limitations. For example, this study does not use statistical data to test the model, which can be expanded in future study. This short-term model assumes the same demand function in the steel market, and fixed supply in dry-bulk shipping. The competition among the major steel producers may result in the change of demand function in different countries. Also, for long-term analysis, it is necessary to consider the responses of the dry bulk carriers to the demand change. This can be considered in the future study.

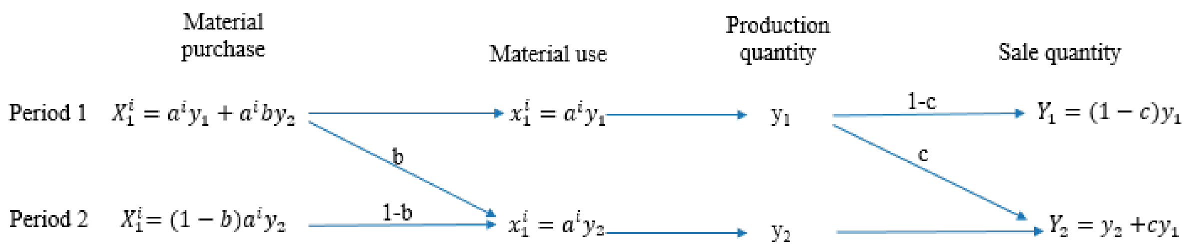
Appendix A

General solution for two-period optimization model

Subject to Leontief production function, the parameters satisfied the conditions as below:

$$X_1^i + X_2^i = x_1^i + x_2^i = a^i y_1 + a^i y_2 = a^i Y_1 + a^i Y_2$$

Consider all variables can represented by y_1 and y_2. b $(0 < b < 1)$ is introduced to present the percentage of material use in period 2 that purchased in period 1. c $(0 < c < 1)$ is introduced to present the percentage of produced products in period in that used for selling in period 2.



The problem of the planer is to maximize the total profit, i.e.,

$$\begin{aligned}\underset{b,c,y_1,y_2}{\text{Max}}\quad \Pi = {} & [\alpha^{st} - \beta^{st}(1-c)y_1](1-c)y_1 + [\alpha^{st} - \beta^{st}(y_2 + cy_1)](y_2 + cy_1) \\ & + (E_1^f - ey_1)p_1^{em} + (E_2^f - ey_2)p_2^{em} - p^{ir}[\mathrm{a}^{ir}(y_1 + y_2)] \\ & - p^{co}[\mathrm{a}^{co}(y_1 + y_2)] - p^{ot}(y_1 + y_2) - \alpha^{fr}[(\mathrm{a}^{ir} + \mathrm{a}^{co})(y_1 + y_2)] \\ & - \beta^{fr}\{[(\mathrm{a}^{ir} + \mathrm{a}^{co})(y_1 + \mathrm{b}y_2)]^2 + [(\mathrm{a}^{ir} + \mathrm{a}^{co})(1-b)y_2]^2\} \\ & - p^{in}[(\mathrm{a}^{ir} + \mathrm{a}^{co})\mathrm{b}y_2 + cy_1] - 2c^c\end{aligned}$$

$s.t.$

$$0 \le b \le 1$$

$$0 \le c \le 1$$

$$y_1 > 0$$

$$y_2 > 0$$

It can be inferred that in the two-period optimization model, the decision variables of steel production are b, c, y_1, y_2. The total profit changes with these four variables. Take the partial derivative of the profit function:

$$\frac{\partial \Pi(\cdot)}{\partial b} = -\beta^{fr}[2\left(\mathrm{a}^{ir} + \mathrm{a}^{co}\right)^2 (y_1 + \mathrm{b}y_2)y_2 - 2\left(\mathrm{a}^{ir} + \mathrm{a}^{co}\right)^2 (1-b){y_2}^2] - p^{in}\left(\mathrm{a}^{ir} + \mathrm{a}^{co}\right)y_2$$

$$\frac{\partial \Pi(\cdot)}{\partial c} = \beta^{st}{y_1}^2(1-c) - [\alpha^{st} - \beta^{st}(1-c)y_1]y_1 - \beta^{st}y_1(y_1 c + y_2) + [\alpha^{st} - \beta^{st}(\mathrm{c}y_1 + y_2)]y_1 - p^{in}y_1$$

$$\frac{\partial \Pi(\cdot)}{\partial y_1} = -\beta^{st}(1-c)^2 y_1 + [\alpha^{st} - \beta^{st}(1-c)y_1](1-c) - \beta^{st}c(y_1 c + y_2) + [\alpha^{st} - \beta^{st}(\mathrm{c}y_1 + y_2)]c - ep_1^{em} - p^{ir}a^{ir} - p^{co}a^{co} - p^{ot} - \alpha^{fr}\left(\mathrm{a}^{ir} + \mathrm{a}^{co}\right) - 2\beta^{fr}\left(\mathrm{a}^{ir} + \mathrm{a}^{co}\right)^2 (y_1 + \mathrm{b}y_2) - p^{in}c$$

$$\frac{\partial \Pi(\cdot)}{\partial y_2} = -2\beta^{st}(y_1 c + y_2) + \alpha^{st} - ep_2^{em} - p^{ir}a^{ir} - p^{co}a^{co} - p^{ot} - \alpha^{fr}\left(\mathrm{a}^{ir} + \mathrm{a}^{co}\right) - 2\beta^{fr}[\left(\mathrm{a}^{ir} + \mathrm{a}^{co}\right)^2 (y_1 + \mathrm{b}y_2)b + \left(\mathrm{a}^{ir} + \mathrm{a}^{co}\right)^2 (1-b)^2 y_2] - p^{in}\left(\mathrm{a}^{ir} + \mathrm{a}^{co}\right)b$$

When $\frac{\partial \Pi(\cdot)}{\partial b} = 0, \frac{\partial \Pi(\cdot)}{\partial c} = 0, \frac{\partial \Pi(\cdot)}{\partial y_1} = 0, \frac{\partial \Pi(\cdot)}{\partial y_2} = 0$, the total profit can be maximized. However, the solution of this equation does not meet the conditions, which means when profit is maximized, raw material inventory and product inventory do not exist at the same time. Therefore, the equation needs to be solved according to the boundary conditions of the variables.

1）No material inventory, no product inventory

When there is no material and product inventory,

$$\frac{\partial \Pi(\cdot)}{\partial y_1} = 0$$

$$\frac{\partial \Pi(\cdot)}{\partial y_2} = 0$$

$$\frac{\partial \Pi(\cdot)}{\partial b} < 0$$

$$\frac{\partial \Pi(\cdot)}{\partial c} < 0$$

$$b = c = 0$$

The equations can be solved as:

$$y_1{}^* = \frac{\alpha^{st} - ep_1^{em} - p^{ot} - p^{ir}a^{ir} - p^{co}a^{co} - \alpha^{fr}\left(a^{ir} + a^{co}\right)}{2\beta^{fr}(a^{ir} + a^{co})^2 + 2\beta^{st}}$$

$$y_2{}^* = \frac{\alpha^{st} - ep_2^{em} - p^{ot} - p^{ir}a^{ir} - p^{co}a^{co} - \alpha^{fr}\left(a^{ir} + a^{co}\right)}{2\beta^{fr}(a^{ir} + a^{co})^2 + 2\beta^{st}}$$

$$b = c = 0$$

$where$

$$-\frac{p^{in}\beta^{fr}\left(a^{ir}+a^{co}\right)^2}{\beta^{st}}-p^{in}<ep_1^{em}-ep_2^{em}<p^{in}\left(a^{ir}+a^{co}\right)+\frac{\beta^{st}p^{in}}{\beta^{fr}(a^{ir}+a^{co})}$$

$$\alpha^{st}-ep_1^{em}-p^{ot}-p^{ir}a^{ir}-p^{co}a^{co}-\alpha^{fr}\left(a^{ir}+a^{co}\right)>0$$

$$\alpha^{st}-ep_2^{em}-p^{ot}-p^{ir}a^{ir}-p^{co}a^{co}-\alpha^{fr}\left(a^{ir}+a^{co}\right)>0$$

The corresponding shipping volume in period 1 is：

$$q_1^*=\left(a^{ir}+a^{co}\right)y_{11}{}^*=\frac{\alpha^{st}-ep_1^{em}-p^{ot}-p^{ir}a^{ir}-p^{co}a^{co}-\alpha^{fr}\left(a^{ir}+a^{co}\right)}{2\beta^{fr}(a^{ir}+a^{co})+2\beta^{st}/(a^{ir}+a^{co})}$$

The corresponding shipping volume in period 2 is：

$$q_2^*=\left(a^{ir}+a^{co}\right)y_{22}{}^*=\frac{\alpha^{st}-ep_2^{em}-p^{ot}-p^{ir}a^{ir}-p^{co}a^{co}-\alpha^{fr}\left(a^{ir}+a^{co}\right)}{2\beta^{fr}(a^{ir}+a^{co})+2\beta^{st}/(a^{ir}+a^{co})}$$

And：

$$q_1^*-q_2^*=-\frac{\left(a^{ir}+a^{co}\right)(ep_1^{em}-ep_2^{em})}{2\beta^{fr}(a^{ir}+a^{co})^2+2\beta^{st}}$$

2）No material inventory

When there is no material inventory

$$\frac{\partial \Pi(\cdot)}{\partial c}=0$$

$$\frac{\partial \Pi(\cdot)}{\partial y_1}=0$$

$$\frac{\partial \Pi(\cdot)}{\partial y_2}=0$$

$$\frac{\partial \Pi(\cdot)}{\partial b} < 0$$

$$b = 0$$

The equations can be solved as:

$$y_1{}^* = \frac{1}{4\beta^{fr}(a^{ir} + a^{co})^2\beta^{st} + 4\beta^{st^2}}\Big\{\big(a^{ir} + a^{co}\big)^2\beta^{fr}p^{in}$$

$$- \beta^{st}\Big[2\big(\alpha^{fr} + p^{ir}\big)a^{ir} + 2(\alpha^{fr} + p^{co})a^{co} - p^{in} + ep_1^{em} + ep_2^{em} + 2\alpha^{st}$$

$$- 2p^{ot}\Big]\Big\}$$

$$+ \frac{1}{4\beta^{fr}(a^{ir} + a^{co})^2\beta^{st}}\Big\{-\big(a^{ir} + a^{co}\big)^2\beta^{fr}p^{in} - \beta^{st}\Big[p^{in} + ep_1^{em} - ep_2^{em}\Big]\Big\}$$

$$= \frac{1}{4\beta^{fr}(a^{ir} + a^{co})^2(\beta^{fr}(a^{ir} + a^{co})^2 + \beta^{st})}\Big\{-\big(a^{ir} + a^{co}\big)^2\beta^{fr}\Big[2\big(\alpha^{fr}$$

$$+ p^{ir}\big)a^{ir} + 2(\alpha^{fr} + p^{co})a^{co} + 2ep_1^{em} - 2\alpha^{st} + 2p^{ot} + p^{in}\Big]$$

$$- \beta^{st}\Big[p^{in} + ep_1^{em} - ep_2^{em}\Big]\Big\}$$

$$y_2{}^* = \frac{1}{4\beta^{fr}(a^{ir} + a^{co})^2(\beta^{fr}(a^{ir} + a^{co})^2 + \beta^{st})}\Big\{-\big(a^{ir} + a^{co}\big)^2\beta^{fr}\Big[2\big(\alpha^{fr} + p^{ir}\big)a^{ir}$$

$$+ 2(\alpha^{fr} + p^{co})a^{co} + 2ep_2^{em} - 2\alpha^{st} + 2p^{ot} - p^{in}\Big]$$

$$+ \beta^{st}\Big[p^{in} + ep_1^{em} - ep_2^{em}\Big]\Big\}$$

$$c^* = \Big\{\Big[\beta^{fr}\big(a^{ir} + a^{co}\big)^2 + \beta^{st}\Big]\Big\{p^{in}\big(a^{ir} + a^{co}\big)^2\beta^{fr} + \beta^{st}\Big[p^{in} + \Big(ep_1^{em} - ep_2^{em}\Big)e\Big]\Big\}\Big\}$$

$$/\{\big(a^{ir} + a^{co}\big)^2\beta^{fr}[2\big(\alpha^{fr} + p^{ir}\big)a^{ir} + 2(\alpha^{fr} + p^{co})a^{co} + 2ep_1^{em} - 2\alpha^{st}$$

$$+ 2p^{ot} + p^{in}] + \beta^{st}\Big[p^{in} + ep_1^{em} - ep_2^{em}\Big]\}$$

$where$

$$ep_1^{em} - ep_2^{em} < p^{in}\left(a^{ir} + a^{co}\right) + \frac{\beta^{st}p^{in}}{\beta^{fr}(a^{ir}+a^{co})}$$

$$ep_1^{em} - ep_2^{em} \leq \frac{-p^{in}\beta^{fr}\left(a^{ir}+a^{co}\right)^2}{\beta^{st}} - p^{in}$$

$$ep_1^{em} - ep_2^{em} < -p^{in}$$

$$\alpha^{st} - ep_1^{em} - p^{ot} - p^{ir}a^{ir} - p^{co}a^{co} - \alpha^{fr}\left(a^{ir} + a^{co}\right) - \frac{p^{in}}{2} > 0$$

$$\alpha^{st} - ep_2^{em} - p^{ot} - p^{ir}a^{ir} - p^{co}a^{co} - \alpha^{fr}\left(a^{ir} + a^{co}\right) - \frac{p^{in}}{2} > 0$$

The corresponding shipping volume in period 1 is：

$$\begin{aligned} q_1^* = \left(a^{ir} + a^{co}\right)y_1{}^* &= \frac{1}{4\beta^{fr}(\alpha^{ir} + p^{co})(\beta^{fr}(a^{ir} + a^{co})^2 + \beta^{st})}\Big\{-\left(a^{ir} + a^{co}\right)^2\beta^{fr}\Big[2\Big(\alpha^{fr} \\ &+ p^{ir}\Big)a^{ir} + 2(\alpha^{fr} + p^{co})a^{co} + 2ep_1^{em} - 2\alpha^{st} + 2p^{ot} + p^{in}\Big] \\ &- \beta^{st}\left[p^{in} + ep_1^{em} - ep_2^{em}\right]\Big\} \end{aligned}$$

The corresponding shipping volume in period 2 is：

$$\begin{aligned} q_2^* = \left(a^{ir} + a^{co}\right)y_2{}^* &= \frac{1}{4\beta^{fr}(\alpha^{ir} + p^{co})(\beta^{fr}(a^{ir} + a^{co})^2 + \beta^{st})}\Big\{-\left(a^{ir} + a^{co}\right)^2\beta^{fr}\Big[2\Big(\alpha^{fr} \\ &+ p^{ir}\Big)a^{ir} + 2(\alpha^{fr} + p^{co})a^{co} + 2ep_2^{em} - 2\alpha^{st} + 2p^{ot} - p^{in}\Big] \\ &+ \beta^{st}\left[p^{in} + ep_1^{em} - ep_2^{em}\right]\Big\} \end{aligned}$$

And：

$$q_1^* - q_2^* = -\frac{(ep_1^{em} - ep_2^{em}) + p^{in}}{2\beta^{fr}(a^{ir} + a^{co})}$$

3）No product inventory

When there is no material inventory,

$$\frac{\partial \Pi(\cdot)}{\partial b} = 0$$

$$\frac{\partial \Pi(\cdot)}{\partial y_1} = 0$$

$$\frac{\partial \Pi(\cdot)}{\partial y_2} = 0$$

$$\frac{\partial \Pi(\cdot)}{\partial c} < 0$$

$$c = 0$$

The equations can be solved as:

$$y_1{}^* = \frac{1}{4\beta^{fr}(a^{ir} + a^{co})^2\beta^{st} + 4\beta^{st^2}}\{\left(a^{ir} + a^{co}\right)^2\beta^{fr}[p^{in}\left(a^{ir} + a^{co}\right) - ep_1^{em} + ep_2^{em}] - 2\beta^{st}\left[\left(\alpha^{fr} - \frac{p^{in}}{2} + p^{ir}\right)a^{ir} + \left(\alpha^{fr} - \frac{p^{in}}{2} + p^{co}\right)a^{co} + ep_1^{em} + p^{ot} - \alpha^{st}\right]\}$$

$$y_2{}^* = \frac{1}{4\beta^{fr}(a^{ir} + a^{co})^2\beta^{st} + 4\beta^{st^2}}\{-\left(a^{ir} + a^{co}\right)^2\beta^{fr}[p^{in}\left(a^{ir} + a^{co}\right) - ep_1^{em} + ep_2^{em}] - 2\beta^{st}[\left(\alpha^{fr} + \frac{p^{in}}{2} + p^{ir}\right)a^{ir} + \left(\alpha^{fr} + \frac{p^{in}}{2} + p^{co}\right)a^{co} + ep_2^{em} + p^{ot} - \alpha^{st}]\}$$

$$b^* = \left\{\left[\beta^{fr}\left(a^{ir} + a^{co}\right)^2 + \beta^{st}\right]\left\{(\alpha^{fr} + p^{co})\left[-a^{co}p^{in} - a^{ir}p^{in} + \left(ep_1^{em} - ep_2^{em}\right)e\right]\beta^{fr} - \beta^{st}p^{in}\right\}\right\}$$

$$/\{(\alpha^{fr} + p^{co})\beta^{fr}\{-\left(a^{ir} + a^{co}\right)^2\beta^{fr}\left[p^{in}\left(a^{ir} + a^{co}\right) - ep_1^{em} + ep_2^{em}\right] - 2\beta^{st}[\left(\alpha^{fr} + \frac{p^{in}}{2} + p^{ir}\right)a^{ir} + \left(\alpha^{fr} + \frac{p^{in}}{2} + p^{co}\right)a^{co} + ep_2^{em} + p^{ot} - \alpha^{st}]\}\}$$

where

$$ep_1^{em} - ep_2^{em} > -\frac{p^{in}\beta^{fr}\left(a^{ir}+a^{co}\right)^2}{\beta^{st}} - p^{in}$$

$$ep_1^{em} - ep_2^{em} \geq \frac{p^{in}\beta^{fr}\left(a^{ir}+a^{co}\right)^2 + \beta^{st}p^{in}}{\beta^{fr}\left(a^{ir}+a^{co}\right)}$$

$$ep_1^{em} - ep_2^{em} > p^{in}\left(a^{ir} + a^{co}\right) - p^{in}$$

$$\alpha^{st} - ep_1^{em} - p^{ot} - p^{ir}a^{ir} - p^{co}a^{co} - \alpha^{fr}\left(a^{ir} + a^{co}\right) + \frac{p^{in}\left(a^{ir} + a^{co}\right)}{2} > 0$$

$$\alpha^{st} - ep_2^{em} - p^{ot} - p^{ir}a^{ir} - p^{co}a^{co} - \alpha^{fr}\left(a^{ir} + a^{co}\right) - \frac{p^{in}\left(a^{ir} + a^{co}\right)}{2} > 0$$

The corresponding shipping volume in period 1 is：

$$q_1^* = \left(a^{ir} + a^{co}\right)({y_1}^* + b^*{y_2}^*)$$

$$= \frac{1}{4\beta^{fr}(\beta^{fr}(a^{ir} + a^{co})^2 + \beta^{st})}\{-\left(a^{ir} + a^{co}\right)\beta^{fr}\left[2\left(\alpha^{fr} + p^{ir} + p^{in}\right)a^{ir} + 2\left(\alpha^{fr} + p^{co} + p^{in}\right)a^{co} + ep_1^{em} + ep_2^{em} - 2\alpha^{st} + 2p^{ot}\right] - \beta^{st}p^{in}\}$$

The corresponding shipping volume in period 2 is：

$$q_2^* = \left(a^{ir} + a^{co}\right)(1 - b^*){y_2}^* = \frac{2\beta^{fr}\left(a^{ir} + a^{co}\right)(y_{11} + y_{12} + y_{22}) + p^{in}}{4\beta^{fr}}$$

$$= \frac{1}{4\beta^{fr}(\beta^{fr}(a^{ir} + a^{co})^2 + \beta^{st})}\left\{-\left(a^{ir} + a^{co}\right)\beta^{fr}\left[2\left(\alpha^{fr} + p^{ir} - p^{in}\right)a^{ir} + 2\left(\alpha^{fr} + p^{co} - p^{in}\right)a^{co} + ep_1^{em} + ep_2^{em} - 2\alpha^{st} + 2p^{ot}\right] + \beta^{st}p^{in}\right\}$$

And：

$$q_1^* - q_2^* = -\frac{p^{in}}{2\beta^{fr}}$$

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