

# A driving–driven perspective on the key carbon emission sectors in China

Liyin Shen<sup>1</sup> · Yingli Lou<sup>1</sup>  · Yali Huang<sup>1</sup> · Jindao Chen<sup>2</sup>

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**Abstract** Recognition of key emission sectors is crucial for carbon reduction. This study identifies key emission sectors and analyzes driving and driven effects of these sectors in the context of China. The Input–Output approach is used to identify key emission sectors. The data used for analysis are collected from Input–Output Table and Energy Statistical Yearbook issued by the National Bureau of Statistics of China for the period of 1990–2012. Three types of key emission sectors are classified in this study, namely overall key sectors, driving-dominant sectors, and driven-dominant sectors. The major overall key emission sectors include Coal Mining and Dressing; Petroleum Processing and Coking; Chemical Products; Metals Smelting and Pressing; Production and Supply of Electric Power, Gas and Water; and Transportation, Storage, Postal and Telecommunications Services. There is one driving-dominant sector, which is Nonmetal Mineral Products. The major driven-dominant sectors include Petroleum and Natural Gas Extraction; Wholesale, Retail Trade, Lodging and Catering Services; and Others (such as finance, property, research and development, entertainment, health, education, and public facilities). Suggestions from policy implications for emission reduction are proposed. The research findings provide important

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✉ Yingli Lou  
20160302057t@cqu.edu.cn

Liyin Shen  
shenliyin@cqu.edu.cn

Yali Huang  
ylhuangyl@cqu.edu.cn

Jindao Chen  
chenjindao@tongji.edu.cn

<sup>1</sup> School of Construction Management and Real Estate, International Research Center for Sustainable Built Environment, Chongqing University, Chongqing, China

<sup>2</sup> Department of Construction Management and Real Estate, School of Economics and Management, Tongji University, Shanghai, China

references for the Chinese government to adopt appropriate emission reduction measures, particularly in addressing these key emission sectors.

**Keywords** Industrial sectors · Key emission sectors · Driving and driven effects · Carbon emission reduction · Input–Output analysis · China

## 1 Introduction

As the largest carbon emitter in the world, China has given increasing attention to reducing carbon emissions and promulgated an ambitious carbon mitigation plan in 2015. According to this plan, the carbon emission per unit of gross domestic product (GDP) in China will be reduced by 60–65% during 2005–2030 (Commission 2016). The achievement of this reduction goal will rely on effective emission mitigations in various emission sectors (Cai et al. 2008). However, as different sectors have different production processes and different influences on the emission generation, emission reduction can only be achieved if reduction measures are effectively applied to those key sectors (Du et al. 2014; Pack 2010; Shen et al. 2016a; Singh et al. 2015; Zhang and Wang 2015). It is therefore important to determine which are the key sectors and what measures are applicable to them in order to effectively achieve emission reductions (Akimoto et al. 2010; Halsnæs and Garg 2011).

The traditional perspective on key carbon emission sectors is that the sector that releases more carbon emission will be the key sector (Gao et al. 2014; Liu et al. 2015b; Roh et al. 2016; Shan et al. 2016; Zhang and Hao 2015; Zhao et al. 2016a), such as transportation, smelting of iron and steel, electric power generation. This method is useful for us to realize the distribution of carbon emissions in different sectors and take further reduction measures. However, this method ignores the complicated relations between different emission sectors. The carbon emissions from a specific sector may be large, but it may be the results driven by other sectors as the products of this sector are heavily demanded by other sectors (Luzon and Elsayegh 2016; Shen et al. 2017; Shuai et al. 2017a, b; Tan et al. 2017; Tarancón et al. 2011). For example, Lin and Long (2016) presented that chemical industry is the second largest industrial source of carbon emissions in China, but products made in chemical industry sector are consumed by many other sectors, such as paper printing sector, textile sector, furniture manufacturing sector. On the other hand, the emissions from a sector may be small, but this sector can drive other sectors to release carbon emissions as this sector consumes products made by other sectors (Liu et al. 2015a; Su and Thomson 2016; Zhao et al. 2016b). So, both driving and driven effects should be taken into consideration when evaluating carbon emissions for a specific sector.

If the focus is only given to the individual emission sector, the effectiveness of carbon reduction measures will be limited as less efforts are paid to other sectors which drive the concerned sector to release emissions. Hence, the overall carbon reduction potential is restricted, whereas understanding each sector from driving-driven perspective can enable us to recognize both the effects that an emission sector drives other sectors and the effects driven by other sectors. This will enable the carbon reduction potential to be achieved to the largest extent. Xie et al. (2016) also pointed out that it is more efficient to implement emission reduction policies from a perspective of the whole industrial chain rather than certain individual sector.

Previous researchers have studied carbon emissions mainly from driving perspective. Huang and Bohne (2012) analyzed the driving effects of emission sectors by using Input–Output analysis, and the results show that indirect emission sectors dominate the total

emission. Daniels et al. (2016) examined the emission driving effects of the electricity sector by calculating embodied carbon dioxide, and the results show that the driving effects of this sector increased during a specific period of time. Brandt (2015) analyzed the emission driving effects of oil and gas extraction sector by calculating embodied carbon emission and found that the driving effects are sensitive to the application of material and infrastructure in this sector. Zhang et al. (2014a) estimated the driving effects of 30 industrial emission sectors in Beijing during the period from 1987 to 2007, demonstrating that the share of indirect energy consumption in total energy consumption increased from 48 to 76%. Zhang et al. (2015b) further estimated the driving effects of 135 industrial emission sectors in China by estimating their indirect carbon emissions, and the results show that China's indirect carbon emissions are dominated by coal-based electricity and power sector. The above discussions demonstrate that previous researches have appreciated the driving effects of various emission sectors by examining their indirect emissions. Nevertheless, the driven effects on emission generation by industrial sectors are neglected.

In considering both driving and driven effects of industrial sectors, Alcántara and Padilla (2003) identified the key sectors in energy consumption in Spain by using the data of 1995. Othman and Jafari (2016) identified the key sectors that produce CO<sub>2</sub> emissions in Malaysia using the data of 2005. However, the data used in these studies are only for 1 year, which cannot demonstrate the impacts of energy consumption changes on the identification of key sectors. In fact, key emission sectors will change in different time periods. The key sectors identified by using one-year data can be improper to guide practice. Therefore, the focus should be given to understand both the changes of key emission sectors and the key sectors themselves. This paper aims to identify the key emission sectors and examine the changes of the key sectors during the period from 1990 to 2012 in the context of China.

The remainder of this paper is organized as follows: Section 2 introduces the method and data used in this research. Section 3 presents the procedures for identifying the key emission sectors for a specific year followed by Sect. 4, which examines the key sectors during the surveyed period. Section 5 displays the discussion on the changes of the key sectors. Section 6 draws a conclusion of this study.

## 2 Research method and data sources

Input–Output method is used in this study to analyze both the driving and driven effects of a specific industrial sector on carbon emissions. The driving effects are expressed by the percentage change in total carbon emission in response to 1% increase in the value added generated by a specific sector. And the driven effects are denoted by the percentage change in the carbon emission released by a specific sector in response to 1% increase in the total value added by all sectors. The methods for calculating these two kinds of effects are explained in the following.

Firstly, the connection between various sectors and the parameters should be defined. Every industrial sector needs the input of products from other sectors, which called intermediate input. On the other hand, each sector also needs primary input, such as the depreciation of fixed assets, compensation for employees, net production taxes. The total primary input is called value added. Supposing there are  $n$  sectors,  $a_{ij}$  refers to the input of sector  $i$  in a unit production of the sector  $j$ ,  $v_j$  refers to the valued added in a unit production of the sector  $j$ . Thus, the framework of the Input–Output coefficients is listed in Table 1.

**Table 1** Framework of the Input–Output coefficients

Input\Output		<i>Sector 1</i>	<i>Sector 2</i>	...	<i>Sector n</i>
Intermediate input	<i>Sector 1</i>	$a_{11}$	$a_{12}$	...	$a_{1n}$
	<i>Sector 2</i>	$a_{21}$	$a_{22}$	...	$a_{2n}$
	...	...	...	...	...
	<i>Sector n</i>	$a_{n1}$	$a_{n2}$	...	$a_{nn}$
	Total intermediate input	$a_1 = \sum_{i=1}^n a_{i1}$	$a_2 = \sum_{i=1}^n a_{i2}$	$a_j = \sum_{i=1}^n a_{ij}$	$a_n = \sum_{i=1}^n a_{in}$
Primary input	Value added	$v_1$	$v_2$	$v_j$	$v_n$
Total input		$a_1 + v_1 = 1$	$a_2 + v_2 = 1$	$a_j + v_j = 1$	$a_n + v_n = 1$

Every industrial *sector j* will release direct carbon emissions denoted by  $C_j$ , and  $C$  is the total direct carbon emissions in all sectors.  $g_j$  is the proportion of *sector j* to the total carbon emissions, as shown in Eq. (1).

$$g_j = \frac{C_j}{C} \tag{1}$$

Thus, let  $A$  be the  $n \times n$  direct consumption coefficient matrix,  $v$  be the  $n \times 1$  value-added matrix,  $g$  be the  $n \times 1$  carbon emission matrix,  $I$  be the  $n \times n$  unit matrix.  $A, v, g, I$  are displayed detailedly in Eqs. (2)–(5).

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \tag{2}$$

$$v = (v_1 \quad v_2 \quad \cdots \quad v_n)^T \tag{3}$$

$$g = (g_1 \quad g_2 \quad \cdots \quad g_n)^T \tag{4}$$

$$I = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{5}$$

The emission-elasticities matrix can be obtained by using Eq. (6), which is introduced by Othman and Jafari (2016) based on the work by Alcántara and Padilla (2003).

$$E = \hat{g}(I - A^T)^{-1}\hat{v} \tag{6}$$

where  $E$  is a  $n \times n$  matrix of emission elasticities,  $\hat{g}$  is the diagonal matrix of  $g$ ,  $\hat{v}$  is the diagonal matrix of  $v$ .  $A^T$  is the transposed matrix of  $A$ .

$$\hat{g} = \begin{pmatrix} g_1 & 0 & \cdots & 0 \\ 0 & g_2 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & g_n \end{pmatrix} \tag{7}$$

$$\hat{v} = \begin{pmatrix} v_1 & 0 & \cdots & 0 \\ 0 & v_2 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & v_n \end{pmatrix} \tag{8}$$

$$A^T = \begin{pmatrix} a_{11} & a_{21} & \cdots & a_{n1} \\ a_{12} & a_{22} & \cdots & a_{n2} \\ \vdots & \vdots & \cdots & \vdots \\ a_{1n} & a_{2n} & \cdots & a_{nn} \end{pmatrix} \tag{9}$$

By applying models (7), (8), and (9) to (6), matrix  $E$  can be obtained in details, as shown in Eq. (10).

$$E = \begin{pmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{pmatrix} \tag{10}$$

By using the data in the matrix  $E$ , further analysis can be calculated. The sum of individual elements in a particular row (representing a specific *sector j*) is the percentage change in total carbon emission in response to 1% increase in the value added by *sector j*. This sum value, denoted as  $E_{Tj}$ , reflects the driving effects of *sector j* on the total carbon emission. This can be described mathematically as follows:

$$E_{Tj} = \sum_{i=1}^n e_{ji} \quad j = 1, 2, 3, \dots, n \tag{11}$$

In line with this, the average driving effects from all sectors can be calculated as follows:

$$E_T = \frac{1}{n} \sum_{j=1}^n E_{Tj} \tag{12}$$

Similarly, the sum of individual elements in a particular column in the matrix  $E$  is the percentage change in carbon emission of *sector j* in response to 1% increase in the total value added by all sectors. This sum value, denoted as  $E_{Dj}$ , reflects the driven effects of the total value contributed by all sectors to *sector j*. This can be described mathematically as follows:

$$E_{Dj} = \sum_{i=1}^n e_{ij} \quad j = 1, 2, 3, \dots, n \tag{13}$$

In line with this, the average driven effects to all emission sectors can be calculated as follows:

$$E_D = \frac{1}{n} \sum_{j=1}^n E_{Dj} \tag{14}$$

$E_T$  and  $E_D$  can be used as filters to identify key emission sectors. The criteria for filtering the key emission sectors are defined in Table 2.

It can be seen from (11), (12), (13) and (14) that, for obtaining the values of  $E_{Tj}$ ,  $E_{Dj}$ ,  $E_T$ , and  $E_D$ , the matrix  $E$  in (10) needs to be established. The calculation of  $E$  can be conducted by referring to formula (6). In this case, there are three kinds of data that we should collect, namely  $A$  in referring to (2),  $v$  in (3), and  $g$  in (4).

$A$  and  $v$  are aggregated from Input–Output Table issued by the National Bureau of Statistics of China.  $g$  is calculated according to (1) by using the data from Energy Statistical Yearbook issued by the National Bureau of Statistics of China. The value of  $C_j$  in (1) is calculated by using the following formula (15), issued by the Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (IPCC 2006).

$$C_j = \frac{44}{12} \times \sum_{k=1}^m E_j^k \times LCV^k \times CF^k \times O^k \tag{15}$$

where 44/12 means the molecular weight ratio of carbon dioxide to carbon,  $E_k$  represents the consumption of the type  $k$  energy in sector  $j$ . Assuming that there are  $m$  types of energy.  $LCV^k$  represents the lower calorific value of the energy  $k$ ,  $CF^k$  represents the carbon emission coefficients of the energy  $k$ , and  $O^k$  is the oxidation rate of the energy  $k$ .

Because the Input–Output Table is not issued annually, the Input–Output Table available covers the years of 1990, 1992, 1995, 1997, 2002, 2005, 2007, 2012, which are used for analysis in this study.

### 3 Key emission sectors for a specific year

In order to analyze the key emission sectors during the surveyed period, this section is to present the procedures of identifying the key emission sectors for a specific year 2012.

#### 3.1 Aggregation of emission sectors

The classification on emission sectors is different not only between Input–Output Table and Energy Statistical Yearbook, but also between different years. It is therefore

**Table 2** Criteria for filtering key emission sectors

	$E_{Tj} < E_T$	$E_{Tj} > E_T$
$E_{Dj} > E_D$	The emission sector $j$ is a driven-dominant sector	The emission sector $j$ is an overall key sector
$E_{Dj} < E_D$	The emission sector $j$ is a non-key sector	The emission sector $j$ is a driven-dominant sector

necessary to aggregate emission sectors for enabling further analysis. By referring to Input–Output Table and Energy Statistical Yearbook in the years of 1990, 1992, 1995, 1997, 2002, 2005, 2007, 2012, all types of emission sectors are aggregated into 26 sectors according to the principle of industry combination (Geng et al. 2013; Liang and Zhang 2011), as shown in Table 3.

### 3.2 Establishment of direct consumption coefficient matrix ( $A$ ) and value-added matrix ( $v$ )

According to model (2) described in methodology section, the direct consumption coefficient matrix  $A$  for 26 emission sectors needs to be established, as shown in formula (16).

**Table 3** Aggregated emission sectors

Number	Sector
1	Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy
2	Coal Mining and Dressing
3	Petroleum and Natural Gas Extraction
4	Metals Mining and Dressing
5	Nonmetal and Other Minerals Mining and Dressing
6	Food and Tobacco
7	Textile Industry
8	Garments, Leather, Furs, and Related Products
9	Timber Processing and Furniture Manufacturing
10	Printing, and Cultural, Educational and Sports Articles
11	Petroleum Processing and Coking
12	Chemical Products
13	Nonmetal Mineral Products
14	Metals Smelting and Pressing
15	Metal Products
16	Equipment for General and Special Purposes
17	Transportation Equipment
18	Electric Equipment and Machinery
19	Electronic and Telecommunications Equipment
20	Instruments, Meters, Cultural and Office Machinery
21	Craft and Other Manufacturing Industry
22	Production and Supply of Electric Power, Gas and Water
23	Construction
24	Wholesale, Retail trade, Lodging and Catering Services
25	Transportation, Storage, Postal and Telecommunications Services
26	Others (such as finance, property, research and development, entertainment, health, education, and public facilities)

$$A_{26 \times 26} = \begin{matrix}
 a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & \cdots & a_{1,22} & a_{1,23} & a_{1,24} & a_{1,25} & a_{1,26} \\
 a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & \cdots & a_{2,22} & a_{2,23} & a_{2,24} & a_{2,25} & a_{2,26} \\
 a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & \cdots & a_{3,22} & a_{3,23} & a_{3,24} & a_{3,25} & a_{3,26} \\
 a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & \cdots & a_{4,22} & a_{4,23} & a_{4,24} & a_{4,25} & a_{4,26} \\
 a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & \cdots & a_{5,22} & a_{5,23} & a_{5,24} & a_{5,25} & a_{5,26} \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \dots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 a_{22,1} & a_{22,2} & a_{22,3} & a_{22,4} & a_{22,5} & \cdots & a_{22,22} & a_{22,23} & a_{22,24} & a_{22,25} & a_{22,26} \\
 a_{23,1} & a_{23,2} & a_{23,3} & a_{23,4} & a_{23,5} & \cdots & a_{23,22} & a_{23,23} & a_{23,24} & a_{23,25} & a_{23,26} \\
 a_{24,1} & a_{24,2} & a_{24,3} & a_{24,4} & a_{24,5} & \cdots & a_{24,22} & a_{24,23} & a_{24,24} & a_{24,25} & a_{24,26} \\
 a_{25,1} & a_{25,2} & a_{25,3} & a_{25,4} & a_{25,5} & \cdots & a_{25,22} & a_{25,23} & a_{25,24} & a_{25,25} & a_{25,26} \\
 a_{26,1} & a_{26,2} & a_{26,3} & a_{26,4} & a_{26,5} & \cdots & a_{26,22} & a_{26,23} & a_{26,24} & a_{26,25} & a_{26,26}
 \end{matrix} \tag{16}$$

Because the 26 sectors are from the aggregation of all types of sectors, a specific aggregated sector may represent several sectors in the initial Input–Output Table addressed in methodology section. For example, the aggregated *sector 22* (Production and Supply of Electric Power, Gas and Water) in Table 3 covers three sectors in the initial Input–Output Table in 2012, including Production and Supply of Electricity and Heat (*sector 22-1*), Production and Supply of Gas (*sector 22-2*), and Production and Supply of Water (*sector 22-3*). In order to get the coefficients in the matrix  $A_{26 \times 26}$ , the direct consumption coefficients need to be adopted from initial Input–Output Table. For example, the coefficient  $a_{22,2}$  in  $A_{26 \times 26}$ , representing the input of *sector 22* in order to produce a unit of *sector 2* (Coal Mining and Dressing), should be the sum of the input of *sector 22-1*, *sector 22-2*, and *sector 22-3* for a unit production of *sector 2*. By referring to the data in Fig. 1 which denotes part of the initial Input–Output Table in 2012, the input of *sector 22* for producing a unit of *sector 2* should be:

$$a_{22,2} = 0.004 + 0.000 + 0.000 = 0.004 \tag{17}$$

On the other hand, the coefficient  $a_{2,22}$ , indicating the input of *sector 2* in order to produce a unit of *sector 22*, should be the weighted value between the input of *sector 2* for

	Sector 2	.....	Sector 22-1	Sector 22-2	Sector 22-3	.....
Sector 2	0.160	.....	0.182	0.066	0.001	.....
	⋮	.....	⋮	⋮	⋮	.....
Sector 22-1	0.040	.....	0.326	0.022	0.158	.....
Sector 22-2	0.000	.....	0.001	0.104	0.000	.....
Sector 22-3	0.000	.....	0.001	0.000	0.044	.....
	⋮		⋮	⋮	⋮	

Fig. 1 Initial Input–Output Table in 2012



a unit production of *sector 22-1*, the input of *sector 2* for a unit production of *sector 22-2*, and the input of *sector 2* for a unit production of *sector 22-3*. And the weighting values for *sector 22-1*, *sector 22-2*, and *sector 22-3* are given, respectively, according to their individual proportion to the total input of the three sectors. According to the initial Input–Output Table, the input value of *sector 22-1*, *sector 22-2*, and *sector 22-3*, respectively, is RMB 4869.336 billion, RMB 312.285 billion, and RMB 170.109 billion. Therefore, weighting values for *sector 22-1*, *sector 22-2*, and *sector 22-3* can be obtained as 0.910, 0.058, and 0.032. As a result, with referring to Fig. 1, the coefficient  $a_{2,22}$  can be calculated as:

$$a_{2,22} = 0.182 \times 0.910 + 0.066 \times 0.058 + 0.001 \times 0.032 = 0.169 \tag{18}$$

The above analysis procedures can be applied to calculating all other coefficients in matrix  $A_{26 \times 26}$ . As a result, the matrix  $A_{26 \times 26}$  in 2012 is obtained in Appendix I of electronic supplementary material.

Furthermore, in order to obtain the value-added matrix  $v$  in formula (3), similar aggregation principle as used for producing matrix  $A_{26 \times 26}$  is adopted. As a result, the matrix  $v_{1 \times 26} = (v_1, v_2, v_3, v_4, \dots, v_{26})^T$  is obtained, as shown in Appendix II of electronic supplementary material.

### 3.3 Establishment of direct carbon emission matrix ( $g$ )

According to model (4) described in methodology section, the value of  $g_i$  needs to be calculated according to model (1). In applying model (1),  $C_j$  needs to be obtained by using formula (15). In (15), the consumption on various types of energy in different sectors ( $E_j^k$ ) is collected, as shown in Table 4. The values for the parameters of *LCV*, *CF*, and *O* for different types of energy are listed in Table 5.

By using the data in Tables 4 and 5, the  $C_j$  is calculated according to formula (15), as shown in Appendix III of electronic supplementary material. And  $g_j$  is further calculated according to formula (1), and as a result, the matrix  $g_{1 \times 26} = (g_1, g_2, g_3, g_4, \dots, g_{26})^T$  in formula (4) is obtained, as shown in Appendix IV of electronic supplementary material.

### 3.4 Driving and driven effects of each emission sectors

To obtain the values of driving effects ( $E_{Tj}$ ) and driven effects ( $E_{Dj}$ ) of each aggregated emission sector, the emission-elasticities matrix  $E_{26 \times 26}$  in model (10) needs to be established. By referring formula (6) and data in Appendix I, Appendix II, and Appendix IV of electronic supplementary material, the matrix  $E_{26 \times 26}$  in 2012 is obtained, as shown in Appendix V of electronic supplementary material.

By referring to formula (11), (13) and data in Appendix V of electronic supplementary material, the driving effects of each sector ( $E_{Tj}$ ) and driven effects of each sector ( $E_{Dj}$ ) are calculated, as shown in Appendix VI of electronic supplementary material, which can be further presented graphically, as shown in Fig. 2.

As addressed in methodology section, the key emission sectors will be identified by applying two parameters, namely driving effects filter ( $E_T$ ) and driven effects filter ( $E_D$ ). According to (12), (14) and using the data in Appendix VI of electronic supplementary material,  $E_T$  and  $E_D$  can be obtained as:

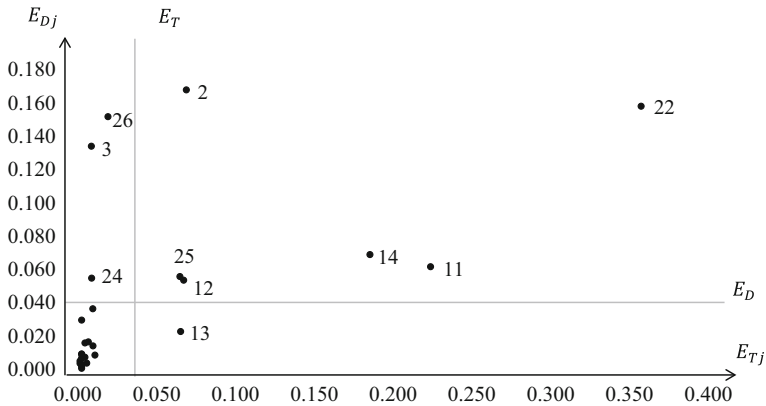
**Table 4** The consumption on various energies in different sectors ( $E_j^k$ ). *Data resource:* (National Bureau of Statistic of China 2013)

Energy types ( $k$ )	Raw coal	Coke	Crude oil	Gasoline	Kerosene	Diesel oil	Fuel oil	Natural gas
<i>Sector (j)</i>								
1	17.661	0.575	0.000	1.929	0.012	13.355	0.020	0.064
2	261.633	0.654	0.000	0.163	0.022	2.152	0.009	0.748
3	4.779	0.000	10.504	0.142	0.000	0.634	0.133	12.294
4	3.129	1.394	0.000	0.144	0.004	1.483	0.001	0.003
5	8.061	0.461	0.237	0.131	0.000	2.048	0.022	0.905
6	38.502	0.144	0.001	0.510	0.002	0.907	0.144	1.289
7	0.630	0.000	0.000	0.009	0.000	0.034	0.010	0.174
8	3.079	0.035	0.002	0.250	0.006	0.295	0.062	0.104
9	4.551	0.042	0.002	0.128	0.001	0.220	0.005	0.103
10	45.827	0.055	0.001	0.229	0.004	0.363	0.093	0.677
11	364.502	0.737	424.134	0.408	0.002	0.209	13.081	9.889
12	201.031	26.112	30.608	0.799	0.040	1.430	5.223	26.137
13	248.140	7.567	0.078	0.332	0.047	2.607	2.312	6.872
14	367.072	342.681	0.002	0.216	0.026	1.459	0.717	5.917
15	3.601	1.043	0.000	0.229	0.013	0.388	0.073	0.732
16	6.996	9.043	0.001	0.641	0.031	0.786	0.026	1.381
17	8.144	1.973	0.001	0.469	0.093	0.827	0.108	2.475
18	4.910	0.179	0.001	0.280	0.005	0.324	0.041	0.597
19	2.454	0.024	0.000	0.139	0.003	0.197	0.032	0.688
20	0.307	0.042	0.000	0.050	0.002	0.051	0.004	0.054
21	5.512	0.130	0.000	0.038	0.018	0.077	0.006	0.124
22	1754.116	0.080	0.025	0.339	0.000	0.782	0.227	23.452
23	7.534	0.063	0.000	2.869	0.079	5.180	0.271	0.126
24	23.620	0.067	0.000	2.001	0.286	2.290	0.087	3.869
25	6.143	0.001	1.194	37.530	17.871	107.270	13.839	15.451
26	22.976	0.220	0.000	14.611	0.742	14.483	0.212	3.308

Unit million tons

**Table 5** Lower calorific value (LCV), carbon emission factors (CFs) and oxidation rate ( $O$ ) of different energy types. *Data resource:* (National Bureau of Statistics of China 2015; IPCC 2006; Geng et al. 2013)

Energy types	LCV(GJ/t) or (MJ/m <sup>3</sup> )	CF (t C/TJ)	$O$
Raw coal	20.908	25.800	0.918
Coke	28.435	29.410	0.928
Crude oil	41.816	20.080	0.979
Gasoline	43.070	18.900	0.986
Kerosene	43.070	19.600	0.980
Diesel oil	42.652	20.170	0.982
Fuel oil	41.816	21.090	0.985
Natural gas	38.931	17.200	0.990



**Fig. 2** Driving and driven effects of various sectors for the year 2012

$$E_T = \frac{1}{26} \sum_{j=1}^{26} E_{Tj} = 0.042$$

$$E_D = \frac{1}{26} \sum_{j=1}^{26} E_{Dj} = 0.042$$

Using  $E_T$  (0.042) and  $E_D$  (0.042) as filters and referring to the criteria established in Table 2, each emission sector can be described as one of four types of classification status:

- (a) Overall key sector ( $E_{Dj} > E_D, E_{Tj} > E_T$ ):
  - sector 2 (Coal Mining and Dressing)
  - sector 11 (Petroleum Processing and Coking)
  - sector 12 (Chemical Products)
  - sector 14 (Metals Smelting and Pressing)
  - sector 22 (Production and Supply of Electric Power, Gas and Water)
  - sector 25 (Transportation, Storage, Postal and Telecommunications Services)
- (b) Driving-dominant sector ( $E_{Dj} < E_D, E_{Tj} > E_T$ ):
  - sector 13 (Nonmetal Mineral Products)
- (c) Driven-dominant sector ( $E_{Dj} > E_D, E_{Tj} < E_T$ ):
  - sector 3 (Petroleum and Natural G Extraction)
  - sector 24 (Wholesale, Retail Trade, Lodging and Catering Services)
  - sector 26 (Others)
- (d) Non-key sector ( $E_{Dj} < E_D, E_{Tj} < E_T$ ):
  - sector 1 (Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy)
  - sector 4 (Metals Mining and Dressing)
  - sector 5 (Nonmetal and Other Minerals Mining and Dressing)
  - sector 6 (Food and Tobacco)
  - sector 7 (Textile Industry)

- *sector 8* (Garments, Leather, Furs, and Related Products)
- *sector 9* (Timber Processing and Furniture Manufacturing)
- *sector 10* (Printing, and Cultural, Educational and Sports Articles)
- *sector 15* (Metal Products)
- *sector 16* (Equipment for General and Special Purposes)
- *sector 17* (Transportation Equipment)
- *sector 18* (Electric Equipment and Machinery)
- *sector 19* (Electronic and Telecommunications Equipment)
- *sector 20* (Instruments, Meters, Cultural and Office Machinery)
- *sector 21* (Craft and Other Manufacturing Industry)
- *sector 23* (Construction)

#### 4 The key emission sectors during the surveyed period (1990–2012)

By applying the procedures for identifying key emission sectors for a particular year presented in Sect. 3, the driving effects ( $E_{Tj}$ ) and driven effects ( $E_{Dj}$ ) for each emission sector during the surveyed period can be obtained, as shown in Table 6. The average annual increase rate of  $E_{Tj}$  can be obtained, denoted as  $\alpha$ , as shown in Table 6. Similarly, the average annual increase rate of  $E_{Dj}$  can also be obtained, denoted as  $\beta$ , as shown in Table 6.

According to the criteria for filtering key emission sectors described in Table 2, a specific sector can be classified between overall key emission sector, driving-dominant sector, driven-dominant sector, and non-key sector. Accordingly, all the emission sectors can be classified into different categories, as shown in Table 7. And the change of the classification status of each emission sector can be established as given in Table 8.

As shown in Table 8, *sector 12* (Chemical Products), *sector 14* (Metals Smelting and Pressing), *sector 22* (Production and Supply of Electric Power, Gas and Water), and *sector 25* (Transportation, Storage, Postal and Telecommunications Services) have always been overall key sectors. *Sector 26* (Others) has always been driven-dominant sector. The status of *sector 1* (Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy), *sector 2* (Coal Mining and Dressing), *sector 3* (Petroleum and Natural Gas Extraction), *sector 11* (Petroleum Processing and Coking), *sector 13* (Nonmetal Mineral Products), and *sector 24* (Wholesale, Retail Trade, Lodging and Catering Services) are changeable.

#### 5 Discussions and policy implications

According to Table 8, it can be found that the major driving-dominant sector is *sector 13* (Nonmetal Mineral Products), and the major driven-dominant sectors are *sector 3* (Petroleum and Natural Gas Extraction), *sector 24* (Wholesale, Retail Trade, Lodging and Catering Services), and *sector 26* (Others). Some sectors have both driving and driven effects on the generation of emission, such as *sector 2* (Coal Mining and Dressing), *sector 11* (Petroleum Processing and Coking), *sector 12* (Chemical Products), *sector 14* (Metals Smelting and Pressing), *sector 22* (Production and Supply of Electric Power, Gas and Water), and *sector 25* (Transportation, Storage, Postal and Telecommunications Services). The majority of these identified key emission sectors have been recognized as key emission

**Table 6** Driving and driven effects of emission sectors in 1990–2012

Sector	Driving effects ( $E_{Dj}$ )										Driven effects ( $E_{Dj}$ )									
	1990	1992	1995	1997	2002	2005	2007	2012	$\alpha$	1990	1992	1995	1997	2002	2005	2007	2012	$\beta$		
1	0.041	0.034	0.023	0.022	0.022	0.018	0.015	0.008	-0.069	0.119	0.084	0.068	0.056	0.040	0.042	0.037	0.037	-0.051		
2	0.023	0.022	0.048	0.050	0.035	0.040	0.042	0.067	0.055	0.051	0.046	0.060	0.077	0.072	0.081	0.134	0.168	0.071		
3	0.011	0.011	0.027	0.033	0.039	0.013	0.010	0.007	-0.002	0.034	0.040	0.069	0.075	0.065	0.075	0.073	0.134	0.069		
4	0.004	0.003	0.003	0.002	0.002	0.001	0.001	0.001	-0.054	0.014	0.010	0.012	0.017	0.013	0.016	0.024	0.030	0.040		
5	0.006	0.006	0.005	0.004	0.004	0.002	0.002	0.003	-0.025	0.017	0.015	0.014	0.013	0.007	0.005	0.006	0.016	0.006		
6	0.033	0.032	0.025	0.020	0.014	0.009	0.008	0.008	-0.061	0.018	0.018	0.022	0.013	0.011	0.010	0.011	0.014	-0.008		
7	0.024	0.024	0.016	0.011	0.007	0.000	0.000	0.000	-0.376	0.027	0.018	0.017	0.018	0.007	0.004	0.003	0.004	-0.081		
8	0.003	0.003	0.002	0.001	0.001	0.001	0.001	0.001	-0.039	0.004	0.002	0.003	0.004	0.003	0.003	0.003	0.002	-0.017		
9	0.003	0.004	0.003	0.002	0.001	0.001	0.001	0.001	-0.050	0.004	0.003	0.004	0.003	0.003	0.003	0.004	0.003	-0.009		
10	0.016	0.016	0.013	0.011	0.009	0.009	0.000	0.009	-0.022	0.019	0.016	0.014	0.015	0.017	0.011	0.010	0.009	-0.034		
11	0.009	0.010	0.166	0.151	0.178	0.190	0.194	0.222	0.225	0.026	0.019	0.056	0.048	0.043	0.063	0.057	0.062	0.052		
12	0.121	0.116	0.115	0.099	0.083	0.069	0.065	0.066	-0.027	0.093	0.081	0.083	0.079	0.065	0.061	0.052	0.054	-0.024		
13	0.116	0.113	0.086	0.072	0.050	0.057	0.049	0.064	-0.025	0.064	0.062	0.049	0.039	0.024	0.025	0.023	0.023	-0.045		
14	0.122	0.129	0.162	0.141	0.135	0.158	0.169	0.184	0.019	0.070	0.084	0.086	0.059	0.068	0.077	0.078	0.069	0.002		
15	0.007	0.006	0.004	0.003	0.003	0.002	0.001	0.001	-0.079	0.012	0.010	0.010	0.010	0.008	0.009	0.009	0.007	-0.025		
16	0.021	0.020	0.013	0.011	0.006	0.005	0.005	0.005	-0.060	0.035	0.036	0.031	0.034	0.022	0.021	0.024	0.017	-0.031		
17	0.012	0.012	0.006	0.005	0.004	0.003	0.003	0.003	-0.058	0.011	0.014	0.011	0.010	0.011	0.010	0.010	0.007	-0.018		
18	0.005	0.005	0.003	0.002	0.001	0.001	0.001	0.001	-0.065	0.013	0.011	0.012	0.012	0.010	0.016	0.012	0.009	-0.011		
19	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	-0.027	0.003	0.004	0.006	0.008	0.008	0.008	0.008	0.009	0.048		
20	0.001	0.001	0.001	0.006	0.000	0.000	0.000	0.000	-0.066	0.003	0.004	0.004	0.006	0.004	0.005	0.006	0.005	0.034		
21	0.013	0.012	0.006	0.004	0.002	0.002	0.001	0.001	-0.015	0.011	0.012	0.003	0.008	0.002	0.003	0.002	0.001	-0.086		
22	0.298	0.337	0.269	0.278	0.319	0.330	0.333	0.356	0.009	0.174	0.193	0.156	0.160	0.203	0.161	0.190	0.158	-0.003		
23	0.012	0.012	0.005	0.004	0.006	0.005	0.004	0.004	-0.040	0.003	0.006	0.003	0.004	0.004	0.003	0.002	0.004	0.020		
24	0.012	0.012	0.009	0.008	0.009	0.007	0.007	0.007	-0.022	0.032	0.084	0.093	0.056	0.056	0.057	0.039	0.055	0.041		

**Table 6** continued

Sector	Driving effects ( $E_{Tj}$ )							Driven effects ( $E_{Dj}$ )							$\beta$			
	1990	1992	1995	1997	2002	2005	2007	2012	$\alpha$	1990	1992	1995	1997	2002		2005	2007	2012
25	0.052	0.071	0.059	0.039	0.056	0.052	0.055	0.063	0.013	0.080	0.081	0.132	0.066	0.072	0.073	0.064	0.056	- 0.009
26	0.033	0.037	0.025	0.019	0.019	0.013	0.010	0.018	- 0.024	0.062	0.095	0.066	0.070	0.097	0.102	0.112	0.138	0.045

**Table 7** Classification of emission sectors in 1990–2012

Key sector type	Overall key sector	Driving-dominant sector	Driven-dominant sector	Non-key sector
<i>Year</i>				
1990	1, 12, 13, 14, 22, 25		2, 26	3, 4, 5, 6, 7, 8, 9, 10, 11, 15, 16, 17, 18, 19, 20, 21, 23, 24
1992	12, 13, 14, 22, 25		1, 2, 3, 24, 26	4, 5, 6, 7, 8, 9, 10, 11, 15, 16, 17, 18, 19, 20, 21, 23
1995	2, 11, 12, 13, 14, 22, 25		1, 3, 24, 26	4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 23
1997	2, 11, 12, 13, 14, 22, 25		1, 3, 24, 26	4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 23
2002	11, 12, 14, 22, 25	13	1, 2, 3, 24, 26	4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 23
2005	2, 11, 12, 14, 22, 25	13	1, 3, 24, 26	4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 23
2007	2, 11, 12, 14, 22, 25	13	3, 24, 26	1, 4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 23
2012	2, 11, 12, 14, 22, 25	13	3, 24, 26	1, 4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 23

sectors from a traditional perspective, for example, the emission *sectors 2, 11, 12, 13, 14, 22, 25, and 26*. However, *sectors 3 and 24* are included as key emission sectors in this study from driving-driven perspective, while they are not considered as key sectors from a traditional perspective. In other words, these emission sectors might have not been addressed in traditional emission reduction practice.

According to the analysis results in Sect. 4, the classification status of some emission sectors is changeable during the surveyed period (1990–2012). For example, as shown in Table 8, *sector 1* was an overall key sector in year 1990, but changed to a driven-dominant sector in the year of 1992, and to a non-key sector in the year of 2012. The change of classification status for individual emission sector reflects the variation of its driving and driven effects. This section will discuss the reasons for the variation from the perspectives of driving and driven effects. For further discussion, *sector 11* (Petroleum Processing and Coking) is selected as a typical sector to analyze the increase in driving effects, and *sector 2* (Coal Mining and Dressing) is selected as a representative to analyze the increase in driven effects.

### 5.1 Increase in driving effects

According to the value  $\alpha$  in Table 6, which represents the average annual increase rate of driving effects, *sector 11* (Petroleum Processing and Coking) assumes the highest value. This indicates that *sector 11* has been driving other sectors to generate emissions with the highest speed among all sectors. In other words, the supply from other sectors to *sector 11* has been driven by the growth of *sector 11*. According to Input–Output Table released by National Bureau of Statistics of China, the supply from all sectors to *sector 11* during the surveyed period is shown in Table 9.

**Table 8** Change of classification status of emission sectors

Year	1990	1992	1995	1997	2002	2005	2007	2012
<i>Sector</i>								
1	●	▼	▼	▼	▼	▼	□	□
2	▼	▼	●	●	▼	●	●	●
3	□	▼	▼	▼	▼	▼	▼	▼
4	□	□	□	□	□	□	□	□
5	□	□	□	□	□	□	□	□
6	□	□	□	□	□	□	□	□
7	□	□	□	□	□	□	□	□
8	□	□	□	□	□	□	□	□
9	□	□	□	□	□	□	□	□
10	□	□	□	□	□	□	□	□
11	□	□	●	●	●	●	●	●
12	●	●	●	●	●	●	●	●
13	●	●	●	●	▲	▲	▲	▲
14	●	●	●	●	●	●	●	●
15	□	□	□	□	□	□	□	□
16	□	□	□	□	□	□	□	□
17	□	□	□	□	□	□	□	□
18	□	□	□	□	□	□	□	□
19	□	□	□	□	□	□	□	□
20	□	□	□	□	□	□	□	□
21	□	□	□	□	□	□	□	□
22	●	●	●	●	●	●	●	●
23	□	□	□	□	□	□	□	□
24	□	▼	▼	▼	▼	▼	▼	▼
25	●	●	●	●	●	●	●	●
26	▼	▼	▼	▼	▼	▼	▼	▼

Classification status: ●—Overall key sector; ▲—Driving-dominant sector; ▼—Driven-dominant sector; □—Non-key sector

It can be seen from Table 9 that the supply from *sector 3* (Petroleum and Natural Gas Extraction) to *sector 11* (Petroleum Processing and Coking) is the largest part and has been increasing rapidly. This means that *sector 11* exerts the largest and increasing driving effects on *sector 3*. There are two possible reasons why *sector 11* has the increase in driving effects on *sector 3*, either because the supply of *sector 3* for a unit production of *sector 11* has increased, or because the production value of *sector 11* has increased. According to the Input–Output Table, the input coefficient of *sector 3* for a unit production of *sector 11* increased from 0.226 to 0.561 during the surveyed period, as shown in Fig. 3. On the other hand, the production value of *sector 11* increased from RMB 92.947 billion to RMB 4001.317 billion during the surveyed period, as shown in Fig. 4. These two reasons lead to the increase in the *sector 11*'s consumption on *sector 3*. Therefore, the driving effects of *sector 11* increased during the surveyed period.

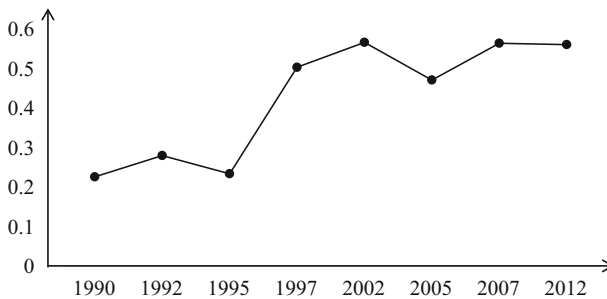
*Sector 11* drives *sector 3* to release carbon emission through consuming petroleum. Over past decades, China's petroleum industry has grown substantially due to the rapid growth in the national economy (Song et al. 2015), which lead to scale expansion of *sector 11* (Petroleum Processing and Coking). Xu et al. (2011) predicted that the petroleum



**Table 9** The supply from all sectors to *sector 11*

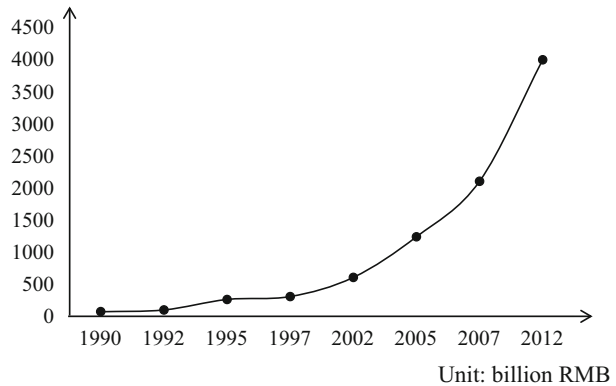
Year	1990	1992	1995	1997	2002	2005	2007	2012
<i>Sector</i>								
1	0.05	0.03	0.14	0.00	0.08	0.11	0.05	0.19
2	11.79	17.09	40.70	12.54	18.97	48.34	111.96	229.65
3	16.51	28.26	61.89	155.98	344.68	585.06	1189.14	2243.78
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.88
5	0.23	0.33	0.83	0.07	0.00	0.00	0.25	0.00
6	0.17	0.08	0.35	0.00	0.00	0.00	12.31	23.19
7	0.32	0.26	1.04	0.08	0.06	0.09	0.13	0.87
8	0.35	0.14	0.78	0.70	0.60	0.83	1.12	1.94
9	0.13	0.08	0.41	0.18	0.24	0.32	0.82	1.00
10	0.26	0.11	0.38	0.14	0.66	0.83	1.46	1.51
11	3.37	3.52	10.20	13.99	25.65	107.55	121.43	283.80
12	2.33	1.66	8.76	6.63	10.77	38.75	39.36	99.44
13	0.87	1.25	4.63	2.78	1.42	2.56	8.62	28.92
14	0.75	0.56	2.85	1.08	3.87	13.80	1.71	0.74
15	0.65	0.59	2.27	0.87	1.92	2.80	8.54	2.20
16	1.56	2.14	6.64	6.04	7.36	14.51	34.55	35.12
17	0.27	0.40	1.57	1.18	1.82	2.32	6.18	1.19
18	0.58	0.45	1.89	2.05	3.71	5.65	3.19	5.17
19	0.06	0.06	0.32	0.60	1.58	1.82	0.43	4.96
20	0.30	0.36	1.35	0.66	1.16	1.57	4.03	6.54
21	0.28	0.31	0.30	1.30	0.65	1.03	1.15	0.91
22	1.08	2.51	8.54	6.86	14.50	46.52	53.20	68.72
23	0.00	0.02	0.10	0.32	0.20	0.25	1.18	5.26
24	1.91	8.82	28.51	11.37	19.22	56.11	34.74	50.57
25	6.08	4.23	19.22	8.57	27.36	51.70	51.76	71.15
26	0.56	2.03	4.79	7.47	17.31	26.12	44.94	89.47

Unit billion RMB



**Fig. 3** The input coefficient of *sector 3* for a unit production of *sector 11*

**Fig. 4** The production value of *sector 11*. Unit billion RMB



industry will continue playing an important role in China's economy. Therefore, the increase in driving effects of *sector 11* will not change without taking mitigation measures.

The above discussions show that the driving effect of *sector 11* is a major contributor to the emission increase in China. Therefore, it is a major challenge to reduce this driving effect in order to achieve the Chinese emission reduction goal. Responding to this challenge, three kinds of policy measures are suggested. Firstly, usage of clean energy for processing petroleum should be widely promoted to reduce the direct carbon emission released by petroleum processing and coking (Yan et al. 2017). Secondly, it is suggested to restrain the scale expansion of petroleum processing and coking through reducing the consumption of petroleum products (e.g., gasoline, diesel, asphalt). For example, the reduction in the consumption on gasoline can be achieved by using more clean-energy automobiles. The reduction in consumption on asphalt can be achieved by reducing the laying of asphalt pavements and roads. Thirdly, it is suggested to reduce the input coefficient for processing and coking petroleum by improving the production efficiency, for example, replacing outdated petroleum processing equipment with advanced technology and facilities.

## 5.2 Increase in driven effects

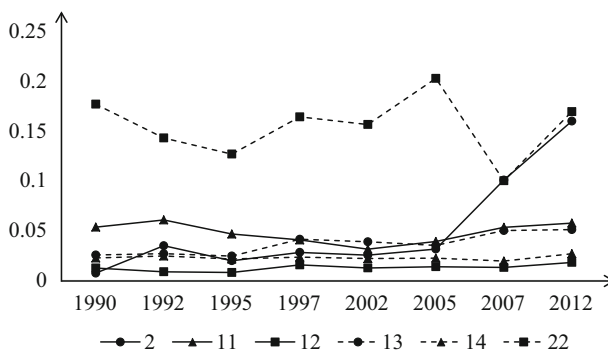
According to the value  $\beta$  in Table 6, which presents the average annual increase rate of driven effects, *sector 2* (Coal Mining and Dressing) assumes the highest value. This indicates that this sector has been driven by all sectors to generate emissions. In other words, the demand for *sector 2* has been driven by the growth of all sectors. According to Input–Output Table released by National Bureau of Statistics of China, the demand for *sector 2* from all sectors during the surveyed is presented in Table 10.

It can be seen from Table 10 that *sector 2* itself, *sector 11* (Petroleum Processing and Coking), *sector 12* (Chemical Products), *sector 13* (Nonmetal Mineral Products), *sector 14* (Metals Smelting and Pressing), and *sector 22* (Production and Supply of Electric Power, Gas and Water) are the major demanding sectors of *sector 2*. There are two possible reasons for the increase in driven effects of *sector 2*, either because the input coefficients of *sector 2* for a unit production of these major demanding sectors have increased, or because the production values of these major demanding sectors have increased. According to the Input–Output Table, the input coefficients of *sector 2* for a unit production of major demanding sectors do not change significantly, as shown in Fig. 5. This means that input

**Table 10** The demands for *sector 2* from all sectors

Year	1990	1992	1995	1997	2002	2005	2007	2012
<i>Sector</i>								
1	0.26	0.73	1.13	2.20	8.87	12.85	2.68	0.54
2	0.38	2.52	2.61	6.23	10.12	22.84	96.99	359.56
3	0.03	0.06	0.11	0.89	1.87	3.86	2.25	3.16
4	0.06	0.22	0.34	0.56	0.64	1.78	2.56	7.48
5	0.27	0.54	1.20	0.67	0.42	0.77	0.88	6.49
6	0.38	1.51	2.52	5.20	4.33	8.54	9.18	18.39
7	0.41	1.65	2.43	3.42	3.80	7.83	10.26	11.65
8	0.05	0.19	0.30	0.56	0.57	1.25	4.26	4.31
9	0.33	0.31	0.99	1.28	2.83	5.07	5.56	5.23
10	0.63	0.62	0.78	2.82	3.42	7.24	7.84	27.37
11	3.89	6.11	12.28	12.54	18.97	48.34	111.96	229.65
12	4.02	4.14	9.44	23.41	26.61	54.84	79.71	216.85
13	4.00	6.77	15.12	36.24	22.43	55.60	113.84	236.88
14	4.27	7.73	17.08	18.06	33.51	69.82	117.71	293.35
15	0.29	0.29	0.67	1.25	1.25	2.46	4.98	13.57
16	0.79	0.67	1.09	3.78	5.84	13.61	13.18	15.07
17	0.18	0.20	0.35	1.34	2.68	6.99	2.78	3.30
18	0.25	0.14	0.25	0.85	0.92	2.50	1.47	2.17
19	0.05	0.06	0.22	0.22	0.45	1.52	0.53	0.00
20	0.03	0.04	0.05	0.11	0.09	0.27	0.80	0.00
21	0.11	0.41	0.13	2.32	1.84	4.84	3.47	7.99
22	12.82	16.83	37.16	72.68	138.23	445.54	337.19	905.94
23	0.28	0.30	0.47	1.05	2.25	3.50	5.69	3.66
24	0.42	1.19	0.90	1.63	4.55	7.28	1.78	0.39
25	1.41	1.87	1.94	2.68	3.60	6.44	6.80	5.70
26	1.59	2.81	2.98	11.90	22.50	41.87	17.40	16.57

Unit billion RMB



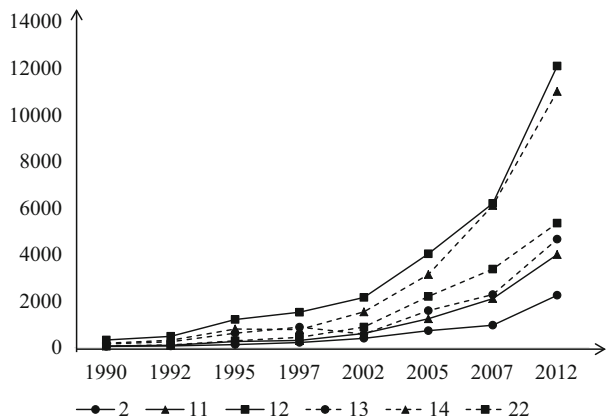
**Fig. 5** The input coefficients of *sector 2* for a unit production of *sectors 2, 11, 12, 13, 14, and 22*

coefficients are not the reason for the increase in the demand for *sector 2*. However, the production values of these major demanding sectors have increased dramatically, as shown in Fig. 6, which caused the increase in demand for *sector 2*. Therefore, the driven effects of the total value contributed by all sectors to *sector 2* increased during the surveyed period.

*Sector 2* has been driven by these six major demanding sectors to release carbon emissions through the consumption of coal. Coal is the principal primary energy source in China (Gao et al. 2014; Wei et al. 2015; Zhang and Da 2013), and it is highly relied upon by all industrial sectors. Many researchers argued that coal will continue to be a key component of the primary energy mix in China for the next few decades (Bhattacharya et al. 2015; Chong et al. 2015; Jiao et al. 2013; Li et al. 2015). Thus, economic growth will lead to increasing consumption on coal in China (Bloch et al. 2012; Halkos and Tzeremes 2011; Zhang et al. 2014b), which will induce the increase in driven effects of *sector 2* (Coal Mining and Dressing).

The above discussions show that the driven effect of *sector 2* is another major contributor to the emission increase in China. In order to mitigate the increase in driven effects of *sector 2*, the following policy measures are suggested. Firstly, equipment and facilities for mining and dressing coal should be updated to reduce the direct carbon emissions. Secondly, the scale expansion of these major coal demanding sectors should be restrained, including *sector 11* (Petroleum Processing and Coking), *sector 12* (Chemical Products), *sector 13* (Nonmetal Mineral Products), *sector 14* (Metals Smelting and Pressing), *sector 22* (Production and Supply of Electric Power, Gas and Water). For example, demand for chemical and nonmetal products can be reduced by encouraging the recycling economy. Thirdly, measures should be adopted to improve the efficiency of utilizing coal. Previous studies have demonstrated that coal efficiency can be improved through measures, such as building highly efficient coal-fired power plants for electricity generation (Bugge et al. 2006; Moullec 2013; Shen et al. 2016b; Zhang et al. 2015a), improving the technology of metal smelting and chemical products manufacturing (Gao and Zhu 2016; Quader et al. 2015).

**Fig. 6** The production values of *sectors 2, 11, 12, 13, 14, and 22*. Unit billion RMB



Unit: billion RMB

## 6 Conclusion

This study suggests that emission effects from various industrial sectors should be examined from driving and driven perspectives. Understanding an emission sector's driving and driven effects explains the influence of the sector on other sectors about emission generation. In referring to the context of China, it has been found that the major overall key sectors are *sector 2* (Coal Mining and Dressing), *sector 11* (Petroleum Processing and Coking), *sector 12* (Chemical Products), *sector 14* (Metals Smelting and Pressing), *sector 22* (Production and Supply of Electric Power, Gas and Water), and *sector 25* (Transportation, Storage, Postal and Telecommunications Services). The major driving-dominant emission sector is *sector 13* (Nonmetal Mineral Products). And the major driven-dominant sectors are *sector 3* (Petroleum and Natural Gas Extraction), *sector 24* (Wholesale, Retail Trade, Lodging and Catering Services), and *sector 26* (Others, such as finance, property, research and development, entertainment, health, education, and public facilities). Furthermore, it has been found from the study that the individual emission sectors are changeable in their classification status between overall key sector, driving-dominant sector, driven-dominant sector, and non-key sector. This indicates that reduction measures applied to individual sectors should be reviewed on regular basis.

The findings from the study have an important value from both practical and theoretical perspectives. The understanding on the classification of emission sectors from driving and driven perspectives tells the importance of formulating different emission reduction measures by considering different types of key emission sectors. Identification of key emission sectors in this study provides important reference for the Chinese government to adopt measures against these key sectors. The driving-driven perspective adopted for examining key carbon emission sectors enables people to know more potential areas where carbon reduction can be achieved. Furthermore, the fact concluded from the study that emission sectors are changeable in their classification status provides guiding references for adjusting carbon reduction policy. In theory, this study contributes to the development of the research discipline of carbon emission. It also provides a useful literature to assist in studying emission sectors in other countries or regions. Further research is recommended to study the reasons why a sector changes from a non-key sector to a key sector or otherwise. Thus, measures can be taken to avoid the change from a non-key sector to a key emission sector.

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## References

- Akimoto K, Sano F, Homma T, Oda J, Nagashima M, Kii M (2010) Estimates of GHG emission reduction potential by country, sector, and cost. *Energy Policy* 38:3384–3393
- Alcántara V, Padilla E (2003) “Key” sectors in final energy consumption: an input–output application to the Spanish case. *Energy Policy* 31:1673–1678
- Bhattacharya M, Rafiq S, Bhattacharya S (2015) The role of technology on the dynamics of coal consumption–economic growth: new evidence from China. *Appl Energy* 154:686–695
- Bloch H, Rafiq S, Salim R (2012) Coal consumption, CO<sub>2</sub> emission and economic growth in China: empirical evidence and policy responses. *Energy Econ* 34:518–528
- Brandt AR (2015) Embodied energy and GHG emissions from material use in conventional and unconventional oil and gas operations. *Environ Sci Technol* 49:13059–13066

- Bugge J, Kjær S, Blum R (2006) High-efficiency coal-fired power plants development and perspectives. *Energy* 31:1437–1445
- Cai W, Wang C, Chen J, Wang K, Zhang Y, Lu X (2008) Comparison of CO<sub>2</sub> emission scenarios and mitigation opportunities in China's five sectors in 2020. *Energy Policy* 36:1181–1194
- Chong CH, Ma L, Li Z, Ni W, Song S (2015) Logarithmic mean Divisia index (LMDI) decomposition of coal consumption in China based on the energy allocation diagram of coal flows. *Energy* 85:366–378
- Commission NDaR (2016) The strategy of energy production and consumption revolution (2016–2030). [http://www.ndrc.gov.cn/zcfb/zcfbtz/201704/t20170425\\_845284.html](http://www.ndrc.gov.cn/zcfb/zcfbtz/201704/t20170425_845284.html)
- Daniels L, Coker P, Potter B (2016) Embodied carbon dioxide of network assets in a decarbonised electricity grid. *Appl Energy* 180:142–154
- Du L, Harrison A, Jefferson G (2014) FDI spillovers and industrial policy: the role of tariffs and tax holidays. *World Dev* 64:366–383
- Gao W, Zhu Z (2016) The technological progress route alternative of carbon productivity promotion in China's industrial sector. *Nat Hazards* 82:1803–1815
- Gao C, Sun M, Shen B, Li R, Tian L (2014) Optimization of China's energy structure based on portfolio theory. *Energy* 77:890–897
- Geng Y, Zhao H, Liu Z, Xue B, Fujita T, Xi F (2013) Exploring driving factors of energy-related CO<sub>2</sub> emissions in Chinese provinces: a case of Liaoning. *Energy Policy* 60:820–826
- Halkos GE, Tzeremes NG (2011) Oil consumption and economic efficiency: a comparative analysis of advanced, developing and emerging economies. *Ecol Econ* 70:1354–1362
- Halsnæs K, Garg A (2011) Assessing the role of energy in development and climate policies—conceptual approach and key indicators. *World Dev* 39:987–1001
- Huang L, Bohne RA (2012) Embodied air emissions in Norway's construction sector: input–output analysis. *Build Res Inf* 40:581–591
- IPCC (2006) 2006 IPCC guidelines for national greenhouse gas inventories
- Jiao JL, Fan Y, Wei YM (2013) The structural break and elasticity of coal demand in China: empirical findings from 1980 to 2006. *Int J Glob Energy Issues* 31:331–344 (314)
- Li BB, Liang QM, Wang JC (2015) A comparative study on prediction methods for China's medium- and long-term coal demand. *Energy* 93:1671–1683
- Liang S, Zhang T (2011) What is driving CO<sub>2</sub> emissions in a typical manufacturing center of South China? The case of Jiangsu Province. *Energy Policy* 39:7078–7083
- Lin B, Long H (2016) Emissions reduction in China's chemical industry—based on LMDI. *Renew Sustain Energy Rev* 53:1348–1355
- Liu H, Liu W, Fan X, Zou W (2015a) Carbon emissions embodied in demand–supply chains in China. *Energy Econ* 50:294–305
- Liu Z, Li L, Zhang YJ (2015b) Investigating the CO<sub>2</sub> emission differences among China's transport sectors and their influencing factors. *Nat Hazards* 77:1323–1343
- Luzon B, Elsayegh SM (2016) Evaluating supplier selection criteria for oil and gas projects in the UAE using AHP and Delphi. *Int J Construct Manag* 1–9
- Moullec YL (2013) Conceptual study of a high efficiency coal-fired power plant with CO<sub>2</sub> capture using a supercritical CO<sub>2</sub> Brayton cycle. *Energy* 49:32–46
- National Bureau of Statistics of China (2013) China energy statistical yearbook. China Statistic Press, Beijing
- National Bureau of Statistics of China (2015) China energy statistical yearbook. China Statistic Press, Beijing
- Othman J, Jafari Y (2016) Identification of the key sectors that produce CO<sub>2</sub> emissions in Malaysia: application of input–output analysis. *Carbon Manag* 113–124
- Pack H (2010) Productivity and industrial development in sub-Saharan Africa. *World Dev* 21:1–16
- Quader MA, Ahmed S, Ghazilla RAR, Ahmed S, Dahari M (2015) A comprehensive review on energy efficient CO<sub>2</sub> breakthrough technologies for sustainable green iron and steel manufacturing. *Renew Sustain Energy Rev* 50:594–614
- Roh S, Tae S, Suk SJ, Ford G, Shin S (2016) Development of a building life cycle carbon emissions assessment program (BEGAS 2.0) for Korea's green building index certification system. *Renew Sustain Energy Rev* 53:954–965
- Shan Y, Liu Z, Guan D (2016) CO<sub>2</sub> emissions from China's lime industry. *Appl Energy* 166:245–252
- Shen L, Shuai C, Jiao L, Tan Y, Song X (2016a) A global perspective on the sustainable performance of urbanization. *Sustainability* 8:783
- Shen L, Song X, Wu Y, Liao S, Zhang X (2016b) Interpretive structural modeling based factor analysis on the implementation of emission trading system in the Chinese building sector. *J Clean Prod* 127:214–227

- Shen L, Shuai C, Jiao L, Tan Y, Song X (2017) Dynamic sustainability performance during urbanization process between BRICS countries. *Habitat Int* 60:19–33
- Shuai C, Chen X, Shen L, Jiao L, Wu Y, Tan Y (2017a) The turning points of carbon Kuznets curve: evidences from panel and time-series data of 164 countries. *J Clean Prod* 162:1031–1047
- Shuai C, Shen L, Jiao L, Wu Y, Tan Y (2017b) Identifying key impact factors on carbon emission: evidences from panel and time-series data of 125 countries from 1990 to 2011. *Appl Energy* 187:310–325
- Singh A, Mishra N, Ali SI, Shukla N, Shankar R (2015) Cloud computing technology: reducing carbon footprint in beef supply chain. *Int J Prod Econ* 164:462–471
- Song M, Zhang J, Wang S (2015) Review of the network environmental efficiencies of listed petroleum enterprises in China. *Renew Sustain Energy Rev* 43:65–71
- Su B, Thomson E (2016) China's carbon emissions embodied in (normal and processing) exports and their driving forces, 2006–2012. *Energy Econ* 59:414–422
- Tan Y, Shuai C, Jiao L, Shen L (2017) An adaptive neuro-fuzzy inference system (ANFIS) approach for measuring country sustainability performance. *Environ Impact Assess Rev* 65:29–40
- Tarancón MÁ, Río PD, Callejas F (2011) Determining the responsibility of manufacturing sectors regarding electricity consumption. *The Spanish Case Energy* 36:46–52
- Wei C, Löschel A, Liu B (2015) Energy-saving and emission-abatement potential of Chinese coal-fired power enterprise: a non-parametric analysis. *Energy Econ* 49:33–43
- Xie X, Shao S, Lin B (2016) Exploring the driving forces and mitigation pathways of CO<sub>2</sub> emissions in China's petroleum refining and coking industry: 1995–2031. *Appl Energy*
- Xu T, Zhang B, Feng L, Masri M, Honarvar A (2011) Economic impacts and challenges of China's petroleum industry: an input–output analysis. *Energy* 36:2905–2911
- Yan J, Chou SK, Chen B, Sun F, Jia H, Yang J (2017) Clean, affordable and reliable energy systems for low carbon city transition. *Appl Energy* 194:305–309
- Zhang Y-J, Da Y-B (2013) Decomposing the changes of energy-related carbon emissions in China: evidence from the PDA approach. *Nat Hazards* 69:1109–1122
- Zhang YJ, Hao JF (2015) The allocation of carbon emission intensity reduction target by 2020 among provinces in China. *Nat Hazards* 79:921–937
- Zhang X, Wang F (2015) Life-cycle assessment and control measures for carbon emissions of typical buildings in China. *Build Environ* 86:89–97
- Zhang L, Hu Q, Zhang F (2014a) Input–output modeling for urban energy consumption in Beijing: dynamics and comparison. *PLoS ONE* 9:e89850
- Zhang YJ, Liu Z, Zhang H, Tan TD (2014b) The impact of economic growth, industrial structure and urbanization on carbon emission intensity in China. *Nat Hazards* 73:579–595
- Zhang G, Yang Y, Xu G, Zhang K, Zhang D (2015a) CO<sub>2</sub> capture by chemical absorption in coal-fired power plants: energy-saving mechanism, proposed methods, and performance analysis. *Int J Greenhouse Gas Control* 39:449–462
- Zhang Q, Nakatani J, Moriguchi Y (2015b) Compilation of an embodied CO<sub>2</sub> emission inventory for China using 135-sector Input–Output tables. *Sustainability* 7:8223–8239
- Zhao X, Hwang BG, Hong NL (2016a) Identifying critical leadership styles of project managers for green building projects. *Int J Construct Manag* 1-11
- Zhao Y, Wang S, Zhang Z, Liu Y, Ahmad A (2016b) Driving factors of carbon emissions embodied in China–US trade: a structural decomposition analysis. *J Clean Prod* 131:678–689