Sustainable Development Research; Vol. 6, No. 1; 2024
ISSN 2690-9898 E-ISSN 2690-9901
https://doi.org/10.30560/sdr.v6n1p10

Trade-Embodied Carbon Emissions in China's Manufacturing Industry Based on the MRIO Model

Tong Lin[1] & Yang Le[1]

[1] School of Management, University of Shanghai for Science and Technology, Shanghai, China

Correspondence: Tong Lin, School of Management, University of Shanghai for Science and Technology, Shanghai, China. Tel: 86-139-7133-1698. E-mail: Naomitl08@163.com

Received: November 1, 2024 Accepted: December 2, 2024 Online Published: December 6, 2024

Abstract

With the rapid development of the economy in China, as early as 2013, China had overtaken the United States as the largest trader of goods. According to the OECD database, since joining the World Trade Organization (WTO), carbon emissions from manufacturing trade have accounted for more than 80% of all sectors in China. Reducing carbon emissions from manufacturing trade can effectively alleviate the carbon emission challenges faced by China. This study constructs a Multi-Regional Input-Output (MRIO) model to estimate the scale of carbon emissions embodied in China's manufacturing trade from 2012 to 2018, and analyzes the differences in carbon emissions among various manufacturing sectors. The results show that between 2012 and 2018, China's manufacturing export trade embodied carbon decreased while import trade embodied carbon increased, with the basic metals sector contributing significantly. Further analysis indicates that the proportion of carbon emissions from intermediate product exports is more than half and is on the rise, while the proportion of direct import of intermediate products and indirect trade energy consumption in the import trade embodied carbon has declined. China, as the "world's factory," has undertaken a large amount of carbon emissions caused by intermediate product trade from developed countries.

Keywords: manufacturing, trade embodied carbon, multi-regional input-output model

1. Introduction

Recently, China's international trade has developed rapidly. In 2013, China became the world's largest trader of goods, with its foreign trade scale ranking first globally (Zhao, 2024). Alongside the continuous and rapid expansion of China's foreign trade scale, environmental pressure issues caused by foreign trade have become increasingly prominent. This is because China's extensive international trade development relies on high-energy-consuming and high-emission production processes, leading to significant consumption of natural resources. Since 1992, the export of manufacturing products has accounted for more than 85% of China's total goods exports(Tao&Tang,2015). In the global manufacturing export market, China's market share has been steadily increasing, and China has rapidly grown into a major global manufacturing product processing and production base with large-scale output and a comprehensive range of categories. The increasing proportion of manufacturing products in China's exports not only exerts pressure on the domestic environment but also draws increasing attention to China in the international community due to carbon emission issues. In July 2021, the European Union proposed the Carbon Border Adjustment Mechanism (CBAM) legislative proposal, aiming to impose carbon taxes on certain imported goods to reduce carbon leakage and protect the environment. The plan will start a transition period from 2023 and fully implement it by 2026. The first batch of industries covered includes cement, electricity, fertilizers, steel, and aluminum, with subsequent coverage extending to other industries. Some scholars have calculated that the implementation of CBAM may increase the cost of China's steel exports to the EU by about 25%(Lv,2023). The manufacturing industry, closely related to CBAM, is the most prominent carbon-emitting industry in China, with China's manufacturing CO2 emissions accounting for 53.27% of the total emissions in 2017(IPCC.2019). As the largest developing country, China's high-carbon emission trend in manufacturing will continue. Manufacturing products occupy an important position in China's trade structure and have a high dependency on the demand of developed economies such as the EU and the United States. The implementation of CBAM will increase the cost of China's high-carbon product exports, and this green trade barrier will have a profound impact on the development of China's manufacturing trade and related industries. As the global climate governance agenda continues to advance, other developed countries may further attempt to introduce similar green trade barrier policies to restrict the development of emerging economies like China.

More and more scholars have begun to explore the issue of carbon emissions in trade.Currently, there are mainly two methods to measure trade-related carbon emissions: the life cycle assessment method and the input-output analysis method. Due to the wide variety of products, it is difficult to analyze each product individually within a limited time using the life cycle assessment method. Moreover, this method requires a high amount of data, and the difficulty and error in accounting for carbon emissions are relatively large, and it lacks analysis of complex interrelationships among multiple entities. The input-output method can analyze trade-related carbon emissions from a macro perspective and focuses on national or regional data, making it a preferred method for analyzing regional trade-related carbon emissions.

(Pachauri & Spreng, 2002) analyzed the energy demand of Indian households based on input-output tables. (Ahmad & Wyckoff, 2003) measured the embodied carbon emissions in global trade from 1990 to 2008 and found that developed countries have transferred more carbon emissions to developing countries through trade than required by the Kyoto Protocol. (Claude, et al., 2005) studied the carbon emissions from energy consumption of Brazilian households, and the results showed that indirect energy demand accounted for a significant proportion. (Mäenpää & Siikavirta, 2007) used input-output models to explore greenhouse gas emissions embodied in Finland's international trade and final consumption. (Qi, et al., 2008) used the input-output method to estimate the embodied carbon in China's import and export trade from 1997 to 2006. (Wiedmann, 2009) considered multi-regional input-output analysis a reliable and relevant method for considering trade-related impacts from a consumption perspective. (Huang, et al., 2010) used the input-output model to measure the embodied carbon of Chinese export products and found that the embodied carbon emissions of export products increased year by year. (Fu & Zhang, 2011) also used the input-output method to estimate and compare the embodied carbon of foreign trade in 16 Chinese manufacturing industries, believing that China's high-carbon emission industries have a comparative advantage. (Wang, 2017) used the input-output model and calculated the CO_2 emissions from consumption of exported, imported, and re-exported products in various industries in China and the United States from 2005 to 2011, indicating that China was a net exporter to the United States between 2005 and 2011.

Looking at the related studies of embodied carbon in domestic and international trade, there are two different measurement methods: one is to measure the direct and indirect carbon emissions embodied in trade volume from the perspective of trade flow. (Yan & Yang, 2010) calculated the embodied carbon in China's foreign trade from 1997 to 2007 and found that the net export embodied carbon emissions amounted to 4894 Gt between 1997 and 2007. (Zhu, 2010) measured the emissions generated by China's export trade activities in 2002 and 2007, and the study showed that the CO2 emissions from China's export trade showed a rapid growth trend, with high-carbon products accounting for a large proportion of China's exports, and high-carbon products have shifted to China's export industry. (Ma & Chen, 2010) measured China's embodied carbon emissions from 2000 to 2009, and the empirical results showed that China maintained a trade surplus in carbon emissions from 2000 to 2009, with high export growth rapidly driving the increase in China's total carbon emissions.

The other category is to measure the domestic embodied carbon emissions caused by foreign final demand from the perspective of final demand. (Fan et al., 2010) believe that final consumption is the root cause of the massive emission of greenhouse gases, and the consumption demand of developed countries has exacerbated this phenomenon. (Wang et al., 2011) used the multi-regional input-output model to analyze the spatial transfer path of embodied CO_2 in China's import and export trade in 2007 and found that most of the products China imported were not for final consumption but for production, and a considerable part of the products produced were for export. Overall, China is emitting CO_2 on behalf of developed countries. (Yan & Zhao, 2014) established a multi-regional input-output model to analyze the consumption-based carbon emissions and carbon spillover effects of various regions, and the study showed that China has always been the largest region for embodied carbon exports, while the United States is the largest region for embodied carbon imports. (Zhang & Peng, 2014) measured 11consumption-side resource and environmental load indicators for 28 developed countries and 12 developing countries (regions) from 1995 to 2009, and compared them with traditional production-side resource and environmental load. The study found that developed countries' consumption-side resource and environmental load is generally higher than their production-side, while the situation is the opposite in developing countries. (Peng et al., 2016) analyzed the impact of external demand on China's energy consumption from 1995 to 2009 and the results showed that developed countries have transferred a large amount of energy consumption to China through import substitution, and the rapid increase in China's external demand energy consumption is mainly due to the export effect of China's intermediate products. (Han et al., 2018) measured and analyzed the consumption-based carbon emissions of the world's major economies (regions) from the perspective of final demand, and found that the trade-related carbon emissions of developing economies like China are mainly to meet the final demand of developed economies, and the trade-related carbon emissions of developing economies are mainly from the manufacturing and energy industries.

Although the two methods yield equal trade-related carbon balances for a country, the "trade-related carbon" measurement method, which calculates the total export embodied carbon from the perspective of trade flow, has the disadvantage of double counting, which can overestimate the results of all countries. With the growth of global intermediate product trade, this method can produce biases. Therefore, this study uses the input-output method to measure the embodied carbon in China's manufacturing import and export trade from the perspective of final demand from 2012 to 2018, and then puts forward targeted suggestions for China's manufacturing industry to reduce emissions. The comparison of CO_2 emissions induced by production and consumption helps clarify and share the mitigation responsibility of China’s manufacturing industry which would be informative for international climate negotiations in the future.

2. Method and Data

2.1 Multi-Regional Input-Output Model

The multi-regional input-output (MRIO) model based on n countries (regions) can be represented as:

$$\begin{pmatrix} Q_{11} & Q_{12} & \cdots & Q_{1n} \\ Q_{21} & Q_{22} & \cdots & Q_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Q_{n1} & Q_{n2} & \cdots & Q_{nn} \end{pmatrix} = \begin{pmatrix} Q_{11} & Q_{12} & \cdots & Q_{1n} \\ Q_{21} & Q_{22} & \cdots & Q_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Q_{n1} & Q_{n2} & \cdots & Q_{nn} \end{pmatrix} \begin{pmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{pmatrix} + \begin{pmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{pmatrix} \quad (1)$$

Equation (1) further represents: $Q = AQ + Y$,which can be derived as $Q = (I - A)^{-1}Y$. Q represents the world total output matrix, $(I - A)^{-1}$ is the Leontief inverse matrix, I where is the identity matrix, and A is the direct consumption coefficient matrix. Y is the final demand vector.

The specific total output of a country (s):

$$Q_s = A_{ss}Q_s + \sum_{r \neq s}^{n} A_{sr}Q_r + Y_{ss} + \sum_{r \neq s}^{n} Y_{sr} \quad (2)$$

After rearranging, we get:

$$Q_s = (I - A_{ss})^{-1}(\sum_{r \neq s}^{n} A_{sr}Q_r + Y_{ss} + \sum_{r \neq s}^{n} Y_{sr}) \quad (3)$$

Among them,

$$Q_r = \sum_{t}^{n} Q_{rt} \quad (4)$$

Substituting equation (4) into (3) yields:

$$\sum_{r \neq s}^{n} A_{sr}Q_r = \sum_{r \neq s}^{n} A_{sr} \sum_{t}^{n} Q_{rt} = \sum_{r \neq s}^{n} A_{sr}Q_{rs} + \sum_{r \neq s}^{n} \sum_{t \neq s}^{n} A_{sr}Q_{rt} \quad (5)$$

Let $L_{ss} = (I - A_{ss})^{-1}$,then the total output of a country (s) can be decomposed into:

$$Q_s = L_{ss} \sum_{r \neq s}^{n} A_{sr}Q_r + L_{ss} \sum_{r \neq s}^{n} \sum_{t \neq s}^{n} A_{sr}Q_{rt} + L_{ss}Y_{ss} + \sum_{r \neq s}^{n} Y_{sr} \quad (6)$$

$L_{ss} \sum_{r \neq s}^{n} A_{sr}Q_r$ is the feedback export; $L_{ss} \sum_{r \neq s}^{n} \sum_{t \neq s}^{n} A_{sr}Q_{rt}$ intermediate product export; $L_{ss}Y_{ss}$ domestic self-sufficiency production; $\sum_{r \neq s}^{n} Y_{sr}$ final product export. Feedback export plus domestic self-sufficiency production is domestic demand production, and intermediate product export plus final product export is foreign demand production.

From this, we can obtain the production of country s to meet the final demand of country t:

$$Q_{st} = L_{ss} \sum_{r \neq s}^{n} A_{sr} Q_{rt} + L_{ss} Y_{ss} \tag{7}$$

$L_{ss} \sum_{r \neq s}^{n} A_{sr} Q_{rt}$ is the production caused by intermediate product exports: intermediate products are exported to a third country, and the third country produces the final product, which is then imported by country t; $L_{ss} Y_{ss}$ is the production caused by final product exports: the final product is directly exported to country t.

Let F_s be the energy intensity matrix of country s, showing the energy consumed per unit of output in the departments of country s, then energy consumption can be written as:

$$E = FLY \tag{8}$$

Expanding it specifically:

$$E = \begin{bmatrix} F_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & F_n \end{bmatrix} \begin{bmatrix} Q_{11} & \cdots & Q_{1n} \\ \vdots & \ddots & \vdots \\ Q_{n1} & \cdots & Q_{nn} \end{bmatrix} = \begin{bmatrix} F_1 Q_{11} & \cdots & F_1 Q_{1n} \\ \vdots & \ddots & \vdots \\ F_n Q_{n1} & \cdots & F_n Q_{nn} \end{bmatrix} \tag{9}$$

Emission Embodied in Export,EEE:

$$EEE_s = F_s \sum_{i \neq s}^{n} Q_{si} \tag{10}$$

Emission Embodied in Import,EEI:

$$EEI_s = F_s \sum_{i \neq s}^{n} Q_{is} \tag{11}$$

Balance of Emission Embodied in Trade,BEET:

$$BEET_s = EEE_s - EEI_s \tag{12}$$

2.2 Data

The multi-regional input-output data used in the article comes from the OECD database released in 2021 (OECD Inter-Country Input-Output (ICIO) Tables 2021 edition), which is a data integration of 36 market economy countries formed by an intergovernmental international economic organization. The article uses the input-output table data from 2000 to 2018 in the OECD 2021 edition as the basis for the study. In addition to the OECD's input-output data, the article also combines other data sources related to specific industries to ensure the comprehensiveness and accuracy of the research. These data sources include the "China Statistical Yearbook," which provides economic operation and statistical data for various industries in China; "China Customs," which provides import and export trade-related information for the study; and the UN Comtrade database, which contains detailed global trade data.

In terms of the manufacturing sector, this article draws on the departmental classification method proposed by (Zhao& Wang, 2014), integrating and categorizing similar departments. This article will follow the OECD table and divide manufacturing into 33 departments, as detailed in Table 1 below.

Table 1. Manufacturing department correspondence table

Manufacturing department correspondence table	
CHN_10T12	Food products, beverages and tobacco
CHN_13T15	Textiles, textile products, leather and footwear
CHN_16	Wood and products of wood and cork
CHN_17T18	Paper products and printing
CHN_19	Coke and refined petroleum products
CHN_20	Chemical and chemical products
CHN_21	Pharmaceuticals, medicinal chemical and botanical products
CHN_22	Rubber and plastics products
CHN_23	Other non-metallic mineral products
CHN_24	Basic metals
CHN_25	Fabricated metal products
CHN_26	Computer, electronic and optical equipment
CHN_27	Electrical equipment
CHN_28	Machinery and equipment, nec
CHN_29	Motor vehicles, trailers and semi-trailers
CHN_30	Other transport equipment
CHN_31T33	Manufacturing nec; repair and installation of machinery and equipment

3. Results and Discussion

3.1 Analysis of the Total and Trend of Embodied Carbon Emissions in China's Manufacturing Industry

According to the calculation results of the multi-regional input-output (MRIO) model, the situation of embodied carbon emissions in China's manufacturing import and export trade from 2012 to 2018 is shown in Figure 1 During this period, the embodied carbon emissions from China's manufacturing export trade have always been higher than those from import trade, showing the characteristics of China as a global manufacturing center.

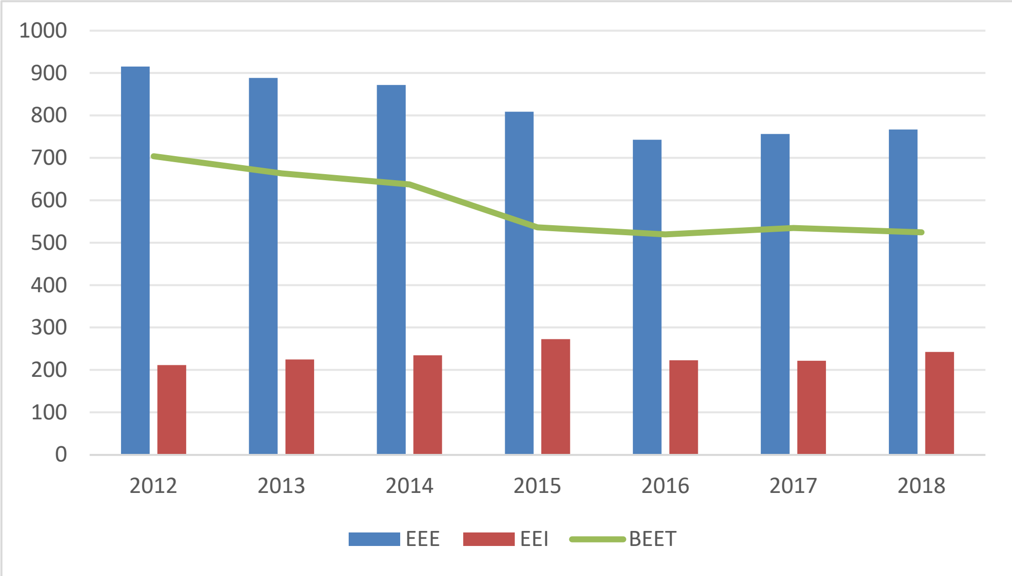

Figure 1. Embodied carbon emissions in Chinese Manufacturing trade (2012-2018)

The embodied carbon emissions from export trade showed a downward trend year by year from 2012 to 2014, but remained at a relatively high level. There was a significant decrease in carbon emissions from 2014 to 2016. In 2015, the Chinese government implemented a series of low-carbon policies, including expanding the pilot of carbon emission trading and establishing a carbon emission trading system. China also actively participated in international climate change negotiations and promoted the establishment of the South-South Climate Cooperation Fund. These measures helped to promote the implementation of domestic emission reduction measures. However, from 2016 to 2018, there was a slight rebound in the embodied carbon emissions from export trade, remaining at about 750 million tons (mt). After 2016, China's economic growth may have driven an increase in energy demand, especially as investment and net exports' share in GDP growth rose, which may have led to the growth of energy-intensive industries and thus increased carbon emissions.

In contrast, the embodied carbon emissions from manufacturing import trade remained relatively stable between 200 and 300mt from 2012 to 2018. Specifically, the embodied carbon emissions from import trade reached a peak of 272mt in 2015. However, in the following years, this figure gradually decreased, reflecting China's efforts to adjust its import structure and promote the introduction of low-carbon products.

Overall, during the study period, China was a net exporter of embodied carbon in manufacturing trade, and the net export trade embodied carbon emissions showed a downward trend, decreasing from 703mt in 2012 to 524mt in 2018. This change indicates that China has gradually reduced its contribution to net carbon emissions in global trade, which is consistent with the country's promotion of sustainable development policies and environmental protection measures.

3.2 Analysis of Embodied Carbon Emissions in China's Manufacturing Industry by Sector

Figure 2 shows based on the calculation of export and import trade embodied carbon emissions in China's manufacturing sectors, the basic metals sector (CHN_24) occupies a significant position in the entire manufacturing industry. From the perspective of exports, the emission proportion of this sector has been increasing year by year, from 45% in 2012 to 55% in 2018. During the study period, almost half of the embodied carbon emissions from China's manufacturing exports came from the exports of the CHN_24 sector, reflecting the importance of this sector in the global supply chain. Secondly, the export products of this sector have a high carbon emission intensity, and the rising proportion of export embodied carbon is also related to the changes in the export structure, reflecting China's production advantages in basic metals.

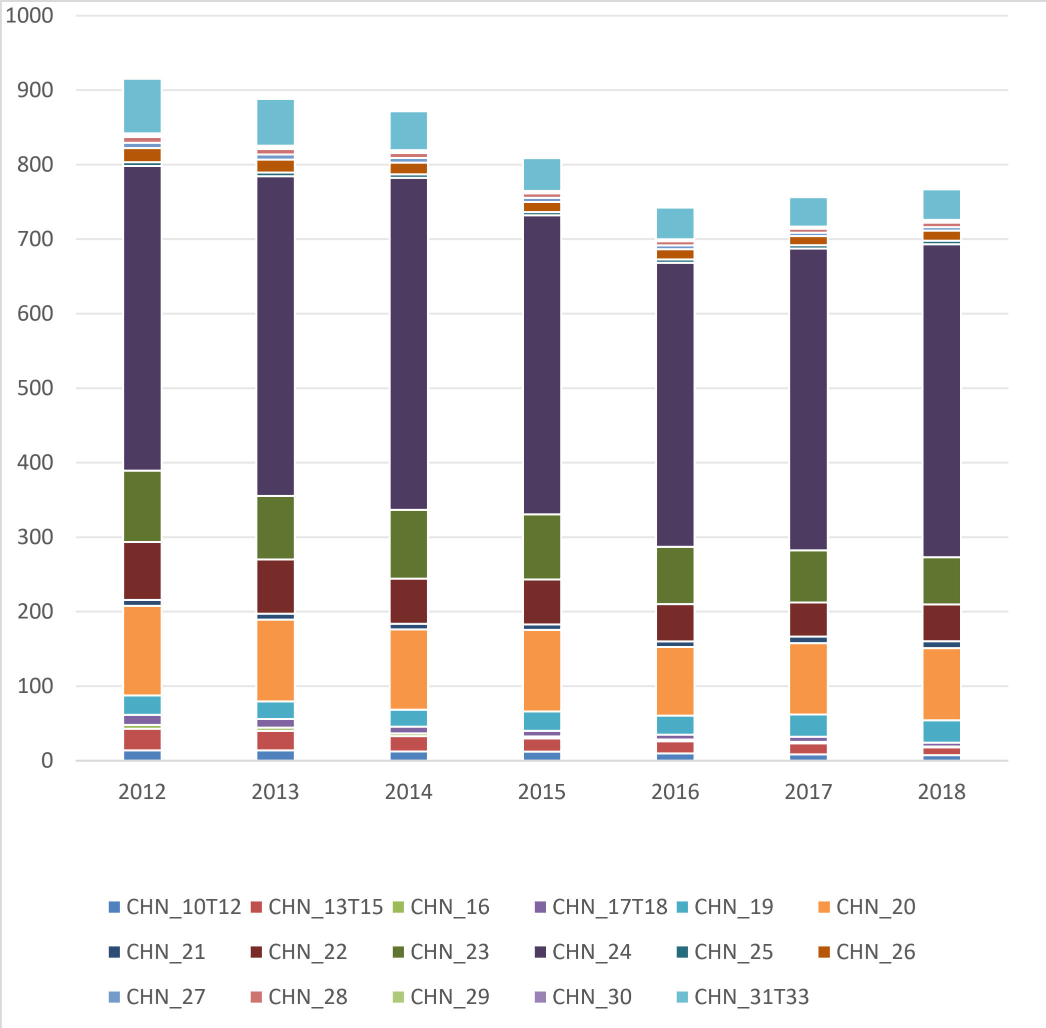

Figure 2. Sectoral embodied carbon in Chinese Manufacturing exports (2012-2018)

Figure 3 shows the CHN_24 sector also has the highest emission proportion in the import side, but import trade embodied carbon proportion has decreased year by year from 51% in 2012 to 46% in 2018. This may be because China may be adjusting its industrial structure, reducing the proportion of high-energy consumption and high-emission industries, and turning to more environmentally friendly and low-carbon industries, thus causing the proportion of the basic metals industry to decrease year by year.

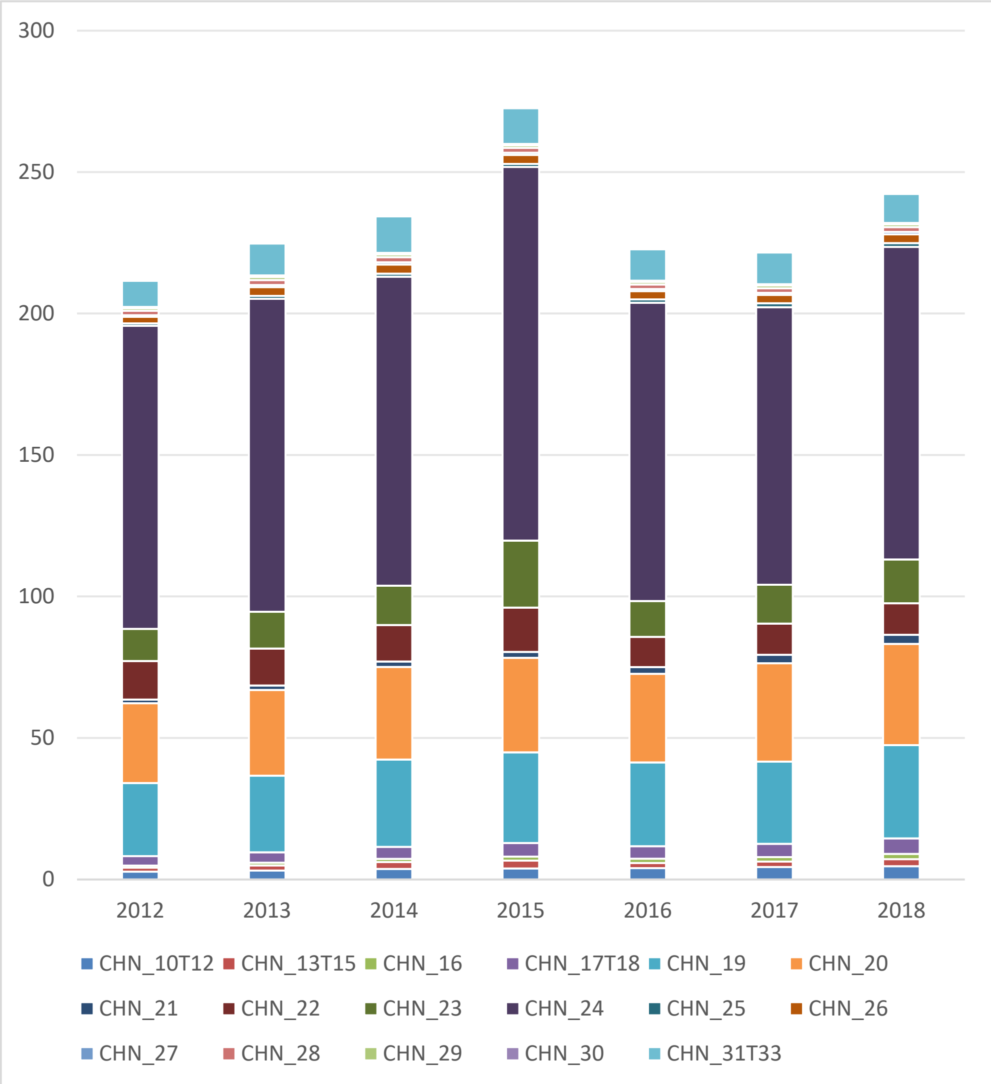

Figure 3. Sectoral embodied carbon in Chinese Manufacturing imports (2012-2018)

Overall, from 2012 to 2018, the export competitiveness of the basic metals sector has increased, and technological progress in this sector has reduced the country's external dependence and improved self-sufficiency.

3.3 Analysis of the Proportion of Intermediate Products in China's Manufacturing Embodied Carbon Emissions

Intermediate products refer to goods that have undergone preliminary processing but have not yet become final products in the production process. They are usually a link in a production chain, used for further processing or assembly to produce final products. Intermediate products can be raw materials, parts, semi-finished products, etc. For example, in automobile production, engines, wheels, and electronic control systems can be considered intermediate products; in food processing, juices, and cans are also intermediate products. The quality and performance of intermediate products directly affect the quality and market competitiveness of the final products.

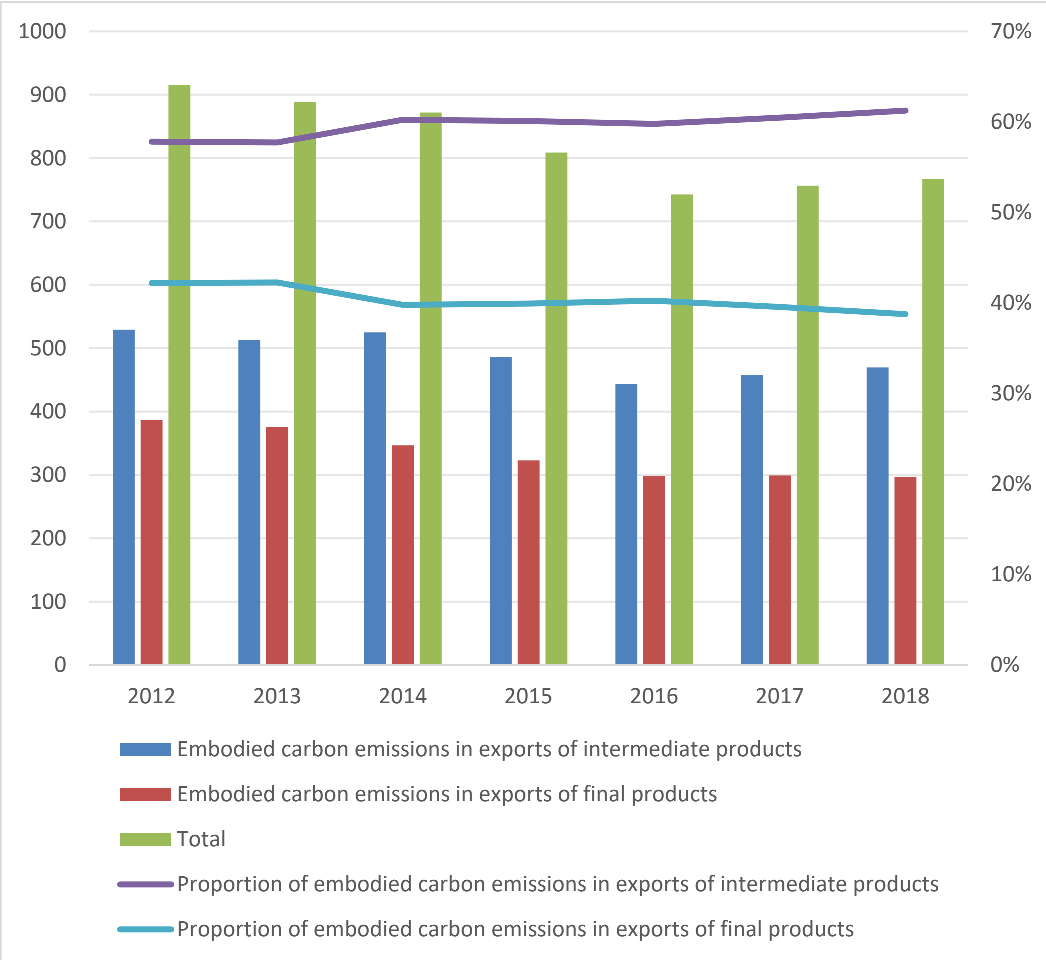

Figure 4. Carbon emission Intensity in Chinese Manufacturing exports (2012-2018)

Assuming country s as the exporting country and country i as the importing country, this paper divides the embodied carbon in trade exports into intermediate product exports and final product exports. Intermediate product exports refer to the emissions caused by exporting intermediate products to a third country, which then produces the final product and imports it into country i. The other part is the carbon emissions caused by the export of final products produced directly to meet the demand of country i.As shown in Figure 4, from 2012 to 2018, the proportion of carbon emissions caused by intermediate product exports in the embodied carbon emissions from Chinese manufacturing exports exceeded 50%, and this proportion has been increasing year by year over time. The high proportion of intermediate products reflects that during the study period, China, as the "world's factory," focused mainly on the production of intermediate products for export. Exports with high carbon emission intensity have led to an overall increase in the proportion of carbon emissions, such as the aforementioned basic metals sector, which is mostly intermediate products. The export of intermediate products involves the transfer of carbon emissions during the product production process. An increase in the export of intermediate products may "transfer" the carbon emissions generated during production in other countries to the exporting country. In other words, although the final consumption may be in other countries, the country producing these intermediate products will bear the responsibility for carbon emissions.

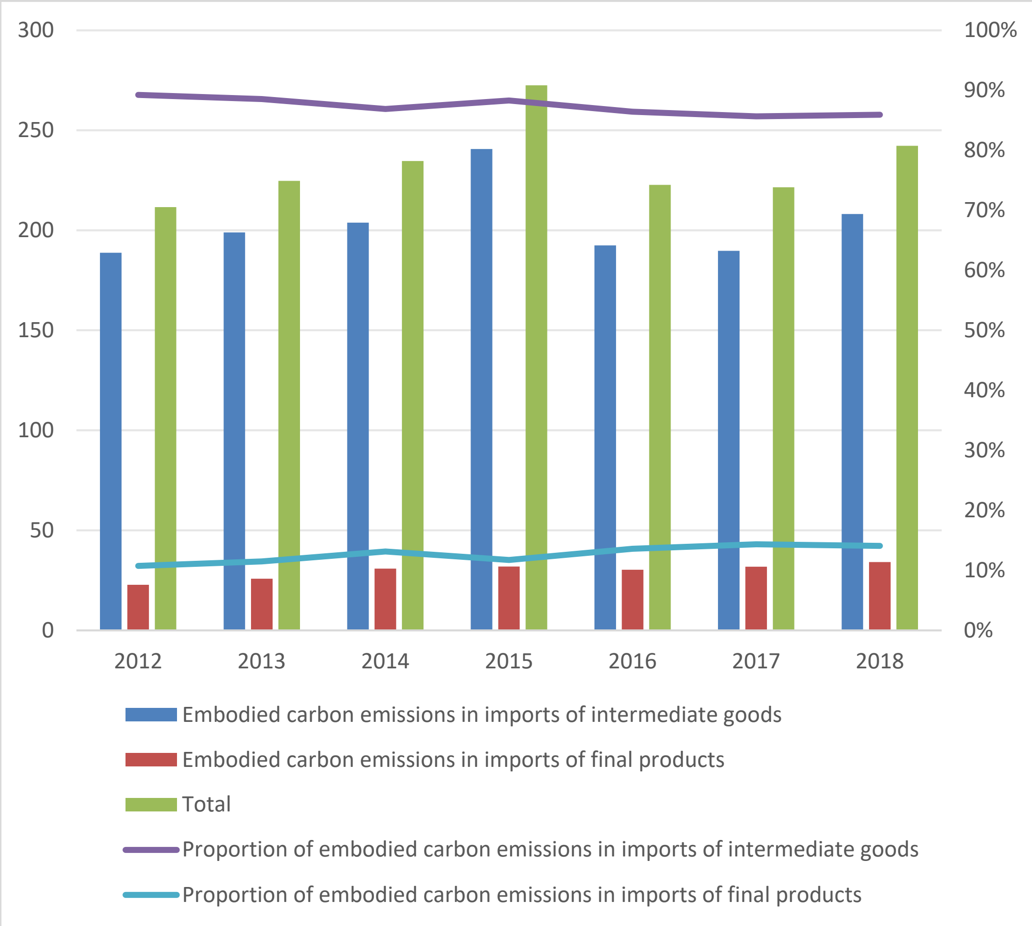

Figure 5. Carbon emission intensity in Chinese Manufacturing imports (2012-2018)

Assuming country s as the exporting country and country i as the importing country, this paper divides the embodied carbon in import trade into direct imports of intermediate products, indirect trade of intermediate products, and direct imports of final products. Direct imports of intermediate products refer to semi-finished goods or components imported by country i for further processing from country s. Indirect trade of intermediate products: indirect imports of intermediate products from a third country, which become part of the final product after processing through multiple countries. Direct imports of final products: country i imports finished consumer goods or use items that do not require further processing. As shown inFigure 5 during the period from 2012 to 2018, the proportion of direct imports of intermediate products has always exceeded 50%. This phenomenon indicates China's position as a manufacturing center in the global value chain, requiring a large number of intermediate products to be imported for processing and assembly. Between 2012 and 2018, the proportion of direct imports of intermediate products experienced a fluctuating trend of decline and then rise, peaking in 2015, followed by a decline again.

Compared with direct imports of intermediate products, the proportion of indirect trade of intermediate products shows a different trend. Between 2012 and 2018, the proportion of indirect trade of intermediate products initially increased, then reached the lowest point in 2015, and then increased again, showing an overall upward trend. During this period, Chinese companies may have optimized supply chain management, reducing costs and risks through indirect trade, leading to an increase in the proportion of indirect trade. As for direct imports of final products, their proportion also showed a trend of increasing and then decreasing, and then increasing again between 2012 and 2018. Overall, direct imports of final products show an upward trend. In general, China is continuously optimizing its import structure and gradually climbing to higher positions in the value chain.

3.4 Analysis of Embodied Carbon Emissions in Chinese Manufacturing Exports by Country

Countries differ in manufacturing technology levels, production efficiency, and energy usage methods, which directly affect embodied carbon emissions. Developed countries may use more advanced technologies and clean energy, thereby reducing the embodied carbon emissions per unit of product, while developing countries may rely on traditional, high-pollution energy sources. Secondly, differences in environmental policies and carbon emission regulations among countries lead to variations in embodied carbon. Some countries may implement strict emission standards, while others may be more lenient. The globalization of manufacturing means that product production often involves cooperation among multiple countries. Therefore, when analyzing trade-related embodied carbon, it is necessary to consider the role of each country in the production chain. For example, a product may undergo processing at different stages in factories in several countries. Alternatively, some countries may primarily import low-carbon products, while others may depend on high-carbon-emitting manufacturing. Thus, analyzing export embodied carbon from a national perspective reveals the carbon responsibility each country bears in global trade, which is very necessary.

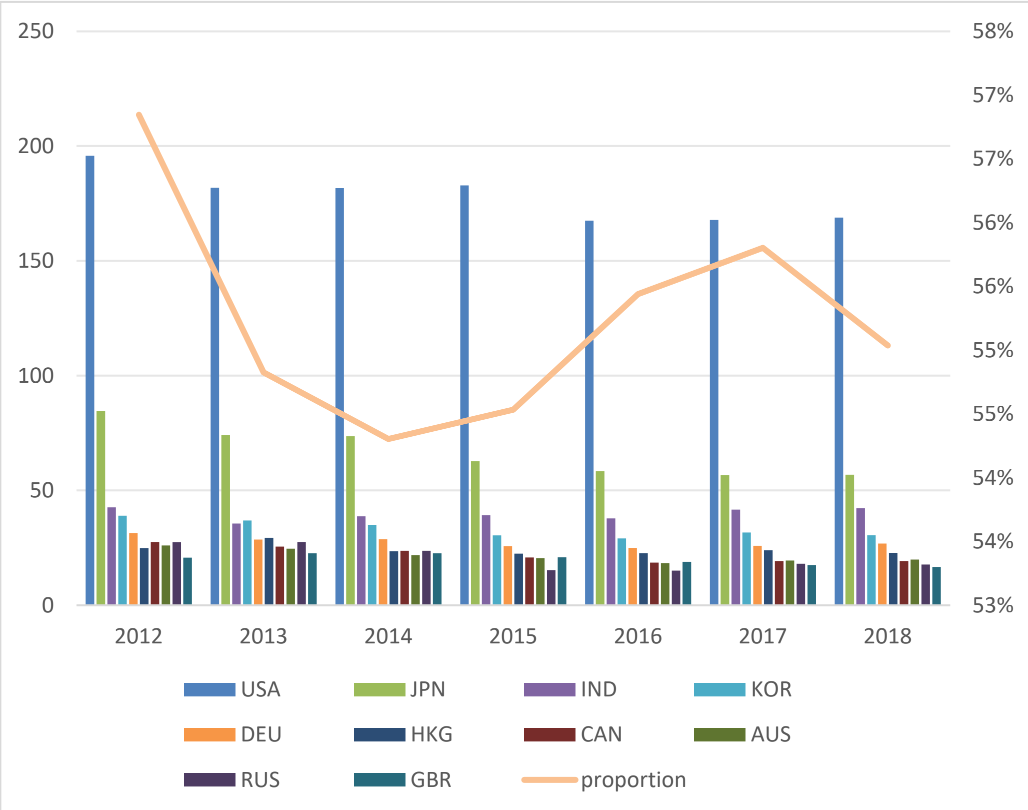

Figure 6. Ranking of embodied carbon emissions in Chinese Manufacturing exports by country (2012-2018)

As a vital base for global manufacturing, China has undertaken a large amount of production demands from developed countries in recent years, leading to a significant increase in embodied carbon in its export trade. According to the data shown in Figure 6, the top ten countries (regions) in terms of embodied carbon generated by China's manufacturing trade to meet their demands are: the United States (USA), Japan (JPN), India (IND), South Korea (KOR), Germany (DEU), Hong Kong (HKG), Canada (CAN), Australia (AUS), Russia (RUS), and the United Kingdom (GBR). China's manufacturing export activities are closely related to the demands of these countries, and during the study period, the embodied carbon from exports to these ten countries accounted for nearly half of China's total export embodied carbon. Specifically, the embodied carbon emissions from manufacturing export trade caused by the demand of the United States rank first, maintaining a high level from 2012 to 2018. Japan's carbon emissions are relatively stable, with a slight decrease in proportion. The carbon emissions of India and South Korea increased significantly in 2015 and 2016. Germany's carbon emissions showed a significant increase in 2017. Hong Kong experienced a decrease in 2015 and 2016, followed by an increase. Canada, Australia, Russia, the United Kingdom: the carbon emissions of these countries are relatively low, but their proportion increased after 2015. Among these ten countries, developed countries are predominant. China's role in global manufacturing is not only as a producer of products but also as an essential link in the industrial chains of developed countries. Especially in the export of intermediate products, this part accounts for more than half of the export trade embodied carbon. These intermediate products include electronic components, machinery equipment, and other raw materials necessary for manufacturing, which often require a significant amount of energy, leading to greenhouse gas emissions. By meeting the demands of developed countries for high-value-added products, China has not only increased its production scale and international competitiveness but also significantly increased its export trade carbon emissions.

Therefore, the large scale of China's greenhouse gas emissions is not entirely due to China's own consumption and production patterns. Developed countries, by outsourcing production, have ostensibly reduced their carbon footprints but have actually shifted these carbon emissions to exporting countries like China. The low-carbon goals of developed countries may not be fully achieved because their "decarbonization" in the production process is actually shifting environmental pressures to developing countries, especially manufacturing powerhouses like China.

This situation not only reflects the imbalance of resources and environmental responsibilities in international trade but also reveals the complexity of global climate governance. Under the backdrop of globalization, the economic activities and carbon emissions of countries are closely connected. Although China has achieved rapid economic development while undertaking production tasks, the increased environmental burden is an issue that cannot be ignored. To address this challenge, China needs to actively promote the green transformation of its manufacturing industry, improve energy efficiency, optimize industrial structures, and improve trade structures to reduce trade-related embodied carbon emissions. Against the backdrop of global climate governance, countries need to re-examine the relationship between trade activities and carbon emissions to achieve a win-win situation for economic development and environmental protection.

4. Conclusions and Policy Implications

4.1 Conclusions

As the world's second-largest economy, China faces increasingly severe environmental issues alongside rapid economic growth. The manufacturing industry, being the sector with the largest scale of trade-related embodied carbon emissions in China, urgently needs to find new methods to effectively reduce emissions. Based on this, this paper constructs a multi-regional input-output model to estimate the embodied carbon emissions from manufacturing import and export trade between China and 77 major countries and other regions globally from 2012 to 2018. The paper further analyzes the results from an overall perspective, different sectors, different trade methods, and different trade counterparts, and ultimately draws the following conclusions:

1) From an overall perspective, the embodied carbon in China's manufacturing export trade has decreased, while that in import trade has increased. The embodied carbon in China's manufacturing export trade decreased by 148.52 million tons from 2012 to 2018. Especially after 2015, the embodied carbon in China's manufacturing export trade has significantly decreased. During this period, the embodied carbon in China's manufacturing import trade increased by 30.7 million tons, peaking at 272.51 million tons in 2015.

2) From the perspective of different manufacturing sectors, nearly half of the embodied carbon emissions in China's manufacturing import and export trade are contributed by the basic metals sector (CHN_24). In terms of exports, the emission share of this sector has been increasing year by year, from 45% in 2012 to 55% in 2018. In contrast to exports, the share of embodied carbon in its import trade has decreased year by year from 51% in 2012 to 46% in 2018.

3) The decomposition of China's import and export trade embodied carbon shows that carbon emissions from intermediate product exports account for 59.54% of China's manufacturing export trade embodied carbon, and from 2012 to 2018, the proportion of intermediate product export emissions in manufacturing export trade embodied carbon has also increased from 57.81% to 59.54%, with an expanding trend. On the other hand, the proportion of direct import of intermediate products and indirect trade-induced energy consumption in China's import trade embodied carbon decreased from 89.3% in 2012 to 85.9% in 2018, and the proportion of direct import of final products is less than 15%. This conclusion indicates that the embodied carbon from China's manufacturing import and export trade is mainly caused by intermediate product trade, and China, as the "world's factory," has undertaken a large amount of emissions from trade products worldwide.

4) From the perspective of different trade counterparts, from 2012 to 2018, the top ten countries (regions) for embodied carbon in China's manufacturing export trade are mostly developed countries, with South Korea and the United States being the highest, and these ten countries (regions) contribute up to 50% of the

embodied carbon emissions from China's manufacturing export trade. This reflects the imbalance of environmental responsibility in international trade, with China causing a significant amount of carbon emissions to meet the manufacturing trade consumption demands of developed countries (regions), thus bearing greater environmental responsibility.

4.2 Policy Implications

Accordingly, we propose some important policy implications:

1) Promote green manufacturing and encourage the manufacturing industry to adopt environmentally friendly materials and clean energy, increase investment in low-carbon technology research and development, and reduce carbon emissions in the production process. This includes strengthening technological innovation and the green transformation and upgrading of the manufacturing industry, building a green manufacturing support system, and promoting the realization of industrial carbon peaks. For instance, in the most emitting basic metals sector, production can seek biofuels to reduce dependence on coal. Additionally, enhance information technology digital management and intelligent control levels, introduce relevant policies, and guide enterprises towards low-carbon transformation through incentives such as subsidies.

2) Optimize the export product structure; China should encourage the export of products or services with high added value and low energy intensity, and phase out the export of low added-value, high-energy consumption products. Moderately increase the export tax rebate rate for green technology products and adjust and optimize the export product structure. In the transportation process, choose low-carbon suppliers and partners to reduce carbon emissions during the transportation of intermediate products. Secondly, attempt to regulate the differences in carbon emissions at different stages of the value chain to achieve sustainable foreign trade development under a low-carbon background. For raw material production enterprises at the source end, appropriately raise the carbon emission access standards and gradually implement an environmental resource tax system to gradually internalize the environmental costs of traditional high-energy consumption, high-emission raw materials.

3) Strengthen international cooperation and share low-carbon technology and management experience. China should increase technological innovation efforts or introduce world-leading energy-saving technologies and clean production technologies. Explore cross-border carbon market connections and promote the establishment of regional joint carbon markets, such as "China-ASEAN," "Belt and Road," etc., to form a more effective carbon market. Advocate for the shared responsibility of carbon emissions and develop a carbon emission responsibility definition plan based on a mechanism that shares responsibility between consumers and producers, making the hidden carbon emission costs explicit.

References

Ahmad, N., & Wyckoff, A. W. (2003). Carbon Dioxide Emissions Embodied in International Trade of Goods. *Ecological Economics, 45*(3), 379-399. https://doi.org/10.1787/421482436815

Claude, A., Lanoie, P., & Patry, M. (2005). Greenhouse gases embodied in the international trade and final consumption of Canada. *Energy Policy, 33*(8), 1049-1056. https://doi.org/10.1016/j.enpol.2005.10.006

Fan, G., Su, M., & Cao, J. (2010). An economic analysis of final consumption and carbon emission responsibility. *Economic Research Journal, 1*, 4-14.

Fu, J., & Zhang, S. (2011). Analysis of Embodied Pollution in China's Manufacturing Imports and Exports: A Method Based on Input-Output. *International Business,* (2), 30-41. https://link.cnki.net/doi/10.13509/j.cnki.ib.2011.02.001

Han, Z., Chen, Y. H., & Shi, Y. (2018). Measurement and decomposition of consumption-based carbon emissions from the perspective of international final demand. *Journal of Quantitative & Technological Economics, 35*(7), 16. https://link.cnki.net/doi/10.13653/j.cnki.jqte.2018.07.007

Huang, M., & Wu, S. (2010). Tracing the Origins and Research Progress of Embodied Carbon in Trade. *Business Economic Review, 11*(2), 1-7.

IPCC. (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Retrieved from https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

Lv, X. (2023). The influence of Carbon Border Adjustment Mechanism on China's Export Industry and China's Countermeasures." *China Sustainability Tribune, 5,* 12-17.

Ma, S. Z., & Chen, Y. (2010). The impact of import and export trade on China's embodied carbon emissions: 2000-2009—An analysis based on a single-region input-output model from the perspective of domestic consumption. *Finance and Trade Economics,* (12), 82-89. https://link.cnki.net/doi/10.19795/j.cnki.cn11-1166/f.2010.12.012

Mäenpää, I., & Siikavirta, H. (2007). Greenhouse gases embodied in the international trade and final consumption of Finland: An input–output analysis. *Energy Policy, 35*, 128-143. https://doi.org/10.1016/j.enpol.2005.10.006

Pachauri, S., & Spreng, D. (2002). Direct and indirect energy requirements and CO2 emissions of urban households in India. *Energy Policy, 30*(1), 37-52. https://doi.org/10.1016/S0301-4215(01)00119-7

Peng, S. J., Wei, T., & Cao, Y. (2016). The impact of foreign demand on China's energy consumption from a global production chain perspective—An empirical study based on the MRIO model. *Jilin University Journal Social Sciences Edition, 56*(6), 51-61+188. https://link.cnki.net/doi/10.15939/j.jujsse.2016.06.004

Qi, Y., Li, H., & Xu, M. (2008). Estimation of Embodied Carbon in China's Import and Export Trade. *China Population, Resources and Environment, 18*(3), 8-13.

Tao, C., & Tang, X. (2015). Evaluation of Export Competitiveness of China's Manufacturing Products. *Dongyue Tribune, 36*(9), 186-190. https://link.oversea.cnki.net/doi/10.15981/j.cnki.dongyueluncong.2015.09.029

Wang, Q. (2017). A Study on the Measurement of Implied Carbon in China-US Trade—Based on Input-Output Model. *Advances in Social Sciences, 6*(6), 704-710. https://doi.org/10.12677/ass.2017.66098

Wang, Y., Wang, W. Q., Fang, X. Q., et al. (2011). An estimation of China's trade carbon transfer from the perspective of international division of labor. *Resources Science, 33*(7), 1331-1337.

Wiedmann, T. (2009). A review of recent multi-region input-output models used for consumption-based emission and resource accounting. *Ecological Economics, 69*(2), 211-222. https://doi.org/10.1016/j.ecolecon.2009.08.026

Yan, Y. F., & Yang, L. K. (2010). China's foreign trade and climate change: A case study of CO2 emissions. *Energy Policy, 38*(1), 350-356.

Yan, Y. F., & Zhao, Z. X. (2014). Consumption-based carbon emissions and carbon spillover effects: A comparison of G7, BRIC, and other countries. *Journal of International Trade,* (1), 99-107. https://link.cnki.net/doi/10.13510/j.cnki.jit.2014.01.010

Zhang, W. C., & Peng, S. J. (2014). A comparative analysis of resource and environmental burdens between developed and developing countries from the consumption and production perspectives. *The Journal of World Economy,* (8), 126-150. https://link.cnki.net/doi/10.19985/j.cnki.cassjwe.2014.08.007

Zhang, W. F. (2010). Strategic adjustment of China's participation in international division of labor under low-carbon economy. *Journal of Nanjing University of Finance and Economics,* (2), 1-5.

Zhao, F. (2024). Accelerating the Transition from a Trading Giant to a Trading Powerhouse. *China Development Observation, 10,* 19-23.

Zhao, Y. H., & Wang, S. (2014). Calculation and analysis of embodied carbon in China-Japan trade based on technological heterogeneity. *Journal of Beijing Institute of Technology (Social Sciences Edition), 16*(1), 12-18+26. https://link.cnki.net/doi/10.15918/j.jbitss1009-3370.2014.01.003

Zhu, Q. R. (2010). Research on the issue of CO2 emissions in China's export trade. *China Industrial Economics,* (1), 55-64. https://link.cnki.net/doi/10.19581/j.cnki.ciejournal.2010.01.005

Copyrights