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Zhu Liu

Carbon Emissions in China

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Carbon Emissions in China

Doctoral Thesis accepted by
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Supervisor's Foreword

By co-supervising Dr. Zhu Liu's Ph.D. Thesis, I'm pleased to introduce the influential and significant work by Dr. Zhu Liu. Dr. Zhu Liu contacted his doctor degree at the Chinese Academy of Sciences in 2009–2014 with the thesis topic of "Carbon emissions in China". Mitigating the human induced carbon emission is one of the most challenging issues facing mankind sustainable development. Dr. Zhu Liu's research about carbon emissions could have global impact on the carbon cycle of the earth system, climate change mitigation and human development.

In his Ph.D. Thesis, Dr. Zhu Liu conducted an analysis based on 4243 coal mines investigations and 602 site experiments to comprehensively test the carbon emissions from coal combustion in China. For the first time the "Measurable, reportable, verifiable" carbon emission factors and total carbon emission inventories are reported for nation, provinces, cities and individual sectors. Dr. Zhu Liu analyzed the feature, pattern and driving forces of China's carbon emissions. Results show that China's carbon emissions are mainly the result of fossil fuel combustion (90 %) and cement production (10 %). Manufacturing and power generation are the major sectors contributing to total carbon emissions, together these sectors accounted for 85 % of China's total carbon emissions. The results also uncovered significant differences in sectoral emission intensity among provinces, implying a huge disparity of technology level among regions. His study further explored China's emission embodied in international trade: the carbon footprints. By analyzing the carbon footprints by nations, Chinese trade represents 34 % of all emissions embodied in trade, and these traded emissions are growing each year. About twenty-five percent of China's carbon footprints are caused by manufacturing products that are consumed abroad. These results provide a basic understanding of China's carbon emissions and further propose a basis to support global mitigation efforts and low-carbon development.

Dr. Zhu Liu showed great insight, enthusiasm and critical thinking abilities during his Ph.D. study. He is always trying to find new approaches for his research. His strong quantitative background but openness to other approaches and his proven ability to publish in the top journals are clearly his most outstanding strengths, and demonstrate himself in establishing himself in academic field.

Sincerely yours

June 2016

Dabo Guan
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Abstract

Anthropogenic climate change driven by human induced carbon emissions, is one of the most serious challenges facing human development. China is currently the world largest developing country, top primary energy consumer and carbon emitter. The nation releases one quarter of the global total (9.2 Gt CO_2 in 2013), 1.5 times that from US. Nearly three-quarters (73 %) of the growth in global carbon emission between 2010 and 2012 occurred in China. Without mitigation, China's emissions could rise by more than 50 % in the next 15 years. Given the magnitude and growth rate of China's carbon emissions, the country has become a critical partner in developing policy approaches to reducing global CO_2 emissions.

Supported by a 5-year joint research programme among more than 100 research institutes globally to investigate carbon emissions in China (Jiao and Stone, 2011), this study presents a systematically evaluation of China's carbon emission from fossil fuel combustion and cement manufacturing process. The main contributions of the study are listed as:

(1) This study was conducted with 4243 mine investigation and 602 site experiments to comprehensively test the qualities of different fuels in China. For the first time the "Measurable, reportable, verifiable" carbon emission factors and total carbon emission inventories are reported for nation, provinces, cities and invidual sectors.
(2) The feature, pattern and driving forces of China's carbon emissions are analyzied. Results show that China's carbon emissions are mainly the result of fossil fuel combustion (90 %) and cement production (10 %). Manufacturing and power generation are the major sectors contributing to total carbon emissions, together these sectors accounted for 85 % of China's total carbon emissions. The results also uncovered significant differences of sectoral emission intensity among provinces, implying a huge disparity of technology level among regions. Less developed provinces with much higher energy intensive technologies, contribute to most of national emission increment since 2000s and cause the whole country's economic structure to become carbon intensive.

(3) The study explored China's emission embodied in international trade: the carbon footprints. By analyzing the carbon footprints by nations, Chinese trade represents 34 % of all emissions embodied in trade, and these traded emissions are growing each year. About twenty-five percent of China's carbon footprints are caused by manufacturing products that are consumed abroad. These, so-called virtual emissions, which are "embodied" in international trade, lead to China having the world's most unbalanced virtual emissions trade with its emissions associated to exports being eight times higher than its emissions associated with imports.

This study provides basic understanding of China's carbon emissions and further proposes a basis to support global mitigation efforts and low-carbon development.

Keywords Sustainability · China · Climate change · Carbon Emissions · Carbon footprint

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Zhu Liu. Dabo Guan, Wei Wei, Steven J. Davis, Philippe Ciais, Jin Bai, Shushi Peng, Qiang Zhang, Klaus Hubacek, Gregg Marland, Robert Andres, Douglas Crawford-Brown, Jintai Lin, Hongyan Zhao, Chaopeng Hong, Tom Boden, Kuishuang Feng, Glen Peters, Fengming Xi, Junguo Liu, Yuan Li, Yu Zhao, Ning Zeng, and Kebin He. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. ***Nature*** 524, 335–338 (2015).

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Zhu Liu, Soeren Linder, Yong Geng, Bing Xue, Fengming Xi, Ying Pan, TianZhu Zhang, Tsuyoshi Fujita. Features, trajectories and driving forces for energy-related GHG emissions from Chinese mega cites: The case of Beijing, Tianjin, Shanghai and Chongqing. ***Energy*** 37, 245–254 (2012).

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Contents

Chapter 1
Introduction

1.1 Scientific Background of Climate Change

Climate change has profound impacts on human survival and development and is considered as the major challenge for sustainable human development. Since the industrial era, the burning of fossil fuels produces considerable greenhouse gas (GHG) emissions into the atmosphere and becomes the major driver of anthropogenic climate change [1]. Human activity, especially the carbon emissions from burning of fossil energy (9.1 billion tons of carbon/year), is the major greenhouse gas emissions [2]. A total of 90–98 % components of the fossil energy (coal, oil, gas, etc.) is carbon, which could be oxidized into carbon dioxide during the combustion process, and nitrous oxide (N_2O) and methane (CH_4), which are also main GHGs that highly related with energy consumption. Nitrous oxide (N_2O) emissions are also mainly from burning fossil fuels. Sources of methane emissions include fossil fuel combustion, waste treatment, and agricultural activities. Other GHGs, such as fluorides, are mainly from chemical production processes. The effects of global warming (global warming potential, GWP) from different greenhouse gases are indicated by the equivalent effect of the carbon dioxide in 100-years. United Nations Framework Convention on Climate Change (UNFCCC) reported that the carbon dioxide released (CO_2), methane (CH_4), and nitrous oxide (N_2O) has GWP equivalents of 1.25 and 310, respectively [1, 3]. In total, carbon dioxide (CO_2) accounts for 63 % of total GWP among all GHGs, methane (CH_4) accounts for about 18 %, nitrous oxide (N_2O) accounts for about 6 %, other GHGs, including sulfur hexafluoride, hydrofluorocarbons, and perfluorocarbons together account for about 13 % of the GWP from all GHGs [1, 3].

Since the industrial era, carbon emissions from energy consumption has completely changed the global carbon cycle, which is one of the basic patterns of geochemical cycles [4]. Global carbon cycle operates on the basis of budgets among the carbon sources and sinks. In addition to burning fossil fuels, the human-induced land changes also contribute 10 million tons of carbon emissions

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per year. The terrestrial forest system and the ocean are the most important carbon sinks that uptake 2.5 billion tons and 2.3 billion tons of carbon from atmosphere every year, respectively [5, 6]. The remaining 4.1 billion tons of carbon in the form of carbon dioxide remain in the atmosphere, driven the change of the dynamic earth system.

It was reported by Keeling et al. that there was a correlation between human-induced carbon emission from energy consumption and the amount of carbon dioxide in the atmosphere [7, 8]. On the timescale of millennium or longer, this correlation appears to be strictly linear [9]. According to inversion of historical data, satellite meteorological observation [10, 11], model analogy [12], and other related data [13–16], anthropogenic carbon emission has far-reaching influences on the global ecosystem, chemical cycles, energy balance, and even the patterns of international politics.

The influences on natural system include the following: droughts, floods, hurricanes, and other extreme weather [17, 18]; glacier melting [19] and sea level rise [20]; loss of biological habitats and desertification [21, 22]; loss of biodiversity [23]. Such impacts could be dangerous and harmful for human society, for example, the deterioration of ecosystem may result in regional water shortage [24, 25] and could cause fights between nations contending for water resources.

The climate change effects are introducing threats to the well-being of the global ecosystem and the entire human race. To analyze the current situation and provide strategic solutions, it is urgent needed to understand the carbon emissions from human activity, which is also the key to human's sustainable development.

1.2 International Efforts on Climate Change Mitigation

Fighting against the severe consequences caused by fossil fuel shortage and climate change, international societies take measures to control fossil fuel consumption and related carbon emissions and to seek low-carbon developmental path. In practice, the development of low-carbon energy such as nuclear power, wind power, solar power, and biomass energy has been listed as national developmental strategy in many countries all around the world. For example, China's nuclear power reached 40 million kilowatt before 2015 [26], and the consumption of renewable energy in USA is required to increase to 0.1 billion tons per year according to the American Clean Energy and Security Act.

Combating climate change requires the collaboration between nations. The Intergovernmental Panel on Climate Change (IPCC) was established collaboratively by World Meteorological Organization (WMO) and United Nations Environment Program, responsible for studying the influence and inhibition practices of climate change. In 1992, The United Nations Framework Convention on Climate Change (UNFCCC) was established to maintain a stable amount of greenhouse gases in the atmosphere, to prevent the climate system from deleterious anthropogenic interference, and to ensure the adaptation of ecosystem to natural climate change, the normal production of crops, and the sustainable development of economy [27, 28].

The Kyoto Protocol that was signed in 1997 and came into effect in 2005 stipulated the principle of “common but differentiated responsibilities” among contracting parties, and formulated the emission reduction targets under this principle [27, 29]. This was the first time that greenhouse gas emission reduction had been statutorily required. The requirement of GHG emission reduction was mandatory for 39 developed countries (Annex I Countries), while it was voluntary for developing countries (Non-Annex I Countries). The Kyoto Protocol also formulated an emission reduction mechanism based on marketing measures, including Clean Development Mechanism and a series of other treaties, which allows the transfer and obtain of carbon offsets on protect level between developed and developing countries. This mechanism has stimulated the establishment of a global carbon trading market. Under Kyoto Protocol, the Annex I Countries has reduced 650 million tons of carbon dioxide since 1990 [30].

In 2007, the participating nations of the 2007 United Nations Climate Change Conference adopted the “Bali Road Map,” which required the developed countries to reduce GHG emission by 25–40 % by 2020. In 2008, Group of Eight (G8 countries) consented on the long-term target to cut 50 % of GHG emission by 2050. In 2012, the contracting parties of Kyoto Protocol agreed to execute the Second Commitment Period from 2013.

However, many countries, especially the developed ones, were divided on the stipulated responsibilities and obligations in Kyoto Protocol and its subsequent treaties because of the enormous amount of economic and social costs incurred by mitigation actions. For example, the USA did not carry out Kyoto Protocol in spite of the fact that it is the major carbon emission sources in the globe. Canada, Japan, New Zealand, and Russia would not participate in the Second Commitment Period. Therefore, the voluntary, scientific, and efficient carbon reduction by developing countries such as China and India under UNFCCC and Kyoto Protocol has become the inevitable choice of global sustainable development.

In the 2015 United Nations Climate Change Conference, the conference negotiated the <Paris Agreement>, a global agreement on the reduction of climate change with the text of which represented a consensus of the representatives of the 196 parties attending it. The Paris Agreement will serve as a foundation for all nations to limit global temperature rise to well below 2 °C, with an aspiration to reach 1.5 °C, and to adapt to climate change impacts already unfolding. This is the first time that international society committing for the first time to a universal agreement to cut greenhouse gas emissions and to avoid the most dangerous effects of climate changes.

1.3 Energy Consumption and Carbon Emission in China

(1) The gigantic energy consumption and carbon emissions

China is the largest developing country in the world, also with the largest amount of population. China's energy consumption and carbon emission have been accelerating, under the influence of rapid urbanization and industrialization. In 2010, China's GDP has overtaken that of Japan and ranked second in the world. However, China has become the largest carbon emitter in 2007, surpassing the USA, and the largest consumer of fossil fuels in 2011. Carbon emission in China has reached approximately 9 billion by 2011, 23 % of the total emission in the world, while the consumption of primary energy in China represented 25 % of the globe. China's carbon emissions from fossil fuel burning and cement production reached 8.50 Gt CO_2 in 2012. China's carbon emissions were only 5.46 Mt CO_2 in 1950; thus, the total emissions increased more than 100-folds during those 60 years. Such a growth rate was the highest among the world's major economies. In 2007, China's carbon emissions surpassed that of the USA; in 2012, China's carbon emissions were almost equivalent to the carbon emissions from both the USA and the EU combined (Fig. 1.1).

(2) Rapid growth in China

There has been a dramatic increase in China's energy consumption and carbon emission during 1990 and 2010. Between 2000 and 2007, the increase in carbon emission of China has represented more than a half of that of the world. During the

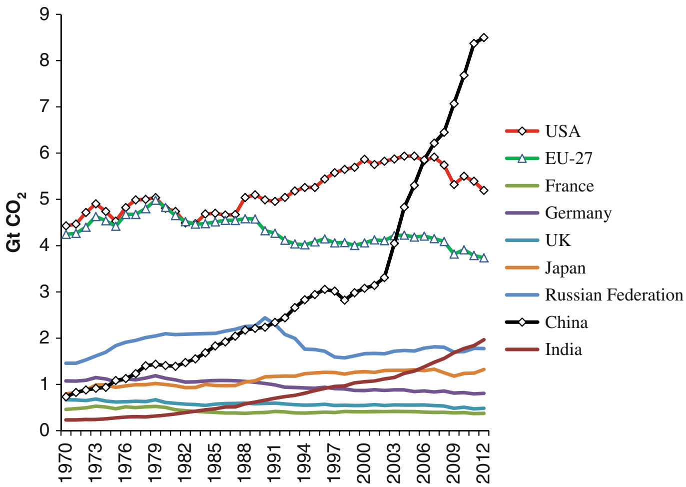

Fig. 1.1 Total CO_2 emissions of major emitters in 1970–2012. China's data on carbon emissions was calculated by the author, the emissions data of the other countries was sourced from the international datasets of CDIAC [31] and EDGAR [32]

time period of 2008 and 2010, the figure has reached over 80 %. During 2005–2011, China increased thermal power generation (by 90 %), steel (94 %), cement (96 %), and vehicle production (223 %), at growth rates exceeding that of GDP (87 %). China also initiated a 4 trillion Yuan ($586 billion) economic stimulus plan after 2008, of which about 85 % was to be used for infrastructure. Today, China accounts for a huge chunk of the world production of crude steel (45 %), cement (60 %), primary aluminum (44 %), coke (64 %), and coal (50 %) [33].

The energy and emission targets that are expressed as ratios of GDP and total emissions do not reduce overall emissions. Moreover, merely rely on rapid expand of production capacity, China could meet its mitigation targets with little development of advanced technology. Much of China's improved energy efficiency has come from a bit upgrading equipment and industrial processes but also significantly larger-scale production capacity. During 2002–2009, the efficiency of China's coal-fired power plants improved by 10 %, while their production more than doubled [33].

Without mitigation measures, projections show, China's emissions will continue to rise by around 3 % per year to 2030. Curbing this growth will entail an emissions reduction between 2015 and 2035 of 30 Gt CO_2 (when comparing with BAU scenario peak at 18 Gt CO_2 by 2035), equivalent to all the world's emissions in 2013 (Fig. 1.2). This is in reach if China follows a best practice low-carbon pathway—keeping the annual emission growth below 2 %, rolling out a national carbon trade system and obtaining 30 % of its energy from renewable sources by around 2035. China's per capita emissions in 2030 would then mirror those of the EU in 2013 (less than 8 t CO_2/person).

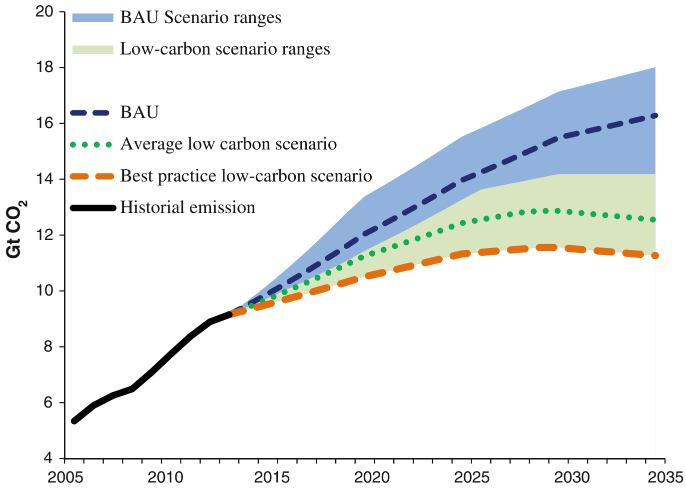

Fig. 1.2 China's carbon emission projections, data source from [34], copyright reserved

(3) The fossil-based energy supply system

Fossil fuels, especially coal, play a dominant role in China's energy consumption structure. Fossil fuel represented 90 % of China's energy supply, and 70 % of it came from coal [35]. In the major industrial processes, China has a lower technical efficiency per product [36], and a higher energy consumption per output [37].

Current energy structure and future economic development determine that China's carbon emission will keep in a high level in the long run. In addition, the cost incurred by adjusting China's energy supply system and industrial structure will be far more than those technologically matured developed countries, with comparatively low-carbon energy mix. Because of the rocketing increase in carbon emission, China's emission per capita is gradually approaching the figure for Western developed countries [31]. Systematic analysis and research into China's energy-related carbon emission are the key for China's to actively combat climate change and develop a low-carbon economy.

1.4 China's National Strategy on Climate Change Mitigation

The Chinese government has actively participated in combating climate change and set energy conservation and emission reduction as fundamental national strategies. From national perspective, the Ministry of Science and Technology and 5 other ministers have collaboratively promulgated the <National Assessment Report of Climate Change> in 2006. In 2007, the government released <China's Policies and Actions for Addressing Climate Change>. China officially announced the national target would be to achieve a 45 % reduction of carbon intensity (Carbon emission per unit of GDP) by 2020 (against 2005 level); such a national target has been allocated into provinces and implemented through "top-down" administrative measures (Table 1.1). "Top-down" command and control policies are the major approach that China is using to meet its energy saving and emissions reduction goals. In its 11th 5-Year Plan (2006–2010), the government set goals that would cut energy intensity (energy in heat per unit of GDP) by 20 % and cut total SO_2 emissions by 10 %. The following 12th 5-Year Plan (2011–2015) called for a 16 % reduction in energy intensity and a 17 % reduction in carbon intensity with mandatory subtargets allocated into regions. The 12th 5-Year Plan further allocated the targets into provinces, with the Eastern coastal regions being allocated more rigorous goals for intensity reduction. To meet the intensity reduction target in the 11th 5-Year Plan (2006–2010), both central and local governments closed thousands of inefficient power plants and factories. Regionally, provinces, cities, and districts have implemented several sustainable developing and construction projects based on the principle of "low-carbon" strategy. In 2010, the National Development and Reform Commission piloted 11 provinces and cities as "low-carbon pilot

Table 1.1 Regional energy intensity targets and achievements in the 11th and 12th 5-Year Plans (2006–2015)

Region	Province	Energy intensity goal (2006–2010) (%)	Energy intensity goal achievement (2006–2010) (%)	Energy intensity in 2010 (ton/10^4 RMB)	Energy intensity goal (2011–2015) (%)
North China	Beijing	−20	−26.59	0.582	−17
	Tianjin	−20	−21.00	0.826	−18
	Hebei	−20	−20.11	1.583	−17
	Shanxi	−22	−20.66	2.235	−16
	Inner Mongolia	−22	−22.62	1.915	−15
Northeastern China	Liaoning	−20	−20.01	1.38	−17
	Jilin	−22	−22.04	1.145	−16
	Heilongjiang	−20	−20.79	1.156	−16
Eastern China	Shanghai	−20	−20.00	0.712	−18
	Jiangsu	−20	−20.45	0.734	−18
	Zhejiang	−20	−20.01	0.717	−18
	Anhui	−20	−20.36	0.969	−16
	Fujian	−16	−16.45	0.783	−16
	Jiangxi	−20	−20.04	0.845	−16
	Shandong	−22	−22.09	1.025	−17
Central and South China	Henan	−20	−20.12	1.115	−16
	Hubei	−20	−21.67	1.183	−16
	Hunan	−20	−20.43	1.17	−16
	Guangdong	−16	−16.42	0.664	−18
	Guangxi	−15	−15.22	1.036	−15
	Hainan	−12	−12.14	0.808	−10
Southwestern China	Chongqing	−20	−20.95	1.127	−16
	Sichuan	−20	−20.31	1.275	−16
	Guizhou	−20	−20.06	2.248	−15
	Yunnan	−17	−17.41	1.438	−15
Northwestern China	Tibet	−12	−12.00	1.276	−10
	Shanxi	−20	−20.25	1.129	−16
	Gansu	−20	−20.26	1.801	−15
	Qinghai	−17	−17.04	2.55	−10
	Ningxia	−20	−20.09	3.308	−15

Source National Development and Reform Commission (NDRC) [40]

regions". For the mitigation activities for companies, China has phased out a great number of small-scale coal-fired power stations and coal mines, which most of them are low efficiency and with high pollutions. The effect of emission reduction during the 11th 5-Year Plan period equaled saving 0.75 billion tons of coal and a reduction of 1.5 billion tons (5 % of the whole world total emissions) of carbon dioxide.

A series of actions and policies from the government and enterprises have revealed considerable contributions made by China in controlling carbon emission and tackling global climate change.

It should also be noted that the Chinese emissions reduction target is based on a relative intensity (emission per unit of GDP) target, not an absolute target. With the rapid economic development and growth in China, a relative reduction (ratio-based indicators) may not necessarily mean a net reduction of CO_2 emissions. A relative improvement may result in a net emissions increase if one country's annual economic growth rate exceeds a certain level. The evaluation of such a relative indicator also depends on which types of GDP (or other units) are used for the calculation. For example, constant price GDP or purchasing power parity (PPP) may provide variations in results because constant price GDP is likely to appear lower than PPP for developing countries. The difference in improvement level becomes larger in both absolute and relative terms when such an indicator is calculated on the basis of GDP. Thus, peaking China's total emission will be the key step for China's carbon emission mitigation.

In 2014, China has committed to peaking its total CO_2 emissions by 2030, under the November 2014 "US–China Joint Announcement on Climate Change and Clean Energy Cooperation" [38]. As a first step, China has addressed the cap of total coal consumption by 4 Gt per year and plans to increase the share of renewable energy by 20 % by 2030. Further integrated effort is needed to help China meet and

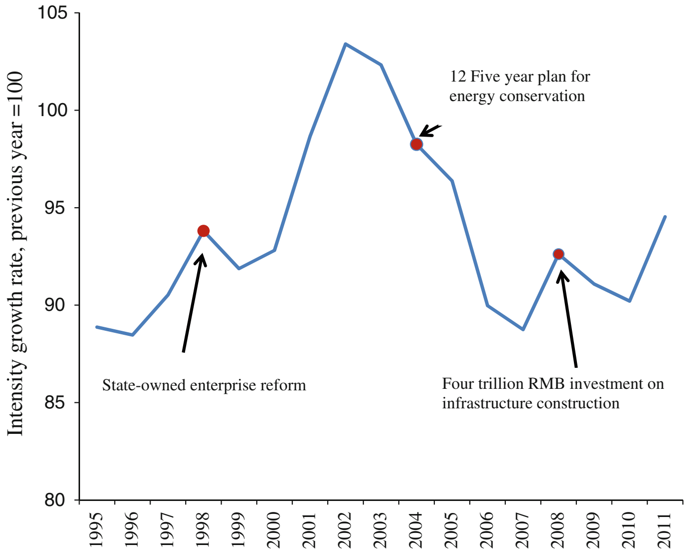

Fig. 1.3 Growth rate of carbon emissions intensity during 1995–2011 (value of previous year has indexed into 100). *Source* [39], copyright reserved

Fig. 1.4 Location of China's provinces

perhaps surpass this goal—an effort that would likely require market-based instruments, technology innovation, energy structure optimization, recycling, as well as international cooperation (Figs. 1.3 and 1.4).

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Chapter 2
China's National, Regional, and City's Carbon Emission Inventories

Consistent, comprehensive, and accurate estimates of carbon emissions from fossil fuel combustion and cement production are fundamental prerequisites to understanding the global carbon cycle and designing evidenced-based policies for reducing carbon emissions. Uncertainty in estimates of carbon emissions from fossil fuel combustion [1–6] arises from inconsistencies in data sources for both activity data (e.g., the amount of fuel burnt or energy produced) and emission factors (EFs, the amount of carbon oxidized per unit of fuel combusted, EF is the product of the net heating value v, net carbon content c, percent carbon content C_{ar}, and oxidization rate o).

2.1 Methodology for Emission Accounting

2.1.1 Calculation of Carbon Emissions from Fossil Fuel Combustion

Carbon emissions are calculated by using activity data, which are expressed as the amount of fossil fuels in physical units used during a production processes (activity data $_{\text{clinker}}$ is the amount of clinker produced) multiplied by the respective emission factor (EF).

$$\text{Emission} = \text{activity data} \times \text{emission factor (EF)} \tag{2.1}$$

Emissions from cement manufacturing are estimated as:

$$\text{Emission}_{\text{cement}} = \text{activity data}_{\text{ clinker}} \times \text{EF}_{\text{clinker}} \tag{2.2}$$

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If data on sectorial and fuel-specific activity data and EF are available, total emission can be calculated by:

$$\text{Emission} = \sum\sum\sum(\text{activity data}_{i,j,k} \times \text{EF}_{i,j,k}) \tag{2.3}$$

where i is an index for fuel types, j for sectors, and k for technology type. Activity data are measured in physical units (tons of fuel expressed as t fuel).

EF can be further separated into net heating value of each fuel v, the energy obtained per unit of fuel (TJ per t fuel), carbon content c (t C TJ^{-1} fuel), and oxidization rate o the fraction (in %) of fuel oxidized during combustion and emitted to the atmosphere. The values of v, c, and o are specific for fuel type, sector, and technology.

$$\text{Emission} = \sum\sum\sum(\text{activity data}_{i,j,k} \times v_{i,j,k} \times c_{i,j,k} \times o_{i,j,k}) \tag{2.4}$$

For the coal extracted in China (e.g., for the 4,243 coal mines analyzed in this study), net heating v and carbon content c values are not directly available, and a more straightforward emission estimate for coal emissions can be obtained using the mass carbon content (C_{ar} in t C per t fuel) of fuels defined by $C_{ar} = c \times v$ so that the total emission can be calculated as:

$$\text{Emission} = \sum\sum\sum(\text{activity data}_{i,j,k} \times C_{\text{ar}\ i,j,k} \times o_{i,j,k}) \tag{2.5}$$

The activity data can be directly extracted as the final energy consumption from energy statistics, or estimated based on the mass balance of energy, the so-called apparent energy consumption estimation:

$$\begin{aligned}&\text{Apparent energy consumption} = \text{domestic production} + \text{imports} - \text{exports}\\&+/- \text{change in stocks} - \text{non energy use of fuels}\end{aligned} \tag{2.6}$$

2.1.2 *Calculation of Carbon Emission from Cement Production*

The carbon emission from cement production is due to the production of clinker, which is the major component of cement. When clinker is produced from raw materials, the calcination process of calcium carbonate ($CaCO_3$) and cement kiln dust (CKD) releases CO_2:

$$CaCO_3 \rightarrow CaO + CO_2$$

The amount of emission can be calculated from the molar masses of CaO (55.68 g $mole^{-1}$) and carbon (12 g $mole^{-1}$) and the proportion of their masses in clinker production. Furthermore, the emission associated with CKD that is not recycled to the kiln is calculated using the CKD correction factor, CF_{cdk}.

Carbon emission from cement production can be calculated by clinker emission factor ($EF_{clinker}$) and clinker production.

$$\text{Emission}_{\text{cement}} = \text{Activity data}_{\text{clinker}} \times \text{EF}_{\text{clinker}} \tag{2.7}$$

$$\text{EF}_{\text{clinker}} = \text{EF CaO} \times (1 + \text{CF}_{\text{cdk}}) \tag{2.8}$$

$$\text{EF CaO}_{\text{clinker}} = \text{Fraction CaO} \times (12/55.68) = \text{Fraction CaO} \times 0.2155 \tag{2.9}$$

Fraction CaO is the mass proportion of CaO per unit clinker (in %).

EF $CaO_{clinker}$ is the mass of total carbon emission released as CaO per unit of clinker (unit: t C per t clinker).

CF_{cdk} is the CKD correction factor (in %).

$EF_{clinker}$ is the mass of total carbon emission per unit of clinker (t C per t clinker)

Clinker is the major component of cement. However, data on clinker production are less widely reported than those of cement production. When the data of clinker production are not available, the clinker-to-cement ratio "$R_{\text{clinker-cement}}$" (in %) can be used for estimating the cement emission factor (EF_{cement}) and further estimate the emission based on cement production.

$$\text{R}_{\text{clinker-cement}} = \text{activity data}_{\text{clinker}}/\text{activity data}_{\text{cement}} \tag{2.10}$$

$$\text{EF}_{\text{cement}} = R_{\text{cement-clinker}} \times \text{EF}_{\text{clinker}} \tag{2.11}$$

$$\text{Emission}_{\text{cement}} = \text{EF}_{\text{cement}} \times M_{\text{cement}} \tag{2.12}$$

The IPCC default Fraction CaO (clinker) is 64.6 %, and the Fraction CaO (cement) is 63.5 %; thus, the IPCC default $EF_{clinker}$ is 0.1384 (t C per t clinker). In the IPCC 1996 guideline, the clinker-to-cement ratio is 95 %, which assumes that most cement is Portland cement and that the corresponding default EF_{cement} is 0.1360 (t C per t clinker). In the IPCC 2006 guideline, the clinker-to-cement ratio is 75 % when no direct clinker production data are available, and the corresponding default EF_{cement} is 0.1065 (t C per t clinker). In this study, the clinker-to-cement ratio is calculated using clinker production statistics and cement production statistics.

It should be noted that the non-energy use of fossil fuels and other industrial process such as ammonia production, lime production, and steel production will also produce carbon emissions. To keep consistent with the scope of international dataset we are comparing, those emissions are not included in this study. Based on the previous study, the total emission of these non-energy fuel use and industry processes was equivalent to 1.2 % of China's emissions from fossil combustion in 2008 [6].

2.1.3 Calculation of Carbon Emission from Industrial Process

Carbon emissions from industrial production refer to the CO_2 released from the physical–chemical process of transforming raw materials into industrial products. The fossil fuels used in this transformation stage are considered the carbon emissions from fossil fuel combustion performed by the industrial sectors and are not considered as the industrial process emissions. For example, emissions from the calcination of calcium carbonate ($CaCO_3 \rightarrow CaO + CO_2$) are considered industrial process emissions. By contrast, emissions from fossil energy usage during the calcination process are considered energy-related emissions.

According to the IPCC's Guidelines for National Greenhouse Gas Inventories, industrial process emissions result from several types of industrial production: Mineral Industry (2A), Chemical Industry (2B), Metal Industry (2C), Non-energy Products from Fuels and Solvent Use (2D), and Other Industry (2H). The detailed classifications are provided in Table 2.1.

In this study, we calculated the emissions from 5 types of major industry production processes. On the one hand, these emissions are not reported in existing emission datasets; on the other hand, the openly accessible data sources can be supported by the calculation.

The IPCC [2] suggested three basic methodologies to estimate industrial process emissions. The Tier 1 approach, also known as the reference approach, is an output-based approach that estimates emissions based on the production volume and the default emission factors. The emissions factors refer to the emission amounts per production unit, which amounts vary depending on the production processes; the global average emission factors will be used in the Tier 1 approach, and the emissions are estimated by the mass production amount and the mass of emissions per production unit (global average value). The Tier 2 approach is also an output-based approach, but estimates emissions based on production and country-specific information for correction emission factors. The calculation process in this approach is similar to the Tier 1 approach, except the global average emission factors are replaced by country-specific values. The Tier 3 approach is an input-based carbonate approach that estimates the emissions based on the carbon inputs. The calculation process requires a material flow analysis of the entire production supply chain. Hence, the Tier 3 approach requires the greatest volume of

Table 2.1 Electricity grid emission factors

Electricity grid emission factor: ($kgCO_2/kWh$)	
Northeast electricity grid:	0.9803
North China electricity grid:	1.0852
East China electricity grid:	0.8367
Central China electricity grid:	1.0297
Northwest electricity grid:	1.0001
South electricity grid:	0.9489

data. For the purpose of data feasibility, we adopted the Tier 1 approach. Our calculation is based accordingly on the following equation:

$$\text{Emission} = \text{Activity data}_i * \text{Emission factor}_i \tag{2.13}$$

Activity data are the amount of industry products at the national level (mass unit: tons). The emission factors (unit: ton CO_2/ton product) are the national average ratio of the amount of CO_2 released for each unit of product. The emission released during the production process of glass, soda ash, ammonia, calcium carbide, and alumina are listed as the following:

(1) **Glass production**: When glass raw materials have been melted, the limestone ($CaCO_3$), dolomite $Ca(CO_3)$, $Mg(CO_3)$, and soda ash (Na_2CO_3) produce CO_2:

$$CaCO_3 \rightarrow CaO + CO_2 \tag{2.14}$$

$$MgCO_3 \rightarrow MgO + CO_2 \tag{2.15}$$

(2) **Soda Ash production**: Soda ash comprises primarily sodium carbonate (Na_2CO_3). CO_2 is emitted during the production of Na_2CO_3; thus, the carbon emissions can be estimated by multiplying the quantity of soda ash consumed by the default emission factor for sodium carbonate:

$$2Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O = 3Na_2CO_3 + 5H_2O + CO_2 \tag{2.16}$$

(3) **Ammonia production:**
Ammonia (NH_3) in the form of major industrial chemical products is synthesized by hydrogen and nitrogen, while both the production processes will release CO_2 as a by-product:
Hydrogen production:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{2.17}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{2.18}$$

Hydrogen and nitrogen production:

$$CH_4 + \text{air} \rightarrow CO + 2H_2 + 2N_2 \tag{2.19}$$

Ammonia synthesis:

$$N_2 + 3H_2 \rightarrow 2NH_3 \tag{2.20}$$

(4) **Calcium Carbide production**
Calcium carbide (CaC_2) is created by heating calcium carbonate ($CaCO_3$) to produce calcium oxide (CaO) and the carbonization process of calcium oxide (CaO). Both processes will release CO_2.

$$CaCO_3 \rightarrow CaO + CO_2 \tag{2.14}$$

$$CaO + 3C \rightarrow CaC_2 + CO \tag{2.21}$$

$$2CO + O_2 \rightarrow 2CO_2 \tag{2.22}$$

(5) **Alumina production**
During the alumina production process, CO_2 is emitted from the consumption of carbon anodes while transforming alumina oxide into alumina metal:

$$2Al_2O_3 + 3C = 4Al + 3CO_2 \tag{2.23}$$

2.2 Emission Factors

International fossil fuel emission datasets such as The International Energy Agency (IEA) [7], Carbon Dioxide Information Analysis Center (CDIAC) [8], British Petroleum (BP) [9], Emission Database for Global Atmospheric Research (EDGARv4.2) [10], Regional Emission inventory in Asia (REAS) [11], and Lawrence Berkeley National Laboratory-China Energy Group [12] also give a range of emission estimates for China (spanning 0.3 Gt C for 2008). A key research gap is the lack of transparent comparisons of the EF used for estimating China's emissions in these different datasets. Specific measurements of the EF are seldom conducted for the fuels (especially the coal) typically used in China. These critical parameters also vary with time and space, following the shifts in the exploitation of different coal mines, or changes in the origin and amount of imported coal. In 2012, for instance, 8 % of the coal used in China was imported compared to only 0.1 % in 1990 [13].

We provide new estimates of EF of coal based on an unprecedented dataset from coal mines and coal samples. China has 12,200 coal mines in total [14]. We collected percent carbon content (C_{ar}, in %) data of raw coal for 4,243 state-owned mines (Fig. 2.3). The total annual production of these 4,243 mines is 1.24 Gt-coal (36 % of the 2011 national total production), and the total reserve for these mines is 86.24 Gt-coal (37.5 % of national total reserve [15]). The average C_{ar} of these 4,243 mines is 58.45 % ($2\sigma = \pm$ 44 %), and the production-weighted C_{ar} is of 53.34 % (Fig. 2.1a). The standard deviation here represents real spatial variability across mines and not data uncertainty.

We also conducted independent chemical composition measurements of C_{ar}, v (in TJ t^{-1} coal), and c (t C TJ^{-1}) in 602 coal samples from 100 main coal mining areas in China. The total annual production of these 100 mining areas is 3.53 Gt-coal (99 % of the 2011 national production). The average C_{ar} for the group of 602 samples (Fig. 2.1b) is 55.48 % ($2\sigma = \pm$ 44 %), and the production-weighted average is 54.21 %. The average c (Fig. 2.1c) of our 602 coal samples is 26.59 t C TJ^{-1} ($2\sigma = \pm$ 11 %) and 26.32 tC TJ^{-1} when weighted by production. The

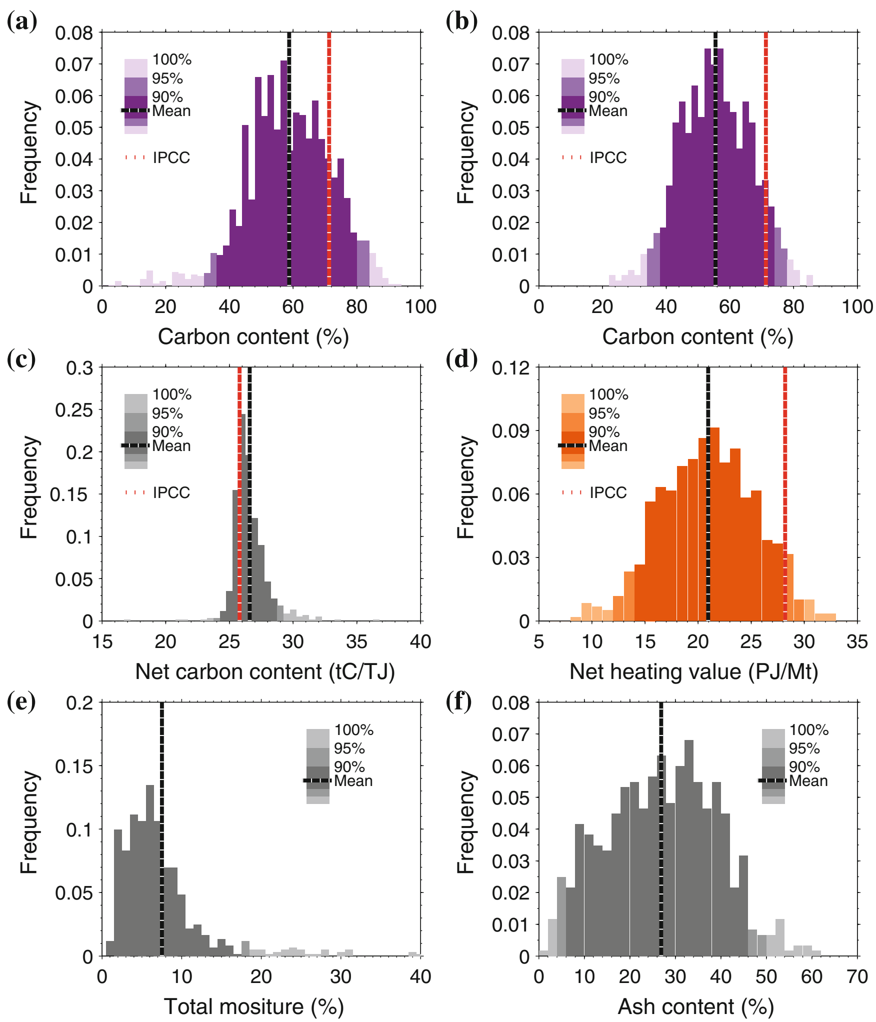

Fig. 2.1 Histograms of Chinese coal properties. Total carbon content of 4243 coal mines (**a**) and 602 coal samples (**b**). *Dashed lines* show mean, and *shading* indicates 90 and 95 % intervals. **c** and **d**, show net carbon content (**c**) and net heating values of the 602 coal samples, respectively. Carbon content for coal mines (**a**) and samples (**b**) is significantly lower than IPCC value, which is mainly because of the lower heating values, *v*, of China's coal (**d**), net carbon content is close to the IPCC value (**c**). Total moisture (**e**) and ash content (**f**) further proved the low quality of China's coal, which is in general with high ash content but low-carbon content

average *v* (Fig. 2.1d) is 20.95 PJ Mt^{-1} ($2\sigma = \pm$ 42 %) and this becomes 20.6 PJ Mt^{-1} when weighted by production. Here as well, the standard deviation represents real spatial variability across samples and not data uncertainty. When collocating samples and mines data on a 1°-by-1° grid, their regression shows a slope close to one (Fig. 2.4), indicating that samples and mines both capture the same (large) spatial variability of C_{ar} across China.

Overall, the coal mine and sample data give consistent average C_{ar} values (58.45 % for mines and 55.48 % for samples) that are also spatially consistent across

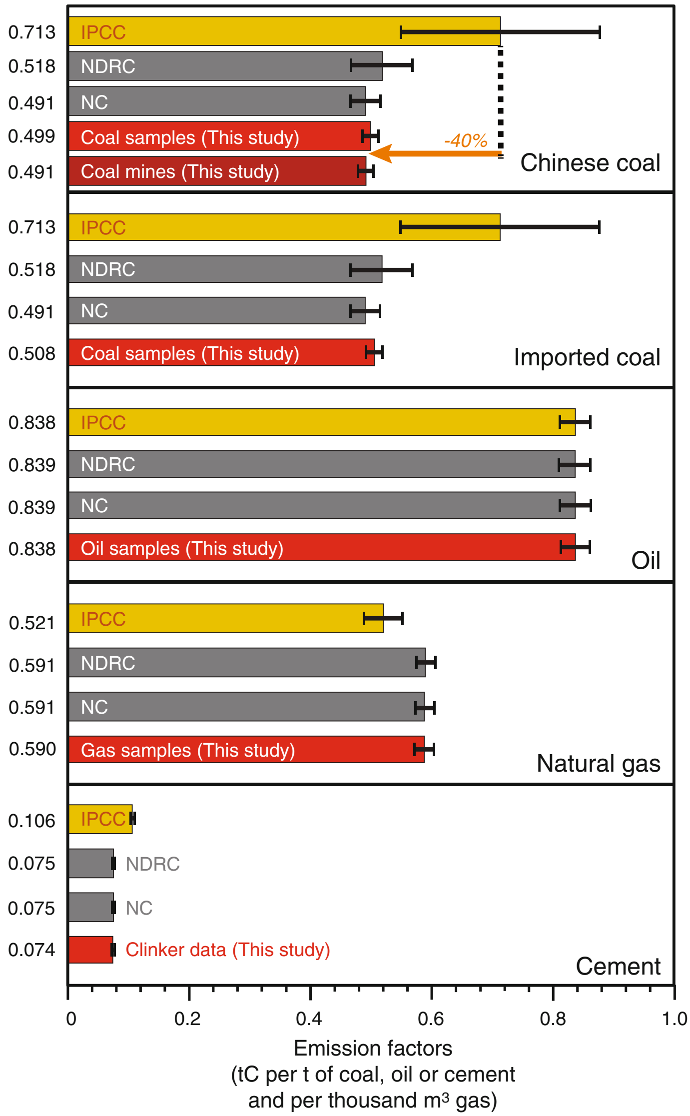

Fig. 2.2 Comparison of emission factors. (in 2012). *IPCC* default value from IPCC guidelines for national emission inventories (1996, 2006). *NDRC* value reported by National Development and Reform Commission (NDRC) in 2008 [20]. *NC* China's National Communication (NC) that reported to UNFCCC (2012 for value in 2005) [23]

the country's very large range of C_{ar}. The mean C_{ar} values are significantly lower than the IPCC default value (71 %) for coal. The C_{ar} for mines and samples show consistent in spatial distribution (Fig. 2.4), indicating the robust of data quality. Decomposing C_{ar} into the net average carbon content (c) and heating values (v), from the coal samples data, we found v = 20.95 PJ Mt^{-1} which is very close to the v reported by NBS (20.91 PJ Mt-coal^{-1}) but significantly less than the default IPCC value (28.2PJ Mt-coal^{-1}) and the average of US coal value [16] (26.81PJ Mt-coal^{-1}). The c of coal (26.59 tC TJ^{-1}) in within 2 % of the IPCC (1996, 2006) default value (25.8tC TJ^{-1}), and NC values reported in 1994 (26.1tC TJ^{-1}).

Because of the average low quality of coal, the v of coal extracted in China is much lower than the global average. This is also reflected by the high-level ash content of China's coal [17, 18]. The average ash content of the 602 coal samples was 26.91 %, significantly higher than the average ash content of US coal samples (14.08 %) [16]. This high ash content is an indirect evidence for a lower EF of coal combustion, but implies larger emissions of particulates containing minerals per unit of coal burned (such as PM 2.5 and fly ash) if fly ash is not removed in power plants, with subsequent effects on air quality [19].

Technology efficiency, reflected in the oxidization rate parameter o defining the fraction of coal consumed that is actually oxidized into CO_2, is another factor that

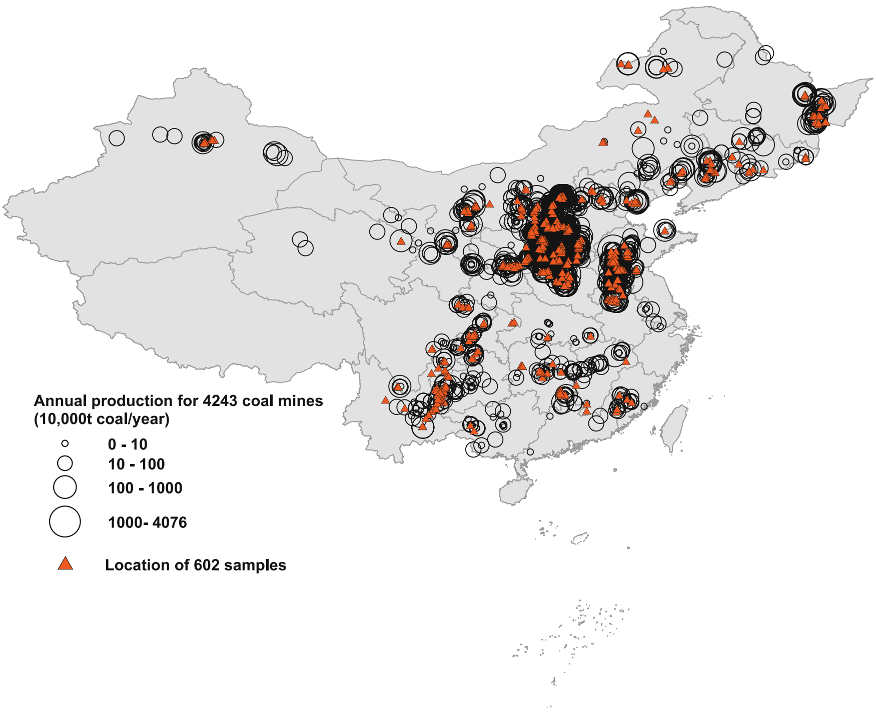

Fig. 2.3 Location of 4243 coal mines (with annual production) and 602 coal samples. The coal samples and mines are consistent with spatial distribution

contributes to EF. To our knowledge, until now there has been no international dataset using China's national-specific *o*. The *o* value varies with the combustion technology and economic sector. We collected data on specific *o* values of energy consumption for 15 major sectors in China with 135 different technologies of fossil fuel combustion based on the national level investigation by NDRC in 2008 [20]. By considering the share of each fuel type for each sector, the weighted average *o* for coal in our calculation is 92 %, lower than the IPCC default value of 98 %, but consistent with China-specific values reported by NDRC (94 %), NC (91.5 %) as well as by Peters et al. [21]. The investigated *o* of oil (98 %) and natural gas (99 %) are close to IPCC default value (within 1 %).

Based on the investigation of C_{ar}, *c*, *v*, and *o*, we updated the EFs (Fig. 2.2) of coal, crude oil, and natural gas combustion in China. The final EF expressed in t C per t-coal in 2012 show that EF from coal mining data (0.4907 t C $tcoal^{-1}$) and coal samples (0.4987 t C t^{-1}) are nearly identical each other and 40 % lower than the IPCC default value (0.713 t C t $tcoal^{-1}$), but close to the specific value reported by NDRC (0.5180 t C t^{-1}) and by NC (0.4910 t C t^{-1}). The value of NDRC and NC is both based on the national investigation of about 1700 government-owned coal mines in 1994 [22] (NDRC has updated *o* in 2005); thus, the results show time

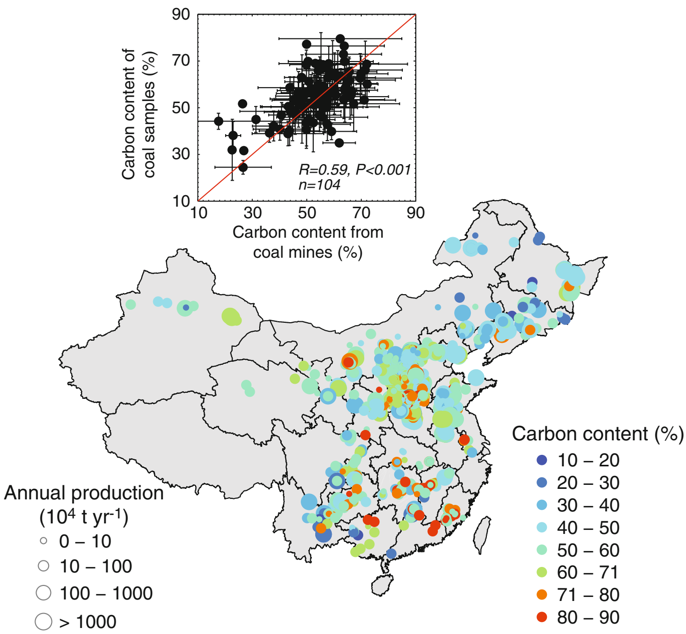

Fig. 2.4 Total carbon content and production of coal mines. The *inset* shows the comparison between carbon content from 602 coal samples and 4243 coal mines ($R = 0.59$, $P < 0.001$, $n = 104$). Each *dot* in the *inset* indicates the average of carbon content from 602 coal samples and 4243 coal mines in the same 1°-by-1° grid. The nearly one-to-one correlation indicates that samples and mines capture the same spatial variability of coal carbon content across China

consistency of EF. The EF of China's natural gas is 11 % higher than the IPCC value. The difference of emission factors for crude oil and cement production process is within 5 % of IPCC (Figs. 2.2, 2.3, and 2.4).

All error bars are 2σ errors.

2.3 China's National Carbon Emission Inventories

2.3.1 Carbon Emission from Energy Combustion

China's carbon emissions from fossil fuel burning and cement production were 8.50 $GtCO_2$ in 2012, making it the country with the largest emissions in the world. China's carbon emissions were only 5.46Mt CO_2 in 1950; thus, the total emissions increased more than 100-folds during those 60 years. Carbon emissions are mainly the result of fossil fuel combustion (90 %) and cement production (10 %). In 2012, 90 % of China's energy consumption was primarily derived from fossil fuel combustion (Fig. 2.5): 68 % from coal consumption, 13 % from oil, and 7 % from gas.

Among the industrial sectors, the emissions are mainly produced by the manufacturing and power generation sectors (see Fig. 2.6). In 2012, manufacturing accounted for 47 % of China's total carbon emissions, while thermal power generation contributed 32 %, and the transportation sector accounted for only 6 %. Such patterns differ with each sector's proportion of emissions from other major emitters, especially from the developed countries where the emissions are mainly from the transportation and household sectors. For example, in the USA, the transportation sector produces 32 % of the total carbon emissions while the industrial sector only accounts for 17 %.

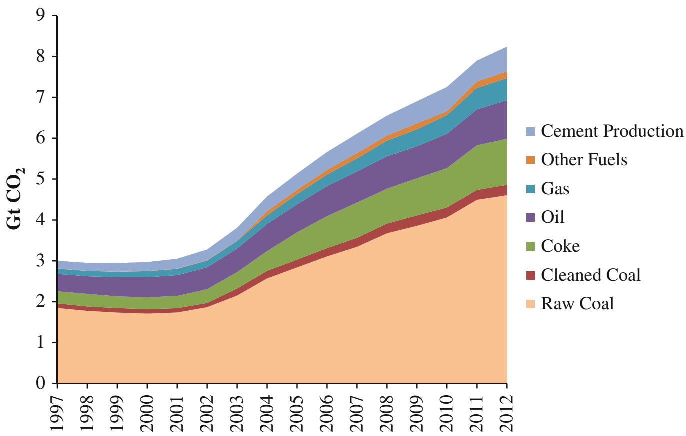

Fig. 2.5 China's national CO_2 emissions by fuels (unit: Mt CO_2)

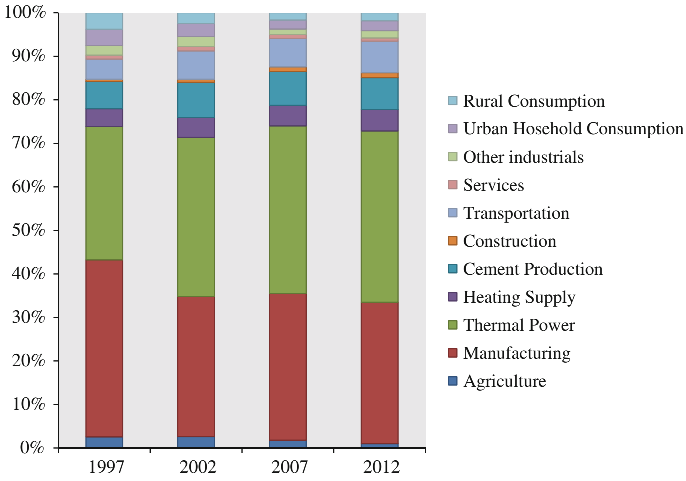

Fig. 2.6 China's national CO_2 emissions by sectors (unit: Mt CO_2)

2.3.2 Carbon Emission from Cement Production Process

Cement process emissions account for about 9 % of China's total carbon emissions [10]. Carbon emissions associated with cement production in China are about half of the global total. CO_2 is emitted during calcining of limestone to produce clinker, which is combined with other ingredients to produce cement. We calculated China's emissions from cement production based on clinker production and EF. We found that carbon emissions of cement production in China were 0.62 Gt CO_2 yr-1 ($2\sigma = \pm 3$ %) in 2012 compared to 0.024 Mt CO_2 yr-1 in 1978. The cement emissions are lower than those reported by international sources. For example, cement emissions are 1.1 Gt CO_2 yr-1 in CDIAC and 0.88 Gt CO_2 yr-1 in EDGARv4.2 (data for 2012).

The large differences in cement carbon emissions are because CDIAC and EDGAR estimated clinker production as a fraction of total cement production, whereas we collected original clinker production data. To calculate the cement process emission, it is more appropriate to use the specific amount of clinker production rather than the total cement production. China's clinker production was not directly reported by national statistics. Therefore, the IPCC proposed a method to estimate it by using a fixed cement-to-clinker ratio, and this method is used by CDIAC and EDGAR. This ratio is estimated to be 95 % in the IPCC 1996 Guidelines [1], which assumed that most cement in China was Portland cement. The more recent IPCC 2006 Guidelines [2] suggested a 75 % cement-to-clinker ratio for developing countries. We found that both IPCC 1996 and 2006 default values result in an overestimation of China's clinker production when compared with official clinker statistics from China Cement Association [24]. These data suggest that the cement-to-clinker ratio was only 58 % in 2012, which is also

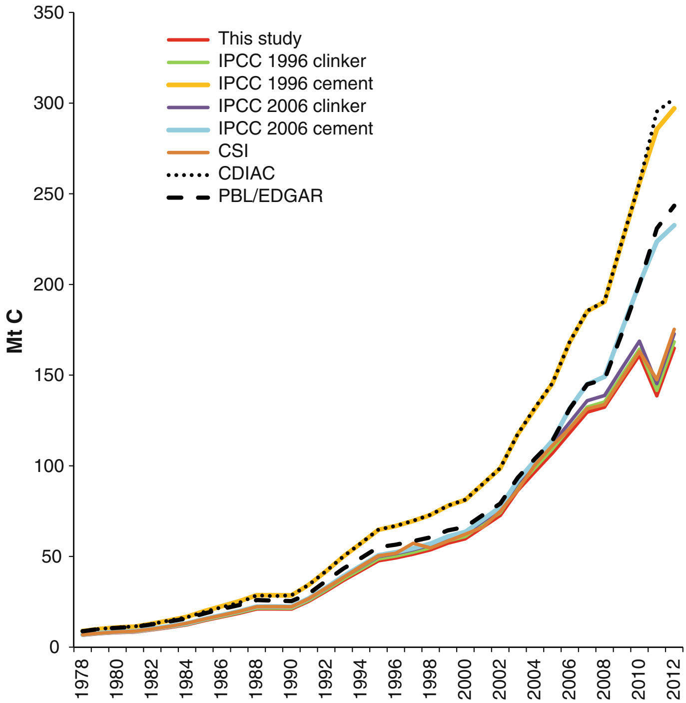

Fig. 2.7 Emission estimates of China's cement production emissions by different sources (1C = 3.6642 CO_2)

consistent with factory-level investigations [25] and other recent studies [26–29]. As a result, our estimation of emissions from cement production (0.62 Gt CO_2 yr-1) is 45 % lower than CDIAC (1.1 Gt CO_2 yr-1) and 32 % lower than that of EGDARv4.2 (0.88 Gt CO_2 yr-1) (Fig. 2.7).

2.3.3 Emission from Industrial Process

The total CO_2 emissions from the production of alumina, plate glass, soda ash, ammonia, and calcium carbide totaled only 43 Mt CO_2 in 1990 but 233 Mt CO_2 in 2013. The cumulative industrial emissions of manufacturing the 5 products are also significant, and during the 1990–2013 period, it measured approximately 2.5 Gt CO_2, exceeding the total annual emissions of India. Annual 233 Mt CO_2 emissions are equivalent to approximately 25 % of the total emissions from cement production. However, such emissions are not reported by current international emission datasets or by China's national emission inventories that are reported to the UN.

The emissions from the production of ammonia and alumina constitute the highest proportion of total emissions from the 5 industrial processes. In 2013, emissions from ammonia and alumina contributed 42 and 31 % of total industrial process emissions, respectively. Emissions from calcium carbide production constituted the third largest contribution, constituting 24 % of total industrial process emissions. The contributions from glass production and soda ash production are relatively small, namely 1.7 and 1.4 %, respectively. For the 1990–2013 period, the industrial emissions of all five production processes increased rapidly. In particular, the emissions from alumina production increased substantially from 12 Mt CO_2 in 2004 to 73 Mt CO_2 in 2013, a sixfold increase within ten years. The trend of increasing emissions from ammonia production is relatively smooth compared with that from the production of the other four products. This finding may be due to the long history of Chinese agricultural development, and the associated demand for ammonia as a fertilizer has been relatively stable because of the scale and status of China's agriculture system. Additionally, the emissions from the production of alumina, calcium carbide, and ammonia fluctuated around the year 2008, which can be explained as the impact on the production processes of the global economic crisis [30]. After 2008, the emissions from these processes continued their rapid growth trends. China initiated a 4,000 billion RMB economic stimulus plan in 2008 to counteract the effects of the global economic crisis and invested most of the capital in infrastructure construction, which stimulated industrial production [31]. For example, the emissions from alumina production doubled during the period 2008–2013. This doubling can be explained by the rapid development of heavy industries after 2008 (Fig. 2.8).

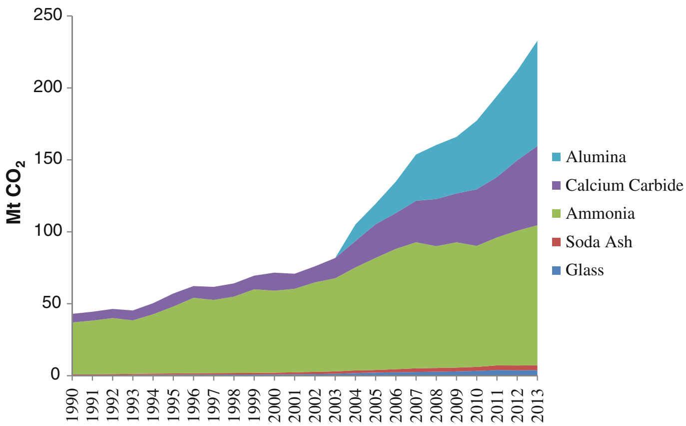

Fig. 2.8 Industrial process emissions from the production of alumina, plate glass, soda ash, ammonia, and calcium carbide in 1990–2013

2.4 China's Provincial Carbon Emission Inventories

2.4.1 Methods

The inventories include carbon emission from energy consumption of 30 provinces, excluding Tibet, Taiwan, Hong Kong, and Macau Special Administrative Region. Data were obtained from National Energy Statistical Yearbook and Provincial Energy Balance Sheet.

The compilation steps are the following:

Determine the energy consumption data of different sectors.
Determine the sectorial emission factor.

Different from national carbon accounting, provincial carbon emission calculation should take cross-regional electricity transmission into consideration. This study adopted the accounting method from a consumption perspective rather than production perspective.

Calculation formula is

$$CO_2 \text{ electricity} = (EF_e \times \text{Activity}_e) \tag{2.25}$$

where

EFe: electricity grid emission factor ($kgCO_2/kWh$)
Activitye: consumption of electricity

National electricity grid can be divided into northeast, north China, east China, central China, northwest, and south regional electricity grid, not including the Tibet Autonomous Region, Hong Kong SAR, Macau SAR, and Taiwan.

The coverage of each regional electricity grid is shown below.
Northeast electricity grid: Liaoning, Jilin, and Heilongjiang

North China electricity grid: Beijing, Tianjin, Hebei, Shanxi, Shandong, and Inner Mongolian Autonomous Region

East China electricity grid: Shanghai, Jiangsu, Zhejiang, Anhui, and Fujian

Central China electricity grid: Henan, Hubei, Hunan, Jiangxi, Sichuan, and Chongqing

Northwest electricity grid: Shaanxi, Gansu, Qinghai, Ningxia Autonomous Region, and Xinjiang Autonomous Region

South electricity grid: Guangdong, Guangxi Autonomous Region, Yunnan, Guizhou, and Hainan

2.4.2 Carbon Emissions from 30 Provinces in 1995–2010

Figure 2.9 shows China's provincial carbon emission patterns in 2010. It is clear that the pattern coincides China's industrial center distribution. It is shown in Tables 2.2 and 2.3 that there was a nation-wide dramatic increase in provincial energy-related carbon emission between 1995 and 2010, especially in underdeveloped areas such as Xinjiang and Inner Mongolia, who mainly relied on heavy and energy-intensive industries.

Industry and thermal power generation are the predominant energy consumers. Among all energy types, the increase in coal consumption represents 80 % of the total increase. The summation of provincial increasing trend is the same as national increasing trend.

It is worth noticing that there was a 5–20 % error between the provincial sum of carbon emission and the national carbon emission based on National Balance Sheet. In 2010, the absolute value of the error is as high as 1.4 billion tons of carbon dioxide, equivalent with the total emission of Japan in the same year. Comparisons between carbon accounting by different organizations reveal that the uncertainty of China's energy-related carbon emission is inevitable under different data sources and choices of emission factors. Possible reasons for this uncertainty are:

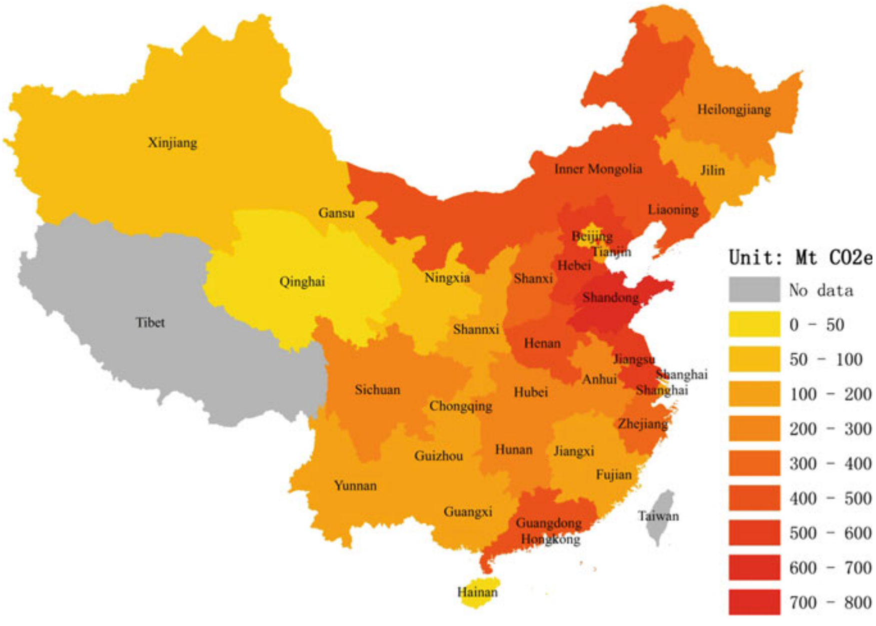

Fig. 2.9 China's provincial CO_2 emissions in 2010 (unit: Mt CO_2)

Table 2.2 China's provincial CO_2 emissions in 1997–2003 (unit: Mt CO_2)

	1997	1998	1999	2000	2001	2002	2003
Beijing	60.75	62.73	66.21	67.35	76.99	76.38	80.91
Tianjin	53.26	54.93	56.09	59.80	62.04	71.75	71.55
Hebei	208.74	232.01	218.91	233.42	248.07	278.96	322.19
Shanxi	148.12	146.93	144.88	147.81	184.29	221.10	245.88
Inner Mongolia	98.79	94.10	98.71	106.98	116.48	127.64	122.24
Liaoning	203.60	197.76	185.59	215.95	190.82	215.62	237.28
Jilin	100.94	86.58	88.06	82.77	87.96	91.06	99.00
Heilongjiang	134.40	134.83	125.79	130.26	126.16	118.50	122.45
Shanghai	108.86	115.92	127.89	125.76	138.17	145.08	155.41
Jiangsu	189.23	191.25	193.01	204.17	196.91	212.72	234.63
Zhejiang	111.43	109.36	113.46	123.81	134.16	144.65	162.44
Anhui	105.11	107.15	109.45	115.77	122.88	128.95	145.01
Fujian	41.20	44.56	56.27	53.51	52.82	64.40	78.41
Jiangxi	50.49	49.64	48.96	50.47	54.93	58.04	70.89
Shandong	177.66	196.42	196.55	173.65	210.87	236.80	313.19
Henan	145.09	145.30	146.17	166.94	168.56	171.04	190.26
Hubei	132.26	130.52	133.64	134.31	126.70	150.45	158.67
Hunan	94.89	95.82	77.14	73.26	71.86	83.40	95.24
Guangdong	160.39	179.25	180.34	189.81	198.45	213.42	241.25
Guangxi	45.81	46.47	47.08	50.59	48.86	48.67	58.70
Hainan	6.73	13.79	7.18	7.75	8.14	No data	14.98
Chongqing	53.39	61.16	66.49	68.03	61.25	65.66	57.94
Sichuan	116.88	116.58	101.97	96.93	99.46	114.23	145.52
Guizhou	72.19	94.36	75.92	79.19	79.05	82.62	105.80
Yunnan	54.38	53.67	51.54	49.88	58.35	69.32	85.07
Shaanxi	63.11	59.94	54.82	54.59	56.27	69.71	74.79
Gansu	47.21	47.59	47.91	51.01	52.60	55.79	63.72
Qinghai	11.58	11.51	13.56	11.92	14.46	15.20	17.46
Ningxia	16.57	17.36	17.14	No data	No data	No data	50.83
Xinjiang	62.67	63.88	62.10	64.67	67.78	63.73	74.09
Industrial process emissions	255.1	267.2	285.64	297.6	329.53	361.41	429.75
Total emissions	3,130.87	3,228.56	3,198.46	3,288.00	3,444.86	3,756.30	4,325.57

China's energy consumption and carbon emission have been accelerating as a result of its rapid economic development, but the statistical technology and management standards lagged behind, not being able to accomplish large-scale quantification and accounting.

Table 2.3 China's provincial CO_2 emissions in 2004–2010 (unit: Mt CO_2)

	2004	2005	2006	2007	2008	2009	2010
Beijing	86.62	91.18	95.86	102.73	98.10	99.14	103.05
Tianjin	82.19	94.35	100.54	109.55	116.47	128.62	134.36
Hebei	366.01	453.87	478.10	515.17	541.16	558.12	663.18
Shanxi	260.21	276.61	306.30	334.19	367.52	371.27	403.45
Inner Mongolia	197.49	230.01	266.97	339.26	412.42	443.29	474.35
Liaoning	255.40	281.84	323.18	358.15	367.64	405.89	456.38
Jilin	108.49	143.52	158.55	170.16	175.93	179.02	198.36
Heilongjiang	133.57	161.01	178.06	189.16	198.00	201.72	217.38
Shanghai	171.53	174.62	202.71	217.10	218.65	200.98	211.26
Jiangsu	306.23	394.21	427.87	453.04	476.90	495.25	555.56
Zhejiang	199.57	235.97	269.29	304.26	310.86	316.54	337.48
Anhui	150.24	147.20	166.43	185.60	213.91	236.86	247.75
Fujian	96.66	117.21	128.19	153.04	157.31	176.81	187.30
Jiangxi	82.58	88.40	99.33	116.46	118.01	126.34	134.84
Shandong	387.01	545.98	590.31	658.49	696.63	718.99	769.12
Henan	225.63	295.72	338.25	409.10	415.01	428.77	490.92
Hubei	176.03	183.83	217.87	242.55	247.93	266.75	319.61
Hunan	109.10	169.15	192.56	212.36	214.75	224.10	243.02
Guangdong	286.92	329.18	353.17	384.73	397.99	421.20	443.59
Guangxi	79.16	88.15	103.93	117.36	118.64	135.39	155.79
Hainan	14.09	15.52	17.34	21.25	25.22	25.67	25.82
Chongqing	63.72	76.77	84.22	92.51	119.54	125.06	124.86
Sichuan	165.36	158.12	165.47	195.20	218.71	245.03	270.10
Guizhou	118.35	136.84	160.43	168.86	160.23	179.14	182.36
Yunnan	53.82	127.86	143.54	153.74	155.99	176.21	183.64
Shaanxi	93.62	102.63	111.77	135.05	153.90	170.55	202.27
Gansu	73.48	81.49	87.58	95.52	101.75	98.33	123.44
Qinghai	18.72	19.54	23.93	25.27	29.78	29.96	28.88
Ningxia	58.53	48.25	56.02	66.81	71.43	79.04	91.11
Xinjiang	92.27	109.13	118.80	129.26	138.97	155.95	166.75
Industrial process emissions	481.96	532.82	616.53	678.54	709.64	819.52	938.13
Total emissions	4,994.56	5,911.00	6,583.09	7,334.49	7,749.00	8,239.51	9,084.10

As most regions of China regard fast economic development as successful political achievement, the local government would conceal the real statistical values, which results in the larger value for provincial sum estimate.

As a result of widespread cross-regional electricity and primary energy transmission, energy consumption may be calculated for several times. For example, raw coal is included as primary energy consumption in its place of production, while washed coal is again included in its place of consumption, leading to errors from duplication.

Uncertainty analysis is crucial to the compilation of carbon inventories, but the quantification of uncertainties is out of the scope of this study. The study of energy-related carbon emission is based on international references, and the uncertainty is +10 %.

2.5 Difference of China's Carbon Emission Estimates Between National and Provincial Statistics

The uncertainty associated with carbon emissions in China comes from both uncertainties regarding activity data and emission factors. The Chinese National Bureau of Statistics (NBS) is the only official source for the data on energy consumption and cement production. NBS reports the national energy consumption data that been used by international organizations such as the United Nations or the World Bank. However, a conspicuous error in energy consumption data, reported by the NBS since 2000s, is that the provincial aggregated energy consumption data are 20 % higher than the national energy consumption data [32]. Therefore, there is significant uncertainty regarding which of the two numbers are more accurate.

China implements a top-down statistics system—the compilation of energy statistics in China occurs under the aegis of the National Bureau of Statistics (NBS) at the central government level which oversees and coordinates the corresponding statistical departments at provincial and county level [33]. The NBS designs and publishes survey principles and reporting formats that are applied to all regional and local statistical department for collecting energy data and information from firms and households. The NBS publishes both national and provincial 'Energy Balance Sheets' annually in China's Energy Statistical Yearbook [34], which provides detailed energy inventory and final energy consumption for the country and each province. In principle, the national energy statistics should be identical to the provincial ones.

In 2009, China's national energy consumption was 3,066 million tons standard coal equivalents (SCE), but the sum of all the provinces was 17 % higher, i.e., 3,572 million tons SCE. The energy data discrepancy between the national total and the sum of the data provided by the provinces has been increasing since the 1990s. The discrepancy was less than 2 % in 1995, but the difference kept increasing to 17 % in 2009. The "official" explanation offered by the NBS is: "as [different] conversion factors [are applied in converting to standard unit of energy consumption], the sum of the data by region is not equal to the [national] total" [34].

If only the conversion factor is to be blamed, then the amount of energy consumed in physical units should still be identical. The amount of raw coal consumption in 2009 from the national Energy Balance Sheet is 2,966 million tons, while aggregated figure from provincial sheets is 3,560 million tons. The discrepancy of coal consumption is 20 %, while the discrepancies of other types of final energy consumption are relatively small (see Fig. 2.10). Furthermore, the difference is due to factors in energy transformation and final energy consumption. For example, the difference of coal washing during energy transformation process between the two data sources can contribute 33 % of the total discrepancy of 594 million tons in raw coal consumption while manufacturing contributes 42 % of the discrepancy.

As a result, China's estimated CO_2 emission from provincial aggregation was 14 % higher than the figure calculated based on the national statistical data in 2010. The discrepancy of 1.4 Gt accounts for about 3 % of the world's total and is larger than Japan's total emissions, which can be ranked as the 5th largest emitter in the world. If we compare the CO_2 emissions from the provincial aggregation with data from other international statistical agencies, the gap ranges from 0.09 Gt (the equivalent of Maldives total emissions [35]) to 1.2 Gt (Japan's total [35]) in 2008.

We conduct analysis to show the uncertainty range of China's emission estimates based on emission factors (EFs) reported in the literature. We collected 12 sets of EF data for fossil fuel combustion from the six following official sources:

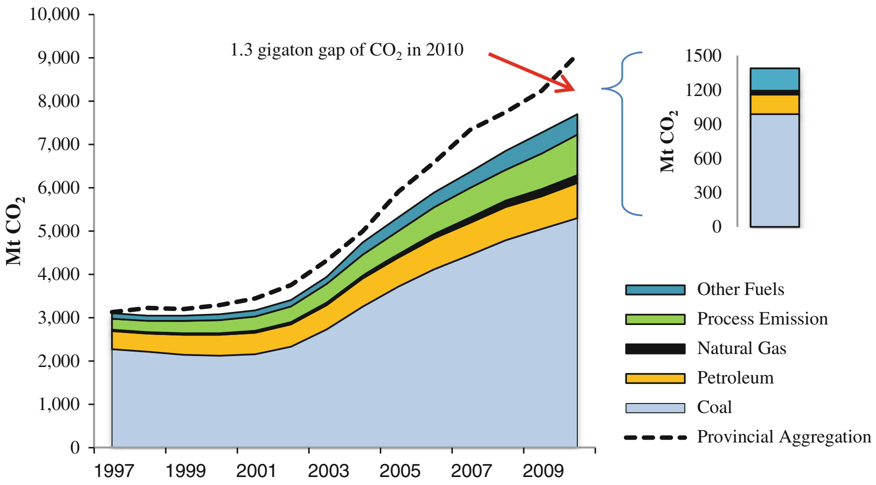

Fig. 2.10 The sources of China's CO_2 emissions by fuel types during 1997–2010. The *left side* "*area chart*" illustrates the increases of CO_2 emissions calculated from the national energy statistics since 1997 breaking down with different fuel type: coal—*light blue*; petroleum—*yellow*; natural Gas—*black*; process emission—*purple*; and other fuels (e.g., coke oven gas, other gas, other coking products, LPG, refinery gas, and other petroleum products)—*dark blue*. The *dash line* represents the aggregated CO_2 emissions calculated from the provincial energy statistics 1997–2010. The *right side* "*column chart*" presents the 1.4 Gt emission gap in 2010 between national and provincial statistics and the pattern of different fuel types in contributing the emission gap

IPCC (1996, 2006) [1, 2], China National Development and Reform Commission (NDRC) [36], UN Statistics (UN) [37], China National Communication on Climate Change (NC) [23], China National Bureau of Statistics (NBS) [13], and Multi-resolution Emission Inventory for China (MEIC) [38]. There are 3 sets of EF in the NDRC data, corresponding to 3 tiers of fuel classifications, 4 sets in NC and 2 sets in UN. We combined these 12 sets of EF with 2 sets of energy statistics derived from national and provincial data [13, 39]. This yielded 24 possible inventories for China's carbon emissions of fossil fuel combustion for 1997–2012. The underlying data used in the commonly used datasets (IEA, CDIAC, BP, EDGAR) are either listed in this data assembly (NBS and IPCC) or not publically available.

The mean value of 24 possible inventories is 2,490 MtC in 2012, and the standard deviation is 372 MtC (15 %). The 2σ standard deviation range suggested by 24 possible inventories is 30 %, which is larger than the reported range of 10 % by current emission datasets such as EDGAR.

A Monte Carlo approach was adopted to assess the distribution range of the emissions by assuming that all reported EF values have the same probability (values have been randomly selected with equal probabilities and calculated for 100,000 times). The mean value of the 24 members' ensemble is 2.43 Gt C in 2012 (95 % confidence interval is +20 %, −11 % and max–min range of +27 %, −15 %). The uncertainty is attributed to the activity data (about 40 % of total uncertainty) and EF (60 %). The variability of EF for coal dominates the total uncertainty (55 % for total uncertainty and 90 % for the uncertainty by EF), whereas the EF for other fuels are more comparable. Different EF values for coal mainly reflect variation in v and hence C_{ar} ($C_{ar} = v \times$ c) values, whereas the variation of c and o is comparatively smaller (less than 10 %).

The distribution range of the emissions is listed in Fig. 2.11.

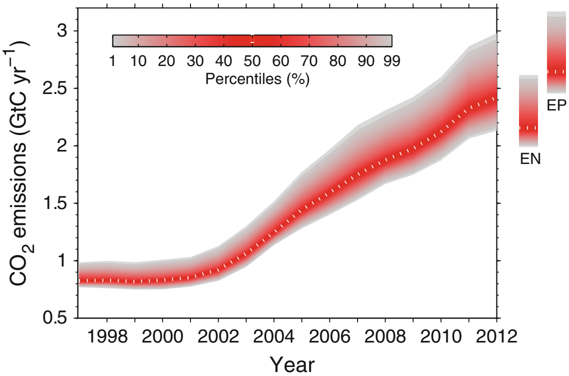

Fig. 2.11 Uncertainty distribution of Chinese CO_2 emissions 1997–2012. Monte Carlo simulations of the Chinese carbon emissions based on a blended activity dataset where national and provincial data are assigned equal probabilities (n = 100,000). Chinese carbon emissions based on national energy activity data (EN) and provincial activity energy data (EP) in 2012 are shown on the *right bar*

We assumed the equal possibility for various EF when conducting the Monte Carlo analysis, and this will expand the uncertainty range. However, both the standard deviation of 24 possible inventories and the Monte Carlo analysis show the significant uncertainty range, implying the considerable system error of the emission estimates by using reported EF; thus, it is critical to perform the emission estimates based on measurement-based EF.

2.6 City's Carbon Emission Inventories

2.6.1 Methodology

The urbanization process has been considered as the major driver for China's development in the coming decades. Cities play an essential role in China's carbon emissions, for example, 85 % of China's direct carbon emissions are from cities [40].

It is difficult to define a city's boundary for carbon emission accounting due to lots of cross-boundary carbon emissions caused by urban metabolism. Cross-boundary exchange of goods, services, commuter travel, and aviation has posed challenges in developing a holistic accounting of emissions associated with human demands for energy and materials in cities. Direct use of primary energy through industrial activity leads to the direct carbon emissions within territorial boundary, and these emissions are usually defined as scope 1. Cities also consume lots of purchased electricity generated by upstream power plant, and the corresponding emissions are defined as scope 2. The consumption of products leads to the emissions from upstream production through supply chain, which is defined as scope 3. Various boundary definitions arouse uncertainties of cities' carbon inventories and then become barriers for the comparability of cities' carbon emission status at global scale.

To undertake quantitative analysis on carbon emissions from Chinese cities is necessary. Practically, China's regional "low-carbon development" strategy mainly targeted in cities. For example, several cities have already initiated their low-carbon development plans, such as Baoding, Shanghai, Guiyang, Hangzhou, Wuxi, Jilin, Zhuhai, Nanchang, and Xiamen [41]. National Reform and Development Commission (NDRC, a ministry leveled agency responsible for national economy planning) initiated national low-carbon demonstration projects in August 2010, in which eight cities were chosen as pilot cities, including Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Guiyang, and Baoding. Academically, studies on carbon emissions in Chinese cities increased sharply, such as Shanghai [42], Shenyang [43], Nanjing [44–46], and Suzhou [45, 47]. Both "top-down" and bottom-up" approaches have been applied, and most of the carbon emissions were calculated based on the IPCC method for national carbon inventory [48]. For example, Dhakal estimated energy consumption and CO_2 emission in 35 cities and analyzed historical changes in Beijing, Tianjin, Shanghai, and Chongqing by using a "top-down" approach [40]. Xi et al. [43] and Bi et al. [44] developed a bottom-up accounting approach with sectoral detailed carbon emissions. These studies created opportunities for global comparison, but a comparison study among different cities from spatial–temporal perspective is still missing, especially between different emission scopes.

Calculation of city's carbon emissions from different scopes:

(1) Direct carbon emission (scope 1) accounting
In this study, we analyzed the scope 1 and scope 2 emissions for Chinese mega cities. The scope 1 emission includes emissions from industrial energy consumption, cement manufacturing process, residential consumption and transportation. Emission from industrial energy consumption can be calculated by the quantity and type of final energy consumption. Emission from cement manufacturing process can be calculated according to the production quantity and the respective emission factor. Car ownership, density of road network, population density, transportation volume, and the provincial emission data can be used to estimate transportation emission. Emission from waste disposal can be calculated by waste disposal quantity and the life cycle emission database. Remote sensing results and GIS technology are used to calculate the carbon emission from changes in land usage.

(2) Cross-regional electricity transmission carbon emission (Scope 2) accounting
The scope 2 emission can be calculated based on electricity production and supply, and the purchase and output of electricity. Here, we calculated the scope 2 emission by using the cross-regional electricity (imported electricity) multiplied by the emission factors (emission per unit of electricity consumption).

(3) Embodies carbon emission (Scope 3)
Scope 3 inventories require detailed information on materials and energy flux and should be calculated through the use of national and regional input–output (IO) models. The scope 3 carbon emission can be calculated according to the consumption quantity of major products, LCA emission database, and the Global Trade Analysis Project (GTAP) [49].

2.6.2 Carbon Emissions in Chinese Megacities: Case Study in Beijing, Tianjin, Shanghai, and Chongqing

Beijing, Tianjin, Shanghai, and Chongqing are four municipal cities directly accountable to the central government (politically equal to one province) in China. The definition of the total population of these four cities is 70 million, about 1 % of global population, and their total GDP counts for 10 % of the whole country in

2009 [50]. Beijing is the capital of China which locates in the northern part of the North China Plain. It covers 16, 808 km^2 area and has a population of 17.6 million and a gross domestic product (GDP) of 1, 215 billion Yuan (RMB) in 2009. Tianjin is east to Beijing, approximately 160 km from Beijing. It covers an area of 11, 920 km^2, with a population of 9.69 million and a GDP of 752 billion Yuan in 2009. Shanghai is an economic center located in Yangtze delta area, with an area of 6340 km^2, a population of 19.2 million, and a GDP of 1, 505 billion Yuan in 2009. Chongqing is located along the upper reaches of the Yangtze River, straddling the region that connects the central and western parts of China. It covers an area of 82, 400 km^2 and has a population of 28.6 million and a GDP of 653 billion in 2009. Therefore, here we performed the scope 1 and scope 2 carbon emission accounting for the aforementioned four municipalities as examples.

The total population of Beijing, Tianjin, Shanghai, and Chongqing is over 70 million, accounting for approximately 1 % of the global population. The total GDP of four municipalities accounts for 10 % of the national GDP. The total GDP, population, and area of the four municipalities in 2009 are shown in Table 2.4.

The calculation of carbon emission is based on the sectorial energy consumption, the quantity of cross-regional electricity supply, and electricity consumption from 1995 to 2010.

Calculation results:

All the four cities have rapid growth of total (scope 1 + scope 2) emissions from 1995 to 2009 (for Chongqing from 1997 to 2009), in which Beijing increased from 81 million tons of CO_2 in 1995 to 155 million tons of CO_2 in 2009, Tianjin increased from 65 million tons of CO_2 in 1995 to 176 million tons of CO_2 in 2009, Shanghai increased from 100 million tons of CO_2 in 1995 to 218 million tons of CO_2e in 2009, Chongqing increased from 58 million tons of CO_2 in 1997 to 144 million tons of CO_2 in 2009, respectively. In total, four big cities emitted approximately 700 million tons of CO_2 in 2009 and contribute to about 2 % of global anthropogenic GHG emissions. In particular, scope 2 contributes significantly to the total amount of carbon emissions and shows a considerable increase both in Beijing and Shanghai. The proportion in Beijing increased from 17 % in 1995 to 32 % in 2009, accounting for 50 million tons of CO_2 in 2009. Shanghai had no input cross-boundary emissions in 1995 and then had 13 % of cross-boundary emission proportion in 2009, accounting for 28 million tons of CO_2 in 2009. The

Table 2.4 Population, GDP, area, and urbanization level of Beijing, Tianjin, Shanghai, and Chongqing

	Population (million)	GDP (billion RMB)	Area (km^2)	Urbanization rate (%)
Beijing	17.6	1215.3	16,410.5	78.2
Tianjin	12.3	721.2	11,917.3	60.9
Shanghai	19.2	1504.7	6,340.5	88.3
Chongqing	28.6	653.0	82,402.9	30.0

fractions of cross-boundary emissions both in Tianjin and Chongqing in 2009 are relatively small with 9 % (15 million tons of CO_2) in Tianjin and 4 % (6 million tons of CO_2) in Chongqing.

Figures 2.12 and 2.13 show the sectoral carbon emission distribution of four municipalities in 1995 (1997 for Chongqing) and 2009. It is clear that industries, thermal electricity generation, and external electricity purchase are the major carbon emission contributors, followed by transportation and heat supply. Emission from

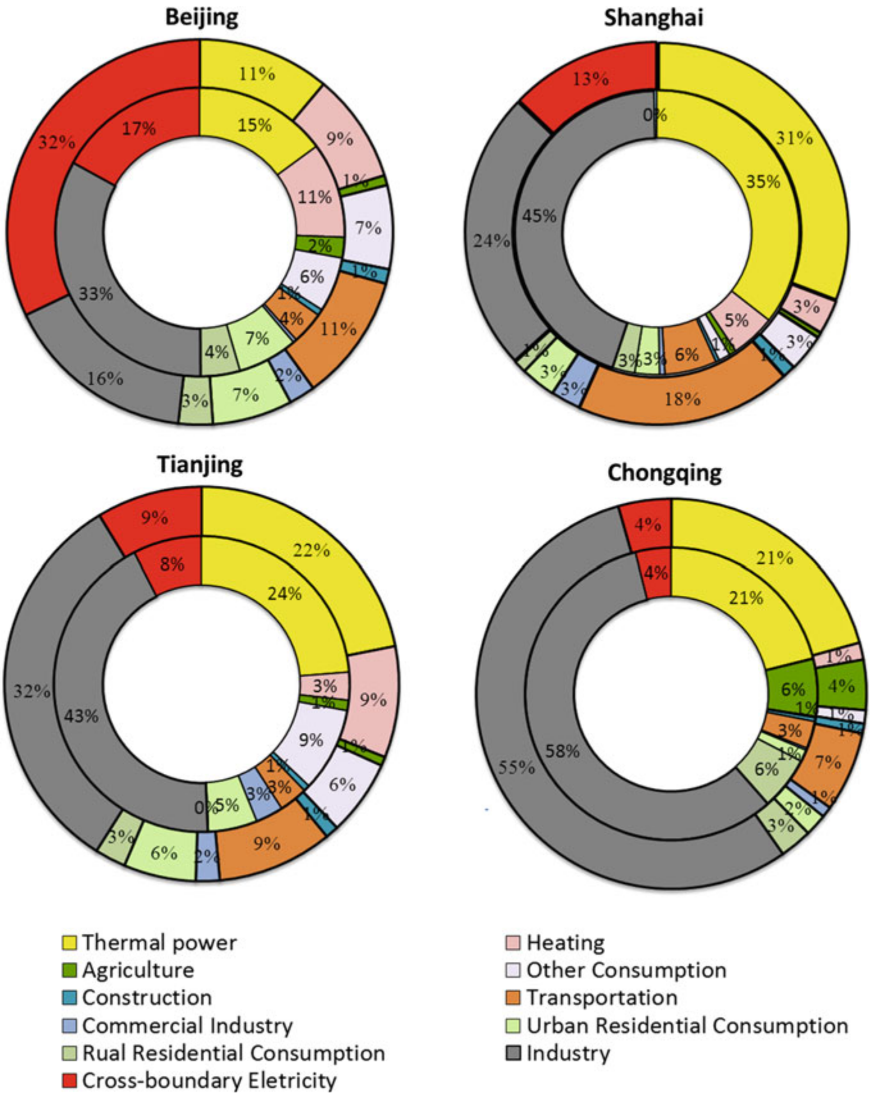

Fig. 2.12 CO_2 emission from different sectors (*inner* year 1995; *external* year 2009)

external electricity purchase (scope 2 emission) represents a large proportion of the total emission and experienced an accelerating increase. For example, emission from external electricity purchase in Beijing accounted for 17 % of the total emission, and the figure increased to 32 % (20 million tons) in 2009. There was no external electricity purchase in Shanghai in 1995, while the proportion rose to 13 % in 2009. The percentage of external electricity in Tianjin and Chongqing was minimal, with 9 and 4 % for Tianjin and Chongqing, respectively. It is manifested that the proportion of scope 2 emission represents the developing and urbanization level of a city to some extent.

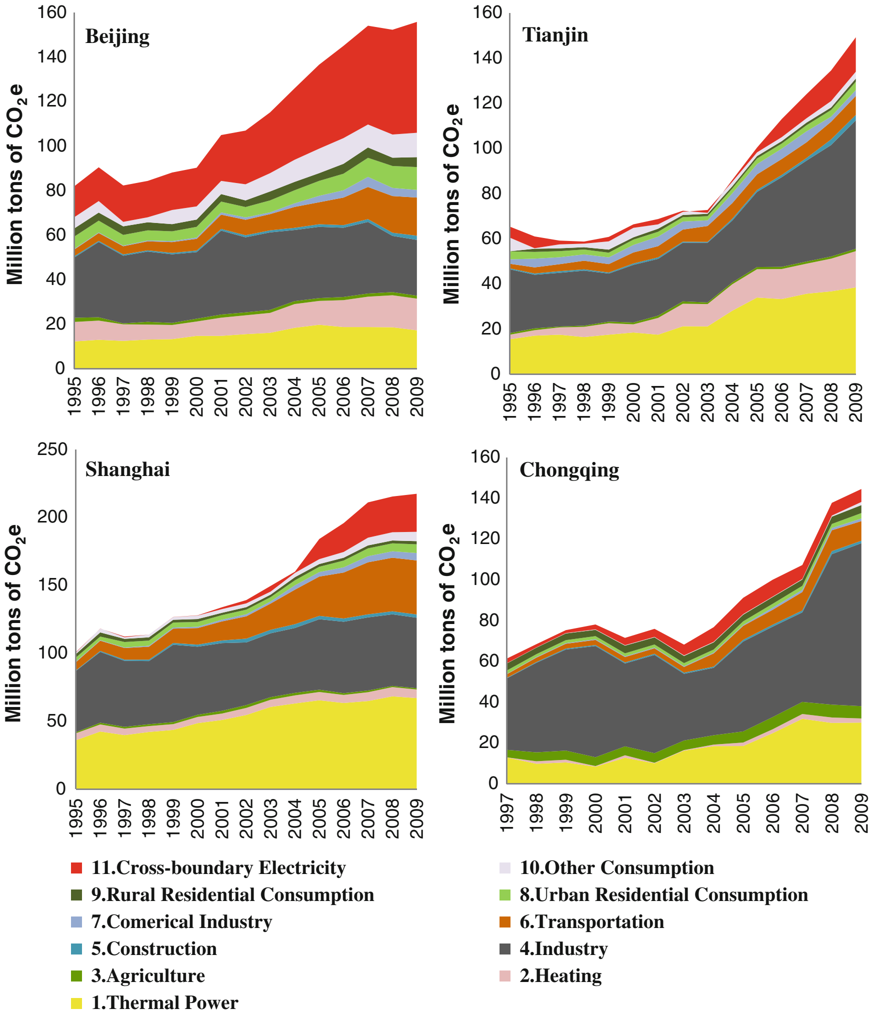

Fig. 2.13 Trajectory of GHG emission from Beijing, Tianjin, Shanghai, and Chongqing (1995–2009)

Apart from the external electricity purchase sector, industries and transportation are two other sectors whose carbon emission increased the most rapidly. The average increase in emission from industries has doubled over the period. Carbon emission from transportation increased from 4 % in 1995 to 32 % in 2009 for Beijing, 1 to 9 % for Tianjin, 6 to 18 % for Shanghai, and 3 to 7 % for Chongqing.

The carbon emission per capita is 8.9 tons, 12.2 tons, 11.3 tons, and 5.1 tons for Beijing, Tianjin, Shanghai, and Chongqing, respectively. The average carbon emission of Beijing, Tianjin, and Shanghai is similar to cities in developed countries, while the emission per capita is lower in Chongqing. As the urbanization level in Beijing and Shanghai has reached 80 %, while Chongqing is only 30 %, the average emission can reveal the economic development level to some extent.

Under the rocketing urbanization process, a great amount of population will surge to urban areas in the following decades. With increasing life quality and the development of infrastructure, the municipal carbon emission in China will further increase. Regions with similar carbon emission quantities as cities of developed countries could be key areas to implement energy conservation and emission reduction strategies.

From per capita point of view, the per capita carbon emissions in Tianjin, Shanghai and Beijing are among at the average international level (Fig. 2.14), while such a figure in Chongqing (5.1 tons of CO_2 per capita) is still low, indicating a potential increasing emission due to their further urbanization initiatives and improvements of citizens' living standards.

The scope 2 emissions from imported electricity use play a significant role in the evolution of the carbon emissions during 1995–2009. Beijing and Shanghai reversed their growth trends of carbon emissions when considering the indirect carbon emissions from imported electricity use since 2004. Besides, the proportion

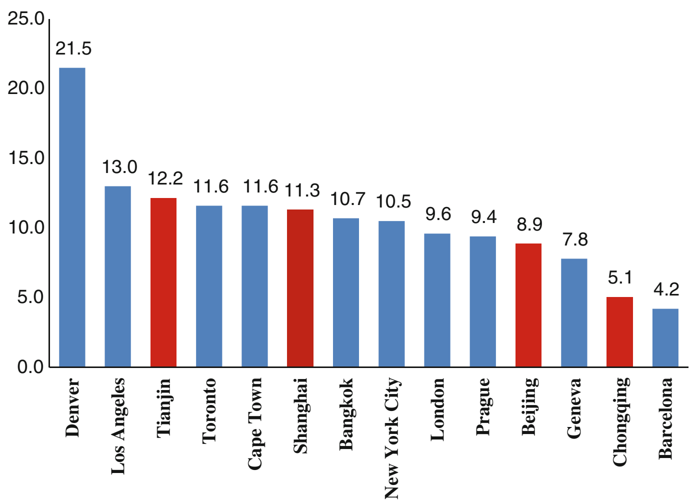

Fig. 2.14 Per capita CO_2 emission for global cities (tCO_2 per capita)

of carbon emissions from cross-boundary electricity keeps growing with city's development. It implies that with city's further development and industrial structure changes (such as more dependence on service-oriented industries), cross-boundary activities will further strengthen, and such cities will further rely on products, energy supply, and material supply from other regions.

2.6.3 Carbon Emissions from 150 Chinese Cities

We found the total carbon emissions from 150 Chinese cities (this is the number of cities for which the emissions data are available) are about 6,006 Mt CO_2 in 2010, which is higher than total emissions from the USA (the second largest emitter) and which accounts for 70 % of China's total carbon emissions. The per capita emissions show the significant variations of Chinese cities. The CO_2 emissions per capita in some Chinese cities are even higher than those of cities in developed countries. For example, the emissions in Tangshan city (in Hebei province), Suzhou city (in Jiangsu Province), Baotou city (in Inner Mongolia), and Zibo City (in Shandong province) are more than 20t CO_2 per capita—not surprisingly, these cities are important resource bases or manufacturing bases for China. However, in general, the per capita emissions in Chinese cities (about 7.5 t CO_2 emissions per capita) are much lower than the cities of developed countries and are approaching the level of global average. The emissions per capita in rural China are much lower than the emissions per capita in urban areas, mainly due to the less-developed infrastructure and a lower standard of living conditions in rural China (Fig. 2.15).

Fig. 2.15 CO_2 emissions in 150 largest Chinese cities in 2012

2.7 Summary

This Chapter compiled the national, provincial, and city's carbon emission inventories, based on the national and provincial Energy Balance Sheet, sectorial energy consumption, and Chinese emission factor by the internationally recognized greenhouse gas inventory compilation method. The national energy-related carbon emission more than doubled from 1990s to 2010s. There was a gradual increase during 1995 and 2001, while the increase has been faster since 2002. Among all fuel types, coal is the major contributor to carbon emission increase. Among all sectors, thermal electricity generation and industries make the greatest contribution, accounting for over 80 % of the total increase.

This chapter also calculated the scope 2 carbon emission of four Chinese municipalities (Beijing, Tianjin, Shanghai, and Chongqing) from 1995 to 2009 and compared the results to scope 1 emission and the per capita emission from other international cities. Because of "urban metabolism," urban areas consume more electricity and commodities from external sources. Scope 2 emission resulting from external purchase of electricity is more significant in more developed municipalities. For example, emissions from external electricity purchase account for 25 % of the total emission in Beijing and Shanghai. Moreover, due to the adjustment of economic structure and the change in heavy industry location, the scope 1 emission of municipalities gradually reaches a plateau or even decline. For instance, the scope 1 energy-related carbon emission of Beijing and Shanghai has decreased since 2008.

This chapter is an indispensible part of the whole research, as it provides strong data basis for the follow-up studies.

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Chapter 3
Carbon Emissions from Regions and Sectors

3.1 Characteristics of China's Regional Carbon Emissions

China is a country with significant regional differences in terms of technology, energy mix, and economic development [1]. The distribution of carbon emissions varies among the 30 mainland provinces (Figs. 3.1, 3.2, 3.3, 3.4 and 3.5). In 2012, the total carbon emissions were mainly contributed by the eastern coastal regions such as Shandong and Zhejiang and by the energy-based provinces such as Inner Mongolia and Shanxi. The provinces such as Inner Mongolia, rich in fossil resources, have experienced a sevenfold increase in CO_2 emissions since 2000. The emissions increment is also very significant for the other fossil-rich provinces [2]. The total emissions from several of the major provinces are already larger than the emissions from certain developed countries. For example, if Shandong were to be considered as a single country, it would be listed as one of the world's top 5 countries with a high level of total carbon emissions (more than 800 Mt CO_2 per year).

This high level of total emissions can be a result of the high population intensity and the living standard of the population. However, the CO_2 emissions per capita for the provinces (Fig. 3.1) show a different pattern when compared with the GDP per capita for the provinces. In general, the developed regions have a high level of GDP per capita, such as Beijing, Shanghai (Beijing and Shanghai are municipalities with administrative level equal to provinces), and Zhejiang provinces. In comparison, several of China's underdeveloped regions have a high level of per capita CO_2 emissions, for example, the per capita emissions in Ningxia and Inner Mongolia are much higher than in the other provinces, and are even higher than the level in the developed countries such as the USA, the UK, and Japan. For example, the per capita emissions in Ningxia alone are approaching 20 t CO_2/person, which is higher than the US average and almost three times higher than the E.U. average.

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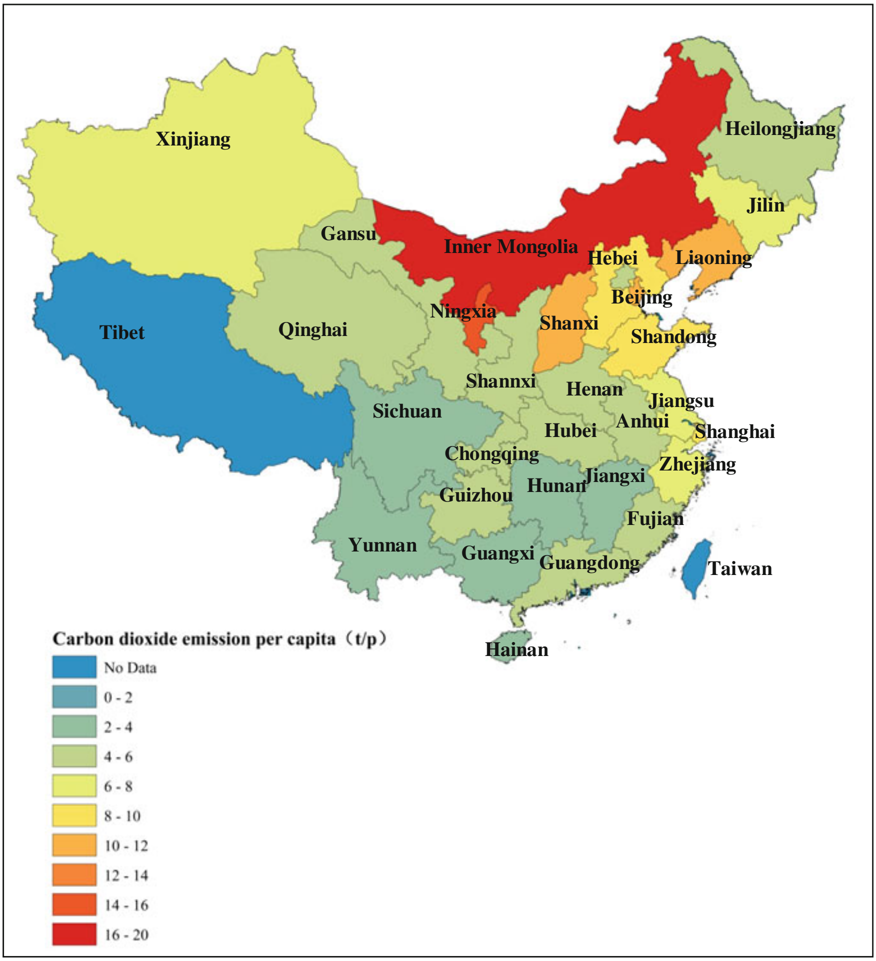

Fig. 3.1 CO_2 emissions per capita in 2012

The high levels of per capita CO_2 emissions in these underdeveloped regions can be explained by two factors: First, these regions serve as energy and resource bases which provide the electricity and industrial materials that have been consumed in other regions. For example, more than one-third of the power generated by Inner Mongolia is exported to other provinces, and the economic value of Inner Mongolia's total export to other provinces is equivalent to about 50 % of the GDP produced by Inner Mongolia [3, 4]. In comparison, the developed regions are mainly the consumers and the importers of the electricity and products that are

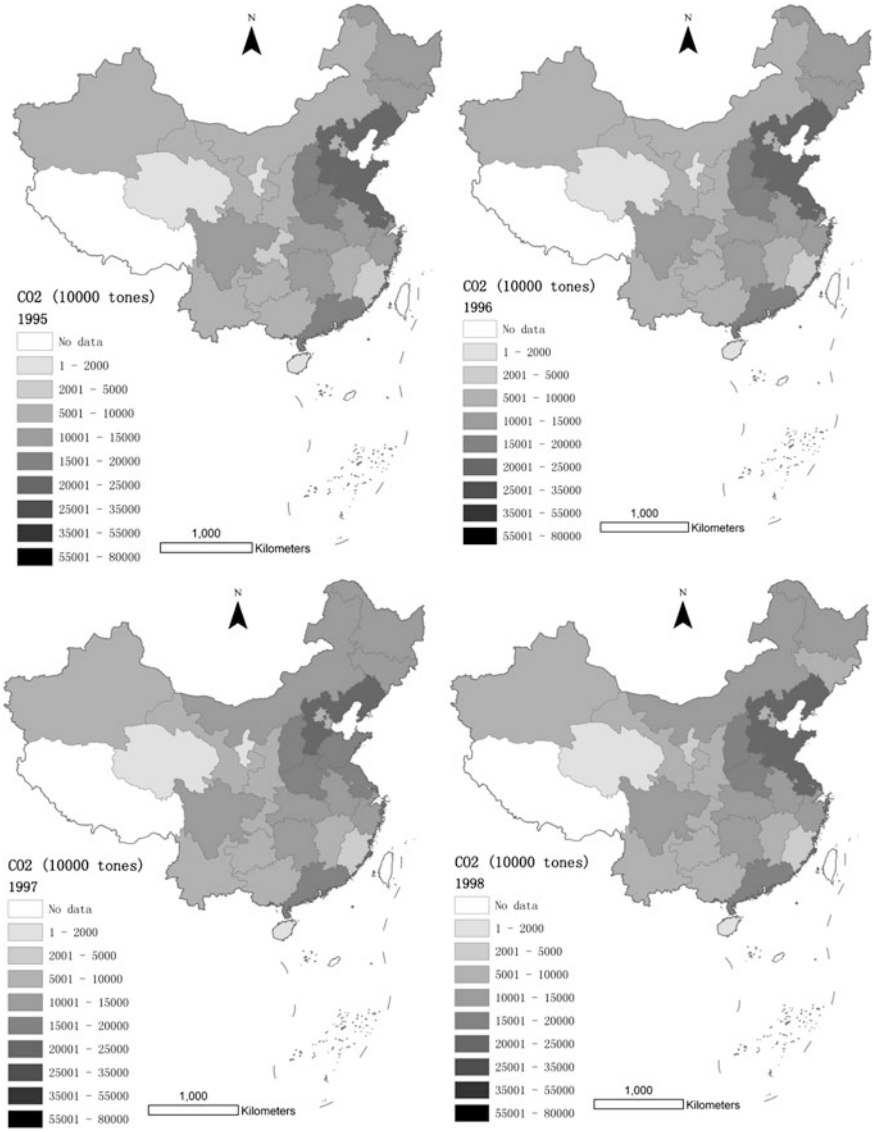

Fig. 3.2 China provincial carbon emissions during 1995–1998

supplied by underdeveloped regions, for example, one-third of Beijing's electricity supply is generated by neighboring regions around Beijing. Second, the carbon intensity of these underdeveloped regions is much higher than that of the developed regions, for example, the carbon intensity of Inner Mongolia, Shanxi, and Ningxia is more than 5 times that of Beijing.

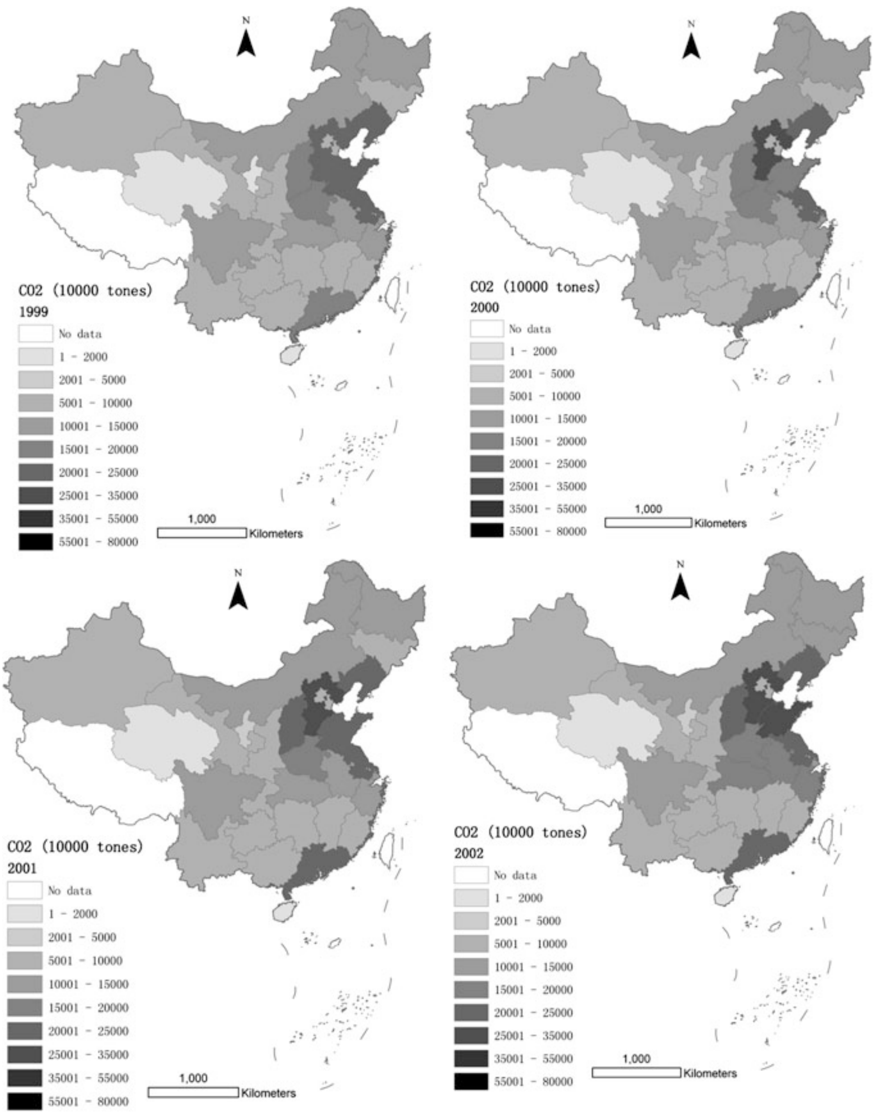

Fig. 3.3 China provincial carbon emissions during 1999–2002

3.2 The Spatial Autocorrelation of China's Carbon Emissions

The spatial distribution pattern is a crucial factor to evaluate environmental, social, and economic development. The spatial distribution attributes include the location, quantity, density, and autocorrelation of a spatial unit. According to Tobler's first

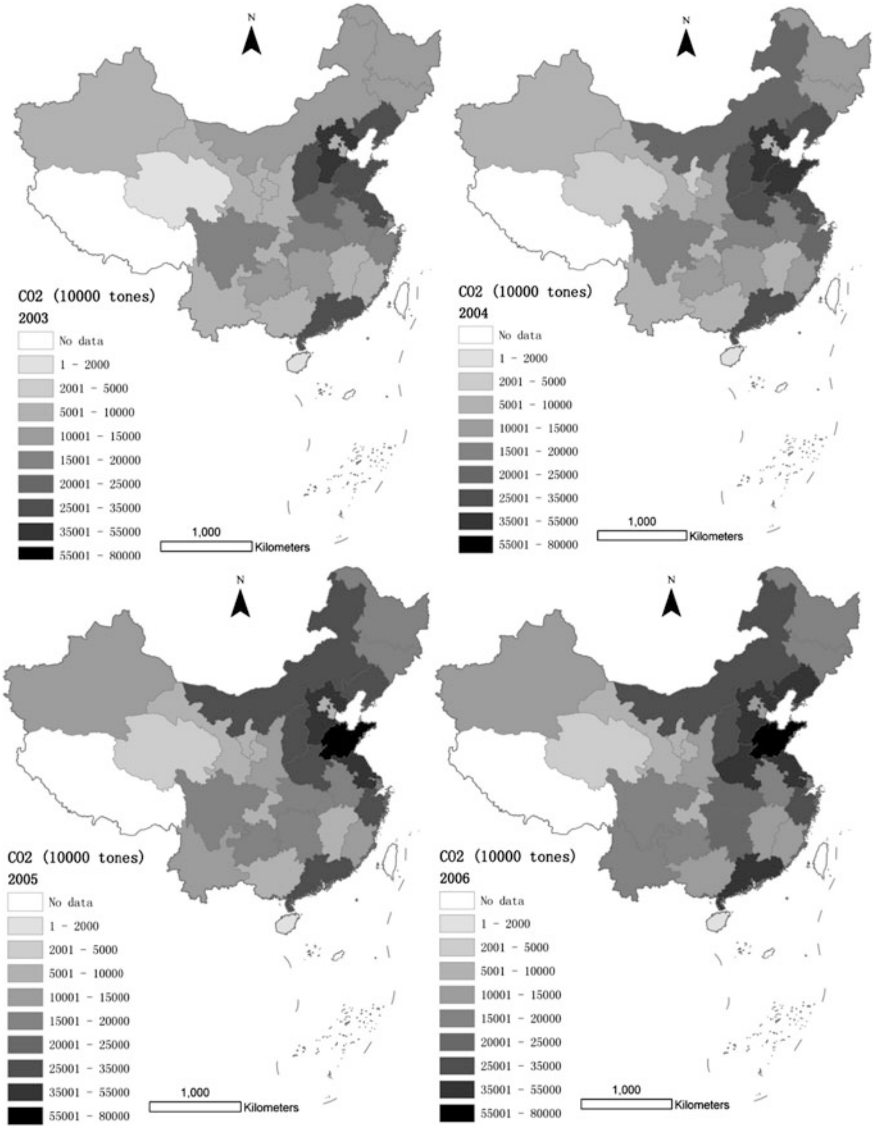

Fig. 3.4 China provincial carbon emissions during 2003–2006

law of geography, all attribute values on a geographic surface are related to each other. As the spatial autocorrelation describes the discreteness of a spatial variable, it is often used to analyze and quantify the spatial distribution, and is crucial to regional economic and environmental change studies. However, there is lack of studies to quantify the spatial distribution of China's regional energy-related carbon emission,

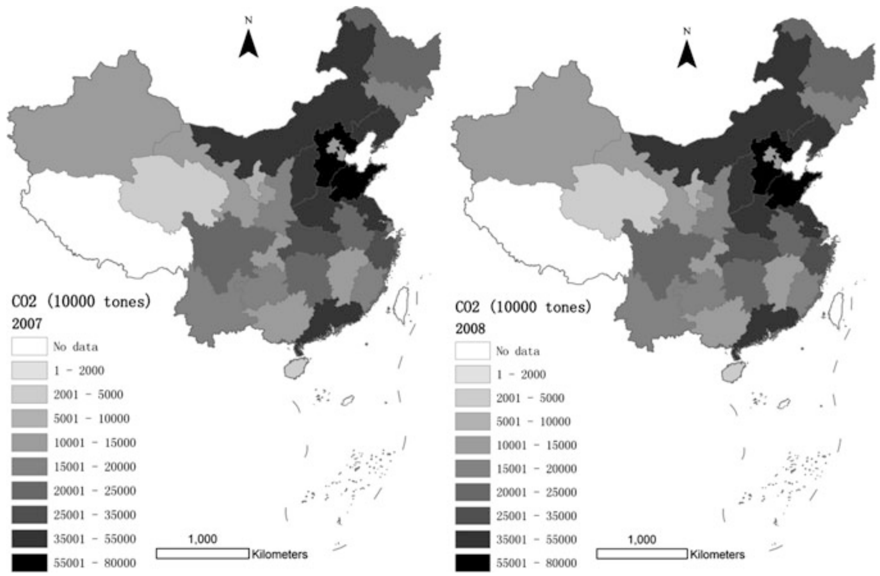

Fig. 3.5 China provincial carbon emissions during 2007–2008

due to unsound regional carbon emission inventories. Chapter 2 has compiled a detailed carbon emission inventory, which provides data for relevant studies.

3.2.1 Methodology—Spatial Autocorrelation

Spatial autocorrelation measures the degree of dependency among observation units in a geographic space. The spatial autocorrelation statistics transform the observation values to binary symmetric spatial weights matrix W to reflect the geographic relationships between n locations:

$$W = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ w_{n1} & w_{n2} & \cdots & w_{nn} \end{bmatrix} \tag{3.1}$$

The spatial weights matrix Wij represents the intensity of geographic relationship between region i and j. Since the spatial attribute (energy-related carbon emission) in this study is a single value, and the space of each province is different with irregular shape, the adjacency rule is adopted.

$$w_{ij} = \begin{cases} 1 & \text{When } i \text{ and } j \text{ are spatially linked} \\ 0 & \text{Others} \end{cases} \quad (3.2)$$

The spatial correlation index represents the degree of geographical relationship by a dimensionless value. Moran I index is used in this study:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (3.3)$$

I: Moran I index
x_i: Attribute value of region i, represented by the energy-related carbon emission

The value of Moran I index ranges [–1, 1], with negative numbers for discreteness, positive number for aggregate, and zero for randomness. Moran I index can be further standardized as statistical value Z to test the spatial autocorrelation between n regions.

$$Z = \frac{I - E(I)}{\sqrt{\mathrm{VAR}(I)}} \quad (3.4)$$

Z: standardized statistical value
$E(I)$: expectation of Moran I index
$\mathrm{VAR}(I)$: variance

Positive and notable Z value indicates the positive spatial autocorrelation, represented by the aggregate of similar observational values (high or low). Negative and notable Z value indicated the negative spatial autocorrelation, represented by the discreteness of similar observational values. Zero indicates random distribution of the observations (Getis and Ord 2010).

3.2.2 Results

ArcGIS is used for analyzing Z value. Regions with high Z value are significant energy-related carbon emitters, and the surrounding areas are important contributors as well. On the contrary, regions with low Z value indicate that there is no special relation between it and the surrounding areas.

Due to low resolution, the provincial carbon inventories cannot fully depict the temporal and spatial changes in carbon emission. Therefore, the temporal and spatial extension method is applied to estimate municipal carbon emission based on the GDP ratio.

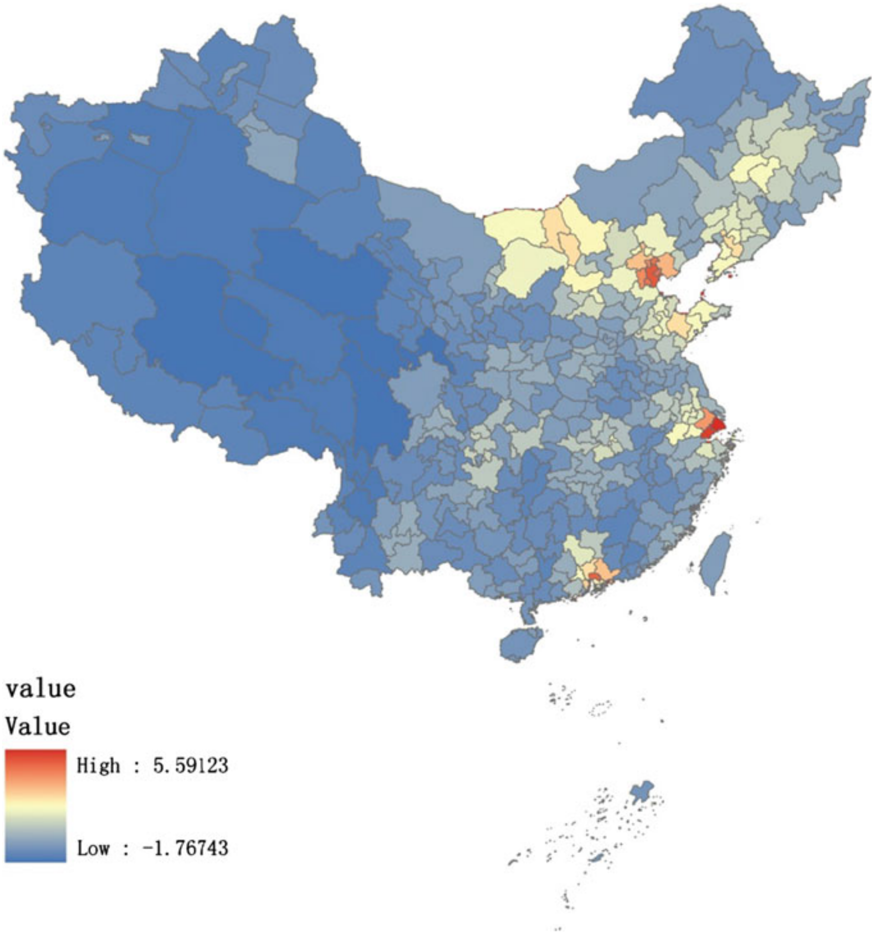

Fig. 3.6 *Z* value of China city carbon emissions in 2008

Figure 3.6 shows the *Z* value of Moran *I* index distribution in 2008 by temporal and spatial extension method. It is indicated that Jing-Jin-Tang, Pearl River Delta, and Yangtze River Delta are industrial centers with highest *Z* values, which are also China's carbon emission hotpots.

3.3 Carbon Emissions from Sectors

The national energy-related carbon emission inventory at sectorial level is shown in Table 3.1. It is clear that heavy industries such as mining, petroleum refining, and smelting, chemical ingredients and manufacturing, non-metal producing, black

Table 3.1 China sectoral emission inventory in 2008

	Emissions(Mt CO_2)
Agriculture	64.84
Mining industry	319.10
Oil and gas processing industry	38.26
Non-ferrous metal mining and dressing industry	8.48
Ferrous metals mining and dressing	2.76
Non-metallic mining and dressing industry	13.38
Other mining and dressing industry	0.08
Timber and mining transport industry	0.00
Food processing industry	30.41
Food production industry	20.26
Beverage industry	15.66
Tobacco industry	1.97
Textile industry	46.71
Clothing and other fiber products industry	5.84
Leather, fur, feather, and related products	2.64
Wood processing and products	8.22
Furniture manufacturing	1.28
Paper and paper products industry	66.41
Printing, reproduction of recording media	1.69
Cultural, educational, and sporting goods manufacturing industry	1.29
Petroleum processing and coking industry	490.14
Chemical materials and chemical products manufacturing	478.84
Pharmaceutical manufacturing	14.10
Chemical fiber manufacturing industry	15.39
Rubber production	9.45
Plastic products industry	8.56
Non-metallic mineral products industry	1189.89
Ferrous metal smelting and rolling industry	1478.40
Non-ferrous metal smelting and rolling industry	90.20
Fabricated metal products	13.23
Ordinary machinery	28.32
Special equipment manufacturing	18.06
Transportation equipment manufacturing	26.94
Electrical machinery and equipment manufacturing	8.40
Electronic and communication equipment manufacturing	8.60
Instrumentation and culture, office machinery manufacturing	1.24
Other manufacturing	10.08
Electricity, steam, hot water production, and supply industry	2486.05
Production and supply	26.47

(continued)

Table 3.1 (continued)

	Emissions(Mt CO_2)
Tap water production and supply	0.86
Building industry	29.39
Transport, storage, and communications sector	426.30
Wholesale, retail trade, and catering	42.74
Other tertiary industry	102.75
Consumption of urban residents	150.96
Consumption of rural residents	125.20

metal smelting, color metal smelting, and the production and supply of heat, steam, and hot water accounted for over 80 % of the total emission. Using the same approach, this study compiled a detailed energy-related carbon emission inventory for 46 industrial sectors of 30 provinces in 2008.

The provincial distribution pattern (Fig. 3.7) of carbon emission among different sectors is similar to that of national pattern. Energy supply (power and heat) is the largest contributor to total emission, followed by metal and non-metal manufacturing, and metal processing. The combined contribution of three aforementioned sectors accounts for more than 70 % of the total emission in most provinces (Fig. 3.8).

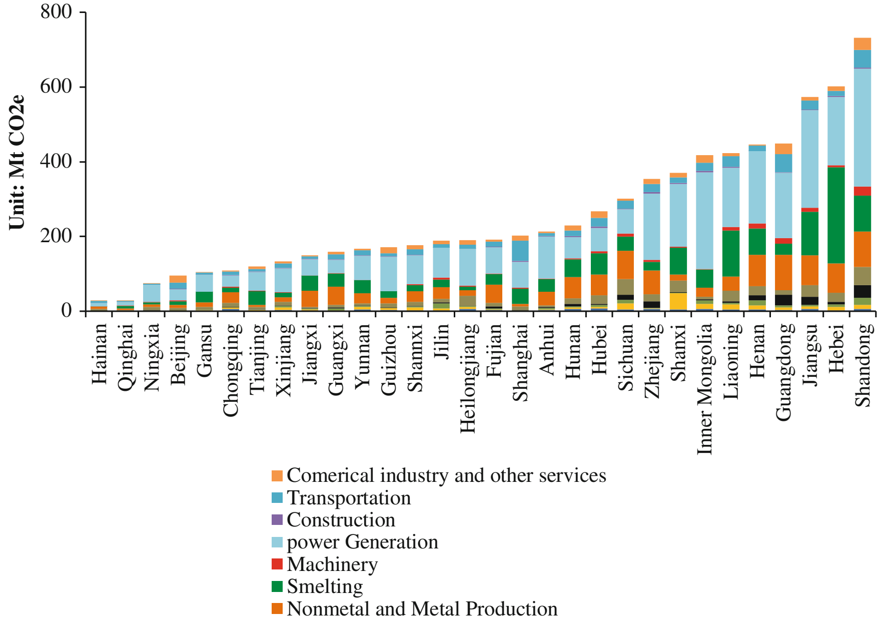

Fig. 3.7 China provincial sectorial carbon emissions in 2008

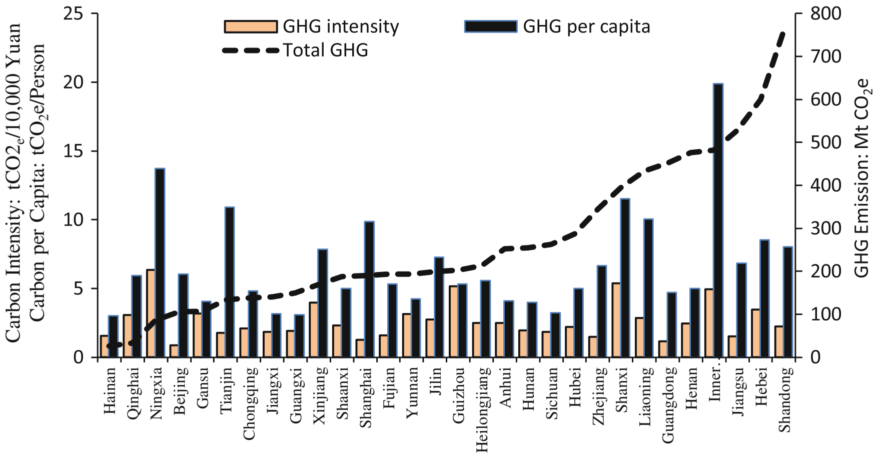

Fig. 3.8 Carbon emission intensity, per capita emission, and total emission in China provinces in 2009

3.3.1 Carbon Intensity for Sectors

The emission intensity is the carbon emission per gross domestic product (GDP). Sectorial GDP contribution is obtained from China Statistical Yearbook and China Economic Census Yearbook (price converted to constant prices using the base year producer price). As the energy consumption sectors did not match the GDP producing sectors, they are adjusted and recombined into 28 carbon emission contributors (Table 3.2).

Apparently, huge disparities exist among the provincial distribution of total emission, emission intensity, and per capita emission. Developed eastern coastal regions (such as Guangdong, Zhejiang, and Jiangsu) have higher total emissions and per capita emissions, but with relatively lower emission intensity. Those middle-leveled regions (such as Hebei, Inner Mongolia, and Shanxi) have both higher total emissions and emission intensity because their economic activities are dominated by intensive resource mining (primary energy) and other heavy industries. Those least developed Western regions (such as Qinghai and Ningxia) have lower total carbon emissions, but higher per capita emissions and emission intensity.

By grouping 28 sectors into 12 industries, results show that “non-metal and metal production,” “smelting and machinery,” and “power generation” sectors are three main contributors for total carbon emission. Particularly, provinces located within industrial clusters (such as Shandong and Hebei) have higher proportion of carbon emission from manufacturing-related sectors, especially from the sector of “non-metal and metal production” and sector of “smelting.” Both Shanxi and Inner Mongolia are energy source-rich areas (especially coal) and have provided a large amount of electricity to their neighboring provinces, thus having higher proportions of carbon emission from power generation sector.

Table 3.2 Sectoral classification for carbon emission inventories

Level 1	Level 2	Level 3 (sector code + sector name)
Agriculture	Agriculture	1. Agriculture
Manufacturing	Mining	2. Coal mining and dressing
		3. Petroleum and natural gas extraction
		4. Metals mining
		5. Non-metal mining
	Food production	6. Food, drinks and tobacco
	Textile, paper, and wood industry	7. Textile industry
		8. Wearing
		9. Forest industry
		10. Papers
	Petroleum and chemical industry	11. Petroleum processing and coking
		12. Chemicals
	Non-metal and metal production	13. Non-metal mineral products
		14. Metal products
	Smelting	15. Smelting
	Machinery	16. Machinery
		17. Transportation equipment
		18. Electric equipment and machinery
		19. Electronic and telecommunications equipment
		20. Instruments, meters, cultural, and office machinery
		21. Other manufacturing industry
	Power generation	22. Production and supply of electric power, steam, and hot water
		23. Production and supply of gas
		24. Production and supply of tap water
Construction	Construction	25. Construction
Transportation	Transportation	26. Transportation, storage, post, and telecommunication services
Commercial industry	Commercial industry and other services	27. Wholesale, retail trade, and catering services
		28. Others

Most importantly, emission intensity illustrated significant disparity of technology level among regions (Table 3.3). The emission intensity in underdeveloped regions is much higher than that in more developed regions, especially in heavy industries. For example, emission intensity of Chemistry (No. 12) production in Hainan is more than twenty times higher than that of in Beijing. Another case in

Table 3.3 Intensity of China provincial carbon emission inventories in 2009 (unit: t CO_2/10,000 RMB)

Sector No.	Anhui	Beijing	Chongqing	Fujian	Gansu	Guangdong	Guangxi	Guizhou	Hainan	Hebei	Heilongjiang	Henan	Hubei	Hunan
1	0.68	0.18	0.53	0.18	0.21	0.09	0.03	0.31	0.20	0.05	0.27	0.09	0.23	0.20
2	0.14	0.01	0.65	0.32	0.21	0.00	0.02	0.95	0.00	0.20	0.61	0.42	0.02	0.07
3	0.00	0.12	0.15	0.00	0.05	0.34	0.00	0.00	0.00	0.19	0.13	0.55	0.44	0.00
4	1.28	0.05	0.08	0.10	0.06	0.02	0.08	0.19	0.12	0.12	0.03	0.04	0.89	0.14
5	1.12	0.04	0.69	0.10	0.16	0.08	0.13	0.05	0.07	0.10	0.10	0.06	0.34	0.86
6	0.34	0.09	0.07	0.10	0.20	0.11	0.30	0.16	0.05	0.21	0.14	0.23	0.19	0.13
7	0.11	0.03	0.23	0.09	0.10	0.13	0.05	0.01	0.05	0.08	0.05	0.12	0.07	0.10
8	0.05	0.10	0.02	0.03	0.05	0.12	0.02	0.01	0.00	0.05	0.00	0.07	0.07	0.04
9	0.25	0.06	0.07	0.16	0.08	0.06	0.29	0.14	0.08	0.17	0.24	0.34	0.19	0.87
10	0.69	0.06	0.43	0.30	0.18	0.27	0.74	0.21	0.70	0.33	0.20	0.70	0.27	0.73
11	0.05	0.32	0.49	0.40	0.98	0.13	0.02	3.59	0.05	0.28	1.62	0.53	0.16	0.52
12	0.16	0.07	0.80	0.20	0.21	0.05	0.48	0.19	1.66	0.31	0.72	0.36	1.05	0.48
13	6.42	1.06	4.03	2.87	3.85	2.67	8.70	6.60	10.73	2.74	7.08	1.92	4.94	5.29
14	0.89	0.50	0.75	1.68	2.23	0.35	1.67	1.74	1.25	2.44	0.96	1.00	3.45	1.50
15	0.02	0.02	0.05	0.02	0.03	0.07	0.06	0.28	0.04	0.06	0.03	0.13	0.08	0.14
16	0.05	0.04	0.07	0.03	0.14	0.02	0.01	0.02	0.01	0.09	0.17	0.12	0.15	0.08
17	0.03	0.04	0.03	0.02	0.10	0.02	0.02	0.08	0.00	0.07	0.07	0.27	0.22	0.07
18	0.03	0.01	0.01	0.01	0.07	0.03	0.01	0.00	0.01	0.04	0.02	0.13	0.08	0.08
19	0.00	0.00	0.00	0.00	0.05	0.01	0.00	0.00	0.01	0.03	0.00	0.05	0.01	0.06
20	0.00	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.04	0.02	0.05	0.02	0.04
21	0.03	0.14	0.03	0.02	0.02	0.09	0.01	0.05	0.00	0.01	2.16	0.14	0.09	0.03
22	13.79	2.47	3.95	5.73	6.77	3.27	3.47	9.30	7.56	6.79	9.63	9.10	7.16	5.35
23	0.33	0.41	0.03	0.49	6.52	0.14	0.06	0.59	11.23	1.22	3.96	0.08	0.02	0.02
24	0.35	0.30	0.02	0.32	0.05	0.81	0.34	2.90	0.01	0.09	0.00	11.38	0.01	0.03
25	0.05	0.06	0.06	0.06	0.28	0.02	0.02	0.08	0.04	0.04	0.01	0.02	0.16	0.05
26	0.27	0.29	0.82	0.49	0.83	0.82	1.09	1.03	1.23	0.28	0.80	0.52	1.17	0.85
27	0.04	0.09	0.10	0.07	0.16	0.11	0.12	1.04	0.15	0.12	0.40	0.04	0.50	0.47
28	0.07	0.12	0.05	0.08	0.03	0.13	0.16	0.45	0.12	0.11	0.24	0.01	0.15	0.10

(continued)

Table 3.3 (continued)

Sector No.	Inner Mongolia	Jiangsu	Jiangxi	Jilin	Liaoning	Ningxia	Qinghai	Shandong	Shanghai	Shaanxi	Sichuan	Tianjin	Xinjiang	Yunnan
1	0.36	0.12	0.11	0.1	0.18	0.15	0.17	0.08	0.06	0.1	0.12	0.2	0.27	0.24
2	0.95	0.44	0.47	0.33	0.89	0.43	1.95	0.19	0	0.14	1.1	0	2.93	1.34
3	0.16	0.05	0	0.48	0.27	0	0	0.08	0	0.5	0.87	0.18	0.18	0
4	0.18	0.02	0.07	0.34	0.22	0	0.03	0.16	0	0.07	0.56	0	0.49	0.24
5	0.34	0.23	0.32	0.39	0.21	0.01	0.58	0.13	0	0.05	0.81	0.52	0.84	1.4
6	0.42	0.1	0.24	0.66	0.15	0.59	0.11	0.18	0.04	0.15	0.34	0.1	1.12	0.15
7	0.11	0.09	0.05	0.04	0.1	0.02	0.14	0.24	0.05	0.1	0.59	0.06	0.22	0.11
8	0.04	0.11	0.02	0.02	0.13	0.04	0	0.14	0.04	0.01	0.17	0.07	0.03	0.02
9	0.48	0.33	0.06	2.13	0.29	0.03	0	0.83	0.04	0.01	0.41	0.09	0.39	0.27
10	0.45	0.38	0.16	0.64	0.25	2.23	0.01	0.49	0.06	0.49	1.14	0.1	0.78	0.44
11	0.72	0.17	0.34	0.09	0.41	1.84	0.71	0.41	0.46	0.76	3.82	0.33	0.87	0.87
12	0.35	0.19	0.03	0.34	0.35	1.21	0.59	0.31	0.03	0.07	0.79	0.13	0.09	0.04
13	3.5	2.76	7.53	5.78	2.46	8.77	4.89	2.39	0.44	3.73	7.62	0.78	7.09	10.45
14	1.68	0.83	1.76	1.62	2.04	1.29	1.73	1.11	0.69	0.91	1.45	0.92	1.53	1.43
15	0.06	0.07	0.05	0.06	0.11	0.06	0.09	0.1	0.04	0.02	0.11	0.06	0.06	0.03
16	0.08	0.08	0.02	0.05	0.12	0.06	0.17	0.14	0.03	0.05	0.16	0.04	0.03	0.02
17	0.02	0.04	0.05	0.09	0.09	0	0	0.1	0.02	0.09	0.26	0.03	0.02	0.01
18	0.19	0.03	0.02	0.03	0.08	0.03	0.71	0.19	0.01	0.02	0.07	0.01	0.03	0.01
19	0	0	0.01	0.03	0.01	0	0	0.04	0	0.06	0.02	0	0.8	0
20	0	0.01	0.01	0.04	0.02	0.08	0	0.06	0	0.03	0.02	0	0.01	0.01
21	0.03	0.01	0.04	0.07	0.13	0	0.04	0.1	0.01	0.11	0.37	0.03	0	0.03
22	21.45	7.7	3.77	7.92	9.03	14.26	5.76	8.55	4.74	10.49	5.43	5.77	21.56	8.32
23	0.23	5.93	0.16	0.06	0.1	1.58	0.19	0.33	0.69	0.16	0.94	0.1	0.9	0.19

(continued)

Table 3.3 (continued)

Sector No.	Inner Mongolia	Jiangsu	Jiangxi	Jilin	Liaoning	Ningxia	Qinghai	Shandong	Shanghai	Shaanxi	Sichuan	Tianjin	Xinjiang	Yunnan
24	4.26	1.23	0.03	0.21	1.25	0	0	3.07	0.9	0.02	0.73	0.01	0.05	2.24
25	0.11	0.03	0.01	0.03	0.04	0.09	0.07	0.06	0.11	0.04	0.06	0.08	0.09	0.09
26	1.01	0.52	0.5	0.84	1.18	1.06	1.04	0.88	0.76	1.03	1.08	0.2	1.38	1.22
27	0.78	0.02	0.07	0.18	0.06	0.25	0.42	0.3	0.14	0.27	0.14	0.12	0.19	0.13
28	0.18	0.06	0.09	0.21	0.13	0.13	0.27	0.15	0.06	0.19	0.02	0.09	0.16	0.09

Inner Mongolia which is one of China's provinces concentrated with energy supply industries, the emission intensity of its electricity is about six times of that in Jiangxi province and five times of that in Shanghai. Similar pattern can be seen in other sectors, while underdeveloped provinces generally have much higher emission intensity for the industrial sectors.

Based on the 2008 China Economic Census Yearbook, we can compile the sectorial carbon emission intensity in 2008, and estimate the emission intensity data for 2009.

On comparison of the emission intensity and per capita emission of 30 provinces in 1997 and 2009, there was a dramatic increase in the per capita emission in Inner Mongolia, Shanxi, Ningxia, and Shandong. One major reason for this is that these regions rely heavily on energy engineering and manufacturing in developing process. The energy intensity of most provinces experienced a sharp decrease over the same period, especially more developed areas such as Beijing, Tianjin, and Shanghai. However, Shanxi, Inner Mongolia, Ningxia, and Xinjiang have experienced an increase in emission intensity by 2009. The low-value-added and emission-intensive developing path will result in enormous environmental impacts and resource pressure in these underdeveloped areas.

It is clear from Table 3.3 that thermal electricity generation and the traditional heavy industries are among the most significant contributors, with the emission intensity of thermal electricity generation reaching 20 t/10000 Yuan (GDP) at some provinces. There was a huge difference between provinces when conducting a comparative analysis. The emission intensity in underdeveloped areas is more significant than that in more developed areas, especially for carbon-intensive industries. For example, the emission intensity of thermal electricity generation in Inner Mongolia is six times larger than that in Shanxi and five times larger than that in Shanghai.

From sectorial perspective, non-metal manufacturing, metal pressing, and thermal electricity generation are industries with the highest carbon emission. Regionally, Shanxi and Inner Mongolia possess abundant coal resources and thus are the major energy supply sources. Therefore, the emission intensity in their energy sectors is significantly higher.

Guangdong, Zhejiang, and Jiangsu have higher total carbon emission, but with their larger GDP, their emission intensity is relatively low. Hebei, Inner Mongolia, and Shanxi have high total carbon emission and emission intensity simultaneously, as they rely heavily on energy industries and energy-intensive industries. The GDP of underdeveloped regions such as Qinghai and Ningxia are smaller. Although they have lower total carbon emission, the per capita emission and emission intensity are higher.

3.4 The Embodied Energy Consumption and Carbon Emissions from China's Industrial Sectors

It will be crucial to study how different industrial sectors use energy for their operations so that appropriate national regulations and standards can be enacted to promote energy-efficient production. Therefore, a comprehensive analysis of energy consumption is required, which should not only focus on the direct energy consumption activities but also consider the indirect activities potentially causing energy consumption throughout the whole supply chain, namely, the embodied energy consumption (direct plus indirect) perspective [5–7]. One sector's embodied energy consumption includes both energy consumption caused by final demand (direct energy consumption) and energy consumption caused by other sector's activities throughout the supply chain (indirect energy consumption) [8]. The embodied energy consumption provides a complete picture that not only considers the direct energy consumption primarily due to final demand but also identifies the drivers of the energy consumption and quantifies the amount of energy usage for which every sector is responsible [6, 9]. Hence, it is critical for policy makers to understand how embodied energy consumption occurs along the entire supply chain. This requires an integrated analysis so that an appropriate energy management policy for industrial sectors can be adopted.

In this section, the embodied energy consumption among China's 29 industry sectors was estimated by using an extended environmental input–output analysis. First, we selectively review the method of our input–output analysis. Then, we quantify and present the embodied energy consumption for 29 industrial sectors in China's economic system. Finally, we discuss the policy implications for sectoral energy conservation policy before drawing our conclusions.

3.4.1 Methodology—Environmental Extend Input–Output Model (EIO)

A comprehensive analysis of energy consumption in industry supply chains requires an appropriate method that does not only focus on the energy consumption due to final demand of one single industrial sector but also consider the use of energy in intermediate production processes by other industrial sectors that are included in the supply chain. The standard Leontief input–output (I–O) model has been extended to the so-called environmental extend input–output model (EIO) to capture energy consumption flows in the economy [9, 10]. EIO describes the energy consumption required to produce a unit of economic output (goods and services) driven by final demand. This tool allows the calculation of the direct energy consumption by a sector's final demand as well as all indirect energy consumption from other sectors within the same supply chain [11, 12]. This "top–down" approach for assessing environmental impacts of the whole economy has been widely applied for national energy analyses after the energy crisis in the early 1970s [9, 13, 14]. Interactions between economic activities, the associated direct and indirect energy consumption, and related environmental impacts can be explicitly determined by the input–output relationship described by Leontief and its extension to cover environmental impacts, e.g., [11, 15–20]. The input–output analysis has been extended to cover interregional and international trade in multi-regional input–output models (MRIO) [9, 13, 21–23]; this type of model has been used to analyze international embodied energy consumption and related CO_2 emissions inventories in the context of the Kyoto Protocol from the perspective of either consumers of goods and services or producers. For a single system boundary, energy consumption associated with the production process comprises the production entity (the production energy consumption) and the total energy consumption in its production activity (the embodied energy consumption). Several scholars have conducted their studies of embodied energy consumption in production activities in China. For example, Lin and Polenske explained energy consumption changes between 1981 and 1987 in China by analyzing effective changes in the production technologies as well as the final demand shift on the consumer side [14]. Liu et al. [24] conducted an energy input–output analysis in China to evaluate the indirect energy consumption of rural and urban households and studied how energy policies influenced final prices; they concluded that energy efficiency improvements not only served as a means to reach energy conservation goals but also had a positive impact on household income. Another example of studying the embodied energy in the supply chain of one single sector is the Polenske and McMichael analysis of the environmental impacts of the coke-making process in China by using an input–output process model [25]; they discovered changes in the production technology of the supplying sectors and the subsequent impacts. Similar studies were also conducted by Liang et al. [26].

This study used the most recently available input–output tables (2007) and constructed the EIO model to reveal China's sectoral embodied energy consumption; the study focuses on China's sectoral direct and indirect energy consumption and considers the related policy implications for energy conservation and efficiency in the national 5-Year Plan.

The EIO model captures the energy consumption of each economic sector from supply chain perspectives. The total output of one economy is expressed:

$$X = Z + y = AX + y \tag{3.5}$$

X represents total economic output, which can be expressed as a vector; Z represents the intermediate demand matrix; y represents the final demand vector, including the components of "rural and urban households consumption," "government consumption," "gross capital formation," "export," and "others", and A represents the economy's direct demand matrix. Matrix A describes the relationship between all sectors of the economy. Assuming that $(I - A)$ is non-singular, then the total economic output vector X can be expressed by Eq. (3.6):

$$X = (I - A)^{-1} y \tag{3.6}$$

I represents the identity matrix, $(I - A)^{-1}$ is the Leontief inverse. Equation (3.2) illustrates the gross output needed to satisfy both the final consumption "y" and the corresponding intermediate consumption "$(I - A)^{-1}$" from each economic sector.

The EIO method combines the economic IO model with sectoral environmental impacts by multiplying the total economic output by each sector's energy intensity (energy consumption per unit economic output from each sector i). The total (both direct and indirect) energy consumption can be expressed by Eq. (3.7):

$$E = FX = Fy + FAy + FA^2y + FA^3y + FA^4y\ldots = F(I - A)^{-1}y \tag{3.7}$$

E represents the matrix of the total embodied energy consumption; F represents the factor vector of the energy intensity for each sector. Fy is the direct energy consumption due to final demand, FAy is the first round of indirect energy consumption due to intermediate industrial activities. FA^2y, FA^3y, FA^4y... (infinite recursive reduction series of FA^jy) are the second, third, fourth,… round indirect energy consumption of intermediate activates. F can be calculated by Eq. (3.8):

$$F_i = D_i/X_i \tag{3.8}$$

F_i represents the intensity factor of sector i; D_i represents the production energy consumption for sector i; X_i represents the total economic output from sector i.

In this study, we adopted the most recently available input–output table, namely the one for the year of 2007 [27], covering 42 economic sectors in total. Production energy consumption data from each sector were extracted from the Chinese Energy Statistics Year Book (CESYB) [28]. The input–output table is available at 42 industrial sectors details, while the energy consumption data have 29 sectors. We aggregate the 42 economic sectors into 29 sectors to keep the two datasets consistent. Table 3.4 presents the 29 sectors classification and more aggregated sector group. This classification principle has been widely used in IO-based energy and carbon footprint research in China [29–31]. Based on Eq. (3.5), A is a matrix with 29*29 elements, Y^ is a diagonal matrix with the values of final energy demand along its diagonal, F is a column vector with energy intensity data of 29 sectors.

3.4.2 Results of Embodied Energy Consumption

Figure 3.9 depicts the comparison results between production-based energy consumption and embodied energy consumption for 6 industrial groups, and Fig. 3.10 depicts the comparison results for 29 economic sectors.

In this study, a system boundary was chosen according to China's territorial boundary, and energy embodied in imports was not included (excluded in the final

Table 3.4 Sectors classification

Group code	Group	Sectoral code	Sector
A	Agriculture	1	Farming, forestry, animal husbandry, fishery, and water conservancy
B	Mining	2	Coal mining and dressing
		3	Petroleum and natural gas extraction
		4	Ferrous metals mining and dressing
		5	Other metals mining and dressing
C	Manufacturing	6	Food processing, food production, beverage production, tobacco processing
		7	Textile
		8	Garments and other fiber production, leather, furs, down, and related production
		9	Timber processing, bamboo, cane, palm and straw production, furniture manufacturing
		10	Paper printing and educational and sports goods production
		11	Petroleum processing and coking, gas production, and supply
		12	Raw chemical materials and chemical production, medical and pharmaceutical production, chemical fiber, rubber production, plastic production
		13	Non-metal mineral production
		14	Smelting and pressing of ferrous and non-ferrous metals
		15	Metal products
		16	Ordinary and special equipment
		17	Transportation equipment
		18	Electric equipment and machinery
		19	Electronic and telecommunications equipment
		20	Instruments, meters, cultural, and office machinery
		21	Other industrial activities
		22	Waste production
D	Power and heating supply	23	Electricity power/heating supply
		24	Gas-fire supply
		25	Hot water production and supply
E	Construction	26	Construction
F	Tertiary industry (service)	27	Transport, storage, postal, and telecommunications services
		28	Wholesale, retail trade, hotels, catering service
		29	Other service activities

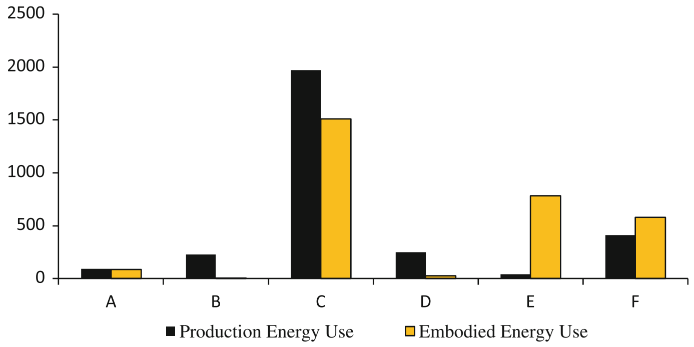

Fig. 3.9 Production-based energy consumption (extracted from the CESYB) and embodied energy consumption (calculated by the EIO model) from 6 sector groups (Units: Mt SCE)

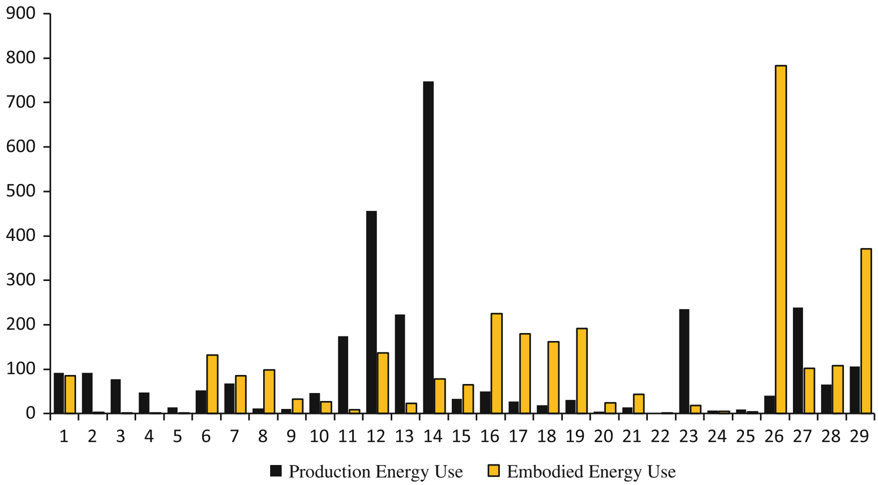

Fig. 3.10 Production-based energy consumption and embodied energy consumption for 29 economic sectors (Units: Mt SCE)

demand Y); thus, the sum of all sector's production-based energy consumption and the sum of their embodied energy consumption are equal. The embodied energy consumption for each sector was the energy consumption reallocated through this sector's supply chain; thus, significant differences exist between production-based energy consumption and embodied energy consumption for 6 groups and 29 sectors. From Fig. 3.9, it is very clear that the "Manufacturing" (Group C) industry was the main contributor to total production-based energy consumption, while "Manufacturing" (Group C), "Construction" (Group E), and "Service Industry" (Group F) were the three main contributors to total embodied energy consumption.

Particularly, the "Manufacturing" (Group C) industry dominated both production-based energy consumption and embodied energy consumption, accounting for 65.8 % of the total amount of production-based energy consumption and 50.4 % of total amount of embodied energy consumption.

With respect to the 29 economic sectors (Fig. 3.10), the sectors of "Petroleum Processing and Coking, Gas Production and Supply" (No. 11), "Raw Chemical Materials and Chemical Production, Medical and Pharmaceutical Production, Chemical Fiber, Rubber Production, Plastic Production" (No. 12), "Nonmetal Mineral Production" (No. 13), "Smelting and Pressing of Ferrous and Nonferrous Metals" (No. 14), "Electricity Power/Heating Supply" (No. 23), and "Transport, Storage, Postal and Telecommunications Services" (No. 27) are the greatest contributors to the total production-based energy consumptions, accounting for 70 % of the total production-based energy consumption. Each of these sectors accounts for 5.8, 15.3, 7.55, 25.0, 7.9, and 8.0 % of total production-based energy consumption, respectively. Meanwhile, the sector of "Construction" (No. 26) is the largest contributor of the total embodied energy consumption (26.1 %), followed by "Other Service Activities" (No. 29) (12.4 %), "Ordinary and Special Equipment" (No. 16) (7.5 %), "Electronic and Telecommunications Equipment" (No. 19) (6.4 %), "Transportation Equipment" (No. 17) (6.0 %), and "Electric Equipment and Machinery" (No. 18) (5.4 %).

Embodied energy consumption from 29 sectors further decomposed into direct energy consumption and indirect energy consumption (Fig. 3.11).

The results indicated that indirect energy consumption accounts for 80 % of the total embodied energy consumption. Particularly, the "Construction" sector has the largest amount of embodied energy consumption, with approximately 95 % of its embodied energy consumption allocated into indirect energy consumption.

To further explore the energy consumption features of typical economic sectors, three sectors were chosen for more a detailed analysis of embodied energy consumption. Based on Eq. (3.3), the embodied energy consumptions of the

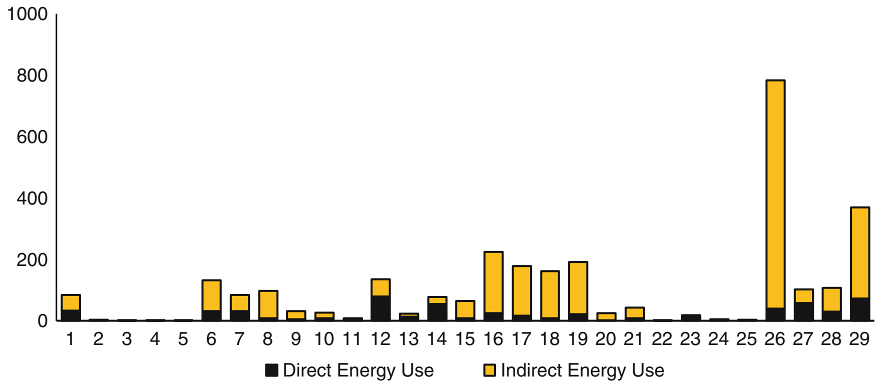

Fig. 3.11 Direct and indirect energy consumption for 29 sectors' final demand (Units: Mt SCE)

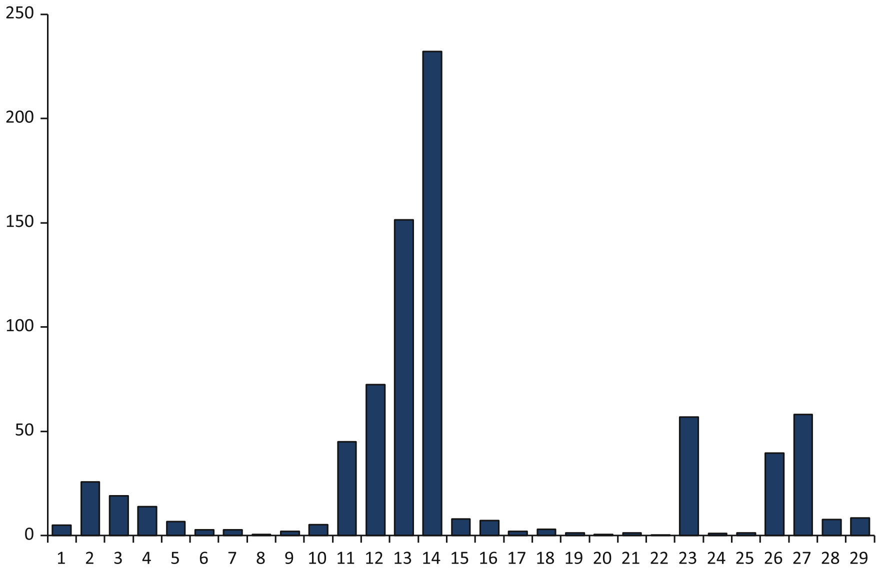

Fig. 3.12 Embodied energy consumption for the "Construction" sector (Units: Mt SCE)

"Construction" sector (No. 26), the "Other Service Activities" sector (No. 29), and the "Ordinary and Special Equipment" sector (No. 16) have been presented in Figs. 3.12, 3.13 and 3.14, respectively.

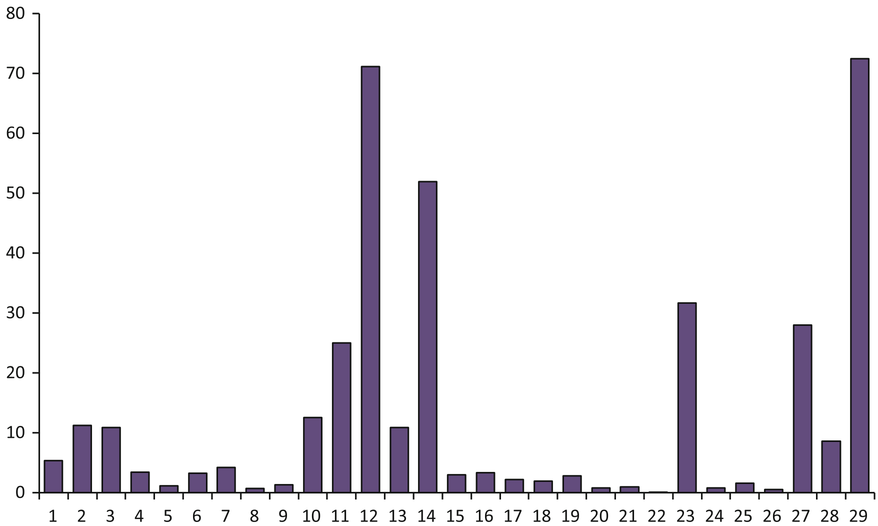

Fig. 3.13 Embodied energy consumption for the "Other Service Activities" sector (Units: Mt SCE)

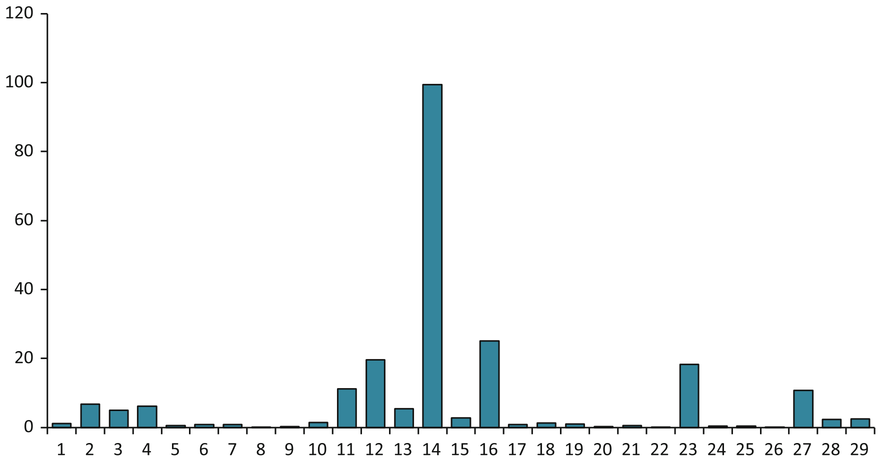

Fig. 3.14 Direct and indirect energy consumption for the "Ordinary and Special Equipment" sector (Units: Mt SCE)

The results showed that the indirect energy consumptions from these three sectors were mainly caused by energy consumptions from their upstream/downstream sectors, especially from the sectors of "Raw Chemical Materials and Chemical Production, Medical and Pharmaceutical Production, Chemical Fiber, Rubber Production, Plastic Production" (No. 12), "Nonmetal Mineral Production" (No. 13), "Smelting and Pressing of Ferrous and Nonferrous Metals" (No. 14), "Electricity Power/Heating Supply" (No. 23), and "Transport, Storage, Postal and Telecommunications Services" (No. 27). Because the sectors of No. 12, 13, and 14 are typical heavy industrial and energy-intensive sectors, the higher proportion of embodied energy consumption in "Construction" and "Other Service Activities" can be explained by the intermediate activities' energy consumption from those energy-intensive sectors.

3.4.3 Discussion and Policy Implications of Embodied Energy Consumption

By employing the EIO method, our study results provided an innovate perspective for explaining the rapid growth of "energy-intensive" sectors in China. While heavy industries such as smelting and pressing of metals are typical energy-intensive sectors and have higher level of production-based energy consumption, sectors such as "Construction" (No. 26) have relatively higher embodied energy consumptions and should be considered energy-intensive sectors from a supply chain perspective.

By uncovering the supply chain energy consumption for a single sector, our results illustrated that those heavy industrial sectors and the relevant energy supply sectors along upstream/downstream supply chains are the main contributors of the high embodied energy consumption for sectors such as "Construction." Consequently, the supply chain energy consumptions contribute to higher values of the embodied energy consumption of certain sectors.

Given the above information, it is necessary to find appropriate explanations for such phenomenon. First, China's soaring economy has been primarily driven by infrastructure construction and capital investment [32, 33]. Such a strategy has been effective in maintaining China's rapid GDP growth even during the global economic recession [34]. Based on the Chinese official statistics [35], capital investment had contributed to 45 % of the annual GDP growth during 2000–2007, whereas household consumption and exports had contributed to 30 and 25 %, respectively. Capital investment creates market demand for the large-scale production expansion of cement, steel, and other highly energy-intensive materials as well as demand for the associated electricity generation to support such production [32, 36, 37]. For example, the average annual growth rate of cement output was 10.7 % from 1985 to 2010. In 2010, China's cement output was 1.87 billion metric tons, accounting for 56 % of the world's total cement production [38]. Similarly, China's steel production had increased from 152 million tons in 2001 to 695.5 million tons in 2011, accounting for 45.5 % of the world's total steel production [39]. Most of the cement and steel were consumed by the supply chain of the "Construction" sector, resulting in this sector being the most intensive sector for embodied energy consumption. Thus, the supply chain demand of such sectors caused very large amounts of production activity in heavy industries; in other words, these sectors are also "energy intensive", but energy consumption is concentrated in supply activity rather than their direct production for final demand.

Secondly, a sector's classification limited the analysis of the energy consumption in the supply chain. Because of the mismatch between sectoral classifications in China's IO tables and the classifications in sectoral energy consumption, we merged similar sectors in this study for consistency between the sectors in IO and the sectors in the energy consumption data; the aggregated sectoral classification contains 29 sectors. Thus, several subsectors may be merged together and some sectors may contain too many sectoral activities, especially "Other Service Activities," for which activities that do not belong to other sectors are all contained within in it. Such classifications of energy consumption sectors have been already widely used for IO-related research in China. For example, a classification of 24 sectors was proposed by Chang [30], 26 sectors were proposed by Chen [29], and 29 sectors were proposed by Zhang [31]; the sectoral aggregation and disaggregation were also discussed by Kahrl and Roland [40] as well as by Chen [29]. Given the scale and proportion of the embodied energy consumption from these sectors, the uncertainty brought about by such simplification cannot negate the result that China's construction and service sectors are actually energy intensive when considering their embodied energy consumption. However, such uncertainty cannot be ignored, especially when the EIO model is coupled with life cycle analysis [41]. Because the CESYB is the only official and open published data source which contains China's sectoral detailed energy consumption, it is impossible to directly improve the data quality based on current statistics system; thus, we encourage any effort of further disaggregation of sectoral energy consumption and improvement in the data quality of China's energy statistics from different sources in the future.

Generally, current Chinese energy conservation policies focus on production-based energy consumption; thus, heavy industries received a lot of attention for their energy-saving efforts. For example, during the 11th 5-Year Plan, energy-saving targets for China's 1000 highest energy-consuming enterprises were arranged by the NDRC, aiming to save approximately 2.9 EJ of energy consumption during 2006–2010 [42]. In 2010, factories with production capacities of 10 million kWh of power generation, 6 million tons of steel, and 25 million tons of iron were closed [43, 44]. Additionally, more ambitious plans have been prepared to improve energy efficiency of 17 heavy industrial sectors (such as cement, iron, and steel) during the 12th 5-Year Plan (2011–2015). However, current policy overlooks the supply chain of those heavy industries. The continuous expansion of those industries would result in multiple increase in energy demand by their upstream suppliers. This would further lead to higher energy consumption for the whole economy [45]. Thus, energy-saving measures and efficiency improvement policies should not only consider the traditional heavy industries but also pay attention to the relevant sectors along their supply chains. An integrated policy approach should be employed instead of only addressing energy efficiency issues in several individual sectors. Such integrity requires that policy makers integrate energy supply management, energy demand management, energy efficiency management, and energy-related emission management throughout the whole supply chain. Moreover, policy makers should seek new economic growth strategies, rather than only relying on infrastructure construction and capital investment. For instance, increasing investment in education service and technological innovation aspects could be helpful for long-term economic growth and the adjustment of the economic structure.

With respect to the "bottom-up" implementation of such energy-saving and efficiency improvement policies, different strategies should be adopted based on a certain sector's energy consumption features. For those heavy industries such as thermal power generation and smelting metal, efforts should focus on the improvement of their efficiency through cleaner production, energy audits, technology updates, compulsory phaseout/shutdown of inefficient and backward manufacturing facilities, capacity-building programs on energy-saving awareness, etc. For those sectors with higher embodied energy consumptions such as the construction sector, efforts should focus on addressing their supply chain energy consumption, such as greening their supply chain and controlling the irrational final demand. Market-based instruments, such as sectoral financial subsidies, preferable tax rates, and low interest bank loans, should be employed so that the energy consumption along the supply chain can be adjusted according to their final demand and consumption.

3.5 Summary

This chapter established a detailed sectorial energy-related carbon emission inventory for 46 industries, calculated the carbon emission intensity of 28 industrial sectors of 30 provinces in 2009, and compared the sectorial coefficient of variance of the carbon emission intensity.

The study indicates that the carbon emission intensity is higher in traditional heavy industries and thermal electricity generation. The calculated sectorial carbon emission intensity and per capita emission reveal that the emission intensity of less-developed areas is higher than that of more developed areas. While most provinces saw a decrease in emission intensity during 1997 and 2009, Shanxi, Inner Mongolia, Ningxia, and Xinjiang experienced increases in emission intensity in 2009 compared with the emission intensity in 1997. The per capita emission increased in all provinces during the same period, with the most increase occurring in Inner Mongolia, Shanxi, Ningxia, and Shandong. The emission-intensive and energy-intensive developing path will pose enormous pressure on the local environment and resources in the less-developed areas.

Spatial and temporal differences in emission intensity and per capita emission are quantified by coefficient of variance (CV) analysis. The variability in provincial emission intensity is more significant than that in provincial per capita emission. The difference mainly stems from the gap between carbon emission intensity between coastal and inland areas. The emission intensity in some underdeveloped areas is dozens of times higher than that in developed areas. Therefore, how to achieve low-carbon development pattern becomes the crucial issue. In the meantime, the difference in sectorial efficiency indicates a novel path for energy conservation and emission reduction—through technological transfer from developed areas to less-developed areas.

Energy consumption from all industrial sectors in China's economy was examined by using an extended environmental input–output (EIO) analysis of latest data from 2007. We compare the direct energy consumed with the embodied energy in the final demand from 29 sectors within each sector. Two different viewpoints on sectoral energy consumption have been presented: Energy consumption is directly associated with the producer entity (production energy consumption) and with where energy consumption is accounted throughout the sector's whole supply chain (embodied energy consumption). The results show that a considerable amount of the energy is embodied in the supply chain, especially for the "Construction" and "Other Service Activities" sectors, which production energy consumption is small. The study further distinguishes the embodied energy consumption between direct (for final demand consumption) and indirect (for intermediate demand between industrial sectors) approaches. About 80 % of China's embodied energy consumption in 2007 was driven by indirect energy consumption. Our results provide a more holistic picture of energy consumption and, therefore, should be considered by policy makers.

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Chapter 4
Driving Factors of China's Carbon Emissions

In this chapter, we adopted the Logarithmic Mean Divisia Index (LMDI) method to investigate the effect of three driving factors on national and provincial carbon emission: economic scale, economic structure, and technological level.

4.1 Methodology

Index decomposition analysis (IDA) is a classic measure to quantify the contribution of various dimensions for shaping the trajectories of energy consumption and carbon emission, due to its adaptability and simplicity [1–4]. Among various index decomposition analysis methods, the Logarithmic Mean Divisa Index (LMDI) method has its own advantages due to its path independency, consistency in aggregation, and easy interpretation of results [2, 4]. Therefore, LMDI method is applied in this study for analyzing how industrial sectoral emission driven the growth of provincial carbon emissions in China. In this study, the historical change of carbon emissions is decomposed into three driving force factors: overall industrial activity (activity effect), activity mix (structure effect), and sectoral carbon emission intensity (intensity effect). Activity effect describes the contribution of GDP to carbon emission increase, namely, total economic scale. Structure effect is an indicator for evaluating the contribution of industrial structure change on carbon emission increase. Intensity effect refers to the effect of carbon intensity (GHG emissions per unit GDP) on carbon emission increase and is used to evaluate the contribution of technology improvement on carbon emission reduction. Comprehensive description of activity effect, intensity effect, and structure effect and the associated calculation have been introduced by Ang [5]. The LMDI decomposition method was based on the IPAT equation and refined by Ang and other scholars [3]. The LMDI is the preferred method since it avoids the allocation

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of unexplained residual terms. It is also consistent in aggregation, which means that the industrial activities can be grouped into sub-groups for further analysis [2]. The decomposition results can be presented in additive and multiplicative forms.

The detailed calculation process is listed as follows:

If E^0 and E^t represent the carbon emission at start year and end year, respectively, and ΔE_{act}, ΔE_{str}, *and* ΔE_{int} represent the economic scale effect, economic structure effect, and technological level effect in the additive approach, then the difference between E^0 and E^t, ΔE_t, is decomposed into the sum of the three aforementioned effects. It is the same with the multiplicative approach.

The formula for additive and multiplicative approaches is as follows:

$$\Delta E_t = E^t - E^0 = \Delta E_{\text{act}} + \Delta E_{\text{str}} + \Delta E_{\text{int}} \tag{4.1}$$

where

$$\Delta E_{\text{act}} = \sum_i w_i * \ln\left(\frac{Q^t}{Q^0}\right) \tag{4.2}$$

$$\Delta E_{\text{str}} = \sum_i w_i * \ln\left(\frac{S_i^t}{S_i^0}\right) \tag{4.3}$$

$$\Delta E_{\text{int}} = \sum_i w_i * \ln\left(\frac{I_i^t}{I_i^0}\right) \tag{4.4}$$

$$w_i = \frac{E_i^t - E_i^0}{\ln E_i^t - \ln E_i^0} \tag{4.5}$$

and

$$D_t = E^t / E^0 = D_{\text{act}} D_{\text{str}} D_{\text{int}} \tag{4.6}$$

where

$$D_{\text{act}} = \exp\left(\sum_i w_i \ln\left(\frac{Q^t}{Q^0}\right)\right) \tag{4.7}$$

$$D_{\text{str}} = \exp\left(\sum_i w_i \ln\left(\frac{S_i^t}{S_i^0}\right)\right) \tag{4.8}$$

$$D_{\text{int}} = \exp\left(\sum_i w_i \ln\left(\frac{I_i^t}{I_i^0}\right)\right) \tag{4.9}$$

$$w_i = \frac{(E_i^t - E_i^0)/(\ln E_i^t - E_i^0)}{(E^t - E^0)/(\ln E^t - E^0)} \tag{4.10}$$

E_t: total carbon emission at end year
E_0: total carbon emission at start year
D_t: ratio of end year emission to start year emission
Q: GDP
S: ratio of sectorial GDP to total GDP
I: emission intensity, represented by carbon emission per GDP.

4.2 Driving Factors of Carbon Emission from 1997 to 2009

The carbon emission intensity and total emission index in China from 1997 to 2009 are shown in Fig. 4.1 (base year: 1997). During 1997–2009, the total GHG emissions remained relatively constant during 1997–2001, sharply increased during 2002–2005, and slow down after 2005. Phase change can also been seen in historical change of carbon emission intensity. In order to find reasons for such changes, LMDI was applied for the following three periods: 1997–2001, 2002–2005, and 2006–2009.

From 1997 to 2001, the total emission remained nearly stable with a decrease in emission intensity. There was a dramatic increase in total emission from 2002 to 2005, and the emission intensity increased accordingly. While the total emission has continued to increase since 2006, the emission intensity has experienced a fall. Therefore, the analysis of driving factors will be conducted in three time periods.

This study adopts the additive approach in decomposition. Figures 4.2, 4.3, 4.4, and 4.5 represent the contribution from economic scale effect, economic structure effect, and technological level effect from 1997 to 2009, from 1997 to 2001, from 2002 to 2005, and from 2006 to 2009, respectively.

It is indicated in Fig. 4.2 that from 1997 to 2009, all provinces experienced remarkable increase in total carbon emission. While the technological advancement offset part of the emission increase, the economic structure effect contributed positively in all provinces, which means that the proportion of heavy industry has been increasing.

From 1997 to 2001 (Stage I), the increase in total carbon emission was limited, and most emission driven by economic scale was offset by technological advancement (Fig. 4.3). The total emissions of Shanghai, Hunan, and the Northeast region even declined due to economic structure adjustment. The structure effect contributed less significantly, but in most provinces it drove an increase in total emission.

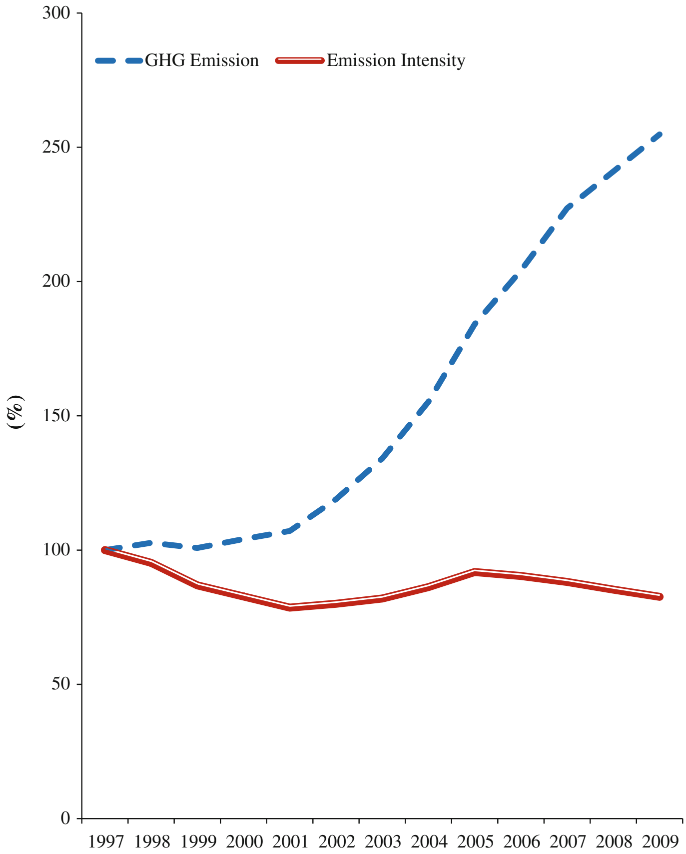

Fig. 4.1 Carbon emission intensity and total emission index in China during 1997–2009

From 2002 to 2005 (Stage II), all provinces experienced dramatic increase in total carbon emission. The economic scale, economic structure, and emission intensity contributed significantly and positively to total carbon emission. The contribution could be several times more than that during 1997–2001.

From 2006 to 2009 (Stage III), the provincial carbon emission continued to increase, represented by the increase in economic scale. While the emission intensity effect dropped significantly, the economic structure still appeared "heavy." With the decline in emission intensity effect, the increase nearly halved that of during 2002–2005.

Results indicate the significant disparity on carbon emissions between Chinese provinces, and more precisely, such disparity is more remarkable in certain industries. While regional inequity of per capita emission is well recognized and aroused pressing concern recently [6], the technology inequities among regions are rarely reported. More importantly, such technology inequity has a direct connection

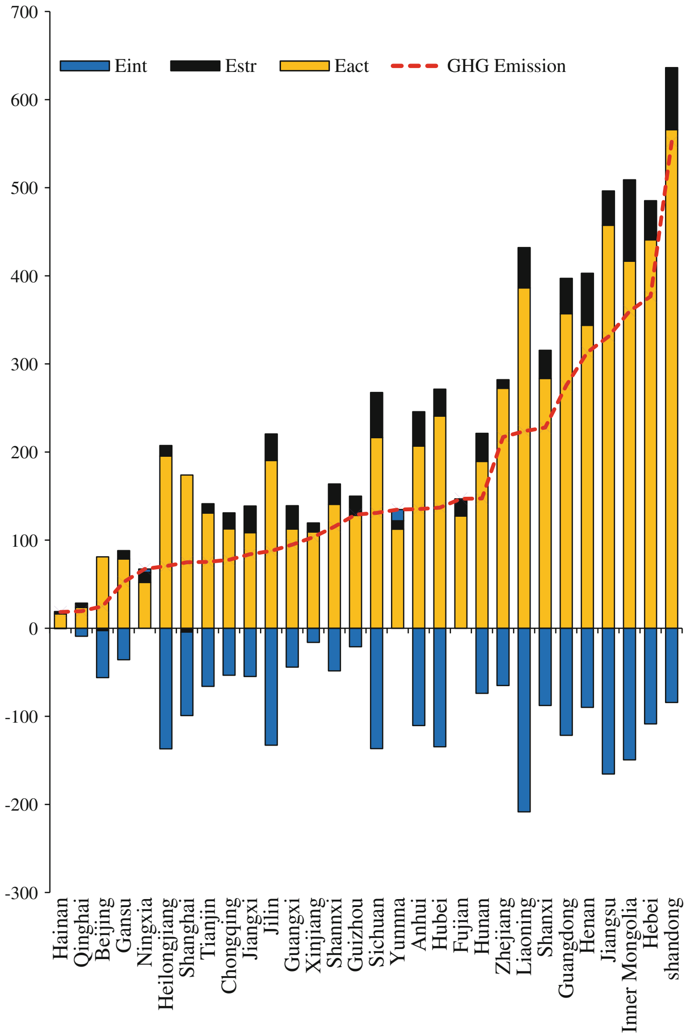

Fig. 4.2 Driving forces for carbon emission of 30 provinces during 1997–2009 (unit: million tons of CO_2)

with China's soaring carbon emission growth in 1997–2009, and intensity increase in underdeveloped regions plays an important role in total emission increase.

The LMDI analysis revealed that the most of carbon emission increase is concentrated at underdeveloped regions since 2001, such as poor areas which struggle with economic growth, coupled with energy-intensive industry and low-efficiency technology (Figs. 4.3, 4.4, and 4.5). Several provinces, such as Inner Mongolia, Ningxia, and Shanxi, have both higher per capita carbon emission and higher emission intensity, implicating lower energy efficiency and carbon-intensive

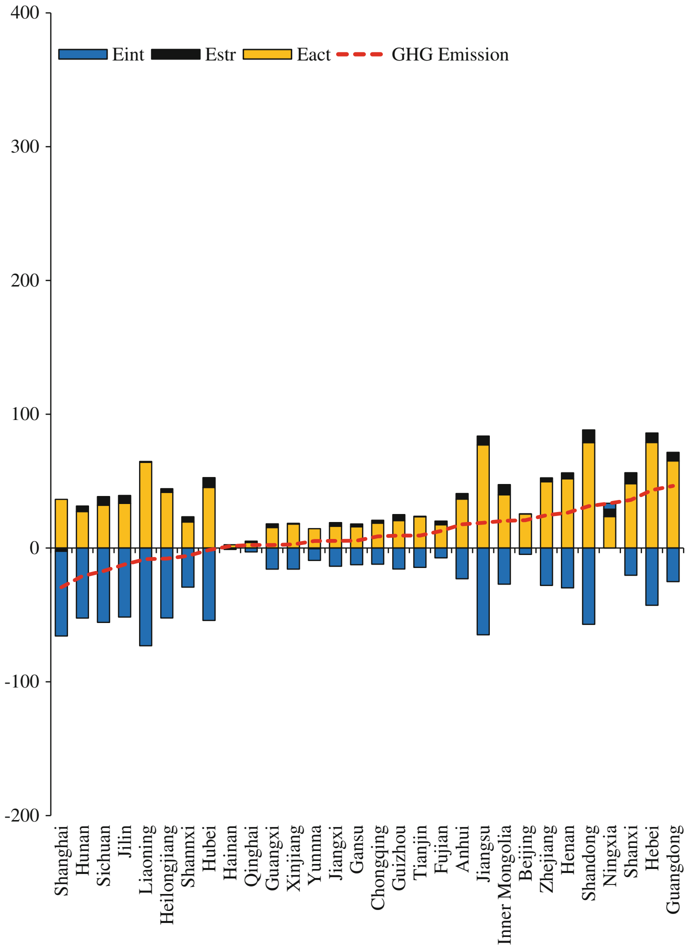

Fig. 4.3 Driving forces for carbon emission of 30 provinces during 1997–2001 (unit: million tons of CO_2)

economic structure. In fact, China's overall economy is largely dependent on primary energy resources and these resources are mainly located in less-developed regions. Our research illustrates that the efficiency in certain sectors are extremely low in those less-developed regions. Besides the economic barrier, such technology barrier becomes a new challenge for sustainable development in these regions.

Technology inequity has a direct effect on China's mitigation actions. On the one hand, the disparity of technology level has not been fully recognized by policy makers; such difference raises a request to revise current energy intensity reduction targets for different provinces. For example, both the Beijing municipality (politically equal to a province) and Liaoning province were ranked as "second level" regions, second highest and equivalent emission reduction targets (17 % energy

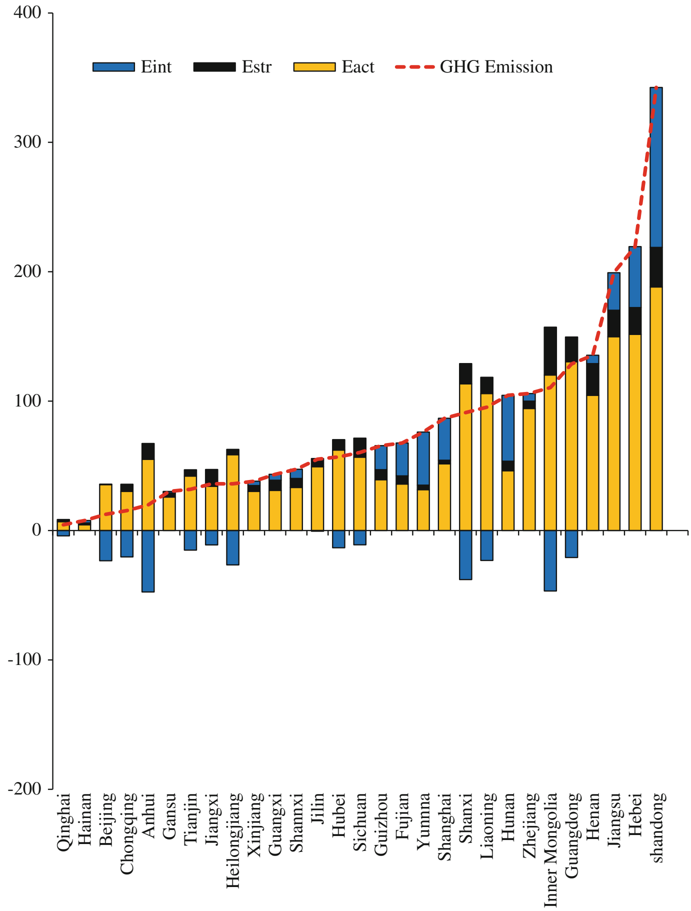

Fig. 4.4 Driving forces for carbon emission of 30 provinces during 2001–2005 (unit: million tons of CO_2)

intensity reduction target). Beijing is a provincial city with a highly developed commercial industry and much reliance on electricity supply from other provinces [7]. Liaoning province, with a large industrial base, is not able to export their industrial base and shift their environmental burden. This unequal playing field and perceived lack of fairness have caused provincial officials to take these emission reduction goals less seriously. On the other hand, the technology inequity causes underdeveloped regions to rely more on low-efficiency and energy-intensive industries, resulting in carbon-intensive economic structure of these regions and of the whole country. The fact is that many less-developed regions double lock both carbon-intensive economic structure and low-efficiency technology with their economic growth. The technology equity will hamper long-term sustainable development for underdeveloped regions.

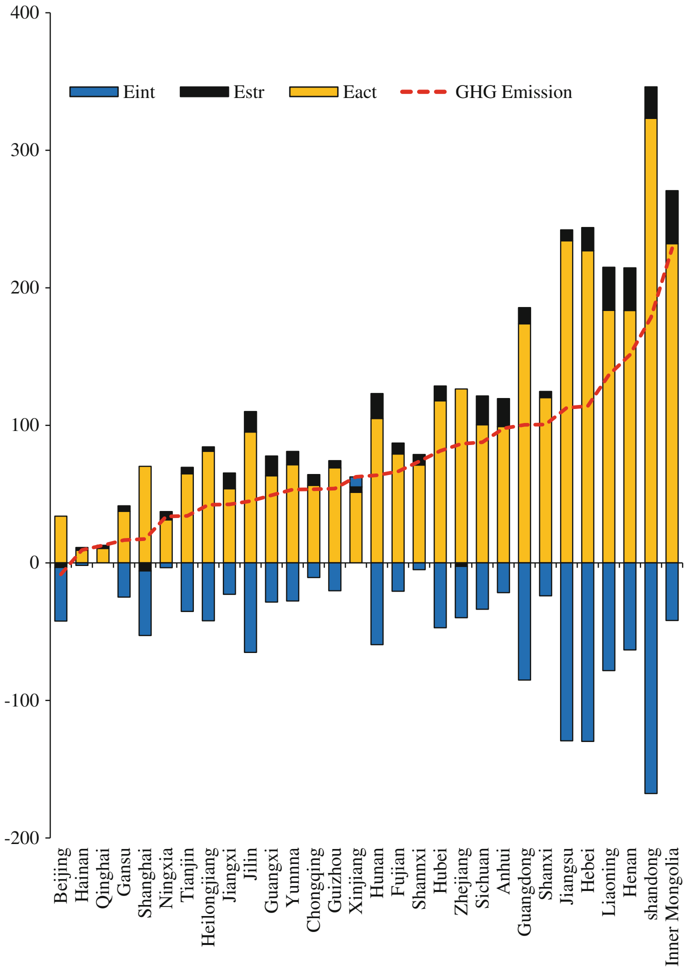

Fig. 4.5 Driving forces for carbon emission of 30 provinces during 2005–2009 (unit: million tons of CO_2)

Currently, China's carbon emission mitigation policies mainly depend on mandatory control of intensity reduction such as the 40–45 % target. For example, the dramatic decrease in GHG intensity since 2005 can be explained by the effect of national energy-saving and emission-reduction policies in its 11th 5-year Plan (2006–2010). Such a policy targets energy-consumption reduction per unit GDP by 20 % and main pollutants reduction (COD and SO_2) per unit GDP by 10 % [8], but there is no mandatory indicator for quantitative control of national and regional economic structure change. Our results illustrate that intensity reduction can contribute to significant offset of total carbon emission increase, especially after 2005. However, most attention has been addressed on efficiency improvement, but little is known about China's economic structure which actually has become more carbon intensive recently. Such a policy blind point will further block China's mitigation actions and lead to a long-term emission increase. Thus, complementary mechanism and technology transfer are urgently needed in China's underdeveloped areas.

4.3 Summary

In this chapter, China's regional and sectoral GHG emission patterns and their driving forces were explored by using detailed energy consumption data at the sector level. We constructed for each province a detailed GHG inventory covering 28 sectors in the year 2009 and used an index composition analysis to explore disparity. Results uncovered significant differences of sectoral emission intensity among provinces, implying a huge disparity of technology level among regions. Less-developed provinces with much higher energy-intensive technologies contribute to the most of the national emission increment during 1997–2009 and cause the whole country's economic structure to become carbon intensive. Our research indicates the inequity of technology level among regions already becomes a main barrier for China's CO_2 mitigation and thus needs more attention from researchers and policy makers.

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Chapter 5
Carbon Emissions Embodied in Trade

This chapter will analyze China's carbon emissions embodied in domestic and international trade, based on the consumption emission accounting. The consumption-based emission accounting is introduced to calculate the trade-related carbon emissions for nations or regions, and the consumption-based emission is widely considered as "carbon footprint" by literatures.

5.1 Methodology

Consumption-based accounting of emissions. An alternative to the production-based accounting of CO_2 emissions (See Chap. 2) is to compile inventories according to where related goods and services are ultimately consumed. Such a consumption-based method accounts for inter-regional exchange of energy supply, goods, and materials by adding emissions embodied in imports to the production-based total and subtracting emissions embodied in exports.

The emissions embodied in a region's imports and exports can be calculated using environmentally extended input–output analysis (EIO). Environmentally extended multi-regional input–output (MRIO) analysis has been widely developed for calculating the embodied carbon emission [1–3], virtual water [4, 5], material use [6], biodiversity loss [7], and land use [8, 9] associated with international trade.

In MRIO framework, different regions are connected through inter-regional trade, Z^{rs}. The technical coefficient submatrix A^{rs} consists of "$[a_{ij}^{rs}]$" is derived from $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$, where z_{ij}^{rs} is the intersector monetary flow from sector i in region r to sector j in region s; x_j^s is the total output of sector j in region s. The final demand matrix is Y consist of "$[y_i^{rs}]$", where y_i^{rs} is the region's final demand for goods of sector i from region r. Therefore, MRIO analysis can be shown as:

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$$\begin{bmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^n \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ A^{31} & A^{31} & \cdots & A^{3n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^n \end{bmatrix} + \begin{bmatrix} \sum_s y^{1s} \\ \sum_s y^{2s} \\ \sum_s y^{3s} \\ \vdots \\ \sum_s y^{ns} \end{bmatrix} \tag{5.1}$$

Using familiar matrix notation and dropping the subscripts, Eq. 5.1 can be written as: $x = Ax + y$ or $x = (I - A)^{-1}y$, where $(I - A)^{-1}$ is the Leontief inverse matrix that captures both direct and indirect inputs required to satisfy one unit of final demand in monetary value; I is the identity matrix. To calculate the consumption-based CO_2 emissions, we then extend the MRIO table with sector-specific CO_2 emissions: $E = k\,(I - A)^{-1}y$, where E is the total CO_2 emissions embodied in goods and services used for final demand and k is a vector of CO_2 emissions per unit of economic output for all economic sectors in all regions.

5.1.1 Estimates of Sectoral Level Imported and Exported CO_2 Emissions

In a region IO model, a regional economy is considered as its system boundary, and thus, exports are treated as final products in a region's economy. Let G_i^r be the total CO_2 emissions in economic sector i and region r, and thus, $\sum_i G_i^r$ represents the production-based emissions in region r. In each region r, there are intermediate consumption, denoted Z_{ij}^r, which represents the domestic purchases of sector i by sector j in region r and final consumption, denoted y_i^r, represents the domestic purchases of sector i by final consumers in region r which includes households, government, and capital investments. In the single-region IO model, exports, e_i^{rs}, from region r to region s are also treated as final consumption. By summing intermediate and final consumption, we can obtain the total output in each region:

$$x^r = Z^{rr} + y^{rr} + \sum_s e^{rs} \tag{5.2}$$

By assuming fixed production ratios, we obtain the technical coefficients, A_{ij}^{rr}, the ratio of input to output, by diving Z_{ij}^{rr} by x_j^r:

$$A_{ij}^{rr} = Z_{ij}^{rr}/x_j^r \tag{5.3}$$

Thus, equation (S1) can be rewritten as:

$$x^r = (I - A^{rr})^{-1} * (y^{rr} + \sum_s e^{rs}) \tag{5.4}$$

where $(I - A^{rr})^{-1}$ is Leontief inverse matrix for region r.

CO_2 emissions are estimated based on the direct emission intensity, k^r in each sector in region r.

$$k_i^r = G_i^r / x_i^r \tag{5.5}$$

Therefore, the total embodied emissions (direct and indirect) in exports from region r to region s can be calculated by:

$$\mathrm{Exp}^r = k^r (I - A^{rr})^{-1} \hat{e}^{rs} \tag{5.6}$$

where Exp^r is a vector of embodied CO_2 emissions in sectoral exports of region r to region s; k^r is a row vector of sectoral emission intensities in region r; $\hat{e}^{rs}$ is a matrix with sectoral export from region r to region s on diagonal.

In turn, the total embodied emissions in imports from region s to region r can be estimated by:

$$\mathrm{Imp}^r = k^s (I - A^{ss})^{-1} \hat{e}^{rs} \tag{5.7}$$

where Imp^r is a vector of embodied CO_2 emissions in sectoral imports of region s to region r; k^s is a row vector of sectoral emission intensities in region s; $\hat{e}^{rs}$ is a matrix with sectoral import from region s to region r on diagonal.

5.1.2 Emissions and Trade Data

In this study, we estimate emissions from fossil fuel energy combustion and cement production, which together account for about 90 % of GHG emissions produced in China. Our calculations include 20 different types of fuel and 46 energy consumption sectors. Further details of data sources and processing methods are available in [10–12].

Our multi-regional input–output (MRIO) relies on data from the Global Trade Analysis Project (GTAP) [13], which includes 129 regions (mostly countries, but some aggregated regions). Although GTAP data cover 57 industry sectors, we aggregate to 30 sectors in order to match input–output tables of interprovincial trade compiled by Liu et al. at the Chinese Academy of Sciences [14]. In turn, we use Liu et al.'s tables to disaggregate the Chinese region in GTAP into 30 subregions (26 provinces and 4 cities). Thus, we have a global MRIO comprised of the latest available economic data that allows us to assess consumption-based CO_2 emissions in each Chinese subregion as well as emissions embodied in trade among these subregions and all 129 other GTAP regions around the world. Technical details of how the Chinese IO tables are nested with the GTAP MRIO are available in [3].

5.2 Carbon Emissions Embodied in Domestic Trade

Consumption-based accounting shows that approximate 40 % of total production-based emissions are embodied in the interprovincial trade in China. In the most developed provinces, such as Beijing, Shanghai, Tianjin, Guangdong, and Zhejiang, imported emissions account for more than 50–80 % of their consumption-based emissions. The well-developed coastal provinces tend to externalize their CO_2 emissions central and west provinces through imports of low valued carbon-intensive goods.

In 2007, 57 % of China's emissions from the burning of fossil fuels were emitted during production of goods and services that were ultimately consumed in different provinces in China or abroad. Beijing–Tianjin, the central coast, and the south coast are the most affluent regions in China, with large net import of emissions embodied in goods from poorer central and western provinces. More than 75 % of emissions associated with products consumed in Beijing–Tianjin occur in other regions. Similarly, the central coast and south coast regions outsource about 50 % of their consumption emissions. Beijing–Tianjin, central coast and south coast are the richest regions in China, and their per capita GDP are about 2–4 times of the per capita GDP in southwest, northwest and central. At the same time, these three wealthy regions import a large amount of goods from poorer regions, thus have a large amount of embodied emissions in their imports. A large amount of emissions from central (32 % of its production-based emissions), northwest (27 %), and southwest (25 %) are induced by the consumption of goods and services or international export in coastal provinces in China.

The results demonstrate the economic interdependence of Chinese provinces, while also highlighting the differences in wealth, economic structure, and fuel mix that drive imbalances in interprovincial trade and associated embodied emissions in traded products.

5.3 Carbon Emissions Embodied in International Trade

China is the world's largest carbon emitter [15] and the largest net exporter of CO_2 emissions embodied in goods and services [16]. In 2007, emissions produced in China (production-based emissions) were 7.3 Gt CO_2, of which 1.7 Gt (23 %) were related to goods exported and consumed in other regions. Several factors contribute to the prodigious imbalance of emissions embodied in China's trade, among them: (1) the large trade surplus between China and its trading partners, (2) the structure of the Chinese economy (i.e., specialization in energy-intensive production), and (3) the emission intensity of Chinese production (i.e., the emissions produced per unit of economic output) [1, 17].

Among these factors, emission intensity is particularly problematic. Although trade in emissions may undermine the efficacy of region-specific climate policies [18], in the case of China it probably also reflects an economically efficient use of production factors [17]. But where Chinese industry produces more emissions than the same industry elsewhere, this economic efficiency is directly opposed to climate change mitigation.

Here, we track emissions embodied in trade among 159 regions using a global multi-regional input–output (MRIO) model of emissions and trade as of the year 2007. The trade and emissions data supporting the model are a combination of the Global Trade Analysis Project (GTAPv8) and province-level input–output tables of China that we constructed [3, 11, 19].

China accounts for 34 % of global total carbon emissions embodied in international trade of imports and exports, ranking highest in the world. When consider the net carbon emission in trade (net emission = emission in export − emission in import), China is the largest net emission exporter and USA is the largest importer in the world (Fig. 5.1a). China's emissions embodied in exports are 8 times the

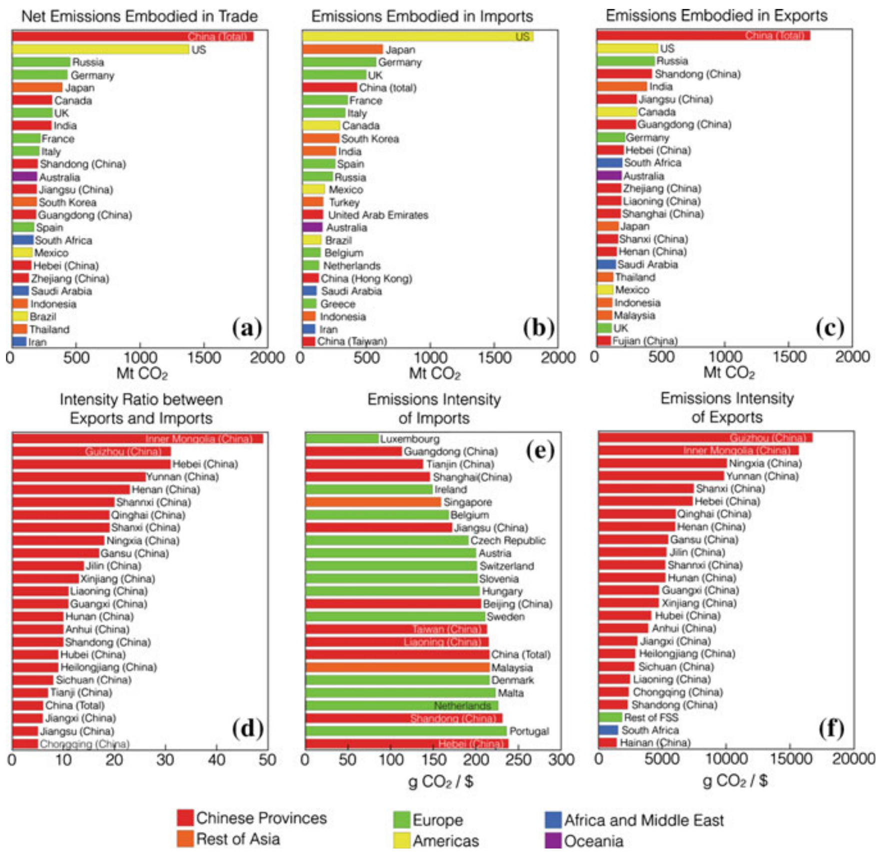

Fig. 5.1 Emissions embodied in trade. Top 25 regions (including countries and Chinese cities/provinces) by net emissions embodied in trade (**a**), gross imports (**b**), gross exports (**c**), the ratio of emission intensity of exports to imports (**d**), and emission intensity of imports (**e**), and emission intensity of exports (**f**)

import emissions, highest in 159 regions, and the ratio between export and import emission is also significantly larger than other countries with large emissions embodied in trade, such as the USA (0.5), India (1.3), Canada (1.2), Germany (0.5), and Australia (1.5).

The unbalanced trade emission is more significant for China's provinces, and 25 of China's 30 provinces are listed as the top regions among 159 world regions with the emission embodied in export higher than the emission embodied in import (Fig. 5.1b, c). There are 11 Chinese provinces with export-embodied emissions being 10 times larger than the emissions embodied in imports. Xinjiang (25 times larger), Shanxi (19), and Hebei (16) have the highest carbon export–import ratio among all 159 countries and regions. China's trade emissions are mainly from few provinces. Shandong (export 178 Mt CO_2 in 2007), Jiangsu (173 Mt), Guangdong (161 Mt), Hebei (139 Mt), and Zhejiang (111 Mt) those five top carbon export provinces account for the 46 % of total 1671 Mt CO_2 that embodied in China's export. On the contrary, Guangdong, Shandong, Jiangsu, Zhejiang, and Henan are the five provinces with highest import emissions (together account for 44 % of total 211 import emissions). Trade-embodied emission exported from several Chinese provinces is already larger than the emission exported from major developed countries. For example, Shandong and Jiangsu listed as world No. 3 and No. 5 region in terms of total emissions embodied in exports, the amount of export-related emission is larger than that of Canada (No. 8) and Germany (No. 10), respectively (Fig. 5.1c).

By calculating the carbon intensity of exports and imports, China's regions are most carbon-intensive exporter among the world. The average carbon intensity of China's international exports (1.35 t CO_2/kt dollar) about 6 times that of China's international imports (0.23 t CO_2/kt dollar). Ranking the global 159 regions with the ratio between carbon intensity of exports and the carbon intensity of imports, China's 29 provinces list within the top 30 of the regions among world regions (Fig. 5.1d), with South Africa (listed as No. 28) being the one exception. More importantly, China's carbon-intensive exports were mainly produced in the poor regions. China's regions with less than $4,000 per capita GDP show dramatic discrepancy of the emission intensity between imports and exports (Fig. 5.2). 80 % of China's export-related emissions are produced by poor regions where the carbon intensity of exports was more than 5 times the carbon intensity of their international imports. For example, Guizhou with a per capita GDP of only $900 in 2007 had an emission intensity for international exports about 31 times of the intensity in international imports, and that ratio is about 49-fold in Inner Mongolia ($3,386), 30-fold in Guizhou (with per capita GDP of $922 in 2007), 26-fold in Yunnan ($1405) and 17-fold in Gansu ($1380). The gap is smaller in China's more developed east coast regions; for example, the ratios in Beijing, Zhejiang, and Shanghai are 2.8, 3, and 4.1, respectively; however, such ratios are still much higher than the ones in other major countries for emissions embodied in trade, such as USA (ratio = 0.8), Germany (0.4), Japan (0.2), Canada (1.1), the UK (0.3), and India (1.7).

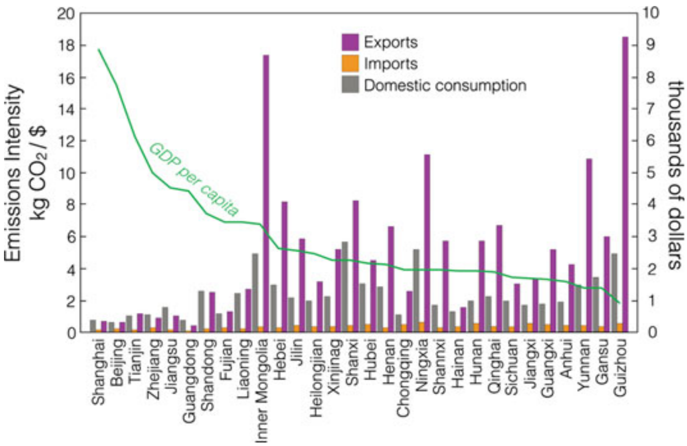

Fig. 5.2 Emission intensity of production. Kilograms of CO_2 per dollar of output in each of 30 Chinese cities/provinces for international export (*purple bars*) and domestic consumption in China (*gray bars*), as well as the emission intensity of goods imported to the city/province from outside China (*orange bars*). The *green curve* shows GDP per capita in each city/province according to the *right* axis

Developed countries are the major consumers of goods that cause carbon-intensive exports originating from Chinese regions. US consumption triggered 395 Mt CO_2 (24 % of China's total 1671 Mt export emission) emissions embodied in exports, followed by Japan (150 Mt CO_2, 9 %), Germany (5 %), Korea (4 %), the UK (4 %), and Russia (3 %). The European Union and other East Asian countries together account for 25 and 15 % of China's export-embodied emissions, respectively. On the other hand, China's exported-embodied emissions accounted for the largest share of emissions imported to other countries. For example, the import emission from China to Japan, the USA, and Russia accounts for 48, 44 and 42 % of their total import-embodied emissions, respectively. The exports are mainly come from Jiangsu, Shandong, Guangdong, Hebei, and Zhejiang, and those top 5 carbon export provinces account for 10.7, 10.4, 9.7, 8.3, and 6.7 % of national total emissions embodied in exports, respectively.

The export-embodied emission is larger than the import-embodied emission in all the 30 provinces. Calculating the embodied emissions by sectors further explained China's high carbon intensive and unbalanced trade. The carbon intensity of China's exporting heavy industrial materials (mining products, chemical products, metal and non-metal products, energy products) is many times higher of its imports and even higher than the same kind of products that been consumed in domestic market. Such carbon-intensive heavy industrial materials are exactly the products that China mostly exported. Metal and non-metal products (account for 37 % of total export carbon), chemical products (22 %), and equipment (15 %) together account for 75 % of China's carbon emission embodied in international exports. On the contrast, the proportion of these three sectors in China's imports is only 19, 16, and 21 %, respectively. Raw mining products have the highest share of emission that embodied in China's imports (23 %). The high level of imported raw mining materials and exported metal and non-metal products implies that China is not just world workshop, but the workshop of most carbon-intensive products. Such phenomenon is significant in China's major carbon export regions, for example, Shandong was the No. 1 province for the emission embodied in international exports (accounting for 11 % of national total emission embodied in international exports), 42 % of the embodied emission (8 Mt CO_2) that Shandong imported from other countries is from mining products, accordingly, 34 % of embodied emission (60 Mt CO_2) that Shandong exported to other countries are coming from metal and non-metal products. The high proportion of imported mining products and exported metal and non-metal products for China's regions implies that China is now the world factory of smelting and processing of raw mining materials, the most carbon-intensive stage among manufacturing supply chain (Figs. 5.3 and 5.4).

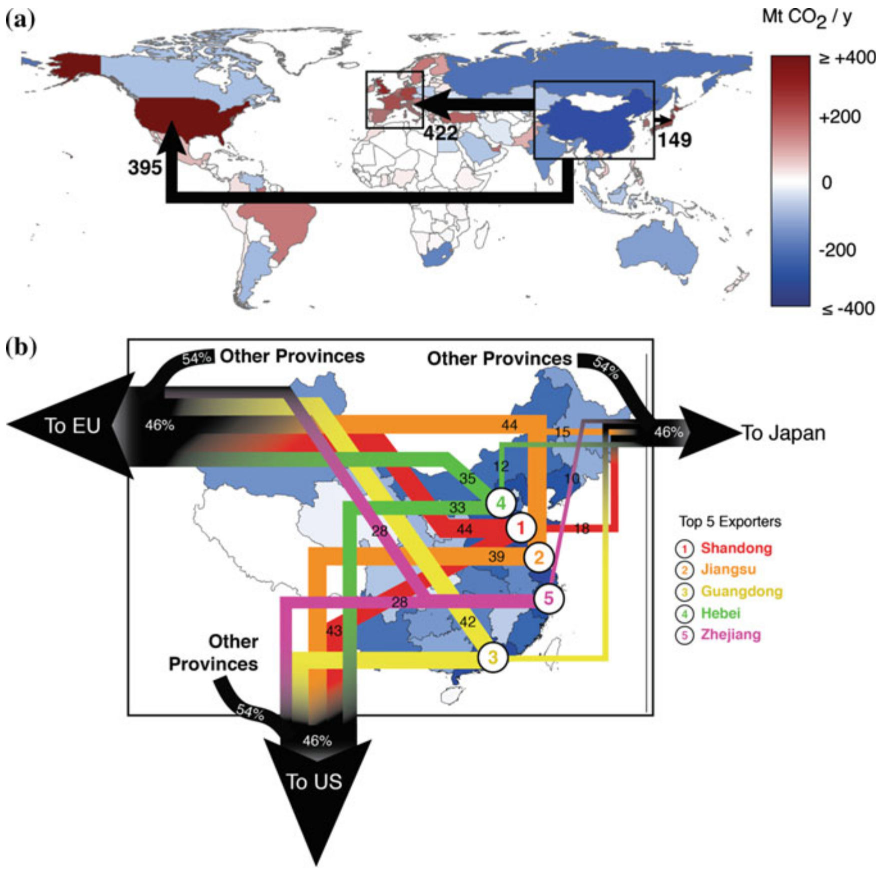

Fig. 5.3 Top exporting provinces. The emissions embodied in goods exported from China to the USA, EU and Japan represented 58 % of all emissions embodied in trade in 2007 (**a**). Five Chinese provinces account for 46 % of these exports (**b**)

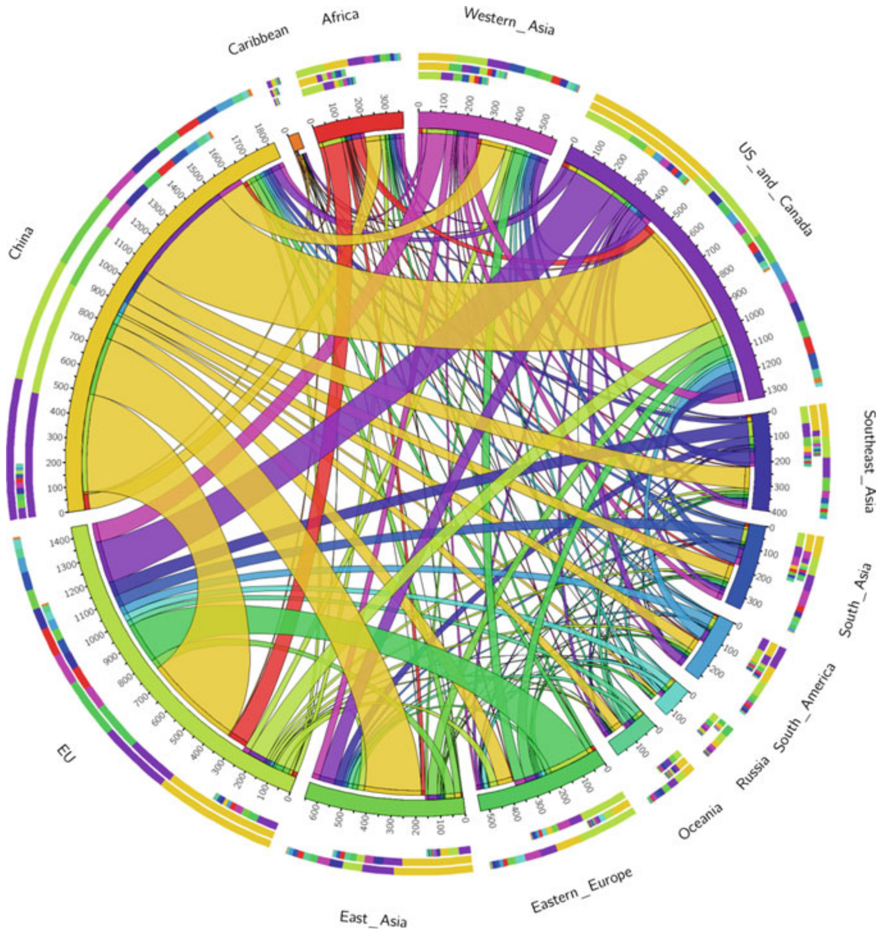

Fig. 5.4 Emissions embodied in international trade. The flow represents the emissions embodied in trade, the *color* represents the original production regions; for example, *red flow* represents the embodied emission that produced by Africa and exported and consumed by other regions

Several factors can contribute to the observed differences in the magnitude and intensity of emissions embodied in exports and imports. First, in recent years, China has become a "factory for the world," with high concentrations of global heavy industry and manufacturing. For example, China produces 60, 51, and 65 % (by mass) of the world's cement, steel, and coke, respectively [20]. Such large imbalances in the volume of traded products may correspond to similarly large imbalances in the emissions embodied in traded products. Figure 5.5 compares the percentage of emissions related to consumed goods that are imported (y-axis) and the percentage of produced emissions that are embodied in exports for a number of industry sectors in China (Fig. 5.5a) and Europe (Fig. 5.5b). For example, 34 %

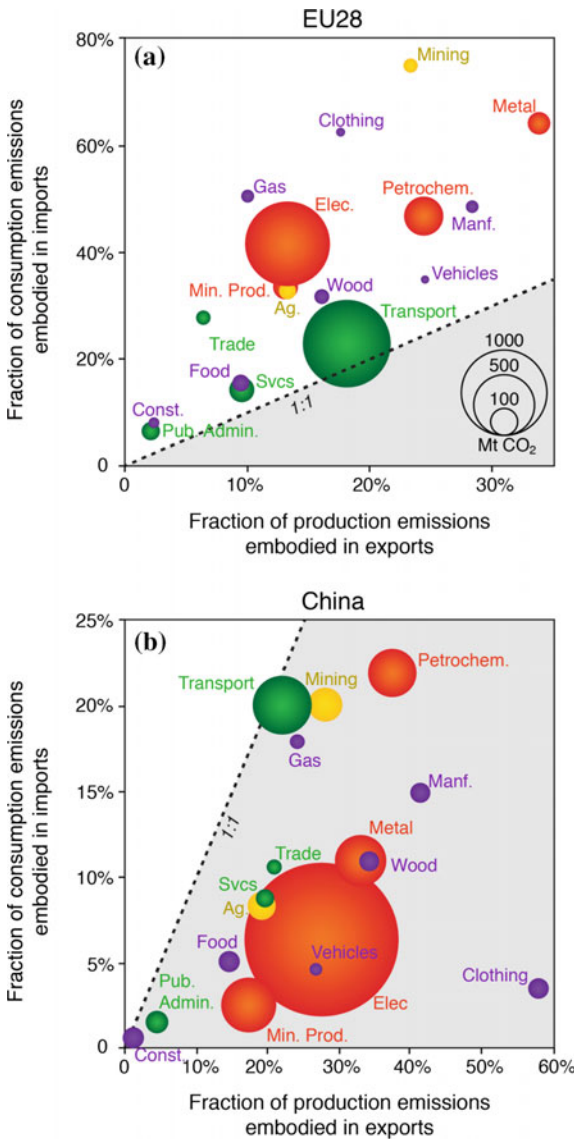

Fig. 5.5 Differences in share of embodied emissions traded by industry categories. *Circles* indicate the share of consumed emissions that are imported (*y*-axis) and the share of produced emissions that are exported (*x*-axis) for a range of industry categories in Europe (**a**) and China (**b**). The size of each circle denotes the sector's total production emissions, providing an indicator of the relative importance of different sectors. The colors of the *circles* indicate whether the industries are primary (*yellow*), secondary and energy intensive (*red*), secondary and non-energy intensive (*purple*), or tertiary (*green*). It should be noted that while the marker area scale is common across both charts (to aid comparison), the *x*- and *y*-axis scales differ. A line representing equal import and export share is shown in each chart. Data are in year 2007

(26 Mt CO_2) of emissions produced by the European metal production industry are embodied in products exported from Europe in 2007, but emissions embodied in all metal products consumed in Europe were 140 Mt CO_2, 64 % of which (90 Mt CO_2) were imported from outside Europe (Fig. 5.5a; red circle labeled "metal"). In comparison, the share of emissions produced by China's metal production sector that is exported is similar to Europe's (33 %; Fig. 5.5b), but the share of emissions related to Chinese consumption of metals that is imported is much lower: 11 %.

Overall, Fig. 5.5 highlights that, across many industry sectors, the share of European consumption (import from other countries) is consistently greater that the share of produced emissions that are exported, and the opposite is true for China. These trade imbalances are evident for both industries (yellow circles) and secondary industries (red and purple circles).

A second factor influencing emissions embodied in trade is the trade structure. Figure 5.4 shows the industry categories that make up Chinese imports, exports, and domestic consumption. Emissions embodied in heavy, energy-intensive products such as metal and non-metal products and equipment make up much larger shares of China's exports (37 and 22 %, respectively) than its imports (19 and 16 %, respectively; light green and dark blue bars in Fig. 5.6). Meanwhile, mining products is the category with the greatest proportion of emissions embodied in Chinese imports (23 %). The dominance of these industries in Chinese trade implies that China is not just the world's workshop, but is engaged in the most emission-intensive stages of manufacturing: the smelting and processing of raw materials. This pattern is visible at the province level, as well; in Shandong, where emissions embodied in trade are largest, 8 Mt CO_2 are embodied in imports of mining products from other countries (42 % of all emissions embodied in imports) and 60 Mt CO_2 are embodied in exported metal and non-metal products (34 % of emissions embodied in the province's exports).

The third major factor is emission intensity, or CO_2 emissions per dollar of output in each particular industry. Such emission intensity reflects both energy intensity (energy consumed per dollar of output) and carbon intensity of energy (CO_2 per unit of energy consumed). The combination of a carbon-intensive power

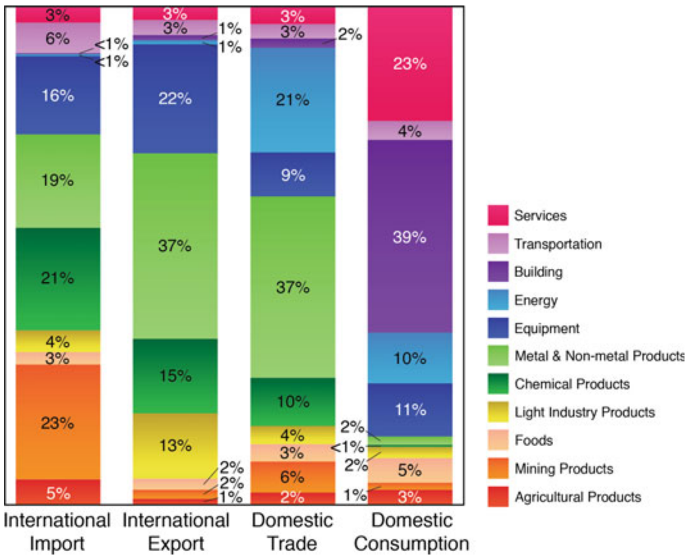

Fig. 5.6 Sectoral share of China's embodied emissions. Data are in year 2007

industry, relying primarily on coal, and of a relatively low value-added of industry thus translate into a high emission intensity of Chinese production. In 2007, 75 % of China's primary energy was supplied by coal, the highest level among major energy-consuming nations. As a result, the carbon intensity of energy consumption in general (for internal consumption and exports combined) in China is extremely high: Chinese exports entail 61 tCO_2/PJ on average, which is almost triple the carbon intensity of imports to China, 24 tCO_2/PJ. The energy intensity of China's exports is similarly high; in 2007, China consumed 22 MJ/$ of output, on average, or more than twice the energy intensity of products imported to China (9 MJ/$). This high energy intensity is underpinned by low value-added and less advanced technology of China's production, as previously suggested by other studies [16, 21] covering the 2002–2010 time period.

5.4 Summary

China's provinces are the most unbalanced regions globally in terms of trade-embodied carbon emissions and with world highest carbon-intensive export. Carbon-intensive production processes and products, such as mining, metal, and non-metal products from China and consumed worldwide, are responsible for making China the country with a significant carbon surplus. Carbon-intensive export is the most significant driver for such unbalanced carbon trade, by assuming the carbon intensity of exports which equal to the intensity of imports for China's 30 provinces, China's total export-embodied carbon emission could reduce to 233 Mt CO_2 from 1,671 Mt CO_2 in 2007, an 86 % reduction with the total amount of 1,438 Mt CO_2 equivalent to the total annual emission in Japan. Decarbonizing the carbon-intensive production of China's underdeveloped regions requires domestic and international efforts on improving the technology level, adjusting economic structure, and de-carbonizing the energy mix. China should improve the energy efficiency and (more broadly) the environmental performance of industrial practices in poor regions, perhaps by adopting technologies already used on China's east coast. Internationally, the gap between the emissions embodied in international exports from the most advanced regions in China in different sectors and the emissions embodied in international exports from the most advanced regions in the world imply that in the medium- to long-term international efforts could consider how to accelerate the diffusion of more advanced technologies to China and within China.

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Chapter 6
Policy Implications for China's Low-Carbon Development

6.1 Disaggregate National Targets into Regions

A single emissions reduction target cannot suit all of China's 30 provinces, which have different energy source mixes, uses, and economic development needs. Peak emission targets need to be designed for each region such that the aggregate sum falls by 2030.

Wealthy cities such as Beijing, Tianjin, and Shanghai that have already reversed emissions growth could cap their emissions and set reduction targets every 5 years. Developed coastal provinces such as Guangdong, Zhejiang, and Jiangsu that have benefited from the pilot emission trading scheme since 2010 should pledge more aggressive and rapid peak targets—such as reducing the current per capita carbon emissions below that of EU countries before 2030 or even 2020. Underdeveloped regions such as Shanxi, Ningxia, and Xinjiang provinces could be allowed to peak after 2030 to leave room for new infrastructure construction.

Fossil fuel use needs to be curtailed first. The state's ambitious plans for national coal consumption to peak by the end of this year at 3.9 billion tonnes and fall thereafter must be met. Beijing and Tianjin are required to halve their coal consumption by 2017 to meet mandated air quality requirements. All conventional coal-fired plants must be converted to gas by the end of 2015, and an additional 13 billion m^3 from western China and 12 billion m^3 of natural gas from overseas are being piped to Beijing and Tianjin, respectively. Smaller cities and other regions too must reduce their coal use.

China can strengthen technology-driven emission intensity (emission per unit of GDP) improvements, especially in less developed provinces. But loopholes also need to be overcome. Emission intensity targets should be supplemented by physical emission efficiency indicators, such as emission per unit production of steel. Such indicators are easier to monitor and verify and can be used to measure efficiency for sectors, as well as individual factories.

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Air quality indicators, such as particulate concentrations, can be integrated with emissions goals. They are currently treated separately. With NDRC in charge of climate change mitigation and the Ministry of Environment responsible for air pollution abatement, duplicate investments and work plans are common. Better coordination between departments and a set of joint emission measures—managed by one agency—are needed.

Climate targets must become decoupled from GDP. Further criteria by which both local and provincial leaders are evaluated for career promotion must include not simply economic development measures, but also the attainment of energy productivity and pollution abatement targets.

6.2 Low-Carbon Technology Revolution

China's economy can be decarbonized only by reducing energy demand and emissions together. Recycling could reduce total energy intensity by 90 % (22), with China one of the world's top producers of materials such as iron and steel. Schemes encouraging "urban mining" of scrap and exchanging by-products among regional factories will be needed. China recycled 70 million tons of steel carps in 2008, and China has potential to replace its 80 % primary steel production by recycling by 2050.

In renewable energy, China is leading the world. Its wind turbines and hydropower stations generated 45 and 720 million kWh in 2010, respectively; both are highest in the world (23). China's total installed renewable capacity (300 GW in 2011) is already twice the USA (146 GW in 2011). However, China is producing more renewable technologies than it is using. Its solar PV manufacturers made panels which could generate 40 GW in 2012, but less than 5 % of that installed domestically (24). Policy attention should focus on the implementation as well as capacity production. China invest world highest 680 billion US dollar in renewable industry in 2011, but further investments in the grid construction and market exploring are urgently needed for absorbing excess renewable capacity.

Great potential remains for low-carbon energy development and implementation in China. For example, further developing wind power alone could meet all the electricity demand projected by 2030, and introducing 640 GW wind capacity (with cost about 900 billion US dollars) over next 20 years will save 30 % of carbon emission in the period. Using China's waste gutter oil (as of 2010) for biomass fuel could reduce 90 million tons of CO_2 (26), equivalent to 14 % of total emission reduction from developing (Annex B in **Kyoto Protocol**) countries during 1990–2008.

Non-renewable options could contribute to the energy transition by creating buffering time for large-scale renewable use. China by now installed 13 GW nuclear power capacities (1 % of China's electricity production) and will increase it to the world leading 80 GW by 2020 (6 % of China's electricity production). Natural gas consumption could reach 250 billion cubic meters by 2020 with double-digit growth in 2010–2020, and the air pollutions such as SO_2 and NO_x can be fundamental reduced by replacing coal with gas. The advantages of these options should be acknowledged yet heavy investment need seriously considered due to their drawbacks in safety, cost, and environment impact.

Energy and emissions targets need to be decoupled from economic performance. Physical intensity indicators, such as emission per unit production of steel, should be used rather than relative economic intensity indicators. Similar to the consumption cap of 3.9 billion tons of coal by 2015, a total emission cap should be introduced to control rising emissions countrywide. Instead of simply shutdown the power plant when cap has been exceed, energy taxes or allowances would be needed to leverage the cap so that social and economic cost can be minimized.

Given one-third of China's emission reabsorbed by its enhanced afforestation and territorial ecosystem in 1980–2000, a carbon budget—considering both emissions and offsets from carbon sinks—should be introduced to reward mitigation efforts. This will encourage diverse measures such as reforestation and afforestation, waste management, and credits from carbon-free energy projects.

Regional compensation mechanisms would encourage technology improvements in poor areas at the expense of populous ones. Targets for industrial sectors rather than regions would lessen disparities between provinces. In order to prevent the "leakage" of the reduction cost among regions, consumption-based accounting should be used for regional emission calculation especially in electricity sector. Mitigation responsibilities should be required through supply chain of energy-intensive enterprises that headquarter in developed regions but leave their production in poor ones. Rigorous environmental standards need to be addressed poor center and west regions, where the environment is vulnerable and lack of protection awareness.

Market mechanisms should be introduced or enhanced. From production perspective, bonus such as tax free, subsidies, and policy facility is encouraged to promote advanced technology and low energy-intensive industries, such as cleaner production, integrated gasification combined cycle (IGCC), carbon capture and storage (CCS) for power plants, and cogeneration. From consumption perspective, step tariff is required since China's top 5 % consumer account for 25 % of electricity use. Moreover, energy market needs reform with transparent and concrete pricing system, which should dominate by energy supply and regulations instead of government intervention.

6.3 Expand Carbon Trading Nationwide

China's pilot ETS traded nearly 14 million tons of CO_2 (less than half percent of the national total) in 2013 but is the second largest such scheme in the world after the EU. The NDRC intends to extend the scheme to all 30 Chinese provinces starting in 2017, making China the world's largest carbon market. A national emission cap must be set and coordinated across the country.

In the pilot ETS, each province sets its own cap and decided which sectors it covered. For example, transport is included in Shanghai's ETS but not in the others. Each province has also determined how compliance is assured. Hubei targets enterprises consuming more than 60,000 tonnes of coal equivalent/year, a threshold 6 times that of Guangdong (10,000 tonnes of coal equivalent/year).

Central government should develop standards and a timeline to unify the cap criteria. The first step should be to introduce a national ETS for the top six emitting industries—power generation, ferrous and nonferrous metallurgy, construction, chemicals production, and aviation services—to be extended later to others. Regulations and laws are needed that make it mandatory for certain enterprises to trade emissions. Accounting and tax treatments need to be clarified.

A cascading management framework of carbon trading needs to be established, with provincial ETS exchanges linked to higher-level regional exchanges. For example, Beijing's exchange could coordinate provincial exchanges across Northern China.

Market mechanisms should be also introduced to the energy supply system. First, the monopoly of electricity and energy supply by major state-owned companies must be broken to encourage the innovation and efficiency improvement. Petro China and Sinopec, the two major state-owned oil companies, together take 80 % of the national oil supply and 10 % of the nation's total carbon emissions.

Second, an energy supply market needs to be set up to allow prices to respond to demand and incentives. The price for delivering energy to the grid is now controlled by the government and is largely static. This causes barriers for connecting renewable energy as low-carbon energy costs more price than thermal power. Subsidies for fossil fuels such as the contract price for selling coal to power plants need to be removed so that renewable and low-carbon energy technology can be competitive. Introducing a carbon tax in certain emission-intensive sectors—starting low and ratcheting up over the next decade—would slow coal and petroleum consumption.

By meeting the challenges we outline, China can lead the global climate mitigation movement and create a pathway toward sustainable, low-carbon development.