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Study of CO_2 emissions in China's iron and steel industry based on economic input–output life cycle assessment

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Abstract With the growing demand, China's iron and steel industry has obtained rapid development since the 1990s. China's steel output reached 220 million tons for the first time in 2003, becoming the first country whose annual production exceeded 200 million tons. The iron and steel is an industry of high energy consumption, high pollution and high emissions which has attracted deep concern of Chinese government. Previous research has estimated the direct CO_2 emissions in individual processes of iron and steel production, while research on the indirect CO_2 emissions from the related sectors of the iron and steel industry is scarce. To explore the whole CO_2 emissions, this paper evaluates the direct and indirect carbon emissions in the iron and steel industry and carbon emission deduction by building an economic input–output life cycle assessment (EIO-LCA) model based on the latest available data of the input–output extension table in 2010 and China's Energy Statistical Yearbook in 2011. The results show that coke and coal produce the most direct CO_2 emissions and raw chemical materials, medical and chemical fiber manufacturing, transportation storage and the postal industry, the electricity heat production and supply industry, nonmetal mineral production, petroleum processing of coke and nuclear fuel processing, coal mining and dressing are the six sectors that produce the largest indirect CO_2 emissions among the 35 sectors in the iron and steel industry. Based on the results, we suggest that China should (1) improve the quality of coke and coal, increase the efficiency of coke and coal, coal blending technology and the cokes' strength, and employ the scrap or cities' minerals as main raw materials in the production, and at the same time, the government and enterprises may increase to invest in technology innovation; (2) and use high-strength iron and steel instead of the ordinary one. Meanwhile, the spatial

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distributions of the six sectors are mainly concentrated in Shandong Province, Jiangsu Province, Zhejiang Province and Shanxi Province. Shandong Province, Jiangsu Province, Zhejiang Province and Shanxi Province may adjust their industrial structure by increasing the proportion of the third industry and accelerating the development of high-tech industries and services.

**Keywords** Iron and steel industry · CO_2 emissions · China · EIO-LCA model · Implications

1 Introduction

The global CO_2 emissions were 36.1 billion tons in 2013, reaching the highest in history, including 10 billion tons in China, 5.2 billion tons in the USA, 3.5 billion tons in the 28 members of the European Unions and 2.4 billion tons in India. China's CO_2 emissions exceeded the sum of the CO_2 emissions in the USA and the European Union, accounting for nearly 30 % of the total global emissions (Friedlingstein et al. 2014). Speaking of the iron and steel industry, CO_2 emissions in this industry accounted for approximately 12 % of the total CO_2 emissions in China which almost doubled the world average ratio of 6.7 % in 2010. There is much space for China's iron and steel industry to reduce the CO_2 emissions though big pressure exists (Shuo 2014).

In November 2014, China announced that CO_2 emissions would peak in 2030 and that China would plan for nonfossil energy to account for 20 % of the energy consumption in 2030 (Xinhuanet 2014). The iron and steel industry is an important basic industry of China's economy and is also an important part of the industrial system. Over the past 10 years, the rapid development of China's economy brought a surge in the demand of steel products. The output of China's crude steel increased from 152.26 million tons in 2001 (Worldsteel 2002) to 821.99 million tons in 2013 (as shown in Fig. 1; Worldsteel 2014). The director general of world steel association recognized that the demand of China's iron and steel might keep no change in the next 5 years (NetEase 2015). However, the process of iron and steel production is complex, and the scale of production and the
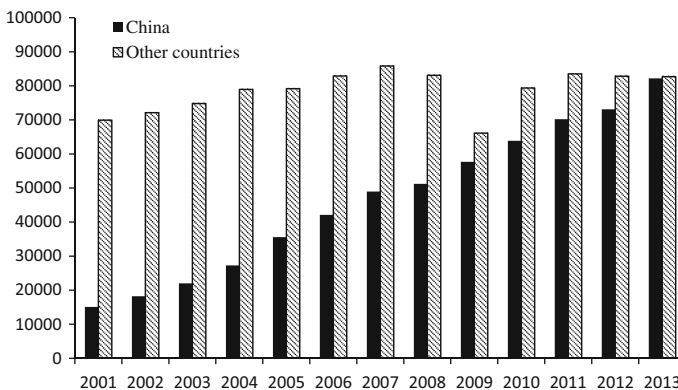
Fig. 1 Crude steel production in China and other countries (ten thousand tons) (*Source*: Worldsteel 2002, 2014)
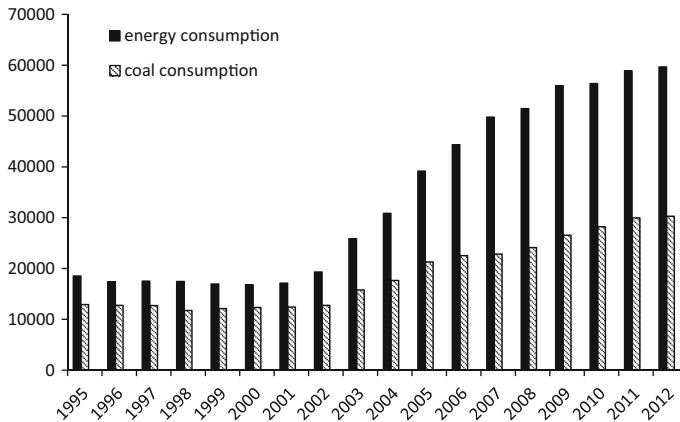
Fig. 2 Energy consumption and coal consumption in China's iron and steel industry (ten thousand tons coal equivalent) (*Source*: China energy statistical yearbook 2009, 2010, 2011, 2012, 2013)

consumption of resources are huge. Coal, electricity and fuel oil account for 69.9, 26.40 and 3.2 %, respectively, of energy consumption in the process of iron and steel production. It is reported that this fuel structure cannot be changed greatly in the short time (China industry insight network 2015), which implies that the iron and steel industry will remain one of the largest CO_2 emission industries, next only to the chemical industry and construction (Fig. 2). So it is important to explore the sources of CO_2 emissions in iron and steel industry to provide more specific basis for government policy making.

2 Literature review

In studies of the CO_2 emissions in the iron and steel industry, many domestic and foreign scholars have used direct calculation methods to calculate the CO_2 emissions in iron and steel industry or the relationship between the development in iron and steel industry and CO_2 emissions. There are also some studies of the intensity of energy and carbon emissions for assessing the future reduction potential of carbon emissions in the iron and steel industry.

2.1 Progress of the calculation and influencing factors of CO_2 emissions in the iron and steel industry

To calculate CO_2 emissions in the iron and steel industry, some scholars have studied them from the entire industry level, while others have done so from an individual enterprise level.

   Guo et al. (2010) established a suitable mathematical model, analyzed the energy balance of Baosteel from 2001 to 2007 and calculated the total CO_2 emissions of 2001–2007 in Baosteel. The growth trend of CO_2 emissions was slightly larger from 2001 to 2004 than the growth trend from 2005 to 2007, with an average growth of 1.6 million tons each year. Zhang and Liu (2012) set emission sources and counted the CO_2 emissions of the fixed source, process and power from 2006 to 2009. The CO_2 emissions of China's steel industry were 16.5 million tons, 19.01 million tons, 18.72 million tons

and 21.97 million tons in 2006, 2007, 2008 and 2009, respectively. Except for 2008, the financial crisis showed a slight decline; the other years all experienced increases. Zhao et al. (2012) calculated CO_2 emissions of the iron and steel industry using a direct calculation. The results indicated that the CO_2 emissions of China's iron and steel industry were 9.7 million tons in 2009, which was 2.4 times that of 2000. Zhang et al. (2013) constructed the carbon footprint model for the production process of iron and steel. The results show that the total carbon footprint in the production process of Nangang was 17.16 million tons in 2011, increasing 53 % from 2005. The carbon footprint per ton was 2.583 tons in 2005 and decreased to 2.245 tons in 2011, and this paper puts forward some suggestions on energy saving and emission reduction. According to the emission factors and the accounting methods of IPCC, Zou et al. (2015) calculated CO_2 emissions of the iron and steel industry in 2000 and 2012, which were 34.36 million tons and 14.24 million tons, respectively.

Tian et al. (2013) conducted an LMDI decomposition analysis to uncover the drivers of China's iron and steel industry using data from 2000 to 2010, and the results showed that the construction sector was the largest embodied energy emission sector for China's iron and steel industry. Weida and Kai (2013) constructed a decomposition model and analyzed the relationship between CO_2 emissions and the influential factors. The results revealed the following: (1) When the output of the iron and steel industry increased by 1 %, CO_2 emissions would increase by an average of 0.26 million tons, and (2) when consuming 1 ton of coal, the released CO_2 emissions were 1.25 tons. Yu et al. (2015) proposed a concise conceptual model and an econometric model to investigate the relationships between CO_2 abatement, investment and technological expenditure and their connections with the economic growth and governmental policies in the iron and steel industry in China. The technological expenditure could significantly reduce CO_2 emissions, and the investment expansion showed a negative impact on CO_2 emission reduction.

2.2 Progress of the future reduction potential of CO_2 emissions in the iron and steel industry

Gielen and Moriguchi (2002) developed a new linear programming model named the steel environmental strategy assessment program to analyze CO_2 emission reduction potentials in the Japanese iron and steel industry. These emissions decreased from a level of 185 Mt in 2000 to approximately 150 Mt in 2020–2030 because of decreased production and increased recycling.

Wang et al. (2007) assessed the CO_2 abatement potential of China's steel industry using long-range energy alternative planning system software to generate 3 different CO_2 emission scenarios for the industry from 2000 to 2030. The average CO_2 abatement per year in the recent policy scenario and in the new policy scenario was 51 million tons and 107 million tons, respectively. Namely, there was great potential for CO_2 abatement in China's steel industry. Thus, adjusting the structure of the industry and technological advancement could play an important role in emission reduction. Chen et al. (2014) used a system dynamics model and a bottom-up energy system model—TIMES (The Integrated MARKAL-EFOM System)—to analyze the steel demand, energy consumption and CO_2 emissions from China's iron and steel industry from 2010 to 2050. The steel production in China will increase from 627 Mt in 2010 to a peak of 772 Mt in 2020 and will then gradually decrease to 527 Mt in 2050. The energy intensity and CO_2 intensity of steel production would continue to decrease during the modeling period. Kuramochi (2015)

used an up-to-date techno-economic assessment to investigate the CO_2 emission reduction potential in the Japanese iron and steel industry for 2030. The results showed that 20 Mte CO_2 emission reductions could be achieved in 2030 compared to a frozen technology scenario, which was equivalent to 12 % of the industry's total emissions in 2010.

2.3 Literature summary

1. As seen from the existing research, researchers estimate the direct CO_2 emissions in the special process in the iron and steel production from the whole industry level or the individual level, but the research on the indirect CO_2 emissions from the related sectors of iron and steel industry is scarce.
2. Although the traditional input–output of energy and environment can calculate the CO_2 emissions of final demand in some sectors, it cannot analyze the implicit CO_2 emissions in the production chain, which lacks the unity of the two perspectives.

To solve the above shortcomings, this paper first determines the boundary of the iron and steel life cycle system, constructing the EIO-LCA model and the matrix of CO_2 emissions in China's iron and steel industry in 2010. Second, this paper measures the direct and indirect CO_2 emissions and CO_2 emissions from each stage of the life cycle using data from China's input–output extension table in 2010 and China's Energy Statistical Year book 2011 and determines the links and sectors of the largest CO_2 emissions, which can provide the basis for practical CO_2 emission reduction.

3 Model and methods

3.1 EIO-LCA model

Hendrickson et al. (1998) put forward the EIO-LCA model to analyze the impact of a product or service production chain on the environment. The EIO-LCA model is similar to the traditional environmental input–output method. But the emission coefficient matrix between the two is different (Wang et al. 2015). In the traditional environment input–output method, a certain pollutant discharge coefficient is a row vector, but the emission factors of the pollutants are a diagonal matrix, which can break down the environmental impact of the final demand of the sector in the production chain in the EIO-LCA model.

The basic assumptions of the EIO-LCA model are as follows: (1) There is a positive proportional relationship between the input and output of the sectors in the national economy; (2) all of the equipment that is used in the production of a product or service can be attributed to a particular sector; and (3) the calculated results of the model are the environmental impact of the process of a product or service corresponding to the final demand of the sector.

The basic model matrix is in the following.

$$X = R(I - A)^{-1}Y \tag{1}$$

where X is the carbon emissions that are caused by Y, Y is the column vector of final demand, I is the unit matrix, A is the direct consumption coefficient matrix, R is diagonal matrix, and R_i is the direct carbon emission coefficient of the sector I (1995).

Table 1 Basic concepts of ferrous metal smelting and processing

32 ferrous metal smelting and processing	3210 Iron-making	
	3220 Steel-making	iron and steel
iron, manganese, chromium and its alloys	3230 Steel rolling	industry
	3240 ferroalloy smelting	

Source: China industry information network (2014)
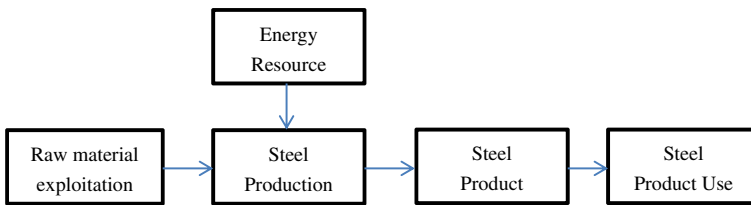
Fig. 3 System boundary of the iron and steel life cycle

3.2 The system boundary of the iron and steel life cycle

Ferrous metals mainly contain iron, manganese, chromium and their alloys, such as steel, iron, pig iron, ferroalloy and cast iron. The main of ferrous metal smelting and processing is the iron and steel industry (Table 1). Thus, the iron and steel industry in this paper is set for ferrous metal smelting and processing.

The system boundary of the iron and steel life cycle contains the raw materials mining and iron and steel which are removed from the plant. The iron and steel life cycle assessment refers to the environment influence in the stage of the iron ore exploitation, transportation, production, recycling and reuse. Based on the study of the International Iron and Steel Institute (World Steel Association 2013) and Zou et al. (2015), the system of the iron and steel industry life cycle is defined as shown in Fig. 3.

This paper estimates the direct emissions, the indirect emissions and the emission deduction throughout the entire life cycle of the iron and steel industry. Referring to the results of Fangqin et al. (2010), the system boundary is calculated in Fig. 4 as follows.

3.3 Method

The calculation model of CO_2 emissions in the iron and steel industry in this paper is the following.

$$C = C_1 + C_2 - C_3 \tag{2}$$

where C represents the total CO_2 emissions in the iron and steel industry; C_1 indicates the direct CO_2 emissions in the iron and steel industry based on the perspective of production; C_2 indicates the total CO_2 emissions in the iron and steel industry based on the perspective
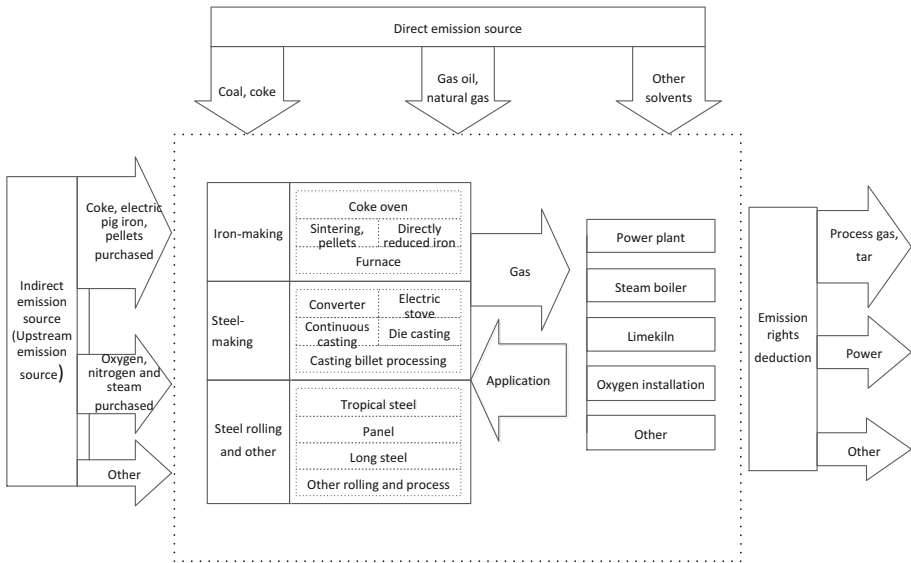
Fig. 4 Calculation system boundary of the iron and steel's enterprise (*Source*: Fangqin et al. 2010)

of demand; and C_3 represents the CO_2 emission deduction, including CO_2 emissions that are generated by the byproducts such as coal gas and tar.

1. C_1

$$C_1 = E_i \times \alpha_i \times \beta_i \tag{3}$$

where E_i indicates the consumption of i, α_i is the standard coal coefficient of i, and β_i is the CO_2 emission coefficient of i.

2. C_2

First, the direct CO_2 emissions of the relevant industries of the iron and steel industry are calculated according to the following formula.

$$b = Rx \tag{4}$$

The column vector b indicates the CO_2 emissions of the production when the final demand y is met, R is the diagonal matrix, and the diagonal elements indicate the CO_2 emissions per unit in the output, where

$$R_i = c_i/x_i \tag{5}$$

R_i is the direct CO_2 emission coefficient of sector i, c_i is the direct CO_2 emissions of the sector, and x_i is the output of the sector.

$$c_i = \rho \times e_i \tag{6}$$

ρ is the CO_2 emissions that are generated by 1 ton of standard coal consumption, and the value of ρ is 2.71 t CO_2/tons standard coal according to the results of Qi (2013); e_i is the standard coal consumption amount of sector i (ten thousand tons).

The matrix of CO_2 emissions in the established iron and steel industry life cycle is shown in Eq. (1).

3. C_3

A certain amount of byproduct such as coal gas and tar will be produced in the production of iron and steel. The byproducts will be converted into electricity, which can reduce CO_2 emissions. Assume that the utilization rate of coal gas and tar in the iron and steel production is 100 % (Zou et al. 2015). Equation (7) shows the CO_2 emission deduction in the process of converting the byproducts into electrical energy.

$$C_3 = \text{Annual electricity} \times CO_2 \text{ emission factor of regional power network} \qquad (7)$$

3.4 Data

The data in the paper come from China's input–output extension table in 2010, China's Energy Statistical Yearbook 2011, Xiamen energy-saving public service network and China Electrical Power Yearbook 2013. The paper merged 65 sectors of China's input–output extension Table 2010 into 35 sectors to match the structure of China's Energy Statistical Yearbook 2011. The sector classification is shown in Table 2. Each sector is represented by one code as 1, 2, … 35.

4 Results and discussions

The results are shown in Figs. 5 and 6. The soundness of the results is analyzed in the following.

4.1 Results

1. C_1

This paper calculated the amount of energy consumption, standard coal coefficient converted and the CO_2 emission coefficients in the iron and steel industry in 2010 (Table 3). The direct CO_2 emissions are 1362.53 million tons. The use of coke and coal produces the largest carbon emissions, which accounts for 99.1 % in the iron and steel industry. The carbon emissions generated by coke accounted for 60 %, and the carbon emissions generated by coal accounted for 39.1 %. The carbon emissions from other seven kinds of energy accounted for only 0.9 %.

2. C_2

As shown in Fig. 5, the largest indirect CO_2 emissions of the related sectors for the iron and steel industry are from raw chemical materials, medical and chemical fiber manufacturing, construction, handicraft manufacturing and other manufacturing products, nonmetal mineral production, petroleum processing coking and nuclear fuel processing, coal mining and dressing. The indirect CO_2 emissions in raw chemical material, medical and chemical fiber manufacturing rank the first in the six sectors, which accounted for 17.9 % in the 35 sectors. The results are mainly due to three reasons.

3. C_3

The provinces and cities covered by the China regional power network and the emission factors in 2010 are shown in Table 4, and the power capacity generated in these regions in 2010 was previously reported (China electrical power press 2013).

Table 2 Sector classification

Sectoral code	Sector	Sectoral code	Sector
1	Farming, forestry, livestock and fishery	19	Ferrous metal smelting and processing
2	Coal mining and dressing	20	Nonferrous metal smelting rolling processing
3	Petroleum and natural gas extraction	21	Metal products
4	Ferrous metals mining and dressing	22	Ordinary equipment
5	Nonferrous metals mining and dressing	23	Special equipment
6	Nonmetallic and other mining	24	Transportation equipment
7	Food processing, food production and beverage production	25	Electric equipment and machinery
8	Tobacco processing	26	Electronic and telecommunications equipment
9	Textile	27	Instruments, meters and cultural and office machinery
10	Textile clothing, shoes, hats manufacturing	28	Handicraft manufacturing and other manufacturing products
11	Leather, fur and feather (cashmere) manufacturing	29	Electricity power/heating supply
12	Timber processing and furniture manufacturing	30	Gaseous fuel production and supply
13	Paper making and printing	31	Water treatment and supply
14	Stationary and sporting goods manufacturing	32	Construction
15	Petroleum processing, coking and nuclear fuel processing	33	Transport, logistics, postal and telecommunication services
16	Raw chemical materials, medical and chemical fiber manufacturing	34	Wholesale, retail trade, hotels and catering services
17	Plastic and rubber products	35	Other service activities
18	Nonmetal mineral production		

Fig. 5 Indirect CO_2 emissions of the related sectors for the iron and steel industry (ten thousand tons)
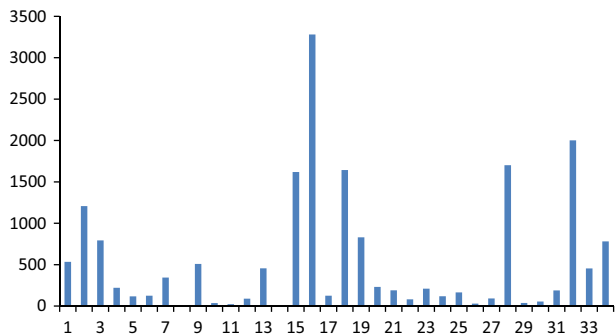
According to formula (7), the amount of the CO_2 emission deduction is calculated as shown in Fig. 6. Namely, the CO_2 emissions reduced in the process of converting the byproducts into electrical energy are 44.1 million tons.
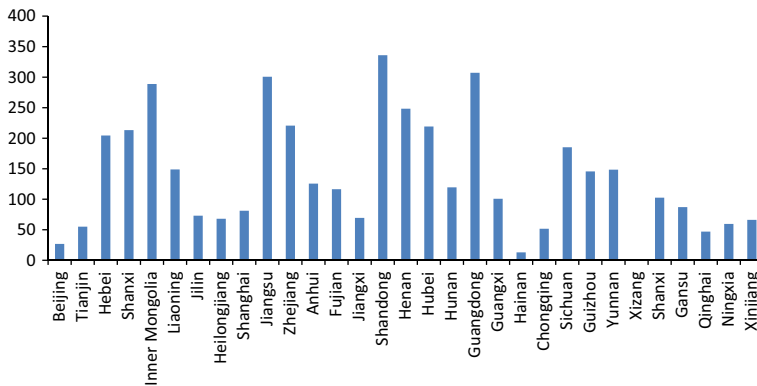
Fig. 6 Amount of emission right deduction (ten thousand tons)

Table 3 Amount of energy consumption, standard coal coefficient converted and CO_2 emission coefficients in the iron and steel industry in 2010

Energy type	The amount of energy consumption (ten thousand tons)	Standard coal coefficient converted (Mtc/t)	CO_2 emission coefficients (tCO$_2$/Mtc)
Coal	28,221.6	0.7143	2.64
Coke	29,448.5	0.9714	2.8602
Crude oil	0.33	1.4286	2.08
Gasoline	13.4	1.4714	2.9251
Kerosene	1.16	1.4714	3.0179
Diesel	99.88	1.4571	3.0959
Fuel oil	23.9	1.4286	3.1705
Natural gas	20.42 (100 million cubic meters)	1.33 (Mtc/ cubic meters)	2.1622
Power	4611.6 (100 million Kwh)	0.0001 (Mtc/Kwh)	0.954

The CO_2 emission coefficient of the power is calculated according to the average carbon dioxide emission coefficient of regional power grid units in China

Source: Xiamen energy saving Center (2012)

4.2 Discussions

(1) On the direct CO_2 emissions in the iron and steel industry

The direct CO_2 emissions are calculated according to the official data and formula published by the National Development and Reform Commission (Xiamen energy saving Center 2012). The data and the formula are all reliable. The proportion of coal and coke accounting for the energy consumption is almost the same with that of Han et al. (2011), whose result was that the average proportion of coal and coke accounting for the energy consumption from 1994 to 2006 was 97.1 %. And also, it can be seen that there was almost no obvious change in the energy consumption structure of the iron and steel in 2010 and the period from 1994 to 2006. This is mainly because China's energy consumption is based on coal resource (China Academic Network 2013; China industry insight network 2015). Seen from technology aspect, the clean coal technology in the production of iron and steel

Table 4 Provinces and cities covered by the China regional power network and the emission factors in 2010 (tCO_2/MWh)

Power network	Provinces and cities covered	Emission factors
Northern China regional power network	Beijing, Tianjin, Hebei, Shanxi, Shandong and Inner Mongolia	0.9914
Northeast China regional power network	Liaoning, Jilin and Heilongjiang	1.1109
Eastern China regional power network	Shanghai, Jiangsu, Zhejiang, Anhui and Fujian	0.8592
Central China regional power network	Henan, Hubei, Hunan, Jiangxi, Sichuan and Chongqing	1.0871
Northwest China regional power network	Shanxi, Gansu, Qinghai, Ningxia and Xinjiang	0.9947
Southern China regional power network	Guangdong, Guangxi, Yunnan and Guizhou	0.9762
Hainan's power network	Hainan	0.7972

Source: Department of Climate Change (2010)

is efficient and feasible (Xinhuanet 2015). Thus, it is necessary to provide the guide and investment for the technology.

(2) On the indirect CO_2 emissions in the iron and steel industry

The CO_2 emissions in the iron and steel industry are measured by using the input–output data in 2010 and input–output model. The indirect CO_2 emissions of the steel industry are comprehensively reflected. The model and data are reliable. Seen from the results, it may be obtained that the spatial distributions of the six sectors are mainly concentrated in Shandong Province, Jiangsu Province, Zhejiang Province and Shanxi Province. The industrial structure of Jiangsu Province and Zhejiang Province is relatively reasonable, as the proportion of the tertiary industrial output value accounting for GDP has exceeded the proportion of the secondary industrial output value accounting for GDP, while there is still existing adjustment space for the two provinces. The industrial structure of Shandong Province and Shanxi Province is relatively unreasonable, and adjustment space is existed.

5 Conclusions and implications

Based on the China's input–output extension table in 2010, the China energy statistical yearbook 2011 and EIO-LCA model, this paper constructs the carbon matrix in the iron and steel industry and places the direct CO_2 emissions and the indirect CO_2 emissions of the iron and steel industry within the same framework. This paper analyzes the CO_2 emissions of the iron and steel industry from three aspects based on a production perspective to calculate direct CO_2 emissions and a demand perspective to calculate the indirect CO_2 emission and carbon emission discount.

(1) From a production perspective, the use of coke and coal produces the largest carbon emissions accounting for 99.1 % in the iron and steel industry, which is related to the structure of energy consumption in China's iron and steel industry. In the next 10–15 years, coal and coke will be the largest contributors in the direct CO_2 emissions in the iron and steel industry. Technological innovation can reduce CO_2 emissions, and it is

important to change the technology for reducing CO_2 emissions. In the worldwide, the US iron and steel industry was the lowest energy consumption and CO_2 emissions per ton, which was achieved through the development and the use of advanced technology (Wu and Zhang 2012).

Therefore, to reduce the direct CO_2 emissions in the production of iron and steel industry, it is necessary to improve the quality of coke and coal, increase the efficiency of coke and coal, coal blending technology and the cokes' strength, and employ the scrap or cities' minerals as main raw materials in the production. At the same time, the government and enterprises may increase to invest in technology innovation. (2) From a demand perspective and carbon emissions per output, the six sectors are the biggest contributors in the indirect CO_2 emissions of the relevant industries of the iron and steel industry. To reduce the indirect CO_2 emissions in the demand process of iron and steel industry, it may use high-strength iron and steels instead of the ordinary ones or reduce the use of iron and steels, which shows that the use of high-strength iron and steel emits less CO_2 than the use of ordinary iron and steel by 5.7 % (China steel news network 2012). Meanwhile, Shandong Province, Jiangsu Province, Zhejiang Province and Shanxi Province can adjust the industrial structure by increasing the proportion of the third industry and accelerating the development of high-tech industries and services. These coastal provinces and Shanxi Province have the advantages of industrial restructure and urgent demand. Shandong Province and Shanxi Province may adjust their industrial structure by increasing the proportion of the tertiary industrial output value accounting for GDP or the R&D investment, fostering new industries, resolving serious excess capacity and accelerating the restructuring of iron and steel, petrochemical industry and so on.

The relevant future research can be done from the following aspects. First, the future research can calculate the CO_2 emissions of the import of iron and steel, if the input–output extension tables of some other countries are obtained. Second, the future research can calculate the CO_2 emissions of iron and steel with the newest data, which can be compared with this research so as to find out the change of CO_2 emissions of China's iron and steel.

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