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Study on Embodied CO_2 Emissions and Transfer Pathways of Chinese Industries

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Abstract: Industries with low direct CO_2 emissions downstream in the industry chain have significant carbon emissions upstream, which is similar to how carbon leakage in interprovincial regions and international commerce affects these regions. Due to the interchange and transit of goods, there are intermediate production and consumption processes across industrial sectors. The CO_2 emissions produced by each sector are insufficient to satisfy the sector's ultimate demand. It will also move along with the industrial chain. Investigating embodied carbon transfer across industrial sectors is crucial to strike a balance between economic growth and greenhouse gas emissions. Locating the key sectors to reduce carbon emissions provides a basis for formulating resource conservation and environmental protection policies. In this study, the industrial sector divides into 24 subsectors, and the embodied CO_2 emissions and carbon transfer pathways of each are examined from the viewpoint of the industrial chain using the Economic Input–Output Life Cycle Assessment (EIO-LCA) and the Hypothetical Extraction Method (HEM). The indirect CO_2 emissions downstream of the industrial chain are higher than the direct carbon dioxide emissions, and the intersectoral carbon transfer constitutes a significant part of the total carbon emissions of the industrial sector. The upstream sector of the industry chain has a significantly higher direct carbon emission intensity than the indirect CO_2 emission intensity, while the downstream sector is the opposite. The production and supply of electricity, gas and water, and raw material industries transfer significant CO_2 to other sectors. The manufacturing industry is mainly the inflow of CO_2. CO_2 flows from the mining industry to the raw material industry and from the raw material industry to the manufacturing industry constitute the critical pathway of carbon transfer between industries. A study on the embodied carbon emissions and transfer paths of various industrial sectors is conducive to clarifying the emission reduction responsibilities and providing a basis for synergistic emission reduction strategies.

Keywords: industrial chain; embodied CO_2 emissions; carbon transfer pathway; HEM

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1. Introduction

Many nations and academics have focused much emphasis on carbon emissions [1,2]. Climate Change 2022: Mitigation of Climate Change, a report from the Intergovernmental Panel on Climate Change (IPCC), was published in April 2022 [3]. The report shows that global greenhouse gas emissions from 2010 to 2019 are at the highest level in human history, reaching 59 billion tons in 2019, which is up 12% from 52.5 billion tons in 2010. In order to effectively reduce greenhouse gas emissions and the increase in the earth's temperature, countries have developed relevant policies to improve energy use efficiency. At the General Debate of the 75th Session of the United Nations General Assembly on 22 September 2020, President Xi Jinping declared that China aims to peak its carbon dioxide emissions by 2030 and work toward attaining carbon neutrality by 2060. As China continues to industrialize and urbanize, it brings problems such as a sharp increase in energy consumption and pressure on the environment [4,5]. China's CO_2 emissions reached 9899.3 Mt in 2020, with a per capita CO_2 emission of 6.9 tons per person. In the face of increasing international pressure, China has taken measures to reduce carbon emissions. However, due to the rapid industrial development, much energy demand remains, putting much pressure on resource-saving and emission-reduction efforts. In 2020, the industrial sector's economic contribution accounted for 30.87% of China's GDP. However, it uses up 66.75% of all the energy and produces over half of China's overall CO_2 emissions (National Bureau of Statistics of China, 2021). CO_2 emissions have dramatically increased due to China's industrial sector's fast expansion [6]. The industrial sector is key to realizing a low-carbon transition via energy saving and emission reduction [7].

Embodied carbon emissions are defined by the United Nations Framework Convention on Climate Change (UNFCC) as the direct and indirect carbon emissions from various operations, from purchasing raw materials to processing, production, and transportation. The indirect CO_2 emissions from the interchange and transit of goods across industries and sectors must also be taken into consideration in addition to the direct CO_2 emissions from burning fossil fuels [8,9]. As production continues to evolve, the linkages between industries continue to deepen. Products from one industry are not only used for final consumption but may also apply in the manufacturing processes of other industries. Accounting for embodied carbon emissions can help explain the "carbon leakage" between economies and reveal "consumption-based" carbon emissions [10]. At the same time, it is not enough to study the embodied carbon emissions. In order to understand the transmission processes and impacts, it is also essential to assess the intricate flow of carbon emissions across sectors. Furthermore, the sector's impact on the energy and environment of the whole economic system is crucial for the industry's energy saving and low-carbon development. HEM can be used to study not only the economic role of sectors [11] but also environmental and resource studies such as resource use and pollutant emissions [12,13]. This research aims to investigate the inter-industry CO_2 emission links using the Hypothetical Extraction Method (HEM) and propose policy suggestions based on the findings.

2. Literature Review

International commerce and industrial transfer are accompanied by embodied carbon emissions, resulting in carbon transfer [14–16]. Studying carbon emission transfer can help to solve the carbon leakage problem and encourage the spread of technologies to achieve carbon emission reduction more effectively. Regarding research scale, the research on carbon transfer can be classified into three categories: carbon transfer between different economies, different regions in a country, and different industries.

Firstly, researchers have focused on transferring CO_2 emissions due to import and export trade between different economies. Due to international trade (e.g., emission-intensive products exported to developing countries), the effectiveness of global carbon emission reduction is difficult to be guaranteed, which can easily lead to the problem of "carbon leakage" [16–18]. The study of carbon transfer between different trading partners can help to clarify the responsibility of carbon reduction and provide a basis for formulating synergistic reduction strategies. Carbon transfer owing to commerce between industrialized and developing nations is one of them, and it is the focus of study on carbon transfer between various economies [19,20]. Chen and Chen empirically analyzed the transfer of CO_2 emissions from three supranational alliances, namely the G7, the BRICs, and the rest of the world, which is caused by global fossil fuel combustion. The results show that trade in most countries leads to a shift in CO_2 emissions [21]. Developed countries responsible for greenhouse gas (GHG) emission reductions achieve their reduction targets by shifting their emission reduction-intensive industries to developing countries. Trade liberalization has boosted CO_2 emissions in Turkey, India, China, and Indonesia, making these nations pollution sinks for industrialized nations [22]. Given that developing nations' industrial technologies lag behind those of rich countries and emit surplus CO_2, global carbon emissions may rise [23].

Scholars have examined the effects of a country's overseas commerce to understand better the carbon transfer between various nations due to international trade [24,25] and bilateral trade on carbon transfer [26,27]. Jiang et al. [28] classified China's production into domestic production, processed exports, and non-processed exports to investigate the impact of heterogeneity in trade patterns on CO_2 transfer in international trade. The study found that global CO_2 emissions would be reduced by 190,000 to 620,000 tons of processing activities in China and shift to other countries such as the United States, Europe, or Brazil. Researchers examined the bilateral commerce of embodied carbon transmission between China and Australia [29], China and Japan [30], and China and the United States [31]. Significant amounts of CO_2 exchange through bilateral commerce with industrialized nations and China is a net contributor to CO_2 emissions.

Secondly, carbon emission transfer between different regions of a country is also one of the current research hotspots. Due to the unequal distribution of various resources, a substantial inter-regional trade is generated among goods and services, leading to the inter-regional transfer of CO_2 emissions. The level of economic growth, population size and density, industrial structure, resource endowment, and residential lifestyle, for instance, varied significantly amongst provinces in China [32]. Investigating the movement of carbon across provinces and regions can reasonably assess the goal of reducing CO_2 emissions in each province and region and lay the foundation for achieving energy-saving and emission-reduction goals. Nine provinces in China's Yellow River Basin had embodied carbon emissions estimated by Yuan et al [33]. In comparison to the top reaches of the provinces, they discovered that the embodied carbon emission transfer between the middle and lower regions of the Yellow River Basin provinces was much more prominent. According to Zhou et al. [34], the northwest (less developed regions) accounted for the majority of the transported embodied carbon to the east coast (developed regions). According to Ning et al. [35], physically adjacent locations experience the carbon emission spillover effect to a greater extent. The inter-regional carbon transfer in China is from northwest to southeast. With plenty of fossil fuels, less developed areas frequently see a net outflow of carbon emissions [36] with no significant spillover effects in provinces farther apart [37].

Finally, as with inter-regional CO_2 leakage, the association of carbon emissions between different industries is complex, with less direct CO_2 emissions from downstream industries in the industry chain closely correlated with more direct CO_2 emissions from upstream sectors [38]. It is possible to control final demand emissions and adjust the energy structure by analyzing CO_2 emissions and transfers from each sector. Some researchers divide industries into industry clusters and study the transfer of CO_2 emissions among each industry cluster. Wang et al. [39] divided Chinese industries into eight industry clusters, analyzed the carbon transfer characteristics of the eight industry clusters, and found that industries with lower direct CO_2 emissions were closely related to high-carbon industries. Zhao et al. [40] divided South Africa's industries into ten industry clusters, demonstrating that high-carbon industry clusters influence low-carbon industry clusters. Other studies have focused on individual industries, examining the carbon linkages between different industries. Du et al. [15] created a network of embodied carbon emissions for 41 industries from 2005 to 2014, showing that most industries contribute more than 70% of total embodied emissions. Zhang et al. [41] analyzed the transfer of sectoral CO_2 emissions caused by household consumption using a Hypothetical Extraction Method. Among them, the electricity and heat sectors and the smelting and pressing metals transfer a large amount of CO_2 outward by providing products for each sector. In contrast, the food and tobacco manufacturing sector are vital in absorbing CO_2 emissions.

The research concluded that industrialized nations export CO_2 to developing countries (less developed locations with ample fossil fuels). Carbon emissions from low-carbon industry clusters are closely related to those from high-carbon industry clusters. Investigators have made some achievements in the research on carbon transfer, but there are still the following shortcomings. First, most studies about carbon transfer have focused on inter-country trade, inter-regional within economies, and inter-industry clusters. There are no adequately studied complex carbon linkages among industrial sectors, and fewer studies classify industrial chains according to the upstream, midstream, and downstream industrial chains. Second, in developing countries such as China, accurate analysis of CO_2 emission transfer between industries and measures for industrial sectors' characteristics is still in the exploratory stage. Building a low-carbon industrial chain is the core of a country's sustainable development, a conscious action to serve the national carbon emission reduction strategy, and a proactive action to comply with green and low-carbon development. Studying the unique characteristics of each sector in terms of carbon emissions and the carbon transfer between sectors is crucial to achieving the win–win goal of economic development, resource conservation, and emission cut. Based on China's national economic classification and industry definitions and from the viewpoint of the industrial chain, this paper divides the industrial sector into four parts: upstream mining, midstream raw material industry, downstream manufacturing, and production and supply of electricity, gas, and water. We used the Economic Input–Output Life Cycle Assessment (EIO-LCA) and Hypothetical Extraction Method (HEM) to trace the carbon transfer paths of each industrial sector and industrial chain. Based on study findings, we proposed various policies.

The structure of this article is as follows. Section 2 proposes the Economic Input–Output Life Cycle Assessment (EIO-LCA) and Hypothetical Extraction Method (HEM) to calculate the embodied CO_2 emissions from China's industrial sectors. Section 3 accounts for each industrial sector's embodied CO_2 emissions ,carbon transfer pathways and decomposes the CO_2 transfer into Internal Emissions (IE), Mixed Emissions (ME), Net Forward Linkage Emissions (NFLE), and Net Backward Linkage Emissions (NBLE). Section 4 proposes policy suggestions based on industrial sectors' embodied CO_2 emissions and carbon transfer between chains.

3. Materials and Methods

3.1. Economic Input–Output Life Cycle Assessment (EIO-LCA)

The Economic Input–Output Life Cycle Assessment (EIO- LCA) is used in this article to calculate the indirect CO_2 emissions from 24 industrial sectors in China in 2017. The input–output analysis examines the quantitative relationship between the inputs and outputs of different economic activities in economic and national systems. Replacing the monetary input–output matrix with a matrix of carbon correlation can be useful to study environmental impacts [42]. Hendrickson [43] combined the input–output (IO) with life cycle assessment (LCA) to create a matrix of environmental impact coefficients capable of assessing the environmental impacts due to final demand in different sectors through the industrial chain. In contrast, the EIO-LCA, which combines LCA with IO, is more accurate. It assesses the environmental impact of the entire product supply chain, from raw materials to product processing to use [44], and considers both direct and indirect impacts. Moreover, EIO-LCA has been proven to have the advantage of more complete boundaries and avoidance of truncation bias [45,46].

In Table 1, z_{ij} denotes the input from sector i to sector j, Y_i is the final demand for products and services in the i sector, and X_i is the total output of sector i. Mathematical models are developed based on the characteristics of IO tables [47,48].

$$\sum_{j=1}^{n} Z_{ij} + Y_i = X_i \tag{1}$$

Sector i satisfies the final demand for household consumption, government consumption, fixed asset formation, inventory changes, and exports, in addition to supplying the intermediate demand of this sector and other sectors. By creating a matrix of direct consumption coefficients, $a_{ij} = z_{ij}/X_j$, Equation (1) can be written as

$$\sum_{j=1}^{n} a_{ij}X_j + Y_i = X_i \tag{2}$$

By matrix operations, Equation (2) can be written as

$$X = [I - A]^{-1}Y \tag{3}$$

I is the unit matrix of n*n, and A is the technical coefficient matrix. $(I - A)^{-1}$ is the Leontief inverse matrix used to account for direct and indirect transactions. To calculate the indirect CO_2 emissions for each industry sector, the matrix of direct CO_2 emission factors of economic output for each sector, E_{dir}, is multiplied.

$$E = E_{dir}X = E_{dir}[I - A]^{-1}Y \tag{4}$$

E represents the CO_2 emission matrix for each industrial sector. The sum of the row vectors of the E matrix represents the direct CO_2 emissions of sector i in the production of products or provision of services, and the column vectors represent the indirect CO_2 emissions of sector j from the use of products or services of the sector i in production. E_{dir} is a diagonal matrix whose diagonal elements are the direct CO_2 emissions generated per unit of economic output for each sector.

Table 1. A simplified version of the IO table.

Input		**Output**					
		Intermediate Demand				**Final Demand**	**Gross Output**
		Sector j, (j = 1, 2,...n)					
Intermediate input	Sector i, (i = 1, 2,...n)	z_{11}	z_{12}	...	z_{1n}	Y_1	X_1
		z_{21}	z_{22}	...	z_{2n}	Y_2	X_2
		...	...		...	...	...
		z_{n1}	z_{n2}	...	z_{nn}	Y_n	X_n
Value added		V_1	V_2	...	V_n	GDP	
Total input		X_1	X_2	...	X_n		

3.2. Hypothetical Extraction Method (HEM)

In order to explore the CO_2 transfer routes across industrial sectors, this research employs the Hypothesis Extraction Method (HEM) to assess the net transfer of CO_2 emissions between sectors. Schultz [49] initially introduced HEM to examine how changes in a sector affect the whole economy. By comparing a sector's output to that of other economic sectors, HEM calculates a particular sector's economic effect. The comparison allows us to distinguish the sector's economic impact and identify the key sectors. B_s denotes the extracted part of the economic system, and B_{-s} denotes the remaining part. In this paper, B_s represents a sector of industry, and for each sector, the economic system can be described as:

$$\begin{pmatrix} X_s \\ X_{-s} \end{pmatrix} = \begin{pmatrix} A_{s,s} & A_{s,-s} \\ A_{-s,s} & A_{-s,-s} \end{pmatrix} \begin{pmatrix} X_s \\ X_{-s} \end{pmatrix} + \begin{pmatrix} y_s \\ y_{-s} \end{pmatrix} = \begin{pmatrix} \triangle_{s,s} & \triangle_{s,-s} \\ \triangle_{-s,s} & \triangle_{-s,-s} \end{pmatrix} \begin{pmatrix} y_s \\ y_{-s} \end{pmatrix} \tag{5}$$

where $X = \begin{pmatrix} X_s \\ X_{-s} \end{pmatrix}$ is the vector of gross output; $y = \begin{pmatrix} y_s \\ y_{-s} \end{pmatrix}$ is the vector of final demands; $A = \begin{pmatrix} A_{s,s} & A_{s,-s} \\ A_{-s,s} & A_{-s,-s} \end{pmatrix}$ is the matrix of technical coefficients; and $(I - A)^{-1} = \begin{pmatrix} \triangle_{s,s} & \triangle_{s,-s} \\ \triangle_{-s,s} & \triangle_{-s,-s} \end{pmatrix}$ is the Leontief inverse matrix.

To analyze the carbon transfer among sectors more clearly and find the correlation relationship of CO_2 emissions among departments, we decompose the B_s into four parts: Internal Emissions (IE), Mixed Emissions (ME), Net Forward Linkage Emissions (NFLE), and Net Backward Linkage Emissions (NBLE) [50]. IE is the CO_2 emissions from the sector that consumes its resources to meet its final demand. ME denotes the CO_2 emissions from sector B_s exchanging products with other sectors to meet their production needs. For example, the goods or services sold by B_s are processed by B_{-s} and then re-purchased by B_s, resulting in CO_2 emissions. NFLE measures CO_2 emissions exports from sector B_s, or the CO_2 emissions produced by one sector to fulfill the demand for output from other sectors. This portion of carbon emissions flows with the output of products and services to other sectors without returning. It is, therefore, also referred to as the net output of carbon emissions. NBLE refers to the CO_2 emissions generated by sector B_s in direct and indirect demand for sector B_{-s} to fulfill the final demand. The net inflow of carbon emissions refers to the carbon emissions from other sectors that B_s absorb to fulfill their production and service demands.

$$IE = F_s(I - A_{s,s})^{-1}y_s \tag{6}$$

$$ME = F_s[\triangle_{s,s} - (I - A_{s,s})^{-1}]y_s \tag{7}$$

$$NFLE = F_s \triangle_{s,-s}\, y_{-s} \tag{8}$$

$$NBLE = F_{-s} \triangle_{-s,s}\, y_s \tag{9}$$

In order to understand the intricate carbon links across industrial sectors, CO_2 emissions are divided into direct CO_2 emissions (DE) and indirect CO_2 emissions (OE). DE is the total CO_2 emissions a sector produces, including IE, ME and NFLE. IE, ME and NBLE are all included in the definition of OE as the CO_2 emissions produced to fulfill a sector's demand. The formula is as follows.

$$DE = IE + ME + NFLE \tag{10}$$

$$OE = IE + ME + NBLE \tag{11}$$

Assuming that sector t is a part of other sectors B_{-s} other than B_s, the CO_2 emissions transferred from sector t to sector s are in Equations (12) and (13).

$$NBLE_{t\longrightarrow s} = F_t \triangle_{t,s} y_s, t \in (-s) \tag{12}$$

$$NFLE_{s\longrightarrow t} = F_s \triangle_{s,t} y_t, t \in (-s) \tag{13}$$

The difference between $NFLE_{s\longrightarrow t}$ and $NBLE_{t\longrightarrow s}$ indicates the net transfer of CO_2 emissions from sector s to sector t.

$$NTE_{s\longrightarrow t} = NFLE_{s\longrightarrow t} - NBLE_{t\longrightarrow s} = F_s \triangle_{s,t} y_t - F_t \triangle_{t,s} y_s, t \in (-s) \tag{14}$$

3.3. Data

To study the embodied CO_2 emissions and CO_2 transfer pathways in China's industrial sector in 2017, input–output data, industrial energy consumption data, value added by industrial sectors, and direct industrial CO_2 emissions data are needed (the data sources are shown in Table 2). Value added by industrial sectors is from the China Statistical Yearbook. Since the value added of the industry was no longer published in 2008, data after 2008 are obtained through annual growth rates calculated by the National Bureau of Statistics of China. The value added of the industry is in constant 2000 prices. The direct industrial CO_2 emissions data are sourced from the China Emission Accounts and Datasets (CEADs). This dataset is according to the revised energy data from the Energy Statistics Yearbook and is more accurate than the default values from the Intergovernmental Panel on Climate Change (IPCC) and the National Development and Reform Commission of China (NDRC) [51] and is closer to the surveyed values in China. The Chinese industry is divided into 24 subsectors according to Industrial classification for national economic activities (GB/T4754-2017) and the Input–Output Table of China, as shown in Table 3.

Table 2. Data and sources.

Data	Sources
Input and output data	China 2017 Input–Output Table
Industrial energy consumption data	Energy Statistical Yearbook
Industrial value added	China Statistical Yearbook and National Bureau of Statistics of China
Direct industrial CO_2 emissions data	China Emission Accounts and Datasets (CEADs)

Table 3. China industrial sector and code.

Code	Industrial Sector	Code	Industrial Sector
A1	Coal Mining	A13	Metal Processing
A2	Petroleum and Gas Extraction	A14	Metal Products
A3	Metal Ores	A15	Ordinary Machinery
A4	Nonmetal Ores	A16	Equipment for Special Purposes
A5	Foods	A17	Transportation Equipment
A6	Textile	A18	Electric Equipment and Machinery
A7	Leather	A19	Electronic Equipment
A8	Wood Products	A20	Measuring Instruments
A9	Paper and Printing	A21	Other Manufacture
A10	Fossil and Nuclear Fuels	A22	Production and Supply of Electric Power and Heat Power
A11	Chemicals	A23	Production and Supply of Gas
A12	Non-Metallic Mineral	A24	Production and Supply of Water

4. Results and Disscussion

4.1. Direct CO_2 Emissions from China's Industry

China's industrial energy usage increased by 6.36% yearly between 2000 and 2019 from 1,030.14 to 3325.03 million tons of standard coal. Direct CO_2 emissions from the industry grew from 2452.39 to 8279.67 million tons. The share of direct CO_2 emissions from industry fluctuates between 81.17% and 86.40%. Industrial CO_2 emissions dominate China's total CO_2 emissions [52], and the share of industrial CO_2 emissions in 2019 is much higher at 84.53% than that of other industries at 15.47%. China's industrial CO_2 emissions can broadly be divided into four different phases: the high growth phase (2000–2006), the slow growth phase (2007–2010), the transition phase (2011–2015), and the decelerated growth phase (2016–2019).

As shown in Figure 1, from 2000 to 2010, China's direct industrial CO_2 emission release increased from 2452.39 to 6805.34 with a yearly growth rate of 10.75%. Since 2000, China's economy has witnessed a new period of rapid development, especially in its industrial sector. China's cement, steel and chemical production has moved to a new level. These greenhouse gas-intensive products have produced a dramatic increase in industrial CO_2 emissions. The growth rates of CO_2 emissions in 2013, 2014 and 2015 were −1.52%, −3.63% and −0.34%, respectively, showing an inverted trend. The declining growth rate of industrial CO_2 emissions from 2016 to 2019 will likely result from the economic slowdown, technological progress and policy initiatives.

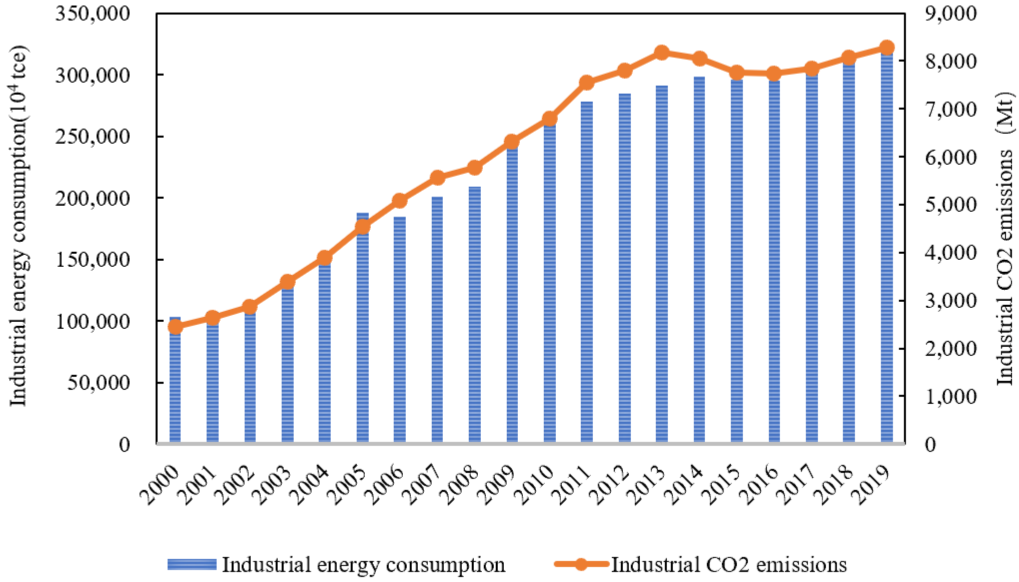

Figure 1. Industrial energy consumption and CO_2 emissions, 2000–2019.

The percentages of CO_2 emissions from various industrial subsectors in Figure 2 show that production and supply of electric power and heat power (A22), metal processing (A13) and non-metallic mineral (A12) ranked in the top three in terms of CO_2 emissions. The amount of CO_2 emissions from the three sectors in total industrial CO_2 emissions increased from 81.85% in 2000 to 92.65% in 2019, with the proportion increasing yearly. Among them, CO_2 emissions from A22 account for about half of the total industrial CO_2 emissions. The proportion increased from 45.89% to 56.06% from 2000 to 2019. Therefore, A22 has considerable potential to mitigate CO_2 emissions and should be given full attention. Both A12 and A13 show different degrees of growth in CO_2 emissions, with A13 growing at a faster rate in comparison.

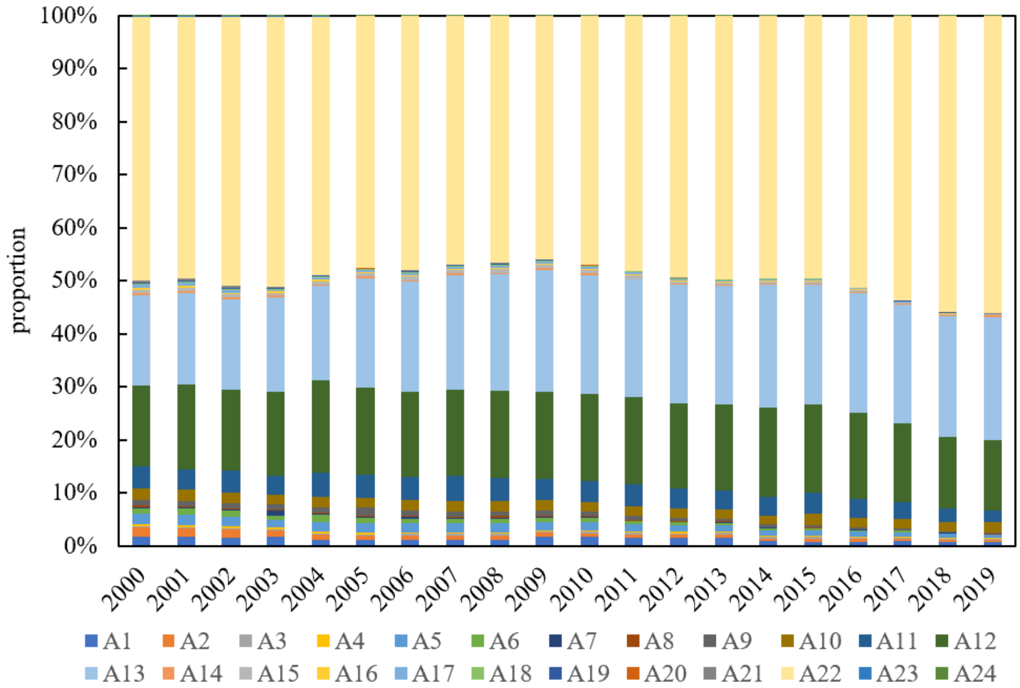

Figure 2. Cumulative percentage of CO_2 emissions from different industry.

4.2. Indirect and Total CO_2 Emissions of the Industrial Sector

All sectors are interconnected and interact, forming the entire economic system. The products and services of one sector may be inputs to other sectors, such as raw materials, energy production or transportation, which can lead to the movement of their environmental impacts between sectors and life stages. The evaluation of the overall CO_2 emissions during each sector's life cycle considers the raw material acquisition, manufacturing, distribution, consumption, and end-of-life phases. The lack of available data makes it difficult to clearly distinguish the CO_2 emissions of products and services at each life stage. Therefore, this essay employs the EIO-LCA to calculate the total cradle-to-grave carbon dioxide emissions of 24 sectors, respectively.

The indirect CO_2 emissions caused by manufacturing in various industrial sectors are very different from the direct CO_2 emissions. Coal mining (A1), petroleum and gas extraction (A2), metal ores (A3), non-metal ores (A4), non-metallic mineral (A12), metal processing (A13), and production and supply of electric power and heat power (A22) account for a higher proportion of direct CO_2 emissions than indirect CO_2 emissions; emissions from these sectors are above 85%. The electricity supply sector and fuel extraction and processing are the "suppliers" of CO_2 emissions. Non-metallic and metal products manufacturing are the "transmitters" of CO_2 emissions [53,54]. Although the share of direct CO_2 emissions is low in some industrial sectors, the share of indirect CO_2 emissions is high, as shown in Figure 3. Among them, the share of indirect CO_2 emissions in electric equipment and machinery (A18) and electronic equipment (A19) is 98.86% and 98.76%, respectively. The high share of indirect CO_2 emission is mainly due to the industrial sector's rapid development and the increasing demand for industrial products in China. The industrial sector generates a massive demand for electricity and heat, which leads to a significant number of CO_2 transfers from the electricity and heat sector to other sectors.

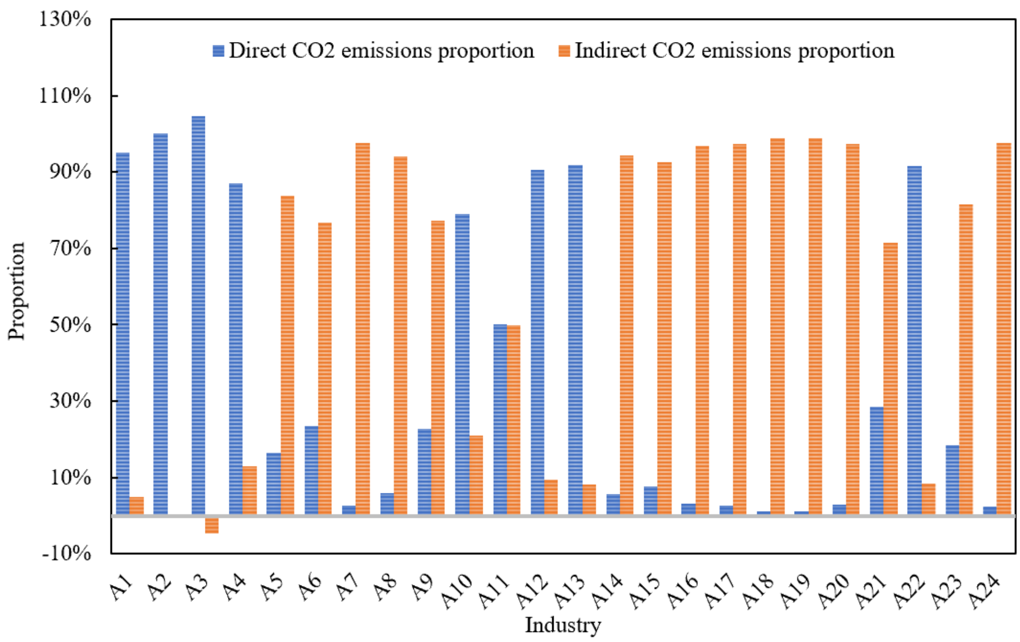

Figure 3. Direct and indirect CO_2 emissions proportion of China's industry in 2017.

Some industrial sectors' direct CO_2 emission intensity is significantly higher than the indirect CO_2 emission intensity, such as the electricity and heat supply industry (A22), non-metallic mineral (A12), metal processing (A13), and coal mining (A1) (see Figure 4). These sectors have high energy intensity and absorb a relatively small amount of carbon transfer from other sectors. These sectors should strive to improve the industry's energy consumption access standards and reduce the proportion of high-carbon fossil energy use in production. At the same time, they are using low-carbon fossil energy, clean energy that reduces the intensity of carbon dioxide emissions. Leather (A7), equipment for special purposes (A16), transportation equipment (A17), electric equipment and machinery (A18) and electronic equipment (A19) are some examples of industrial sectors having low direct CO_2 intensity and high indirect CO_2 intensity. While most of these sectors utilize less primary energy and are at the bottom of the industrial chain, most upstream sectors have high rates of direct CO_2 emissions. By creating industrial parks and agglomerations and encouraging resource recycling and reuse, carbon emission reduction goals can be met.

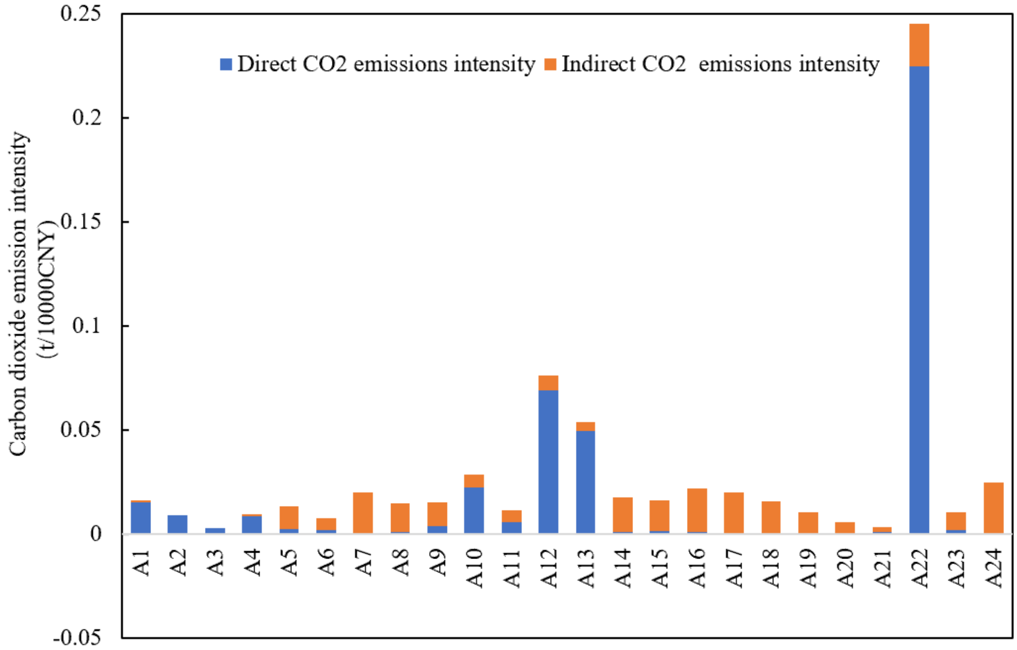

Figure 4. Industrial sectors CO_2 intensity in China in 2017.

4.3. Accounting of CO_2 Emissions Transfer between Industrial Sectors

In order to achieve China's carbon neutral and carbon-peaking emission reduction targets and promote industrial low-carbon development, it is essential to identify carbon transfer pathways in key carbon-emitting sectors. China's industrial sectors produce much CO_2 emissions in manufacturing and consumption. The internal effect, mixed effect, net forward effect, net backward effect, and net CO_2 transfer are used to analyze the carbon transfer channel among various sectors and industrial chains. According to the national economic classification standards and industry definitions, China's 24 industrial sectors are divided into four parts: the upstream mining industry, the midstream raw material industry, the downstream manufacturing industry and the production and supply of electricity, gas and water. The upstream mining industry includes A1, A2, A3 and A4, and the midstream raw material industry includes A10, A11, A12, A13 and A21. A5, A6, A7, A8, A9, A14, A15, A16, A17, A18, A19 and A20 are manufacturing industries. Production and supply of electricity, gas and water are A22, A23 and A24. The analysis of carbon emission correlation between industries lays the foundation for clarifying the responsibility of each industry to reduce emissions and accomplish the objective of reducing emissions as early as possible.

4.3.1. Internal Emissions and Mixed Emissions

The industrial sectors emit a large amount of CO_2 to meet the production needs of their sectors. The 24 industrial sectors consume resources in their sectors to generate a total of 700.3 Mt of CO_2, accounting for 8.93% of direct industrial CO_2 emissions and 19.74% of indirect industrial CO_2 emissions. A significant industry for attention for energy conservation and emission reduction in China is the production and supply of electrical energy and heating power (A22), which consumes as much as 365.77 million tons of CO_2 emissions from the sector's resources. The sum of CO_2 transferred by the mixed emissions of each sector only accounts for 0.21% of direct carbon dioxide emissions and 0.47% of indirect CO_2 emissions, which has a relatively small impact on the transfer of CO_2 emissions from China's industry (see Figure 5).

4.3.2. Net Forward Linkage Emissions

The Net Forward Linkage Emissions reflect the outflow of CO_2 emissions between industrial sectors. Up to 3836.9 Mt CO_2 outflow is produced by the electricity and heat generation and supply sector, representing 53.84% of the total NFLE produced by the industrial sector (see Figure 5). The industry supplies most of the energy for the other industries by burning fossil fuels. The production and delivery of electric power and heat power (A22), non-metallic mineral (A12), and metal processing account for the bulk of China's industrial exports of CO_2 emissions (A13). In 2017, the total CO_2 outflow from the three sectors was 6578.51 million tons, accounting for 92.31% of the total industrial CO_2 outflow.

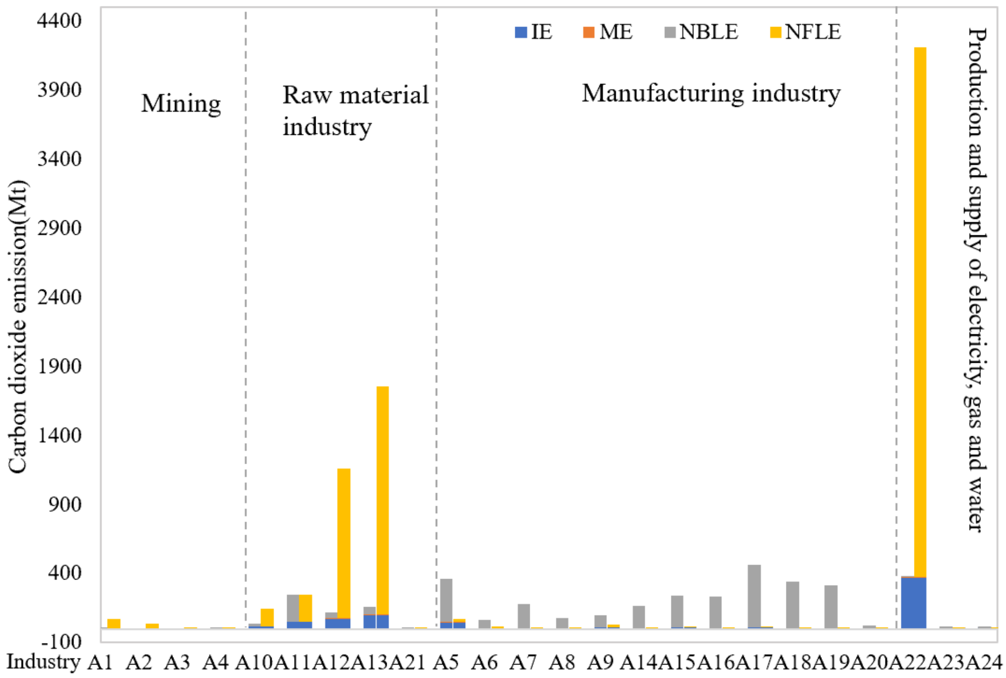

Figure 5. Cluster stack of direct and indirect CO_2 emissions for 24 sectors of industry.

4.3.3. Net Backward Linkage Emissions

The Net Backward Linkage Emissions reflect the inflow of CO_2 emissions between industrial sectors. Transportation equipment (A17), which accounted for 456.85 Mt of CO_2 inflows in 2017 and 16.14% of the industrial sector's overall CO_2 inflows, is the sector with the highest CO_2 inflows, as shown in Figure 5. The increasing demand for energy-intensive materials for manufacturing transportation equipment due to the booming urbanization and transportation industry in China has influenced the inter-industrial CO_2 flows in China. In addition, the electric equipment and machinery (A18), foods (A5) and electronic equipment (A19) sectors have a more extensive inflow of CO_2, accounting for 12.01%, 11.11% and 11% of the total industrial CO_2 inflow, respectively. These sectors absorb large amounts of CO_2 to meet the sector's final demand.

As shown in Figure 6, the direct CO_2 emissions from the mining industry upstream of the chain, the raw material industry in the midstream, and the power, gas, and water production and supply are significantly higher than the indirect CO_2 emissions. The downstream of the manufacturing chain absorbs a significant portion of the CO_2 emissions, and the indirect CO_2 emissions are more excellent than the direct CO_2 emissions. The mining industry uses a large amount of fossil energy in mineral exploration, mining, processing and metallurgy. The raw materials industry directly processes and produces the extracted industrial products to provide raw materials for manufacturing. Thermal power generation still dominates electricity generation in the power sector, burning large amounts of coal, heavy oil, coke oven gas and blast furnace gas. The high dependence of these industries on primary energy sources results in significant direct CO_2 emissions. The manufacturing industry relies on the mining and raw material industries to further process industrial products, which produces less direct CO_2 emissions but more indirect CO_2 emissions.

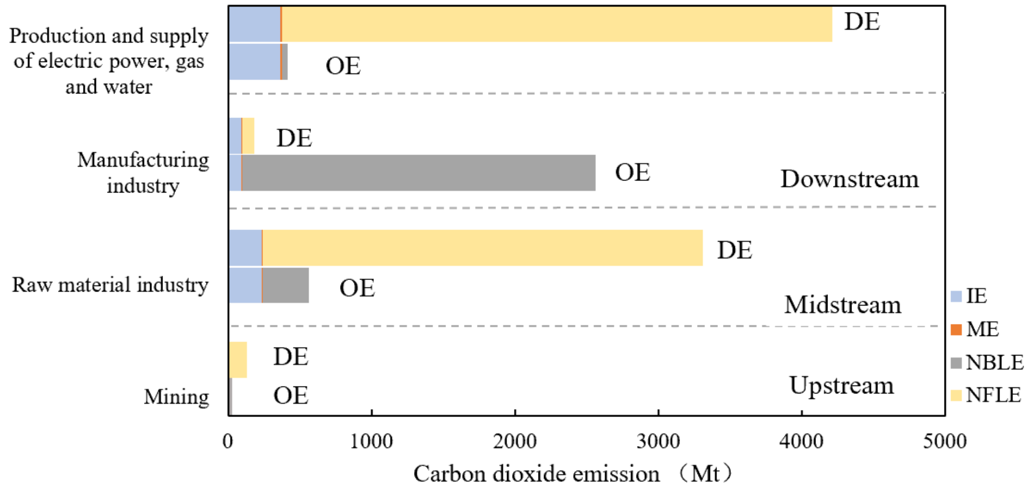

Figure 6. Grouped stacking diagram of CO_2 emissions from industry chain.

4.3.4. CO_2 Emissions Transfer Pathway

The difference between the CO_2 outflow (NBLE) and inflow (NFLE) between sectors is defined as the net transfer of CO_2 (NTE). The sectors with a net transfer of CO_2 emissions of more than one million tons were filtered, and the CO_2 transfer was represented by drawing a chord diagram, as shown in Figure 7. The width of the line in the graph indicates the net transfer of CO_2 between industrial sectors. The more extensive the transfer, the more comprehensive the line. Fifteen industrial sectors are net CO_2 outflow, and nine are net CO_2 inflow sectors. The sectors with more extensive net CO_2 inflow are not the same as those with enormous net outflow.

The net CO_2 outflow sectors are those sectors where the outflow of CO_2 is greater than the inflow, mainly concentrating on the upstream and midstream of the industrial chain. The direct CO_2 emission intensity is significantly higher than the indirect CO_2 emission intensity. The primary flow direction of carbon transfer from the industrial sector is the electric and metal processing industry's manufacturing and supply. The two sectors exported 2186.99 million tons of CO_2 in 2017, accounting for 86.9% of the total CO_2 transfer. These industries directly consume energy and generate materials that require much energy for manufacturing further in the industrial chain [9].

The net CO_2 inflow sector refers to the sector where the CO_2 inflow is more extensive than the outflow, such as the food processing, textile, wood processing, and transportation equipment manufacturing industries. These sectors of the economy are primarily downstream, and the raw materials produced upstream are used to process and create the goods. For example, the raw materials of the transportation equipment in the manufacturing industry are mainly steel and aluminium alloy, and the sector is mainly processing, manufacturing, assembling and assembling, which produces less CO_2 emissions from direct energy consumption. In 2017, the transportation equipment manufacturing sector had an inflow of 456.85 Mt CO_2, while the outflow was only 3.1 Mt CO_2. These downstream sectors of the industry chain do not directly consume energy. The creation of emission reduction strategies should also concentrate on the downstream sectors of the industry chain and design synergistic emission reduction methods because their manufacture demands significant amounts of energy supply and energy-intensive materials.

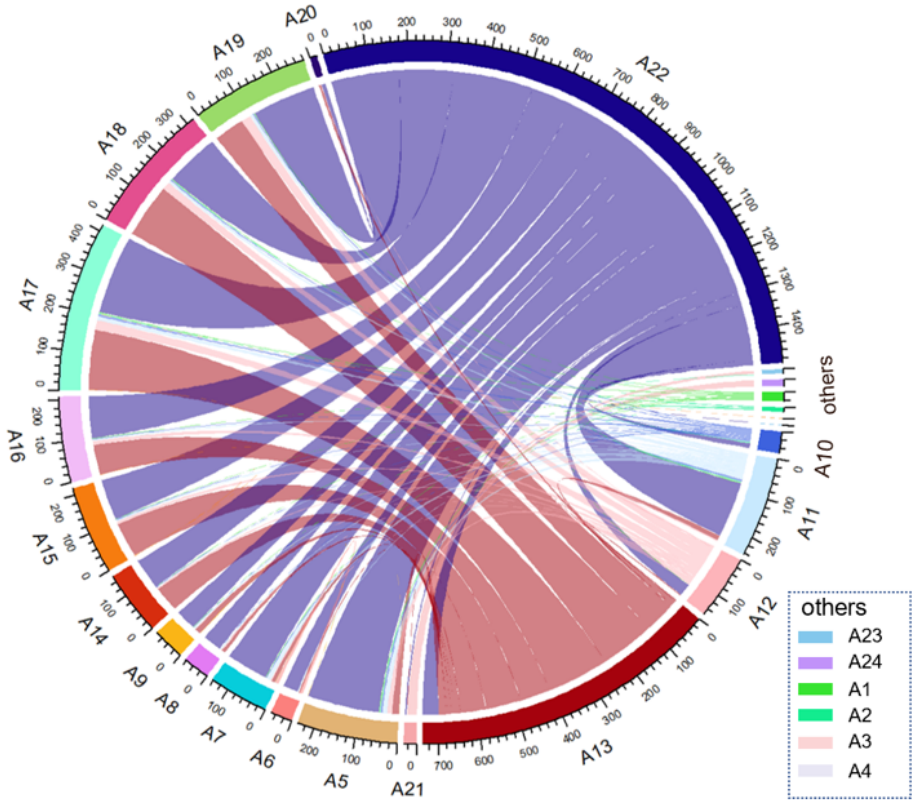

Figure 7. Chord chart of CO_2 transfer in 24 sectors of industry in 2017.

As shown in Figure 8, CO_2 flows from the mining industry to the raw materials industry and from the raw materials industry to the manufacturing industry constitute the main carbon transfer pathway between industries. As the linkages between industries continue to deepen, the flow of products from the electricity sector leads to separating manufacturing and consumption sites, resulting in a transfer of carbon emissions. The power, gas, and water production and supply, which provides electricity and energy to other sectors, is the largest sector in terms of the net outflow of carbon dioxide emissions. The transfer of 235.09 Mt CO_2 and 11,253.64 Mt CO_2 to the raw materials and manufacturing industries is vital for achieving China's emission reduction targets [55]. The manufacturing sector is the main influx of CO_2, absorbing 2,182.96 Mt of CO_2 from mining, raw material industries, and the production and supply of water, gas, and electricity. The direct production demand from the downstream sector of the industry chain impacts carbon emissions, and the indirect production demand significantly impacts carbon emissions [56]. Studying the main flow directions and pathways of carbon transfer is crucial to achieving carbon reduction in the industrial sector. Based on the research results, effective emission reduction measures can be formulated.

The industrial sector is an important engine driving socio-economic development and is a significant source of energy consumption and CO_2 emissions [7]. A carbon reduction approach centered on the industrial sector is the primary path for China's current and future low-carbon sustainable development [57]. The allocation of responsibility for emission reduction based on producer responsibility ignores the CO_2 emissions implicitly generated in the industrial chain due to product transportation and exchange, which puts the relevant industries under unequal policy pressure. Suppose emission reduction measures are taken only for sectors with high direct CO_2 emissions without considering the impact of intermediate demand from other sectors. In that case, it may lead to poor emission reduction results. It is difficult to effectively exploit the differences in carbon abatement costs of different industrial sectors to achieve a win–win outcome for both the abatement effect and the economic environment.

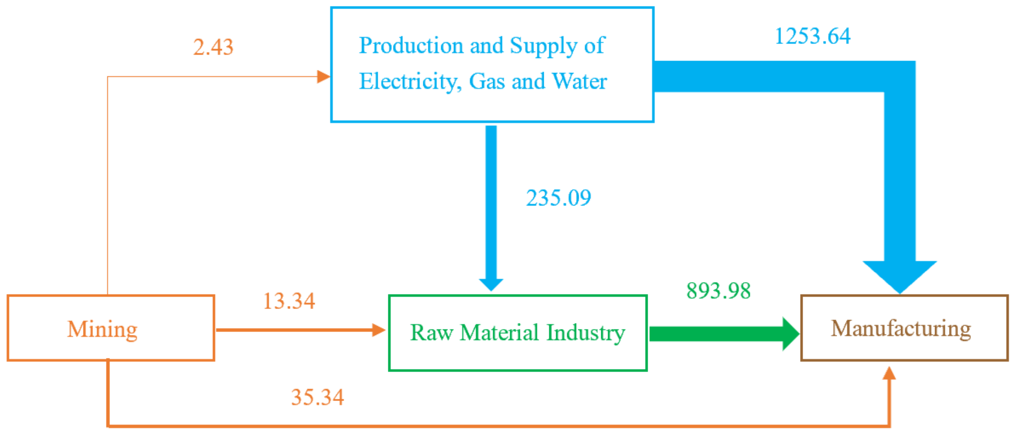

Figure 8. Carbon transfer path of industrial sector. (The blue lines show the transfer of CO_2 from the Production and supply of electricity, gas and water to others; The orange lines represent the transfer of CO_2 from mining to others. The green line is CO_2 transferred from raw material industries to manufacturing. The wider the lines, the greater the CO_2 transfer.)

In this paper, a study of the embodied carbon and carbon transfer pathways in industries finds that the electricity, heat, gas, and water production and supply industries convert energy into electricity, gas, and water for the production and manufacturing of mining, raw material industries, and manufacturing. Due to the large amount of fossil energy burned in the production process, the direct CO_2 emissions generated are more than the indirect CO_2 emissions, and a large amount of CO_2 is transferred to other industries. Renewable energy plays a crucial role in carbon emission reduction [58,59]. In China's green transformation and low-carbon development background, it is necessary to increase the proportion of renewable energy use and gradually reduce the scale of fossil energy, gradually improving the structure of energy consumption [60] . Manufacturing is a main influx of CO_2, producing much greater indirect CO_2 emissions than direct CO_2 emissions. Therefore, manufacturing should upgrade the level of low-carbon technology innovation and focus on the research and application of key practical technologies. At the same time, the upper, middle, and lower reaches of the industry chain should share the responsibility to reduce emissions and develop collaborative emission reduction strategies.

5. Conclusions and Suggestions

In this paper, we demonstrate the CO_2 emission linkages among 24 industrial sectors in China using the EIO-LCA and the HEM to map the pathways of CO_2 emission transfer among sectors. The carbon linkages among industrial systems are complex, and the development of downstream industries in the industrial chain increases the output of upstream industries. The Internal Emissions, Mixed Emissions, Net Forward Linkage Emissions, and Net Backward Linkage Emissions clearly show the amount of CO_2 transferred by each sector to achieve final demand.This research not only studies the carbon transfer of various sectors but also innovatively conducts in-depth analysis from the perspective of an industrial chain. It also provides data support for various industries to formulate coordinated emission reduction strategies.

The study found that the indirect CO_2 emissions of the industrial sector downstream of the chain are higher than the direct CO_2 emissions. Intersectoral carbon transfers constitute a significant part of the total CO_2 emissions of the industrial sector. Most sectors upstream of the industrial chain have significantly higher direct CO_2 emission intensity than indirect. These sectors have high energy intensity and absorb relatively little carbon transfer from other sectors. Sectors downstream of the industry chain have lower direct

CO_2 emission intensity, lower primary usage of energy, and higher indirect CO_2 emission intensity. The creation and provision of water, gas, electricity and raw materials industries transfer massive CO_2 emissions to other sectors, with manufacturing being the main influx of CO_2. CO_2 flows from the mining industry to the raw material industry and from the raw material industry to the manufacturing industry constitute the main inter-industrial carbon transfer pathway. According to the findings of the study, the following proposals are made:

The primary output sectors of carbon transfer include the upstream mining industry, the midstream raw material industry, and the industries that produce and provide electricity, gas, and water. Reducing the amount of high-carbon fossil fuels used and increasing the amount of low-carbon fossil and clean energy usage is the goal throughout the manufacturing process. In areas with concentrated mineral resources, industrial parks and clusters should be established to promote recycling resources and other measures to achieve carbon emission reduction targets.

Future emission reduction initiatives should concentrate on energy consumption in the downstream and energy-intensive industries upstream and midstream of the industrial chain. Government departments should further guide and encourage downstream industries to increase energy conservation and emission reduction investment to achieve a green upgrading of production mode. To encourage the development of energy-saving and emission-reduction technologies and the modernization of manufacturing equipment, fiscal and tax policies and related incentive and regulatory measures might be established, such as tax incentives for cleaner production industries and low-interest green loans.

While different industrial sectors are interdependent, advancing production technology across all industries is vital to support industrial transformation and upgrading. In order to realize both the reduction of industrial carbon emissions and economic growth objectives, from the perspective of structural optimization, it is also essential to alter the CO_2 transfer structure between industrial sectors.

This study has obtained some meaningful conclusions and suggestions, but there are still some limitations and deficiencies that need further improvement. The research data need to be updated. Since the input–output data and direct carbon dioxide emission data of various sectors have not been updated, the data from 2017 are used for analysis in this paper. In addition, more research dimensions and methods are worth further exploration.

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