Examining China’s Industrial Structure Changes and Forecast the Carbon Emissions from Energy Intensity Industries Based on Simulation Model - Focusing on Iron and Steel Industry in China

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Zhaoling LI

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Zhaoling LI

ABSTRACT

China has experienced rapid industrialization and now is facing various challenges, such as environmental pollution and economic development pressure. To evaluate the industrial development process of China, and find a most influential industry to estimate its carbon reduction potential and its impact on the whole industrial network, in the first part of this study, a normative social relationship analysis method, Social Network Analysis (SNA), is imported and combined with Input-Output Analysis. This integrated research model can quantitatively display the impact of one industry on the whole industrial network and the industrial structure related carbon emission during the period of 2000 to 2012. Based on the evaluation indicators like degree centrality, betweenness centrality, impact on other industries, direct and indirect carbon emission and some other parameters, like economic contribution and social welfare, it was found that China's manufacturing industries, especially the iron and steel industry, have larger effect on industrial structure and environmental impact than the service industries and agriculture. Therefore, iron and steel industry will be selected as the research subject in the next part of research.

According to the results in the first section, iron and steel industry was chosen as the representative industry to find the possible solutions on national economic and environmental problems. The iron and steel industry is facing various problems, such as heavy environmental pollution, high resource consumption, overcapacity and low added value. Industrial upgrading is urgently needed. To choose an appropriate development condition for the iron and steel industry, assess the carbon emission reduction potential in medium-term (2007-2030), and evaluate the corresponding impact on environment and national development under different conditions, in this part of research, a non-linear environmental-economic model is built up based on the industrial input-output relationship. Finally, we hope to forecast whether China would achieve the carbon emission intensity reduction target or Intended Nationally Determined Contributions (INDCs), which is by 2020, China will lower carbon dioxide emissions per unit of GDP by 40% to 45% from the 2005 level; by 2030, China will lower carbon dioxide emissions per unit of GDP by 60% to 65% from the 2005 level and increase the share of non-fossil fuels in primary energy consumption. China's Input-Output table 2007 was used as the data source, assisting by some official data issued

by National Bureau of Statistics of China. Six scenarios are designed including business as usual (BaU), production structure change and technology upgrading (tec), the carbon tax (tax) and carbon trading (tra) policy implications, as well as two combination scenarios (cob-1, integrated technology upgrading and carbon tax policy, and cob-2, including technology upgrading, carbon tax and carbon trading policy). The results are as follows:

(1) GDP will increase 7.69% every year averagely from 2007 to 2030 in BaU scenario. Carbon tax brings the most GDP loss during the three human intervention measures, but the average annual growth rate is still as high as 7.64%. Carbon trading policy will have the minimal impact on national economy, and the GDP loss caused by technology upgrading is limited. The average annual growth rate in the two combination scenarios are 7.67% and 7.64%, respectively.

(2) The largest reduction in carbon emission will occur in Technology upgrading scenario. The average annual growth rate is only 4.71%, 2% less than that in BaU scenario. The carbon reduction effects of environmental policies are also obviously. For the two combination scenarios of three intervention methods, cob-2 has much stricter carbon reduction effect than cob-1. Moreover, in tec, cob-1, and cob-2 scenarios, the increase rate in carbon emission will slow down after 2027, which means the target of carbon emission peak in 2030 may be realized.

(3) Carbon intensity (EpG) will keep decreasing in each scenario. Corresponding to the carbon emission reduction effect, the carbon emission intensity in technology upgrading scenario will have the largest decrease amount. The two environmental policies have similar effect on carbon emission intensity decrease. For the two combination scenarios, cob-1 will meet the carbon reduction target of 2020. Cob-2 scenario will achieve the carbon intensity reduction target of both 40% decrease in 2020 and 60% decrease in 2030 comparing to the level in 2005.

(4) Technology upgrading will decrease the crude steel production most during the three measures, while, carbon trading policy has less effect. Carbon tax will promote the most on EAF development, because of the low carbon emission in Electric Arc Furnace (EAF) route. The proportion of EAF will increase from16.9% in 2007 to 52.55% in in 2030. The production structure in carbon trading scenario will not be influence a lot, which means this policy will only bring temporary carbon emission reduction effect, instead of long-term benefit.

(5) Electricity production will reduce with the crude steel output decrease. As the electricity is one important energy source for EAF, therefore this study also considered the electricity production

structure by developing the nuclear power. As the result, the share of nuclear power will increase to about 30% in 2030. According to the national nuclear power development plan, combining with the power generation amount in each scenario, the proportion of nuclear power in each scenario will be satisfied by the national plan.

In conclusion, industrial upgrading, including technological updating, production structure adjustment and resources circulation, is the fundamental of resource conservation and low-carbon development. The carbon reduction effect of carbon tax policy is also considerable. However, carbon trading policy still needs to be adjusted according to Chinese market. On the other hand, the reduced production of crude steel and the corresponding reduced electricity demand are also essential for carbon emission reduction.

Key words: carbon emission reduction; industrial network, industrial upgrading, environmental policy

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Abbreviations:

BaU, Business as usual;

BF, Blast Furnace;

BF-BOF, Blast Furnace-Basic Oxygen Furnace;

C2ES, Center for Climate and Energy Solutions;

cob-1, Combination of technology upgrading and carbon tax scenario;

cob-2, Combination of technology upgrading, carbon tax and carbon trading scenario;

CO_2e, CO_2 equivalent;

CNY, Chinese yuan;

EAF, Electric Arc Furnace;

GDP, Gross Domestic Product;

GHG, greenhouse gases;

IEA, International Energy Agency;

INDCs, Intended Nationally Determined Contributions;

I-O, Input-Output;

IPCC, Intergovernmental Panel on Climate Change;

NBS, National Bureau of Statistics of China;

ppm, parts per million;

RCPs, Representative Concentration Pathways;

SNA, Social Network Analysis;

tax, Carbon tax scenario;

tce, tons of standard coal-equivalent;

tec, Technology upgrading scenario;

tra, Carbon trading scenario;

USD, USA dollar;

Chapter 1 Introduction

1.1 Background

1.1.1 Carbon cap to deal with climate change

Global warming is recognized as the main reason of melting glaciers, sea-level rise, biological extinction, extreme weather and other problems affecting the living environmental condition. Greenhouse gases (GHGs) emission is regarded as an important factor of climate change and global warming. The concentration of carbon dioxide in the atmosphere have experienced an accelerated growth from 280 parts per million (ppm) CO_2 equivalent (CO_2e) at the beginning of Industrial Revolution (around 1750s) to over 430 ppm recently with the development of industrialization (Hasanbeigi et al., 2014a; IPCC, 2007a; Mohajan, 2011; Shakun et al., 2012). Stabilizing the carbon dioxide concentration at 450 ppm CO_2e are recognized as the carbon cap to avoid the increase of temperature within 2.0 ℃ comparing to the pre-industrial levels and maintain the ecosystem balance (IPCC, 2014).

Many institutes conducted simulation works to estimate the carbon emission growth under climate mitigation and adaptation. For example, Intergovernmental Panel on Climate Change (IPCC) conducted four different Representative Concentration Pathways (RCPs) considering the population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy to make projections. Results showed that to control the CO_2 concentration within 430-480 ppm, the annual CO_2 emission should decrease to zero growth, even "carbon negative". Matthews and Zickfeld (2012) conducted an intermediate-complexity coupled climate-carbon model to estimate the temperature changes under zero CO_2 emission, non-CO_2 greenhouse gas emission, aerosol emission and their combinations. Results showed that zero CO_2 and other greenhouse gases emission, while maintaining constant aerosol forcing will decrease the global temperature rapidly and close to pre-industrial level by 2200. Non-CO_2 greenhouse gases emission will make the temperature increase 1.2 ℃ above 2010 level (2.2 ℃ above pre-industrial temperatures) by the year 2200 after elimination CO_2 and aerosol emissions. Global temperatures will only increase 0.1 ℃ by 2200 as a result of keeping CO_2 emissions' increase rate normally and constant non-CO_2 greenhouse gas and aerosol forcing after 2010. Moreover, CO_2 concentration will decrease after 2010 because of the removal effect of land and ocean carbon sinks under zero CO_2 emission scenario. If we stopped emitting greenhouse gases and aerosols, global temperature will increase 0.3 ℃ from 2010 to 2020 because of the initial forcing increase from the fast removal of aerosols and tropospheric ozone, then decrease under the effect of methane and nitrous oxide (Fig. 1-1).

Some other organizations also made estimates about the 2 ℃ target fulfillment based on the emission reduction promise from each country. For example, Climate Interactive assessed the implementation path of 2.0 ℃ target by applying the C-ROADS model, a scientifically reviewed climate simulator which aggregates the proposals of countries and country groups to calculate long-term global climate impacts. Results showed that the global temperature will increase 4.2 ℃ in 2100 comparing to preindustrial levels in reference scenario (with a range of uncertainty of 2.5 – 5.5 ℃). Concentration of CO_2e in atmosphere will be 890 ppm. 3.3 ℃ increase in the national plans scenario, which means no change after national contribution pledge period. If we want to limit the temperature increase under 2.0 ℃ (around 1.8 ℃), all countries need to peak their emissions by 2030 and with 5% emission decrease rate per year in developed countries and 3.5% per year in developing countries in the post-2030 period. If the developed countries peak the emissions by 2025 and then reduce steadily at 10% per year, developing countries peak at 2030 then decrease with 8% per year, then the temperature increase can be controlled within 1.5 ℃ (Interactive, 2017).

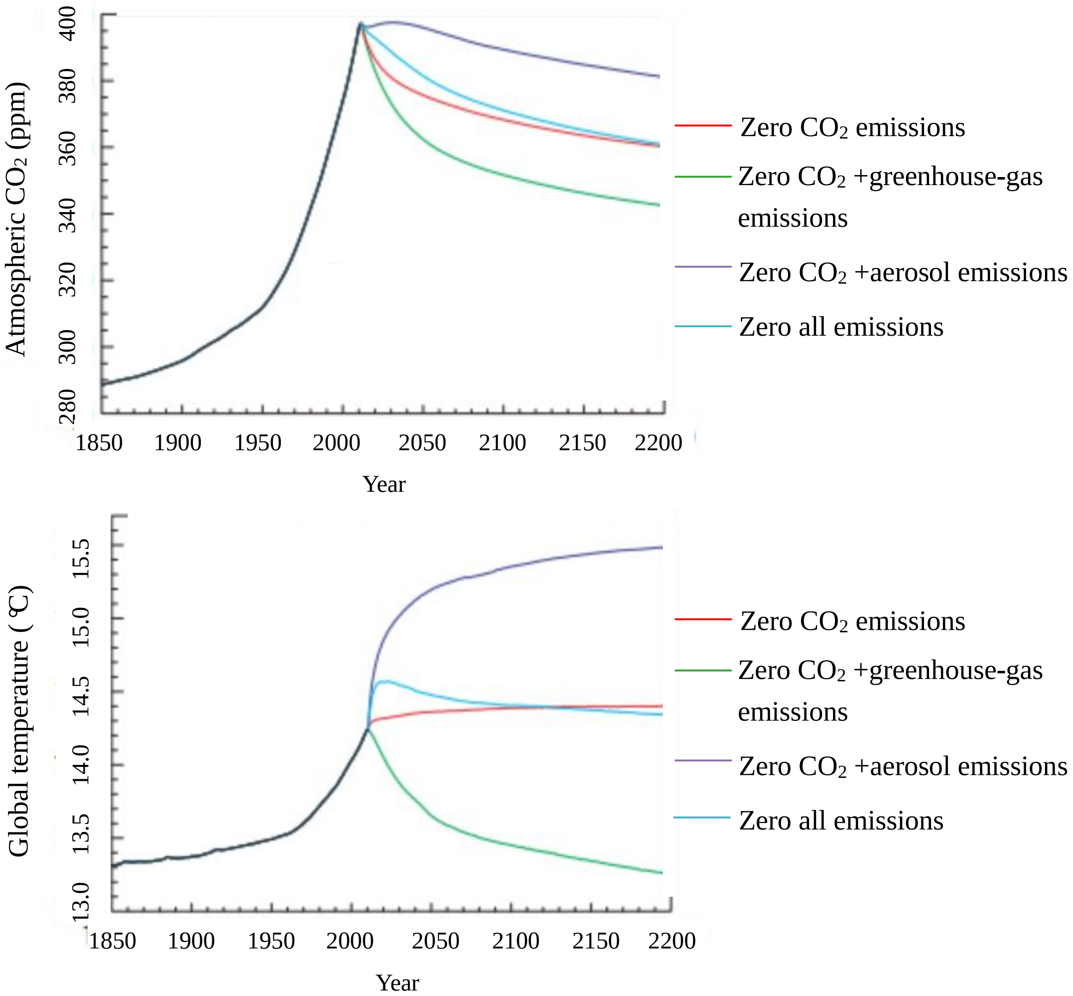

Fig. 1-1 Global climate response to zeroed emissions of greenhouse gases and aerosols

Source: Matthews and Zickfeld, 2012

1.1.2 Source of GHG emissions and energy consumption in the world

As the result from Matthews and Zickfeld (2012), greenhouse gases have the greatest effect on global warming. Greenhouse gas (GHG) is defined as those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal Protocol (IPCC, 2007b).

In 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), energy, industrial processes and product use, agriculture/forestry and other land use and waste are considered as the major anthropogenic factors of GHG emissions. Energy is considered as the most important source of GHG emissions (Fig. 1-2). 68.0% anthropogenic GHG emissions came from energy consumption. Of which, 90.0% were CO_2 emissions, 9.0% were CH_4, while, N_2O accounted for 1.0%. While, the emission amount of livestock and agriculture only shared 11.0% of the global anthropogenic GHG emissions. CH_4 and N_2O emissions are the major product. Industrial processes not related to energy, which contribute 7.0% of the total GHG emissions, mainly produce fluorinated gases and N_2O. Remained 14.0% emissions come from other sources. (IEA, 2016a; IPCC, 2013).

Depending on the category of greenhouse gases, 87.0% of human CO_2 emissions come from fossil fuel combustion. 9.0% and 4.0% of CO_2 emit from land use changes and industrial process, respectively (Le Quéré et al., 2012). Despite the less emission of CH_4 and N_2O, their greenhouse effect is 23 times and 296 times that of CO_2, respectively. 60.0% of anthropogenic CH_4 emissions are due to fossil fuel production and intensive livestock farming. Other sources include landfills and waste (16.0%), biomass burning (11.0%), rice agriculture (9.0%) and biofuels (4.0%) (Bousquet et al., 2006). Agriculture, fossil fuel use and industrial processes are responsible for 77.0% of all human N_2O emissions. Other sources include biomass burning (10.0%), atmospheric deposition (9.0%) and human sewage (3.0%) (Denman et al., 2007). Therefore, to control the fossil fuel consumption is the most efficient way to reduce GHG emissions.

With the development of industrialization, fossil fuel consumption and the corresponding greenhouse gases emission increased rapidly (Fig. 1-3). Based on the statistic of BP p.l.c. (2016), the world energy consumption increased more than three times from 4000.0 million ton in 1965 to 13147.0 million ton in 2015. Fossil fuels like coal, oil and natural gas accounted for 86.0% of the world total energy consumption in 2015. Of which, oil is the most consumed fossil fuel. It increased 2.8 times from 1525.4 million ton in 1965 to 4331.3 million ton in 2015. Coal combustion follows and 3839.9 million ton oil equivalent coal were used in 2015. Natural gas consumption increased 5.3 times from 587.4 million ton oil equivalent in 1965 to 3135.2 million ton oil equivalent in 2015. For other energy types, hydropower consumption increased 4.3 times and 892.9 million ton oil equivalent hydropower were consumed in 2015. In 2015, 583.1 and 117.3 million ton oil equivalent nuclear power and bio-energy were consumed. The consumption amount of solar power and wind power were 57.3 and 190.3 million ton oil equivalent in 2015, respectively.

In terms of the geographic departmentalization, Europe and North America, as the pioneer and fastest growing area in industrial revolution, primary energy consumption in these two areas are much higher than other regions at the beginning of statistical period (Fig. 1-4). Then, the energy consumption in Europe decreased a little to 2834.0 million ton oil equivalent in 2015. The consumption amount in North America changed to be stable after 2008. The energy consumption in Asia Pacific increased rapidly from 441.4 million ton oil equivalent in 1965 to 5498.5 million ton oil equivalent in 2015. It is becoming the biggest energy consumer region, which is almost equal to the sum consumption of North America and Europe. In the early period, Japan contributed most of the consumption and China followed behind. After 1977, the energy consumption of China excessed Japan and the average annual growth rate increased to 7.1% after 2002. From another point of view, 35 OECD countries consumed 41.9% of the world total primary energy consumption amount in 2015. While, the remain 58.1% were shared by other countries.

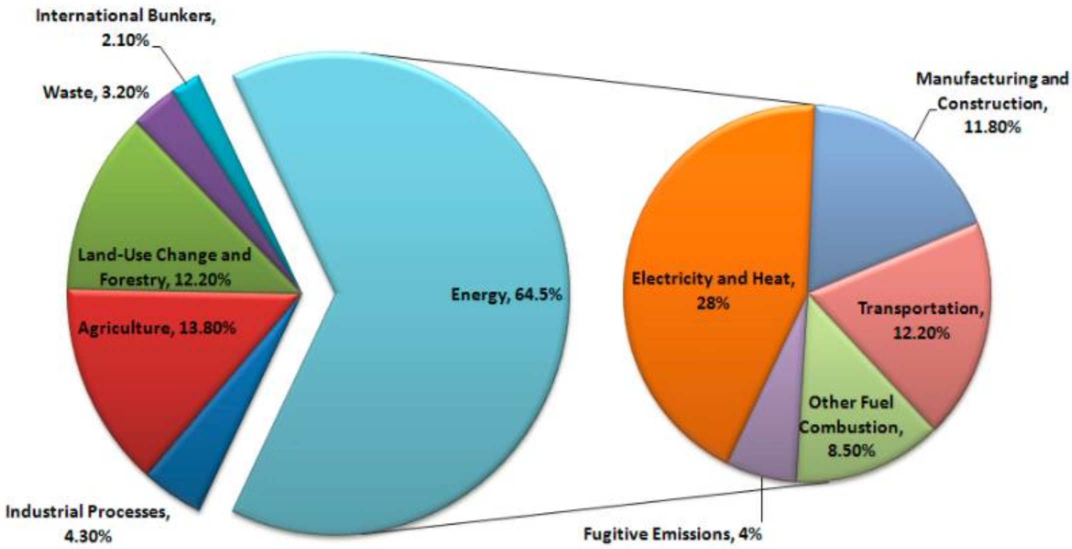

Fig. 1-2 Global anthropogenic GHG emissions by sector in 2005

Source: C2ES, 2017; IEA, 2016b

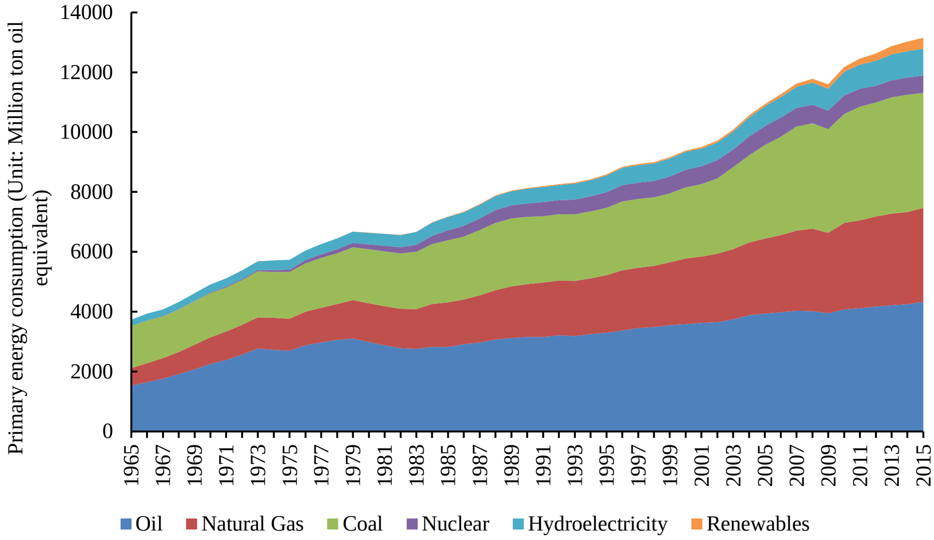

Fig. 1-3 World energy consumption by source

Source: BP Statistical Review of World Energy, 2016

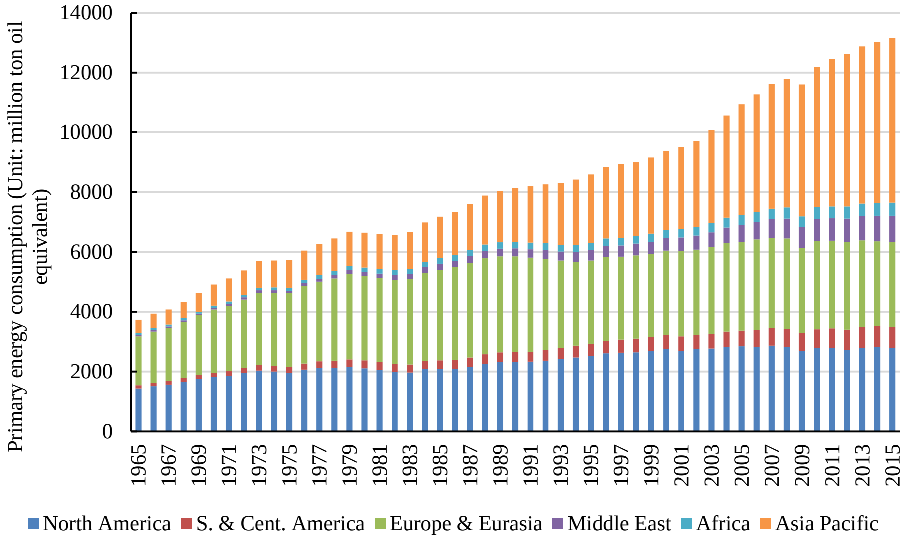

Fig. 1-4 World energy consumption by region

Source: BP Statistical Review of World Energy, 2016

1.1.3 Energy consumption and GHG emissions in China

With the rapid industrialization, the energy consumption in China was also promoted and increased sharply especially after the year 2002 (Fig. 1-5). According to the statistic of National Bureau of Statistics of China (NBS), the total energy consumption increased 2.9 times from 1469.6 million ton coal equivalent in 2000 to 4299.1 million ton coal equivalent in 2015. It accounted for 22.9% of the world total consumption and half of the total Asia Pacific consumption, even a little higher than the Europe consumption. Coal is the major energy source of China, which accounted for more than 60.0% of the total energy consumption. In 2007, the proportion of coal consumption reached the biggest point, about 72.5%. Then, this ratio decreased to 63.7% in 2015. Oil is the second biggest energy source of China. However, it only accounted for about 20.0% of the total energy consumption in China. The oil consumption increased 2.4 times from 323.3 million ton coal equivalent in 2000 to 786.7 million ton coal equivalent in 2015. While, its proportion decreased from 22.0% in 2000 to 16.4% in 2009, then increase a little to 18.3% in 2015. Natural gas consumption increased 7.8 times from 32.3 million tons coal equivalent in 2000 to 253.6 million ton coal equivalent in 2015. Its share has also risen from 2.2% in 2000 to 5.9% in 2015. The proportion of renewable energy, like hydropower, nuclear power and wind power increased from 10.2% in 2000 to 19.0% in 2015. The consumption amount increased 4.9 times from 107.3 million ton coal equivalent in 2000 to 520.2 million ton coal equivalent in 2015.

China's CO_2 emission increased more than 130 times from 78.1 million ton in 1960 to 10249.5 million ton in 2013 (World bank, 2017). Its share in world total emissions also increased from 8.3% in 1960 to 28.6% in 2013. CO_2 emissions from fossil fuel combustion accounted for more than 80.0% of the total CO_2 emissions. In the late 1970s and early 21 contrary, this ratio was even higher than 90.0%. Coal consumption is one of the most important reasons (Fig. 1-6). CO_2 emissions from coal combustion accounted for more than 80.0% of the total fossil fuel combustion emissions. In recent years, the proportion decreased from 85.6% in 2009 to 82.9% in 2014. Oil combustion, which shared 20.0% of the fossil fuel consumption, contributed 13.0% CO_2 emissions in 2014. Natural gas is the cleanest fossil fuel. It accounted for 6.0% of the fossil fuel consumption, while only emitted 3.6% of the total emission amount. Other greenhouse gases emission, like CH_4 and NO_2, are much lower than CO_2. In 2012, only 143.4 thousand ton CH_4 and 55.8 thousand ton NO_2 were emitted. 38.0%

and 41.0% of CH_4 emission came from oil and natural gas combustion, respectively in 2012. Most of the NO_2 emissions came from coal combustion (63.0%). NO_2 from Oil consumption accounted for 31.0% of NO_2 emissions. Only 4.0% NO_2 emissions came from natural gas consumption.

In terms of the different industry sectors, secondary industry and service industry are the two biggest emitters, which accounted for about 80% of China's total greenhouse gases emission in 2012 (Fig. 1-7). Of which, emissions from secondary industry was 5464.8 million ton, occupying 45.0% of national emissions in 2012. Service industry was only 1.2% less than secondary industry with 5317.5 million ton of GHG emissions. The rest of industries shared other 20.0% of GHG emissions. Transportation industry had relatively bigger energy requirement and emissions. 591.1 million ton GHG emissions came from this industry, occupying 4.9% of the total emissions. Post and computer industry followed behind with 287.4 million ton GHG emissions and shared 2.4% of the total amount. Agriculture and power, heat and water supply industry accounted for 1.3% and 1.2% of the total emissions, with 158.3 million ton and 146.4 million ton emissions in 2012. Construction industry emitted the least, only 101.8 million ton (calculated based on China's energy balance table 2012).

Within the secondary industry, heavy industries are the main GHG emission sources. For example, iron and steel industry shared 28.5% of the industrial total emissions, with 1558.3 million ton emissions. Nonmetal production, like cement production and glass production, emitted 1025.8 million ton GHG emissions, which shared 18.8% of the industrial emissions. Metal production occupied 13.7% of the industrial emission and emitted 749.4 million ton emissions. Emissions in chemical industry are also considerable, which emitted 616.2 million ton GHG emissions in 2012 and took up 11.3% of the total industrial amount. Mining industry, other manufacturing industry and energy production industry shared 6.9%, 5.8% and 5.7% of the total industrial emissions. Light industries only contributed 8.4% of the industrial emissions. Of which, clothing, leather and other products industry and textile industry emitted the most with 146.2 million ton and 114.8 million ton GHG emissions, shared 2.7% and 2.1% of the industrial emissions, respectively in 2012. Food production, wood production and paper printing only shared 1.7%, 0.7% and 1.2% of the industrial emissions. Therefore, to control the GHG emissions in the critical industrial sectors, especially the four biggest emitters in heavy industry category, will bring substantial results.

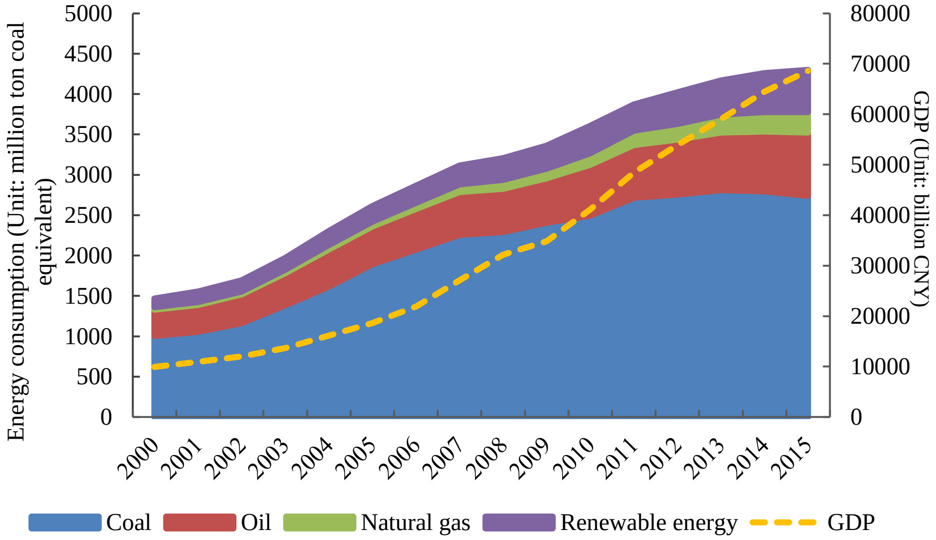

Fig. 1-5 Energy consumption and GDP in China

Source: National Bureau of Statistics of China (NBS, 2016)

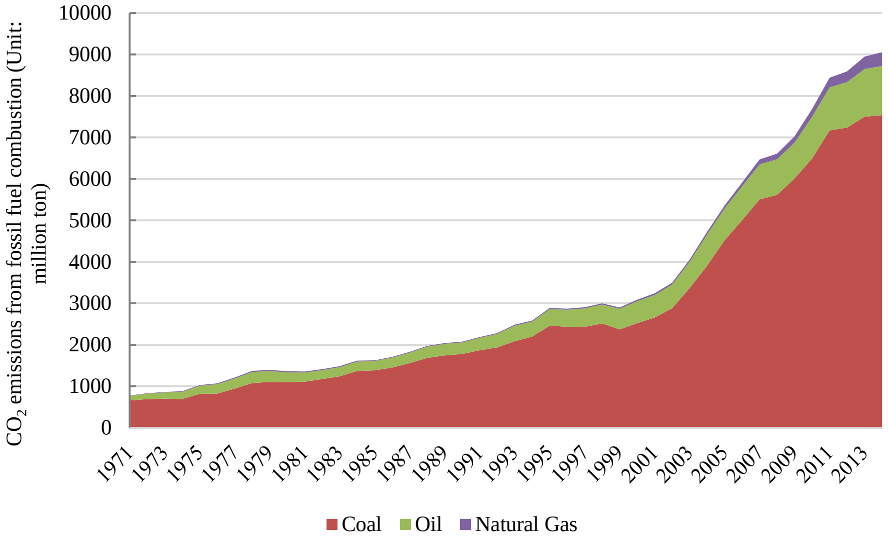

Fig. 1-6 CO_2 emissions from different kinds of fossil fuel combustion in China

Source: World Bank, 2017

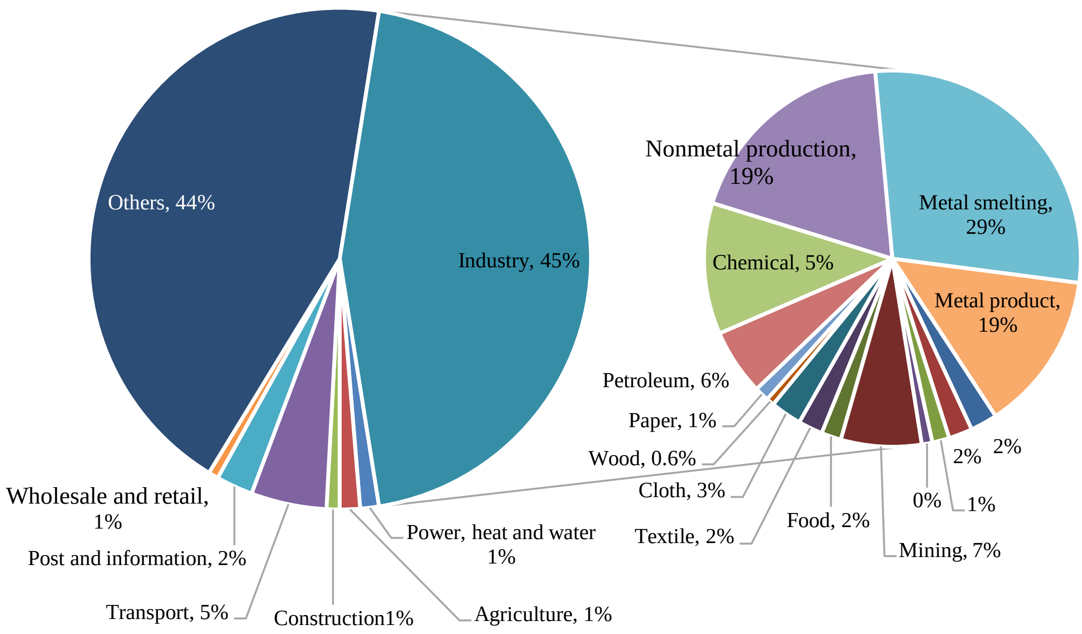

Fig. 1-7 China’s carbon emission structure in 2012 (this study)

1.2 Literature review and current problems

1.2.1 Research method of carbon emission study

Lots of researchers had made great efforts to decrease the carbon emission in China. To find the different influencing factors and their effect on promoting the carbon emission, decomposition analysis has been widely applied. For example, Wu et al. (2006) analyzed China's CO_2 emissions during 1980 and 2002 by conducting Log-Mean Divisia Index (LMDI) method. Results showed that before 1996, economic scale, fuel mix and energy intensity on the energy-demand side were the main drivers for the CO_2 emissions. While, the effects of structure and efficiency changes on the energy-supply side were not obviously. After 1996, efficiency improvement in end-use sectors and energy transformation sectors was the primary reason for China's CO_2 emissions decrease. In the research result of Wang et al. (2005), energy intensity decline contributed 95% of the CO_2 emission decrease from 1957 to 2000 identified by LMDI method. Other reasons, like fossil fuel mix and renewable energy penetration were only accounted for 1.6% and 3.2%, respectively. Industrial activity and energy intensity are recognized as the major reasons for China's industrial carbon emission changes in the research of Lin et al.'s (2007) research over the period 1998-2005. On the other hand, Chang et al. (2008) and Su and Ang (2012) analyzed the CO_2 emissions in China by applying Structural decomposition analysis (SDA) method. According to the results in decomposition analysis, some researchers tried to decrease the total national or regional emissions by dealing with the main driving force factor. For example, Wang et al. (2011) tried to decline 40%-45% CO_2 emissions intensity in Fujian and Anhui provinces compared with 2005 level by decreasing the energy intensity and developing nuclear power and renewable energy.

1.2.2 Industrial carbon emission research

In terms of the research subjects, the critical emitters, like iron and steel industry, chemical industry, electricity industry and cement industry, in heavy industries received more attentions. Liu et al. (2007) confirmed that the raw chemical materials and chemical products, nonmetal mineral products and smelting and pressing of ferrous metals account for 59.31% of total increased industrial CO_2 emissions. Therefore, these industries should be among the top priorities for enhancing energy efficiency and driving their energy intensity close to the international advanced level.

Sims et al. (2003) analyzed the cost, GHG emissions in global electricity system by 2010 and

2020. This research summarized that by using the modern thermal power stations with steam cycle can exceed 40% efficiencies based on lower heating value (LHV). Pebble bed modular reactor (PBMR) in nuclear power can effectively improve the safety with lower cost. Physical carbon sequestration is a good method of carbon capture as 80%-90% of the CO_2 in a flue gas stream can be captured. Finally, it estimated that by 2020, 15% of carbon emission in electricity industry can be reduced on a global scale, along with cost saving benefits. Ou et al. (2011) analyzed the primary fossil energy consumption and greenhouse gases emission for electricity generation and supply in China. Results found that coal power pathway is the only major contributor of primary fossil energy consumption and GHG emissions in 2007. GHG emissions intensity in 2020 will decrease to 220.470g CO_2e/MJ with the development of nuclear and renewable energy, and to 169.014g CO_2e/MJ if carbon dioxide capture and storage technology is employed. Cai et al. (2007) also estimated the CO_2 emission reduction potential in China's electricity sector using long-range energy alternative planning system (LEAP) method. Structure adjustment and technical mitigation measures are considered as effective measures to decrease the CO_2 emissions. Nuclear and hydropower will be an important factor to reduce the carbon emission intensity in power generation sector in China.

For the cement industry, Lei et al. (2011) fund that PM 2.5 and PM 10 emissions from cement industry accounted for 26.9% and 29.0% of the total amount in 2005. Total suspended particulates (TSP) emissions from cement industry shared 21.4% of the total amount. 7.7% and 12.5% of the total CO and CO_2 emissions came from cement industry, respectively. By implementing clinker substitution, thermal efficiency improvement and fuel alternative, the CO_2 emissions from cement industry will reduce 12.8% by 2020. Wang et al. (2013) found that cement production activity effect and clinker production activity effect are the dominant factors to increase the total GHG emissions of Chinese cement industry. While, energy intensity effect can help decrease the total GHG emissions. Energy structure brings more GHG emissions for cement industry, which play an opposite effect with emission factor effect. Liu et al. (2015) proposed that the carbon emission in cement industry is overestimated. The new estimated emission amount in their research is 12% less than the latest inventories that China reported to the UNFCCC and 14% less than the estimate by EDGAR version 4.2. This research also perceived the carbon sink function of cement.

For Chemical industry, Lin and Long (2014) adopted the factor decomposition and the EG co-integration methods to investigate the influencing factors of fossil energy consumption and measure the saving potential of fossil fuel in Chemical industry. They concluded that labor productivity effect and sector scale effect can increase the energy consumptions in Chemical industry. While, energy intensity effect and energy structure effect can effectively decrease the energy demand. By estimating the energy saving potential, 46.8 million ton coal equivalent (Mtce) and 100.5 Mtce can be conserved in 2015 and 2020, respectively, under the ideal scenario. In another work, Lin and Wessh (2013) estimated that coal consumption in chemical industry can be substituted by other clean energies, like natural gas, and thus decrease the GHG emissions.

Iron and steel industry is another important energy-intensive industry. Wen et al. (2014) analyzed the energy conservation and CO_2 emissions mitigation potential of China's iron and steel industry using Asian-Pacific Integrated Model (AIM). Results showed that 14.18% and 14.53% of energy and CO_2 emissions will be decreased in 2020 comparing BaU scenario by implementing strengthen policy, like higher carbon tax price. It is also indicated that technology promotion has stronger effect on energy saving and emissions reduction than structure adjustment. Ali Hasanbeigi et al. (2013) focused on then technology upgrading. They estimated that the total technical energy efficiency improvement potential and electricity conservation potential in China from 2010 to 2030 by importing 23 advanced measures will be 11,999 PJ and 251 TWh in 2030. Correspondingly, 139 Mt CO_2 emissions and 237 Mt CO_2 emissions will be saved due to the decrease of energy and electricity consumption reduction. They also analyzed the energy use trends of China's key medium- and large-sized steel enterprises during 2000-2030 by improve the utilization rate of ferrous scrap. Results showed that the energy intensity of crude steel production will decrease from 17 GJ/t in 2015 to 13 GJ/t in 2030 under a high scrap usage scenario. Of which, the energy efficiency of EAF route will be 6 GJ/t in 2030, decreased 50% comparing to the level in 2015. BOF will only decrease 2 GJ/t from 18 GJ/t in 2015 to 16 GJ/t. The ratio of EAF produced crude steel will increase from about 10% in 2015 to 35% in 2030 under high scrap usage scenario (Hasanbeigi et al., 2014a).

Chen et al. (2014) assessed the medium-term energy consumption of iron and steel industry in China using system dynamics model and The Integrated MARKAL-EFOM System (TIMES) model by considering technique update and energy recovery. As the estimate result of this research, the crude steel production will peak in 2020, then decrease gradually. The share of EAF steel production will increase significantly from 9.8% in 2010 to 45.6% in 2050. By installing the advanced technologies, the energy intensity of crude steel production will keep decreasing. Wang et al. (2007) applied LEAP software to forecast the CO_2 emissions from iron and steel industry. This results showed that if all the regulations and policies in iron and steel industry had been fully implemented, 51 million tons CO_2 emissions would be reduced. The corresponding costs would be 9.34 billion dollars. While, there will be 107 million tons CO_2 emissions abatement under more ambitious regulations and industrial standard, which needs 80.95 billion dollar incremental costs.

Besides the modeling estimation research, some researchers also put the iron and steel industry into the industrial symbiosis to fully improve the energy efficiency of iron and steel industry by increasing the utilization rate of waste heat and scrap. For example, Dong et al. (2013b) designed one industrial symbiosis network aimed to increase the energy flux and waste reuse in iron and steel industry in Liuzhou city, China. In this system, iron and steel industry will connect to cement, chemical, aluminum industry and society. Results showed that, by improving the usage of gas, steam, red mud and slag in iron and steel industry, the industrial comparable energy consumption reduced by 60 kgce/ton, water consumption reduced by 0.57 m^3/ton and total 5.7 million ton annually, waste utilization rated increased to 90%, coal consumption reduced by 670,000 ton coal equivalent, total economic benefit was over 1 billion CNY (158 million USD) annually.

Some other researches tried to find the main influence factors for the relatively higher energy consumption and carbon emission in iron and steel industry. Hasanbeigi (2014a) adopted LMDI method and found that the production structure (share of BF-BOF and EAF route) and the pig iron ratio used as feedstock in each process route will be the two most important factors for reducing the energy consumption in iron and steel industry in the near future. Xu and Lin (2016) analyzed the influencing factors about the CO_2 emissions in iron and steel industry using Vector Autoregressive model. Results showed that energy efficiency plays a dominant role in reducing CO_2 emissions in iron and steel industry. Economic growth has more impact on emission reduction than industrialization due to the massive fixed asset investment and industrial energy optimization. While, urbanization has significant effect on driving up CO_2 emissions because of mass urban infrastructure and real estate construction.

1.2.3 Industrial network research

When comparing the influence of each industry on industrial network, the GDP contribution rate is the most common and most intuitive point of discussion in industrial structure analysis. For example, Wang et al. (2010a) analyzed the different development features of the industrial structure in China, Japan and US using intermediate input rate variations and the added value ratio changes based on an input-output analysis. Lu and Deng (2011) evaluated the industrial structure of China's western provinces according to GDP growth and financial investment. A series of cluster analysis methods were conducted to divide the industries into different grades based on their impact on industrial network including hierarchical cluster analysis (Liang et al., 2013), industrial-complex model (Gordon & McCann, 2000), and K-means algorithm (Cui et al., 2013).

Three major industries, primary industry, secondary industry and tertiary industry, are mainly considered as the research objective. For example, Cui and Yang (1998a) evaluated the industrial structure of Hebei and its 11 cities according to the ratios of three industries. Zhang et al. (2014) confirmed that a change in industrial structure by improving the share of tertiary industry in the total GDP could curb carbon emission. Some researchers were concerned with an industrial level analysis. For instance, Lu and Deng (2011) found that the industrial structure of Hebei was dominated by high pollution industries such as iron and steel manufacture and the chemical industry. Twelve criteria were used to separate 28 sectors into three clusters in the research of Liang et al. (2013) and the industries in cluster 1 were observed to have a large effect on industrial structure optimization.

Based on the literature review, we found that comparing to other methods, only simulation model analysis could forecast the medium- and long- term carbon emission and give an estimation results on different impact factors. However, the most important problem in current researches is that these analyses mainly focused on the bottom-up research which only pay attention to the optimization effect and corresponding changes of the intervention methods in the target industry. The associated impact of these industrial optimization measures on national economy or other industries are rarely considered. Moreover, the simulation researches on these industries only focused on limited aspects because of the limitation of bottom-up research. There is no comprehensive top-down model that integrated technology, policy and other factors to get the impact on the entire industrial network. Another problem is that there is no comprehensive research to compare the varying impact of these heavy industries. For example, which industry have higher economic contribution and GHG emissions on national development and should be optimized preferentially. A more scientific evaluation system should be built.

1.3 Significance and objective of this study

To fill these two research problems mentioned in the end of section 1.2, this research will be conducted from the following aspects:

(1) An industry which has biggest impact on national development will be selected firstly.

(2) A top-down simulation model about the most influential industry will be built up. All the impact factors related to this most influential industry and occurred in the actual society will be fully considered in the simulation model to estimate its medium-term carbon reduction potential, and the environmental and economic response on national level.

(3) Policy suggestions on China's industry restructure and specific heavy industries will be provided.

To achieve these research targets, Social Network Analysis (SNA), a normative tool used to analyze the human social relationship, structure and resource liquidity between each member will be introduced into the industrial network analysis for the first time. Therefore, the different influencing effect of each industry on the whole industrial network can be revealed, so that the most influential industry can be found.

After finding the most influential industry, a non-liner top-down environmental-economic simulation research will be conducted to find the carbon emission reduction potential of this industry, and estimate the overall impact on other industries and national level. By doing this simulation work, both technology upgrading, energy and waste recycling, environmental policy and industrial structure effect will be integrated. Moreover, carbon trading policy will also be considered in the simulation.

The significant of this research are summarized as follows:

(1) This research will give a theoretical basis and practical direction on the feasibility of industrial structure research and the combination between Input-Output table and SNA;

(2) A comprehensive top-down simulation research will give guidance for both industrial

development and national response.

1.4 Main contents and outline of this study

This thesis consists of four chapters. The content of each chapter is summarized as follows:

Chapter 1 is the introduction of research background. This part gives an overview on global warming and its effect on climate change and sea level rise, severe situation of human greenhouse gases emission and the estimate of the global carbon emission cap to avoid the disasters caused by global warming. After that, the sources of GHG emissions are discussed. Energy consumption in world wild and China are listed afterwards. In literature review part, the basic means to reduce the GHG emissions in typical energy-intensive industries are summarized, and found the shortcomings of the current researches. Then we determined the research objects and significant of this research.

In chapter 2, the industrial structure research will be conducted first as an antecedent study to find the most influential industry. In this section, Social Network Analysis will be conducted and combined with Input-Output analysis to identify the different impact of each industry on China's industrial structure and the environmental impact of each industry.

In chapter 3, the most influential industry will be selected as the representative industry. A brief introduction about this industry in China will be given in this chapter, including the technology route of this industry, development situations, problems and corresponding policy measures. Then, a no-liner environmental-economic modeling based on the current industrial problems and industrial development plan will be built up. The modeling concepts, equations and parameters used in this work will be showed in detail. Both technology upgrading, production structure changes and environmental policies will be considered in this model. Then, the simulation result, discussion and conclusion of this part of research will be given.

The final discussion and conclusions will be provided in Chapter 4. Policy suggestions will be summarized for the low carbon and sustainable development in China. Please see Fig. 1-1 to find more details about the research framework.

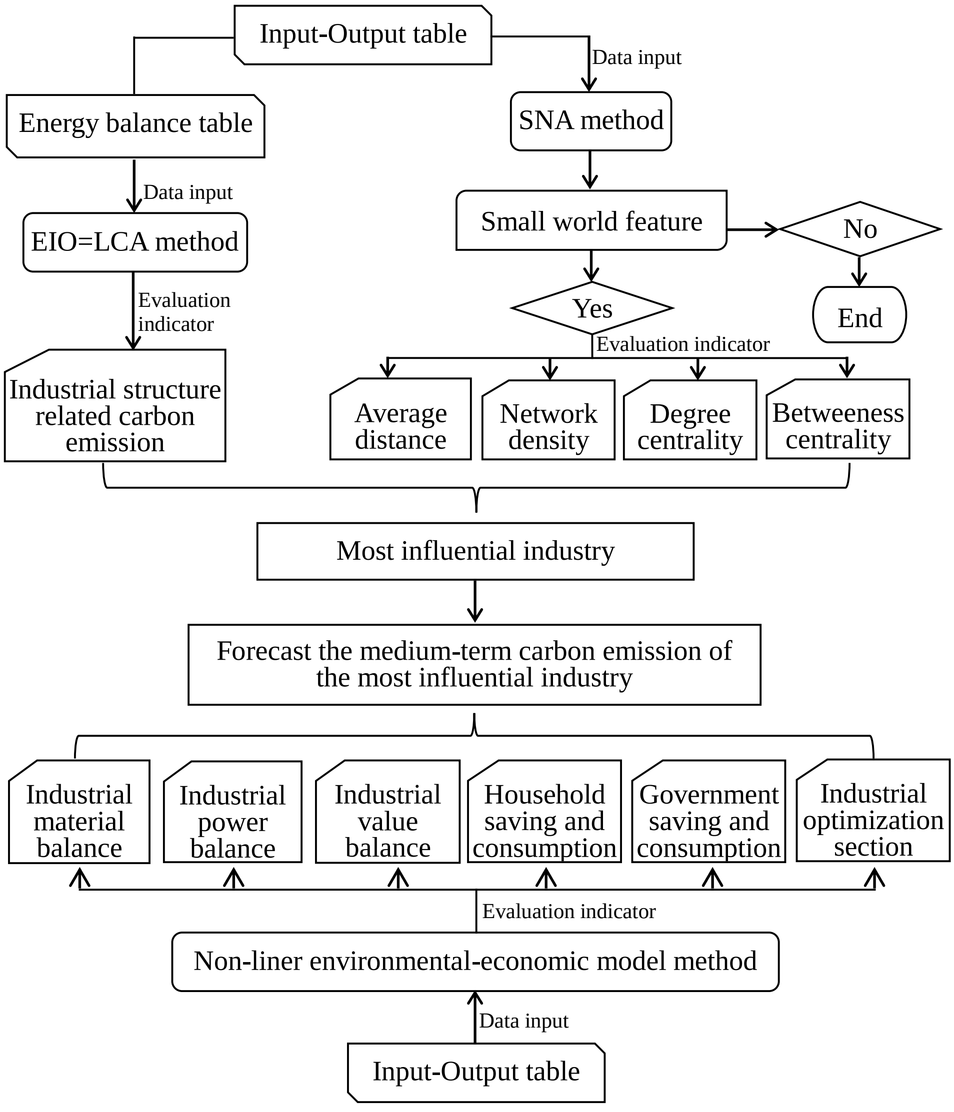

Fig. 1-8 Research framework

Chapter 2 Examining the impact of each industry on the industrial network

2.1 Introduction

Industry is the primary source of energy consumption, greenhouse gas (GHG) emissions and environmental pollution (Dong et al., 2013a; Dong et al., 2014a). According to IPCC AR5, total emissions from the industrial sector reached 14.86 $GtCO_{2e}$ in 2010, representing 30% of the total global GHG emissions (Stocker, 2014). Moreover, the industrial network structure affects resource utilization and has corresponding environmental effects (Cui & Yang, 1998b; Zhang & Deng, 2010). Therefore, it is crucial for all industrial sectors to reduce both resource and energy consumption (Mi et al., 2015). In this context, the adjustment of the industrial structure can significantly contribute to the conservation of natural resources and the protection of ecosystems so that sustainable development can be realized (Zhang & Deng, 2010; Zhou et al., 2013).

There are three important stages in China's industrial structure development showed in Fig. 2-1. The first stage is from early 1950s to 1970s. During this period, China's economy is dominated by agriculture and the first industry is the biggest industry. The secondary industry and service industry remained at the primary development level. From 1970s to the middle 1980s, the ratio of secondary industry excessed the first industry and China entered the early stage of industrialization. However, the ratio of tertiary industry was still less than the first industry. After middle 1980s, the position and importance of secondary industry was further strengthened. The proportion of tertiary industry excessed the first industry and increased quickly becoming an important driver of economic growth. While, the share of first industry in the national GDP plummeted and the gap with other two industries continued enlargement.

From the global view, although the importance of first industry decreased in China, it became more and more important in the global market (Table 2-1). In 1990, the added value of China's first industry only accounted for 8.6% of the global agriculture. However, it increased to 21.3% in 2008. The proportion of second industry in the global level increased from 2.2% in 1990 to 10.8% in 2008. While, only 2.3% increase in tertiary industry during this period, which is much lower than first and secondary industries. This result also indicated that the development of service industry in China is lagging behind relatively (World Bank).

Here are several features in China’s industrial structure. Within the first industry, the structure of modern agriculture is transferring from traditional plants to various forms of comprehensive development. Manufacturing industry is becoming more and more important in the secondary industry and the energy consumption pressure also increased due to the development of metal related manufacturing. The competition of China’s technology intensive industries increased obviously in the global market. Producer service is the main driving force for the development of tertiary industry. While, the effect of wholesale and retail and real estate in life service is also significant.

However, which industry has relatively higher influence on the whole industrial network is still unclear. Therefore, the objective of this chapter is trying to find the most influential industry on the related industries and national economy and environmental.

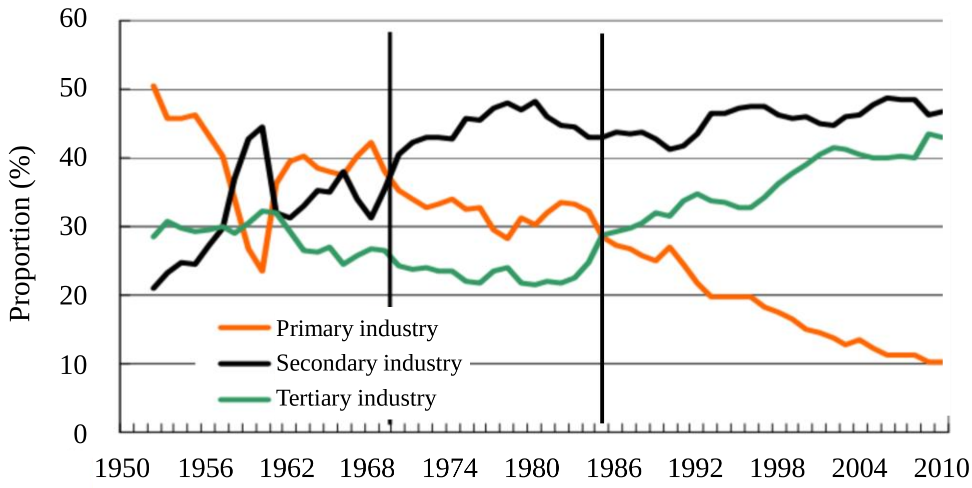

Fig. 2-1 Development process of the industrial structure in China

Source: National Bureau of Statistics of China (NBS), 2011

Table 2-1 Proportion of the China's GDP and industrial added value in the world (%)

	GDP	Primary industry	Secondary industry	Tertiary industry
1980	1.7	7.4	2.3	0.7
1985	2.5	10.6	3.2	1.3
1990	1.6	8.6	2.2	0.9
1995	2.5	12.0	4.0	1.3
2000	3.7	16.0	6.3	2.3
2005	4.9	17.8	8.7	3.2
2008	7.1	21.3	10.8	4.1

Source: World Bank, 2009

2.2 Methodology

2.2.1 SNA-IO Model construction

Social Network Analysis (SNA) is a normative tool to analyze the social relationship, structure and resource liquidity between each actor in a network (Scott, 2012; Wasserman & Faust, 1994). It has been widely used in social and behavioral sciences, including virtual community (Albert et al., 1999; Chen & Ting, 2013), biological areas (Kwait et al., 2001; Williams & Martinez, 2000) and forest research (Fuller et al., 2008; Harris et al., 2008). A body of research has applied SNA to industrial ecology because it can facilitate the operation of industrial symbiosis networks by combining the impact of both economic and environmental aspects and focusing on the network structure morphology, the interaction patterns and the effects on the outcomes of the collaboration (Chertow, 2007; Domenech & Davies, 2009). For example, Wei et al. (2012) applied SNA to industrial restructuring and a transferring analysis based on cross-region mergers and acquisitions. Domenech and Davies (2011) applied this method in industrial symbiosis network research in Kalundborg.

The Input-Output analysis method can reveal the complex interdependency and mutual relationships between each industrial sector connected by departmental monetary transactions (Dong et al., 2016). However, it is difficult to evaluate the industrial structure on a macro scale and indicate the status of one industry in the entire network. Therefore, combining the Input-Output table and SNA not only can provide a theoretical and methodological framework for understanding industrial networks but can also reveal the inner structure of the industrial network, quantitatively evaluate the position of each member and the financial connection between them (Domenech & Davies, 2011).

The construction process for the IO-SNA model is shown in Fig. 2-2. Firstly, input-output tables of China for the last five years, which were 2002, 2005, 2007, 2010 and 2012 were used as the data source for this model. To reconcile the different separation criteria in each year, more than 100 industrial classifications in Input-Output table were merged into 37 sectors (Table 2-2). Second, the model was divided into two parts, and one part was the industrial structure evaluation using the SNA method. The input-output relationships or the capital flow between each industry was taken as the edge of the network, and the "Small world" theory was the basis of the model's feasibility. If the industrial structure conformed to this theory, then the model analysis could be continued. If not, then the model failed. The second part of the model is an environmental impact evaluation using the EIO- LCA method to calculate the industrial structure-related carbon emission. Finally, the industrial structure-related carbon emission, network density, average distance, degree centrality and betweenness centrality are considered as the key indicators for the evaluation of the social relationship between each industry, their status in the entire network and the environmental impact. The calculation process will subsequently be explained in detail. The industrial evolutionary features can be fully revealed by this model. Given the directivity of capital flow, the industrial network is considered as a directed network. To avoid the enclosed ring case, the intermediate input of each node to itself is removed.

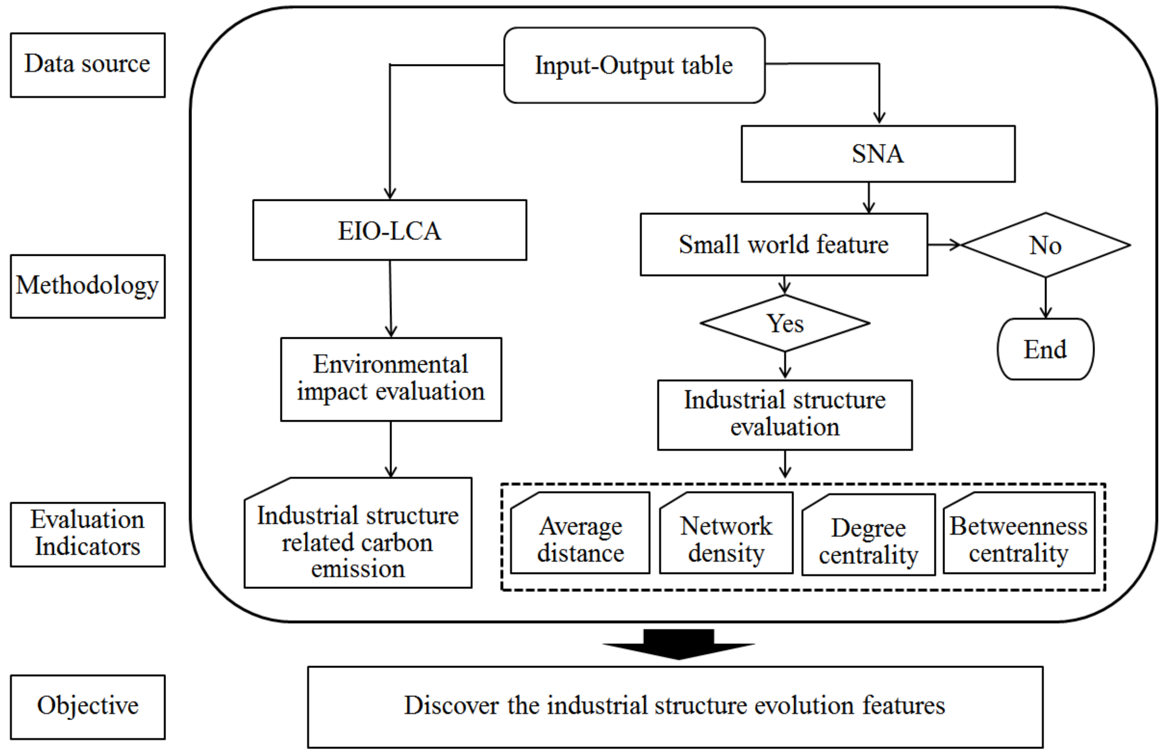

Fig. 2-2 Research framework of the hybrid SNA-IO Model

Table 2-2 Code table of the industry department

Number	Industry	Number	Industry
1	Agriculture, forestry and fishing	20	Gas production and supply industry
2	Coal mining, Petroleum and natural gas exploitation	21	Water production and supply industry
3	Metal mining industry	22	Construction industry
4	Nonmetallic mineral and other mining industry	23	Transportation and warehousing industry
5	Food manufacturing and tobacco processing industry	24	Postal, information transmission, computer service and software industry
6	Textile industry	25	Wholesale and retail trade industry
7	Textile garments, shoes, hats, leather, down and their product industry	26	Accommodation and catering industry
8	Wood processing and furniture manufacturing	27	Financial industry
9	Paper printing, culture, education and sports goods, instrumentation and other handicraft	28	Realty industry
10	Petroleum processing, coking and nuclear fuel processing	29	Leasing and business services industry
11	Chemical industry	30	Research and experimental development industry
12	Nonmetallic mineral products industry	31	Resident services and other services
13	Iron and steel industry	32	Education
14	Metal products industry	33	Health, social security and social welfare
15	General/special equipment manufacturing industry	34	Culture, sports and entertainment
16	Transportation equipment manufacturing industry	35	Public management and social organization
17	Electrical, communications equipment, computers and other electronic equipment manufacturing	36	Comprehensive technical service industry
18	Scrap and waste	37	Water conservancy, environmental and public facilities management industry
19	Electricity and heat production, supply industry		

(1) Feasibility analysis

Small-world characteristics are necessary prerequisite for the application of SNA, which is defined as a network in which the typical distance between two randomly chosen nodes (the number of steps required) grows proportionally to the logarithm of the number of nodes in the network (Wall & Knaap, 2007; Watts & Strogatz, 1998). A network with a short average distance and a high clustering coefficient between each node can be called a "small world network" (Sun et al., 2014; Watts, 1999). The average distance means the average shortest distance between each node in the network, and can be used to evaluate the transmission efficiency. The average distance is calculated as:

$$B = \frac{\sum_{i \neq j} b_{ij}}{n(n-1)} \tag{2-1}$$

where n is the number of nodes in the network, and b_{ij} is the shortest distance between node i and node j.

The clustering coefficient is separated into the node clustering coefficient and the network clustering coefficient. The former means the proportion of actual edges between one industry node and its neighbors accounting for the maximum possible edges. The latter represents the average clustering coefficient value of each node. The larger the clustering coefficient is, the closer association between each node. These two indexes are used to show the subgroup integrated degree of the actors in the network, which can be obtained by

$$C_i = \frac{V_m}{m_i(m_i-1)/2}\ ; \quad C = \frac{1}{n}\sum_{i=1}^{n} C_i \tag{2-2}$$

where C_i is the clustering coefficient of node i, C is the network clustering coefficient, V_m is the number of edges among m_i nodes (excluding i), m_i is the number of nodes adjacent to node i, and $m_i(m_i-1)/2$ is the maximum possible number of edges between m_i nodes.

(2) Centrality

Centrality reflects the importance of one industry within the entire network. It can be further classified into degree centrality and betweenness centrality.

1) Degree centrality

Degree centrality means the boundary amount that connects to one node. The more direct connections, the more important a position that the node occupies, which can also be termed as "in the central". That is, if an industry has more connections with other industries, it is usually considered as prominent or having high prestige. At the same time, this industry will have a dominant position and a priority right in the industrial network. Due to the directivity of the connection that indicates "who gives what to whom", degree centrality can be separated into in-degree and out-degree. The in-degree of node i measures the material input from other industries to i; the out-degree of node i reflects the material output from node i to other industries (Hanneman & Riddle, 2005; Sun et al., 2015). If the direction does not play a role during the analysis then it can be ignored, and the network is undirected. A disconnection between any of these nodes may cause a serious disturbance to network operation and lead to fragmentation. Via this principle, we can strengthen the industrial network by increasing the connection path ways between the nodes, especially nodes that have weak connections with others.

We apply the weighted out-degree and in-degree of node i for the next step analysis, calculated as follows

$$\text{Weighted out-degree: } E_{out(i)} = \frac{\sum_{j=1}^{n} x_{ij}}{n-1} \tag{2-3}$$

$$\text{Weighted in-degree: } E_{in(i)} = \frac{\sum_{j=1}^{n} x_{ji}}{n-1} \tag{2-4}$$

$$\text{Weighted degree Centrality: } E_{(i)} = \frac{E_{out(i)}+E_{in(i)}}{2} \tag{2-5}$$

where *n* is the number of nodes in the network, x_{ij} is the connections from node *i* to *j*, and x_{ji} is the connections from node *j* to *i*.

2) Betweenness centrality

Betweenness centrality measures the ability to pass information and to ensure the cohesiveness of a node. If a node with high betweenness centrality changes its development direction and gives up its mediating role, the indirect connection between the upstream and downstream industries will break and a new partnership is difficult to form in the short term. Therefore, the industrial network may be paralyzed (Lv & Fu, 2010). Thus, a higher betweenness centrality of an industrial sector indicates a larger impact on the overall network. Betweenness centrality is calculated as follows:

$$F_i = \frac{\sum_{j}^{n}\sum_{h}^{n} g_{jh}(i)}{(n^2-3n+2)/2} \tag{2-6}$$

where $g_{jh}(i)$ is the number of the shortest pathway between industries j and h that through industry i; $j \neq h$, $h \neq i$, $j<h$.

2.2.2 Carbon emission calculation

The fuel types considered in this study are consistent with the categories defined in the China Energy Statistical Yearbook. The corresponding GHG emissions are calculated according to the IPCC national GHG inventory guidelines. To be in accord with China's national GHG inventory, this study only considered three kinds of GHG emissions (i.e., carbon dioxide, methane and nitrous oxide) and converted them to carbon dioxide equivalents (CO_{2e}) (IPCC, 2006; Liu et al., 2012). The energy-related CO_2 emissions in sector i are based on energy consumption, carbon emission factors and the fraction of oxidized carbon by fuel. The equation is as follows:

$$E_{ci}^{d} = \sum_j C_{ij} EF_j O_j M \quad (2\text{-}7)$$

where E_{ci} represents the CO_2 emission in sector i, the subscript i represents the energy consumption sectors, the subscript j is the fuel type, C_{ij} is the consumption of fuel j by sector i (TJ), EF_j is the CO_2 emission factor of fuel j (tC/TJ), O_j is the oxidation rate of fuel type j, and M is the molecular weight ratio of carbon dioxide to carbon (44/12). A similar method is used in the CH_4 and N_2O emission calculations.

The carbon emission intensity is the average carbon emission rate per unit of GDP. This indicator allows the carbon emission in different years and different regions to be compared; therefore, we can objectively characterize the change in emissions. The carbon emission intensity can be calculated by:

$$I_{Ci} = \frac{E_{Gi}^{d}}{GDP_i} \quad (2\text{-}8)$$

where I_{ci} is the carbon emission intensity in industry i, E_{Gi} is total direct GHG emissions in industry i (tons) including CO_2, CH_4, and N_2O, and GDP_i is the added value of industry i (USD).

Each industry has a double attribute in the industrial network. On the one hand, an industry needs raw material and services from upstream sectors to proceed with production. On the other hand, its products and services can be used as raw materials by downstream industries. Carbon emission in each sector can also be considered from these two aspects. The Economic Input-Output Life Cycle Assessment (EIO-LCA) proposed by Hendrickson et al. (Hendrickson et al., 1998) provides us a way to follow the carbon flow track between each industry. It has been widely used in environmental studies including greenhouse gas research (Zhao et al., 2012). The conversion relationships are listed below.

$$X = (I + A + A^2 + A^3 + \cdots)Y = (I - A)^{-1}Y \quad (2\text{-}9)$$

$$r_i = \frac{E_{Gi}^d}{x_i} \quad (2\text{-}10)$$

$$E_G^i = \hat{R}(I - A)^{-1}\hat{Y} \quad (2\text{-}11)$$

where *X* is the total production of each sector (column vector), x_i is the total production of industry *i*, X= (x_1, x_2,…, x_3), *I* is the unit matrix, *A* is the direct requirements coefficient, *Y* is a column vector of the final demand, r_i denotes the environmental impact of sector *i* and R= (r_1, r_2,…, r_n), and $E^i{}_G$ means the indirect GHG emission matrix, $E^i{}_G = e_{ij}$.

$$e_i = \{e_{ij}\}\ (i = 1, 2, \ldots, n; j = 1, 2, \ldots, n) \quad (2\text{-}12)$$

$$e_j = \{e_{ij}\}\ (i = 1, 2, \ldots, n; j = 1, 2, \ldots, n) \quad (2\text{-}13)$$

where Σe_i is carbon emission in production process, which can also be termed as the production perspective carbon emission of industry *i*, Σe_j is the consumption perspective carbon emission of industry *j*, which means the carbon emission hidden in the raw material that comes from upstream.

Therefore, the carbon sources of each industry can be calculated by a consumption perspective calculation which would indicate the actual environmental impact and responsibility of a country (Mózner, 2013). By comparing the carbon source changes with time, the industrial structure-related carbon emission can be found.

In this part, the data source comes from the Chinese Energy Statistics Yearbook (NBSC) and IPCC 2006. Several parameters used in the carbon emission calculations refer to the previous works by research of Liu et al. (2012) and Geng et al. (2013b).

2.3 Results

2.3.1 Feasibility of SNA-IO model

As one of the largest developing countries, China's economy has experienced rapid development in last three decades. The average distances between each industry in China are getting closer decreasing from 1.057 to 1.037 (Table 2-3). This suggests that one industry in the network will access to another one by passing 1.057-1.037 industries. The short average distance, large distance-based cohesiveness and relatively large clustering coefficients confirm that the industrial networks in China are consistent with small-world characteristics. Thus, we can use an SNA to assess the industrial network in China based on Input-Output data.

Table 2-3 Comprehensive evaluation index of the industrial structure in China

	2002	2005	2007	2010	2012
Average distance	1.057	1.050	1.044	1.049	1.037
Distance-based cohesiveness	0.926	0.929	0.978	0.975	0.982
Clustering coefficient	0.865	0.811	0.799	0.762	0.746

2.3.2 Centrality analysis of the industrial association network

(1) Degree centrality analysis

The degree centrality of each industry in typical years in China is shown in Fig. 2-3. The results show that the degree centrality change in China fluctuated, including the in-degree and out-degree centrality, decreased heavily in 2007 and then increased slightly in 2012. Few industries did not conform to this pattern. For example, the iron and steel industry (13) kept growing from 2002 to 2012 because it provided indispensable material for social construction and important strategic material. The value of out-degree centrality in most industries is higher than their in-degree centrality, for instance, the agriculture industry (1), mining and quarrying industries (Node 2-4 in Appendix table), chemical industry (11) and metal-related industries in manufacturing, which means that these industries output more material for downstream than they input from upstream. A similar situation exists in the electricity production industry (19), transportation industry (23), commerce (25) and financial industry (27). Other industries behave in an opposite manner, in that they need more material for less output.

Secondary industry development is predominant in China, as indicated by an in-degree centrality and out-degree centrality higher than that of the agriculture and the service industries. The food manufacturing industry (5), petroleum processing (10), chemical industry (11), iron and steel industry (13), general/special equipment manufacturing industry (15) and electronic manufacturing (17) are examples. The effect of the agriculture industry (1) decreased during these years. This could be due to the development of the food manufacturing industry and it also reflects the transition from an agricultural country to industrial country, combined with other indexes such as GDP proportion. Manufacture-related service industries, for example, the transportation industry (23), commerce (25) the financial industry (27) and commercial service (29) are the primary drivers of service industry development, of which the financial industry (27) has shown the most rapid increase and is the industry with the most potential.

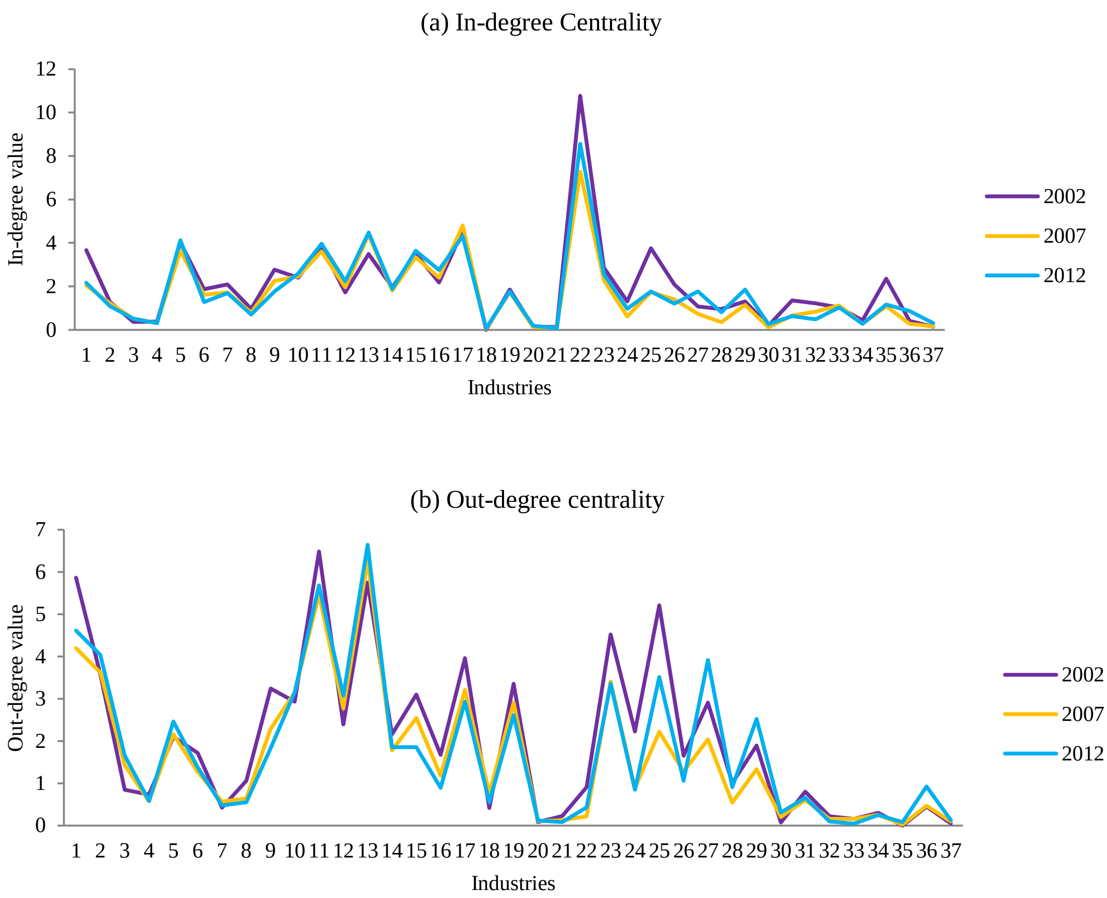

Fig. 2-3 In-degree centrality (a) and out-degree centrality (b) of each industry in China

(2) Betweenness centrality analysis

The betweenness centrality value of each industry in typical years in China is shown in Fig. 2-4. The high betweenness centrality of an industry represents its central position in resource delivery and its great effect throughout the entire industrial network. Manufacturing industries have higher betweenness centrality than other industries in China, which fully illustrates their central roles in resource delivery in the whole industrial network and power to impact the whole network, especially the Chemical industry (12), iron and steel industry (13). The paper printing industry (9) and electronic manufacturing (17) had the highest betweenness centrality in 2002 and 2007. The electricity production industry (19) and some service industries, such as the research development industry (30), also had relatively high betweenness centrality.

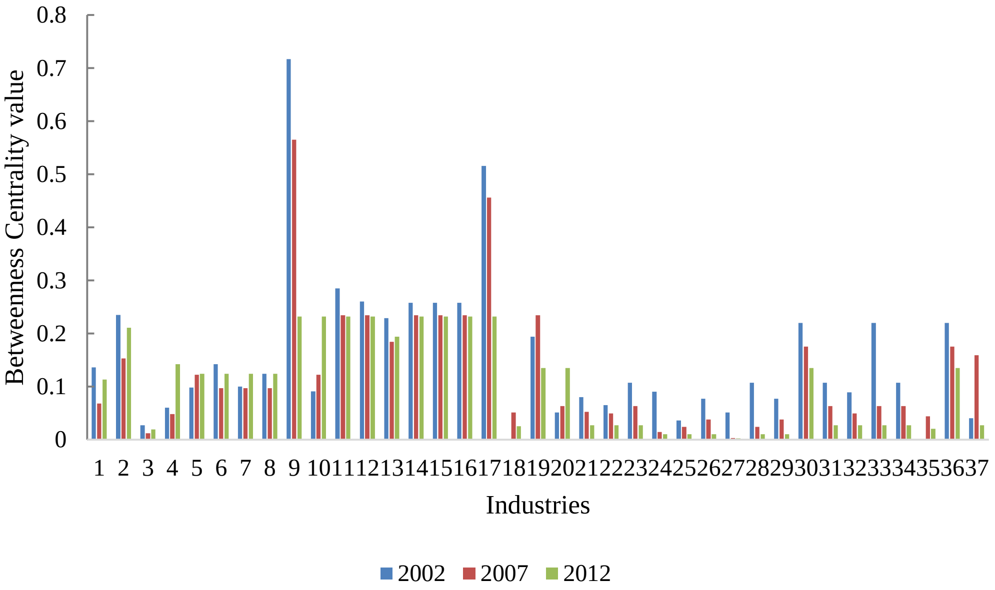

Fig. 2-4 Betweenness centrality of each industry in typical years in China

2.3.3 Cohesive subgroups

Cohesive subgroups are the small groups constituted by the actors with direct and close economic ties within the industrial network. Accordingly, the 37 industries were separated into 8 subgroups by SNA. More industries in one subgroup represents a longer industrial chain and higher impact on the industrial network. During the research period, iron and steel industry (13) is always belonging to a relatively long industrial chain, which means this industry can influence more industries and has higher impact on the whole industrial network.

Table 2-4 Constitution of cohesive subgroups

	Subgroup 1	Subgroup 2	Subgroup 3	Subgroup 4	Subgroup 5	Subgroup 6	Subgroup 7	Subgroup 8
1997	1,5,25	6,7,8,9,33	16,17,22,28, 30	27,31,32,39, 35	2,3,18,19,20 ,21	10	4,12,13,14,1 5, 24	11,23,26,29
2000	1,5,25,33	2,6,7	10,19,20,21, 30,34	26,27,32,35	3,18	15,28,29,31	4,9,11,12,13 ,17,23,24	8,14,16,22
2002	1,4,8,11,12, 13,23,25,29, 31	14,15,16,17, 22	2,3,18,19,20 ,21	10,	5,6,7,26	9,30,33,35	24,27,28	32,34,36,37
2005	1,8,9,35	16,17,22,15, 30,14	7,6,5,33,26	28,37,36,34	2,20,3,18,29 ,21	10	23,12,13,4,6 24	11,29,25,31, 27
2007	1,5,4,7,8,32	22,16,35	28,29,33,24	26,36,37,34	2,3,18,19,21 ,27	10,20	4,11,12,23,3 0,31,25	9,13,14,16,1 7
2010	1,5,25	6,7,34	31,32	23,26,27,28, 33,45,36	2,3,18,20	10,19	4,29,24,30,1 1,8,12,22	9,14,21,16,1 7,13,15

2.3.4 Environmental effect of each industry on industrial structure

To render the carbon emission index comparable between different years, the carbon emission intensity and its rate of change was the focus of this study. Based on the statistical rule of energy balance table of China, industries 28-37 have been merged as industry 28 in Fig. 2-5. The results showed that although China's total carbon emission is relatively higher, its carbon emission intensity decreased in almost all industries from 2002 to 2012, especially the gas production industry (20) from 2007-2012. The emission reduction effect of food production (5), textile industry (6) and petroleum production (10) is also remarkable. Mental mining (3) and nonmetal production industry (12), metal production (14) and accommodation industry (26) experienced a quick emission reduction in the early days of the research period, but continuity was lacking. The scrap (18) and construction industry (22) are the only two industries for which the carbon emission intensity increased.

An indirect carbon emission analysis from both production and consumption perspective provides an approach to understand the carbon sources and destinations of each sector in terms of the flow of finances and material. Fig. 2-6 uses the iron and steel industry (13) as an example to show its environmental impact on industrial network from the consumption perspective. As the results showed, about one quarter carbon emission investment came from the industry itself. This means if we reduce the carbon emission from iron and steel industry, the indirect carbon emission in the whole industrial network would be reduced significantly.

This industry also has big influence on related industries. With the increasing production of crude steel in these years, the demand from coal mining industry increased quickly from 6.62% in 2002 to 8.05% in 2012. Iron ore used as the raw material of iron and steel industry which comes from metal mining industry also increased its input to iron and steel industry from 7.39% in 2002 to 12.19% in 2012. Demand from chemical industry (11) increased slightly from 5.74% in 2002 to 6.22% in 2012. These results suggest that carbon emission reduction in iron and steel industry will decrease the demand and corresponding carbon emission from upstream industries and indirect carbon emission from downstream industries.

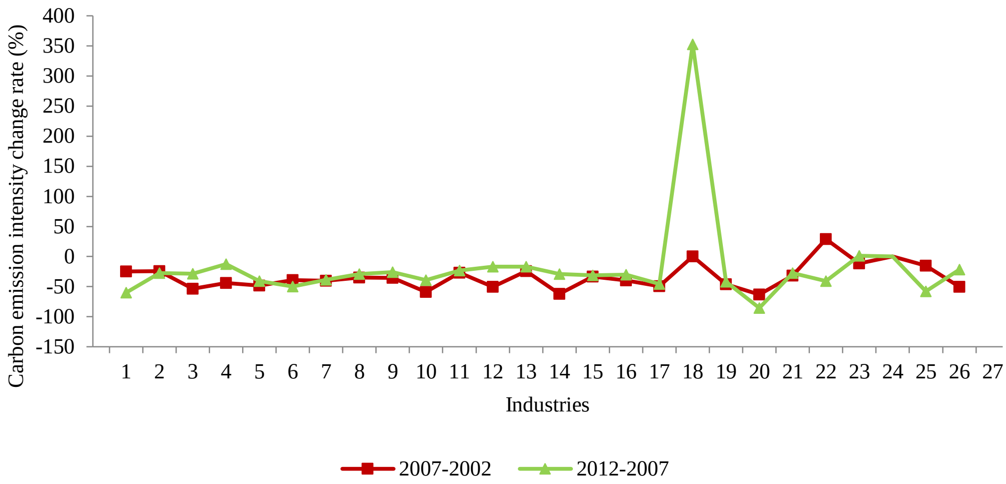

Fig. 2-5 Carbon emission intensity change rate of China from 2002 to 2012

Note: 2007-2002 indicate the carbon emission intensity reduction from 2002 to 2007; the same meaning of 2012-2007

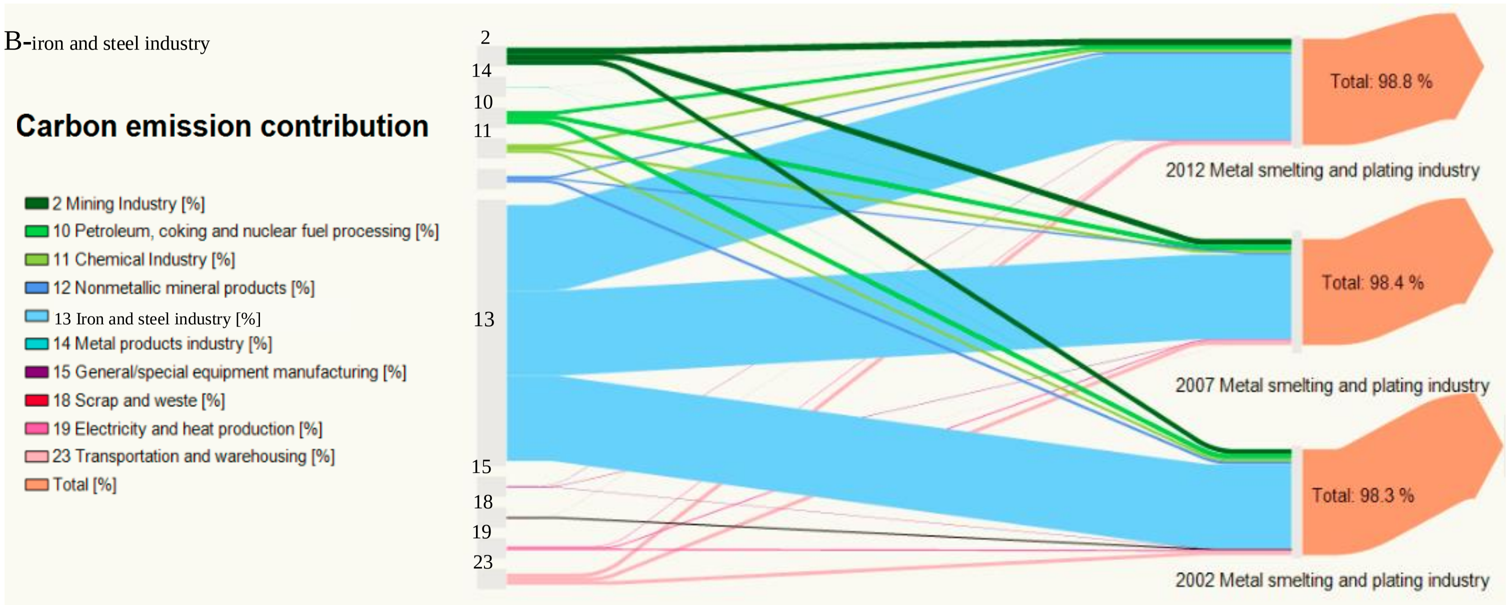

Fig. 2-6 Industrial structure-related carbon emission for iron and steel industry

2.4 Summary

This article provided a hybrid IO-SNA model to find the most influential industry on the industrial network. By understanding the position of each industry in the entire network and its related industries, the impact on an industry itself, the surrounding industries, and even the entire network should be seriously considered before making policy. A new view of structure-related carbon emission can be used to monitor the implementation of new energy exploration and via more detailed data.

China's industrialization is transitioning from the intermediate stage to the advanced stage. However, from this part of research, we can see that the energy-intensive labor-intensive and capital-intensive industries still dominate the national development. Iron and steel industry (13) has relatively higher impact on the whole industrial network due to its higher in-degree/out-degree centrality, good performance on betweenness centrality and more connected industries. Combining the great GDP contribution (about 4% of the total GDP in 2012), environmental impact (accounted for about 27% of the industrial emissions in 2012) and social influence, like employment promotion ability (4.05 million employees in 2014), iron and steel industry are selected as the most influential industry in China's industrial network and will be the research object in the next step.

Chapter 3 Forecasting the carbon reduction potential of Iron and steel industry

3.1 Introduction of Iron and steel industry

With the increasing productivity in Iron and steel industry, its influence and impact improved greatly in recent years. The production of crude steel in China kept a rapid increasing in last two decades and became the largest country of crude steel production since 1996 (Worldsteel, 2015). Fig. 3-1 shows the crude steel output in China and world except China. Now, China is becoming the global steel-producing and consumption center. The crude steel production in China peaked in 2014, which is 822.698 million ton. The share of Chinese crude steel production stabilized at more than 49% of the world total production after 2013. Meanwhile, China also consumed about 45% of the global steel production due to the quick urbanization and the tremendous infrastructure construction.

China's iron and steel industry also has a huge influence on the international market as the large export amount. 11.06% steel products were export to Korea, EU and East Asia Nations (CSDRI, 2008). Although this ratio decreased to 5.74% in 2013, the export volume remained the same which only fractionally less than the total output of South Korea (Worldsteel, 2015). The net export of steel production was 79.35 million ton in 2014, which is the equal amount of 84.42 million ton crude steel, and increased 65.72% comparing to the year 2013. In 2015, China exported 14.48% of the total steel product. At the same time, China also needs to import steel production from Korea, Japan and Taiwan. The import volume from these three regions accounted for 86.43% of the total import amount.

On the other hand, its huge demand of iron ore and ferrous scrap obtained from the international market also pull up the global economy. In 2014, China imported 932.69 million ton of iron ore from 68 countries. Of which, 548.30 million ton came from Australia shared 58.79% of the total import amount. Brazil shared 18.32%, about 170.90 million ton. South Africa was the third biggest iron ore supplier, about 43.59 million ton iron ore to China accounting for 4.67% of the total import amount. 0.19 million ton ferrous scrap was imported from some developed counties, and this amount was 42.57% less than in 2013. However, the scrap price increased by 12.82% compared to 2013.

The production process of iron and steel industry includes cooking, iron making, steel making, continuous casting and rolling (Fig. 3-2). Each process will be introduced in detail as below.

(1) Coking

Coke is the most important energy source of iron and steel industry. Coal used as the raw material is input into the coke oven and transfer to coke by high-temperature retorting, release coke oven gas, including CO, CO_2 and CH_4, etc, at the same time. The energy intensity of this process is 4.3 GJ/t coke in 2000. With the technical progress, the energy consumption decreased to 3.1 GJ per ton coke in 2010.

(2) Iron making

Iron making is the most energy intensive process in each individual production process, although the energy intensity had decreased from 13.5 GJ/t pig iron in 2000 to 12.0 GJ/ton pig iron in 2010. In this process, coke, iron ore, limestone and other auxiliary materials will be fed into the Blast Furnace (BF). Inside the furnace, $CaCO_3$ in limestone will react with SiO_2 mixed in iron ore and generate slag and CO_2 to purify the final product. Coke will change to CO_2 and CO by reacting with O_2, then, CO_2 will be reduced to CO by C. After that, CO will be used to reduce the Fe_2O_3, FeO or Fe_3O_4 in iron ore into Fe, which we call the final product as liquid iron.

(3) Steelmaking- Blast Furnace-Basic Oxygen Furnace

BF-BOF is the major production process in China, more than 80% of crude steel in China was made by BF-BOF because of the high purity and low cost of the product. This proportion even increased to 93% in 2013 (Worldsteel, 2015). Liquid iron made in BF will be transported to Blast Furnace-Basic Oxygen Furnace (BF-BOF) to make crude steel. The purpose of this process is to further remove the impurities, like S, Ca, C, P and so on. Reaction temperature comes from the physical heat of liquid iron, reaction heat from the chemical reaction between components. None extra energy will be needed in this process. Therefore, the energy intensity of BF-BOF was only 0.3 GJ/t crude steel in 2010, and then decreased to 0.1 GJ/t crude steel in 2010. But if we take all the raw material production process into consideration, the final energy intensity of BF-BOF is 19.0 GJ/t crude steel (Hasanbeigi et al., 2014a).

(4) Steelmaking-Electric Arc Furnace

Electric Arc Furnace (EAF) is another important tool to make crude steel. It uses electricity and ferrous scrap as the raw material. Sometimes a certain liquid iron will also be added to improve the quality of products. Electricity is the energy source for EAF which input through graphite electrode. The reaction between electrode and furnace burden provides heat for crude steel making. Comparing to the BF-BOF, EAF is easier to control the emissions and metallurgical process, making the production more flexible. With the development of EAF, its energy intensity also decreased from 3.2 GJ/t crude steel in 2000 to 2.2 GJ/t crude steel in 2010. While, the final energy intensity considering all the raw material production process is only 12.8 GJ/t crude steel, much lower than BF-BOF route (Hasanbeigi et al., 2014a).

(5) Casting

Casting means to inject the liquid crude steel into the mold using steel ladle to make it into steel ingot or billet. There are two types of casting, one is mould casting method, the other one is continuous cast steel (continuous casting). Continuous casting is becoming more and more popular, because of the low cost, high yield and high labour productivity. The continuous casting ratio in the countries with high crude steel production capacity are excessed 90%.

(6) Rolling

In the rolling process, billet or ingot are changed to different shapes under huge pressure. Generally, the rolling process are separated into hot rolling and cold rolling according to the different rolling temperature. Its energy intensity decreased from 2.5 GJ/t finished steel in 2000 to 1.8 GJ/t finished steel in 2010 (Hasanbeigi et al., 2014a).

Considering the huge carbon emission in iron and steel industry, necessary measures must be taken. This chapter will build up an environmental-economic model based on nonlinear optimization model to predict carbon emission of Iron and steel industry in China. iron and steeliron and steeliron and steeliron and steeliron and steel

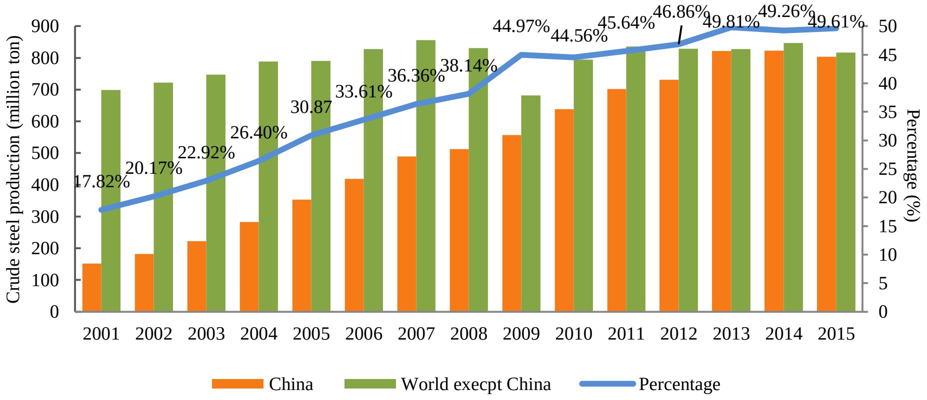

Fig. 3-1 Crude steel production of China and world except China

Source: Worldsteel, 2016

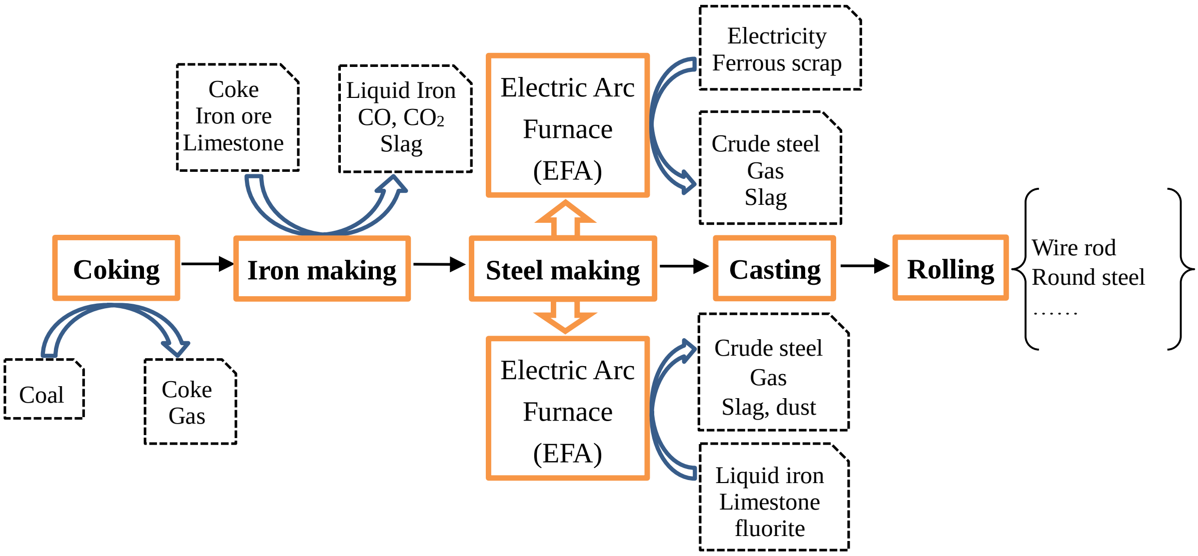

Fig. 3-2 Production process of iron and steel industry

3.2 Problems and policy response to China's iron and steel industry

3.2.1 Problems in China's iron and steel industry

With the rapid development, more and more drawbacks of iron and steel industry are becoming more and more obviously. The problems can be summarized as below:

(1) Higher energy intensity

High energy intensity is the most obvious features of iron and steel industry due to its high dependence on coal production. The final energy intensity in China's Iron and steel industry is 23.11 GJ/ton crude steel. While, in U.S., the final energy intensity is only 14.90 GJ/ton crude steel, which is 35.53% lower than that in China (Hasanbeigi et al., 2014b). Generally, the energy intensity of iron and steel industry in China is 20% higher than developed countries (Camco & Institute, 2010). Similarly, the carbon emission of China's iron and steel industry accounted for about 24.6% of the total emissions, 18% higher than the average level in developed country (Li et al., 2016). Here are several reasons for the higher energy intensity in iron and steel industry in China.

Lower installation rate of advanced technology: In the iron and steel industry, the technology and production process upgrade is the basic method of saving energy and they could bring great effect on energy conservations. According to the estimation of IEA based on 2007 data, China could save 6.1 GJ/t crude steel and the U.S. could save 2.4 GJ/t crude steel through adoption of best available technologies by 2050 (IEA, 2010).

In China, the adaptation of energy saving technologies is still have big potential to improve due to the high installation cost (Li & Zhu, 2014). The installation rate of Top Gas Recovery Turbine unit (TRT), Coke dry quenching (CDQ) and LT-Purification and recovery (LT–PR) of converter gas in key large and medium-sized enterprises are 30%, 52% and 20%, respectively; coal moisture control technology has been applied only in a small number of enterprises (CSDRI, 2011). As a consequence, in the large- and medium-enterprises, the energy consumption in 48.6% of sintering circuit, 37.8% iron making, 76% BF-BOF and 38.7% of EAF were higher than the national standard. The gas release rate in BF and BF-BOF was 6% and 10%, respectively, and the waste heat recover rate was less than 40% in 2010.

In addition, as a side effect of dis-advanced technology, the by-product or waste energy during the production process of iron and steel industry is not fully recycled. The waste heat potential in

China's iron and steel industry was 4.87 GJ/t crude steel, which equals to 26.08% of the total energy consumption (Zhang et al., 2013). The energy efficiency would increase 10% when the recovery energy is taken into consideration (Oluleye et al., 2016). However, some typical energy recycle facilities were rarely installed. For example, the heat recovery from sintering and sinter cooler only installed 20%. Only 40% BF installed pulverized coal injection. Number of BF-BOF installed with Recovery of BOF gas and sensible heat facility installed only accounted for 40% of the total furnace amount (Zhang et al., 2017).

Unreasonable production structure: There are two approaches for the crude steel making as introduced before, BF-BOF and EAF. EAF route can save 50% energy consumption than BF-BOF route. However, EAF in China is not widespread enough. Only 7% of crude steel was made by EAF in China in 2013 (Fig. 3-3), while, the average EAF ratio in critical crude steel production countries is 40.5%. The lower ratio of EAF only bring limited effect to decrease the industrial energy intensity.

Besides that, the ratio of liquid iron added into EAF is increasing year by year. In 2000, the liquid iron ratio in EAF was only 0.25 t/t crude steel, while it increased to 0.47 t/t crud steel in 2010. This is another key factor that increases the industrial energy intensive as higher pig iron ratio brings greater energy intensity for EAF route. There are 5GJ/t crude steel energy intensity gap between 0.4t and 0.1t pig iron/t crude steel utilization. Even if the ratio of EAF in China increase to the same level with U.S., the energy intensive in China's Iron and steel industry would still be 19.2% higher than the U.S., due to the final energy and 12.37% more energy-intensive in terms of primary energy (Hasanbeigi et al., 2014b). The high price of ferrous scrap is the most important reason which will be introduced later.

Small scale furnace: The volume of furnace has great impact on energy efficiency. Energy consumption in China's large and medium plants in 2004 was 705 kgce per tonne of steel, only 7.5% higher than that in Japan (656 kgce per ton). However, energy consumption in China's small steel plants was as high as 1045 kgce per tonne of steel (Guo & Fu, 2010; Wen et al., 2014). The energy consumption of China's Iron and steel industry accounts for approximately 15% of the total domestic energy consumption in recent years. However, if small- and medium-sized steel enterprises are taken into consideration, then a 10–20% gap of specific energy consumption and a 25–30% higher steel production cost exist compared with international advanced level (Zhang et al., 2017).

Bigger scale furnace has higher energy efficiency. For example, an investigate showed that BF with less than 1000 m^3 volume accounted for 81.6% in 2007, but only produced 136.55 million ton liquid iron and emitted 179.3 million ton CO_2 (emission intensity is 1.31 t CO_2/t iron). Of which, furnace with less than 299 m^3 volume shared 23.1% of the total furnace amount. But only produced 7.6% of the annual liquid iron output, and emitted 8.0% of the total emission in iron making process (Table 3-1). The furnace between 300-999 m^3 shared 58.5% of the total furnace number. They only produced 46.7% of the total liquid iron, and emitted 49% of the CO_2 emissions. While, 18.5% of the BF with larger than 1000 m^3 volume produced 45.8% of the liquid iron production. They emitted 43% of CO_2 emissions. The emission intensity of BF larger than 1000 m^3 is about 1.17 t CO_2/t iron (Camco & Institute, 2010). Comparing to the international standard of BF installation, the international BF volume is concentrated into 3000-4999 m^3, the policy standard of BF is larger than 1000 m^3. The installed BF-BOF and EAF volume are 200-350 t and 100-200 t, respectively. While, in China, the capacity of these three kinds of furnace are 300-3000 m^3, 20-200 t and 20-100 t, respectively (Zeng et al., 2009).

(2) Overcapacity

Different with the environmental protection purpose of close down the out dated capacity, the problem of overcapacity has influenced the benefit in iron and steel industry. In 2008, the utilization of steel production capacity was 76%. During the 12^{th} Five-year plan, the utilization rate of crude steel production capacity was decreased from 79% in 2010 to 70% in 2015. In 2015, the production capacity was 1.13 billion ton, while, only 0.80 billion ton crude steel was produced. There are lots of negative effect brought by the overcapacity. The first one is decrease the industrial benefit. Overcapacity, especially supply exceeds demand, will cause vicious competition. The iron and steel enterprises will contend for markets by reducing the product price. The benefit and funds invested in research and development must be weakened, resulting in the insufficient of technology innovation ability. According to the report of Greenpeace, the debt rate in Key large and medium-sized enterprises was over 70% in 2015 (Liu & Hu, 2016). Similarly, this contradiction will also extension to the international market as the international market are considered as a way out of overcapacity.

Secondly, overcapacity will also promote the energy consumption and environmental pollution. From 2005 to 2007, energy consumed by iron and steel industry increased 32.7% from 3598.82 billion standard coal to 4777.44 billion standard coal, which is 6.1% higher than the increase rate in same period. Consequently, the ratio of energy consumption in iron and steel industry accounted for the total amount increased from 16.1% to 18.0%. Environmental pollution by iron and steel industry is also seriously. The upstream industry was also affected that the SO_2 emission from ferrous metals mining industry increased 107.3% from 801 thousand ton to 1661 thousand ton. Dust and smoke dust emission increased 7.3% and 22.9%, respectively. In 2008, the dust emission of iron and steel industry and its upstream industries ranged second in the total 39 industries. SO_2, smoke dust and solid waste emissions ranged the third in China. Quantity of Wastewater effluent was in fifth place. On the other hand, the increased iron and steel output led to the transport tensions in recent years. The volume of freight traffic in iron and steel industry and rotation volume of product transport increased 73.8% and 73.6%. While, the total volume of freight traffic and rotation volume of product transport only increased 47.7% and 52.4%. The transportation amount and turnover volume of steel product, iron ore and coke increased from about 17% to 22.3% of the total amount, respectively.

(3) Restrictions on international markets

As the raw material of iron and steel product, iron ore and ferrous scrap are heavily relying on imports to meet the demand in China. According to the world steel statistic year book, the production of iron ore in China was 597.12 million ton in 2006, and it decreased to 1381.29 million ton in 2015. However, the production quality was much lower than other countries. If the output converts to correspond with world average Fe content, the iron ore production amount was only 355.76 million ton in 2006 and decreased to 123.50 million ton in 2015. The import amount of iron or in China was 326.20 million ton in 2006, and then increased almost three times in 2015, which was 953.37 million ton. More than half of the imported iron ore came from Australia. Brazil is the second import source of iron ore, and it shares about 19% of the total import amount. High import rate of iron ore results in that the production cost and steel product price are largely rely on the international raw material price. The price of iron ore increased heavily from less than 20 USD/t in 2002 to about 90 USD/t in 2008. In 2009, the price decreased a little to less than 60 USD/t, but it rebound to 110 USD/t in 2010. The highest price was occurred in 2011 with 190 USD/t, then it decreased gradually to 50 USD/t in

2015. The average price of steel production in China also fluctuated according to the iron ore price (Kent, 2013).

Besides the iron ore, import price of ferrous scrap is another factor to affect the steel production price and ratio of crude steel made by EAF. In 2006, China imported 5.39 million ton scrap. In 2009, this amount increased to 13.69 million ton, and then decrease to 2.33 million ton in 2015. Low recycle rate of ferrous scrap from the society is one important reason of scrap shortage in China. Although the storage of steel product and corresponding ferrous scrap keeps increasing in recent decade, the period of massive obsolescence has not yet arrived. On the other hand, the low quality of recycled scrap affected the production quality of crude steel.

(4) High carbon emission in power generation

As the upstream industry of iron and steel industry, high carbon emission intensity in power generation industry will also affects the final emissions intensity of iron and steel industry. In China, more than 80% of electricity were generated by thermal power before 2011. Although, in recent years, this ratio decreased gradually, the proportion was still as high as 73.68% in 2015. Of which, more than 90% of the thermal power are coming from coal combustion. If we take the emissions in energy conversion from fuel to electricity process into the electricity generation industry, then the carbon emission from this industry accounted for more than 50% of the national emissions. In the world's major countries, Spain and Germany focus on solar power development. The renewable power accounted for 20% of the total power generation in 2010. Moreover, the ratio of nuclear power was also as high as 29.2%. France has the highest nuclear power installation, which was 79.4% in 2010. 59% of electricity was generated by hydropower in Canada in 2010. Petroleum and natural gas combustion in Japan provided more than half of the power generation. Natural gas combustion and nuclear power were the major sources of electricity in U.S. (IEA, 2015; NBS, 2015). On the other hand, the energy efficiency in China increased from 29% in 1990 to 34% in 2008, but it was still 7% lower than the highest efficiency in Japan, and for the fossil power generation efficiency, China was 3.1% less than the world average level and 14.2% less than the world most efficient country (Oda et al., 2012).

Considering the carbon reduction target published by Chinese government, it is desperately needs to upgrade and reform the production status and tap the carbon reduction potential of Iron and steel industry in China.

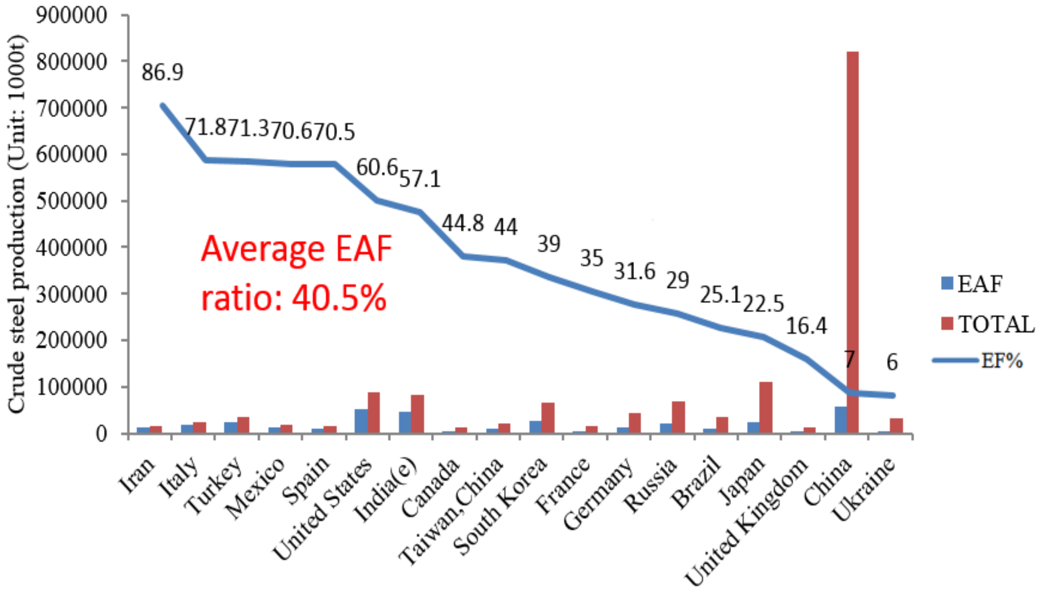

Fig. 3-3 EAF ratio in critical crud steel makers in 2013

(Source: World steel yearbook, 2015)

Table 3-1 The production and emission efficient of different scale Blast Furnace in 2007

BF Volume	Number	%	Annual output (billion ton iron)	%	Annual CO_2 emissions (billion ton)	%	CO_2 emissions intensity (t CO_2,e/t iron)
<100	9	2.3	0.95	0.4	1.3	0.4	1.37
101-299	82	20.8	18	7.2	23.9	7.6	1.33
300-999	231	58.5	117.6	46.7	154.1	49.0	1.31
1000-1999	39	9.9	41.8	16.6	50.6	16.1	1.21
2000-2999	28	7.1	55.5	22.1	65	20.7	1.17
>3000	6	1.5	17.8	7.1	19.4	6.2	1.09
Total	395		251.65		314.3		1.25

Source: Chinese iron and steel Association, (Camco & Institute, 2010)

3.2.2 Policy response

Series policies were announced to cope with the deficiency in iron and steel industry, such as curb the severe environment contamination problems and promote the industrial upgrade in iron and steel industry.

(1) Elimination of backward production capacity

As early as the 9th Five-Year plan (1996-2000), China started to advocate clean production and eliminate backward production capacity of 5 million ton which saved 20,000 ton pollutants emissions (Ministry of Industry and Information Technology). In the 11th Five-year plan and 12th Five-year plan, elimination of backward production capacity was stressed again. According to the requirement of "The Adjustment and Revitalization Plan of the Iron & Steel Industry", before the end of 2010, Blast Furnace with less than 300 m^3 volume should be phased out altogether. Blast Furnace under 400 m^3 volume should be phased out before the end of 2011 (Camco & Institute, 2010). In "iron and steel industry adjustment and upgrade plan" issued in 2009, BF-BOF and EAF lass than 30 ton production capacity will be closed before the end of 2011. In the notification issued by Ministry of Industry and Information Technology of China (MIIT) in 2009, BF-BOF under 120 ton, EAF under 70 ton and Blast Furnace with less 1000 m^3 production capacity established after August 2005 will be phased out. However, due to the revenue benefit, lack of supervision and employee reemployment issues, this regulation was carried out difficultly.

(2) Capacity compression

Capacity compression is mutually reinforcing with elimination of backward production capacity, as the out dated facilities will be compressed firstly. Therefore, in this part, the overall target will be introduced. To curb the overcapacity, in 2009, China's government issued the "Some opinions on the suppression of overcapacity and repeated construction in some industries and guidance to the healthy development of industries". In this document, it specified that, in principle, the expand capacity projects will not be approved in the future three years (Camco & Institute, 2010). It was point out in the latest "Five Year Plan (13th)" that cutting the steel production capacity is imperative. In the beginning of 2016, "Comments on the development of the steel industry to eliminate excess capacity" was issued by the State Council and proposed that on the base of previous compression capacity, another 0.1-0.15 billion crude steel production capacity will be cut in next five years and new capacity installation is strictly prohibited. At the end of 2016, “iron and steel industry adjustment and upgrade plan (2016-2020)” was published by MIIT. Of which, the target by 2020 was mention in the first time that the production capacity of crude steel will be “net” decreased 0.1-0.15 billion ton.

During 2013-2015, China’s iron and steel industry started to clean the severe excess capacity, because of the production capacity kept increasing under various elimination and compression policies. In 2013, the government published one guidance to encourage the large-scale enterprises to transfer to group management mode for upgrading their equipment and technologies and enhance the competitiveness. Another guidance also pointed out that before the end of 2015, 15 million iron making capacity and 15 million crude steel making capacity will be shut down.

(3) Technology upgrading

To enhance energy conservation and emission reduction, and promote construction of energy-efficient systems, a series of measures and multiple binding targets have been identified in China’s national development strategy plan. In the “Guidance on energy conservation and emission reduction in iron and steel industry” issued by MIIT in 2010, it was predicted that at the end of 2011, the comprehensive energy consumption in key large- and medium-enterprises were less than 620 kg standard coal/t steel. Fresh water consumption should be less than 5 m^3/t steel, and the water repeating utilization factor should be higher than 95%. Dust emissions in iron and steel industry should be less than 1.0 kg/t steel, SO_2 emission should less than 1.8 kg/t steel. The utilization rate of steel slag, iron slag, dust sludge, and tailings should arrive 94%, 97%, 99% and 10%, respectively. Another 22 million tons of standard coal saving capacity should be added. At the end of 12^{th} Five-year plan, the energy and water consumption in key large- and medium-enterprises should achieve the international average level and the comprehensive energy consumption should less than 615 kg standard coal/t steel. Other parameters please refer to the Table 3-2. In addition, steel industry was preferentially included into the environmental policies, like carbon trading market in China to promote the industrial upgrading and decrease the carbon emission.

Table 3-2 Major indicators of iron and steel industry development in 12th Five-year plan

NO.	Indicator	2005	2010	2015	Increase rate in 2015
1	Energy consumption per unit of output decreased				18%
2	CO_2 emission per unit added value				18%
3	Energy consumption per ton steel decrease (kgce)	694	605	≤580	≥4%
4	Fresh water consumption per ton steel decrease (m^3)	8.6	4.1	≤4.0	≥2.4%
5	SO_2 emission per ton steel decrease (kg)	2.83	1.63	≤1	≥39%
6	COD per ton steel decrease (kg)	0.25	0.07	0.065	7%
7	Utilization rate of solid waste increase (%)	90	94	≥97	≥3%
8	Research funds account for the income (%)	0.9	1.1	≥1.5	≥0.5%

Source: Ministry of industry and information technology of the people's republic of China

(4) Development of clean electricity

In the China's five-year plan, power generation industry is also focused as the key industry that needs to be improved, as it's the source or breakthrough point to adjust the national energy structure. The development of renewable energy, such as nuclear power, wind power and solar power, have been strongly promoted in past few years in China. It will be further quickly developed to weaken the dominate position of thermal power. According to the 13th Five-year plan, the installed capacity of hydropower will increase to 350 million kilowatts from the 290 million kilowatts level in the end of 12th Five-year plan. The wind power installation capacity will increase twice from 100 million kilowatts in the end of 12th Five-year plan to 200 million kilowatts in the 13th Five-year plan. By the end of 2015, only 35 million kilowatts solar power are installed. Until 2020, this installation capacity will increase to 100 million kilowatts. Gas as a relatively clear fossil fuel energy will also be vigorously developed in the 13th Five-year plan.

The steady voltage supply is necessary for industrial production and for the high-quality steel production. However, solar power and wind power cannot satisfy this requirement combining with the immature power grid in China. On the other hand, hydropower will be saturated in someday. Nuclear power is a kind of power with zero carbon emission and long-term supply. It will also promote the development of high-tech manufacturing industries. Therefore, an ambitious nuclear power development target was put forward in China to provide both steady and lasting electricity supply. By the year 2020, the operation installed capacity of nuclear power will be 40 million kilowatts, which will be two times higher than the net capacity in the end of 2014. Annual electricity generation will be 260-280 billion kilowatt hour. The nuclear capacity under construction should be 18 million kilowatts at the end of 2020 (IAEA, 2015; NDRC, 2007). In 2030, the installed capacity of nuclear power will be 200 million kilowatts; and this capacity will further improve to 400 million kilowatts in 2050 (OECD, 2012).

3.3 Methodology

3.3.1 Modeling framework

To address the problems in iron and steel industry, this study will conduct a no-liner environmental-economic model to forecast the medium-term carbon emission in iron and steel industry, as well as the socio-economic response from the national perspective. The simulation period is from 2007 to 2030 with 2007 as the base year. Input-Output table of China 2007, assisting by some official data issued by National Bureau of Statistics of China and other official databases, like Worldbank statistic, reports from the Chinese energy group in Lawrence Berkeley National Laboratory and published paper, is adapted to present the database and construction the model framework. 135 industries are merged into 22 categories, including 8 usual industries (u), 4 power generation industries (p), 6 iron and steel industries (I), 2 raw material industries for iron and steel industry (r) and 2 energy supply industries for iron and steel industry (e) (Table 3-3).

In iron and steel making plant, coke comes from two kinds of sources to put into iron-making process, one is made within the plant, which is generally happened in medium- and large-sized plant. Another route is buying from the coke plant outside the iron and steel making plant. Input-output table is statistics based on the different product, which means these two kinds of different coke sources are summed into together. As the carbon tax policy and carbon trading policy will also be taken into consideration in this research, which are implemented based on the enterprise category, coking industry in the Input-output table is separated into coke-1 and coke-2. Of which, coke-1 is for general energy supply and outside the boundary of iron and steel plant; while coke-2 is included into the iron and steel factory, which is specializing for iron making within the factory. Therefore, iron and steel industry is consisting of coke-2, iron making, crud steel making (including BOF and EAF route), casting and nonferrous metal. Due to the higher carbon emission and big energy conservation potential, only the first three process will be further optimized in this research. Ferrous scrap as the row material of EAF is separated from the scrap industry, and forms raw material category with mining industry. Nuclear power is a key sector in power generation sector as its higher stability than new energy power and lower emission factor comparing to thermal power. Recycled electricity from waste pressure and waste heat from Iron and steel industry is also considered as one sector in power category.

Table 3-3 Industry classification

Code	sector	Code	sector
Usual industry		**Iron and steel industry**	
1	Agriculture	13	Coke-2
2	Light industry	14	Steel making
3	Chemicals	15	Crude steel-BOF
4	Non-metal industry	16	Crude steel-EAF
5	Metal production	17	Casting
6	Water, natural gas and heat production	18	Non-ferrous metal manufacturing
7	Waste (without ferrous waste)	**Raw material industry**	
8	Construction and service	19	Coal mining
Power generation		20	Ferrous waste
9	Thermal power	**Energy supply industry**	
10	Recycle power	21	Petroleum products
11	New energy power	22	Coke-1
12	Nuclear power		

3.3.2 Scenario setting and research assumptions

(1) Scenario setting

Six scenarios are set in this study (Table 3-4). There is no further technology upgrading or policy implementation in BaU scenario. The iron and steel industry will develop as the present situation. "tec" scenario is defined to estimate the development trends of Iron and steel industry under technology upgrading, eliminate and replace the backward production capacity (BF under 1000 cubic meters' capacity, BOF and EAF under 200 ton and 100 ton, respectively. The EAF route with relatively low carbon emission intensity will also be promoted according to the international level to perfect the production structure. Carbon tax policy will be introduced in "tax" scenario. All the industries need to pay for their carbon emission. At the same time, carbon tax will be used as subsidy and provided to EAF route, nuclear power, new energy power, recycle power and ferrous scrap recycle industry to encourage their development. In addition, steel industry was preferentially included in carbon trading market in the five pilot cities in China. Therefore, carbon trading scenario, "tra" scenario, is integrated into the simulation research for the first time. As the national carbon trading market will be open in 2017 announced by the government, the carbon trading mechanism in this research will also start from 2017. Carbon quota of Iron and steel industry is calculated by historical emissions. In practice, the carbon trading price is dominated by the carbon trading market which includes all the enterprises with large emissions amount. However, in this research, only iron and steel industry is endowed with carbon trading property, and cannot establish a complete carbon trading market. Therefore, the carbon trading price will be changed as the general commodities.

Besides the individual effect of each measure, we also estimate the compound effect by forecast the effect of combination scenarios. "cob1" represents the combination of technology upgrading and carbon tax policy. "cob2" is the total intervention effect of three measures. Due to the shortage of price mechanism in carbon trading scenario, the combination of carbon trading and carbon tax / carbon trading and technology upgrading will not be considered. The necessary parameters are showed in Table 3-5. The advanced technologies considered in this research please refer to Hasanbeigi et al. (2013) and Wen et al (2014)

According to the industry classification and scenario settings, a schematic energy, material, value and electricity flow is illustrated in Fig. 3-4. Within the industrial network, usual industry provides materials to other industries. Electrical industry generates electricity for other industries. Energy from coke and petroleum industry promotes the iron and steel industrial development. Raw material industry provides coal and ferrous scrap for iron and steel industry. At the same time, the industrial network interacts with the international market using import and export, and connects with household and government by consumption, direct/indirect tax and carbon tax. Subsidy from the government will provide to crude steel-EAF, ferrous scrap industry and renewable energy industries.

(2) Research assumptions

Some premises and assumptions are shown below:

1). Production quality in BF-BOF and EAF is ignored;

2). Coke is used as the only source of energy supply for Iron making. Other energy sources like petroleum coke are not included;

3). Liquid Iron and ferrous scrap are the raw materials of Crud steel, ignoring the solid iron or other material input;

4). Recycled gas will be imported to the furnace to participate in the reaction rather than burn, only using waste heat and waste press to generate the recycled electricity (no carbon emission in this process).

Table 3-4 Case setting in the model

	Technical Innovation	Carbon tax	Carbon trading
BAU	×	×	×
tec	○	×	×
tax	×	○	×
tra	×	×	○
cob1	○	○	×
cob2	○	○	○

Table 3-5 Basic parameters and assumptions of Iron and steel industry

Parameters	2007	2007-2010	2010-2020	2020-2030
Liquid Iron feed in EAF	0.2 t/t	0.15 t/t	0.1 t/t	0.1 t/t
Recycle rate of converter gas	75 m^3/t	81 m^3/t	110 m^3/t	120 m^3/t
Carbon tax	30CNY/t	30 CNY/t	90 CNY/t	200 CNY/t
Scrap ratio in BOF	14%	13%	10%	10%
Power consumption of EAF	559kWh/t	520 kWh/t	488 kWh/t	468 kWh/t

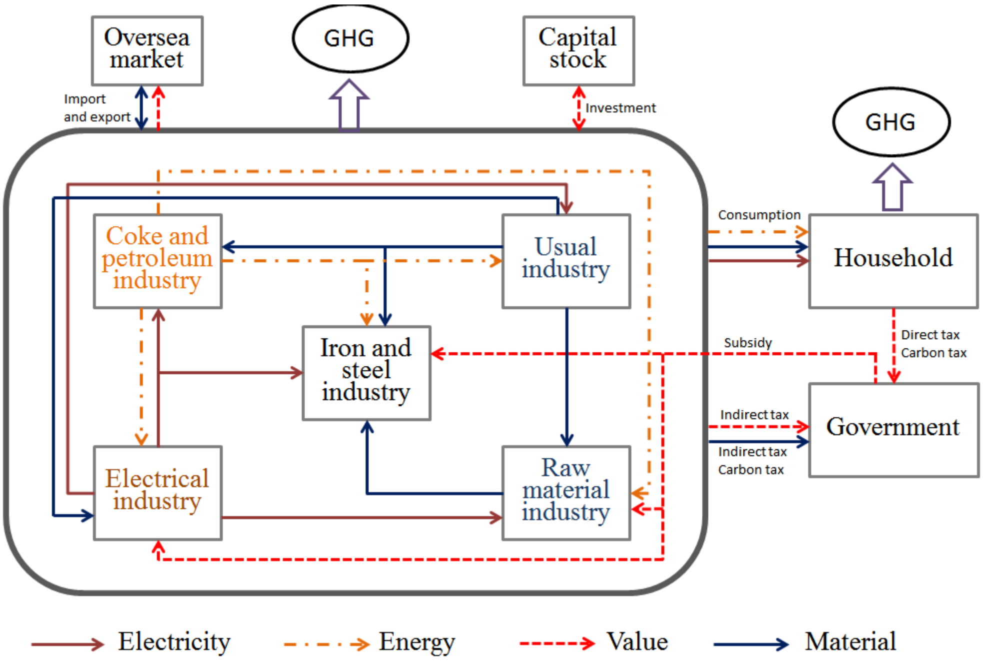

Fig. 3-4 Model framework

3.3.3 Model formulation

The non-liner environmental-economic model are established based on the input-output balance relationship reflected in the I-O table and the energy, material flow reflected from Fig. 3-4 between each industry. There are three parts in this model: socio-economic model, environmental model and iron and steel industry model. The socio-economic model includes three major balances, which are material balance, value balance and energy balance. Other elements including revenue, expenditure, consumption, income, saving and investment will also be added into the equations to build a complete social and economic system. Economic effect of each scenario will be got from this part. Environmental model can calculate the carbon emission from iron and steel industry and the whole industrial system to evaluate the environmental effect in each scenario. Iron and steel industry model can show the reaction effect of this industry under human intervention.

The model formulations are organized as below:

(1) Socio-economic model

Social-economic model is the basic model of this study. It is to construct a "virtual community" closer to the real society to ensure the simulation results of this model are close to reality. Three main balance relationships and some auxiliary sections are included into this part:

Material flow balance

The material flow balance describes the demand and supply balance of commodities and services in the I-O table. The total supply of commodities or services should not less than the intermediate input to other industries, government and household consumption, capital formation and net export.

$$X_i(t) \geq \sum_j A_{ij} X_j(t) + C_i(t) + G_i(t) + \sum_j Q_{ij}\, \Delta k_i(t) + E_i(t) - M_i(t) \quad (i,j = u,e,I,p,r) \quad (4\text{-}1)$$

In which, X_i, output of industry i (en);

A_{ij}, input coefficients of goods or/and services from industry i to sector j (ex);

C_i, household consumption of goods or/and services in industry i (en);

G_i, government consumption of goods or/and services i in usual industry (en);

Q_{ij}, input coefficients of goods for the capital stock formation from industry i to sector j (ex);

Δk_i, capital stock formation provided by industry i (en);

E_i, export of industry i (en);

M_i, import of industry i (en);

Value flow balance

The value balance is based on the longitudinal balance in I-O table. It expresses the relationship between industry income and expense. The income of each industry is no larger than the its expense including intermediate consumption, business surplus and employer income, depreciation and indirect taxes. Price adjustment rate eliminates the price distinctions among different industries and makes the output of all industries comparable within the whole simulation time horizon. Price adjustment rate in 2005 is set as 1, considering the national target is set based on the 2005 level. In this dynamic model, if the income exceeds expense, the extra investment will be discounted or unmarketable due to lack of demands to make the cost to be greater than income. At that time, the model will stop to make the market rebalance. If the income is less than the cost, then the model will increase investment to make the market return to balance.

Carbon tax and subsidy policy will be introduced in carbon tax scenario, and all industries will be involved. While, carbon trading policy will be only applied in iron and steel industry in carbon trading scenario.

$$P_j(t)X_j(t) + \zeta \quad (t) = \sum_i P_j(t)A_{ij}\, X_j(t) + Y_j(t) + P_j(t)\delta_j K_j(t) + P_j(t)\tau_j^i X_j(t) + \tau_j^c(t)EC_j X_j(t) \;\; (i = u, e, I, p, r;\; j = u, e, p, r) \tag{4-2}$$

$$P_I(t)X_I(t) + \zeta \quad (t) = \sum_i P_I(t)A_{iI}\, X_I(t) + Y_I(t) + P_I(t)\delta_I K_I(t) + P_I(t)\tau_I^i X_I(t) + \tau_I^c(t)EC_I X_I(t) + Ct_I(t)Tp(t) \;\; (i = u, e, I, p, r) \tag{4-3}$$

In which, P_j, price rate of industry j (ex);

ζ, subsidy for EAF route, nuclear power, new energy power, recycle power and ferrous scrap recycle industry (en);

Y_j, household income of industry j (en);

δ_j, depreciation rate of industry j (ex);

K_j, capital stock of industry j (en);

τ^i_j, indirect tax rate of industry j (ex);

τ^c_j, carbon tax price of industry i (ex);

EC_j, carbon emission coefficient of industry j (ex);

Ct_I, carbon emission more than the carbon quota in iron and steel industry (en);

Tp, carbon trading price in iron and steel industry (ex)

Energy flow balance

Energy flow balance expresses the balance relationship of electricity supply from four power generation industries and electricity demand by each industry, household, government, capital formation and net export.

$$X_p(t) \geq \sum_j A_{pj} X_j(t) + C_p(t) + G_p(t) + E_p(t) - M_p(t) \quad (i, j = u, e, I, p, r) \tag{4-4}$$

$$X_p(t) = X_9(t) + X_{10}(t) + X_{11}(t) + X_{12}(t) \tag{4-5}$$

X_p, output of power generation sectors (en);

C_p, household electricity consumption (en);

G_p, government electricity consumption (en);

E_p, electricity export (en);

M_p, electricity import (en);

Household income and expenditure

Household income is the sum of operating surplus and labor remuneration for each industry. It is determined by the income rate. Total household income of all industries is composed of two parts: direct tax and disposable income. Of which, disposable income includes household saving and household consumption.

$$Y_i(t) \geq P_i(t) \mu_i X_i(t) \quad (i = u, I, e, p, n) \tag{4-6}$$

$$Yh(t) = \left(1 - \tau^d\right) \sum_i Y_i(t) \quad (i = u, I, e, p, n) \tag{4-7}$$

Y_i, household income of industry i (en);

P_i, price rate of industry i (ex);

μ_i, income rate of i industry (ex);

Yh, disposable income (en);

τ^d, direct tax rate (ex);

$$P_i(t) C_i(t) = (1 - \beta) Yh(t) \alpha_i \quad (i = u, I, n) \tag{4-8}$$

$$P_j(t) C_j(t) + \tau_j^{hc} EC_h C_j(t) = (1 - \beta) Yh(t) \alpha_j \quad (j = e, p) \tag{4-9}$$

$$\sum_{i+j} \alpha_{i+j} = 1 \tag{4-10}$$

$$S_h(t) = \beta Y_h(t) \tag{4-11}$$

C_i, household consumption in industry i (en);

β, house hold saving rate (ex);

α_i, share of i industry's consumption in the total household consumption (ex);

EC_h, GHG emission coefficient of household consumption (ex);

τ^{hc}_j, household carbon tax of industry j (ex);

S_h, house hold saving (en);

Government budget

Government budget is comprised of government consumption and government saving. Direct tax levied on household income, indirect tax levied on each industry and carbon tax levied on the carbon emission in each industry are the main sources of government income. It equals to the government expenditure including government consumption in each industry, government saving and subsidies provide to the five industries. Of which, carbon tax equals to the total subsidy.

$$\sum_i \tau_i^i P_i X_i(t) + \tau_i^d \sum_i \mu_i X_i(t) + \sum_i \tau_i^c EC_i X_i(t) + \tau_{e,p}^{hc} EC_h C_{e,p}(t) = \sum_i P_i(t) G_i(t) + S_g(t) + \zeta(t) \quad (4\text{-}12)$$

$$\sum_i \tau_i^c EC_i X_i(t) + \tau_{e,p}^{hc} EC_h C_{e,p}(t) = \zeta(t) \quad (4\text{-}13)$$

P_i, price rate of industry i (en);

G_i, government consumption in industry i (ex);

S_g, government saving (en);

ζ, subsidy for EAF route, nuclear power, new energy power, recycle power and ferrous scrap recycle industry (en);

Investment and capital stock

All the household saving and government saving are used as net investment and net export for industries.

$$\sum_i [\Delta k_i(t) - \delta_i K_i(t)] + \sum_i [E_i - M_i] = S_h(t) + S_g(t) \quad (4\text{-}14)$$

$$K_i(t+1) = (1 - \delta_i) K_i(t) + \Delta k_i(t) \quad (4\text{-}15)$$

$$X_i(t) \le h_i K_i(t) \quad (4\text{-}16)$$

$\triangle K_i$, capital stock formation of industry i by each sector (en);

K_i, capital stock of sector i (en);

δ_i, depreciation rate of sector i (ex);

h_i, capital production coefficient of industry i (ex)

(2) Iron and steel industry model

Iron and steel industry includes 6 sectors, which are coke-2 (coke making), iron making, crude steel made by BOF, crude steel made by EAF, steel rolling products sector and ferroalloy, non-ferrous metal smelting sector.

$$X_I(t) = X_{13}(t) + X_{14}(t) + X_{15}(t) + X_{16}(t) + X_{17}(t) + X_{18}(t) \tag{4-14}$$

In which, X_I, total output of iron and steel industry (en);

Carbon emission from iron and steel industry

As the carbon trading policy is imported into iron and steel industry, the carbon emission in this industry are separated into two parts, including carbon quota (emissions do not need to pay) and excess emissions (need to buy the carbon emission right). According to the calculation method of carbon quota in iron and steel industry issued by Chinese government, Carbon quota equals to the sum of historical discharge (average level of last three years' emission), initial emission reduction quotas and new project quota. The carbon trading market is planned to extend across the country in 2017. The industry initial emission reduction quota means the enterprises installed energy saving technologies during 2006 to 2011, and got the government funding based on the amount of saving energy. Considering the slowly industrial upgrading in that period, this quota is supposed to be zero. As this research assume to implement the production capacity replacement, which means several outdated or small scale furnace would upgrade to advanced large scale production capacities without new capacity installed. Therefore, the new project quota is also set as zero.

$$EC_I X_I(t) = Cq_I(t) + Ct_I(t) \tag{4-15}$$

$$CQ_I(t) = {}^1\!/_3\left(EC_I X_I(t-3) + EC_I X_I(t-2) + EC_I X_I(t-1)\right) \tag{4-16}$$

In which, EC_I, carbon emission coefficient of iron and steel industry (en);

Cq_I, carbon quota of iron and steel industry (en);

Ct_I, carbon emission more than the carbon quota in iron and steel industry (en);

Carbon emission from iron and steel industry also can be separate as emissions came from production process and emissions from electricity consumption. Of which, the carbon emission coefficient of production process can be improved by advanced technology installation, waste energy recycles and environmental protective facilities running.

$$EC_i X_i(t) = EC_i^p(t) X_i(t) + EC_i^e X_i(t) \quad (i = 13,14,15,16,17,18) \tag{4-17}$$

$$EC_i^p(t+1) = EC_i^p(t) - R_i^t(t+1) - R_i^r(t+1) - R_i^e(t+1) \quad (i = 13,14,15,16,17,18) \tag{4-18}$$

$$R_i^t(t+1) = (1 + l_i)\, R_i^t(t) \quad (i = 13,14,15,16,17,18) \tag{4-19}$$

$$R_i^r(t+1) = (1 + ll_i) R_i^r(t) \quad (i = 13,14,15,16,17,18) \tag{4-20}$$

$$R_i^e(t+1) = (1 + lll_i) R_i^e(t) \quad (i = 13,14,15,16,17,18) \tag{4-21}$$

In which, EC^p_I, carbon emission factor in production process of iron and steel industry (en);

EC^e_I, carbon emission factor of electricity (en);

R^t_i, carbon emission coefficient reduce amount by advanced technology installation (en);

R^r_i, carbon emission coefficient reduce amount by waste energy recycle (en);

R^e_i, carbon emission coefficient reduce amount by environmental protective facilities running (en);

l_i, ll_i, lll_i, increase rate of carbon emission coefficient reduce (ex)

The carbon emission coefficient of electricity is reduced by the electricity demand decrease in iron and steel industry, carbon emission coefficient decrease in thermal power industry, proportion improvement of renewable electricity. Moreover, there are no carbon emission in renewable electricity industries. Therefore, the carbon emission coefficient of total electricity industry is depending on the emissions coefficient of thermal power industry.

$$ED_i(t+1) = ED_i(t) - EDt_i \quad (i = 13,14,15,16,17,18) \tag{4-22}$$

$$\varepsilon_E(t) = n(t)\varepsilon(t) \tag{4-23}$$

$$\varepsilon(t+1) = o\varepsilon(t) \tag{4-24}$$

$$n(t) = \gamma_9(t)X_9(t)/(\gamma_9(t)X_9(t) + \gamma_{10}(t)X_{10}(t) + \gamma_{11}(t)X_{11}(t) + \gamma_{12}(t)X_{12}(t)) \tag{4-25}$$

$$\gamma_i(t+1) = (1 + w)\gamma_i(t) \quad (i = 9,10,11,12) \tag{4-26}$$

$$EC_i^e(t) = ED_i(t)\varepsilon_E(t) \quad (i = 13,14,15,16,17,18) \tag{4-27}$$

In which, ED_i, electricity demand of each sector in iron and steel industry (en);

EDt_i, electricity demand decrease of each sector in iron and steel industry brought by technology upgrading (ex);

ε_E, carbon emission factor of total electricity industry (en);

n, ratio of thermal power generation in the total electricity generation (en);

ε, carbon emission factor of thermal power industry (en);

o, carbon emission factor change rate of thermal power industry (ex);

γ, power generation coefficient (en);

w, increase rate of power generation coefficient in each electricity generation sectors (ex);

Ferrous scrap recycle is depending on the obsolescence period of different steel production. According to the estimate of scholars in Northeastern University in China, the recyclable scrap will increase quickly after 2016. They also provide the forecasting method, which is the reference of the recycle amount of ferrous scrap in this research:

$$X_{22}(t) \geq (0.08+0.06)\mathrm{Xcru(t)} + 0.32\mathrm{Xcru(t-15)} + 0.6\mathrm{Xcru(t-50)} \quad (4\text{-}28)$$

$$\mathrm{Xcru(t)} = X_{15}(t) + X_{16}(t) \quad (4\text{-}29)$$

In which, Xcru, output of crude steel (en);

(3) Environmental model

The total carbon emission are the sum of the emissions from whole industrial network and household consumption of electricity and fossil fuel. Carbon emission intensity means the carbon emission per unit of GDP.

$$GHG = \sum_i EC_i X_i(t) + EC_h C_{e,p}(t) \;\; (i = u, I, e, p, n) \quad (4\text{-}30)$$

$$EpG(t) = \frac{GHG(t)}{GDP(t)} \quad (4\text{-}31)$$

In which, GHG, total carbon emission (en);

EPG, carbon emission intensity (en);

(4) Objective function

The objective of this model is to maximum the total GDP during the research period from 2007 to 2030. GDP is the summary of added value in I-O table, including household income, depreciation and indirect tax. Given to the inflation affections, a discount rate is given to the GDP to make the

GDP in different years comparable. The average inflation rate, 5%, in recent years is set as the discount rate.

$$MAX\sum_{t=1}^{24}\left(\frac{1}{1+\rho}\right)^{t-1}GDP \tag{4-32}$$

$$GDP(t)=\sum_{j}\left[Y_j(t)+P_j(t)\delta_j K_j(t)+P_j\tau_j^i X_j(t)\right]\ (j=u,I,e,p,n) \tag{4-33}$$

In which, ρ, social discount rate (ex);

Y_j, household income of sector j (en);

P_j, Price rate of sector j (en);

τ^i_j, indirect tax rate of sector j (ex);

X_j, Product of sector j (en);

t_1=2007…t_{24}=2030;

3.4 Results

3.4.1 National GDP

GDP will increase from 26604.38 billion CNY in 2007 to 157618.60 billion CNY in 2030 in BaU (Fig. 3-5), with 7.69% average annual growth rate (Table 3-6). GDP increase rate will rarely be affected by the intervening measures. In technology upgrading scenario, the GDP increase rate only 0.01% less than that in BaU. At the end of research period, the GDP shortfall in tec scenario comparing to BaU will be only 462.7 billion CNY. Carbon tax policy will bring a relatively bigger influence on national economy development comparing to other two measures. However, the annual average GDP increase rate is still as high as 7.64%, which is only 0.05% less than that in BaU scenario. The GDP gap between BaU and carbon tax scenario in 2030 will be 1833.2 billion CNY. Carbon trading policy has a neglectable effect on national GDP development. The increase rate and GDP amount in 2030 is almost same with that in BaU scenario. In the two combination scenarios, “cob-2” scenario which integrates all the three intervening measures will bring the most GDP loss. The annual average growth rate in this scenario is 7.64%. Although this ratio is same as carbon tax scenario, the GDP gap between BaU scenario and cob-2 scenario in 2030 will be 1995 billion CNY, a little larger than the GDP output in carbon tax scenario. While, the adverse effect of cob-1 scenario is less than that in cob-2 as the effect of carbon trading is excluded. The average annual increase rate of GDP is 7.67% in cob-1 scenario. This part of result also proved that the carbon reduction measures on iron and steel industry only bring limited negative impact for the national economy.

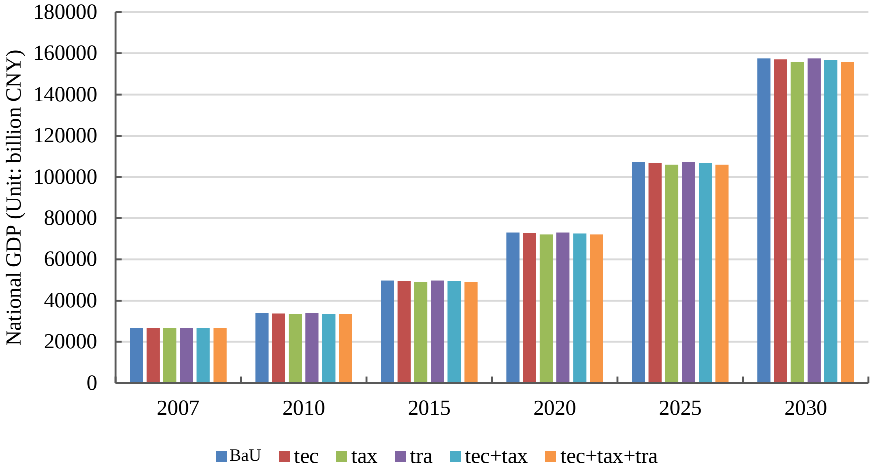

Fig. 3-5 GDP of China from 2007 to 2030 in each scenario

Table 3-6 Average annual growth rate of GDP and GHG emissions in each scenario

Scenario	Annual growth rate		Total GDP* (billion CNY)	Total carbon emission* (billion ton)
	GDP	GHG		
BaU	7.69%	6.67%	1792050.36	334. 43
tec	7.68%	4.71%	1786863.80	280.45
tax	7.64%	5.96%	1771518.65	312.68
tra	7.69%	5.87%	1791342.88	291.84
tec+tax	7.67%	4.33%	1782206.73	251.18
tec+tax+tra	7.64%	4.12%	1769708.01	239.03

Note: *, the sum of each year's GDP/carbon emission from 2007 to 2030

3.4.2 Carbon emission

Unlike the GDP changes in each scenario, carbon emission will vary greatly in each scenario. In BaU, the annual growth rate of carbon emission is 6.67% (Table 3-6) and the emissions will increase more than 4.7 times from 5.78 billion ton in 2007 to 27.25 billion ton in 2030 (Fig. 3-6). Technology upgrading is the most effective method to reduce the GHG emissions among three intervening measures, which will release 17.44 billion ton carbon emission in 2030 with 4.71% annual average growth rate. This amount is 36% less than the emissions in BaU scenario in same period. Although the carbon emission in carbon trading scenario will be only 0.49 billion ton less than the emissions in carbon tax scenario, the emission reduction effect of carbon trading policy during 2017 to 2025 is more obviously than carbon tax scenario. At the beginning of the policy implementation, its carbon emission reduction effect is even stronger than technology upgrading. Hoever, this momentum will not be sustained during later periods. The average annual increase rate of carbon tax scenario is 5.96%, which is only 0.09% higher than that in carbon trading scenario. Unlike carbon trading policy, the carbon emission reduction effect of carbon tax scenario will become obviously after 2026. Two combination scenarios of three intervention methods (cob-1 and cob-2) have the strictest carbon reduction effect, and the annual growth rate are 4.33% and 4.12%, which are 2.34% and 2.55% less than BaU, respectively. These two scenarios show similar growth trend that the carbon emission increase smoothly in the early stage, then accelerate a little in the middle stage. While, the carbon emission increase rate will slow down after 2027, which give the possibility to peak the carbon emission around 2030.

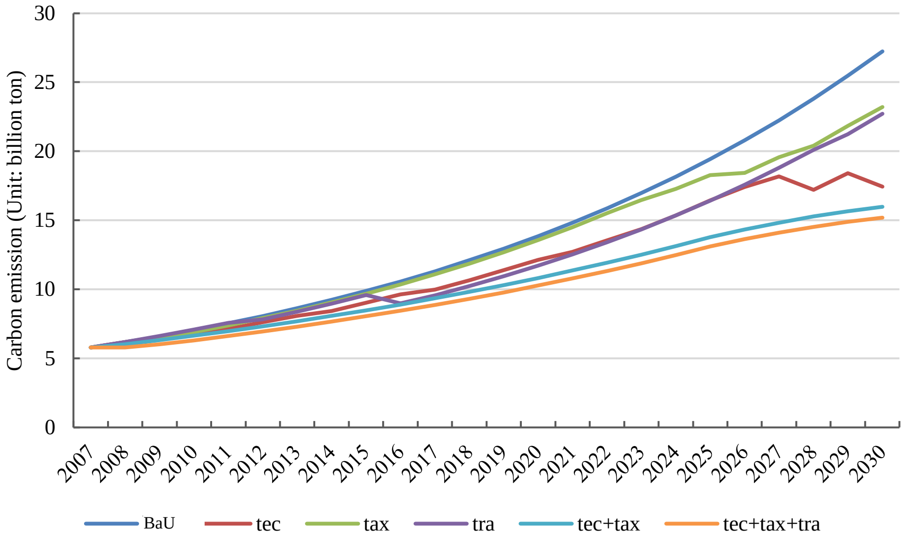

Fig. 3-6 Carbon emission in different scenarios

3.4.3 Carbon emission intensity changes

Despite the increasing carbon emission, carbon emission intensity (EpG) will keep decreasing in each scenario (Fig. 3-7). Of which, 18.10% carbon emission intensity will decrease 18.10% in BaU scenario from 2.17 t/10000 CNY in 2007 to 1.78 t/10000 CNY to 2030. Corresponding to the carbon emission reduction effect, technology upgrading is the most effective method to decrease the carbon emission intensity among the three measures. Carbon emission intensity in this scenario will decrease almost half during the research period from 2.17 t/10000 CNY in 2007 to 1.11 t t/10000 CNY in 2030. The effect of carbon tax policy is least obvious. But it still decreased 31.38% during the research period, and the carbon emission intensity in 2030 is 16.24% less than the level in BaU. Carbon trading policy will decrease 33.58% of carbon emission intensity from the basic year's level to 1.44 t/10000 CNY 2030, which is 18.90% less than the level in BaU in 2030.

The two combination scenarios show the strongest reducing effect, 53.08% of carbon emission intensity will be decreased in cob-1 scenario, and the carbon emission intensity will be only 1.02 t/10000 CNY in 2030. In cob-2 scenario. The carbon emission intensity will reduce from 2.17 t/10000 CNY in 2007 to 0.98 t/10000 CNY in 2030, with 55.03% decrease. This scenario will reduce the intensity value in half comparing to the level in BaU in 2030. As the target of carbon emission intensity decrease in China, the carbon emission intensity in 2020 should be during 1.52 t/10000 CNY to 1.39 t/10000 CNY (40%-45% decrease), and in 2030, this intensity level should be during 1.01 t/10000CNY to 0.89 t/CNY (60%-65% decrease). As the simulation result, only these two combination scenarios will meet the 40% INDCs target of 2020 and only cob-2 scenario will achieve the 60% carbon emission intensity decrease target of China in 2030 comparing to the level in 2005. However, none simulation scenario in this research can reach the 45% and 65% carbon emission intensity reduction target in 2020 and 2030, respectively.

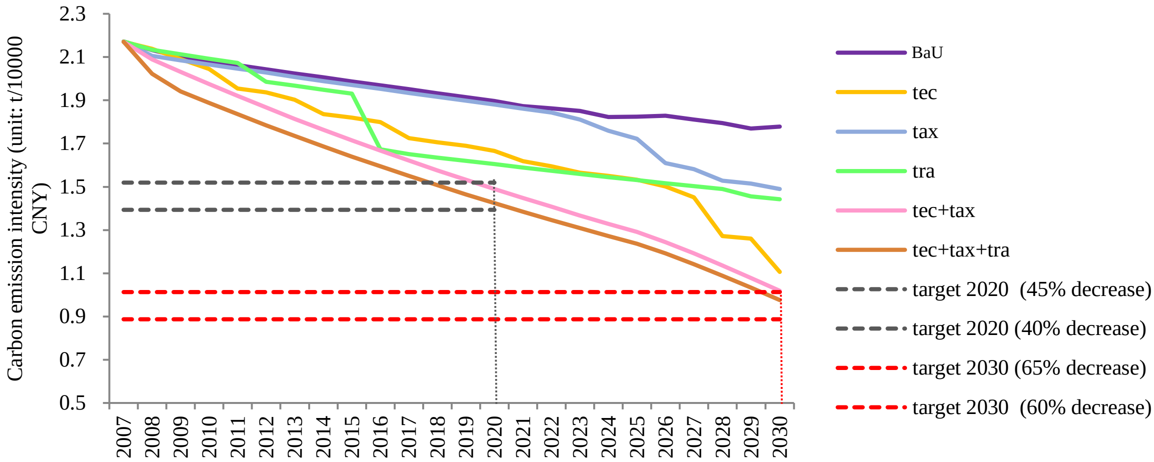

Fig. 3-7 Carbon emission intensity changes in each scenario

3.4.4 Production of crude steel

Fig. 3-8 shows the comparison between real crude steel output and the simulation result in BaU scenario from 2007 to 2015. Before 2014, the crude steel production in the model result matched the actual output well. Deviation between real data and simulation result from 2007 to 2013 is between -4.36% to 2.06%, indicating the accuracy and reliability of the simulation model. The actual crude steel output decreased after 2014 because of the profit loss caused by aggravation of overcapacity and government macro-control. However, in BaU scenario, we didn't import these factors, so the result keeps increasing.

The crude steel production will keep growing in BaU scenario from 489.29 million ton in 2007 to 3551.18 million ton in 2030 with 8.61% average annual growth rate (Fig. 3-9). The tra scenario has the lowest restrict effect on crude steel production, but the output in 2030 is still 35.17% less than the production in BaU scenario. In this scenario, the crude steel output will increase 78.75 % from 489.29 million ton in 2007 to 2302.34 million ton in 2030 and the average annual growth rate is 6.67%. In tax scenario, the crude steel production will increase less than two times during the research period with 2.79% growth averagely every year. In 2030, the output will be 946.01 million ton, which is 73.36% less than the output in BaU scenario. The crude steel output in tec scenario will remain stable during the early and middle simulation period. While, it will decrease a little after 2026. In the two combination scenarios, a slight increase will occur in cob-2 scenario from 489.29 million ton in 2007 to 534.00 million ton in 2030. The average annual growth rate is 0.36%. While in cob-1 scenario, the output will increase first from the base year level to 513.58 million ton in 2022 and then decline to 391.55 million ton in 2030.

In terms of the different crude steel production route, the production structure in BaU scenario will be no changes, the ratio of BF-BOF and EAF will remain 83.10% and 16.90% (Fig. 3-10). Carbon tax policy will push the EAF route development most. Crude steel produced by EAF will increase from 16.9% in 2007 to 47.59% in 2030. This ratio is higher than the target of 40.5%, which is the average level of critical crude steel makers. Technology upgrading also has great effect on EAF route promotion. The ratio of crude steel made by EAF will increase to 29.95% in 2030, 13.04% higher than the level in 2007. In carbon trading scenario, EAF will contribute 24.61% of the total crude steel in 2030, which is the weakest promotion effect on EAF development. The two combination scenarios will bring significant effect on EAF promotion. Of which, EAF will produce 31.96% of the total crude steel. While, the ratio of EAF in cob-2 scenario will be 4% higher than that in cob-1 scenario in 2030, which is 35.77%.

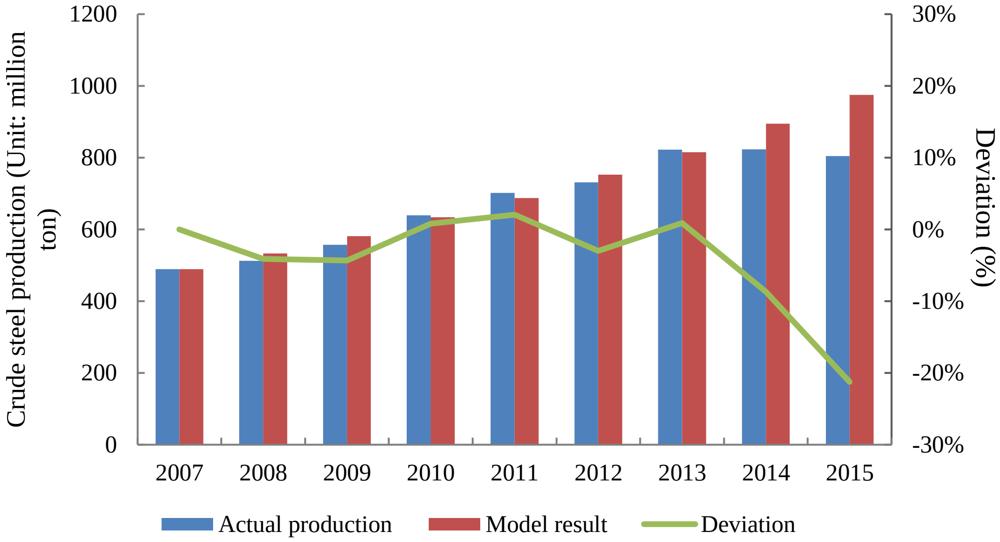

Fig. 3-8 Comparison of actual crude steel production and result in BaU scenario

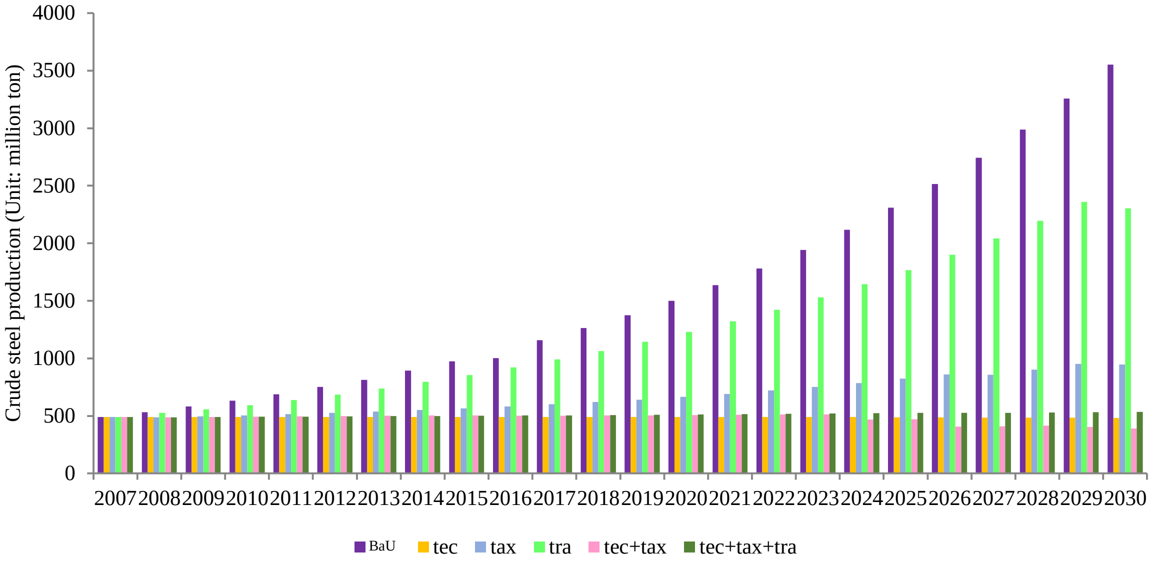

Fig. 3-9 Physical output of crude steel in each scenario

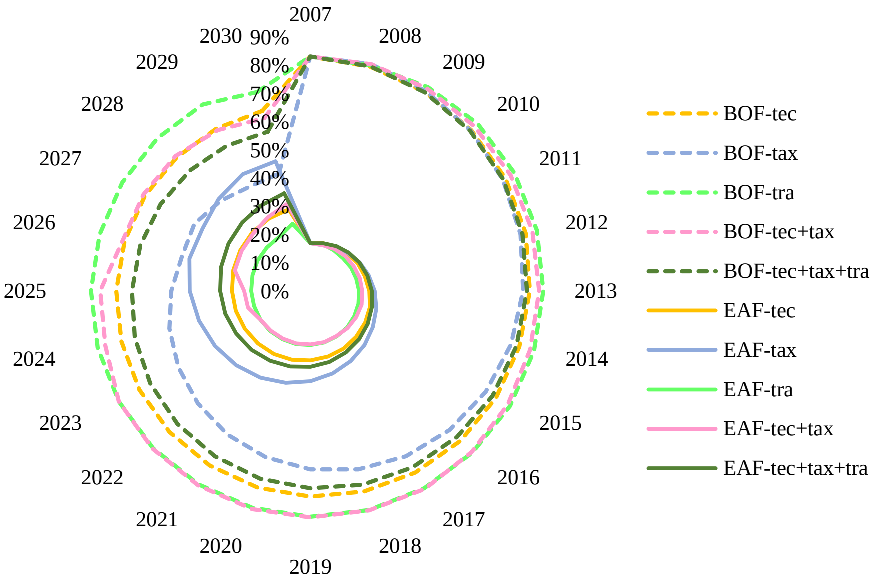

Fig. 3-10 Ratio of BOF and EAF in different scenarios during the research period

3.4.5 Power generation

Power generation is choosing as another parameter to calibrate the model. The comparison result shows that similar with the crude steel production, before 2014, the model results in BaU scenario match the actual power generation well (Fig. 3-11). The deviation between real data and simulation result from 2007 to 2013 is ranged from -4.11% to 2.97% indicating the accuracy and reliability of the simulation model. While, in 2014 and 2015, with the decrease of crude steel output, the power generation also declined correspondingly.

To provide a steady and clean power for industrial production, we introduced nuclear power in this research. Results show that in BaU scenario, the power generation will increase more than 7 times from 3244.81 billion KWh in 2007 to 23550.42 billion KWh in 2030. The average annual growth rate is 8.61% (Fig. 3-12). With the decreasing output and power demand of Iron and steel industry, the power generation will also decrease correspondingly in the five intervention scenarios. Electricity production amount in carbon trading scenario will increase the most among the three introduced measures. In this scenario, the power generation will increase to 10117.99 billion KWh in 2023, then decrease to 7460.60 billion KWh in 2030. The average annual growth rate is 3.53%. Under the influence of carbon tax policy, power generation amount will only increase to 4396.07 billion KWh in 2030 with 1.27% of average annual growth rate. While, in technology upgrading scenario, the power generation will gradually reduce. In 2030, there will be only 2340.10 billion KWh generated. Two combination scenarios show similar trend. Electricity production will decrease first from 2007 to middle-stage of this study, and then growth to 3210.44 and 3276.95 billion KWh in 2030, respectively.

Nuclear power has different development degrees in each scenario. The ratio of nuclear power in the total power generation will remain the same in BaU scenario. The fastest growing of nuclear power will occure in technology upgrading scenario with 19.07% average annual growth rate. In 2030, nuclear power will generate 33.91% electricity for the total power grid. Carbon trading scenario follows behind with 14.28% average annual growth rate, and in 2030, nuclear power in this scenario will account for 24.87% of the total amount. However, nuclear power under the influence of carbon trading policy will only increase 9.89% every year. There will be only 19.31% electricity made by nuclear power in 2030 in this scenario. In the two combination scenarios (cob-

1 and cob-2 scenario) which hit the INDCs target, the proportion of nuclear power will increase to 33.72% and 34.04% in 2030, respectively. Their average annual growth rate are 19.56% and 20.26%, respectively.

Based on the national nuclear power generation target, there will be 280 billion TWh generated by nuclear power in 2020, and this amount will increase to 1400 billion TWh in 2030. Comparing the generation target in 2030 with the simulation results, this target will share 5.94%, 59.83%, 31.85% 18.77% 43.61% and 42.72% in BaU, tec, tax, tra, cob-1 and cob-2 scenario in 2030, respectively. Form this result, we can get the information that the nuclear power generation target only cannot satisfy the simulation results in BaU and carbon trading scenario. The simulation results can total be satisfied and realized in other scenarios, especially the two combination scenarios. This means, the carbon emission intensity reduction target can be satisfied based on the combination of technology upgrading, carbon tax policy and carbon trading policy in accordance with this study.

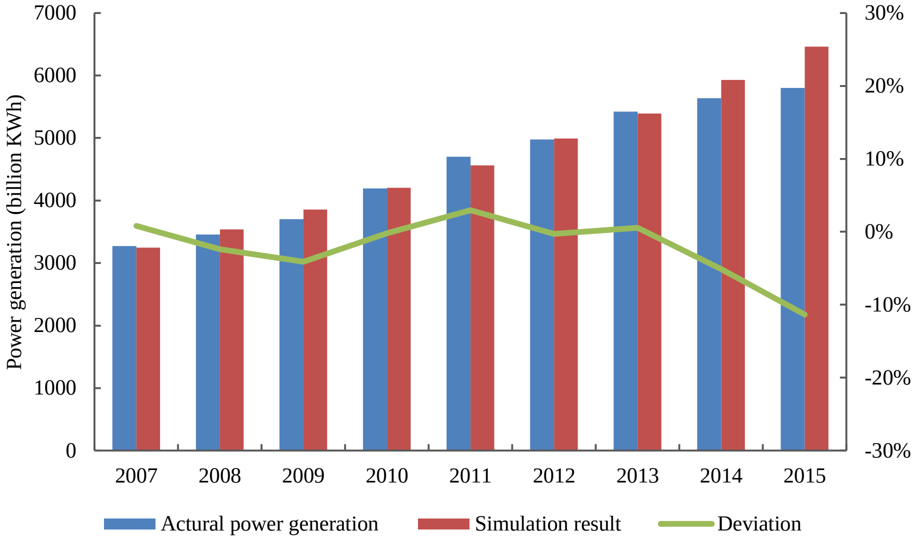

Fig. 3-11 Comparison of actual crude steel production and result in BaU scenario

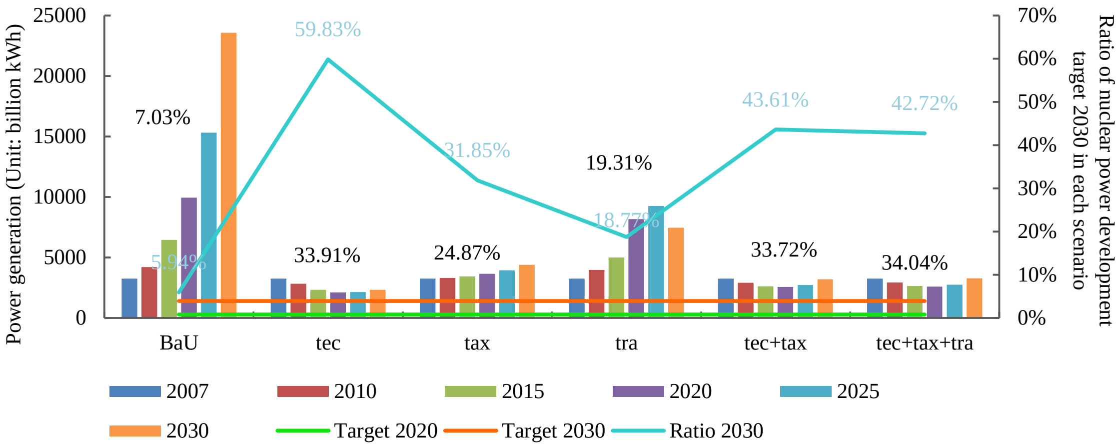

Fig. 3-12 Simulation result of power generation and the national target of nuclear power

Note: target 2020, the nuclear power generation amount based on the national nuclear power development target in 2020;

Target 2030, the nuclear power generation amount based on the national nuclear power development target in 2030;

Ratio 2030, share of the nuclear power generation amount of national target 2030 in the total power generation in each scenario;

Percentage number beyond the bar (black), the ratio of electricity generated by nuclear power in each scenario;

3.5 Discussion

To make a comprehensive top-down evaluation on the carbon emission reduction potential in iron and steel industry, a non-liner economic-environmental model with high feasibility was built up and applied. In this model, advanced technologies, crude steel production structure upgrading, carbon tax and carbon trading factors are fully taken into consideration. By doing this simulation work, we hope to find the overall influence of iron and steel industry adjustment on national economy, industrial structure and environmental protection, at the same time, judge the implementation effect of carbon trading policy in China based on the its future effect for the first time.

Industrial upgrading, including technological and equipment upgrade, production structure adjustment and resources circulation, is the fundamental of resource conservation and low-carbon development. In this research, the technology upgrading scenario shows great effort on carbon emission reduction, economic development and production structure changes. Technology upgrading is an effective measure of energy conservation. Hasanbeigi et al. (2013) estimated that the cumulative energy saving of China's Iron and steel industry from 2010 to 2030 is equal to around 72% of total primary energy supply of Latin America, or 168% of primary energy supply of Brazil in 2007 by implementing 23 energy efficiency technologies and measures. The development of EAF route can efficaciously economize energy consumption comparing to BOF route and decrease environmental pollution. The biggest energy intensive gap between BOF and EAF will be 10.5GJ/t crude steel and the crude steel production of EAF will increase to 35.00% in 2030 in Hasanbeigi's research (2014a). Wen et al. (Wen et al., 2014) found that the energy intensity in iron and steel industry will decrease from 0.625 t ce/t crude steel in 2010 to 0.547 t ce/t crude steel in 2020 and the additional energy saving potential will be 58.2 million tce in 2020, correspondingly, 218.0 million ton CO_2 will be mitigated. Technology promotion is the main driver for this result. Moreover, the crude steel production will remain the same during the research period under the influence of technology upgrading. This may be caused by the investment. Under the technology upgrading speed and the corresponding cost of different technologies, the investment may transfer to update the technologies, there would not be any investment left for the production expansion. However, the GDP will keep high-speed development in this scenario. This part indicated that production capacity compression on iron and steel industry will rarely affect the national economy and we can take this change to finish the technology upgrading and industrial transformation.

In this research, carbon tax policy will bring more financial loss than other two scenarios, but the average annual increased rate is still as high as 7.64%. The carbon reduction effect of carbon tax policy with limited GDP loss has been confirmed by lots of former researches (Guo et al., 2014; Liu & Lu, 2015; Tian et al., 2016). In the simulation results of Dong et al. (2017), the average annual growth rate of China's GDP in carbon tax scenario is only 0.3% less than that in BaU scenario. While the carbon emission will reduce from 12.2 billion tons in BaU scenario to 7.0 billion ton at most. Carbon tax policy is sensitive to the carbon emission factor. It has strong inhibition effect on energy intensive industries or energies, like coal, by increasing the production cost or product price (Metcalf, 2007). In this research, BF-BOF route and thermal power industry consume lots of fossil fuel energies and bring huge amount of carbon emission (NBS, 2015; Zhu et al., 2016). Therefore, the production cost will be greatly increased due to the carbon tax policy and the added value must be decreased correspondingly. As the model object is to maximize the GDP, the development of BF-BOF and thermal power will not be given precedence. That is one important reason to decrease the proportion of crude steel made by BOF and thermal power. Meanwhile, the subsidy will be provided to five industries, including crude steel-EAF, nuclear power, renewable power, recycled power and ferrous scrap recycle. These industries will get the priority development right in this model. Therefore, the EAF route and nuclear power will be greatly promoted. This mechanism was also confirmed by former researchers. For example, in Song's (2016) research, the biodiesel production and power generation recovered from waste could amount to72.11 thousand t and 1.59 billion kWh, respectively, under the promotion of carbon tax and subsidy policies. Among the different production technologies, the organic wastewater biogas industry has the highest output and net profit due to the most subsidies.

Considering the better effect and the uncertainty of carbon tax implementation, we did a follow-up study. Regional unbalance carbon tax policy is put forward due to the various regional resources endowment in China. Liaoning is selected as the research area, Rest of China (ROC) is set as the contrast. Ten carbon tax scenarios are designed in this research (Table 3-7). Results show that only 5.54% Gross Domestic Product (GDP) will be lost at most, while, 44.92% CO_2 emissions will be decreased at most in 2030 caused by carbon tax in Liaoning province. The output (the sum of added valued and intermediate input) and carbon emission of iron and steel industry will decrease with the carbon tax price increase. The competitiveness of iron and steel industry will also be weakened due to the high carbon tax.

Table 3-7 Carbon tax levels under different mitigation scenarios

Scenario	Item	Unit	Region	Sector	2015	2020	2025	2030
taxC2P4	CO_2	USD/ton	Liaoning	Total	14.36	46.53	78.71	110.89
	CO_2	USD/ton	ROC	Total	7.18	23.27	39.36	55.45
taxC3P4	CO_2	USD/ton	Liaoning	Total	14.36	46.53	78.71	110.89
	CO_2	USD/ton	ROC	Total	10.77	34.90	59.03	83.17
taxC4P4	CO_2	USD/ton	Liaoning	Total	14.36	46.53	78.71	110.89
	CO_2	USD/ton	ROC	Total	14.36	46.53	78.71	110.89
taxC5P4	CO_2	USD/ton	Liaoning	Total	14.36	46.53	78.71	110.89
	CO_2	USD/ton	ROC	Total	19.14	62.05	104.95	147.85
taxC8P4	CO_2	USD/ton	Liaoning	Total	14.36	46.53	78.71	110.89
	CO_2	USD/ton	ROC	Total	28.71	93.07	157.43	221.78
taxC4P2	CO_2	USD/ton	Liaoning	Total	7.18	23.27	39.36	55.45
	CO_2	USD/ton	ROC	Total	14.36	46.53	78.71	110.89
taxC4P3	CO_2	USD/ton	Liaoning	Total	10.77	34.90	59.03	83.17
	CO_2	USD/ton	ROC	Total	14.36	46.53	78.71	110.89
taxC4P5	CO_2	USD/ton	Liaoning	Total	19.14	62.05	104.95	147.85
	CO_2	USD/ton	ROC	Total	14.36	46.53	78.71	110.89
taxC4P8	CO_2	USD/ton	Liaoning	Total	28.71	93.07	157.43	221.78
	CO_2	USD/ton	ROC	Total	14.36	46.53	78.71	110.89

Note: “C” represents ROC; “P” means Liaoning province. “tax C2P4” means carbon tax of ROC in 2030 is 2/4 of Liaoning province

Carbon trading market had been tested in seven provinces and municipalities since 2013. Until May 2017, the cumulative traded carbon quota is 158 million tons valued 3.72 billion CNY (GZEEX, 2017). It is affecting an annual 1.5 billion ton of CO_2 emissions (Liu et al., 2013). The carbon trading market will be implemented nationwide in 2017, and there is no correlate evaluation about the effect of carbon trading policy on a national scale. Referring to the experience in EU which built up the emissions trading scheme (ETS) as early as 2005, it was confirmed that EU ETS has promoted some abatement efforts from European firms. A 2006 survey of European firms also showed that EU ETS prompted 15% of respondents to take abatement measures and 65% of respondents had taken some abatement measures (Hepburn, 2007). In this research, carbon trading policy only endows in iron and steel industry. It works well on carbon emission reduction and economic stability maintenance. However, its effect on production structure changes are not obviously as the ratio of EAF and nuclear power are not being promoted a lot. Therefore, carbon trading policy only can be used as an auxiliary means to restrict the behavior of the factory and reduce the carbon emission. We still need to update the industrial structure by installing advanced technologies and develop the low carbon production route.

The national carbon emission intensity reduction target will be achieved in the two combination scenarios. Technology upgrading and two carbon policies will be synergistic in these two scenarios to bring more carbon emission reduction effects comparing to the single measure. In Wen's research, the combination of technology upgrading and carbon tax will bring 12.61% more decrease of CO_2 emissions intensity from 2010 to 2020 (Wen et al., 2014). On the other hand, the reduced production of crude steel and the corresponding reduced electricity demand are also essential for carbon emission reduction.

3.6 Summary

Based on the optimization results of iron and steel industry, the national economy will only suffer a very little impact which can be neglected. While, thr carbon emission intensity will reduce heavily, especially in the two combination scenarios. At the same time, the proportion of EAF and nuclear power will be more than 30% in the two combination scenarios, which play a great role to reduce direct carbon emission in iron and steel industry and electricity industry.

Comparing to the three intervening scenarios, technology upgrading can bring great advantage for the industrial long-term development. It is the basic measure to decrease the industrial carbon emission intensity. It also works for promoting the production structure changes. Carbon tax policy has less effect than industrial upgrading. Although the cumulative carbon emission reduction effect of carbon trading policy is better than the carbon tax policy, the production structure change function is worse than carbon tax policy. Therefore, carbon trading policy should be only used as supplementary measure.

Chapter 4 Conclusions and recommendations

This study presented a whole research idea that by evaluation the industrial structure to found the most influential industry in the whole industrial network, then, through optimizing the most influential industry to find its correlation effect on national industrial structure. In the first part research, a social relationship research method, Social Network Analysis (SNA), is introduced in the industrial network research for the first time and combined with Input-Output analysis. By doing this work, iron and steel industry is considered as the most influential industry for the industrial network and set as the research object in the next part of research. Then, Input-Output based environmental-economic simulation model is conducted to predict the comprehensive carbon emission reduction potential in iron and steel industry through technology upgrading and environmental policy implementation. In this part, carbon trading policy is also considered as the influence factor and predict its economic and environmental effect. Specific findings of this study are showed as follows:

4.1 Results summary and discussion

With the quick industrialization and industrial structure transformation and upgrading, the current rough evaluation method about three big industries cannot satisfy the cognitive requirement of industrial structure. We need more detail information on the inner connection and interactional relationship between each industry. Therefore, SNA, a normative tool on social relationship analysis, is introduced and combined with I-O analysis. Degree centrality betweenness centrality, cohesive subgroups and indirect carbon emission are used as the evaluation index. Iron and steel industry are finally decided as the most influential industry based on these indexes and its relatively bigger influence on national economy, social welfare and environmental effect than other industries.

In the second part of research (chapter 3), a simulation work is taken to fix the problems in iron and steel industry to predict the carbon emission reduction potential and the effect on nation economy in this industry. According to the simulation results, after implementing the technology upgrading and environmental policies, the cumulative financial loss brought by different measures in each scenario will be only 1.25% at most comparing to the BaU scenario. While, carbon emission reduction will be 28.53% comparing to BaU scenario during the research period. National carbon emission intensity will decrease more than 50% from 2007 to 2030. The effect on production structure changes is also obvious that the proportion of EAF rout and nuclear power with low carbon emission will be more than 30% in the total output.

Comparing each measure, technology upgrading will have the strictest inhibiting effect on over capacity, carbon emission reduction and carbon emission intensity reduction. The financial loss brought by this scenario is limited. The possible reason of these results may be because of the investment. Most of the investment are devoted to the technology updating and production route conversion, instead of expanded production. This measure will bring long-term advantages for the iron and steel industry. Therefore, technology upgrading should be considered as the primary measure to be implemented. Carbon tax policy also has great promotion effect on production structure change and carbon emission intensity decrease. Its effect on carbon emission reduction is not obviously comparing to other two measures. However, considering the long-term advantages brought by EAF route development, this measure can be considered as the main lever over emissions reduction. Although the carbon emission reduction effect of carbon trading policy is larger than the carbon tax, its promotion effect on production structure change is not obvious, which means this measure only brings temporary benefits for the iron and steel industry and lacks of persistence.

These three measures cooperate well in the two combination scenarios. Both the carbon emission and carbon emission intensity will decrease the most during the six scenarios. While, the financial loss is also bigger than other scenarios. The cumulative GDP loss in co-2 is 1.25% comparing to the BaU scenario. These two combination scenarios are the only two scenarios which will meet the national carbon emission intensity reduction target in 2020, and cob-2 is the only one which can meet the target in 2030. We adopted and optimized one industry to meet the national emissions intensity reduction target, because, on the one hand, the direct carbon emission in iron and steel industry share the most of the industrial total carbon emission, which is more than 25%. Therefore, optimizing the carbon emission in iron and steel industry will bring a huge carbon emission decrease for the industrial network. On the other hand, from the indirect carbon emission point of view, the self-emission of iron and steel industry is quite high that more than 80% of total indirect carbon emission came from the self-demand emissions. Moreover, the iron and steel industry has lots of connections with other industries, which means the carbon emission intensity reduction in iron and steel industry will also bring great influence in other industries.

4.2 Conclusions and policy suggestions

This research fished a whole-part-whole research including past analysis, present statement and future predict. The first part research is conducted from the whole industrial structure view. It gives a more detailed evaluation on China's industrial structure changes during the past 15 years. Form this part of research, we can get that the energy intensive industries, capital intensive industries and labor intensive industries are still dominating the industrial structure in China. Therefore, the government should further promote the development of tertiary industries, as well as improve the added value rate and decrease the carbon emission in the service industries. Considering the industrial structure related carbon emission, the proportion of renewable energy should be further increased, and the government should guide the industries to transfer their energy intensity by choose the energy or material with lower embodied carbon.

Iron and steel industry is choosing as the research object as its bigger influence on national economy, environment and social welfare. Technology upgrading is the basic solution of high carbon emission intensity in iron and steel industry. Facing the problem of overcapacity, we should change the investment object from production expansion to technology updating. This measure will bring considerable environmental benefit and limited GDP loss. Carbon tax policy will also be beneficial for the long-term development of iron and steel industry, and it can be implemented at appropriate times. However, carbon trading policy only has short-term carbon emission reduction effect. Therefore, we suggest that this policy should only be used as an assistant measure.

References

Albert, R., Jeong, H., Barabási, A.L. 1999. Internet: Diameter of the world-wide web. *Nature*, **401**(6749), 130-131.

Bousquet, P., Ciais, P., Miller, J.B., Dlugokencky, E.J., Hauglustaine, D.A., Prigent, C., Van der Werf, G.R., Peylin, P., Brunke, E.G., Carouge, C., Langenfelds, R.L., Lathiere, J., Papa, F., Ramonet, M., Schmidt, M., Steele, L.P., Tyler, S.C., White, J. 2006. Contribution of anthropogenic and natural sources to atmospheric methane variability. *Nature*, **443**(7110), 439-443.

BP p.l.c. 2016. BP Statistical Review of World Energy June 2016. https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf

C2ES. Global anthropogenic GHG emissions by sector Vol. 2017. https://www.c2es.org/facts-figures/international-emissions/sector.

Cai, W., Wang, C., Wang, K., Zhang, Y., Chen, J. 2007. Scenario analysis on CO_2 emissions reduction potential in China's electricity sector. *Energy Policy*, **35**(12), 6445-6456.

Camco, Institute, E.R. 2010. Beyond Copenhagen: mechanisms to finance and deliver GHG emissions reductions in the iron and steel sector in China Vol. 2017. http://neec.no/uploads/Steel%20Report%20EN.pdf.

Chang, Y.F., Lewis, C., Lin, S.J. 2008. Comprehensive evaluation of industrial CO_2 emission (1989–2004) in Taiwan by input–output structural decomposition. *Energy Policy*, **36**(7), 2471-2480.

Chen, B.-J., Ting, I.-H. 2013. Applying social networks analysis methods to discover key users in an interest-oriented virtual community. *7th International Conference on Knowledge Management in Organizations: Service and Cloud Computing*. Springer. pp. 333-344.

Chen, W., Yin, X., Ma, D. 2014. A bottom-up analysis of China's iron and steel industrial energy consumption and CO_2 emissions. *Applied Energy*, **136**, 1174-1183.

Chertow, M.R. 2007. "Uncovering" industrial symbiosis. *Journal of Industrial Ecology*, **11**(1), 11-30.

China Steel Development and Research Institute. 2008. China iron and steel industry yearbook 2008.

China Steel Development and Research Institute. 2015. China iron and steel industry yearbook 2015.

China Steel Development and Research Institute. 2011. China iron and steel industry yearbook 2011.

Cui, D., Yu, Y., Song, Z. 2013. Spatial evolution of industrial structure in Hebei province *Research Journal of Applied Sciences, Engineering and Technology*, **5**(6), 2142-2146.

Cui, F., Yang, Y. 1998a. The assessment on the influence of industrial structure on urban ecological environment. *China Environmental Science*, **18**(2), 166-169.

Cui, F., Yang, Y.S. 1998b. The assessment on the influence of industrial structure on urban ecological environment. *China Environmental Science-Chinese Edition*, **18**, 166-169.

Denman, K.L., Brasseur, G.P., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D.A., Heinze, C., Holland, E.A., Jacob, D.J., Lohman, U., Ramachandran, S., Leite da Silva Dias, P., Wofsy, S.C., Zhang, X., Steffen, W. 2007. Couplings between changes in the climate system and biogeochemistry. in: *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA.

Domenech, T., Davies, M. 2009. The social aspects of industrial symbiosis: the application of social network analysis to industrial symbiosis networks. *Progress in Industrial Ecology, an International Journal*, **6**(1), 68-99.

Domenech, T., Davies, M. 2011. Structure and morphology of industrial symbiosis networks: The case of Kalundborg. *Procedia-Social and Behavioral Sciences*, **10**, 79-89.

Dong, H., Dai, H., Geng, Y., Fujita, T., Liu, Z., Xie, Y., Wu, R., Fujii, M., Masui, T., Tang, L. 2017. Exploring impact of carbon tax on China's CO_2 reductions and provincial disparities. *Renewable and Sustainable Energy Reviews*, **77**, 596-603.

Dong, H., Fujita, T., Geng, Y., Dong, L., Ohnishi, S., Sun, L., Dou, Y., Fujii, M. 2016. A review on eco-city evaluation methods and highlights for integration. *Ecological Indicators*, **60**, 1184-1191.

Dong, H., Geng, Y., Xi, F., Fujita, T. 2013a. Carbon footprint evaluation at industrial park level: a hybrid life cycle assessment approach. *Energy Policy*, **57**, 298-307.

Dong, H., Ohnishi, S., Fujita, T., Geng, Y., Fujii, M., Dong, L. 2014a. Achieving carbon emission reduction through industrial & urban symbiosis: A case of Kawasaki. *Energy*, **64**, 277-286.

Dong, L., Gu, F., Fujita, T., Hayashi, Y., Gao, J. 2014b. Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China. *Energy Policy*, **65**, 388-397.

Dong, L., Zhang, H., Fujita, T., Ohnishi, S., Li, H., Fujii, M., Dong, H. 2013b. Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki's experience and practice in Liuzhou and Jinan. *Journal of Cleaner Production*, **59**, 226-238.

Fuller, M.M., Wagner, A., Enquist, B.J. 2008. Using network analysis to characterize forest structure. *Natural Resource Modeling*, **21**(2), 225-247.

Geng, Y., Sarkis, J., Ulgiati, S., Zhang, P. 2013a. Measuring China's circular economy. *Science*, **339**(6127), 1526-1527.

Geng, Y., Zhao, H., Liu, Z., Xue, B., Fujita, T., Xi, F. 2013b. Exploring driving factors of energy-related CO_2 emissions in Chinese provinces: a case of Liaoning. *Energy Policy*, **60**, 820-826.

Gordon, I.R., McCann, P. 2000. Industrial clusters: complexes, agglomeration and/or social networks? *Urban Studies*, **37**(3), 513-532.

Guo, Z., Fu, Z. 2010. Current situation of energy consumption and measures taken for energy saving in the iron and steel industry in China. *Energy*, **35**(11), 4356-4360.

Guo, Z., Zhang, X., Zheng, Y., Rao, R. 2014. Exploring the impacts of a carbon tax on the Chinese economy using a CGE model with a detailed disaggregation of energy sectors. *Energy Economics*, **45**, 455-462.

China Emissions Exchange. 2017. 2013-2015 carbon market investment, Vol. 2017. http://files.gemas.com.cn/carbon/201705/20170515150055959.pdf.

Hanneman, R.A., Riddle, M. 2005. Introduction to social network methods, University of California Riverside.

Harris, J.K., Luke, D.A., Burke, R.C., Mueller, N.B. 2008. Seeing the forest and the trees: using network analysis to develop an organizational blueprint of state tobacco control systems. *Social Science & Medicine*, **67**(11), 1669-1678.

Hasanbeigi, A., Jiang, Z., Price, L. 2014a. Retrospective and prospective analysis of the trends of energy use in Chinese iron and steel industry. *Journal of Cleaner Production*, **74**, 105-118.

Hasanbeigi, A., Morrow, W., Sathaye, J., Masanet, E., Xu, T. 2013. A bottom-up model to estimate the energy efficiency improvement and CO_2 emission reduction potentials in the Chinese iron and steel industry. *Energy*, **50**, 315-325.

Hasanbeigi, A., Price, L., Chunxia, Z., Aden, N., Xiuping, L., Fangqin, S. 2014b. Comparison of iron and steel production energy use and energy intensity in China and the U.S. *Journal of Cleaner Production*, **65**, 108-119.

Hendrickson, C., Horvath, A., Joshi, S., Lave, L. 1998. Economic input–output models for environmental life-cycle assessment. *Environmental Science & Technology*, **32**(7), 184-191.

Hepburn, C. 2007. Carbon trading: a review of the Kyoto mechanisms. *Annual Review of Environment and Resources*, **32**, 375-393.

International Atomic Energy Agency. 2015. *Nuclear poer reactors in the world*, Austria.

International Energy Agency. 2016a. *CO_2 emissions from fuel combustion Highlights*.

International Energy Agency. 2016b. *CO_2 emissions from fuel conbustiron - Highlights*. *2016 ed*.

International Energy Agency. 2015. *Energy Statistics of OECD Countries 2015*. OECD Publishing, Paris.

International Energy Agency. 2010. *Energy technology perspectives 2010: Scenarios and strategies to 2050*. IEA, Paris.

Interactive, C. National Climate Plans and Additional Scenarios, Vol. 2017. https://www.climateinteractive.org/programs/scoreboard/scoreboard-science-and-data/.

IPCC, Intergovermental Panel on Climate Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*. IGES, Japan.

IPCC, Intergovermental Panel on Climate Change. 2007a. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, Intergovermental Panel on Climate Change. 2007b. *Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

IPCC, Intergovermental Panel on Climate Change. 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, Intergovermental Panel on Climate Change. 2014. Climate change 2014 synthesis report summary for policymakers.

Kent, C. 2013. Reflections on China and mining investment in Australia, Vol. 2017. http://www.rba.gov.au/speeches/2013/sp-ag-150213.html.

Kwait, J., Valente, T.W., Celentano, D.D. 2001. Interorganizational relationships among HIV/AIDS service organizations in Baltimore: A newtwork analysis. *Journal of Urban Health*, **78**(3), 468-487.

Le Quéré, C., Andres, R.J., Boden, T., Conway, T., Houghton, R.A., House, J.I., Marland, G., Peters, G.P., Van der Werf, G., Ahlström, A., Andrew, R.M., Bopp, L., Canadell, J.G., Ciais, P., Doney, S.C., Enright, C., Friedlingstein, P., Huntingford, C., Jain, A.K., Jourdain, C., Kato, E., Keeling, R.F., Klein Goldewijk, K., Levis, S., Levy, P., Lomas, M., Poulter, B., Raupach, M.R., Schwinger, J., Sitch, S., Stocker, B.D., Viovy, N., Zaehle, S., Zeng, N. 2012. The global carbon budget 1959–2011. *Earth System Science Data Discussions*, **5**(2), 1107-1157.

Lei, Y., Zhang, Q., Nielsen, C., He, K. 2011. An inventory of primary air pollutants and CO_2 emissions from cement production in China, 1990–2020. *Atmospheric Environment*, **45**(1), 147-154.

Li, L., Lei, Y., Pan, D. 2016. Study of CO_2 emissions in China's iron and steel industry based on economic input–output life cycle assessment. *Natural Hazards*, **81**(2), 957-970.

Li, Y., Zhu, L. 2014. Cost of energy saving and CO_2 emissions reduction in China's iron and steel sector. *Applied Energy*, **130**, 603-616.

Liang, S., Zhang, T., Jia, X. 2013. Clustering economic sectors in China on a life cycle basis to achieve environmental sustainability. *Frontiers of Environmental Science & Engineering*, **7**(1), 97-108.

Lin, B., Long, H. 2014. How to promote energy conservation in China's chemical industry. *Energy*

Policy, **73**, 93-102.

Lin, B., Wesseh, P.K. 2013. Estimates of inter-fuel substitution possibilities in Chinese chemical industry. *Energy Economics*, **40**, 560-568.

Liu, H., Hu, Y. 2016. Greenpeace report: Inquiry 2016 De-capacity of China's iron and steel industry.

Liu, L.C., Fan, Y., Wu, G., Wei, Y.M. 2007. Using LMDI method to analyze the change of China's industrial CO_2 emissions from final fuel use: an empirical analysis. *Energy Policy*, **35**(11), 5892-5900.

Liu, Y., Lu, Y. 2015. The economic impact of different carbon tax revenue recycling schemes in China: A model-based scenario analysis. *Applied Energy*, **141**, 96-105.

Liu, Z., Geng, Y., Park, H.S., Dong, H., Dong, L., Fuijita, T. 2016. An emergy-based hybrid method for assessing industrial symbiosis of an industrial park. *Journal of Cleaner Production*, **114**, 132-140.

Liu, Z., Guan, D., Crawford-Brown, D., Zhang, Q., He, K., Liu, J. 2013. Energy policy: A low-carbon road map for China. *Nature*, **500**(7461), 143-145.

Liu, Z., Guan, D., Wei, W., Davis, S.J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G. 2015. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature*, **524**(7565), 335-338.

Liu, Z., Liang, S., Geng, Y., Xue, B., Xi, F., Pan, Y., Zhang, T., Fujita, T. 2012. Features, trajectories and driving forces for energy-related GHG emissions from Chinese mega cites: the case of Beijing, Tianjin, Shanghai and Chongqing. *Energy*, **37**(1), 245-254.

Lu, Z., Deng, X. 2011. China's western development strategy: policies, effects and prospects. Munich Personal RePEc Archive, Paper No. 35201

Lv, K., Fu, M. 2010. Construction and structural measurement of the inter-regional industrial spatial networks in China. *Economic Geography*, **30**, 1785-1791.

Mózner, Z.V. 2013. A consumption-based approach to carbon emission accounting–sectoral differences and environmental benefits. *Journal of Cleaner Production*, **42**, 83-95.

Matthews, H.D., Zickfeld, K. 2012. Climate response to zeroed emissions of greenhouse gases and aerosols. *Nature Climate Change*, **2**(5), 338-341.

Metcalf, G.E. 2007. A Proposal for a US Carbon Tax Swap: An Equitable Tax Reform to Address

Global Climate Change," The Hamilton Project, Brookings Institution. October.

MIIT, Ministry of Industry and Information Technology. 2010. Eliminating the small blast furnace before the end of the year. http://news.xinhuanet.com/2010-04/23/c_1250681.htm. Date of access, 5 Sep 2016.

Ministry of industry and information technology of the people’s republic of China. 2011. Notice on the 12th five-year plan of the steel industry. http://www.gov.cn/zwgk/2011-11/07/content_1987459.htm

Mi, Z.F., Pan, S.Y., Yu, H., Wei, Y.M. 2015. Potential impacts of industrial structure on energy consumption and CO_2 emission: a case study of Beijing. *Journal of Cleaner Production*, **103**, 455-462.

Mohajan, H. 2011. Dangerous effects of methane gas in atmosphere. *International Journal of Economic and Political Integration*, **1(2)**, 3-10.

NBS, Natinal Bureau of Statistics of China. 2015. Annual data of electricity generation. http://data.stats.gov.cn/easyquery.htm?cn=C01&zb=A0201&sj=2015

NDRC, Natinal Development and Reform Commission. 2007 Medium and long-term nuclear power development target (2005-2020), Vol. 2017. http://www.snptc.com.cn/sylj/zcfg/gnflfg/201705/P020170520355788429493.pdf.

Oda, J., Akimoto, K., Tomoda, T., Nagashima, M., Wada, K., Sano, F. 2012. International comparisons of energy efficiency in power, steel, and cement industries. *Energy Policy*, **44**, 118-129.

OECD. 2012. Focus on China: experience and challenge. in: *Nuclear power development in China: Views and prospects of the OECD nuclear energy agency*, OECD. Paris.

Oluleye, G., Jobson, M., Smith, R., Perry, S.J. 2016. Evaluating the potential of process sites for waste heat recovery. *Applied Energy*, **161**, 627-646.

Ou, X., Xiaoyu, Y., Zhang, X. 2011. Life-cycle energy consumption and greenhouse gases emission for electricity generation and supply in China. *Applied Energy*, **88**(1), 289-297.

Scott, J. 2012. *Social network analysis*. Sage Publication, London.

Shakun, J.D., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z., Otto-Bliesner, B., Schmittner, A., Bard, E. 2012. Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature*, **484**(7392), 49-54.

Sims, R.E., Rogner, H.-H., Gregory, K. 2003. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energy Policy*, **31**(13), 1315-1326.

Song, J., Yang, W., Li, Z., Higano, Y., Wang, X.e. 2016. Discovering the energy, economic and environmental potentials of urban wastes: An input–output model for a metropolis case. *Energy Conversion and Management*, **114**, 168-179.

Stocker, T. 2014. *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Su, B., Ang, B. 2012. Structural decomposition analysis applied to energy and emissions: some methodological developments. *Energy Economics*, **34**(1), 177-188.

Sun, L., Xue, B., Geng, Y., Zhang, L. 2015. Analysis on regional industries based on input-output table and SNA: a case of seven provinces in Eastern China. *Journal of East China Normal University (Natural Science)*, **1**, 224-233.

Sun, L., Xue, B., Zhang, Z., Zhang, L., Geng, Y. 2014. A SNA-based measurement on industrial structure change and industrial networking of China. *Ecological Economy*, **30**, 83-87.

The World bank. Indicators. https://data.worldbank.org/indicator.

Tian, X., Dai, H., Geng, Y. 2016. Effect of household consumption changes on regional low-carbon development: A case study of shanghai. *China Population, Resources and Environment*, **26**, 55-63.

Wall, R., Knaap, B., VD. 2007. Sustainability with an evolving world city network. *Proceedings of 2007 International Forum on Metropolitan Region Development*. pp. 31-51.

Wang, C., Chen, J., Zou, J. 2005. Decomposition of energy-related CO_2 emission in China: 1957–2000. *Energy*, **30**(1), 73-83.

Wang, D., Fang, C., Gao, X. 2010a. Comparison on Evolution of Industrial Linkage Structure Based on Input-Output Table amomg China, Japan and the US. *Progress in Geography*, **29**(5), 609-618.

Wang, D., Fang, C., Gao, X. 2010b. Comparison on evolution of industrial linkage structure based on Input-Output table among China, Japan and the US. *progress in Geography*, **29 (5)**, 609-618.

Wang, K., Wang, C., Lu, X., Chen, J. 2007. Scenario analysis on CO_2 emissions reduction potential in China's iron and steel industry. *Energy Policy*, **35**(4), 2320-2335.

Wang, R., Liu, W., Xiao, L., Liu, J., Kao, W. 2011. Path towards achieving of China's 2020 carbon emission reduction target—a discussion of low-carbon energy policies at province level. *Energy Policy*, **39**(5), 2740-2747.

Wang, Y., Zhu, Q., Geng, Y. 2013. Trajectory and driving factors for GHG emissions in the Chinese cement industry. *Journal of Cleaner Production*, **53**, 252-260.

Wasserman, S., Faust, K. 1994. *Social network analysis: Methods and applications*. Cambridge university press.

Watts, D.J. 1999. *Small worlds: the dynamics of networks between order and randomness*. Princeton university press.

Watts, D.J., Strogatz, S.H. 1998. Collective dynamics of 'small-world' networks. *Nature*, **393**(6684), 440-442.

Wei, L., Zhang, Q., Zhao, L. 2012. Industrial restructuring and transferring based on complex networks of CRMAs. *Economic Geography*, **32**(2), 89-93.

Wen, Z., Meng, F., Chen, M. 2014. Estimates of the potential for energy conservation and CO_2 emissions mitigation based on Asian-Pacific Integrated Model (AIM): the case of the iron and steel industry in China. *Journal of Cleaner Production*, **65**, 120-130.

Williams, R.J., Martinez, N.D. 2000. Simple rules yield complex food webs. *Nature*, **404**(6774), 180-183.

Worlsteel. 2015. Steel statistical yearbook 2015.

Worrell, E., Blinde, P., Neelis, M., Blomen, E., Masanet, E. 2010. Energy efficiency improvement and cost saving opportunities for the US iron and steel industry-an Energy star (r) guide for energy and plant managers. University of California.

Wu, L., Kaneko, S., Matsuoka, S. 2006. Dynamics of energy-related CO_2 emissions in China during 1980 to 2002: the relative importance of energy supply-side and demand-side effects. *Energy policy*, **34**(18), 3549-3572.

Xu, B., Lin, B. 2016. Assessing CO_2 emissions in China's iron and steel industry: a dynamic vector autoregression model. *Applied Energy*, **161**, 375-386.

Zeng, S., Lan, Y., Huang, J. 2009. Mitigation paths for Chinese iron and steel industry to tackle global climate change. *International Journal of Greenhouse Gas Control*, **3**(6), 675-682.

Zhang, H., Dong, L., Li, H.Q., Chen, B., Tang, Q., Fujita, T. 2013. Investigation of the residual heat recovery and carbon emission mitigation potential in a Chinese steelmaking plant: A hybrid material/energy flow analysis case study. *Sustainable Energy Technologies and Assessments*, **2**, 67-80.

Zhang, J.F., Deng, W. 2010. Industrial structure change and its eco-environmental influence since the establishment of municipality in Chongqing, China. *Procedia Environmental Sciences*, **2**, 517-526.

Zhang, Q., Zhao, X., Lu, H., Ni, T., Li, Y. 2017. Waste energy recovery and energy efficiency improvement in China's iron and steel industry. *Applied Energy*, **191**, 502-520.

Zhang, Y.J., Liu, Z., Zhang, H., Tan, T.D. 2014. The impact of economic growth, industrial structure and urbanization on carbon emission intensity in China. *Natural Hazards*, **73**(2), 579-595.

Zhao, H., Geng, Y., Xi, F., Liu, Z., Dong, H. 2012. Analysis of CO_2 emissions related to sectoral energy consumption in Liaoning Province based on production and consumption perspectives. *Research of Environmental Sciences*, **25**(11), 1290-1296.

Zhou, M., Chen, Q., Cai, Y. 2013. Optimizing the industrial structure of a watershed in association with economic–environmental consideration: an inexact fuzzy multi-objective programming model. *Journal of Cleaner Production*, **42**, 116-131.

Zhu, C., Tian, H., Cheng, K., Liu, K., Wang, K., Hua, S., Gao, J., Zhou, J. 2016. Potentials of whole process control of heavy metals emissions from coal-fired power plants in China. *Journal of Cleaner Production*, **114**, 343-351.

Appendix

Table A-1 Input coefficients from usual industries to usual industries (A_{UU})

	Agriculture	Light industry	Chemicals	Non-metal industry	Metal production	Water, natural gas and heat production	Waste (no ferrous waste)	Construction and service
Agriculture	0.140657	0.200305	0.026896	0.000381	0.003925	0.000023	0.000335	0.011012
Light industry	0.098614	0.343635	0.038930	0.037423	0.025054	0.011191	0.002162	0.060342
Chemicals	0.076272	0.075208	0.416432	0.076150	0.057606	0.007549	0.031461	0.037638
Non-metal industry	0.001417	0.004547	0.006890	0.165930	0.011751	0.002387	0.002974	0.054005
Metal production	0.014669	0.027207	0.036830	0.073677	0.417151	0.109421	0.002772	0.085277
Water, natural gas and heat production	0.002406	0.007324	0.026135	0.032940	0.011608	0.327992	0.005900	0.010301
Waste (no ferrous waste)	0.000040	0.004757	0.002394	0.010284	0.003279	0.000053	0.074970	0.000000
Construction and service	0.063574	0.082870	0.087024	0.110051	0.088271	0.109229	0.017676	0.195943

Table A-2 Input coefficients from energy supply industries to energy supply industries (A_{RE})

	Petroleum products	Coke-1
Petroleum products	0.061397	0.018656
Coke-1	0.000000	0.010756

Table A-3 Input coefficients from usual industries to power generation industries (A_{UP})

	Thermal power	Recycle power	New energy power	Nuclear power
Agriculture	0.000012	0.000000	0.000016	0.000003
Light industry	0.007563	0.000000	0.010145	0.002013
Chemicals	0.002569	0.081649	0.002288	0.000684
Non-metal industry	0.001696	0.034976	0.001778	0.000451
Metal production	0.084894	0.104928	0.112380	0.022595
Water, natural gas and heat production	0.000062	0.000000	0.000083	0.000015
Waste (no ferrous waste)	0.262218	0.012500	0.351535	0.069792
Construction and service	0.076683	0.174880	0.100375	0.020410

Table A-4 Input coefficients from usual industries to iron and steel industries (A_{UI})

	Coke-2	Steel making	Crude steel-BOF	Crude steel-EAF	Casting	Non-ferrous metal manufacturing
Agriculture	0.000013	0.000044	0.000017	0.000014	0.000042	0.000122
Light industry	0.007844	0.005361	0.004890	0.004069	0.006691	0.008580
Chemicals	0.016125	0.003044	0.007943	0.006609	0.006075	0.025173
Non-metal industry	0.018379	0.024501	0.035793	0.029783	0.010827	0.008640
Metal production	0.041301	0.047757	0.053084	0.044170	0.071609	0.041766
Water, natural gas and heat production	0.000266	0.065676	0.011447	0.009524	0.020711	0.045223
Waste (no ferrous waste)	0.053318	0.007914	0.008314	0.006918	0.008533	0.011495
Construction and service	0.104018	0.071813	0.053424	0.044453	0.075156	0.073614

Table A-5 Input coefficients from usual industries to energy supply industries (A_{UE})

	Petroleum products	Coke-1
Agriculture	0.000025	0.000013
Light industry	0.007459	0.007844
Chemicals	0.019125	0.016125
Non-metal industry	0.001569	0.018379
Metal production	0.025135	0.041301
Water, natural gas and heat production	0.000155	0.000266
Waste (no ferrous waste)	0.011146	0.053318
Construction and service	0.055392	0.104018

Table A-6 Input coefficients from usual industries to raw material industries (A_{UR})

	Coal mining	Ferrous waste
Agriculture	0.002677	0.000089
Light industry	0.013924	0.000811
Chemicals	0.038296	0.008328
Non-metal industry	0.013054	0.000787
Metal production	0.116259	0.005082
Water, natural gas and heat production	0.000789	0.074193
Waste (no ferrous waste)	0.062448	0.002201
Construction and service	0.110084	0.016962

Table A-7 Input coefficients from power generation industry to usual industries (A_{PU})

	Agriculture	Light industry	Chemicals	Non-metal industry	Metal production	Water, natural gas and heat production	Waste (no ferrous waste)	Construction and service
Thermal power	0.005986	0.008044	0.020790	0.027098	0.005779	0.001126	0.055940	0.004541
Recycle power	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
New energy power	0.001069	0.001436	0.003712	0.004838	0.001032	0.000201	0.009987	0.000811
Nuclear power	0.000137	0.000184	0.000474	0.000618	0.000132	0.000019	0.001276	0.000104

Table A-8 Input coefficients from power generation industry to power generation industry (A_{PP})

	Thermal power	Recycle power	New energy power	Nuclear power
Thermal power	0.042101	0.000000	0.056470	0.011206
Recycle power	0.000000	0.000000	0.000000	0.000000
New energy power	0.007516	0.019587	0.009804	0.002001
Nuclear power	0.000961	0.000000	0.001288	0.000256

Table A-9 Input coefficients from power generation industries to iron and steel industries (A_{PI})

	Coke-2	Steel making	Crude steel-BOF	Crude steel-EAF	Casting	Non-ferrous metal manufacturing
Thermal power	0.018598	0.023893	0.011836	0.107165	0.025090	0.045376
Recycle power	0.000000	0.000000	0.001512	0.013687	0.000000	0.000000
New energy power	0.003320	0.004266	0.000601	0.005444	0.004479	0.008101
Nuclear power	0.000424	0.000545	0.000270	0.002445	0.000572	0.001035

Table A-10 Input coefficients from power generation industries to raw material industries (A_{PR})

	Coal mining	Ferrous waste
Thermal power	0.018140	0.000422
Recycle power	0.000000	0.000000
New energy power	0.003238	0.000075
Nuclear power	0.000414	0.000019

Table A-11 Input coefficients from power generation industries to energy supply industries (A_{PE})

	Petroleum products	Coke-1
Thermal power	0.004333	0.018598
Recycle power	0.000000	0.000000
New energy power	0.000774	0.003320
Nuclear power	0.000099	0.000424

Table A-12 Input coefficients from iron and steel industries to usual industries (A_{IU})

	Agriculture	Light industry	Chemicals	Non-metal industry	Metal production	Water, natural gas and heat production	Waste (no ferrous waste)	Construction and service
Coke-2	0.000000	0.000001	0.002370	0.001703	0.000754	0.000214	0.000292	0.000143
Steel making	0.000000	0.000085	0.000034	0.000358	0.004728	0.001041	0.000014	0.000969
Crude steel-BOF	0.000000	0.000026	0.000188	0.000831	0.005826	0.000000	0.000005	0.000039
Crude steel-EAF	0.000000	0.000005	0.000038	0.000169	0.001185	0.000000	0.000001	0.000008
Casting	0.000237	0.003376	0.002497	0.017902	0.076588	0.001511	0.001102	0.034134
Non-ferrous metal manufacturing	0.000004	0.001409	0.006625	0.005037	0.077347	0.003940	0.000063	0.004286

Table A-13 Input coefficients from iron and steel industries to power generation industries (A_{IP})

	Thermal power	Recycle power	New energy power	Nuclear power
Coke-2	0.000009	0.000000	0.000000	0.000000
Steel making	0.000004	0.000000	0.000005	0.000001
Crude steel-BOF	0.000005	0.000000	0.000006	0.000001
Crude steel-EAF	0.000001	0.000000	0.000001	0.000000
Casting	0.000730	0.000000	0.000980	0.000194
Non-ferrous metal manufacturing	0.000051	0.000000	0.000068	0.000013

Table A-14 Input coefficients from iron and steel industries to iron and steel industries (A_{II})

	Coke-2	Steel making	Crude steel-BOF	Crude steel-EAF	Casting	Non-ferrous metal manufacturing
Coke-2	0.006790	0.051097	0.026620	0.001636	0.012734	0.002863
Steel making	0.000000	0.042143	0.164833	0.082875	0.029884	0.004018
Crude steel-BOF	0.000010	0.004284	0.037216	0.000000	0.161229	0.001732
Crude steel-EAF	0.000002	0.000871	0.000000	0.030966	0.032789	0.000352
Casting	0.000670	0.015698	0.005430	0.004518	0.129563	0.008033
Non-ferrous metal manufacturing	0.000122	0.012193	0.022816	0.018985	0.040409	0.328822

Table A-15 Input coefficients from iron and steel industries to raw material industries (A_{IR})

	Coal mining	Ferrous waste
Coke-2	0.000160	0.000057
Steel making	0.000295	0.003644
Crude steel-BOF	0.000876	0.000003
Crude steel-EAF	0.000178	0.000001
Casting	0.032166	0.003401
Non-ferrous metal manufacturing	0.003517	0.007224

Table A-16 Input coefficients from iron and steel industries to energy supply industries (A_{IE})

	Petroleum products	Coke-1
Coke-2	0.000000	0.006790
Steel making	0.000000	0.000000
Crude steel-BOF	0.000000	0.000010
Crude steel-EAF	0.000000	0.000002
Casting	0.000565	0.000670
Non-ferrous metal manufacturing	0.000249	0.000122

Table A-17 Input coefficients from raw material industries to usual industries (A_{RU})

	Agriculture	Light industry	Chemicals	Non-metal industry	Metal production	Water, natural gas and heat production	Waste (no ferrous waste)	Construction and service
Coal mining	0.000677	0.004336	0.055910	0.126775	0.004648	0.003651	0.060615	0.005180
Ferrous waste	0.000017	0.003171	0.001596	0.004407	0.002186	0.039092	0.000053	0.000000

Table A-18 Input coefficients from raw material industries to power generation industries (A_{RP})

	Thermal power	Recycle power	New energy power	Nuclear power
Coal mining	0.207132	0.000000	0.077075	0.059809
Ferrous waste	0.000027	0.000000	0.000036	0.000008

Table A-19 Input coefficients from raw material industries to iron and steel industries (A_{II})

	Coke-2	Steel making	Crude steel-BOF	Crude steel-EAF	Casting	Non-ferrous metal manufacturing
Coal mining	0.378166	0.323380	0.188860	0.067192	0.146075	0.175056
Ferrous waste	0.000114	0.021187	0.000000	0.407140	0.001213	0.000000

Table A-20 Input coefficients from raw material industries to raw material industries (A_{RR})

	Coal mining	Ferrous waste
Coal mining	0.074990	0.001369
Ferrous waste	0.000526	0.065794

Table A-21 Input coefficients from raw material industries to energy supply industries (A_{RE})

	Petroleum products	Coke-1
Coal mining	0.659703	0.378166
Ferrous waste	0.000066	0.000114

Table A-22 Input coefficients from energy supply industries to usual industries (A_{EU})

	Agriculture	Light industry	Chemicals	Non-metal industry	Metal production	Water, natural gas and heat production	Waste (no ferrous waste)	Construction and service
Petroleum products	0.008064	0.004163	0.057368	0.026022	0.003951	0.002002	0.014021	0.034830
Coke-1	0.000000	0.000002	0.003754	0.002697	0.001194	0.000338	0.000463	0.000227

Table A-23 Input coefficients from energy supply industries to power generation industries (A_{EP})

	Thermal power	Recycle power	New energy power	Nuclear power
Petroleum products	0.025951	0.000000	0.000000	0.530744
Coke-1	0.000014	0.000000	0.000000	0.000000

Table A-24 Input coefficients from energy supply industries to iron and steel industries (A_{EI})

	Coke-2	Steel making	Crude steel-BOF	Crude steel-EAF	Casting	Non-ferrous metal manufacturing
Petroleum products	0.018656	0.002992	0.005414	0.004505	0.019361	0.012490
Coke-1	0.010756	0.080937	0.042165	0.002591	0.020171	0.004536

Table A-25 Input coefficients from energy supply industries to raw material industries (A_{ER})

	Coal mining	Ferrous waste
Petroleum products	0.034810	0.000530
Coke-1	0.000254	0.000090

Table A-25 Parameters feed in the model

	Industry	Indirect tax	Depreciation rate	GHG emission rate (t/CNY)	Income rate
Usual industries	Agriculture	0.000977686	0.0842	2.26293E-05	0.555941076
	Light industry	0.058405839	0.1182	1.71295E-05	0.142509693
	Chemicals	0.039022291	0.1061	7.35577E-05	0.135173091
	Non-metal industry	0.059284799	0.2013	0.00013851	0.179500677
	Metal production	0.041241332	0.093	5.83875E-06	0.132505938
	Water, natural gas and heat production	0.004316138	0.1	9.72399E-07	0.799118018
	Waste (no ferrous waste)	0.043340065	0.0845	2.14519E-05	0.052013256
	Construction and service	0.051982134	0.11026667	2.03074E-05	0.335945737
Energy supply industries	Petroleum products	0.042624901	0.085	0.000111783	0.077461828
	Coke-1	0.092933443	0.085	8.18511E-05	0.190714339
Iron and steel industry	Coke-2	0.092933443	0.085	8.78209E-05	0.190714339
	Steel making	0.052284582	0.0556	0.002472382	0.114551258
	Crude steel-BOF	0.06927758	0.0667	2.78142E-05	0.19854049
	Crude steel-EAF	0.057643733	0.0625	2.88245E-05	0.102059274
	Casting	0.046059455	0.0625	3.9047E-05	0.09586508
	Non-ferrous metal manufacturing	0.052616652	0.0556	2.98778E-05	0.121098267
Power generation industry	Thermal power	0.031408399	0.0612	2.3418E-05	0.187193904
	Recycle power	0.02	0.0435	0	0.509813293
	New energy power	0.041844459	0.06496667	0	0.169446424
	Nuclear power	0.008359703	0.0518	0	0.2196426
Raw material industry	Coal mining	0.086232539	0.098	5.6983E-05	0.335292723
	Ferrous waste	0.006474208	0.1	0	0.799118018

Table A-26 Parameters feed in the model (Continued)

	Industry	Added value	Share in the total household consumption	Capital income coefficient
Usual industries	Agriculture	0.586161082	0.126115571	2.87938847
	Light industry	0.227906557	0.232018671	4.37923348
	Chemicals	0.203116174	0.021786461	3.66864084
	Non-metal industry	0.274707447	0.001963408	5.60381267
	Metal production	0.196004934	0.080327772	4.17833604
	Water, natural gas and heat production	0.808612477	0	19.3112803
	Waste (no ferrous waste)	0.288322319	0.00870012	0.43789417
	Construction and service	0.460210335	0.457772791	1.52549678
Energy supply industries	Petroleum products	0.152808226	0.005176606	2.59768067
	Coke-1	0.321106838	0	2.26914421
Iron and steel industry	Coke-2	0.321106838	0	2.26914421
	Steel making	0.190405442	0	2.35897063
	Crude steel-BOF	0.300578898	0	2.03596809
	Crude steel-EAF	0.17459614	0	4.19656495
	Casting	0.176782862	0	1.7929719
	Non-ferrous metal manufacturing	0.192971687	0	2.88729671
Power generation industry	Thermal power	0.279802303	0.051654252	1
	Recycle power	0.57147996	0	1.044
	New energy power	0.275666783	0.003167106	1.00917682
	Nuclear power	0.279802303	0.009943406	1
Raw material industry	Coal mining	0.472904964	0.001373837	1.907368
	Ferrous waste	0.808921146	0	30.0397693