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CASE STUDY

Reducing carbon emissions in China: Industrial structural upgrade based on system dynamics

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ABSTRACT

China is now in urgent need to accelerate the transformation of the economic development model, promoting industrial structure upgrades in order to reduce carbon emissions. The goals are to relieve energy constraints, guarantee economic security, and reduce environmental pressures. This study calculated the industrial influence coefficients (IIC) and the industrial carbon emission coefficients (ICEC) of all industries in China in 2007. A system dynamics model was built to simulate the GDP growth and total carbon emissions in three scenarios. Scenario analyses have shown that the industrial structure adjustment based on the calculations of IIC and ICEC is better than the one based on the Chinese Industrial Restructuring Catalog. This study provides a solid research foundation for the government to adjust the industrial structure and reduce carbon emissions.

1. Introduction

The effect of greenhouse gases, especially carbon dioxide, on human health and the natural environment highlights the need to reduce carbon emissions. However, the rapid growth in carbon emissions in China is the cause of concern and the conflict between economic development and natural resources conservation is inevitable. Political interference, such as the imposition of a production cap has been arbitrarily applied in the process of carbon emission reduction. Alternatively, upgrading the industrial structure could have a significant impact on the development of the national economy, by promoting the transformation of the economic growth mode, energy conservation, and environmental protection. The internal structure of industries and the interrelationship between different industries need to be examined to improve resource allocation and achieve a situation of mutual benefit.

One widely used approach for calculating industrial carbon emissions is the input–output analysis developed by Leontief [1]. This method is frequently applied to assess energy, CO_2 emissions, and other pollutant emissions [2]. A previous study by Hawdon and Pearson [3], has discussed the relationship between energy and economy using the input–output analysis. Murthy et al. [4] have analyzed CO_2 emissions from energy consumption by an input–output structural decomposition model for different sectors of the Indian economy in 1990. Later, Limmeechokchai and Suksuntornsiri [5] have used an input–output table to analyze the trend or energy intensity and emission factors of all final consumptions in 1995, 1998, 2001, and 2006. Chang et al. [6] have evaluated industrial CO_2 emissions in Taiwan from 1989 to 2004 by an input–output method. Recently, Liu and Guo [7] have improved the compilation method of energy input–output tables in China for 1992, 1997, 2002, and 2005. They have calculated and analyzed direct primary energy intensities, total primary energy intensities, as well as rural and urban household indirect energy consumptions. In the present study, the input–output analysis was used to calculate the industrial influence coefficients (ICCs) and industrial carbon emissions coefficients (ICECs) of 28 sectors in China in 2007.

To gain insight into the relationship between the industrial structure, GDP, and total carbon emissions, a system dynamics model was created. System dynamics was founded during the mid-1950s by Professor Jay Forrester of the Massachusetts Institute of Technology [8]. This approach is a useful mathematical modeling technique for framing, understanding, and discussing complex issues and problems. Thus, an increasing number of scholars use system dynamics to

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understand industrial processes and analyze energy policy issues [9–11], or electricity industry problems [12–14]. In particular, Tao and Li [15] have used a system dynamics model to simulate Hubbert Peak, specifically for the Chinese oil production, and established three scenarios for its estimation. Another study, by Kilanc and Or [16], has used a system dynamics model to analyze the competitive electricity market dynamics in the long run. Ochoa and Ackere [17] have built a system dynamics model based on the dynamics of capacity expansion followed by different scenario analysis. More recently, Huang and Liu [18] have established a system dynamics model to analyze the effects of the floating price mechanism on the gasoline and diesel markets of Taiwan.

In the present study, IICs and ICECs were calculated based on input–output tables to analyze the upgrade of industrial structure in China. The system dynamics model reflected the necessary causal relations and their feedbacks on all industries in China. In addition, it simulated the GDP growth and total carbon emissions in three scenarios for the year of 2020. The main contribution of the use of this system dynamics model is to aid the Chinese government to make the necessary adjustments to the industrial structure promoting its upgradation and reducing carbon emissions.

2. Determination of the IIC and ICEC

IIC denotes the influence of each industry on each other in terms of the contribution to GDP. The higher the IIC value the larger the impact an industry has on others. It reveals the industrial linkage between a sector and the national economy. ICEC is the industrial carbon emission coefficient, which denotes the total (direct and indirect) CO_2 emission intensities of a sector [19,20]. In Appendix A, element M_i is the total CO_2 emission intensity of sector i, revealing the ICEC of sector i. Regarding the input–output tables they were obtained from China's National Bureau of Statistics for a total of 42 sectors for the year 2007 [21]. As sector classifications in input–output tables differed from those in energy data, all input–output tables were aggregated into 28 energy consumption sectors, as shown in Table 1.

Energy consumption data of the 28 sectors of China were obtained from the energy balance tables provided by the China Energy Statistical Yearbook for 2008 [21]. Energy consumption comprises nine types of energy, including coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, and electricity. The CO_2 emission factor and net calorific value of each type of energy used for calculating CO_2 emissions were obtained from the IPCC Guidelines for National Greenhouse

Table 1
Sectors and codes.

Code	Sector
1	Agriculture, hunting, forestry, and fishing
2	Mining and washing of coal
3	Extraction of petroleum and natural gas
4	Mining and processing of metal ores
5	Mining and processing of non-metal ores and other ores
6	Manufacture and processing of foods, beverages, and tobacco
7	Manufacture of textile
8	Manufacture of textile wearing apparel, footwear, caps, leather, fur, and feather
9	Processing of timber and manufacture of furniture
10	Manufacture of paper, printing, articles for culture, education, and sport activity
11	Processing of petroleum, coking, and nuclear fuel
12	Chemical industry
13	Manufacture of non-metallic mineral products
14	Smelting and pressing of metals and manufacture of metal products
15	Manufacture of machinery
16	Manufacture of transport equipment
17	Manufacture of electrical machinery and equipment
18	Manufacture of communication and other electronic equipment
19	Manufacture of measuring instruments and machinery for cultural activity and office work
20	Manufacture of artwork and other manufacturing
21	Recycling and disposal of waste
22	Production and distribution of electric and heat power
23	Production and distribution of gas
24	Production and distribution of water
25	Construction
26	Transport, storage, and post
27	Wholesale, retail trade, hotels, and restaurants
28	Other services

Source: [19].

Gas Inventories [22,23]. The IICs and ICECs for each sector in 2007 were calculated using the method described in Appendix A and are presented in Fig. 1.

The scatter plot in Fig. 1 is divided into four quadrants: by 0.0006 in the X-axis and 1 in the Y-axis. Some sectors in the fourth quadrant have large ICECs but small IICs. These sectors are: sector 2 (Mining and washing of coal), sector 4 (Mining and processing of metal ores), sector 5 (Mining and processing of non-metal ores and other ores), sector 11 (Processing of petroleum, coking, and nuclear fuel), sector 22 (Production and distribution of electric and heat powers), sector 23 (Production and distribution of gas), sector 24 (Production and distribution of water), and sector 26 (Transport, storage, and post). These eight sectors contribute little to China's GDP growth but present substantial carbon dioxide emissions, most of them being indispensable energy industries to daily life in China. So, when considering the national industrial structural adjustment program, priority should be given to such industries. This adjustment could reduce carbon emissions and may have less impact on China's economic growth, promoting a low-carbon economy.

By contrast, there are six sectors in the second quadrant that have large IICs but small ICECs. These sectors are: sector 7 (Manufacture of textile), sector 8 (Manufacture of textile wearing apparel, footwear, caps, leather, fur, and feather), sector 9 (Processing of timber and manufacture of furniture), sector 10 (Manufacture of paper, printing, articles for culture, education, and sport activity), sector 18 (Manufacture of communication and other electronic equipment), and sector 19 (Manufacture of measuring instruments and machinery for cultural activity and office work). Most of these sectors correspond to light industries that have low CO_2 emission levels and significantly contribute China's GDP. These industries should be encouraged to increase the scale of production.

3. System dynamics model

The established system dynamics model is presented in Fig. 2 and the equations are described in Appendix B.

The GDP growth in China was quite fast from 2005 to 2007, but has slowed down from

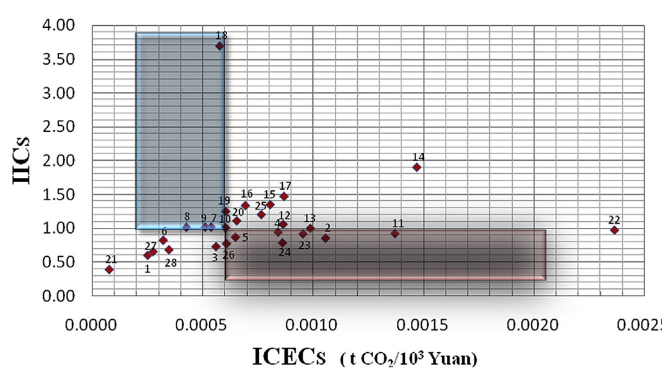

Fig. 1. Scatter diagram of industrial influence coefficients and industrial carbon emission coefficients. Source: [19,21].

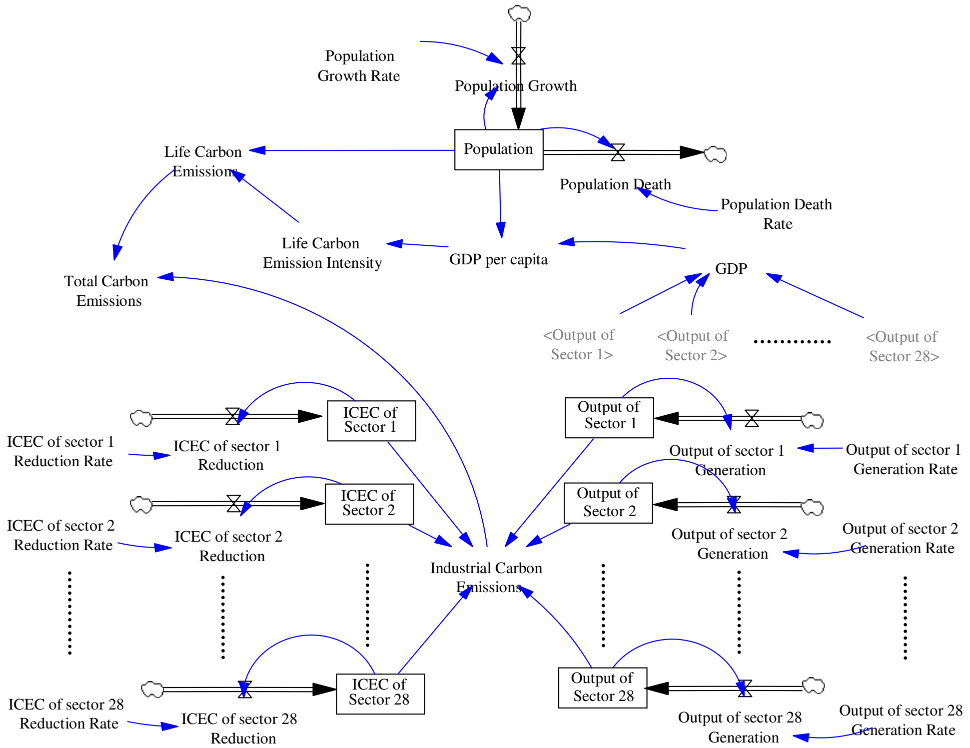

Fig. 2. System dynamics model for GDP and total carbon emissions.

2008 to 2010. According to the National economic policy, during the next ten years the growth rate of GDP is expected to slow down. In the present study, the growth rate of 28 sector's outputs from 2005 to 2010, based on China Statistical Yearbook, was calculated. Subsequently, the growth rate of the 28 sector's outputs in three scenarios was independently simulated for the 2011–2020 period. It was assumed that, from 2010, the rate of ICEC in the 28 sectors would not change in these three scenarios. The results are presented in Table 2.

In Table 2, the growth rate of 28 sectors' outputs for scenario 1 (from 2010 to 2020) was considered the baseline of the system dynamics model. Scenario 2 was produced according to the Chinese Industrial Restructuring Catalog for the year 2011 [24]. Scenario 3 was produced based on the results of the calculations of IICs and ICECs of the 28 sectors in section 2. Results from scenario 2 show that, in the catalog, sectors 1 (Agriculture, hunting, forestry, and fishing), 2 (Mining and washing of coal), 11 (Processing of petroleum, coking, and nuclear fuel), 14 (Smelting and pressing of metals and manufacture of metal products), 16 (Manufacture of transport equipment), 19 (Manufacture of measuring instruments and machinery for cultural activity and office work), 22 (Production and distribution of electric power and heat power), 23 (Production and distribution of gas), 25 (Construction), 27 (Wholesale, retail trade, and hotel, restaurants), and 28 (Other services) should be the primary target for industrial structure adjustments. Hence, the growth rates of these sectors' outputs were increased by 3% in the model. Sectors 7 (Manufacture of textile), 8 (Manufacture of textile wearing apparel, footwear, caps, leather, fur, and feather), 10 (Manufacture of paper, printing, articles for culture,

Table 2
The output growth rate and ICEC rate in 28 sectors from 2005 to 2020.

Sector	Output growth rate from 2005 to 2020					ICEC rate from 2010 to 2020
	2005–2007	2008–2010	2011–2020 in scenario 1	2011–2020 in scenario 2	2011–2020 in scenario 3	
1	0.11337	0.09709	0.04950	0.07950	0.04950	−0.09762
2	0.19182	0.16428	0.08376	0.11376	0.05376	−0.11609
3	0.23917	0.20482	0.10443	0.10443	0.10443	−0.12519
4	0.33458	0.28653	0.14609	0.14609	0.11609	−0.18734
5	0.19350	0.16571	0.08449	0.08449	0.05449	−0.10536
6	0.23611	0.20220	0.10310	0.10310	0.10310	−0.03492
7	0.22848	0.19567	0.09977	0.06977	0.12977	−0.02561
8	0.22209	0.19019	0.09697	0.06697	0.12697	0.019599
9	0.22725	0.19462	0.09923	0.09923	0.12923	−0.01346
10	0.16196	0.13870	0.07072	0.04072	0.10000	−0.01573
11	0.28205	0.24154	0.12316	0.15316	0.09316	−0.13812
12	0.23508	0.20132	0.10265	0.10265	0.10265	−0.05051
13	0.31477	0.26956	0.13744	0.13744	0.13744	−0.04742
14	0.29827	0.25543	0.13024	0.16024	0.13024	0.049442
15	0.24888	0.21313	0.10867	0.10867	0.10867	0.089085
16	0.27870	0.23868	0.12169	0.15169	0.12169	0.103854
17	0.30694	0.26285	0.13402	0.10402	0.13402	0.130035
18	0.25986	0.22254	0.11347	0.11347	0.14347	0.097163
19	0.23634	0.20240	0.10320	0.13320	0.13320	0.052618
20	0.24699	0.21152	0.10785	0.10785	0.10785	0.000313
21	0.38988	0.33389	0.17024	0.17024	0.17024	2.296234
22	0.31816	0.27247	0.13892	0.16892	0.10892	0.040508
23	0.24958	0.21373	0.10898	0.13898	0.07898	−0.1398
24	0.15786	0.13519	0.06893	0.06893	0.03893	−0.04753
25	0.17393	0.14895	0.07594	0.10594	0.07594	0.07608
26	0.17296	0.14812	0.07552	0.07552	0.04552	−0.00471
27	0.12436	0.10650	0.05430	0.08430	0.05430	0.014299
28	0.15991	0.13695	0.06983	0.09983	0.06983	−0.08442

education, and sport activity), and 17 (Manufacture of electrical machinery and equipment) are the industries that should suffer restrictions according to the catalog. Therefore, their growth rates were decreased by 3%. When analyzing the results for scenario 3, the industrial structures of sectors 2 (Mining and washing of coal), 4 (Mining and processing of metal ores), 5 (Mining and processing of non-metal ores and other ores), 11 (Processing of petroleum, coking, and nuclear fuel), 22 (Production and distribution of electric power and heat power), 23 (Production and distribution of gas), 24 (Production and distribution of water), and 26 (Transport, storage and post) should be upgraded first, whereas those of sectors 7 (Manufacture of textile), 8 (Manufacture of textile wearing apparel, footwear, caps, leather, fur, and feather), 9 (Processing of timber and manufacture of furniture), 10 (Manufacture of paper, printing, articles for culture, education, and sport activity), 18 (Manufacture of communication and other electronic equipment), and 19 (Manufacture of measuring instruments and machinery for cultural activity and office work) should be encouraged. Therefore, the growth rates of the former sectors were decreased by 3% and those of the latter sectors were increased by 3%.

The comparison between GDP and total carbon emissions of China from 2008 to 2020, among three different scenarios, is presented in Figs. 3 and 4.

These two figures clearly show that both GDP growth and total carbon emissions in scenario 2 are higher than in scenario 1. The adjustment of the industrial structure of those selected industries in scenario 2 (according to the Chinese Industrial Restructuring Catalog) shows that GDP could increase accompanied by a rise in total carbon emissions in China. However, the results of scenario 3 are different. The model predicts a slower growth of the GDP when comparing to both scenarios 1 and scenario 2, and the total carbon emissions would be lower.

The underlying reason for these results is that some low-carbon industries present on the Chinese Industrial Restructuring Catalog for the year 2011, require a lot of intermediate inputs, which derive from high-carbon industries. Therefore, it is difficult for those industries to achieve a reasonable balance between industrial structure adjustment and economic growth following the suggestions of this catalog. The method for calculating the IICs and ICECs point out that sectors 7(Manufacture of textile), 8(Manufacture of textile wearing apparel, footwear, caps, leather, fur, and feather), 9(Processing of timber and manufacture of furniture), 10(Manufacture of paper, printing, articles for culture, education, and sport activity), 18(Manufacture of communication and other electronic equipment), and 19(Manufacture of measuring instruments and machinery for cultural activity and office work) should be encouraged, and sectors 2(Mining and washing of coal), 4(Mining and processing of metal ores), 5(Mining and processing of non-metal ores and other ores), 11(Processing of petroleum, coking, and nuclear fuel), 22(Production and distribution of electric power and heat power), 23(Production and distribution of gas), 24(Production and distribution of water), and 26(Transport, storage and post) should be limited. Based on this, output growth rate in these sectors was adjusted by 3% up and down respectively. Adjusting the industrial structure of these industries would not have a greater impact on GDP growth in China, but may reduce the total carbon emissions. Therefore, the method for calculating the IICs and ICECs was found to be useful, as verified by the system dynamics model. It is a useful mathematical modeling technique that can be employed to show a clear direction to the upgrade of industrial structures, so as to effectively reduce the total carbon emissions in the process of national economic growth.

4. Issues to be addressed

This study revealed the essential relationship between industries, and proposed the upgrading of industrial structures for carbon emission reduction through the use of a system dynamics model. However, there are still some uncertainties associated with IICs and ICECs determination, and in demonstrating the system dynamics model.

Firstly, the system dynamics model established in this study did not take into account variables such as population growth and carbon emission intensity variation, which may undermine the accuracy of the results. Additionally, some parameters that affect GDP and industrial structure were not integrated into the flow chart (Fig. 2), such as employment and technological advan

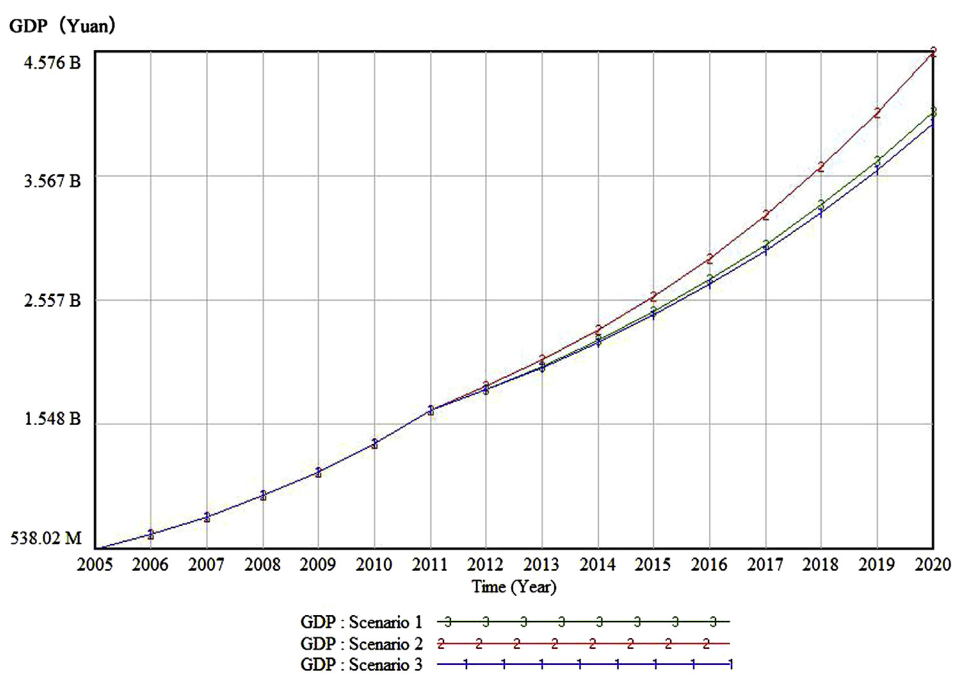

Fig. 3. Comparison of simulation results for GDP in three scenarios.

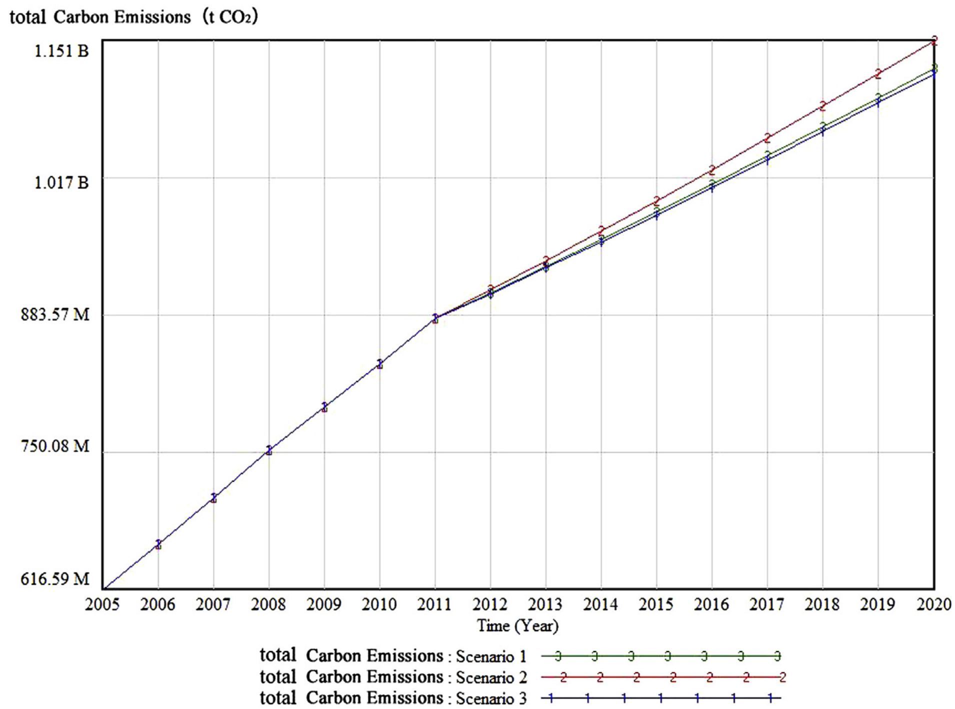

Fig. 4. Comparison of simulation results for total carbon emissions in three scenarios.

cement. An attempt to calculate the population growth rate was also made, yet a precise number was difficult to determine and, therefore, was not taken into consideration. A causal chain was constructed as accurately as possible.

Secondly, the different classifications between the input—output tables and the Energy Statistical Yearbook may have originated some uncertainties. The Energy Statistical Yearbook was aggregated into 28 sectors. This step may have generated errors, such as the results for sectors 18(Manufacture of communication and other electronic equipment) and 22(Production and distribution of electric power and heat power) in Fig. 1. The processes of these two sectors were carefully examined so as to yield rigorous results.

5. Conclusions and recommendations

Fossil energy (such as coal, oil and natural gas) has brought great wealth to humankind, but not without a cost. The increase of greenhouse gas emissions, especially carbon dioxide has caused global warming. One effective way to reduce carbon emissions is to develop a low-carbon economy in which industrial structure adjustment is imperative.

It is therefore essential to implement the necessary adjustments to the industries with the highest carbon emissions. By calculating the IICs and ICECs of each sector, the main differences among industries can be found. This method can thus provide a more rigorous approach in the process of selecting industrial structure upgrade, rather than solely reducing the productivity of those industries, the following conclusions were drawn:

(1) Regarding structure upgrade, the following industries should be given priority: mining and washing of coal, mining and processing of metal ores, mining and processing of non-metal ores and other ores, processing of petroleum, coking, and nuclear fuel, production and distribution of electric and heat powers, production and distribution of gas, as well as production and distribution of water, transport, storage, and post. Also, a low-carbon strategy planning should be incorporated.
(2) Other industries that make significant economic contributions and emit relatively less CO_2 should be reinforced. These are: manufacture of textile, manufacture of textile wearing apparel, footwear, caps, leather, fur, and feather, processing of timber and manufacture of furniture, manufacture of paper, printing, articles for culture, education, and sport activity, manufacture of communication and other electronic equipment, as well as manufacture of measuring instruments and machinery for cultural activity and office work. These industries should be promoted extensively because of their high economic value and low carbon emissions.
(3) The methods used in the present study for Industrial structure upgrading selection are different from those on which the Chinese Industrial Restructuring Catalog is based. A possible explanation might be that little attention was paid to the amount of emissions associated with complex linkages among sectors in the catalog. To further uncover the nature of inter-industrial CO_2 emission linkages in an economic system, it is hereby suggested that a particular methodology, known as the Hypothetical Extraction Method (HEM), is applied. This method is based on linkage analysis and may be a useful tool to explore the inter-industrial CO_2 emission linkages and discuss the climate-change policy in China.

The results from this study have direct policy implications: (1) Smart growth through innovative must be advocated. In the past, Chinese economy has profoundly benefited from intense use of energy, which has now been proven to be detrimental to sustainable economic growth. In light of this, China should commit itself to upgrade industrial structures and develop innovative, low-carbon technologies. However, the time still required to optimize these new technologies along with the urgency for economic growth, make short-term structural adjustment hard to achieve. As a consequence, when addressing climate change mitigation, low-carbon energy usage may be more advantageous when compared to industrial structure optimization. (2) A reduction of carbon-intensive industry activities might pose a risk to other economically key sectors in China. Low-carbon economy development should not only focus on individual industry carbon emissions, but CO_2 emission linkages should also be considered. (3) The optimization and upgrade of the industrial structure at a macroeconomic scale should be promoted. The use of alternative energy sources such as solar and wind power, the development of environmental protective solutions and energy-saving technology could be regarded as valuable options to reduce carbon emissions.

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Appendix A

The formula of IIC is described as follows:

$$\delta_i = b_i \Big/ \left(\frac{1}{n} \sum_{i=1}^{n} b_i \right), i = 1, 2, 3, \ldots, n \tag{A.1}$$

where δ_i is the IIC of sector i, and b_i is the column sum of the Leontief inverse matrix.

The input–output analysis was performed to calculate industrial carbon emissions. The standard input–output model is defined as follows, see Ref. [20]:

$$X = AX + Y \tag{A.2}$$

where X is the total output vector and Y is the final demand vector. A is a direct input coefficient matrix demonstrating the relationship among all sectors, in which $A_{ij} = X_{ij}/X_j, (i, j = 1, 2, 3, \ldots, n)$ is the amount of input from sector i is required directly to produce per unit output from sector j. AX is the intermediate input vector. When solving for the total output, Eq. (A.2) can be represented as:

$$X = (1 - A)^{-1} Y = CY \tag{A.3}$$

where I is the identity matrix and C is the Leontief inverse matrix$(I - A)^{-1}$, in which C_{ij} is the amount of output from sector i required directly and indirectly to produce per unit final demand from sector j.

The direct CO_2 emission intensity was estimated as a ratio of direct CO_2 emissions to the total input:

$$\theta_i = \sum_{k=1}^{m} f_k R_k P_{ik} / X_i \tag{A.4}$$

where θ_i is the direct CO_2 emission intensity of sector i and the element of the direct CO_2 emission intensity row vector θ, f_k is the CO_2 emission factor of energy k ($k = 1$, 2,..., m), R_k is the net calorific value of energy k, P_{ik} is the energy k consumption of sector i in physical units, and X_i is the total input of sector i in monetary units.

Total (direct and indirect) CO_2 emission intensities are calculated by multiplying the direct CO_2 emission intensity row vector θ by the Leontief inverse matrix$C$:

$$M = \theta C \tag{A.5}$$

where M is the total CO_2 emission intensity row vector. Element M_i is the total CO_2 emission intensity of sector i, showing the CO_2 emissions for the production of one unit in sector i. Hence, the industry carbon emission coefficient is M in Eq. (A.5).

Appendix B

In the system dynamics model, the equations applied are as follows:

$$G = \sum_{i=1}^{n} q_i, i = 1, 2, 3, \ldots, n \tag{B.1}$$

$$I = \sum_{i=1}^{n} ICEC_i \times q_i, i = 1, 2, 3, \ldots, n \tag{B.2}$$

$$L = L_i \times P \tag{B.3}$$

$$T = I + L \tag{B.4}$$

where G is the GDP and q_i is the output of sector i. I represents the industrial carbon emissions, represents the ICEC of sector i calculated in the second section. L represents life carbon emissions, L_i represents the life carbon emission intensity and P denotes the population of China. T represents total carbon emissions of China.

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