sustainability

Article

Input–Output Analysis of China's CO_2 Emissions in 2017 Based on Data of 149 Sectors

Fan He [1,2], Yang Yang [1,2], Xin Liu [3], Dong Wang [1,2], Junping Ji [1,2,*] and Zhibin Yi [4]

1 School of Economics and Management, Harbin Institute of Technology, Shenzhen, Shenzhen 518055, China; 20S057027@stu.hit.edu.cn (F.H.); 20S057004@stu.hit.edu.cn (Y.Y.); clayton_wang@163.com (D.W.)
2 Shenzhen Engineering Laboratory of Big Data for Low-Carbon Cities, Harbin Institute of Technology, Shenzhen, Shenzhen 518055, China
3 School of Environment and Energy, Peking University Shenzhen Graduate School, Shenzhen 518055, China; bill.xinliu@pku.edu.cn
4 College of Tourism and Service Management, Nankai University, Tianjin 300350, China; zbyi@nankai.edu.cn
* Correspondence: jijunping@hit.edu.cn; Tel.: +86-135-0285-1983

Abstract: High-precision CO_2 emission data by sector are of great significance for formulating CO_2 emission reduction plans. This study decomposes low-precision energy consumption data from China into 149 sectors according to the high-precision input–output (I–O) table for 2017. An economic I–O life cycle assessment model, incorporating sensitivity analysis, is constructed to analyze the distribution characteristics of CO_2 emissions among sectors. Considering production, the electricity/heat production and supply sector contributed the most (51.20%) to the total direct CO_2 emissions. The top 10 sectors with the highest direct CO_2 emissions accounted for >80% of the total CO_2 emissions. From a demand-based perspective, the top 13 sectors with the highest CO_2 emissions emitted 5171.14 Mt CO_2 (59.78% of the total), primarily as indirect emissions; in particular, the housing construction sector contributed 23.97% of the total. Based on these results, promoting decarbonization of the power industry and improving energy and raw material utilization efficiencies of other production sectors are the primary emission reduction measures. Compared with low-precision models, our model can improve the precision and accuracy of analysis results and more effectively guide the formulation of emission reduction policies.

Keywords: carbon emissions; input–output analysis; energy allocation; life cycle assessment

Citation: He, F.; Yang, Y.; Liu, X.; Wang, D.; Ji, J.; Yi, Z. Input–Output Analysis of China's CO_2 Emissions in 2017 Based on Data of 149 Sectors. *Sustainability* **2021**, *13*, 4172. https://doi.org/10.3390/su13084172

Academic Editor: Silvia Fiore

Received: 26 February 2021
Accepted: 6 April 2021
Published: 8 April 2021

1. Introduction

With increasing global climate change, the reduction of carbon emissions whose major source is energy combustion [1] has become the focus of all countries. In 2019, China had the highest carbon emissions accounting for approximately 27.9% of global carbon emissions [2]. Therefore, it is important to reduce the country's emissions in order to contribute to global climate change mitigation. At the 75th United Nations General Assembly in September 2020, China proposed to achieve peak CO_2 emissions by 2030 and carbon neutrality by 2060. To facilitate formulation of emission reduction plans, it is necessary to study China's carbon emissions from energy combustion based on a higher sector resolution.

The aggregation and decomposition of emission sectors are important aspects of research on CO_2 emissions mitigation. The classification of sectors in the China Energy Statistical Yearbook (e.g., [3]) varies from that used in the input–output (I–O) table (e.g., [4]). The former lists approximately 40 categories, while in the latter, there are >100 sectors. To maintain consistency between the two with energy consumption data, most studies aggregate the I–O tables into approximately 40 sectors. However, this may cause inaccurate estimations and distortion of carbon emissions at the sectoral level [5–8]. Lenzen [9] proved that, in case information required for sectoral decomposition is lacking, the results of sectoral decomposition based on a small amount of actual data are better than the results of sectoral aggregation. Lindner et al. [10] demonstrated that when the power sector was disaggregated, an increased amount of information led to an increased accuracy in the carbon emission intensity of each sector obtained through sectoral decomposition. Therefore, it is necessary to further split the sectors and use higher sector resolution data to investigate carbon emissions and, thus, improve the reliability and accuracy of the analysis results.

There are two methods for sectoral disaggregation. The first method involves decomposition of the I–O table and most studies using this method usually only focus on a few typical sectors [8,11–16], such as the construction and power sectors. Meng et al. [11] divided the construction sector into 12 subsectors based on the sectoral intermediate purchases and investment data and obtained the extended I–O table of 53 sectors of Beijing city. Linder et al. [12] used regional information and cost data for operation and maintenance of power plants to split the electricity sector into transmission, distribution and eight other subsectors representing different types of technology in power plants. Moreover, some studies have used other methods to obtain power subsectors [13,15]. However, the decomposition method cannot be effectively applied to the complete I–O table. It cannot satisfy the requirement of decomposing the energy consumption table; hence, we do not employ this method in our study.

The second method is to decompose energy consumption data or carbon emission data. Few studies apply this method, as it has higher requirements for sectoral data. Insufficient sectoral data may introduce biases in this allocation method [17]. In general, energy consumption data are allocated based on the sectoral intermediate purchases or demands and carbon emissions data are allocated based on the sectoral carbon emission intensity. Minx et al. [18] and Zhang et al. [17] decomposed the carbon emission and energy consumption data, respectively, of multiple sectors to correspond to sectors in the I–O table. The allocation coefficients obtained by Minx et al. were based on the carbon emission intensity of 95 sectors derived by normalization and that of the latter, was based on sectoral direct inputs. Douglas and Nishioka [19] allocated carbon emission data based on the sectoral intermediate demands. However, these studies have their own limitations. The sector resolution of Douglas and Nishioka [18] was too low and only included 41 sectors, even after decomposition. After using the allocation method, the number of sectors in Zhang et al. [17] and Minx et al. [18] were 95 and 135, respectively. However, the latter lacks more accurate allocation coefficients than the former, because it assumed that all I–O sectors that map to the one energy sector have the same emission intensity (the number of carbon emission intensity data before normalization were only 44). Although Zhang et al. [17] is the most accurate of the three; they did not deduct the non-energy use of fuels when calculating the total carbon emissions. Moreover, the allocation method of their study also needs to be improved.

To solve the above shortcomings, the present study uses the 2017 I–O table of 149 sectors in China and decomposed energy consumption data to construct an economic I–O life cycle assessment (LCA) carbon emission analysis model [20]. The model incorporates production- and demand-based perspectives to analyze the distribution of carbon emissions from energy combustion among sectors. Most of the current studies employ structural decomposition analysis (SDA) to analyze carbon emissions [18,21–23]. However, the core objective of this study is to analyze the sectoral distribution characteristics of high-precision carbon emission data of China. Therefore, we utilize the economic I–O LCA (EIO–LCA) [20], even though it appears relatively simple, to analyze carbon emissions. Furthermore, as uncertainty management is indispensable to any model development and evaluation [24], we incorporated sensitivity analysis of changing number of sectors in our model to improve the reliability of our results.

There exist a few studies that apply uncertainty or sensitivity analysis in the I–O model of environmental extension [25]. However, the incorporation of sensitivity analysis into the framework of this study makes our approach a novel one. Our study improves on the allocation method used in Zhang et al. [17] by extending the number of sectors from 45 to 149. Specifically, when the distribution coefficient is 0, we modified the coefficient to make our allocation reasonable. Compared with other similar work [17,18], our results are more accurate. We achieved this accuracy by adopting more precise allocation coefficients. Additionally, we address the limitation that Zhang et al. [17] failed to deduct the non-energy use of fuels.

The rest of this paper is structured as follows: Section 2 details the methods and data sources used in this study, focusing on the method of energy consumption data allocation. Section 3 analyzes and discusses the results. Finally, Section 4 summarizes the conclusions, highlights the limitations and puts forward the main policy suggestions.

2. Method and Data

2.1. Method

2.1.1. EIO–LCA Model

This study used the EIO–LCA model [20] to analyze China's carbon emissions. The model is expressed by Equation (1):

$$\mathbf{B} = \mathbf{R}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{y}}, \tag{1}$$

where $\mathbf{B}$ represents the sectoral carbon emission matrix; $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix, where $\mathbf{I}$ is an identity matrix and $\mathbf{A} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}$, which is a direct consumption coefficients matrix of the I–O table; $\hat{\mathbf{y}}$ is diagonal matrix of the final demand column in I–O table; and $\mathbf{R} = \mathrm{diag}(r_{11}, r_{22}, \cdots r_{nn})$, which is the amount of CO_2 directly emitted by a sector per unit of monetary output, where $r_{ii} = \frac{c_i}{x_i}$, c_i represents sectoral carbon emissions, x_i represents the total sectoral output.

2.1.2. Energy Consumption Data Allocation Method

Few studies completely divide the energy consumption sector according to the sector classification of the I–O table. We primarily referred to Zhang et al. [17] and Minx et al. [18] as they are more representative. The former represents the allocation of energy consumption data based on direct inputs and the latter represents the allocation of carbon emissions data based on carbon emission intensity. Minx et al. [18] obtained the carbon emission intensity of 95 sectors (the number of sectors of I–O table) in three steps. First, the output was aggregated into the sector classification used in the energy and emissions data; second, the emission intensity of 44 sectors (the number of sectors of energy consumption table) was obtained; finally, all I–O sectors that map to the one energy sector were assumed to have the identical emission intensity which was normalized to obtain the emission intensity of 95 sectors. To obtain the carbon emission inventory of 135 sectors, Zhang et al. [17] first calculated the energy consumption data allocation coefficients according the direct inputs of the fuel production sectors; then, these coefficients were multiplied with the corresponding energy consumption data to derive the energy consumption table of 135 sectors; the process can be formulated as Equation (2):

$$e_{k,\mathrm{ja}} = e_{k,\mathrm{j}} \times \frac{z_{\mathrm{p,ja}}}{z_{\mathrm{p,ja}} + \ldots + z_{\mathrm{p,jk}}}, (2 \le k < 135) \tag{2}$$

where $e_{k,\mathrm{ja}}$ and $e_{k,\mathrm{j}}$ represent the consumption of fuel type (k) corresponding to sectors ja and j, respectively; $z_{\mathrm{p,ja}}$ and $z_{\mathrm{p,jk}}$ represent the intermediate inputs of sector p to sectors ja and jk. Sectors ja ... jk are all subsectors of sector j.

Thus, we split some sectors of the energy consumption table according to the "Industrial classification for national economic activities" (GB/T 4754-2017) [17,26]. There were 149 sectors after decomposition (Table A1) and for ease of presentation, the sectors in the figures are represented by their corresponding numbers. Briefly, different types of energy were correlated with 149 sectors that produce the corresponding type of energy. Then, the allocation coefficients of energy consumption data were linked to the proportion of the sectoral intermediate inputs in the I–O table. Finally, this ratio was multiplied by the energy consumption of the corresponding sector in the energy consumption table of 45 sectors to derive an energy consumption table of 149 sectors. A schematic of this method is shown in Figure 1.

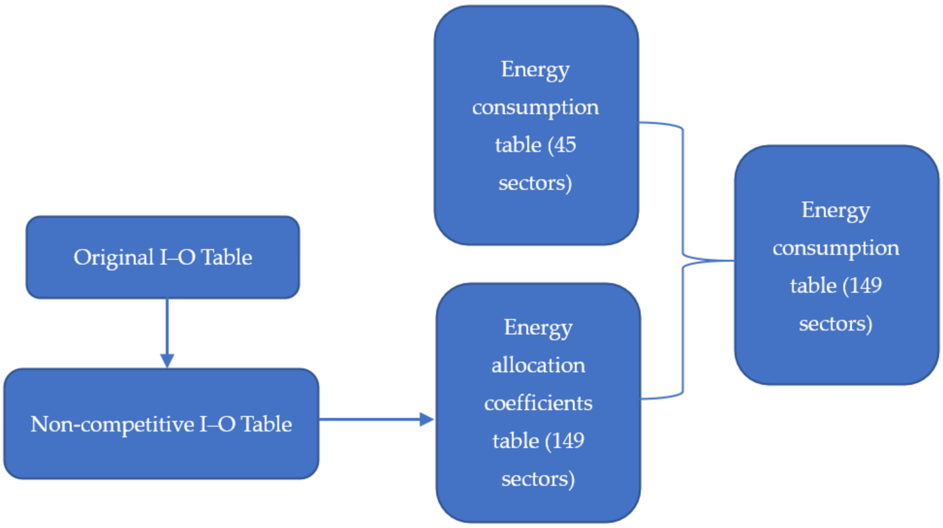

Figure 1. Schematic of energy consumption data allocation method (I–O: input–output).

Before allocating the energy consumption data, the energy consumption data allocation coefficient of each sector was calculated using Equations (3) and (4):

$$d_{p,ji} = \frac{z_{p,ji}}{z_{p,j}} \tag{3}$$

$$z_{p,j1} + z_{p,j2} + \ldots + z_{p,jn} = z_{p,j}, \ (2 \leq n < 149) \tag{4}$$

where p indicates the sector producing this type of fuel (energy) in the I–O table of 149 sectors (Table 1); $d_{p,ji}$ indicates the allocation coefficient of energy production sector p corresponding to sector ji; $z_{p,ji}$ and $z_{p,j}$ represent the intermediate inputs of sector p to sector ji and j, respectively; sectors j1, j2 . . . jn are all subsectors of sector j and $2 \leq n < 149$. The corresponding relationship is shown in Table A1. Figure 2 shows the schematic diagram that explains the attainment of allocation coefficients of energy consumption data. We considered raw coal consumed by farming (sector 01) as an example. Its allocation coefficient is equal to the intermediate input of mining and washing of coal (sector 06) to farming (sector 01), divided by the intermediate input of sector 06 to the primary industry (sectors 01–05). The parameters are appropriately represented in Figure 2. The production sector of raw coal corresponds to the mining and washing of coal (sector 06) in the I–O table, coke corresponds to the processing of coal (sector 42), natural gas corresponds to the extraction of petroleum and natural gas (sector 07) and gasoline corresponds to the processing of refined petroleum and nuclear fuel (sector 41). Finally, the energy allocation coefficients corresponding to the four fuel production sectors (sectors 06, 07, 41 and 42) can be calculated according to corresponding sectors.

Table 1. Energy consumption data allocation (I–O: input–output).

I–O Table Number	Fuel (Energy) Production Sector (p) In The I–O Table	Corresponding Fuel Type (k) In The Energy Consumption Table
06	Mining and washing of coal	All coal products
07	Extraction of petroleum and natural gas	Crude oil, liquefied natural gas and natural gas
41	Processing of refined petroleum and nuclear fuel	All petroleum products
42	Processing of coal	Coke, coal gas and other coking products

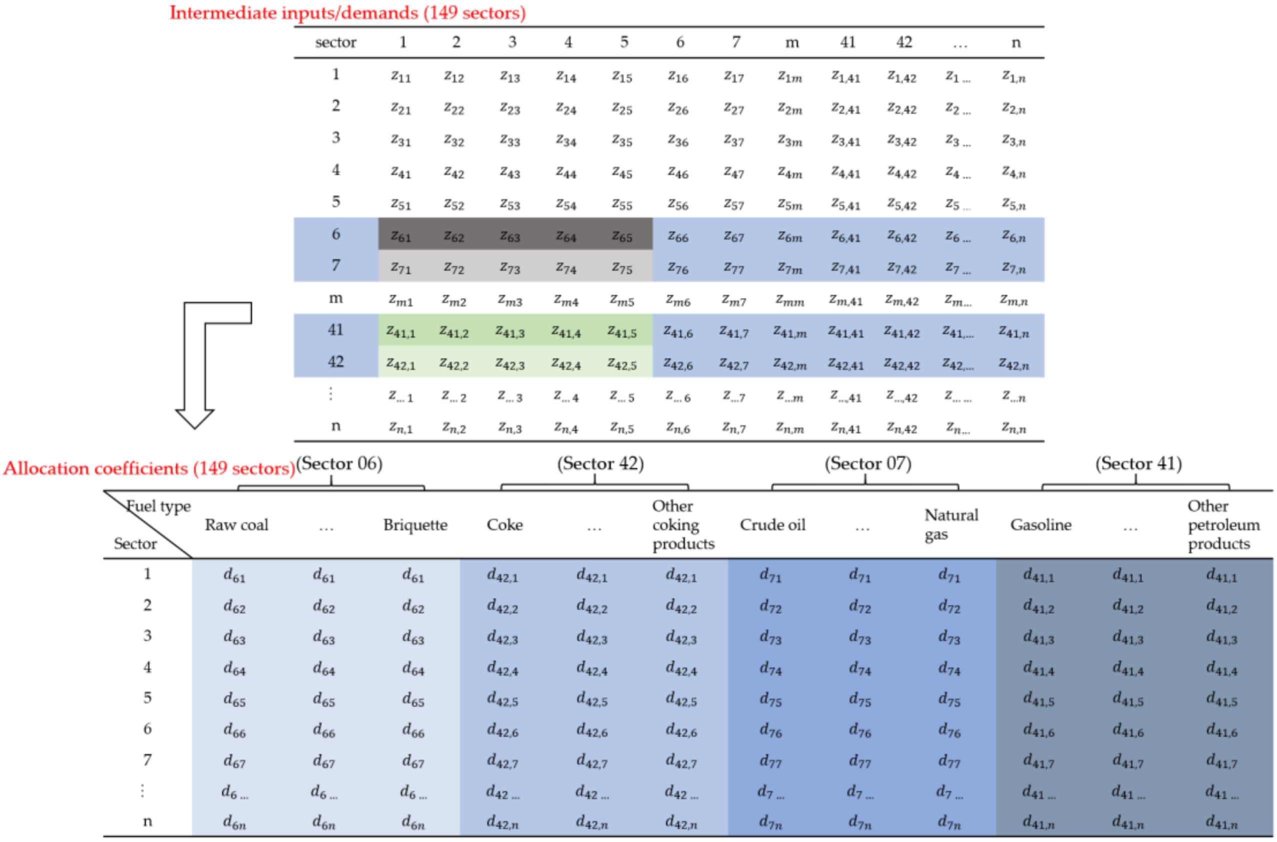

Figure 2. Schematic diagram for deriving the energy consumption data allocation coefficients.

Then, using the allocation coefficients obtained above, the energy consumption of different energy types in the 149 sectors can be calculated by Equations (5) and (6):

$$e^{D}_{k,ji} = e^{A}_{k,j} \times d_{p,ji}, \tag{5}$$

$$e^{D}_{k,j1} + e^{D}_{k,j2} + \ldots + e^{D}_{k,jn} = e^{A}_{k,j}, \ (2 \leq n < 149) \tag{6}$$

where **D** and **A** represent the disaggregated and aggregated matrices, respectively; they correspond to a 149 × 149 and 45 × 45 matrix; k represents different types of energy; $e^{D}_{k,ji}$ indicates the consumption of k corresponding to the sector ji in the energy consumption table of 149 sectors; and $e^{A}_{k,j}$ indicates the consumption of k corresponding to the sector j. As an example of the application of this equation: the consumption of raw coal by farming (sector 01) in the energy consumption table of 149 sectors should be equal to the consumption of raw coal by agriculture, forestry, animal husbandry and fishery (sector 01 in the 45-sector classification) multiplied by the allocation coefficient of raw coal corresponding to the farming (sector 01).

However, according to the above calculation process, there are still some energy consumption data that cannot be fully allocated. Specifically, the intermediate input of a certain energy production sector to other sectors (corresponding to one or more sectors in the I–O table of 149 sectors) may be 0. For example, in Table 1, the intermediate input of processing of coal (sector 42) to the primary industry (sectors 01–05) is 0, but agriculture, forestry, animal husbandry and fishery (sector 01 in the 45-sector classification) consume coke and other coking products. Similarly, the intermediate input of the extraction of petroleum and natural gas (sector 07) to wholesale/retail trade and catering (sectors 117–120) is also 0; however, wholesale/retail trade and catering (sector 44 in the 45-sector classification) consume natural gas.

Zhang et al. [17] did not consider the above problems. However, we provide specific solutions. In case, the intermediate input is 0 when the energy consumption data are allocated, then the allocation coefficient corresponding to processing of coal (sector 42) is updated to the allocation coefficient corresponding to the mining and washing of coal (sector 06); similarly, the allocation coefficient corresponding to the extraction of petroleum and natural gas (sector 07) is updated to the allocation coefficient corresponding to the processing of refined petroleum and nuclear fuel (sector 41). In this manner, we can use the adjusted allocation coefficients to calculate the energy consumption of 149 sectors.

After obtaining the preliminary energy consumption table of the 149 sectors according to the above-mentioned allocating method, the amount of energy loss was allocated to each sector based on the proportion of energy consumption of various sectors. Next, the energy consumption for raw materials was obtained according to the proportion of energy consumption in sectors 41–60 (except for sector 50, which does not use energy for raw material); this value was then subtracted from the total energy consumption to obtain the energy consumption for combustion. The energy consumption for power generation and heating were allocated to the production and supply of electric/heat power (sector 98) and the net international marine fuel consumption was allocated to sectors 105–116 according to the proportion of energy consumed in the sector.

2.1.3. Sectoral CO_2 Emission Calculation Method

In this study, the sectoral approach was used to calculate CO_2 emissions from energy combustion in order to improve the accuracy of the sub-sectoral CO_2 emission data to the maximum extent. According to the energy consumption table of the 149 sectors obtained by the above method, the CO_2 emissions of these sectors can be calculated by Equation (7):

$$c_{k,j} = e^{\mathbf{D}}_{k,j} \times lvh_k \times CF_{k,j}, \tag{7}$$

where $c_{k,j}$ represents the CO_2 emissions produced by sector j consuming fuel k; $e^{\mathbf{D}}_{k,j}$ represents the consumption of fuel k by sector j; lvh_k represents the average low calorific value of fuel k; and $CF_{k,j}$ represents the carbon emission factor of fuel k consumed by sector j, which can be written as Equation (8):

$$CF_{k,j} = C_{k,j} \times O_{k,j} \times 44/12, \tag{8}$$

where $C_{k,j}$ represents the carbon content of fuel k consumed by sector j and $O_{k,j}$ represents the carbon oxidation rate of fuel k consumed by sector j.

2.2. Data

2.2.1. Non-Competitive I–O Table

This study only analyzes the impact of China's domestic economic activities on sectoral carbon emissions. However, the 2017 I–O table of 149 sectors issued by the National Bureau of Statistics of China [4] is a competitive I–O table, which integrates domestic products and services with imported products and services in intermediate inputs. This approach may overestimate the impact of the final demands on sectoral carbon emissions [27,28]. To solve this problem, the methods of Chen et al. [29] and Tian et al. [30] were used for reference to construct the 2017 non-competitive I–O table by dividing the intermediate inputs and final demands into domestic and import parts. We assumed that the import rates of a sector's intermediate and final demands (excluding exports) were identical and equal to the sector's average import rate. Then, the demand for imported products were subtracted from the sector's intermediate and final demand according to this ratio to obtain the intermediate and final demands of domestic products, as expressed by Equations (9) and (10):

$$z_{ij} = z_{ij}^{O} \times \left(1 - a_i^{M}\right) \tag{9}$$

$$f_i = f_i^{O} \times \left(1 - a_i^{M}\right) \tag{10}$$

where z_{ij} and f_i represent the intermediate and final demands in the non-competitive I–O table, respectively; z_{ij}^{O} and f_i^{O} represent the intermediate and final demands in the original competitive I–O table, respectively; $a_i^{M} = \frac{m_i}{g_i}$ represents the average import rate of sector i; m_i represents the imports of sector i; and g_i represents the sum of the total intermediate demand and the total final demand excluding exports of sector i.

2.2.2. Energy Consumption Data and Carbon Emission Factors

The energy consumption data used in this study were obtained from the energy balance sheet and final physical energy consumption table by industry in the 2018 China Energy Statistical Yearbook [3]. The I–O data were obtained from the non-competitive I–O table of 149 sectors after processing (as in Section 2.2.1). The carbon emission factor data were from the "Provincial Greenhouse Gas Inventory Compilation Guide (Trial)" [31] and "2005 People's Republic of China National Greenhouse Gas Inventory" [32].

3. Results and Discussion

3.1. Sectoral CO_2 Emissions Based on the Production Perspective

Figure 3 shows the direct CO_2 emissions of various sectors in China. The production and supply of electric/heat power (sector 98) was the sector with the highest direct CO_2 emissions (4429.59 Mt), accounting for 51.20% of the total CO_2 emissions from all sectors. Each of the top 10 sectors emitted >100 Mt of CO_2 (Table 2), leading to a collective direct CO_2 emission of 7061.11 Mt, which accounted for 81.62% of the total CO_2 emissions from all sectors. As most of the CO_2 emissions were generated from these 10 sectors, from a production-based perspective, emission reduction policies should focus on the production practices of them to control the corresponding direct CO_2 emissions.

Table 2. Sectors with the 10 highest direct CO_2 emissions.

	Sector	**Direct CO_2 Emissions (Mt)**	**Proportion of Total CO_2 Emissions from All Sectors**
98	Production and supply of electric and heat power	4429.59	51.20%
62	Rolling of steel	1283.75	14.84%
108	Cargo transport via road and support activities	344.27	3.98%
61	Steelmaking	174.81	2.02%
56	Manufacturing of brick, stone and other building materials	171.60	1.98%
43	Manufacturing of basic raw chemical materials	152.62	1.76%
41	Processing of refined petroleum and nuclear fuel	143.36	1.66%
110	Water cargo transport and support activities	136.06	1.57%
54	Manufacturing of cement, lime and gypsum	117.24	1.36%
63	Smelting of iron and ferroalloy	107.82	1.25%
	Total	7061.11	81.62%

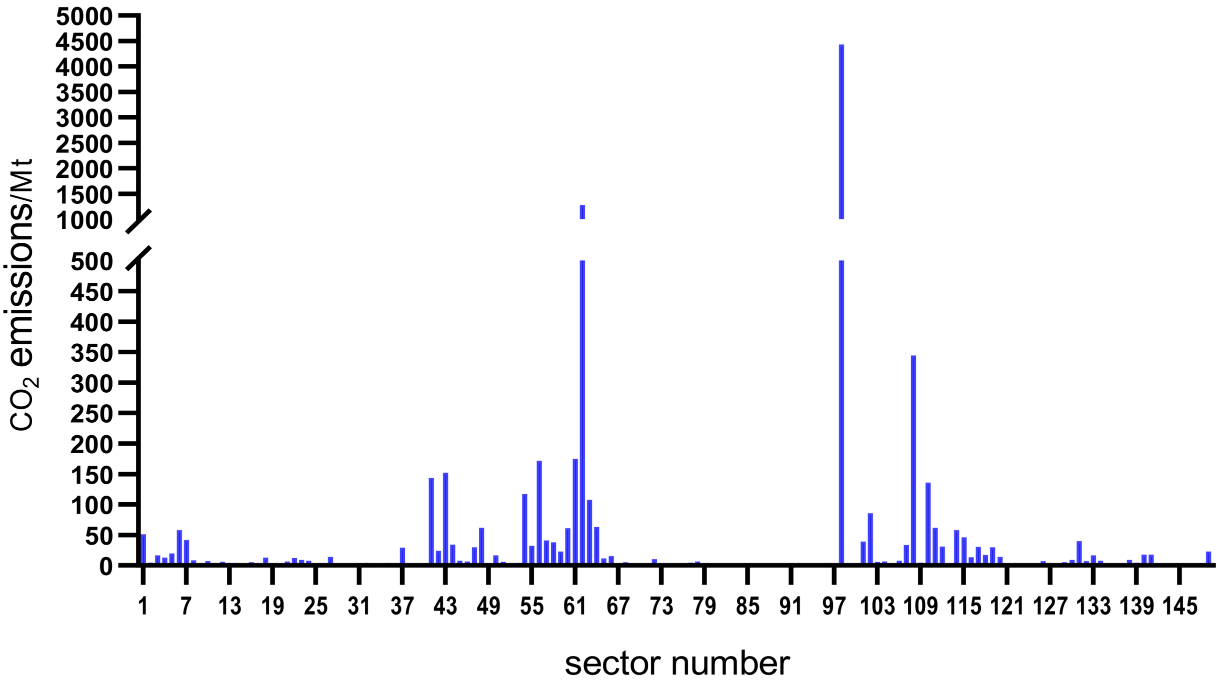

Figure 3. Direct CO_2 emissions of different sectors.

Figure 4 presents the relationship between the direct CO_2 emissions of sector 98 (production and supply of electric/heat power) and the final demands of other sectors. This shows that 91.10% of CO_2 emissions from sector 98 were generated by providing electricity and heat to other sectors (not including sector 98 itself). The top seven sectors (sectors 101, 98, 102, 77, 103, 141 and 149) that consumed the most electricity and heat induced 2184.19 Mt of CO_2 emissions from sector 98, which is nearly half of the total direct emissions from this sector (Table 3). The highest contribution was from housing construction (sector 101), which accounted for 19.98% of the total direct emissions from the supply of electric and heat power (Table 3). Therefore, emission reduction in sector 98 could commence considering the following two aspects. First, improvement of the power generation efficiency of electric/heat power and controlling carbon emissions in the power generation process. Second, improvement of the power efficiency of other sectors, especially the six sectors listed in Table 3, to control power consumption in production activities.

Table 3. Direct CO_2 emissions from the production and supply of electric/heat power (sector 98) caused by the electric/heat demand of the top seven sectors.

	Sector	Direct CO_2 Emissions from Sector 98 (Mt)	Proportion of Total CO_2 Emissions from Sector 98
101	Housing construction	884.89	19.98%
98	Production and supply of electric and heat power	394.40	8.90%
102	Civil engineering construction	381.67	8.62%
77	Manufacture of cars	144.78	3.27%
103	Construction and installation	132.89	3.00%
141	Health	123.41	2.79%
149	Public management and social organization	122.15	2.76%
Total		2184.19	49.31%

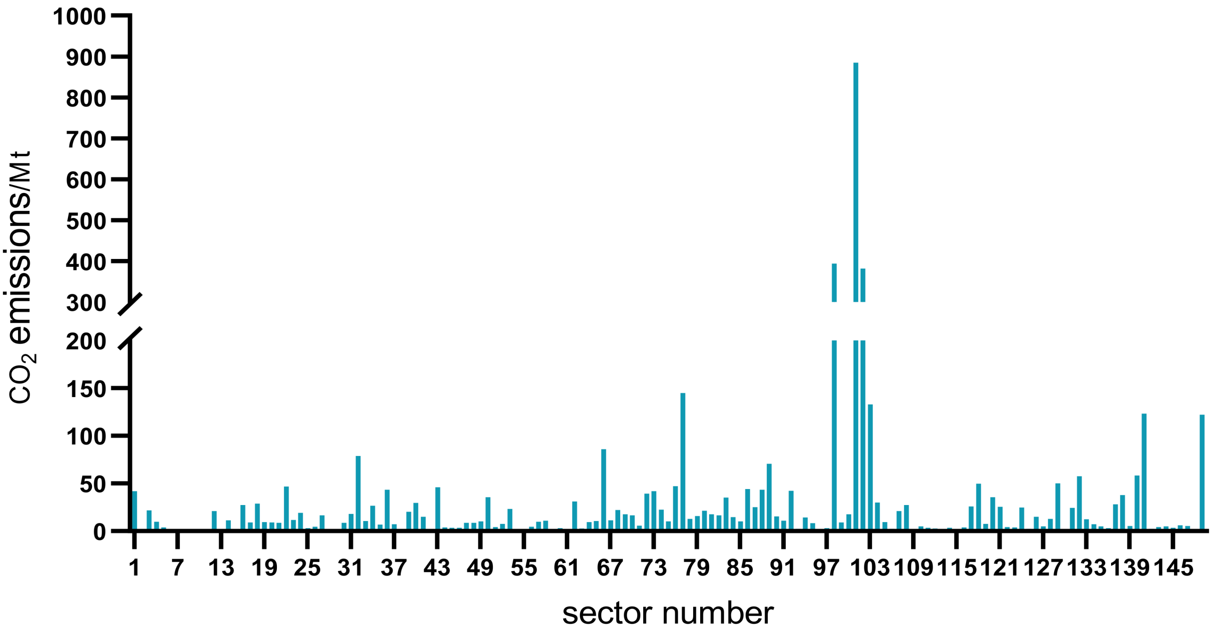

Figure 4. Composition of direct CO_2 emissions from the production and supply of electric/heat power (sector 98).

3.2. Sectoral CO_2 Emissions Based on the Demand Perspective

In some cases, the production activities of upstream and downstream sectors influence the CO_2 emissions of other sectors. The embodied CO_2 emissions caused by the final demands of various sectors in China are displayed in Figure 5. The highest embodied emissions were caused by the final demand of housing construction (sector 101), which contributed 2073.73 Mt of CO_2 (23.97% of the total emissions; Table 4), most of which was emitted by other sectors along the supply chain. The top 13 sectors with the highest embodied emissions contributed 5171.14 Mt of CO_2, accounting for 59.78% of the total emissions from all sectors. The embodied CO_2 emissions of most sectors were mainly indirect emissions. Therefore, from a demand-based perspective, the focus should be on formulating emission reduction policies for the final demands of these 13 sectors to control corresponding CO_2 emissions.

Table 4. Embodied CO_2 emissions of major sectors.

Sector		Embodied CO_2 Emissions (Mt)	Proportion of Total CO_2 Emissions
101	Housing construction	2073.73	23.97%
102	Civil engineering construction	960.17	11.10%
98	Production and supply of electric and heat power	402.13	4.65%
77	Manufacture of cars	287.78	3.33%
103	Construction and installation	220.07	2.54%
141	Health	209.06	2.42%
149	Public management and social organization	205.11	2.37%
66	Manufacture of metal products	173.00	2.00%
108	Cargo transport via road and support activities	154.35	1.78%
62	Rolling of steel	145.27	1.68%
32	Manufacture of textile, clothing apparel and accessories	127.67	1.48%
89	Manufacture of communication equipment	107.38	1.24%
140	Education	105.40	1.22%
Total		5171.14	59.78%

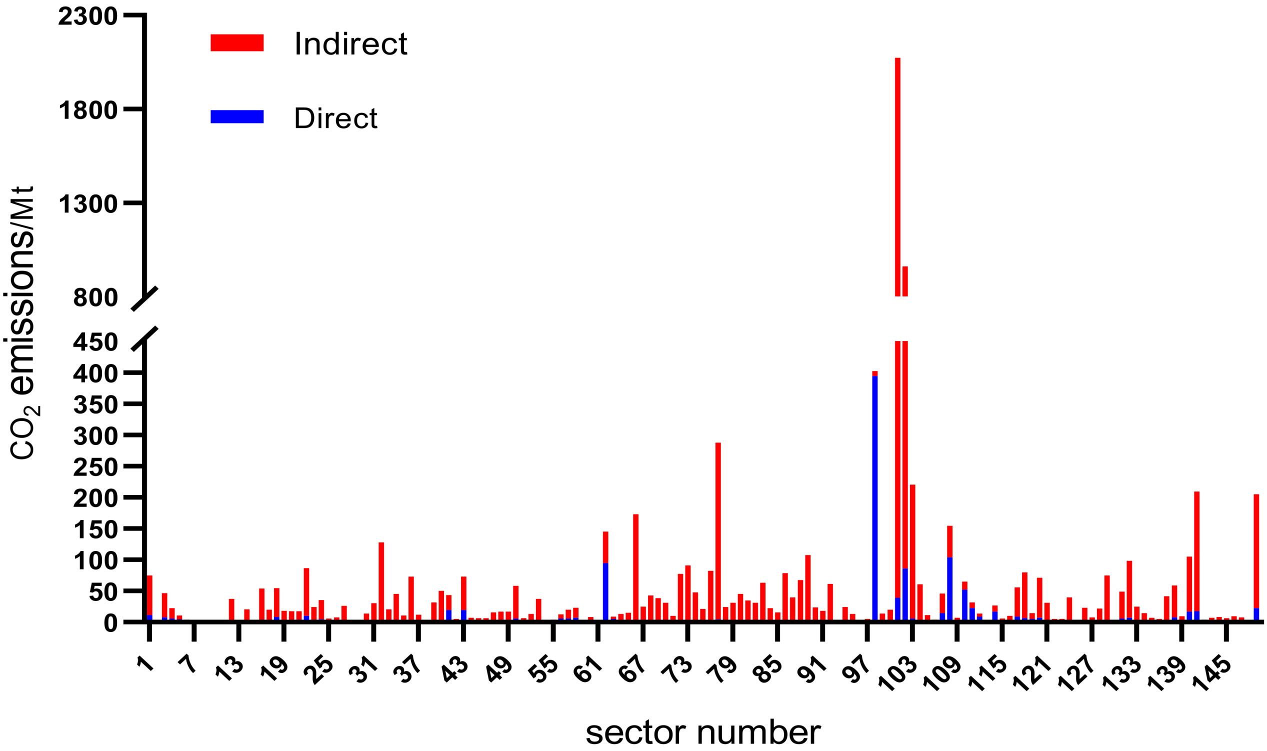

Figure 5. Sectoral embodied CO_2 emissions by final demand.

Because the embodied CO_2 emissions of housing construction (sector 101) accounted for the largest proportion of the total emissions, we decomposed the CO_2 emissions caused by the final demand of sector 101 to observe the contributions of various sectors to it (Figure 6). Table 5 shows that the highest contribution was from sector 98 (production and supply of electric/heat power; 884.89 Mt CO_2), accounting for 42.67% of the total emissions of sector 101. The next highest contribution was from the rolling of steel subsector (sector 62; 24.91%); however, the sector itself (sector 101) accounted for only 1.88% (Table 5). Therefore, the following two key points based on the final demand of the housing construction sector for controlling the CO_2 emissions caused must be considered. First, improvement of the efficiency of the use of raw materials for housing construction and reduction of the use of main raw materials while maintaining the final demand remains. Second, implementation of technological upgrades in the six sectors specified in Table 5 to control the amount of direct CO_2 emissions during their production stages.

Table 5. Embodied CO_2 emissions of major sectors caused by the final demand of the housing construction sector.

Sector		Embodied CO_2 Emissions (Mt)	Proportion of Total CO_2 Emissions Caused by Sector 101
98	Production and supply of electric and heat power	884.89	42.67%
62	Rolling of steel	516.48	24.91%
56	Manufacture of brick, stone and other building materials	123.83	5.97%
54	Manufacture of cement, lime and gypsum	77.62	3.74%
61	Steelmaking	62.07	2.99%
108	Cargo transport via road and support activities	51.62	2.49%
Total		1716.51	82.77%

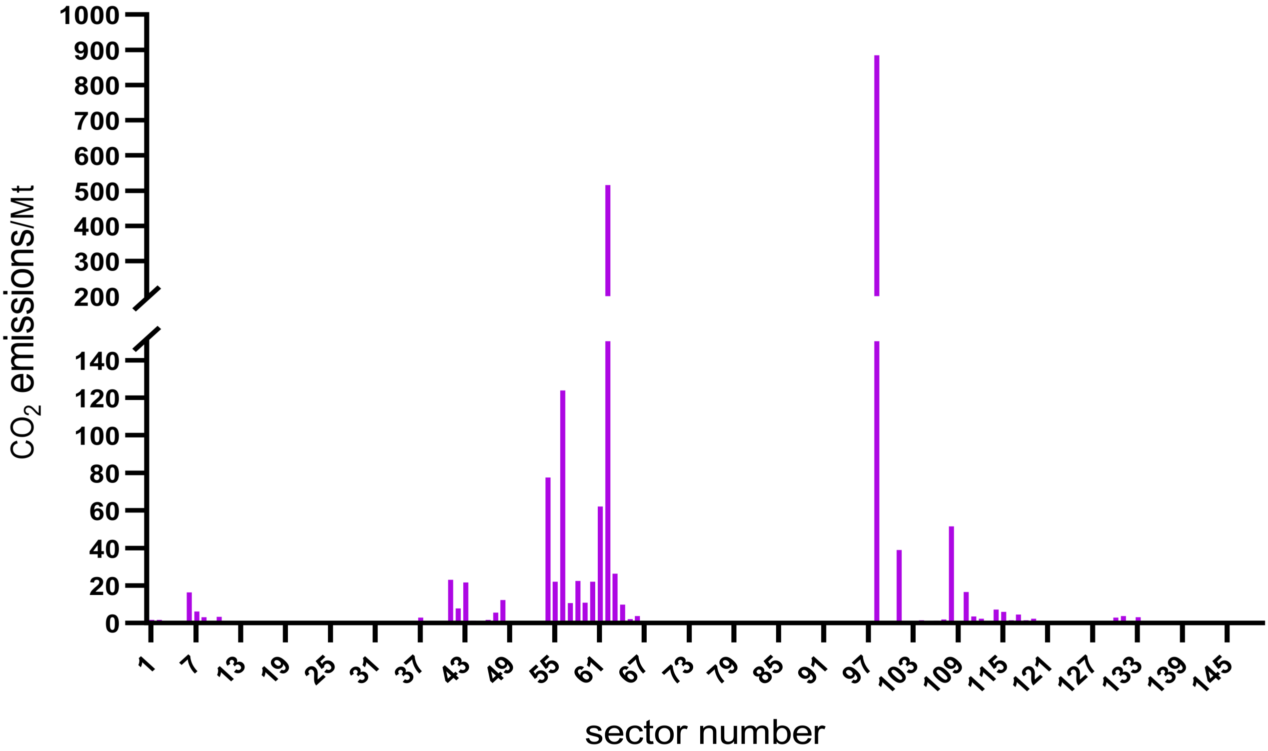

Figure 6. Composition of embodied CO_2 emissions caused by the final demand of the housing construction sector.

3.3. Comparisons with Similar Studies

Chang et al. [14] and Zhang et al. [17] both used disaggregated I–O model to analyze issues in the field of energy or environment. Chang et al. [14] developed an I–O LCA model that disaggregated the construction sector of I–O tables into 14 subsectors, including 13 building types and civil engineering projects, to calculate the product chain energy of different building types in China. Their results indicated that aggregation in the construction sector led to a 15–225% overestimation of the product chain energy of buildings; the difference in material consumption of different building types cannot be sufficiently reflected in the aggregated I–O model, consequently affecting the accuracy of the calculation of the building embodied energy. This is similar to our results, which suggests that the disaggregated model has a higher-precision sectoral level and thus, can more precisely reflect the link of carbon emissions between sectors and improve the accuracy of our analysis. Zhang et al. [17] also obtained similar results, indicating that the use of aggregated models will distort the allocation of embodied carbon emissions in sectors with large carbon emissions.

However, the total carbon emissions calculated by Zhang et al. [17] were inaccurate. First, the non-energy use of fuels was incorrectly included for combustion, leading to overestimation of the total carbon emissions by double counting the carbon emissions of this part. Second, their conclusions stated that the total carbon emissions of the 135-sector classification were different from those of the 42-sector classification, which does not agree with the results of our study. According to the energy consumption data allocation method used in Zhang et al. [17], when the original energy consumption table of the 42 sectors is split into the energy consumption table of the 135 sectors, the total calculated carbon emissions in these two cases should be equal because the total energy consumption is constant. In Section 3.4, we compare China's 2017 carbon emission inventory of 149 sectors with that of 45 sectors, whereby the total CO_2 emissions in both cases were the same, but the distribution of CO_2 emissions between sectors differed.

3.4. Comparison of CO_2 Emission Inventories: 149 Sectors and 45 Sectors

To obtain the CO_2 emission inventory of 45 sectors, we aggregated the sectors in the 2017 I–O table according to the "Industrial classification for national economic activities" (GB/T 4754-2017) [26] to make them consistent with the sectors in the energy consumption table. After processing the I–O table of 149 sectors into 45 sectors, the EIO–LCA model was used to analyze the CO_2 emissions of these 45 sectors.

The results demonstrated that the sum of the direct CO_2 emissions of groups of subsectors in the carbon emission matrix of the 149 sectors was the same as that of the larger sectors of the 45 sectors. For example, the sum of the direct CO_2 emissions of sector 61–63 in the 149 sectors was equal to the CO_2 emissions of sector 26 in the 45 sectors (Figure 7). However, the embodied CO_2 emissions were inconsistent. Considering the construction industry as an example, the embodied CO_2 emissions of this sector in the 45-sector classification were 3238.72 Mt, while the sum of embodied CO_2 emissions of sectors 101–104 of the 149-sector classification was 3314.52 Mt (2.34% more than the former). This is because direct sectoral CO_2 emissions data were used for the analysis in the EIO–LCA model. However, such differences were not distinct and had a negligible impact on the subsequent analysis; therefore, Figure 8 shows the relationship between the embodied CO_2 emissions of the construction sector in the 45-sector classification and the corresponding sectors in the 149-sector classification from a demand-based perspective.

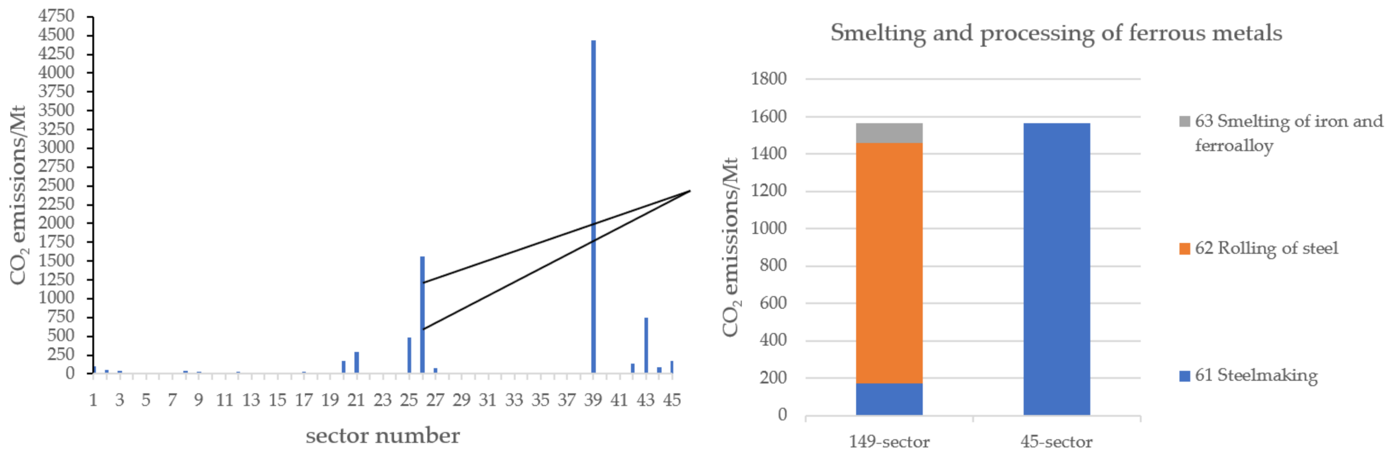

Figure 7. CO_2 emission decomposition of the smelting and processing of ferrous metals sector from the production-based perspective.

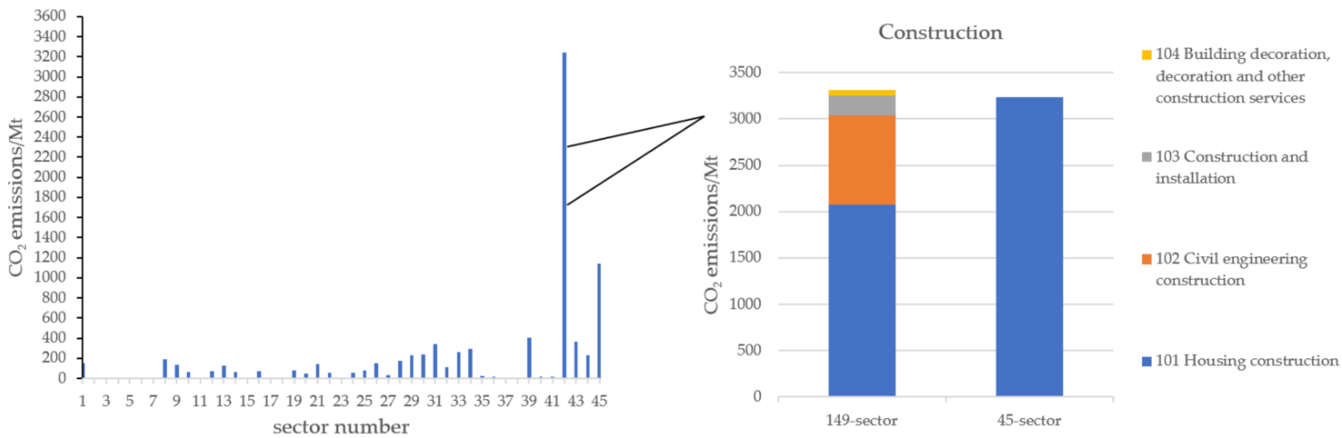

Figure 8. Decomposition of the embodied CO_2 emissions of the construction sector from the demand-based perspective.

Table 6 compares the details of the two classifications of the CO_2 emission inventory. In the 45-sector classification, the ratio of direct CO_2 emissions from the top 5 to the total CO_2 emissions is 86.88% and the ratio of embodied CO_2 emissions is 63.40%. Similarly, in the 149-sector classification, the ratios are 74.03% and 45.59%, respectively. This indicates that the sector concentration of the 45-sector CO_2 emission inventory is higher. Moreover, the sectors with large CO_2 emissions in the 149-sector inventory are all subsectors of the sectors in the 45-sector inventory (e.g., sectors 61 and 62 are subsectors of sector 26; sectors 101, 102 and 103 are subsectors of sector 42) suggesting that the 149-sector CO_2 emission inventory is more precise and accurate. For example, the 45-sector CO_2 emission inventory reveals that sector 42 contributes the most embodied CO_2 emissions; however, sector 101 is the largest emitter of CO_2 emissions in the 149-sector CO_2 emission inventory. In contrast, other subsectors of the construction sector (e.g., sector 104, building decoration and other building services) contributed marginally (Figure 4); however, in the CO_2 emission inventory of 45 sectors, it was only possible to determine that the construction sector led to the highest emissions, while it was not possible to distinguish the contributions of this sector's subsectors.

Table 6. Comparison of the CO_2 emission inventories of the 45-sector and 149-sector classifications.

Category of Inventory	Total CO_2 Emissions	Top 5 Sectors with the Largest Direct CO_2 Emissions	Proportion of CO_2 Emissions from the Top 5 to the Total	Top 5 Sectors with the Largest Embodied CO_2 Emissions	Proportion of CO_2 Emissions from the Top 5 to the Total
CO_2 emission inventory of 45 sectors	8650.76 Mt	sector 39 (4429.59 Mt) sector 26 (1566.37 Mt) sector 43 (743.18 Mt) sector 25 (484.26 Mt) sector 21 (292.34 Mt)	86.88%	sector 42 (3238.72 Mt) sector 45 (1139.31 Mt) sector 39 (402.53 Mt) sector 43 (365.77 Mt) sector 31 (337.74 Mt)	63.40%
CO_2 emission inventory of 149 sectors	8650.76 Mt	sector 98 (4429.59 Mt) sector 62 (1283.75 Mt) sector 108 (344.27 Mt) sector 61 (174.81 Mt) sector 56 (171.60 Mt)	74.03%	sector 101 (2073.73 Mt) sector 102 (960.17 Mt) sector 98 (402.13 Mt) sector 77 (287.78 Mt) sector 103 (220.07 Mt)	45.59%

Therefore, when decomposing embodied CO_2 emissions by the final demand of a certain sector, the analyses based on the CO_2 emission matrix of 149 sectors are more specific and targeted. Accordingly, this approach can also help us to analyze the distribution characteristics of sectoral CO_2 emissions in detail. On the contrary, the analyses of the CO_2 emission matrix of 45 sectors can only provide general conclusions, which may lead to imprecise and inaccurate emission reduction policies.

3.5. Sensitivity Analysis

The number of sectors in the I–O tables published by the National Bureau of Statistics vary for different years; this may lead to unreliable results from carbon emission analyses when using the I–O model based on the classification of I–O tables. To enhance the reliability of sectoral analysis results, we performed sensitivity analysis by altering the number of sectors in the experiment and analyzing the results. We consequently obtained the 95 sector (shown in Table A2) carbon emission inventory and the 135 sector (shown in Table A3) carbon emission inventory according to the energy consumption data allocation method. The analysis results of the sectoral distribution characteristics of these two carbon emission inventories are detailed below.

In the carbon emission inventory of 95 sectors, the production and supply of electricity and heat power remains the largest contributor of direct carbon emissions, with smelting and processing of ferrous metals occupying the second place. These two sectors account for approximately 70% of the total emissions from all sectors. On decomposing carbon emissions from the production and supply of electricity and heat power, we discovered that the construction sector contributes the most to CO_2 emitted by the production and supply of electricity and heat power, followed by the sector itself. Moreover, the construction sector is the largest contributor of embodied carbon emissions with production and supply of electricity and heat power sector occupying the second place. Further analysis revealed that the construction sector's carbon emissions can be primarily attributed to the production and supply of electricity and heat power and smelting and processing of ferrous metals; the former provides electricity to the construction sector and the latter provides the main raw materials. Together, these two sectors contribute to > 70% of the total emissions from the construction sector (Figure 9). In the inventory of 135 sectors, the top two sectors with the largest direct carbon emissions are the production and supply of electricity and heat power (4429.59 Mt CO_2) and rolling of steel (1283.75 Mt CO_2). The rolling of steel subsector contributes to > 80% of the carbon emissions from the smelting and processing of ferrous metals sector. By analyzing the sectoral distribution characteristics, we found that the direct CO_2 emissions from the production and supply of electric/heat power caused by the electric/heat demand of the construction sector is the largest, followed by the sector itself. This observation is the same for the inventory of 95 sectors. Moreover, the two sectors with the largest embodied carbon emissions are also the same as those for inventory of 95 sectors. Additionally, decomposing the embodied carbon emissions from the construction sector revealed that the supply of electricity and steel are the two major contributors, which correspond to the production and supply of electricity/heat power and the rolling of steel sector, respectively (Figure 10).

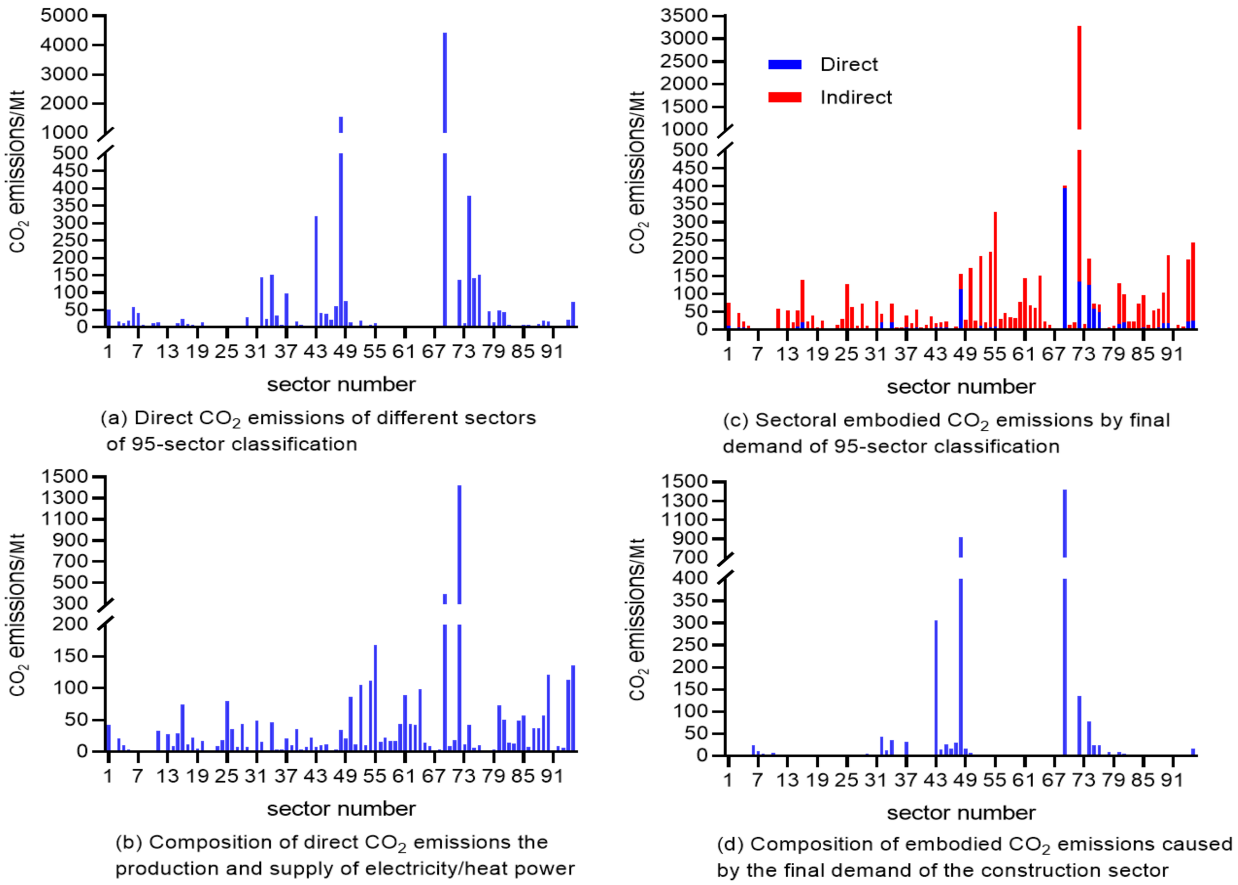

Figure 9. CO_2 emissions of 95 sectors based on the perspectives of production and demand.

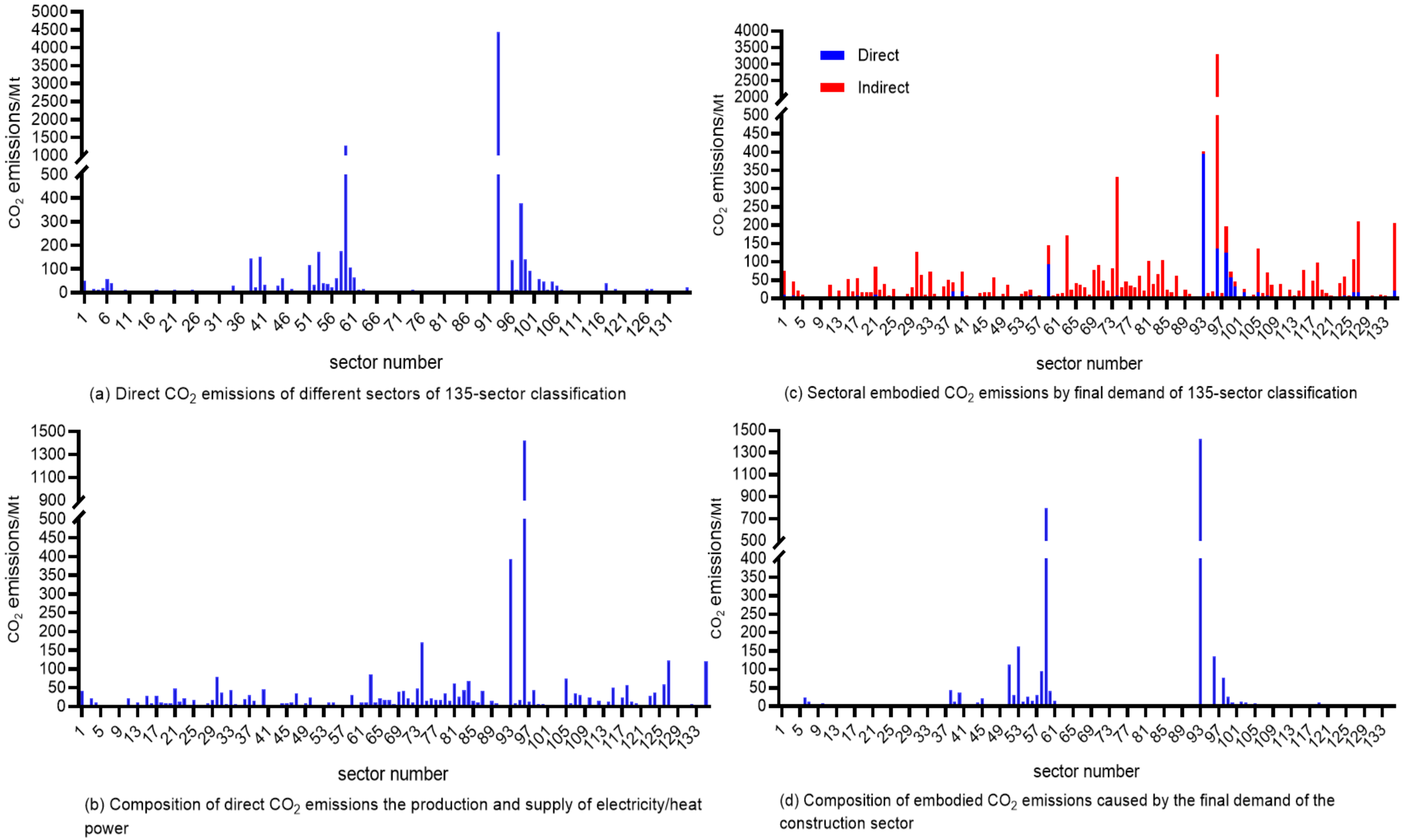

Figure 10. CO_2 emissions of 135 sectors based on production and demand perspectives.

On reducing the number of sectors to 95 and 135, we discovered that the sectoral distribution characteristics of carbon emissions vary with the number of sectors: the coarser the sector classification, the higher the sector concentration of carbon emissions. However, the classification level of sector does not affect the carbon emissions of those sectors that have not been split. These results are general and give strong support to the reliability of our analysis.

4. Conclusions and Suggestions

4.1. Conclusions

The number of sectors in the I–O table is usually more than that in the energy consumption table. Hence, most studies elect to aggregate the sectors of the I–O table to ensure that the sector classification of the energy consumption table is consistent with that of the I–O table; however, this can introduce inaccuracies to the results. In this study, we decomposed some sectors of the energy consumption table to make both tables consistent; then, we used the EIO–LCA model to analyze the decomposed energy consumption table. The following conclusions can be drawn.

The production and supply of electric/heat power (sector 98) contributed the most direct CO_2 emissions, accounting for 51.20% of the total CO_2 emissions from all sectors. In addition, the sectors with the 10 highest direct CO_2 emissions accounted for >80% of the total CO_2 emissions, indicating a high sector concentration of direct CO_2 emissions, which should be the focus of emission reduction policies.

Considering the demand-based perspective, 5171.14 Mt of CO_2 was emitted by the top 13 sectors with the highest embodied CO_2 emissions, which accounted for 59.78% of the total CO_2 emissions from all sectors. Among these 13 sectors, the highest embodied CO_2 emissions corresponded to housing construction (sector 101), which accounted for 23.97% of the total CO_2 emissions. Moreover, the embodied CO_2 emissions of most sectors were mainly indirect emissions.

We compared the CO_2 emission matrices of 45 sectors and 149 sectors; however, the results based on the 45-sector inventory were not sufficiently accurate. In contrast, the CO_2 emission matrix of 149 sectors provided a more detailed perspective for the analysis of the relationship between the CO_2 emissions of different sectors, which can be used for effective development of guidelines and formulation of emission reduction policies.

On performing a sensitivity analysis, we found that the results of this study are general, that is, the higher the sector resolution, the lower the sector concentration of carbon emissions. Moreover, the sector classification level does not affect the carbon emissions of those sectors that have not been split. In future studies, SDA analysis can be employed to investigate China's high-precision carbon emission data.

It should be noted that this study had some limitations. When processing the competitive I–O table into a non-competitive I–O table, we assumed that the import rate within a sector was the same and equal to the ratio of imports/total output. This assumption may lead to two types of errors. First, the carbon intensity of imported products may be different from the carbon intensity of domestic products in China. If products are imported from developed countries, the value may be lower than that of China. Second, it is inaccurate to use only one import rate value for a certain sector. However, because we did not have adequate details on China's import structure and import intensity by sector, we only focused on the sectoral distribution characteristics of CO_2 emissions from domestic production and not those from imports. Therefore, the assumption of competitive imports was still adopted. Third, the energy consumption data allocation method based on the non-competitive I–O table of 149 sectors (Section 2.2.1) may have made the allocation coefficients of different types of energy the same, which is not the case. For example, the consumption of all petroleum products, such as gasoline and diesel, is distributed according to the allocation coefficients corresponding to the processing of refined petroleum and nuclear fuel (sector 41). The allocation method assumes that the ratio of petroleum products consumed by all sectors is constant. However, road freight transportation services may consume relatively more gasoline, while machinery supporting agricultural services may consume relatively more diesel. To solve this problem, more detailed sectoral energy consumption data from the National Bureau of Statistics of China are needed for future studies.

4.2. Policy Suggestions

From a production-based perspective, the formulation of emission reduction policies should focus on the 10 sectors with the highest CO_2 emissions (Table 2). Emission reduction measures could commence by incorporating the following aspects: first, development of low-carbon energy and promotion of decarbonization of the power industry; second, improvement of energy efficiency in other sectors in order to control energy-related carbon emissions of production activities, especially in the seven sectors listed in Table 3.

From a demand-based perspective, the formulation of emission reduction policies should focus on the 13 sectors with the highest CO_2 emissions (Table 4). Taking housing construction (sector 101)—with the largest embodied CO_2 emissions—as an example, the CO_2 emissions caused by final demand could be controlled based on the following aspects: first, improvement in raw material utilization efficiency in the housing construction sector and to reduction in the use of raw materials while maintaining the final demand; second, upgradation of technology in the six sectors (Table 5) that contribute significantly to embodied CO_2 emissions to control direct emissions during the production stage of these sectors.

Author Contributions: Conceptualization, J.J.; data curation, F.H. and Y.Y.; formal analysis, F.H. and Y.Y.; funding acquisition, J.J., D.W. and Z.Y.; investigation, F.H. and X.L.; methodology, F.H. and J.J.; project administration, F.H. and Y.Y.; resources, J.J.; software, F.H. and X.L.; supervision, J.J.; validation, F.H., Y.Y. and X.L.; visualization, F.H.; writing—original draft, F.H.; writing—review & editing, Y.Y., X.L., D.W., J.J., Z.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Starting Research Fund from Harbin Institute of Technology, Shenzhen (No. GD45001017), the Low-carbon Economics Development Program of Harbin Institute of Technology, Shenzhen (SZDRC [2018] No. 725) and the National Key Research and Development Program of China (No. 2019YFC0507505).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Sector correspondence between input–output table and energy consumption table.

Consumption of Energy by Sector		Input–Output Table by Sector	
Sector		Sector	
01	Agriculture, forestry, animal husbandry and fishery	01	Farming
		02	Forestry
		03	Animal husbandry
		04	Fishery
		05	Service in support agriculture, forestry, animal husbandry and fishery
02	Mining and washing of coal	06	Mining and washing of coal

Table A1. *Cont.*

Consumption of Energy by Sector		Input–Output Table by Sector	
	Sector		Sector
03	Extraction of petroleum and natural gas	07	Extraction of petroleum and natural gas
04	Mining and processing of ferrous metal ores	08	Mining and processing of ferrous metal ores
05	Mining and processing of non-ferrous metal ores	09	Mining and processing of non-ferrous metal ores
06	Mining and processing of nonmetal ores	10	Mining and processing of nonmetal ores
07	Support activities for mining and mining of other ores	11	Support activities for mining and mining of other ores
08	Processing of food from agricultural products	12	Grinding of grains
		13	Processing of forage
		14	Refining of vegetable oil
		15	Manufacture of sugar
		16	Slaughtering and processing of meat
		17	Processing of aquatic products
		18	Processing of vegetables, fruits, nuts, and other foods
09	Manufacture of foods	19	Manufacture of instant foods
		20	Manufacture of dairy products
		21	Manufacture of condiments and fermented products
		22	Manufacture of other foods
10	Manufacture of liquor, beverages, and refined tea	23	Manufacture of alcohol and liquor
		24	Manufacture of beverages
		25	Manufacture of refined tea
11	Manufacture of tobacco	26	Manufacture of tobacco
12	Manufacture of textile	27	Manufacture of cotton, chemical fiber textile, and dyeing finishing products
		28	Manufacture of wool spinning and dyeing finishing products
		29	Manufacture of hemp, silk spun textiles, and processed products
		30	Manufacture of knitting or crocheting and related products
		31	Manufacture of textile products
13	Manufacture of textile, clothing apparel, and accessories	32	Manufacture of textile, clothing apparel, and accessories
14	Manufacture of leather, fur, feather, footwear, and related products	33	Manufacture of leather, fur, feathers, and related products
		34	Manufacture of footwear
15	Processing of timber, manufacture of wood, bamboo, rattan, palm, and straw products	35	Processing of timber, wood, bamboo, rattan, palm, and straw products
16	Manufacture of furniture	36	Manufacture of furniture
17	Manufacture of paper and paper products	37	Manufacture of paper and paper products
18	Printing and reproduction of recording media	38	Printing and reproduction of recording media

Table A1. *Cont.*

Consumption of Energy by Sector		Input–Output Table by Sector	
Sector		Sector	
19	Manufacture of articles for culture, education, arts and crafts, sports and entertainment activities	39	Manufacture of Arts and crafts
		40	Manufacture of articles for culture, education, sports and entertainment activities
20	Processing of petroleum, coking and processing of nuclear fuel	41	Processing of refined petroleum and nuclear fuel
		42	Processing of coal
21	Manufacture of raw chemical materials and chemical products	43	Manufacture of basic raw chemical materials
		44	Manufacture of fertilizers
		45	Manufacture of pesticides
		46	Manufacture of paints, printing inks, pigments, and similar products
		47	Manufacture of synthetic materials
		48	Manufacture of special chemical products and explosives, pyrotechnics, fireworks products
		49	Manufacture of chemical products for daily use
22	Manufacture of medicines	50	Manufacture of medicines
23	Manufacture of chemical fibers	51	Manufacture of chemical fiber
24	Manufacture of rubber and plastic products	52	Manufacture of rubber
		53	Manufacture of plastic
25	Manufacture of non-metallic mineral products	54	Manufacture of cement, lime, and gypsum
		55	Manufacture of gypsum, cement products, and similar products
		56	Manufacture of brick, stone, and other building materials
		57	Manufacture of glass and glass products
		58	Manufacture of ceramic products
		59	Manufacture of refractory products
		60	Manufacture of graphite and other non-metallic mineral products
26	Smelting and processing of ferrous metals	61	Steelmaking
		62	Rolling of steel
		63	Smelting of iron and ferroalloy
27	Smelting and processing of non-ferrous metals	64	Smelting of non-ferrous metals and manufacture of alloys
		65	Rolling of non-ferrous metals
28	Manufacture of metal products	66	Manufacture of metal products
29	Manufacture of general purpose machinery	67	Manufacture of boiler and prime mover
		68	Processing of metal machinery
		69	Manufacture of material handling equipment
		70	Manufacture of pump, valve, compressor, and similar machinery
		71	Manufacture of machinery for culture activity and office work
		72	Manufacture of other general purpose equipment

Table A1. *Cont.*

Consumption of Energy by Sector		Input–Output Table by Sector	
Sector		Sector	
30	Manufacture of special purpose machinery	73	Manufacture of special purpose machinery for mining, metallurgy and construction
		74	Manufacture of special purpose machinery for chemical industry, processing of timber and nonmetals
		75	Manufacture of special purpose machinery for agriculture, forestry, animal husbandry and fishery
		76	Manufacture of other special purpose machinery
31	Manufacture of automobiles	77	Manufacture of cars
		78	Manufacture of auto parts and accessories
32	Manufacture of railway, ship, aerospace, and other transport equipment	79	Manufacture of railroad transport and urban rail transit equipment
		80	Manufacture of ships and related equipment
		81	Manufacture of other transport equipment
33	Manufacture of electrical machinery and apparatus	82	Manufacture of generators
		83	Manufacture of equipment for power transmission and distribution and control
		84	Manufacture of wire, cable, optical cable, and electrical appliance
		85	Manufacture of batteries
		86	Manufacture of household appliances
		87	Manufacture of other electrical machinery and equipment
34	Manufacture of computers, communication and other electronic equipment	88	Manufacture of computer
		89	Manufacture of communication equipment
		90	Manufacture of radar, broadcasting and television equipment and its supporting equipment
		91	Manufacture of audiovisual apparatus
		92	Manufacture of electronic component
		93	Manufacture of other electronic equipment
35	Manufacture of measuring instruments machinery	94	Manufacture of measuring instruments machinery
36	other manufacture	95	Manufacture of other products
37	Utilization of waste resources	96	Recycling and processing of waste resources and material products
38	Repair service of metal products, machinery and equipment	97	Repair service of metal products, machinery and equipment
39	Production and supply of electric and heat power	98	Production and supply of electric and heat power
40	Production and supply of gas	99	Production and supply of gas
41	Production and supply of water	100	Production and supply of water

Table A1. *Cont.*

Consumption of Energy by Sector		Input–Output Table by Sector	
Sector		Sector	
42	Construction	101	Housing construction
		102	Civil engineering construction
		103	Construction and installation
		104	Building decoration, decoration and other construction services
43	Transport, storage and post	105	Passenger transport via railway
		106	Cargo transport via railway and support activities
		107	Urban public traffic and highway passenger transport
		108	Cargo transport via road and support activities
		109	Water passenger transport
		110	Water cargo transport and support activities
		111	Air passenger transport
		112	Air cargo transport and support activities
		113	Transport via pipeline
		114	Multimodal transport and shipping agent
		115	Handling and storage
		116	Post
44	Wholesale and retail trade and catering	117	Wholesale
		118	Retail
		119	Hotels
		120	Catering services
45	Others	121	Telecommunications
		122	Broadcast television and satellitetransmission services
		123	Internet and related services
		124	Software service
		125	Information Technology service
		126	Monetary finance and other financial Services
		127	Capital market services
		128	Insurance
		129	Real estate
		130	Leasing
		131	Business services
		132	Research and experimental development
		133	Professional technical service
		134	Technology promotion and application services
		135	Management of water conservancy
		136	Ecological protection and environment management
		137	Management of public facilities and land
		138	Residential services

Table A1. *Cont.*

Consumption of Energy by Sector		Input–Output Table by Sector	
Sector		Sector	
		139	Other services
		140	Education
		141	Health
		142	Social work
		143	Journalism and publishing activities
		144	Broadcasting, movies, televisions and audiovisual activities
		145	Cultural and art activities
		146	Sports activities
		147	Entertainment
		148	Social security
		149	Public management and social organization

Table A2. The 95-sector classification for I–O table.

Sector		Sector	
01	Farming	49	Smelting and processing of non-ferrous metals
02	Forestry	50	Metal products
03	Animal husbandry	51	Boiler and prime mover
04	Fishery	52	Metalworking machinery and other general machinery
05	Service in support agriculture, forestry, animal husbandry and fishery	53	Cultivation, forestry, animal husbandry and fishery machinery
06	Mining and washing of coal	54	Other special equipment
07	Extraction of petroleum and natural gas	55	Manufacture of automobiles
08	Mining and processing of ferrous metal ores	56	Manufacture of railroad transport and urban rail transit equipment
09	Mining and processing of non-ferrous metal ores	57	Manufacture of ships and related equipment
10	Mining and processing of non-metallic minerals and other mining	58	Manufacture of other transport equipment
11	Grain mill products, feeding stuff production and vegetable oil	59	Generators
12	Sugar refining	60	Household appliances
13	Slaughtering and meat processing	61	Other electric machinery and equipment
14	Prepared fish and seafood	62	Electronic computer
15	Other food processing and production	63	Electronic appliances and elements
16	Manufacture of foods	64	Other electronic and communication equipment
17	Wines, spirits and liquors	65	Measuring instruments machinery
18	Non-alcoholic beverage and refined tea	66	Other manufacturing products

Table A2. *Cont.*

	Sector		Sector
19	Tobacco products	67	Utilization of waste resources
20	Cotton textiles	68	Repair service of metal products, machinery and equipment
21	Woolen textiles	69	Production and supply of electric and heat power
22	Hemp textiles	70	Production and supply of gas
23	Knitted mills	71	Production and supply of water
24	Manufacture of textile products	72	Construction
25	Manufacture of textile, clothing apparel, and accessories	73	Railway transport
26	Manufacture of leather, fur, feather, footwear, and related products	74	Highway transport
27	Processing of timber, manufacture of wood, bamboo, rattan, palm, and straw products	75	Water transport
28	Manufacture of furniture	76	Air transport and other transport
29	Manufacture of paper and paper products	77	Pipeline transport
30	Printing and reproduction of recording media	78	Warehousing
31	Manufacture of articles for culture, education, arts and crafts, sports and entertainment activities	79	Post
32	Processing of refined petroleum and nuclear fuel	80	Wholesale and retail trade
33	Processing of coal	81	Catering
34	Basic raw chemical materials	82	Finance
35	Fertilizers	83	Insurance
36	Pesticides	84	Real estate
37	Manufacture of other chemical products	85	Scientific research and experiment
38	Manufacture of chemical products for daily use	86	Technology promotion and application services
39	Medical and pharmaceutical products	87	Water conservancy , environmental management and public infrastructure management
40	Chemical fibers	88	Residential services
41	Rubber products	89	Education
42	Plastic products	90	Health
43	Cement, lime, plaster and other building materials	91	Social work
44	Glass and glass products	92	Culture, arts, radio, television, film and audio-video
45	Ceramic products	93	Sports activities
46	Fireproof products	94	Public administration and social organization
47	Graphite and other non-metallic mineral products	95	Other services
48	Smelting and processing of ferrous metals		

Table A3. The 135-sector classification for I–O table.

Sector		Sector	
01	Farming	69	Manufacture of other general purpose equipment
02	Forestry	70	Manufacture of special purpose machinery for mining, metallurgy and construction
03	Animal husbandry	71	Manufacture of special purpose machinery for chemical industry, processing of timber and nonmetals
04	Fishery	72	Manufacture of special purpose machinery for agriculture, forestry, animal husbandry and fishery
05	Service in support agriculture, forestry, animal husbandry and fishery	73	Manufacture of other special purpose machinery
06	Mining and washing of coal	74	Manufacture of automobiles
07	Extraction of petroleum and natural gas	75	Manufacture of railroad transport and urban rail transit equipment
08	Mining and processing of ferrous metal ores	76	Manufacture of ships and related equipment
09	Mining and processing of non-ferrous metal ores	77	Manufacture of other transport equipment
10	Mining and processing of non-metallic minerals and other mining	78	Manufacture of generators
11	Grinding of grains	79	Manufacture of equipment for power transmission and distribution and control
12	Processing of forage	80	Manufacture of wire, cable, optical cable, and electrical appliance
13	Refining of vegetable oil	81	Manufacture of batteries and household appliances
14	Manufacture of sugar	82	Manufacture of other electrical machinery and equipment
15	Slaughtering and processing of meat	83	Manufacture of computer
16	Processing of aquatic products	84	Manufacture of communication equipment
17	Processing of vegetables, fruits, nuts, and other foods	85	Manufacture of radar, broadcasting and television equipment and its supporting equipment
18	Manufacture of instant foods	86	Manufacture of audiovisual apparatus
19	Manufacture of dairy products	87	Manufacture of electronic component
20	Manufacture of condiments and fermented products	88	Manufacture of other electronic equipment
21	Manufacture of other foods	89	Manufacture of measuring instruments machinery
22	Manufacture of alcohol and liquor	90	Manufacture of other products
23	Non-alcoholic beverage and refined tea	91	Recycling and processing of waste resources and material products
24	Manufacture of tobacco	92	Repair service of metal products, machinery and equipment
25	Manufacture of cotton, chemical fiber textile, and dyeing finishing products	93	Production and supply of electric and heat power
26	Manufacture of wool spinning and dyeing finishing products	94	Production and supply of gas
27	Manufacture of hemp, silk spun textiles, and processed products	95	Production and supply of water

Table A3. *Cont.*

	Sector		Sector
28	Manufacture of knitting or crocheting and related products	96	Construction
29	Manufacture of textile products	97	Railway transport
30	Manufacture of textile, clothing apparel, and accessories	98	Highway transport
31	Manufacture of leather, fur, feather, footwear, and related products	99	Water transport
32	Processing of timber, manufacture of wood, bamboo, rattan, palm, and straw products	100	Air transport
33	Manufacture of furniture	101	Pipeline transport
34	Manufacture of paper and paper products	102	Multimodal transport and shipping agent
35	Printing and reproduction of recording media	103	Handling and storage
36	Manufacture of Arts and crafts	104	Post
37	Manufacture of articles for culture, education, sports and entertainment activities	105	Wholesale and retail trade
38	Processing of refined petroleum and nuclear fuel	106	Hotels
39	Processing of coal	107	Catering services
40	Manufacture of basic raw chemical materials	108	Telecommunications and other information transmission services
41	Manufacture of fertilizers	109	Internet and related services
42	Manufacture of pesticides	110	Software service
43	Manufacture of paints, printing inks, pigments, and similar products	111	Information Technology service
44	Manufacture of synthetic materials	112	Monetary finance and other financial Services
45	Manufacture of special chemical products and explosives, pyrotechnics, fireworks products	113	Capital market services
46	Manufacture of chemical products for daily use	114	Insurance
47	Manufacture of medicines	115	Real estate
48	Manufacture of chemical fiber	116	Leasing
49	Manufacture of rubber	117	Business services
50	Manufacture of plastic	118	Research and experimental development
51	Manufacture of cement, lime, and gypsum	119	Professional technical service
52	Manufacture of gypsum, cement products, and similar products	120	Technology promotion and application services
53	Manufacture of brick, stone, and other building materials	121	Management of water conservancy
54	Manufacture of glass and glass products	122	Ecological protection and environment management
55	Manufacture of ceramic products	123	Management of public facilities and land
56	Manufacture of refractory products	124	Residential services
57	Manufacture of graphite and other non-metallic mineral products	125	Other services
58	Steelmaking	126	Education

Table A3. *Cont.*

	Sector		Sector
59	Rolling of steel	127	Health
60	Smelting of iron and ferroalloy	128	Social work
61	Smelting of non-ferrous metals and manufacture of alloys	129	Journalism and publishing activities
62	Rolling of non-ferrous metals	130	Broadcasting, movies, televisions and audiovisual activities
63	Manufacture of metal products	131	Cultural and art activities
64	Manufacture of boiler and prime mover	132	Sports activities
65	Processing of metal machinery	133	Entertainment
66	Manufacture of material handling equipment	134	Social security
67	Manufacture of pump, valve, compressor, and similar machinery	135	Public management and social organization
68	Manufacture of machinery for culture activity and office work		

References

1. Ardakani, M.K.; Seyedaliakbar, S.M. Impact of energy consumption and economic growth on CO_2 emission using multivariate regression. *Energy Strateg. Rev.* **2019**, *26*, 100428. [CrossRef]
2. Friedlingstein, P.; O'Sullivan, M.; Jones, M.W.; Andrew, R.M.; Hauck, J.; Olsen, A.; Peters, G.P.; Peters, W.; Pongratz, J.; Sitch, S.; et al. The Global Carbon Budget 2020. *Earth Syst. Sci. Data* **2020**, *12*, 3269–3340. [CrossRef]
3. NBSC. *China Energy Statistical Yearbook 2018*; China Statistics Press: Beijing, China, 2019. (In Chinese)
4. NBSC. *Input-Output Tables of China 2017*; China Statistics Press: Beijing, China, 2019. (In Chinese)
5. Steen-Olsen, K.; Owen, A.; Hertwich, E.G.; Lenzen, M. Effects of Sector Aggregation on CO_2 Multipliers in Multiregional Input–Output Analyses. *Econ. Syst. Res.* **2014**, *26*, 284–302. [CrossRef]
6. De Koning, A.; Bruckner, M.; Lutter, S.; Wood, R.; Stadler, K.; Tukker, A. Effect of aggregation and disaggregation on embodied material use of products in input–output analysis. *Ecol. Econ.* **2015**, *116*, 289–299. [CrossRef]
7. Su, B.; Huang, H.C.; Ang, B.W.; Zhou, P. Input–output analysis of CO_2 emissions embodied in trade: The effects of sector aggregation. *Energy Econ.* **2010**, *32*, 166–175. [CrossRef]
8. Li, J.; Wei, W.; Zhen, W.; Guo, Y.; Chen, B. How Green Transition of Energy System Impacts China's Mercury Emissions. *Earth's Future* **2019**, *7*, 1407–1416. [CrossRef]
9. Lenzen, M. Aggregation versus Disaggregation in Input–Output Analysis of the Environment. *Econ. Syst. Res.* **2011**, *23*, 73–89. [CrossRef]
10. Lindner, S.; Legault, J.; Guan, D. Disaggregating Input–Output Models with Incomplete Information. *Econ. Syst. Res.* **2012**, *24*, 329–347. [CrossRef]
11. Meng, F.; Liu, G.; Chang, Y.; Su, M.; Hu, Y.; Yang, Z. Quantification of urban water-carbon nexus using disaggregated input-output model: A case study in Beijing (China). *Energy* **2019**, *171*, 403–418. [CrossRef]
12. Lindner, S.; Legault, J.; Guan, D. Disaggregate the electricity sector of China's input-output table for improved environmental life-cycle assessment. *Econ. Syst. Res.* **2013**, *25*, 300–320. [CrossRef]
13. Luo, F.; Guo, Y.; Yao, M.; Cai, W.; Wang, M.; Wei, W. Carbon emissions and driving forces of China's power sector: Input-output model based on the disaggregated power sector. *J. Clean. Prod.* **2020**, *268*, 121925. [CrossRef]
14. Chang, Y.; Ries, R.J.; Man, Q.; Wang, Y. Disaggregated I-O LCA model for building product chain energy quantification: A case from China. *Energ. Buildings* **2014**, *72*, 212–221. [CrossRef]
15. Langarita, R.; Duarte, R.; Hewings, G.; Sánchez-Chóliz, J. Testing European goals for the Spanish electricity system using a disaggregated CGE model. *Energy* **2019**, *179*, 1288–1301. [CrossRef]
16. Liu, L.; Huang, G.; Baetz, B.; Cheng, G.; Pittendrigh, S.M.; Pan, S. Input-output modeling analysis with a detailed disaggregation of energy sectors for climate change policy-making: A case study of Saskatchewan, Canada. *Renew. Energ.* **2020**, *151*, 1307–1317. [CrossRef]
17. Zhang, Q.; Nakatani, J.; Moriguchi, Y. Compilation of an Embodied CO_2 Emission Inventory for China Using 135-Sector Input-Output Tables. *Sustainability* **2015**, *7*, 8223–8239. [CrossRef]
18. Minx, J.C.; Baiocchi, G.; Peters, G.P.; Weber, C.L.; Guan, D.; Hubacek, K. A "Carbonizing Dragon": China's Fast Growing CO_2 Emissions Revisited. *Environ. Sci. Technol.* **2011**, *45*, 9144–9153. [CrossRef]

19. Douglas, S.; Nishioka, S. International differences in emissions intensity and emissions content of global trade. *J. Dev. Econ.* **2012**, *99*, 415–427. [CrossRef]
20. Hendrickson, C.; Horvath, A.; Joshi, S.; Lave, L.B. Economic Input–Output Models for Environmental Life-Cycle Assessment. *Environ. Sci. Technol.* **1998**, *32*, 184A–191A. [CrossRef]
21. Wu, S.; Li, S.; Lei, Y.; Li, L. Temporal changes in China's production and consumption-based CO_2 emissions and the factors contributing to changes. *Energy Econ.* **2020**, *89*, 104770. [CrossRef]
22. Li, Q.; Wu, S.; Lei, Y.; Li, S. Dynamic features and driving forces of indirect CO_2 emissions from Chinese household: A comparative and mitigation strategies analysis. *Sci. Total Environ.* **2020**, *704*, 135367. [CrossRef]
23. Wang, Z.; Su, B.; Xie, R.; Long, H. China's aggregate embodied CO_2 emission intensity from 2007 to 2012: A multi-region multiplicative structural decomposition analysis. *Energy Econ.* **2020**, *85*, 104568. [CrossRef]
24. Eker, S.; Rovenskaya, E.; Obersteiner, M.; Langan, S. Practice and perspectives in the validation of resource management models. *Nat. Commun.* **2018**, *9*, 5359. [CrossRef] [PubMed]
25. Sajid, M.J.; Qiao, W.; Cao, Q.; Kang, W. Prospects of industrial consumption embedded final emissions: A revision on Chinese household embodied industrial emissions. *Sci. Rep.* **2020**, *10*, 1–20. [CrossRef] [PubMed]
26. NBSC. 2017 Industrial Classification for National Economic Activities (GB/T 4754—2017). Available online: http://www.stats.gov.cn/tjsj/tjbz/hyflbz/201710/t20171012_1541679.html (accessed on 29 September 2017).
27. Liu, Y.; Chen, S.; Chen, B.; Yang, W. Analysis of CO_2 emissions embodied in China's bilateral trade: A non-competitive import input–output approach. *J. Clean. Prod.* **2017**, *163*, S410–S419. [CrossRef]
28. Su, B.; Ang, B.W. Input–output analysis of CO_2 emissions embodied in trade: Competitive versus non-competitive imports. *Energy Policy* **2013**, *56*, 83–87. [CrossRef]
29. Chen, B.; Li, J.S.; Chen, G.Q.; Wei, W.D.; Yang, Q.; Yao, M.T.; Shao, J.A.; Zhou, M.; Xia, X.H.; Dong, K.Q.; et al. China's energy-related mercury emissions: Characteristics, impact of trade and mitigation policies. *J. Clean. Prod.* **2017**, *141*, 1259–1266. [CrossRef]
30. Tian, Y.; Xiong, S.; Ma, X.; Ji, J. Structural path decomposition of carbon emission: A study of China's manufacturing industry. *J. Clean. Prod.* **2018**, *193*, 563–574. [CrossRef]
31. Chinese Development and Reform Commission. Provincial Greenhouse Gas Inventory Compilation Guide (Trial). Available online: http://www.cbcsd.org.cn/sjk/nengyuan/standard/home/20140113/download/shengjiwenshiqiti.pdf (accessed on 1 December 2020).
32. Sector of Climate Change, National Development and Reform Commission. *2005 People's Republic of China National Greenhouse Gas Inventory*; China Environmental Science Press: Beijing, China, 2014. (In Chinese)