UNIVERSITY OF EAST ANGLIA

China Emissions Accounts and Low-Carbon Development in Cities

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Abstract

China, the world's second-largest economy, has witnessed a miracle in its economic growth. With lifestyle changes and rapid economic growth in China, China's CO_2 emissions have tripled during the past decades. China is now the world leading energy consumer and CO_2 emitter. China is playing an increasingly important role in global emissions reduction and climate change mitigation.

The accurate account of CO_2 emissions is the foundation of any emission analysis and further reduction actions. However, there are no official published emission inventories in China. All the previous studies calculated China's emissions by themselves, making the emissions inconsistent and incomparable with each other. The first part of this PhD thesis compiles the time-series Intergovernmental Panel on Climate Change (IPCC) territorial CO_2 emission inventories for China and its provinces from 1997 to 2015. The multi-scale emissions inventories are constructed in a uniform format (by 46 socio-economic sectors and 17 fossil fuels). An open-access database "ceads.net" is built based on this PhD study. CEADs is the first open-access emission database providing self-consistent and transparent data for China.

Chapter 4 finds that the total CO_2 emissions of China increased rapidly during the past 16 years with an average increase of 7.8% per year. The emissions peaked in 2013, at 9,534 million tonnes (Mt). The detailed analysis of the CO_2 emissions by sectors and fossil fuel sources finds that coal-related fuels and the manufacturing sectors, especially the "power and heat", are the primary contributor to the national emissions. Chapter 4 also examines the per capita CO_2 emissions and the emission intensity of China. The results show that the per capita emissions increased quickly from 2.4 (2000) to 6.7 (2015) tonnes, while the emission intensity keeps decreasing during the period. Both comparison and Monte Carlo uncertainty analyses are conducted to China's emissions. The result shows that the uncertainties of the national CO_2 emissions are roughly (-15%, 25%) at a 97.5% confidential level.

Similar analyses are conducted at the provincial level in Chapter 4 as well. The results show that Shandong emitted the most CO_2 cumulatively among the 30 provinces, followed by Hebei, Jiangsu, Guangdong, and Henan. The fossil fuel and sector-specific analysis of the provincial CO_2 emissions describe detailed emissions of each province.

The per capita emissions and emission intensities of each province are also presented in this study.

In order to have a better understanding of China's CO_2 emissions, Chapter 5 provides further analysis of emission characteristics of the lime industry and petroleum coke for the first time. The lime industry is the second largest process-related emission contributor followed by the cement. The results show that, in 2012, the process-related CO_2 emissions in China's lime production accounted for 141.72 Mt, while the electricity and fossil fuel-related emissions accounted for 55.95 and 4.42 (Mt) respectively. Further discussions of the reduction policy recommendations of China's lime industry are presented in this study based on the economic and environmental assessment of different lime kilns. As for the petroleum coke consumption, its combustion produced 26.2 Mt CO_2, 807 tonnes CH_4, and 137 tonnes N_2O in 2014. The petroleum coke-related emissions are increasing fast. During the past five years, its emissions increased by 87%, which is remarkably high compared to the 19.4% growth rate of total CO_2 emissions in China. Considering the petroleum coke is a dirty and un-environmental friendly fossil fuel type, the quick growth of petroleum coke consumption should be of serious concern to the government.

Further to the national and provincial emission inventories, Chapter 7 examines the CO_2 emissions from Tibet and its cities. This is the first study to quantify Tibet's emissions. The results show that Tibet emitted a total of 5.52 Mt of CO_2 related to fossil fuel combustion and cement production in 2014. The per capita and emission intensity of Tibet are much lower than the national average level. The city-level analysis shows that over half of Tibet's CO_2 emissions are induced in Lhasa city.

The second part of this PhD thesis examines the CO_2 emissions from Chinese cities and discusses the possible low-carbon development pathways of cities at different industrialisation and development stages. Being the basic units for human activities and major contributors to emissions, cities are major components in the implementation of climate change mitigation and CO_2 emission reduction policies. Increasing attention is now being paid to city-level emission reduction and climate change mitigation in China.

Chapter 3 firstly develops a series of methods to compile CO_2 emission inventories for Chinese cities with different data availabilities. The emission inventories of cities are constructed with the consistent scope and uniform with the national and provincial emission inventories calculated above. Chapter 6 then applies the methods to examine emissions characteristics in 182 cities. The results show that the top-emitting cities represent a disproportionately large fraction of the total emissions from the 182 cities. The top five emitting cities (Tangshan, Shanghai, Suzhou, Nanyang, and Chongqing) accounts for 11% of the total emissions. More high-emitting cities can be found in northern and eastern China compared with other regions.

Chapter 6 further applies the cluster analysis to cluster the 182 case cities into five groups with distinct pillar industries describing their different industrialisation stages and development pathways. The results find that there is labour division among Chinese cities, the most developed cities (service-based and high-tech industry cities) are supported by nearby manufacturing cities. In turn, the manufacturing cities are supported by nearby energy production centres. In this way, different cities should have different low-carbon roadmaps designed based on their current industrialisation stages and development pathways.

Chapter 6 also finds that efficiency gains could be a practical and effective way to reduce CO_2 emissions. The sectoral-based calculation of the cities' emission reduction capacities via technical improvements show that up 31% of the 182 cities' emissions can be reduced if the strongest reduction strategies been applied. The results suggest that China's near-term goals of reducing its emissions intensity may be feasibly accomplished by targeted technological improvements, buying time for the longer-term strategies of shifting to non-fossil energy and a more service-based economy. Moreover, improving and optimizing the energy and carbon efficiency of industrial production processes and operations could help lower the costs of advanced technologies and thus facilitate their deployment in less-developed cities and countries beyond China.

This PhD study has great real-world significance and has filled in several research gaps in China's emission accounts and cities' low-carbon development. The research also provides solid and robust data support for future academic research on China's emission topics and emission reductions policy-making in China. First of all, this PhD study provides the first open-access China emission database providing the multi-scale CO_2 emission inventories. Secondly, this PhD study analyses the detailed emission characteristics of China, its provinces, and cities, as well selected key industries. Specific and efficient emission control policies targeting the major emission sources are discussed based on the analysis. Also, based on the city-level emission accounts, this PhD study analyses the low-carbon roadmaps for cities at different industrialisation stages and development pathways.

Furthermore, considering the wide ranges of Chinese cities' industrialisation maturity, the cross-section analysis of China's cities may disclose the emissions characteristics of the whole industrialisation process. The emission reduction roadmaps designed in this study for cities at different industrialisation stages also provide references for other developing countries at similar stages of industrialisation.

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PhD Achievements

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Principal Investigator of Eastern ARC Workshop / Research Fund, China's new normal on CO_2 emissions and its impact on low-carbon development: Integrated analysis of Energy-Environment-Economy nexus, £725

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Chinese Government Award for Outstanding Self-Financed Students Abroad, China Scholarship Council, 2016, $6,000

Applied Energy Highly Cited Original Paper, Applied Energy and Elsevier, 2016

PGR Prize for Best Paper, Social Science Faculty, University of East Anglia, 2014-2015, £200

Award for Publication, School of International Development, University of East Anglia, 2015 / 2016 / 2017, £500

Joint Leverhulme Trust and Social Sciences Faculty Postgraduate Studentships at the University of East Anglia, 2014-2017, £14,000 per annual plus tuition fee

Reviewer of the Special Report on Global Warming of 1.5 °C of Intergovernmental Panel on Climate Change (IPCC)

Reviewer of Applied Energy (IF=7.182), Journal of Cleaner Production (IF=5.715), Earth's Future (IF=4.938), Scientific Data (IF=4.836)

Membership of the American Geophysical Union (AGU), the International Society for Industrial Ecology (ISIE)

Software copyright "Multi-scale emission calculator for China", National Copyright Administration of China, 06/12/2017

Chapter 1 Introduction

1.1. China's CO_2 emissions growth

China, the world's second-largest economy, has witnessed a miracle in its economic growth. The Gross Domestic Product (GDP) of China has increased over 180 times since 1978 when China began its 'opening up' policy. China's real GDP increased 29 fold from 1,321 in 1978 to 39,896 billion yuan in 2015 (at 2000 constant price, see the yellow bars in Figure 1-1). With lifestyle changes and rapid economic growth in China (Hubacek et al., 2011), energy consumption in China has increased rapidly. The total energy consumption increased from 586 in 1980 to 4,022 Mt's standard coal equivalent (Mtce) in 2015 (NBS, 2016a). China is now the world's largest consumer of primary energy (Guan et al., 2009) and consumes 20.3% of global primary energy every year (BP, 2011).

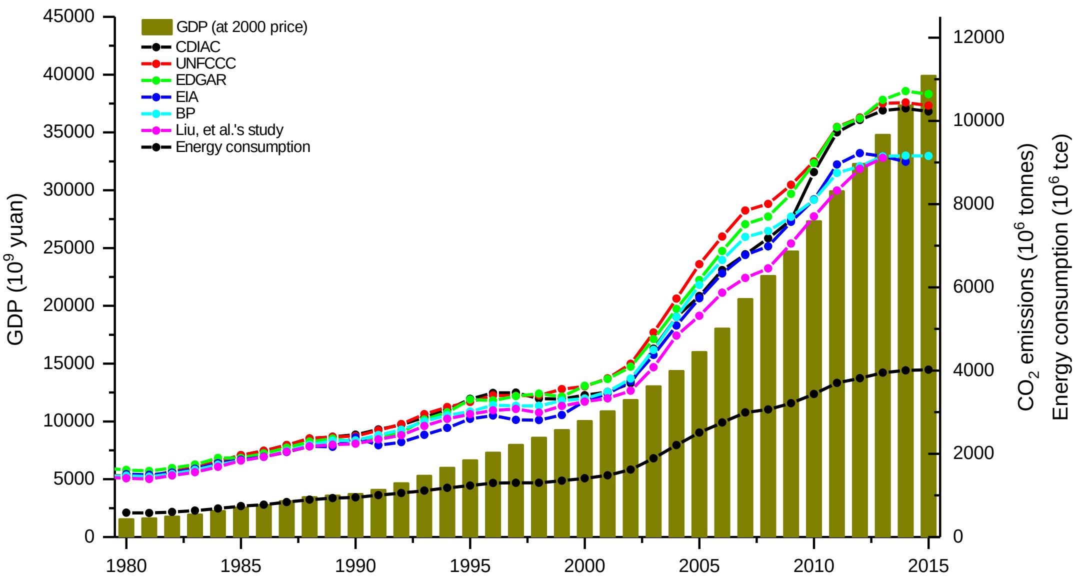

Figure 1-1 China's GDP, Energy consumption, and CO_2 emissions, 1980-2015
Data source: GDP at 2000 constant price (NBS, 2016b), Energy consumption (NBS, 2016a), Carbon Dioxide Information Analysis Centre (CDIAC) (Boden et al.; Le Quéré et al., 2016), Emission Database for Global Atmospheric Research (EDGAR) (Olivier et al., 2016), U.S. Energy Information Administration (EIA) (EIA), British Petroleum (BP) (BP, 2016), Liu, et al.'s study (Z. Liu, Guan, et al., 2015)

This huge energy consumption has led to high levels of greenhouse gas emissions. China's CO_2 emissions have increased rapidly in the past decades. Figure 1-1 presents China's CO_2 emissions growth estimated by different academic/research institutes. It should be noted that the Carbon Dioxide Information Analysis Centre (CDIAC), Emission Database for Global Atmospheric Research (EDGAR), and Liu et al.'s estimates include both CO_2 emissions from fossil fuel consumption and cement production. U.S. Energy Information Administration (EIA) and British Petroleum (BP) estimates do not include process emissions from cement production.

Figure 1-1 shows that China's CO_2 emissions rose steadily and slowly in the pre-WTO era (1978-2002). Taking data from CDIAC as an example, the CO_2 emissions increased from 1,462 to 3,694 Mt during this period, at a rate of 8% per year. Then China witnessed a quick emission growth from 2002 to 2007. The annually averaged growth rate between the periods reached 13%. This expansion led China to surpass the U.S. in 2006, to become the world's top CO_2 emitter (Guan et al., 2009). As a result of the rapid growth in China's CO_2 emissions, China now accounts for approximately 28% of global emissions, see Figure 1-2. In the pre-2000, China accounted for less than 15% of global emissions (8% in 1978 and 15% in 2005).

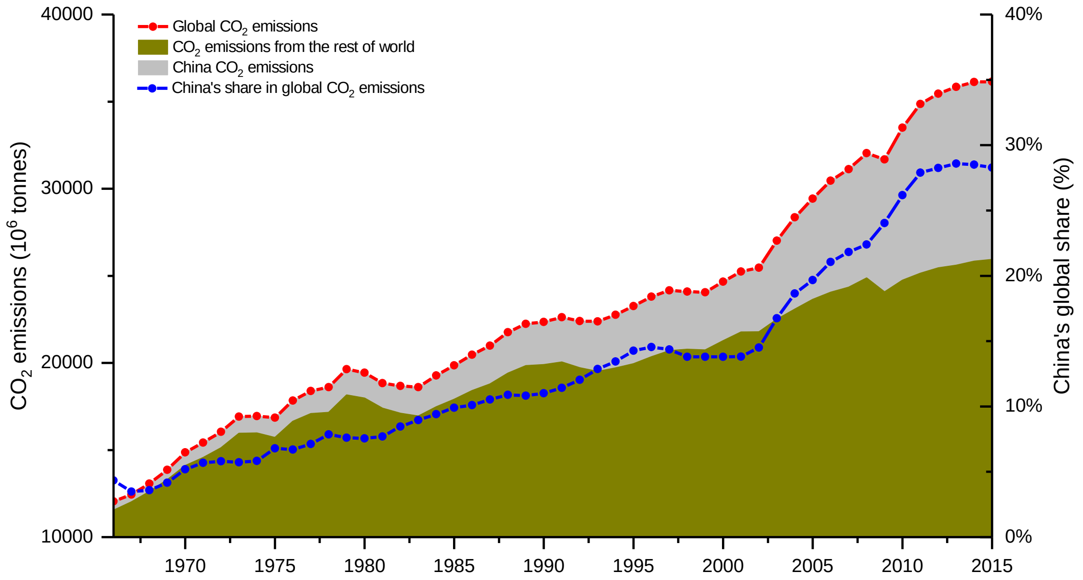

Figure 1-2 China and global CO_2 emissions, 1966-2015
Data source: CDIAC (Boden et al.; Le Quéré et al., 2016)

1.2. China's ambitious reduction plans and its global impacts

China has initiated an ambitious plan to fight climate change. The government has already undertaken a series of emissions controls under the central commanding administration. A number of policies have been developed during the past decades.

In June 2007, the National Development and Reform Commission (NDRC) promised to increase its efforts to control China's greenhouse gas emissions and make a reduction of 20% in energy intensity (per GDP energy consumption) by 2010 in the "National Scheme on Climate Change" (NDRC, 2007b). Mandatory environmental targets have also been formally written into the national Five-year Plans. In the 11^{th} Five-year Plan (2006-2010), China issued targets for a 20% reduction in energy intensity (NDRC, 2006b;2007a). In the 12^{th} Five-year Plan (2011-2015), China introduced a market-based domestic emission trading scheme. The mechanism underlying the trading system has now been established in 7 pilot markets (NDRC, 2011b;2011c;2013a).

Since 2014, the Chinese government issued more policies to control climate change and took on further responsibilities. In September 2014, NDRC published the "National Scheme on Climate Change (2014-2020)" which stated that by 2020, emission intensity (per GDP CO_2 emissions) would drop 40-45% compared to the year 2005 (NDRC, 2014). China announced that it would peak its CO_2 emissions by 2030 under the "U.S.-China Joint Announcement on Climate Change" (The White House, 2014), released during the Beijing APEC meeting in November 2014. In 2015, in the report "Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions" submitted to the United Nations Framework Convention on Climate Change (UNFCCC), the Chinese government updated its emission intensity reduction target. The government promised to achieve a 60-65% reduction in China's emission intensity by 2030 compared with its 2005 level (The Chinese Government, 2015). In 2016, China announced the launch of a nation-wide emission trading scheme from 2017 based on current pilot schemes operating in 5 cities (Beijing, Shanghai, Tianjin, Chongqing, and Shenzhen) and 2 provinces (Hubei and Guangdong) (J. H. Davis et al., 2015) to help to deliver its CO_2 emission peak by 2030. This implies more climate change actions will be focused and conducted at more downscale levels in the near future, such as city.

China is now playing an increasingly important role in global emissions reduction and climate change mitigation.

From one side, the above emission reduction actions have already significantly reduced global emissions. For example, China's restrained policies on coal consumption and its encouragement of policies on renewable energy development have resulted in global emissions decreases in 2015 for the first time (Le Quéré et al., 2015). Furthermore, the "60-65%" emission intensity decreasing target promised by China in the Paris Agreement will further reduce the country's emissions in the next decades. Considering the large amount of China's current emissions, such an emission intensity decreasing action will profoundly contribute to global emissions reduction and climate change mitigation.

From the other side, China is demonstrating more and more leadership on global climate change mitigation. After the United States withdrew from the Paris Agreement, many were concerned that the United States was giving up its leadership on global climate change actions, meanwhile, China should take more responsibility (H.-B. Zhang et al., 2017). Indeed, the United States withdrawing from the Paris Agreement has been a critical influence on China. A recent analysis using the CGE model found that by withdrawing from the Paris Agreement, the United States would gain more carbon emission spaces as well as lower carbon prices (H.-C. Dai et al., 2017). In turn, less emission spaces are left to other countries, especially China, the world's largest developing country. Considering these factors, the Chinese government has already taken actions to lead the global climate change fight. For example, China convened a high-level meeting of energy ministers from countries to discuss how to deploy clean energy as soon as the United States quite the Paris Agreement in June 2017 (TIME, 2017).

1.3. Huge uncertainties and discrepancies in China's CO_2 emission accounts

An accurate account of CO_2 emissions is the foundation of any emission analysis and further reduction actions. The quality of emission data has been formally written into the "Paris Agreement": "*In accounting for anthropogenic emissions and removals corresponding to their nationally determined contributions, Parties shall promote environmental integrity, transparency, accuracy, completeness, comparability and consistency, and ensure the avoidance of double counting…(Article 4, Adoption of Paris Agreement)*" (UNFCCC, 2015).

As for China, accurate emission data is not only the first step towards achieving its emissions reduction targets but also the foundation of assessing its reduction actions'. For example, China has promised to reduce its emission intensity by 40-45% and 60-65% by 2020 and 2030, respectively. Both the targets' base years are set at 2005. Therefore, accurate accounts of the 2005 CO_2 emissions is particularly important. Different emission accounts of 2005 may lead to different emission cuts as well as the remaining carbon space until 2030. However, CO_2 emission accounts for China are not well documented. There is no annual, officially published emission report in China. The Chinese government has only published national CO_2 emissions three times: in 1994 (NDRC, 2004), 2005 (NDRC, 2013c), and 2012 (NDRC, 2016b).

Some research institutions publish China's total CO_2 emissions annually (Boden et al.; BP, 2016; EIA; Le Quéré et al., 2016; Olivier et al., 2016). However, their estimates exist huge discrepancies (Guan et al., 2012b; Pan et al., 2013; Shan, Liu, Liu, et al., 2016). In 2013, the discrepancy between their estimates exceeded 1,300 Mt (15%), see Figure 1-1. The 1,300 Mt gap is approximately equal to Japan's total emissions in 2011 (1,243 Mt, CDIAC), even higher than total emissions from Africa (1,267 Mt, CDIAC). Considering that Japan was the 5th top-emitter in the world at that time (European Commission, 2016), discrepancies in China's emission accounts should not be underestimated. Compared with China's three official CO_2 emissions for 1994, 2005, and 2012, estimates by international academic institutes have been relatively high. In 2012, as an example, EDGAR and CDIAC reported China's CO_2 emissions as 10,057 and 10,020 Mt, respectively. The estimations were 8% higher than the official estimate, which was 9,323 Mt (NDRC, 2016b). Furthermore, all the existing datasets only present the national total CO_2 emissions. There are scarcely any open-access datasets providing the CO_2 emission inventories constructed according to fossil fuel types and industrial sectors for China, its 30 provinces, and hundreds of cities.

Apart from the discrepancies and uncertainties, China's current emission accounts are uncompleted. For example, most of the previous studies focused on the fossil fuel- and cement-related emissions only (Gregg et al., 2008a; Yu Lei, Zhang, et al., 2011a; Y. Lei, Zhang, et al., 2011b; Y. Liu et al., 2009; Z. Liu, Guan, et al., 2015). There are seldom studies examining the process-related CO_2 emissions from other industrial processes besides the cement production. Indeed, the cement production is the largest emission source of process-related emission in China's industry. However, some other emission sources need deeper analysis as well to better determine the emission characteristics of China. In particular, there are still no studies discussing the emissions from the lime industry in China. The lime industry is the second largest process-related emission source in China, the emission characteristics and reduction policies should therefore be discussed in detail. Also, previous studies mainly focused on the emissions from traditional energy sources such as raw coal, cleaned coal, crude oil, gasoline. Few studies involved the emissions from some newly-appeared and fast-growing energy sources, such as the petroleum coke. What's more, due to a lack of data and its small quantity, the CO_2 emission from Tibet is missing, making China's national and provincial emission accounts incomplete.

In order to fill this research gap, this PhD study compiles the time-series CO_2 emission inventories for China and its provinces from 1997 to 2015. The emissions are calculated based on the mass balance theory using two approaches, the sectoral and reference approaches. The inventories are constructed based on data from 46 socio-economic sectors and on 17 fossil fuels. The uniform-formatted emission inventories provide solid and robust data support for emission reductions policy-making in China. The study also examines the emission status of key industries in China, such as the lime industry and petroleum coke, as well as emissions from Tibet and its cities.

1.4. Cities are the central to global climate change mitigation and emission reductions

In spite of there not being a definition of "city" in the Paris accord and the SDGs, in all the submissions focused on the national level, cities are considered as the major components in the implementation of climate change mitigation and CO_2 emission reduction policies.

First of all, cities are the basic units for human activities (Van den Hoven et al., 2012), and the main consumers of energy and emitters of CO_2 throughout the world (Satterthwaite, 2008; Yufei Wang et al., 2015). As a result of urbanization, the world's urban population grew from 220 million in 1900 (13% of the world's population) to 3,530 million in 2011 (52% of the world's population) (Kennedy et al., 2015). The International Energy Agency (IEA) estimates that CO_2 emissions from energy use in cities will grow by 1.8% per year between 2006 and 2030, with the share of global CO_2 emissions rising from 71% to 76% (IEA, 2009). As for China, energy usage in cities accounts for 85% of total emissions, which is much higher than those of the USA (80%) or Europe (69%) (Dhakal, 2009;2010).

The high energy demand and huge CO_2 emissions of cities not only increase the natural resources crisis and environment press, but also increase the residents' health problems through air pollution (Kan et al., 2009). For example, the smog and $PM_{2.5}$ have been seen as a first-line index to measure one city's air and environmental quality in China since 2013 (Z. Li et al., 2017).

What's more, city inhabitants suffer from other climate change problems. Around 90% of the prosperous urban area are located near the coast (Skah, 2016). They are exposed to greater risk of flooding caused by global warming and the associated sea level rise. Other interior cities also face the danger from extreme weather, geological hazards, urban waterlogging, etc. induced by climate change. Therefore, the cities have the motivation to deal with the climate change.

Fourthly, without the support from cities, the national policies cannot be executed effectively. Despite the fact that climate policies are usually designed at the national level, they are actually implemented at the city level. Also, considering the cities' different natural resources endowments and development pathways, each city should have some specific emission reduction actions designed based on its unique emission characteristics. In China, this is particularly true. There are over 330 cities in China, which are at different stages of industrialisation with distinct development pathways. Therefore, cities are the key components in the climate change policy making.

Above all, cities are the central to global climate change mitigation and emission reductions. Many low-carbon projects and actions have been taken at the city-level, such as the Local Governments for Sustainability (ICLEI) and C40 Cities Climate Leadership Group (C40).

The ICLEI is one of the main organisations for such efforts. ICLEI is made up of 200 local governments from 43 countries in 1990, and now involves more than 1500+ local governments from 100+ countries[3]. ICLEI currently launches 10 urban initiatives that help the city government deal with changes and promote sustainability[4], such as

[3] http://www.iclei.org/about/who-is-iclei.html
[4] http://www.iclei.org/agendas.html

"sustainable city", "low-carbon city", "sustainable local economy and procurement", "resource-efficient and productive city". Such efforts have already helped dozens of cities undertaken climate change and emission reduction actions. Despite dozens of cities from developing countries such as Brazil, India, South Africa, Indonesia, Philippines have joint the ICLEI. However, Chinese cities have low participants in the ICLEI, only Guiyang and the 'Sino-German industrial zone' in Foshan join the ICLEI[5].

By contrast, Chinese cities are very active participants in the C40 Group. C40 is a global network of 43 megacities from 34 countries, which focuses on addressing climate change and driving city's low-carbon actions. There are 10 Chinese cities in the group: Beijing, Chengdu, Dalian, Guangzhou, Hong Kong, Nanjing, Qingdao, Shanghai, Shenzhen, and Wuhan[6]. What's more, Chinese cities are taking significant roles in the C40 cities group. For example, Wuhan hosted a workshop held by the C40, World Resources Institute (WRI) and China Quality Certification Centre (CQC) in June 2017 to discuss how to develop emission inventories and share carbon reduction experiences.

A major reason there are different levels of participation by Chinese cities in the ICLEI and C40 group is that membership of either of the two international societies is not a legal requirement in China. The Chinese local governments have their own initiatives to join any of them. Also, in China's performance reviews of local government officials, economic growth (i.e. GDP) has been seen as the only achievement. There have been no evaluations on 'climate change mitigation', 'emission reductions' or 'low-carbon development' for a long time (Z. Liu et al., 2013). Even the official Low-carbon City Pilots programme (LCCPs), which is launched by NDRC from 2010 to 2012, only captured 36 cities (Yufei Wang et al., 2015).

Above all, it has been a global trend to focus the climate change mitigation and emission reductions at a city level, especially for China. Emission accounts and low-carbon development for Chinese cities are urgently needed.

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[5] http://www.iclei.org/iclei-members/iclei-members.html
[6] http://www.c40.org/cities

1.5. Emission accounts and low-carbon development for Chinese cities are urgently needed

Since the early 2000s, both the central and local governments of China have been seeking a series of energy and emissions reduction measures at city-level (NDRC, 2007a;2007b;2011b;2013a;2014; The White House, 2014). One of the most recent high-level initiatives is that China launched the "Emission Trading Scheme (ETS)" nationwide in the 19th December 2017. Under this scheme, energy consumption and CO_2 emissions are monitored and controlled at the city and firm level. The central government sets the overall emission quota, then the emission quota is allocated to each plant by the local government (provincial and city-level). The first stage ETS includes the power plants only. The power sector is the largest emission sources in China, contributes around 40% of the national total emissions every year. The energy and emission data of the power sector can be easily accessed. In China, all the power plants are state-owned business, the energy consumption and emission are consistently and systematically recorded by the State Electricity Regulatory Commission and the National Energy Administration. However, if the ETS is promoted to city-level of other industry sectors, the emission data can be a non-negligible constraint. Therefore, understanding the emission status of cities is urgently required in China.

1.5.1. The definition and management of Chinese cities

Chinese cities are defined as the prefecture-level administrative units in this study and span both urban and rural geographies. According to the latest administrative planning report, there are currently 338 cities in China (NBS, 2015a). Among the 338 cities, four of them are municipality cities, which are directly controlled by the central government: Beijing, Shanghai, Tianjin, and Chongqing.

Normally, the 338 cities are classified into six tiers based on the comprehensive assessment of indexes such as economic, population, welfare level, education resources, and medical resources (R. Yang, 2008). Four cities are classified as the 1st Tier: Beijing, Shanghai, Guangzhou, and Shenzhen. These three cities represent the most developed level in China. 15 cities belong to the 2nd Tier: Chengdu, Hangzhou, Wuhan, Chongqing, Nanjing, Tianjin, Suzhou, Xi'an, Changsha, Shenyang, Qingdao, Zhengzhou, Dalian, Dongguan, and Ningbo. Most of them are provincial capital cities. Another 30, 70, 90 cities belong to the 3rd, 4th, and 5th Tiers. The remaining 129 undeveloped cities are the 6th Tier (L. Wang, 2014).

Each city is managed by one local party committee and one local authority in China. The city's party committee reports to the provincial party committee, and the city's government reports to the provincial party government. In order to fit with the western political system, there is a dual system of government at a city level. The city's party secretary and mayor are the top leaders of one city, they take responsibility for the party committee and government, respectively. However, the management of the city's party committee and government are not mutually independent. The secretary manages the party affairs of one city with the support from the government, while the mayor manages the city with support from the party committee. The city-level policies are usually made by the city's government under the supervision of its provincial government (Z. Fang, 2003; G. Li et al., 2008; Q. Liu, 2013).

1.5.2. Emissions of Chinese cities

Due to data deficiency, CO_2 emissions of Chinese cities are not well documented, among the 300+ Chinese cities, only a few megacities with consistent energy data (Beijing, Tianjin, Shanghai, and Chongqing) have time-series emission accounts (Q. Chen et al., 2017). Another 300+ cities of various sizes and stages of development lack consistent and systematic energy statistics.

The compilation of greenhouse gas emission inventories at the city level for China represents a considerable challenge. First, it is difficult to define a city's boundary for greenhouse gas emissions accounting because energy and material flow among cities may bring a large quantity of cross-boundary greenhouse gas emissions (S. Liang et al., 2011; Wolman, 1965). Commercial activities are much more frequent in cities, compared with inter-provinces/nations, which is another significant challenge. Second, data for energy consumption and industrial products are very limited for most cities in China and also non-comparable (Z. Liu, Liang, et al., 2012). Data used in previous studies are from various sources, including city statistical documents, remote sensing images, direct interviews with local governmental officials, and published reports/literature (Xi et al., 2011). Those data require systematic reviews for consistency and accuracy.

Aiming to address this research gap, this study develops a series of methods to construct the emission inventories for Chinese cities with different data availabilities. This study then constructs the emission inventories for hundreds of cities using the methods. The city-level emission inventories calculated in this study have the consistent scope and format of national and provincial inventories, making comparisons between inventories possible.

1.5.3. Cities' industrialisation stages and low-carbon developments

At the 19th national congress of the communist party of China held in October 2017, the Chinese central government plans to eliminate nationwide poverty by 2020. This means that economic development is still the first important task in current China. In the next five to ten years, China will continue to promote economic growth and its focus on the real economy's development. However, the economic growth is a key driver for CO_2 emissions according to previous studies (Chertow, 2001; Peters et al., 2012), showing a strong correlation with energy consumption as well (Govindaraju et al., 2013; F. Li, Dong, et al., 2011). Much work has been done to explore the balance between economic growth and efforts to reduce CO_2 emissions (De Bruyn et al., 1998; Suri et al., 1998). How to achieve low-carbon development needs serious consideration. The reduction of energy consumption and emissions should be designed to avoid excessive economic problems. Taking into consideration that cities in China may be at different stages of industrialisation and development, the low-carbon roadmaps of cities should be designed in consideration of their individual stage of industrialisation and development.

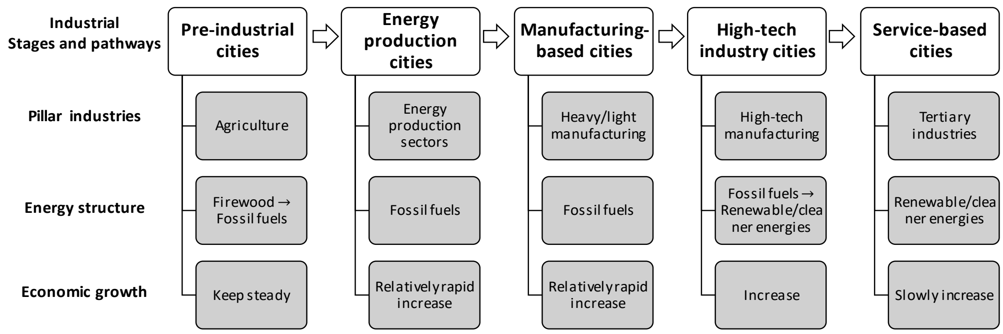

Figure 1-3 Industrialisation and development stages of cities

Note: The industrial stages and pathways are developed based on Fitzgerald (2010); the transitions of cities' energy structure are developed based on Fouquet et al. (2012); the transitions of cities' pillar industries and economic growth are developed based on H. Shen (2005), Chenery et al. (1986), Laitner (2000), and Jun Zhang (2002).

Following the industrialisation process, cities can be categorised into five stages, see Figure 1-3.

The first category is pre-industrial cities, of which the main industry is agriculture, including farming, forestry, animal husbandry, and fishery conservancy. The major energy source in these cities is firewood. The economy is stable or grows slowly. For example, most cities in Tibet and Xinjiang are still at the pre-industrial stage.

Beyond the pre-industrial stage, some cities develop energy production or manufacturing. This makes these cities energy producers or manufacturing-based in which fossil fuels are the major energies used. During the energy production and manufacturing stage, there is a rapid increase in both industrial output and wealth.

After decades of development, some manufacturing cities undergo a comprehensive economic structural transformation. Their pillar industries are transformed from energy production, heavy-/light-manufacturing to high-tech manufacturing. Some of them even come to rely extensively on the service sectors (i.e., tertiary industries). These cities represent the most developed and advanced level of industrialisation. They produce high value-added products with little resource consumption. They usually have the lowest per capita emissions and emission intensities compared with cities in other categories, due to less energy-intensive industry structure and cleaner energy mix. The renewable and cleaner energies (such as solar power, nuclear and imported electricity) make up larger proportions of the high-tech or service-based cities' energy mix compared with cities in other categories. Economic growth usually slows down in these cities and remains steady at a high-level.

Considering the different industrialisation stages and development pathways of Chinese cities, this study firstly clusters the hundreds of Chinese cities into five groups with different pillar industries, describing their particular industrialisation stages and development pathways. This study then calculates the emission reduction capacities of cities via technical improvements. Low-carbon roadmaps are discussed for cities at different industrialisation and developmental stages.

Considering the wide ranges of Chinese cities' industrialisation stages (some developed cities in China are at the post-industrialisation stage while the rural and remote regions in China are still at the beginning stage of industrialisation), the cross-section analysis of China's cities may disclose the emissions characteristics of the whole industrialisation process. The emission reduction roadmaps designed in this study for cities at different industrialisation stages also provide references for other developing countries at similar stages of industrialisation.

1.6. Research purpose, objectives, and framework

1.6.1. Research purpose and objectives

Considering the large discrepancies/data gaps in China and its regional CO_2 emission accounts, this study firstly calculates China's multi-scale (national, provincial, and city-level) CO_2 emissions status based on mass balance theory. Methods for city-level energy data collection are developed. The Monte Carlo simulation method is employed to discuss the reliability of the estimated CO_2 emissions. Then, using cluster analysis, the study clusters the hundreds of Chinese cities into five groups with different pillar industries, describing their distinct industrialisation stages and development pathways. Lastly, the emission reduction capacities of different city groups are estimated and possible low-carbon roadmaps for cities are discussed. The specific objectives of this research are:

- To compile CO_2 emission inventories of China and its provinces from 1997 to 2015. The emissions are calculated based on updated emission factors and the most up to date energy activity data. The inventories are constructed using both sectoral and reference approaches. The emissions include 17 fossil fuels burned in 46 socioeconomic sectors (fossil fuel-related emissions) and those from cement production (process-related emissions);
- To analyse the CO_2 emissions from China's lime industry, petroleum coke consumption, and Tibet/its cities, which are previously blank;
- To develop a series of feasible methodology for city-level energy activity data collection with different data availabilities;
- To construct CO_2 emissions inventories for 180+ Chinese cities. The city-level emission inventories have the same scope and format of national and provincial inventories, making them comparable and consistent with each other;
- To identify the pillar industries of the 180+ Chinese cities and group them into five groups at different industrialisation stages and development pathways;

- To estimate the CO_2 emission reduction capacities via technical improvements for each city group, and discuss possible low-carbon development roadmaps of cities.

This study has great real-world significance and has filled in several research gaps in China's emission accounts and cities' low-carbon development. The research also provides solid and robust data support for future academic research on China's emission topics and emission reductions policy-making in China. First of all, this study provides the first open-access China emission database providing the multi-scale CO_2 emission inventories. Secondly, this study analyses the detailed emission characteristics of China, its provinces, and cities, as well selected key industries. Specific and efficient emission control policies targeting the major emission sources are discussed based on the analysis. Also, based on the city-level emission accounts, this study analyses the low-carbon roadmaps for cities at different industrialisation stages and development pathways.

Furthermore, considering the wide ranges of Chinese cities' industrialisation stages, the cross-section analysis of China's cities may disclose the emissions characteristics of the whole industrialisation process. The emission reduction roadmaps designed in this study for cities at different industrialisation stages also provide references for other developing countries at similar stages of industrialisation.

1.6.2. Research framework and thesis structure

Figure 1-4 presents the overall framework for this PhD study. The whole study is formed by two parts: "China emission accounts" and "Low-carbon development in cities".

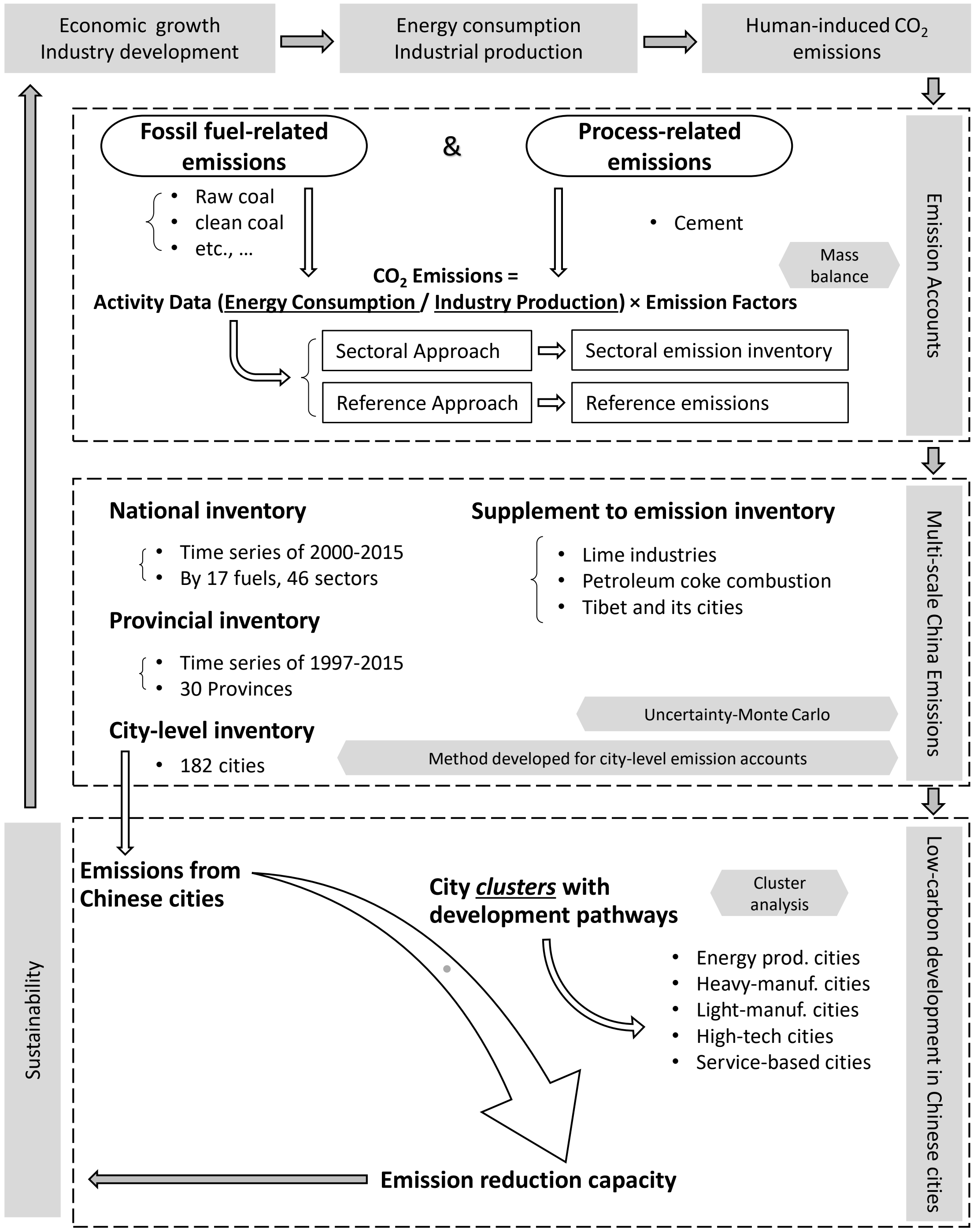

Figure 1-4 Research framework

This thesis consists of 8 chapters. Chapter 1 introduces the study. Chapter 2 provides background information and discusses previous studies in the relevant fields. Chapter 3 presents the methods used in this study. The innovations in methods of city-level emission accounting are developed in section 3.5 of Chapter 3.

Chapter 4 to Chapter 7 are result chapters. Chapter 4 discusses the emissions of China and its provinces. Section 4.1 presents the national CO_2 emission inventories from 2000 to 2015, calculated using both a sectoral-approach and reference-approach. Section 4.2 presents time-series CO_2 emissions and socio-economic indexes of 30 Chinese provinces from 1997 to 2015. Section 4.3 discusses the uncertainties of the estimated emissions and comparisons with other existing inventories.

Chapter 5 examines the CO_2 emissions characteristics of China's key industries. Section 5.1 discusses CO_2 emissions from the lime industry, which is the second largest process-related emissions source; section 5.2 examines the emissions from petroleum coke consumption, a rapidly increasing energy type in China.

Chapter 6 discusses the CO_2 emissions and low-carbon development pathways of Chinese cities. In Section 6.1, this study illustrates the CO_2 emissions of 180+ cities. Section 6.2 clusters the 180+ Chinese cities into five groups. The emission reduction capacities via technical improvements and low-carbon roadmaps for city groups at different industrialisation and development stages are then discussed in Section 6.3.

CO_2 emissions from Tibet and its cities were calculated separately using a different method and these are presented in Chapter 7. This is the first English language study to examine CO_2 emissions of Tibet and its cities, thereby providing an important supplement to national and provincial emissions data.

Chapter 8 summarizes the major conclusions and limitations of the whole study. Ideas and proposals for future research are also presented in Chapter 8.

The work of Chapter 3 to Chapter 7 has been integrated into six journal papers, four of them have been accepted and published (see the Appendix at the end of the thesis). The author acknowledges all the contributions by the co-authors. The publications are jointly published with several colleagues, the author of this PhD thesis is the first author of all the publications. The author contributes over 85% of the publications by leading the studies, analysing the data, and writing the drafts. The permissions of all the copyrights have been approved by the co-authors and publishers already.

The city-level method design in Chapter 3 has been integrated into a journal paper submitted to the *Journal of Cleaner Production*, which has been accepted and published (DOI 10.1016/j.jclepro.2017.06.075). The work of Chapter 4 has been integrated into two journal papers. One submitted to the journal *Applied energy*, which has been accepted and published (DOI 10.1016/j.apenergy.2016.03.073); and the other one submitted to *Scientific Data*, which has been accepted and published (DOI 10.1038/sdata.2017.201). The work of Chapter 5, section 5.1 has been integrated into a journal paper submitted to the journal *Applied Energy*, which has been accepted and published (DOI 10.1016/j.apenergy.2015.04.091). The work of Chapter 5, section 5.2 has been integrated into a journal paper, which is accepted by the journal *Applied Energy*. The work of Chapter 6 has been integrated into a journal paper accepted by the journal *Science Advances*. The work of Chapter 7 has been integrated into a journal paper submitted to the *Earth's Future*, which has been accepted and published (DOI 10.1002/2017EF000571).

Table 1-1 below shows the notations and abbreviations used in this PhD thesis.

Table 1-1 Notations, abbreviations in this PhD study

Notations and abbreviations	Explanations
AD_i	Consumption of fossil fuel i of the whole industry
AD_{i-ADS}	Consumption of fossil fuel i at ADS scale
AD^*_{i-ADS}	Comprehensive energy consumption of sector j at ADS scale
AD_{ij}	Consumption of fossil fuel i in sector j
AD_{ij-ADS}	Consumption of fossil fuel i in sector j at ADS scale
AD_t	Production of industrial process t
ADS	Short for "Industrial enterprises above designated size"
BP	British Petroleum
CDIAC	Carbon Dioxide Information Analysis Centre
CE_{ij}	CO_2 emissions from fossil fuel i combusted in sector j
CE_t	CO_2 emissions from industrial process t
CHRED	China High-Resolution Emission Gridded Data
EBT	Energy balance table
EBT_{city}	City's energy balance table
$EBT_{province}$	Provincial energy balance table
EDGAR	Emission Database for Global Atmospheric Research
EF_i	Overall emission factor of fossil fuel i
EF_t	Emission factor of industrial process t
EIA	U.S. Energy Information Administration
GDP	Gross domestic products
GIS	Geographic Information System
i (subscript)	Fossil fuel type
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
j (subscript)	Sector
m	ADS multiplier, refers to the multiple of the whole industrial output to that of the industry above the designated size
MEIC	Multi-resolution Emission Inventory for China
Mt	million tonnes
tce	ton standard coal equivalent
NAQSIQ	National Administration for Quality Supervision and Inspection and Quarantine
NBS	National Bureau of Statistics, P.R. China

NC	National Communications on Climate Change of China
NCV_i	Net caloric value of fossil fuel i
NDRC	National Development and Reform Commission, P.R. China
O_{ij}	Oxygenation efficiency of fossil fuel i combust in sector j
p	City-province percentage
s (subscript)	Items of the Energy balance table
t (subscript)	Industrial process and product
UNFCCC	United Nations Framework Convention on Climate Change

Note: in alphabetical order

Chapter 2 Research background

This chapter provides an extensive review of literature on emission calculation methods, China's energy statistics systems, and different approaches to allocate the CO_2 emissions. These backgrounds are used for developing the China-specific CO_2 emission inventory construction methods in Chapter 3. The previous studies on CO_2 emission accounts and analysis are also examined in this chapter.

Section 2.1.1 introduces and compares three methods, three scopes, and four system boundaries of CO_2 emissions which are widely used in previous global CO_2 emission accounts. Section 2.1.2 introduces the fossil fuel- and process-related CO_2 emissions, which are the major sources of human-induced emissions. Section 2.1.3 introduces the CO_2 emission calculation methods developed by IPCC (2006) based on the mass-balance theory. Section 2.2 introduces China's energy statistics system. The energy statistics system in China is the knowledge base of further emission accounts developed for China and its sub-national regions. Previous studies on China's CO_2 emissions, city-level emission accounts of China and other countries are examined in section 2.3. Finally, the research gaps in previous studies on China and its cities' emission accounts and analysis are discussed in section 2.4.

2.1. CO_2 emission accounts

2.1.1. Approaches, scopes, and boundaries

Generally speaking, CO_2 emissions can be allocated to one country/region using the following three methods (Barrett et al., 2013):

- Territorial-based CO_2 emissions. The administrative-territorial emissions refer to emissions "*taking place within national (including administered) territories and offshore areas over which the country has jurisdiction (page overview.5)*" (IPCC, 1996). Territorial emissions do not include any emissions from international transport such as aviation, shipping, and tourism (Barrett et al., 2013). Administrative-territorial emissions can be used to evaluate human-induced emissions by domestic production and resident activities directly within one region's boundaries (Kennedy et al., 2011; Kennedy et al., 2010).

- Production-based CO_2 emissions. Production-based emissions are wider in scope than territorial-based emissions. In the production-approach, not only "*emissions from international aviation and shipping are typically allocated to the country of the relevant vessel's operator (page 453)*" (Barrett et al., 2013), but also the "*emissions from international tourism are allocated based on where individual tourists are resident, rather than their destination (page 453)*" (Barrett et al., 2013). The system boundary of production-based emissions is the same with the System of National Accounts, which is used for GDP accounts.
- Consumption-based CO_2 emissions. Consumption-based emissions are estimated as "*all emissions occurring along the chains of production and distribution are allocated to the final consumer of products (page 211)*" (Wiedmann, 2009). In other words, consumption-based emissions evaluate how much emissions are consumed by one country/region, rather than how much emissions are produced within the country/region's boundary. Consumption-based emissions can be calculated via many methods. They can be simply estimated as: production-based emissions + emissions embodied in import products - emissions embodied in export products. They can also be estimated based on international trade data via economic models such as the input-output method (Mi et al., 2016; Peters, 2008).

When analysing emission issues and further reduction-policy making, all three emissions have their place. For example, consumption-based CO_2 emissions can "*demonstrate the potential for international carbon leakage (page 5687)*" (S. J. Davis & Caldeira, 2010), as well as the hidden driving sources of emission growth. At the same time, territorial-based emissions present the current CO_2 emission induced within one country/region's administrative boundary. Territorial-based emissions can be seen as the foundation of the other two emissions in that both production- and consumption-based emissions are calculated on the basis of territorial-based emissions.

There are different metrics for expressing the greenhouse gas emissions of spatial boundaries. Table 2-1 presents different measurement terms defined by the World Resources Institute and World Business Council for Sustainable Development (Kennedy et al., 2010; WRI & WBCSD, 2014). Scope 1 emissions include the emissions that are produced within the boundaries of the nation or region. The emissions include in-boundary components from fossil fuel combustion, waste disposal, industrial processes, product use, and other in-boundary activities. Scope 2 emissions include the out-of-boundary emissions related to the imported electricity/heat used within the regional boundary (Tian et al., 2013). Scope 3 emissions refer to emissions induced by product and service imports.

Table 2-1 Definitions of scopes for greenhouse gas emission estimations

Term	Spatial boundaries	Components
Scope 1	In-boundary emissions	Fossil fuel combustion Industrial process and product use Waste/landfill disposition emissions Agriculture, forestry, and other land use emissions
Scope 2	In-boundary heat/electricity use	Out-of-boundary heat/electricity emissions at power plants
Scope 3	Out-of-boundary energy consumption	Aviation and marine fuels’ combustion Imported products and services

Combining the three emission accounts methods (territorial, production, and consumption) and three emission scopes, Z. Liu, Feng, et al. (2015) define four system boundaries to account for regional emissions: system boundary 1 is scope 1 emissions; system boundary 2 includes both scope 1 and 2 emissions; system boundary 3 includes both scope 1 and 3 emissions; while system boundary 4 refers to the consumption-based emissions (or carbon footprint), shown in Table 2-2.

Table 2-2 Definitions of system boundaries for greenhouse gas emission accounts

	Emissions from in-boundary fossil fuel burning, industrial production, etc. for domestic consumption	Emissions from in-boundary fossil fuel burning, industrial production, etc for exports	Emissions embodied in imported heat and electricity	International aviation and shipping	Emissions embodied in imports
Scope 1	x	x			
Scope 2			x		
Scope 3			x	x	x
Territorial emissions	x	x			
Production emissions	x	x		x	
Consumption emissions	x		x	x	x
System boundary 1	x	x			
System boundary 2	x	x	x		
System boundary 3	x	x	x	x	x
System boundary 4	x		x	x	x

As shown in Table 2-2, the IPCC administrative territorial emissions are consistent with scope 1 and system boundary 1 emissions. As discussed above, territorial emissions (i.e., scope 1 and system boundary 1) can present the real CO_2 emission emitted within one country/region's boundary by excluding the emissions embodied in the import products, heat/electricity, and inter-boundary aviation/shipping/tourism. Therefore, this study adopts the IPCC administrative territorial accounting method in the following emission accounts and further emission reduction analysis.

2.1.2. Fossil fuel- and process-related CO_2 emissions

As shown in Table 2-1 and Table 2-2, the IPCC administrative territorial CO_2 emissions come from fossil fuel combustion, industrial processes, waste/landfill disposal, as well as agriculture, forestry, and other land use (known as AFOLU). Among the emission sources, fossil fuel combustion and industry production make up the major part of total CO_2 emissions. According to China's latest National Communication on Climate Change (NC), fossil fuel- and process-related emissions comprise 93.3% (or 8,688 Mt) and 12.8% (or 1,193 Mt) of the total national CO_2 emissions in 2012 (9,317 Mt) (NDRC, 2016b)[7].

The fossil fuel-related CO_2 emissions refer to CO_2 emitted during combustion of fossil fuels. According to mass balance theory, the carbon elements in fossil fuels are converted to CO_2 during the oxidizing reaction - burning, as shown in Equation 2-1.

$$C + O_2 \triangleq CO_2 \uparrow$$ *Equation 2-1*

Process-related emissions refer to CO_2 emitted as a result of physical-chemical reactions in the production process, not the energy combusted by industry (Shan, Liu, & Guan, 2016): *"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 (page 240)"* (Z. Liu, 2016c). Taking the lime industry as an example, lime is usually processed in five basic steps (see Figure 2-1): limestone is first quarried; the quarried rocks are then transferred to the crushing and screening unit to size the stones for the calcination stage; correct-size stones are fed into the kiln and heated, where $CaCO_3$ dissociates into CaO and CO_2; quicklime is then milled, hydrated with water, and classified to increase the product quality; and the product is finally packed and stored (Sagastume Gutiérrez et al., 2012).

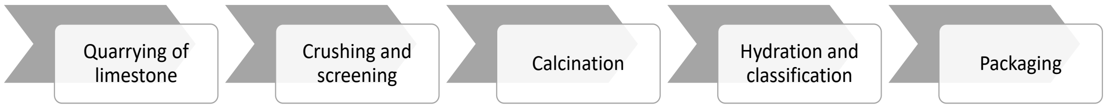

Figure 2-1 General process of the lime industry

At the calcination stage, calcium oxide (CaO or quicklime) is formed by heating limestone to dissociate the carbonate (see Equation 2-2). This step is usually performed in a shaft or rotary kiln at high temperature, and the process releases CO_2, which is called the process-related emissions.

[7] Note that the emissions from landfill and forestry are negative (-576 Mt) considering their function as carbon sink, therefore the total emissions proportion of fossil fuel combustion and industry production is over 100%.

$$CaCO_3 \triangleq CaO + CO_2 \uparrow$$ *Equation 2-2*

2.1.3. CO_2 emission estimation method

According to the IPCC (2006), "*the most common simple methodological approach is to combine information on the extent to which a human activity takes place (called activity data) with coefficients which quantify the emissions or removals per unit activity (called emission factors, EF) (vol.1, page 1.6)*". This IPCC estimation method is the simplest approach to calculate fossil fuel- and process-related emissions, and is widely used by scholars all over the world. There are also some other complex modelling approaches to calculate the CO_2 emissions which are usually used for higher tiers, such as *"the stock change methods used in the AFOLU sector which estimates CO_2 emissions from changes over time in carbon content of living biomass and dead organic matter pools (vol.1, page 1.6)"* (IPCC, 2006).

Equation 2-3 presents the fossil fuel-related CO_2 emission calculation, while process-related emissions can be calculated using Equation 2-4.

$$CE_i = AD_i \times NCV_i \times CC_i \times O_{ij}$$ *Equation 2-3*

$$CE_t = AD_t \times EF_t$$ *Equation 2-4*

In Equation 2-3, CE_i refers to the CO_2 emissions from fossil fuel type i, the subscript i refers to fossil fuel types. AD_i, the activity data, which means that fossil fuel consumption by the corresponding fuel types i. NCV_i refers to the net caloric value of fuel i, which is the heat produced per physical unit of fossil fuel combustion. CC_i (carbon content) is the CO_2 emissions per net caloric value produced of fossil fuel i. O_{ij} is oxygenation efficiency and refers to the oxidation ratio of fossil fuels i burning in sector j.

In Equation 2-4, CE_t refers to the process-related CO_2 emissions from industrial process t and AD_t is the activity data for process-related emissions accounting, which refers to industrial products' production. EF_t refers to the emissions factors of the industrial process t, which means the CO_2 emitted during producing per unit of a t product.

The IPCC calculation method has been widely used in previous studies to estimate the CO_2 emissions of China and its provinces (Guan et al., 2008; Guan et al., 2012a; Z. Liu, 2016a; Shan, Liu, Liu, et al., 2016), emissions from certain industry sectors (Shan, Liu, & Guan, 2016; Sheinbaum et al., 2010), and from specific fossil fuels (Korsbakken et al., 2016a; Pan et al., 2013) in China.

2.2. China's energy statistics system

Energy statistics in China are generally undertaken by the National Bureau of Statistics (NBS) with support from the Bureau of Statistics of the local governments. NBS sets uniform rules for the whole country's energy statistics. Therefore, the energy statistics scopes and methods are unified across the country and within different administrative units.

2.2.1. Energy types and sectors

There are currently 30 types of energy used in China (see Table 2-3). Among the 30 energy types, three of them (raw coal, crude oil, and natural gas) are known as primary energy sources, while the rest, 27 types, are classified as secondary energy types. The primary energies refer to energies exploited directly from the natural world. The secondary energies are transformed from the primary energies during energy processes. For example, cleaned coal is transformed from raw coal by removing ash, sulphur content and other impurities. According to the energy processes, 11 energies are classified as coal-related energy, as they are transformed from raw coal, while 14 and 2 energies are classified as oil- and gas-related energy. The coal-, oil-, and gas-related energies are fossil fuels as they are hydrocarbons and contain carbon elements. Despite over 75% of the heat and electricity in China being generated by fossil fuels (such as raw coal and natural gas) (NBS, 2016a), they do not have any carbon elements themselves, so heat and electricity are considered as non-fossil fuels.

Table 2-3 Energy types used in China

Category	Energy types	Category	Energies
Coal-related	Raw coal	Oil-related	Fuel oil
	Cleaned coal		Naphtha
	Other washed coal		Lubricants
	Briquettes		Petroleum waxes
	Gangue		White spirit
	Coke		Bitumen asphalt
	Coke oven gas		Petroleum coke

	Blast furnace gas		Liquefied petroleum gas (LPG)
	Converter gas		Refinery gas
	Other gas		Other petroleum products
	Other coking products	Gas-related	Natural gas
Oil-related	Crude Oil		Liquefied natural gas (LNG)
	Gasoline	Non-fossil fuels	Heat
	Kerosene		Electricity
	Diesel oil	Other energy	

In order to comply with the System of National Accounts in China, energy consumption is organised by the System of National Accounts sectors. According to the National Administration for Quality Supervision and Inspection and Quarantine (NAQSIQ), the 46-sector-division is the most common sectoral classification in China (NAQSIQ, 2011) (see Table 2-4).

In Table 2-4, the sector "Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy" ($j = 1$) is known as the primary industry while sectors $j \in [2, 41]$ are secondary industry, including both manufacturing ($j \in [2, 40]$) and construction ($j = 41$). Transportation, wholesale, and other service sectors comprise the tertiary industry ($j \in [42, 44]$). Due to all administrative boundaries (national, provincial, and city) spanning both urban and rural geographies in China, urban ($j = 45$) and rural ($j = 46$) household energy consumption is listed separately in the table. The abbreviations for sectors defined in Table 2-4 are used throughout the thesis for the same of brevity.

Table 2-4 System of National Accounts sectors

j	Socioeconomic sectors	Abbreviations
1	Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy	Farming
2	Coal Mining and Dressing	Coal mining
3	Petroleum and Natural Gas Extraction	Petro. and gas ext.
4	Ferrous Metals Mining and Dressing	Ferrous mining
5	Nonferrous Metals Mining and Dressing	Nonferrous mining
6	Non-metal Minerals Mining and Dressing	Non-metal mining
7	Other Minerals Mining and Dressing	Other mining
8	Food Processing	Food processing
9	Food Production	Food production
10	Beverage Production	Beverage
11	Tobacco Processing	Tobacco
12	Textile Industry	Textile
13	Garments and Other Fibre Products	Garments
14	Leather, Furs, Down and Related Products	Leather
15	Timber Processing, Bamboo, Cane, Palm Fibre & Straw Products	Timber
16	Furniture Manufacturing	Furniture

17	Papermaking and Paper Products	Papers
18	Printing and Record Medium Reproduction	Printing
19	Cultural, Educational and Sports Articles	Cultural
20	Petroleum Processing and Coking	Petroleum proc.
21	Raw Chemical Materials and Chemical Products	Chemicals
22	Medical and Pharmaceutical Products	Medicals
23	Chemical Fibre	Chemical fibre
24	Rubber Products	Rubber
25	Plastic Products	Plastic
26	Non-metal Mineral Products	Non-metal prod.
27	Smelting and Pressing of Ferrous Metals	Ferrous proc.
28	Smelting and Pressing of Nonferrous Metals	Non-ferrous proc.
29	Metal Products	Metal prod.
30	Ordinary Machinery	Ordinary equip.
31	Equipment for Special Purposes	Special equip.
32	Transportation Equipment manufacturing	Transport equip.
33	Electric Equipment and Machinery	Electric equip.
34	Electronic and Telecommunications Equipment	Electronic equip.
35	Instruments, Meters, Cultural and Office Machinery	Instruments
36	Other Manufacturing Industry	Other manuf.
37	Scrap and waste	Waste
38	Production and Supply of Electric Power, Steam and Hot Water	Power and heat
39	Production and Supply of Gas	Gas
40	Production and Supply of Tap Water	Water
41	Construction	Construction
42	Transportation, Storage, Post and Telecommunication Services	Transportation
43	Wholesale, Retail Trade and Catering Services	Wholesale
44	Other Service Sectors	Other services
45	Urban Resident Energy Consumption	Household-urban
46	Rural Resident Energy Consumption	Household-rural

2.2.2. Energy Balance Table (EBT)

China’s energy statistics system uses the Energy Balance Table (EBT) to provide the aggregate information about energy production, transformation and final consumption (Qiu, 1995), The table can indicate the energy flow of one region. Table 2-5 shows the items that make up the balance table.

The EBT consists of 28 items which can be categorised into four parts: “primary energy supply” provides information about energy supply, such as production and import; “input and output of transformation” refers to primary energy input and secondary energy output in energy transformation processes; “loss” covers all non-combustion energy loss during transportation, transformation and utilization; "final consumption" covers all energy supplied to the final consumer for all energy uses. In particular, "non-energy use" in final consumption refers to energy consumed without burning, such as energy used as chemical material.

Table 2-5 Energy Balance Table

No. (s)	Item
1	Total Primary Energy Supply
1.1	Indigenous Production
1.2	Recovery of Energy
1.3	Import
1.4	Domestic Airplanes & Ships Refuelling Abroad
1.5	Export
1.6	Domestic Airplanes & Ships Refuelling in China
1.7	Stock Change
2	Input & Output of Transformation
2.1	Thermal Power
2.2	Heating Supply
2.3	Coal Washing
2.4	Coking
2.5	Petroleum Refineries
2.6	Gas Work
2.7	Natural Gas Liquefaction
2.8	Briquettes
3	Loss
4	Total Final Consumption
4.1	Farming, Forestry, Animal Husbandry, Fishery Conservancy
4.2	Industry
4.3	Non-Energy Use
4.4	Construction
4.5	Transport, Storage and Post
4.6	Wholesale, Retail Trade and Hotel, Restaurants
4.7	Other
4.8	Residential Consumption
4.91	Urban
4.92	Rural
5	Statistical Difference
6	Total Energy Consumption

Figure 2-2 shows the energy flow of Beijing city in 2010, which is drawn according to Beijing's EBT 2010. The blue blocks describe the items from the first and third part of the energy balance table: “Primary Energy Supply” and “Loss”, while the purple blocks present the items from “Final Consumption” (the fourth part) in the balance table. The aqua blocks are energy transformation processes, which in Beijing's case include “Thermal Power”, “Heat Generation”, “Coal Washing”, “Coking and Petroleum Refineries”.

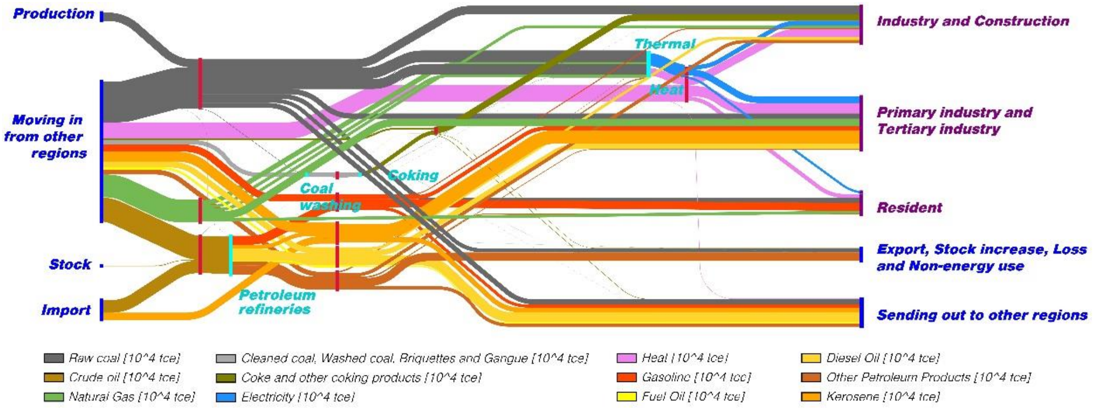

Figure 2-2 Beijing energy flow 2010
Data source: NBS (2011b)

2.2.3. Sectoral final energy consumption

The energy balance table counts the whole manufacturing sectors as one entire component, shown as "Industry" ($s = 4.2$) in Table 2-5. However, the manufacturing sectors are the major energy consumer and is responsible for the majority of CO_2 emissions. In addition, the manufacturing sectors are also the primary area for applying low carbon technologies (Z. Liu et al., 2013).

The "Sectoral final energy consumption table" provided by NBS (2014-2016) presents the final energy consumption of 39 sub-manufacturing sectors, corresponding to the 46-sector classification provided by NAQSIQ (2011) ($j \in [2, 40]$ in Table 2-4). The final energy consumption in the table refers to energy used by the final consumers, excluding energy transformation inputs.

By replacing the "Industry" item of the EBT with the detailed data from the "Sectoral final energy consumption", the 46-sectors' energy consumption comprises the final energy consumption from production activities and household in one administrative region.

2.3. Previous studies on China's CO_2 emission accounts

2.3.1. National and provincial emission accounts and analysis

Despite the fact that there is no annual, officially published emission report in China, the academic research on China's CO_2 emissions has increased rapidly since 2010. The total publications (including both journal paper and book) have increased from 416 in

2000 to 2,799 in 2010, and then 12,156 in 2017 according to Science Direct (Figure 2-3).

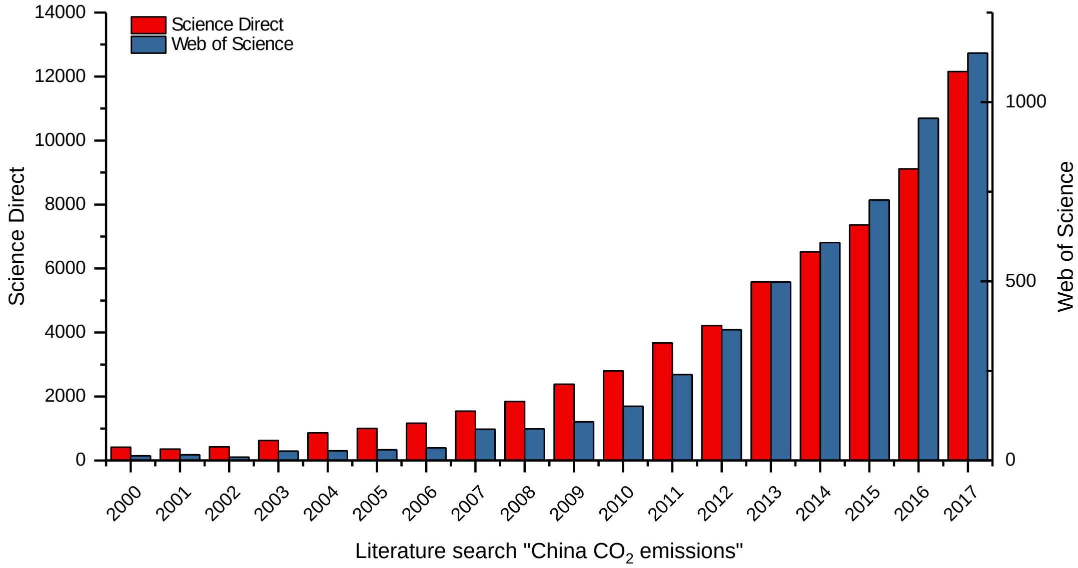

Figure 2-3 Literature search of "China CO_2 emissions"

As discussed above, the Chinese government has only published national CO_2 emissions figures three times: in 1994 (NDRC, 2004), 2005 (NDRC, 2013c), and 2012 (NDRC, 2016b). The previous studies on China-related CO_2 emissions either collected the emission data from global emission databases, or calculated China's emissions individually. The different data sources may bring uncertainties and discrepancies to the studies. This study summarized the previous studies on China's CO_2 emissions by emission data sources.

Studies collecting China's CO_2 emissions from global emission databases

Lots of the previous studies on China's CO_2 emissions collected the CO_2 emissions from these existing global emission databases. My previous literature investigation shows that 17% (or 21) of the 127 related SCI papers published during the last ten years collected China's CO_2 emission data from global databases directly (Shan, Liu, Liu, et al., 2016).

For example, Pao et al. (2011) collected the CO_2 emissions of China, Brazil, Russian, and India from the EIA emission database to examine the Granger causality relationships between CO_2 emissions and other three indexes (energy consumption, foreign direct investment, and GDP) of these four countries. Similarly, Chang (2010) employed the energy consumption and CO_2 emission data from IEA to test the multivariate co-integration Granger causality relationships between China's CO_2 emissions, energy consumption, and economic growth. Jalil et al. (2009) used World Bank (2007)'s time-series CO_2 emissions data of China to examine the Environmental Kuznets relationship between per capita GDP and CO_2 emissions. The study time spanned from 1975 to 2005. The study found that there was such Environmental Kuznets relationship between the per capita GDP and CO_2 emissions in the case of China for long-run time. J. B. Ang (2009) used the CDIAC emission data to investigate the relationships of China's CO_2 emission with research and technology transfer in the past 50 years. The results found that China's carbon dioxide emissions had negatively correlated relationships with its "*research intensity, technology transfer and the absorptive capacity of the economy to assimilate foreign technology (page 2658)*" (J. B. Ang, 2009). Govindaraju et al. (2013) collected the CO_2 emissions from the BP review of world energy 2011 to explore and compare the dynamic link between CO_2 emissions and economic growth in India and China. The results indicated that the nexus relationship between economic growth and CO_2 emissions are only found in China, not in India. When discussing the relationships between the financial development and CO_2 emissions in China, Y. J. Zhang (2011) also collected China's CO_2 emission data 1980-2009 from the BP Statistical Review of World Energy 2010. The econometric-based results showed that China's CO_2 emissions were significantly driven by its quick financial development.

To summarize, several global emission databases are frequently used to collect China's emission data, such as the EDGAR (Olivier et al., 2016), the Global Carbon Project (Le Quéré et al., 2016), and the CDIAC (Boden et al.) (see also section 1.3 and Figure 1-1). However, these emission datasets have many limitations.

Firstly, different methods and scopes have been used in these global emissions databases, making them inconsistent and incomparable with each other (Janssens-Maenhout et al., 2017). For example, "t*he fifth assessment report (AR5) of IPCC working group III (*IPCC, 2014*) reported the GHG emissions combines CO_2 emissions related to fossil fuel use from* IEA (2012) *with other CO_2 emissions sources and non-CO_2 emissions from EDGAR (page 3)*" (Janssens-Maenhout et al., 2017).

Secondly, all the activity data used in these global emissions databases are non-transparent, making the emissions difficult to verify. The transparency of activity data is necessary to quantify the uncertainties of the emissions, and increase the credibility of the data. The non-transparent data especially affects the credibility of China's emission estimates. The Chinese government has officially revised its national energy consumption three times since 2000 (in 2005, 2009, and 2014). Each modification increased China's energy data by 5-10% (Heran Zheng et al., 2018). CO_2 emissions of China should be calculated based on the most up-to-date energy consumptions. However, these global emission databases do not disclose their data sources clearly.

Thirdly, there are great uncertainties in the emission factors used by these global emission databases. Shan et al. (2018)'s comparison study of seven sources of emission factors found that the Coefficient of Variation (CV, a measure of uncertainty) of different fuels' emission factors varies from 33% to 1%. In addition, Z. Liu, Guan, et al. (2015) found that the IPCC default emission factors, which are widely used by these emission databases, are around 40% higher than China's specific emission factors. The range of emission factors increase the uncertainties of emissions estimated by these global emission databases.

The above three limitations bring great discrepancies between estimates of China's CO_2 emissions from these global emission databases (shown in Figure 1-1 and section 1.3). After examining and comparing the emissions of these datasets, this study finds that, in 2013, the range of China's CO_2 emission estimates from these global emission databases even exceeded 1,300 Mt (15%), which is approximately equal to Japan's total emissions in 2011 (1,243 Mt, CDIAC), even higher than total emissions from Africa (1,267 Mt, CDIAC). Japan was the 5th top-emitter in the world at that time (European Commission, 2016).

In addition, these emission datasets only provide the total emissions of the country, rather than detailed emission inventories by sectors and energy types, or emissions from regions in China (at provincial and city-level). Such general emission data cannot support detailed emission analysis and related emission reduction policy making.

Studies calculating China and its regional CO_2 emissions by themselves

Restricted by the above limitations of the global emission databases, some previous studies calculated China and its regional CO_2 emissions by themselves when analysing China's emission characteristics.

For example, B. Ang et al. (1997) calculated the CO_2 emissions for manufacturing sectors in China and South Korea from 1980-1993. The study then compared the drivers of the changes in CO_2 intensities of the three regions with two general decomposition methods. The results showed that the countries' CO_2 emission intensities are significantly influenced by the changes in their sectoral energy intensities. B. Q. Lin et al. (2010) evaluated the carbon dioxide emissions embodied in China's international trade based on the self-calculated direct CO_2 emissions in 2005. The direct CO_2 emissions were calculated by the authors using the IPCC emission factors and sectoral energy consumption from NBS. The CO_2 emissions embodied in the trade chain were estimated with the Input-output method. The study found that, in 2005, the total production-based CO_2 emissions (i.e., direct emissions from fossil fuel combustion) were 5,458 Mt in China. Meanwhile, the consumption-based CO_2 emissions (indirect emissions embodied in international trade and supply chain) were as high as 4,434 Mt. Similar to Chang (2010)'s study, X. P. Zhang and Cheng (2009) examined the existence of Granger causality between China's energy consumption, CO_2 emissions, and economic growth over the period 1960-2007. But differently, X. P. Zhang and Cheng (2009) calculated China's CO_2 emissions with energy data from NBS. The analysis confirmed that the GDP had a unidirectional Granger causality relationships to energy consumption. Meanwhile, the energy consumption also had a unidirectional Granger causality relationships to CO_2 emissions. The results implied that there are no bidirectional causality relationships between the economic growth and energy consumption/CO_2 emissions in China from 1960-2007. In other words, neither increases in the energy consumption or CO_2 emissions were necessary to grow China's economy. Minx et al. (2011) calculated China's 2007 CO_2 emissions with the official energy consumption and IPCC emission factors based on the methods used in their previous studies (Peters et al., 2006; Peters et al., 2007). The study then employed the Structural Decomposition Analysis (SDA) to examine the driving forces of China's CO_2 emission's rapid increase in the nineties and early 21^{st} century. The study attibuted China's quickly emission growth to structural change in China's economy. Can Wang et al. (2005) estimated China's CO_2 emissions for 1957-2000, and then applied the Index Decomposition Analysis (IDA)-Logarithmic Mean Divisia Index (LMDI) to examine the driving forces of China's emission growth during the research period. The results indicated that energy emission decreasing, energy mix optimization, and renewable energy penetration might bring emission reductions in the future. Similarly, L.-C. Liu et al. (2007a) calculated the CO_2 emissions of 36 manufacturing sector from 1998-2005. The study then employed the IDA-LMID method to discuss the contributors to the CO_2 emission change in the 36 manufacturing sectors. The results found that the industrial activity and energy intensity were the overwhelming drivers of the emission changes.

Apart from the calculations of China's national emissions, a number of previous studies have been conducted to examine the regional emissions of China. For example, S. S. Wang, Zhou, et al. (2011) calculated China's provincial emission data from 1995 to 2007. Then the study examined the provincial relationships among CO_2 emissions, energy consumption, and economic growth in China. The results found that these three variables are co-integrated at the province-level. The economic growth and energy consumption induced the provincial CO_2 emissions in China. In turn the CO_2 emissions and economic growth drove the energy consumption as well. Du et al. (2012) calculated the CO_2 emissions for 29 provinces during 1995-2009 (Chongqing is merged with Sichuan province in this empirical study). The study collected the emission factors from IPCC and NDRC, while the activity data of energy consumption were collected from NBS. Based on the provincial emission data, the authors discussed the drivers of provincial emission growth in China. The results found that the top three driving forces of China's provincial CO_2 emission growth were economic growth, technical development, and industry structure change. The study also forecasted the emission trends using scenario analysis. The scenario analysis of future emission prediction showed that China would experience continuous emission growth until 2020. Q. W. Wang, Zhou, et al. (2012) estimated the fossil fuel-related CO_2 emissions for 28 provinces from 2001-2007. The study then discussed the huge differences and inequality of the environmental and economic efficiency in different areas of China. K. S. Feng et al. (2012) calculated the CO_2 emissions for 28 provinces in 2002 and 2007 with NBS activity data and IPCC emission factors. The study then applied the Input-output method and SDA to discuss the drivers of regional emission growth from 2002 to 2007 in China. The results found that there is significant differences between China's three economic zones (eastern-coastal, central, and western zones) in terms of CO_2 emission growth. Q.-M. Liang et al. (2007) calculated the provincial CO_2 emission inventories in 1997. By using the eight-regional input-output model and scenario analysis, this study forecast the energy consumption and CO_2 emissions of year 2010 and 2020. The results indicated that China's energy consumption and CO_2 emissions would increase up to 2020 under the driving of population growth across all the eight regions. However, if the efficiency of energy end-use could be improved, the potential capacities of energy and emission saving were substantial as well. Clarke-Sather et al. (2011) investigated the inequality of carbon emissions among China provinces by calculating the reference-approach provincial CO_2 emissions 1997-2007. The CO_2 emissions were estimated by using IPCC emission factors. The study then revealed the inequality of China's regional per capita CO_2 emissions, which was slight lower than the regional inequalities within China's economy.

Similar to the global emission databases, there are also many limitations and large uncertainties laid in these self-calculated emissions.

The largest uncertainties are within the selection of emission factors. By investigating the 127 related studies published in the SCI journals in the last ten years, this study finds that nearly half of them collect the emission factors from IPCC, including Cheng et al. (2014), L. Chen, Yang, et al. (2013), and J. Fan et al. (2012). 32 of them used the NDRC or NBS emission factors, such as R. Guo et al. (2010) and Y. L. Dong, Ishikawa, et al. (2010). Few studies measured the emission factors based on experiments. For example, J. Zhang et al. (2000) measured emissions of 8 types' greenhouse gases/air pollutants (including CO_2, CO, CH_4, TNMHC, N_2O, SO_2, NO_x, TSP) from China's household stoves. Sun et al. (2011) used emission factors from a nationwide sampling investigation when calculating the energy-related CO_2 emissions of China's iron and steel industries. Y. M. Wei et al. (2007) collect the emission factors of coal, petroleum, and natural gas from "Energy Research Institute" (Z. Zhang, 2000), while the emission factors of electricity and heat were collected from their own calculation. Q. F. Chen, Ma, et al. (2013) used "*the emissions concentration and fluxes of CO_2 with the static opaque chamber –GC technique and eddy covariance technique*" to measure emissions. Apart from the uncertainties from the emission factors, the in-consistent and differences in the calculation methods, scope, and activity data sources also increased the uncertainties of the previous emission calculations.

Another key limitation of these self-calculated CO_2 emissions in previous studies is that the calculated emissions cannot be effectively re-used. Firstly, these self-calculated emissions are usually not published along with the publications and not available to download easily. The studies only present the analytical results and conclusions in the publications, rather than providing the full emission data. Secondly, these studies only conducted one-time calculation. The self-calculated CO_2 emissions are not updated with the latest activity data and emission factors.

Previous studies focusing on CO_2 emissions from specific sector/energy

As the global emission databases only provide the overall CO_2 emissions, or simply by several primary fossil fuel types, some previous studies on China's sector/energy-specific emission fields calculate the CO_2 emissions by themselves.

For example, Donglan et al. (2010) calculated the rural and urban residential CO_2 emissions 1994-2004 based on activity data from NBS and IPCC emission factors. The study then compared the difference between rural and urban China in energy consumption and CO_2 emissions. The results showed that the population had distinct impacts on China's urban and rural residential CO_2 emissions. The population effect increased China's urban residential CO_2 emissions, while decreased its rural residential CO_2 emissions since 1998. Pan et al. (2013) calculated China's coal-related CO_2 emissions in 2010 based on reference-approach coal consumption and investigated emission factors. W. Wang, Zhang, et al. (2011) estimated the CO_2 emissions from the transport sector in China from 1985 to 2009. The estimates showed that the whole transport-related CO_2 emissions increased quickly from 79.67 to 887.34 Mt during 1985-2009, at an average rate of 10.56% per year. The highways transport was the major contributor to the whole transport-related CO_2 emissions.

These previous studies on specific sector/energy provided important and substantial supplements to the national/regional emissions in China. However, most of these previous sector/energy-specific studies focused on some major emission sources, such as coal (Pan et al., 2013), cement industry (Y. Liu et al., 2009), residential energy usage (Donglan et al., 2010). CO_2 emissions from other small but fast-growing sectors and energy types need detailed analysis.

2.3.2. Emission accounts of global cities

Compared to national and provincial emissions accounts, far fewer studies have focused on city-level emissions. After reviewing the previous literature on city-level CO_2 emissions, this study finds that this research field is gaining more and more attention, especially after 2010. Based on the literature statistics of Science Direct, the publications on city-level emissions have increased from 471 in 2000 to 1,650 in 2010, and 5,667 in 2017, shown in Figure 2-4.

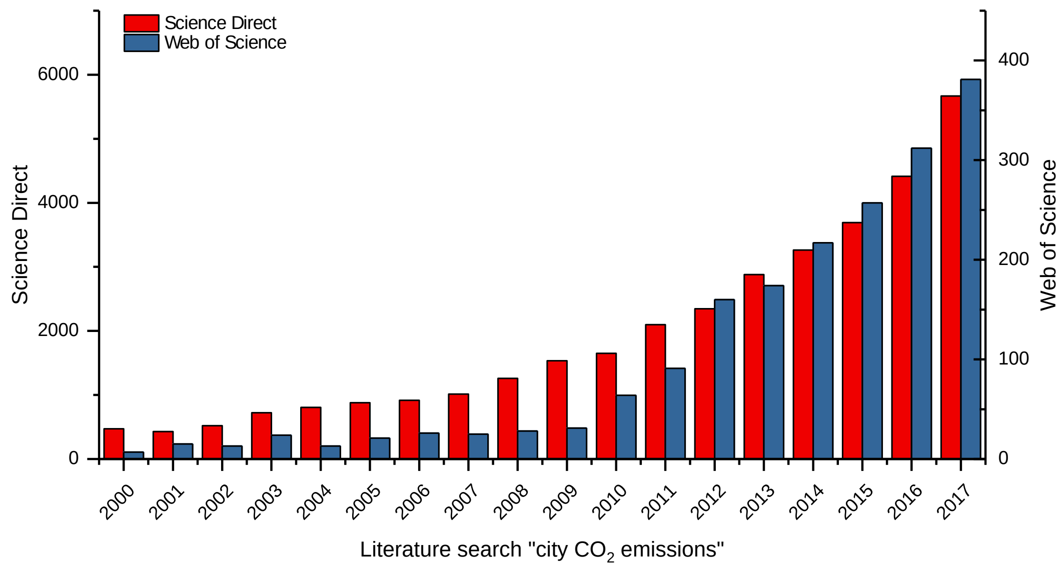

Figure 2-4 Literature search of "city CO_2 emissions"

Climate change actions should be designed and conducted at the city-level. The city's local governments should take the responsibility to reduce the emission and manage the climate. Previous literature has clarified the importance of city-level climate change actions. For example, Sharp et al. (2011) addressed the importance of city governments developing and implementing the climate change mitigation policies. The city-level climate actions also had significant effects on the national and global climate change mitigation and sustainability. Romero Lankao (2007) discussed the local governments' responsibility on climate change management. The results suggested that "*policy networks and research groups should been critical in launching the climate agenda (page 519)*". The study also conducted empirical analysis of greenhouse gas emissions from Mexico City in 2000 from 8 sectors: residential, industrial, commercial, transportation, electricity generation, solid wastes, agricultural, and government.

However, compared to national and provincial emissions accounts, far fewer studies have focused on city-level emissions. This study also finds that these previous city-level studies have geographical restrictions, as well as methods limitations.

First of all, lots of the previous studies on city-level emissions focused on the megacities from developed countries with consistent and transparent data sources, especially American cities. This is primarily due to the data availability.

For example, Ramaswami et al. (2008) developed "*a demand-centred, hybrid life-cycle-based methodology for conducting city-scale greenhouse gas inventories (page 6455)*", and applied the method to one American city: Denver in Colorado. The results found that the total greenhouse gas emissions of Denver in 2005 were 14.6 Mt, among which 52% were contributed by energy use in residential households and manufacturing sectors. Such methods are employed by Hillman et al. (2010)'s subsequent research on eight American cities: Denver, Boulder, Fort Collins, Arvada, Portland, Seattle, Minneapolis, and Austin. The study found that the cross-boundary emissions contributed averagely 47% of the eight cities' in-boundary greenhouse gas emissions. The sectoral analysis of the eight cities' emissions showed that the energy consumption in buildings and facilities is the most primary source of human-induced greenhouse gas emissions, accounted for 47.1%. Then the regional surface transportation and food production contributed 14.7% and 6.4% to the total emissions, respectively. Fuel production, airline transportation, shipping (freight trucking), cement production, and water/waste processing emitted the remaining 6.4%, 4.8%, 2.8%, 2.2%, and 1.3% emissions. Similarly, Parshall et al. (2010) and Markolf et al. (2017) also estimated the scope 1 emissions of American cities. Parshall et al. (2010) found that the buildings and industrial manufacturing consumed 37% to 86% of the cities' total energy consumption, while the urban area consumed 37% to 77% of the transport-related gasoline and diesel. Markolf et al. (2017) calculated the CO_2 emissions of 100 American cities in 2014. The results showed that Lancaster had the least emissions of 4.1 Mt, while Houston have the most emissions of 170 Mt. The overall average emissions of the 100 case cities are 27 Mt in 2014. Fragkias et al. (2013) calculated the time series emission data of American cities from 1999 to 2008. The study then analysed the relationship between cities' size (population size) and CO_2 emissions. The analysis found that the cities' CO_2 emissions efficiency had a positive correlation with their size: larger cities have higher emission efficiency than smaller cities.

Nowadays, the city-level emissions are studied in a more international view, by analysing more global cities, especially cities from developing countries. For example, Ibrahim et al. (2012) discussed the understanding of seven protocols for greenhouse gas emission inventory construction, and then applied the protocols to three cities for case study: Shanghai, New York, and Paris. The study then suggested defining the scopes clearly in the future city-level emission accounts. D'Almeida Martins et al. (2011) introduced and analysed the emission reduction and climate change mitigation actions of two Brazil megacities: Sa˜o Paulo and Rio de Janeiro. Ali et al. (2012) used the Lahore Metropolitan city (the capital city of Punjab province, Pakistan) as cases to analyse the city-level emissions. The study calculated the 1971 to 2010 carbon emissions based on energy consumption from five sectors: agriculture, manufacturing, commercial, transportation, and residential usage. The study then applied the autoregressive integrated moving average (ARIMA) model to forecast Lahore Metropolitan city's carbon emissions for the next 20 years. The results found that the industrial manufacturing and residential sectors are the most primary contributors to the Lahore Metropolitan city's energy consumption and CO_2 emissions. The emission feature and trends would keep the same for the next 20 years. Matese et al. (2009) observed the carbon fluxes of Florence in Italy for 3 and half months to estimate the CO_2 emissions. The observation-based emissions were compared with emissions estimated by inventory sources as well. Similarly, Harvey (1993) discussed the CO_2 emissions of Toronto, Canada. Gomi et al. (2010) designed the low-carbon scenarios for Kyoto city.

Lots of scholars have noticed the geographical limitation of city-level emission accounts nowadays. Some studies gradually accounted the emissions of large scale cities. For example, Creutzig et al. (2015) built an energy/emission dataset including 274 global cities, and present the aggregate potential for urban climate change mitigation. The study found that 37% of the urban direct energy consumption and 88% of the urban transport-related energy consumption can be explained by the cities' economic activities, transportations, and urban construction. The study also predicted the urban-related emissions would increase more than threefold followed the current urban expansion and industrialisation. Sugar et al. (2012) reported emissions from 230+ Chinese cities, Ramaswami, Jiang, et al. (2017) and their follow-up study developed a comprehensive emission database named Chinese City Industry-Infrastructure (CCII)

(Ramaswami, Tong, et al., 2017). The CCII database presented the city-level direct and scope 1+2 CO_2 emissions, which are consistent with the national energy statistics and emission accounts. The database included 637 Chinese cities, which span both the prefecture and county-level cities.

Secondly, the previous studies on city-level emissions have severe methodological weakness and limitations. Nearly all the previous city-level GHG emissions inventories were calculated using a bottom-up approach, i.e., by using energy consumption data surveyed from several sectors. The sectors are set differently from study to study, making the cities' CO_2 emissions inconsistent and in-comparable across studies, as well as inconsistent with the national and regional emission inventories. The national and regional emission inventories are usually constructed by energy types and sectors.

For example, H. Wang, Zhang, et al. (2012) calculated carbon emissions of 12 Chinese provincial capital cities by 6 sectors, including industrial energy consumption, transportation, household energy consumption, commercial energy consumption, industrial processes and waste. Glaeser et al. (2010) examined the CO_2 emissions from four different sectors of several American cities. The four sectors are road transport, public transit, home heating, and residential energy usage. The authors found that cities in California have the lowest average CO_2 emission, while cities in Texas and Oklahoma have the highest average amounts.

Differently, Kennedy et al. (2010) compiled carbon emissions inventories that cover electricity, heating and industrial fuels, ground transportation fuels, aviation and marine transportation, industrial processes and product use, and waste for 10 global megacities from eight countries: "*Los Angeles County, Denver City and County, Greater Toronto, New York City, Greater London, Geneva Canton, Greater Prague, Barcelona, Cape Town and Bangkok*". In accordance with their method, Kennedy et al. (2014) complied greenhouse gas inventories for 22 global cities, which included 3 Chinese cities: Beijing, Tianjin, and Shanghai. The 22 global cities are selected with different climate conditions, economic level, and industrialisation stages. The study suggested that cities should make their specific emission reduction policies based on their emission/economic/climate characteristics. Furthermore, Kennedy et al. (2015) quantified the energy and material flow from the world's 27 megacities from 2001 to 2011, including four Chinese cities: Beijing, Shanghai, Guangzhou, and Shenzhen.

Based on the energy and material flow data, this study also investigated the statistical relationships between electricity consumption, heat/manufacturing fuel usage, economic growth and populations for the 27 global megacities. The results found that the megacities' energy consumptions and GDP grew faster than their population growth. The electricity and transport fuel consumption only grew at half of their GDP growth rate. Similar account methods were also used in Kennedy et al. (2011) and Kennedy et al. (2009)'s subsequent research. Kennedy et al. (2011) analysed the greenhouse gas baseline measures of cities from France and India, while Kennedy et al. (2009) focused on 10 global cities: Bangkok, Barcelona, Cape Town, Denver, Geneva, London, Los Angeles, New York, Prague, and Toronto. Dodman (2009) compared the greenhouse gas emissions of 26 global cities collected from previous studies and discussed the emission patterns of the city-level emissions, as well as their main drivers.

In this way, the previous assessments of city-level emissions either focused on several megacities with consistent and systematic energy statistics, or focused on the total emissions (or combining emissions of several sectors altogether). The bottom-up sectoral based emissions of cities are in-consistent with the national and regional emission inventories, making the multi-scale emission studies unavailable. Also, such general emission data cannot support detailed city-level emission analysis and related emission reduction policy making. Detailed emission inventories constructed by fossil fuel types and sectors are thus urgently needed for large scale cities.

2.3.3. City-level emissions' research of China and methods

Due to data limitation, the CO_2 emissions from Chinese cities have not been widely researched until 2005. According to Web of Science, the publications about CO_2 emissions of Chinese cities increased from 1 in 2005 to 73 in 2015. The publications then increased rapidly to 152 in 2017, see Figure 2-5.

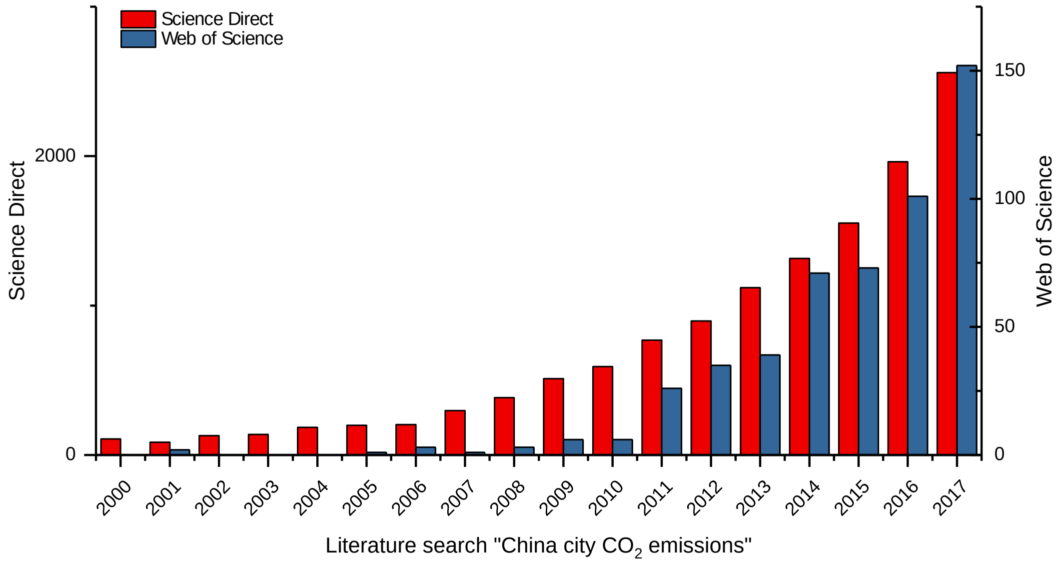

Figure 2-5 Literature search of "China city CO_2 emissions"

Different scopes and methods have been applied to calculate the city-level emissions in China. Most of the previous studies on Chinese cities have focused on scope 1 and scope 2 CO_2 emissions only, with a few paying attention to scope 3 CO_2 emissions, such as Mi et al. (2016), J. Meng et al. (2017), J. Y. Lin et al. (2013), K. Tong et al. (2016), W. Liu et al. (2014). Based on the IPCC (1996) recommend method, NDRC (2011a) designed an emission account system for China's sub-national regions. Furthermore, in the "Global Protocol for Community-Scale Greenhouse Gas Emission Inventories" and "International Local Government GHG Emissions Analysis Protocol", WRI, C40, et al. (2014) and ICLEI (2009) provided the bottom-up approach for city-level emission accounts with higher precisions. The ISO 14064 and 37120 series of standards also provide the guidelines for enterprises' emission accounts (F. Yang et al., 2016). Some multi-disciplinary techniques such as spatial/geographical analysis and economic models (B. Cai, 2012a; L. Meng et al., 2014) are also used in city's emission accounts.

The IPCC calculation method is the most common method used in scope 1 and 2 CO_2 emission accounts for Chinese cities. The emissions are calculated as activity data (energy consumption or industrial productions) timed by emission factors. This method is consistent with the method used for national and provincial emission accounting. For example, Bi et al. (2011) compiled greenhouse gas emission inventories for Nanjing from 2002 to 2009. The emission inventories were constructed by six different sectors:

industry, transportation, household energy use, commerce, industrial production, and solid waste disposal. The study found that the industry, industrial production, and transport contributed 37-44%, 35-40%, and 6-10% of the overall greenhouse gas emissions respectively. J. Cong et al. (2013) chose Jiyuan city as an example to calculate the CO_2 emissions from fossil fuel combustion in industries and process-related emissions. The study proposed that this accounts method could be used for other small and medium-sized cities like Jiyuan. Xie et al. (2009) estimated the fossil fuel-related CO_2 emissions of Shanghai from 1995 to 2007 using the IPCC reference-approach method. The study also drew the carbon flow charts for Shanghai.

However, compared with the global-scale research, there is a dearth of CO_2 emission inventory research on Chinese cities. Most of the previously studied on China's city-level emission focused on the four municipalities (which are provincial cities), 30+ provincial capital cities, or several megacities which have consistent energy statistics, shown in Table 2-6. Some other studies have discussed the emissions of cities in specific regions of China, such as the Jing-Jin-Ji area (Beijing, Tianjin, and Hebei region), Yangtze River delta. Table 2-6 categorizes previous relevant studies by the spatial distribution of their case cities.

Table 2-6 Spatial distribution of Chinese cities analysed in previous studies

City clusters	Studies
Four municipalities	Z. Liu, Liang, et al. (2012), Sugar et al. (2012), G. Dai (2013), C. Liu et al. (2010), Y. Zhou, Wu, et al. (2010), S. Y. Zhou, Chen, et al. (2010), L. X. Zhang et al. (2011), J. Y. Zhang et al. (2013), Gielen et al. (2001), K. Feng et al. (2014), M. L. Song et al. (2014), and L. Li et al. (2010)
Provincial capital cities	Dhakal (2009), C. Fang et al. (2015), K. Yin et al. (2014), Du (2010), L. J. Xu, Zhou, et al. (2017), H. Wang, Zhang, et al. (2012) and D. Yin et al. (2017)
Jing-Jin-Ji cities	Jiang et al. (2015), Y. Zhang, Zheng, et al. (2016), and Hongmei Zheng et al. (2017)
Yangtze River Delta cities	Y. Zhao et al. (2015), X.-H. Zhu et al. (2017), M. Song et al. (2015), and Xibao Xu et al. (2015)
Pearl River Delta cities	G. M. Cong (2014)
Shandong peninsula cities	P. Xu (2014) and Q. W. Guo (2014)
Central China cities	Xinwanghao Xu, Huo, et al. (2017), and X. Q. Li (2014)
Others	H. S. Wang, Wang, et al. (2014) (Suzhou), J. Y. Lin et al. (2014) (Xiamen), J. Cong et al. (2013) (Jiyuan), Y. H. Zhu (2014) (Lanzhou), L. Dong et al. (2013) (Liuzhou), and M.-x. Wei et al. (2014) (Ordos)

Spatial distribution of city-level emission studies in China

This study summarizes the previous studies on Chinese cities according to their case regions: four municipalities, provincial capital cities, megacities, cities in specific developed regions.

- Emission studies of four municipalities in China

Beijing, Tianjin, Shanghai, and Chongqing are known as four municipalities in China, which are directed controlled by the central government. They have the same administrative position as provinces. The four municipalities therefore have the consistent and systematic energy statistics, making their CO_2 emission inventories simple to construct. Many previous studies have accounted the CO_2 emissions from these four municipalities, as well as discussed their emission characteristics.

For example, Z. Liu, Liang, et al. (2012) compiled scope 1 and 2 greenhouse gas emission inventories for four Chinese municipalities from 1995 to 2009. The results showed that the cities' greenhouse gas emissions are majorly contributed by manufacturing energy consumption and power-plants' coal combustion. K. Feng et al. (2014) estimated both the production-based and consumption-based CO_2 emissions of four municipalities in China. The production-based CO_2 emissions were calculated with activity data from NBS and emission factors from IPCC. The consumption-based CO_2 emissions were then calculated with input-output methods based on the production-based CO_2 emissions. Sugar et al. (2012) compiled the 2006 emission inventories for three Chinese municipalities (Beijing, Shanghai, and Tianjin). The study also compared the three cities' emissions with 10 other global megacities. The results showed that the per capita greenhouse gas emissions of Beijing, Shanghai, and Tianjin were 10.7, 12.8, and 11.8 tonnes, respectively in 2006. Y. Zhou, Wu, et al. (2010) discussed the greenhouse gas emission control policies on Beijing's transport sector during the 2008 Olympic Game period. Beijing was divided into 2055 1km×1km grid cells in this study. Not only CO_2, but also air pollutants such as CO, VOC, NO_x, PM_{10} were analysed. The results showed that the emission control policies reduced the emission intensity by roughly 45% effectively. S. Y. Zhou, Chen, et al. (2010) discussed the greenhouse gas emissions and energy/water consumption of Beijing in 2002. Greenhouse gases of CO_2, CH_4, and N_2O are involved in this study. The study then applied the input-output model to examine the environmental driving forces of Beijing in 2002. L. X. Zhang et al. (2011)

applied the long-range energy alternatives planning (LEAP) to Beijing's 2007 CO_2 emissions to discuss the possible low-carbon development pathways of Beijing. J. Y. Zhang et al. (2013) calculated the energy-related CO_2 emissions of Beijing in 1995, 2000, 2005, and 2009. The authors used the emission factors from IPCC in the research. The study mainly focused on Beijing's manufacturing production and household energy use. Then the study applied the IDA method to decompose Beijing's emission changes. Gielen et al. (2001) examined the energy consumption and greenhouse gas emissions for Shanghai in 1995. Then Shanghai's emissions were forecasted to 2020 by using Market Allocation (MARKAL) optimisation model. Further discussion about Shanghai's emission reduction policies were also presented in this study aiming at CO_2, SO_2, and NO_x. M. L. Song et al. (2014) discussed the energy consumption and emissions from the transport sectors in Shanghai from 2000 to 2010. In L. Li et al. (2010)'s study, the authors estimated Shanghai's CO_2 emissions from 1995 to 2006. The results showed that Shanghai totally emitted 184 Mt CO_2 in 2006, and the average emission growth rate over the 10 years was 6.22% per year. Then scenario analysis was conducted to predict Shanghai's energy demand and CO_2 emissions until 2020.

- Emission studies of provincial capital cities and other megacities in China

China is made up of 31 provinces (including the four municipalities, excluding Taiwan, Hong Kong, and Macao). Each province has a capital city, which has the most developed economic and advanced technical level in the province. Some previous studies also focused on these provincial cities as well as other megacities in China, estimated and analysed the CO_2 emissions of these cities.

For example, H. Wang, Zhang, et al. (2012) examined the CO_2 emissions of 12 Chinese cities from 2004 to 2008: "*Beijing, Shanghai, Tianjin, Chongqing, Guangzhou, Hangzhou, Nanjing, Zhengzhou, Shenyang, Wuhan, Wuxi and Lanzhou*". Beside Wuxi, the other 11 cities are provincial capitals. Wuxi locates in the Yangtze River Delta, which is the most developed and abundant region in China. The emission inventories of the cities were calculated as a bottom-up approach in this study. Based on the emission data, this study discussed the cities emission-socioeconomic index of the cities, such as per capita emissions. Dhakal (2009) examined the energy consumption and CO_2 emissions of all Chinese provincial capital cities. The study then discussed China's urban energy consumption and emission characteristics based on these selected cities, which contribute up to 18% of China's total population and 40% of China's total energy consumption/CO_2 emissions. C. Fang et al. (2015) accounted the time-series emission accounts of 30 provincial capital cities in China (excluding Lhasa, the capital city of Tibet) from 1990 to 2010. The study then investigated the city-level relationships between CO_2 emissions and urban form. K. Yin et al. (2014) applied the eco-efficiency to examine the sustainability of the provincial capital cities in China.

- Emission studies of cities in specific developed regions

Some other studies also focused on cities in specific regions, such as the Jing-Jin-Ji area, Yangtze River Delta, Pearl River Delta. The Jing-Jin-Ji area includes to Beijing, Tianjin, and Hebei provinces, which is the capital circle in China. The Yangtze River Delta refers area near the mouth of Yangtze River, which includes cities in Jiangsu, Zhejiang province, and Shanghai. The Pearl River Delta refers area near the mouth of Pearl River, which includes part of Guangdong cities, Hong Kong, and Macao. The Yangtze River and Pearl River Delta cities are the most developed and abundant areas in China.

For example, Y. Zhang, Zheng, et al. (2016) investigated the energy consumption and emission changes between 2002 and 2007 of Jing-Jin-Ji cities. The ecological network was combined with the input-output model to explore the ecological roles of the cities. X.-H. Zhu et al. (2017) calculated the energy-related CO_2 emissions from the manufacturing sectors of the 17 Yangtze River Delta cities from 2005 to 2014. The results showed that the total manufacturing-based CO_2 emissions of the 17 cities increased by 1.6 times during the 10 years. Economic and population growth were the major contributions. This study also predicted the possible emission reduction capacities of these cities from 2015 to 2020. Y. Zhao et al. (2015) constructed the CO_2 emissions and air pollutants inventory for Nanjing, which is the capital of Jiangsu province. The emission inventory was constructed with 3km×km resolution. M. Song et al. (2015) estimated the carbon emissions based on energy consumption of the Yangtze River Delta cities from 1995 to 2010. The contributions of four different indexes to the cities' emission growth were identified and compared: economic growth, population growth, energy intensity, energy mix. The results indicated that the economic growth "was the most significant factor in explaining the increases in carbon emissions in the region (144.19%). The effects of energy intensity, population size, and energy structure were −60.97%, 19.25%, and −2.47%, respectively (page 620)" (M.

Song et al., 2015). Xibao Xu et al. (2015) focused on the residential CO_2 emissions of three cities in Yangtze River Delta: Nanjing, Ningbo, and Changzhou. The authors calculated the household carbon emission of the three case cities based on structured questionnaire surveys. The study found that these three cities' average household carbon emissions were 5.96 tonnes in 2010.

Above all, the research gap of China's city-level emission accounts mainly laid in the geographical restrictions. Most of the previously studied only focused on the four municipalities, 30+ provincial capital cities, or cities from specific developed regions. There is no overall emission accounts of China's hundreds of cities based on the mass balance theory. This research gap is primarily caused by data quality issues in the records kept by Chinese cities. Considering it is unpractical to improve the data quality of these cities within a short timeframe, some studies attempted to use spatial, geographical, or economic models to estimate the CO_2 emissions for Chinese cities. However, such spatial/geographical/economic-based methods can only estimate the total CO_2 emissions of the cities, rather than the detailed emission inventories by energy types and sectors.

Methods used in China's city-level emission estimates

- Using spatial and geographical analysis

By using spatial and geographical techniques, some previous studies have calculated the CO_2 emissions for Chinese cities based on geographical information and spatial grid data.

For example, B. Cai (2012a) and his team conducted a series of studies on the CO_2 emissions accounts with 1-km spatial grid data. B. Cai et al. (2014b) then defined four types of urban boundaries for Chinese cities, and used Tianjin as a case to compare the four scopes' CO_2 emissions. The CO_2 emissions from four boundaries were compared and discussed in this study. A similar study was conducted for Shanghai as well (B. Cai et al., 2014a). B. Cai et al. (2017) calculated the scope 1 and scope 2 CO_2 emissions for Chinese cities in 2012 with the grid data. They discussed the socio-economic and geographical features of Chinese cities as well. Furthermore, B. Cai et al. (2018) built a dataset called China High-Resolution Emission Gridded Data (CHRED) with the gridded data. The dataset estimated Chinese cities' fossil fuel-related CO_2 emissions based on energy consumption data collected using a bottom-up approach based on industrial facility data and other geographical information. Mingshu Wang and Cai (2017) compared the gridded energy data as well as emissions from three different sources: CHRED, EDGAR and Fossil Fuel Data Assimilation System (FFDAS). The study found that the CHRED data was the most consistent with the provincial data published by NBS. This study also developed empirical models to reconcile data from the three sources.

Doll et al. (2000) found that there were strong relationships between cities' CO_2 emissions and their nighttime light imagery. They designed a method to calculate the cities' CO_2 emissions according to the nighttime light imagery. This is a sound method for developing countries who may lack consistent energy statistics. Other similar study includes Ma et al. (2012). A few subsequent studies employed a similar method for Chinese cities. L. Meng et al. (2014) examined the 1995-2010 CO_2 emissions of Chinese cities based on the night-time light imagery and energy consumption data. Yan Wang and Li (2017) calculated the CO_2 emissions from Chinese cities in 2013 and produced a city-level emission map of China. Similar methods were also used to calculate the energy consumption of Chinese cities (C. He et al., 2012; Shi et al., 2014; Y. Su et al., 2014).

A few more studies have also estimated the greenhouse gas emission for some individual cities with Geographic Information System (GIS)-based methods, such as Xue et al. (2013) (Beijing), Y. Zhang et al. (2014) (Beijing), and R. Q. Zhao et al. (2012) (Nanjing).

- Using economic models and other methods

Some studies estimate cities' emissions using economic models, such as the GDP-emission intensity model (P. Xu, 2014), input-output method (Mi et al., 2016), CGE models. Such economic-based methods are called "top-down approach".

For example, P. Xu (2014) estimated the carbon emissions of six cities located in the Shandong Peninsula (Qingdao, Dongying, Yantai, Weifang, Weihai, and Rizhao) with GDP and emission intensity. In this study, carbon emissions equalled to emission intensity multiplied by GDP. The emission intensities of the six cities were calculated based on the per GDP energy consumption and other information collected from the cities' statistical yearbooks and government reports. J. Y. Lin et al. (2014) calculated the historical CO_2 emissions for Xiamen with the integrated indicators of energy intensity and emission factors, and predicted Xiamen's emissions till 2020. Similarly, Auffhammer et al. (2016) decomposed the CO_2 emissions from the industry sectors of 287 Chinese cities.

The input-output method are usually used to estimate the consumption-based CO_2 emissions (scope 3 emissions). Due to the frequent trade among cities, lack of data, and the complexity of calculation, only few studies have calculated the consumption-based emissions of Chinese cities. For example, Mi et al. (2016) employed the input-output method to calculate the consumption-based CO_2 emissions of 13 Chinese cities in 2007 (Shanghai, Beijing, Chongqing, Tianjin, Shenyang, Dalian, Ningbo, Qingdao, Harbin, Xian, Shijiazhuang, and Hengshui). The study found that consumption-based emissions of Chinese cities were very different from their territorial emissions. This study found that megacities, such as Shanghai and Beijing, imported 70% of its consumption-based emissions from other regions, while in manufacturing-based cities, such as Tangshan, about 45% of their territorial CO_2 emissions were driven by producing export products. Similarly, J. Meng et al. (2017) calculated the black carbon emissions of four municipalities with the same method. Similar consumption-based emission studies for Chinese cities include K. Feng et al. (2014) and J. Y. Lin et al. (2013).

2.4. Research gaps

2.4.1. Research gaps on national and provincial emission accounts in China

Based on the literature review above, this study finds that the CO_2 emissions accounts of China and its provinces are not well documented. There is no annual, officially published emission report in China. The Chinese government has only published national CO_2 emissions three times: in 1994 (NDRC, 2004), 2005 (NDRC, 2013c), and 2012 (NDRC, 2016b). Research institutions and scholars calculate China's total CO_2 emissions previously. The previous studies on China-related CO_2 emissions, either calculated China's emissions individually, or collected the emission data from global emission databases.

However, there are great discrepancies between the estimates of China's CO_2 emissions by global emission databases, the range even exceeded 15% in 2013. This results in wide uncertainties in further CO_2 emission analysis. The huge discrepancies among emission estimates are mainly caused by the difference in emission account scope, the difference in emission factors, and differences in activity data. What's more, the existing global emission databases only provide the total CO_2 emissions of the country, or simply by several primary energy sources, there are no open-access detailed emission inventories by energy sources and sectors for China. Also, none of the global emission databases provides the transparent activity data (energy consumption and industrial productions) used for their emission accounts, making their estimates unverifiable.

In order to close these research gaps, this study designs a series of methods based on China's energy statistical system, constructs the emission inventories for China and its 30 provinces. The emission inventories are constructed by 17 fossil fuel types and 46 socioeconomic sectors. This study also provides the transparent activity data and emission factors used for the emissions calculation to make the inventories verifiable. The national and provincial transparent emission inventories can be re-used for further studies.

2.4.2. Research gaps on the emission characteristic analysis of China

The above literature review finds that most of the previous studies on China's emissions focused on the fossil fuel- and cement-related emissions only (Gregg et al., 2008a; Yu Lei, Zhang, et al., 2011a; Y. Lei, Zhang, et al., 2011b; Y. Liu et al., 2009; Z. Liu, Guan, et al., 2015). There are seldom studies examining the process-related CO_2 emissions from other industrial processes besides the cement production. Although, the cement production is the largest emission source of process-related emission in China's industry. Some other emission sources need deep analysis as well to better figure emission characteristics of China. Especially, there is still no studies discussed the emissions from the lime industry in China. Lime industry is the second largest process-related emission source in China, the emission characteristics and reduction policies should be discussed in details. To close this research gap, this study examines the emissions from China's lime industries, discusses the possible emission reduction policies as well.

Also, previous studies mainly focused on the emissions from traditional energy sources such as raw coal, cleaned coal, crude oil, gasoline. Few studies involved the emissions from some newly-appeared and fast-growing energy sources, such as the petroleum coke. In the followed study, the petroleum coke is selected as a case study. The emissions from petroleum coke are analysed in details.

What's more, due to the data lacking and its small amount, the CO_2 emission from Tibet is vacant, making China's national and provincial emission accounts incompleteness. This study closes the research gap by estimating the CO_2 emissions of Tibet and its cities for the first time.

2.4.3. Research gaps on city-level emissions in China

By reviewing the latest emission-related studies on global and Chinese cities, this study finds that the analysis on city-level emission accounts are far from "well-documented" compared with the national/provincial research: "*only approximately 45% of prefecture-level cities in China have emission estimates with different levels. The CO_2 emission data available for prefecture-level cities are scarce (page 198)*" (Q. Chen et al., 2017).

Similar to the national emission accounts, there are great discrepancies in the formats and scopes of different studies. When using the IPCC calculation method, emissions are calculated by energy consumption from certain sector sets. The sectors' setting differs from study to study. For example, in H. Wang, Zhang, et al. (2012)'s study, the emission inventories were constructed by six sectors: industrial energy consumption, transportation, household energy consumption, commercial energy consumption, industrial processes, and waste disposal. In contrast, Kennedy et al. (2010) compiled carbon emissions inventories that include electricity, heating and industrial fuels, ground transportation fuels, aviation and marine transportation, industrial processes, product use and waste disposal. The discrepancies in the formats and scopes of city-level emissions make the results from different studies incomparable. There are significant discrepancies of the cities' emissions calculated by different studies. For example, the fossil fuel-related CO_2 emissions of Beijing in 2010 were estimated as 201, 170, and 100 Mt by Y. He (2014), Y. X. Su (2015), and Shao et al. (2016), respectively.

In addition, the previous city-level emission inventories are usually calculated by methods differ from the national/provincial emission inventories. The national/provincial inventories are usually compiled according to the energy balance table, while emissions from cities are usually simply calculated based on several sectors' energy consumption. This makes the current city-level emissions inconsistent and incomparable with the national and provincial emissions. However, this is majorly restricted by data accessibility. Seldom cities have the energy balance table. This study closes the research gap by developing a series of methods to estimate the cities' energy balance table. With the city-level energy balance table, further studies can apply the national/provincial inventory construction method to cities, making the city-level emission inventory consistent and comparable.

What's more, city selections in previous studies are limited in significant ways. As discussed above, most of the existing studies focus on a few specific megacities, such as four municipality cities and a few provincial capital cities with consistent and systematic energy statistics. Other 330+ Chinese cities lack detailed emission analysis. In this study, 180+ generic cities are investigated to fill in this research gap.

Finally, despite some previous studies discussed the potential of low-carbon transitions for cities, but most of them focused on one or two individual cities, such as Sharp et al. (2011), Romero Lankao (2007),. L. X. Zhang et al. (2011), and Gielen et al. (2001). However, under the view of national industrialisation and globalization, the city-level low-carbon roadmaps should be discussed based on hundreds of cities at different industrial stages and development pathways. This study fills in this research gap by involving 182 cities in the city-level low-carbon roadmap design in China.

Chapter 3 Emission accounts methods developed for China and its regions

This is a method chapter of this PhD thesis. In this chapter, specific CO_2 emission accounts methods are developed for China and its regions based on the IPCC emission calculation method (introduced in Chapter 2, section 2.1) and China's energy statistics system (introduced in Chapter 2, section 2.2). This chapter also collects data for the following chapters on China and its regions' CO_2 emission accounts.

Section 3.1 states the accounting scope of the CO_2 emissions estimated in this PhD study. Section 3.2 introduces the construction of both sectoral- and reference-approach emissions inventory based on China's energy statistics system. Section 3.3 to 3.5 collects the parameters and activity data for the emission calculation. Section 3.3 discusses the China-specific emission factors based on an extensive comparison of 9 sources' emission factors. Section 3.4 collects the national and provincial activity data, while section 3.5 develops a series of methods to handle the deficient city-level activity data. Validation analysis of the developed methods is presented in section 3.5 as well.

3.1. Scope of CO_2 emission accounts in this study

This study uses the IPCC administrative territorial method to account the China CO_2 emissions (scope 1). The emissions include two parts: fossil fuel- and process-related CO_2 emissions. The fossil fuel-CO_2 emissions cover all the emissions induced by fossil fuel combustion for production activities and household usage in China. As for the process-related emissions, this study investigates the cement production only, which accounts for approximately 75% of China's total process-related CO_2 emissions (NDRC, 2013c).

This study employs both the sectoral- and reference-approach for the national and provincial CO_2 emission inventories. The two approaches lead to two different ways of calculating CO_2 emissions and constructing inventories. Considering the frequent energy trade among cities, the city-level reference-approach emission inventory may have large uncertainties, this study, therefore, only focuses on the sectoral-approach emissions of cities in China.

3.2. Sectoral- and reference-approach emission inventory

3.2.1. The sectoral-approach inventory construction

The sectoral-approach fossil fuel consumption is calculated as the sum of final consumption of fossil fuel and input usage in the energy transformation process. The final consumptions are presented in the “Final consumption” part of the energy balance table. As for the “Input and output of transformation”, only the energy inputs for “Thermal power” and “Heating supply” are burnt; the energy inputs in other energy transformation processes belong to non-combustion consumption, which should be excluded from the sectoral-approach fossil fuel consumption used for the CO_2 emissions calculation. For example, the “Coal washing” process inputs raw coal and outputs cleaned coal and other washed coal. All the coal elements in raw coal are transformed into cleaned coal and other washed coal. There is no oxidation reaction during the process. Based on mass balance theory, no CO_2 will be emitted. In addition, the “Non-energy use” and “Loss” should be removed from the total consumption as these parts do not emit CO_2 either. Therefore, the sectoral-approach to fossil fuel consumption can be calculated as “Final consumption” + “Thermal power (Transformation)” + “Heating supply (Transformation)” - “Loss” - “Non-energy use” (Peters et al., 2006).

Particularly, “Non-energy use” consumption should be removed from sector “Chemicals”, “Medicals”, “Chemical fibre”, “Rubber”, and “Plastic” according to the proportion. Non-energy consumption is assumed to be used as raw material inputs in these five sectors only. The “Loss” energy should be removed from every sector per proportion as well.

The sectoral-approach emission inventory is constructed based on the sectoral-approach fossil fuel consumption. After calculating the CO_2 emissions induced by the final consumption of fossil fuel in 46 sectors, the emissions induced by thermal power and heat supply can be allocated to the sector “Power and heat”.

Emissions from electricity and heat generated within regional boundaries are calculated based on primary energy input usage (such as raw coal inputs for thermal power and heat supply), which are included in the fossil fuel-related emissions (Peters et al., 2006). The administrative-territorial emission inventories (scope 1) exclude emissions from imported electricity and heat consumption from outside the city boundary (which is Scope 2 emissions), as well as the inter-city transportation energy consumption, due to the lack of data and huge uncertainty.

Based on China's energy statistical system, the sectoral-approach CO_2 emission inventories are compiled by 17 fossil fuels and 46 sectors in this study. As discussed in previous section 2.2, there are 27 kinds of fossil fuels in China's official energy statistics, i.e. listing in the lasted energy balance table in China energy statistical yearbook (NBS, 2016a). This study merges them into 17 when calculating the fossil fuel-related CO_2 emissions, due to some fossil fuels' small consumption and similar quality with others, shown in Table 3-1.

Table 3-1 Fossil fuel types involved in this study

i	Fuels in China's Energy Statistics	Fuels in this study	i	Fuels in China's Energy Statistics	Fuels in this study
1	Raw coal	Raw coal	11	Kerosene	Kerosene
2	Cleaned coal	Cleaned coal	12	Diesel oil	Diesel oil
3	Other washed coal	Other washed coal	13	Fuel oil	Fuel oil
4	Briquettes	Briquette	14	Naphtha	Other petroleum products
	Gangue			Lubricants	
5	Coke	Coke		Petroleum waxes	
6	Coke oven gas	Coke over gas		White spirit	
7	Blast furnace gas	Other Gas		Bitumen asphalt	
	Converter gas			Petroleum coke	
	Other gas			Other petroleum products	
8	Other coking products	Other coking products	15	Liquefied petroleum gas (LPG)	Liquefied petroleum gas (LPG)
9	Crude Oil	Crude oil	16	Refinery gas	Refinery gas
10	Gasoline	Gasoline	17	Natural gas	Natural gas

In order to have better analyses of the emission inventories, this study classifies the 39 manufacturing sectors into 4 groups: Energy production sectors, Heavy-manufacturing sectors, Light-manufacturing sectors, and High-tech industry sectors. Energy production sectors include 5 sub-sectors which produce both primary and secondary energies ($j \in \{[2,3], 20, [38,39]\}$). The heavy-manufacturing, as well as light-manufacturing, has no clear-cut definition previously. This study defines that heavy-manufacturing as 16 sub-sectors that input natural resources to produce energy-intensities intermediate products ($j \in \{[4,7], 21, [23,32], 40\}$), such as "Ferrous mining" and "Non-metal prod.". 13 sub-sectors are classed as light-manufacturing which mainly produces final products ($j \in \{[8,19], 22\}$), such as "Food processing", "Furniture" (NBS, 2015d), while high-tech industry refers to 5 sub-sectors with high and new technologies ($j \in [33, 37]$).

In addition, the tertiary industries are grouped together as service sectors ($j \in [42, 44]$), while "Farming" ($j = 1$), "Construction" ($j = 41$), "Urban and Rural household energy usage" ($j \in [45, 46]$) are defined as "Others" in this study.

The emissions from "Farming" and residential sectors (household-urban and household-rural) in this study may have a different scope with those of the Europe countries. As this study only considers the fossil fuel- and process-related emissions, the emissions from "Farming" sector here refer to the emissions from energy utilization by farming, rather than the emissions from the agriculture, forestry and land use (which approximately accounts for 10-12% of the total global anthropogenic greenhouse gas emissions in 2005 (IPCC, 2006)). The emissions from agriculture, forestry and land use are not included in this study. Also, the emissions from residential sectors refer to the emissions induced by fossil fuel used by households, such as the natural gas or coal gas for cooking. The emissions related to the electricity consumption in households are allocated to the power plants. The emissions related to gasoline consumption by private car are allocated to the "Transportation" sector. Therefore, the emission share of the "Farming" and residential, and "Transportation" sectors of China are normally smaller than those of the Europe countries.

As for the CO_2 emission from industrial processes, this study allocates the emissions from cement to the sector "Non-metal prod.". In this way, the sectoral-approach CO_2 emission inventory is constructed in 46 socioeconomic sectors.

Table 3-2 Sectors' categories

j	Socioeconomic sectors	Category	
1	Farming	Others	
2	Coal mining	Manufacturing	Energy production
3	Petro. and gas ext.		Energy production
4	Ferrous mining		Heavy manufacturing
5	Nonferrous mining		Heavy manufacturing
6	Non-metal mining		Heavy manufacturing
7	Other mining		Heavy manufacturing
8	Food processing		Light manufacturing
9	Food production		Light manufacturing
10	Beverage		Light manufacturing
11	Tobacco		Light manufacturing
12	Textile		Light manufacturing
13	Garments		Light manufacturing
14	Leather		Light manufacturing
15	Timber		Light manufacturing
16	Furniture		Light manufacturing
17	Papers		Light manufacturing
18	Printing		Light manufacturing
19	Cultural		Light manufacturing
20	Petroleum proc.		Energy production
21	Chemicals		Heavy manufacturing
22	Medicals		Light manufacturing
23	Chemical fibre		Heavy manufacturing
24	Rubber		Heavy manufacturing
25	Plastic		Heavy manufacturing
26	Non-metal prod.		Heavy manufacturing
27	Ferrous proc.		Heavy manufacturing
28	Non-ferrous proc.		Heavy manufacturing
29	Metal prod.		Heavy manufacturing
30	Ordinary equip.		Heavy manufacturing
31	Special equip.		Heavy manufacturing
32	Transport equip.		Heavy manufacturing
33	Electric equip.		High-tech industry
34	Electronic equip.		High-tech industry
35	Instruments		High-tech industry
36	Other manuf.		High-tech industry
37	Waste		High-tech industry
38	Power and heat		Energy production
39	Gas		Energy production
40	Water		Heavy manufacturing
41	Construction	Others	
42	Transportation	Services sectors	
43	Wholesalele		
44	Other services		

45	Household-urban	Others

3.2.2. The reference-approach inventory construction

The reference approach is "*a top-down approach, using a country's energy supply data to calculate the emissions of CO_2 from combustion of mainly fossil fuels (page 6.5)*" (IPCC, 2006). The only difference between the two approaches is that reference approach emissions are calculated based on reference fossil fuel consumptions, rather than sectoral consumption. The reference fossil fuel consumption is estimated based on mass balance of energy (R.J Andres et al., 2012; Robert J Andres et al., 2014; Z. Liu, Guan, et al., 2015). The consumption is the mass balance of fuels produced domestically for fossil fuel production, trade, international fuelling and change in stock (see Equation 3-1). The items in Equation 3-1 can be collected from the first part "Primary energy supply" in the energy balance table.

Reference fossil fuel consumption = indigenous production + imports – exports + moving in from other provinces – sending out to other provinces ± stock change – non-energy use – loss   *Equation 3-1*

The reference fossil fuel consumption considers only three primary fossil fuel types (raw coal, crude oil and natural gas). Accounting errors due to energy transformation between primary and second fossil fuel types can be avoided (e.g., coal washing, coking, and thermal power). Taking the national energy utilization in 2015 as an example (see Figure 3-1), raw coal, crude oil and natural gas are presented as grey, orange and green lines, respectively. In general, there are two sources of fossil fuels: indigenous production (shown as the yellow module) and imports (shown as the blue module). Excluding exports, stock decreases, losses and non-energy use, the reference fossil fuel consumption can be obtained in Equation 3-1.

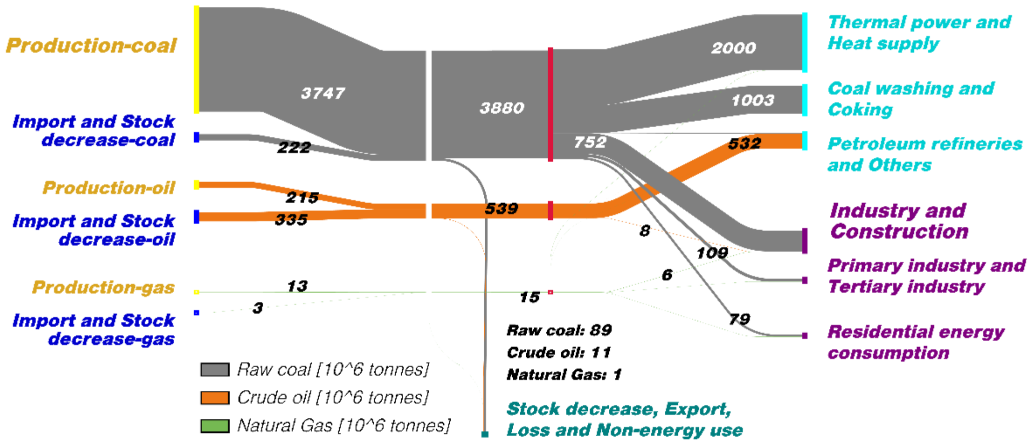

Figure 3-1 Chinese energy flows, 2012
Data source: NBS (2014)

The red module in Equation 3-1 is the reference fossil fuel consumption, which totalled 3,880 Mt of raw coal in 2015, 539 and 15 tonnes of crude oil and natural gas, respectively. Taking raw coal as an example, raw coal is the largest primary fossil fuel type used in China. Only a small amount of raw coal was used by the final consumption sectors (the purple module in Figure 3-1 940 Mt). Most raw coal was transformed into secondary energy types (the aqua module in Figure 3-1 3,023 Mt), such as electricity, heat, cleaned coal, coke. Therefore, the reference primary fossil fuel consumption includes all fossil fuel types consumed within one regional boundary.

Technically, the sectoral-approach fossil fuel consumption (calculated according to consumption-side data) and the reference-approach fossil fuel consumption (calculated according to production-side data) should be equal. However, due to statistical error and the poor quality of China's energy statistics, there is around a 5% difference between the two consumption rates (NBS, 2014). Hence, IPCC (2006) recommends that: "*It is good practice to apply both a sectoral approach and the reference approach to estimate a country's CO_2 emissions from fuel combustion and to compare the results of these two independent estimates (page 6.5)*". Furthermore, "*Improved comparability between the sectoral and reference approaches continues to allow a country to produce a second independent estimate of CO_2 emissions from fuel combustion with limited additional effort and data requirements (page 6.5)*" (IPCC, 2006).

Based on the reference fossil fuel consumption calculation (Equation 3-1), the reference-approach inventories in this study are constructed by the six components: "Indigenous production", "Import", "Export", "Stock decrease/increase", "Loss", and "Non-energy use" of the three primary energies (raw coal, crude oil, and natural gas).

The process-related emissions are listed separately in the reference-approach inventories.

3.3. Emission factors

IPCC, NDRC, UN, and several other research institutes provide the emission factors (net caloric value, carbon content, oxygenation efficiency) for China. This study summarises the emission factors from eight different sources: IPCC, NBS, NDRC, Initial National Communication on Climate Change (NC1994), Second National Communication on Climate Change (NC2005), Multi-resolution Emission Inventory for China (MEIC), UN-China, UN-average (shown in Appendix Table 1).

After examining the 127 SCI-papers published in the past ten years (2004-2014), this study finds that nearly half of the previous studies on China's CO_2 emission accounts adopt the IPCC default emission factors, such as Cheng et al. (2014), L. Chen, Yang, et al. (2013), and J. Fan et al. (2012), see Figure 3-2. 32 of them collect the emission factors from NDRC or NBS, such as R. Guo et al. (2010) and Y. L. Dong, Ishikawa, et al. (2010). 21 of them cited from research institutions directly, for example, S. J. Davis and Caldeira (2010) cites the emissions from Global trade analysis project (GTAP) version 7 and CDIAC; Lan et al. (2012) and Berezin et al. (2013) use emissions from various databases including EDGAR version 4.2; S. J. Davis, Caldeira, et al. (2010) collects emissions from IPCC report on emission scenarios (Nakicenovic et al., 2000). Four studies estimated the CO_2 emissions/emission factors based on experiments. J. Zhang et al. (2000) measured emissions of 8 types' greenhouse gases/air pollutants (including CO_2, CO, CH_4, TNMHC, N_2O, SO_2, NO_x, TSP) from China's household stoves. Sun et al. (2011) used emission factors from a nationwide sampling investigation when calculating the energy-related CO_2 emissions of China's iron and steel industries. Y. M. Wei et al. (2007) collect the emission factors of coal, petroleum, and natural gas from "Energy Research Institute" (Z. Zhang, 2000), while the emission factors of electricity and heat were collected from their own calculation. Q. F. Chen, Ma, et al. (2013) used "*the emissions concentration and fluxes of CO_2 with the static opaque chamber –GC technique and eddy covariance technique*" to measure emissions.

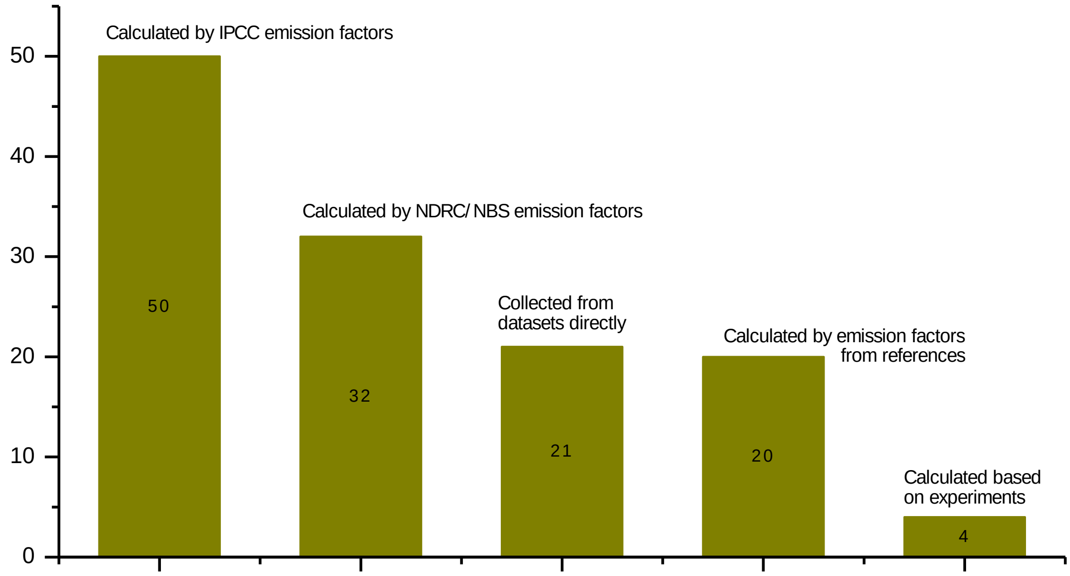

Figure 3-2 Emission data sources of 127 SCI papers during 2004 to 2014

However, the above emission factors provided by institutes have limitations. Firstly, the NDRC, NC1994, and NC2005 emission factors may be outdated. The NC1994 and NC2005 emission factors are used for the 1994 and 2005 emission inventories' compilation. The emission factors are calculated based on the energy quality investigation of the inventorying year. Owing to the series of policies on China's energy optimal utilization (Guan et al., 2016) and the development of clean coal technology in recent years (W. Chen et al., 2010; Lu et al., 2008; L. Zhao et al., 2007), China's fossil fuel qualities have changed greatly in recent years. Secondly, the IPCC emission factors are called "default value", IPCC encourages countries to use their own emission factors when calculating the CO_2 emissions. "*Good practice is to use the most disaggregated, technology-specific and country-specific emission factors available, particularly those derived from direct measurements at the different stationary combustion sources (page 2.24)*" (IPCC, 2006). Therefore, it is inaccurate to calculate current China's CO_2 emissions using these previous emission factors (Jackson et al., 2016; Korsbakken et al., 2016b; Le Quéré et al., 2015; Olivier et al., 2015).

Table 3-3 Comparisons of emission factors

Raw coal	NCV_i (PJ/mt)	$CC_i(tC/TJ)$	O_i (%)
IPCC (Coking bituminous coal)	28.20	25.80	0.98
IPCC (Bituminous coal)	25.80	25.80	0.98
IPCC (Anthracite)	26.70	26.80	0.98
NBS	20.91	26.37	0.94
NDRC	20.91	26.37	0.94
NC1994	20.93	24.26	0.90
NC2005	22.35	25.83	0.92
MEIC	19.06	25.80	1.00
UN-China	20.91	25.80	1.00
UN average	29.30	25.80	1.00
Z. Liu, Guan, et al. (2015)	20.60	26.32	0.92
Crude oil	NCV_i (PJ/mt)	$CC_i(tC/TJ)$	O_i (%)
IPCC	42.30	20.00	0.99
NBS	41.82	20.08	0.98
NDRC	42.62	20.08	0087
NC1994	41.87	20.00	0.98
NC2005	42.62	20.08	0.98
MEIC	41.82	19.91	1.00
UN-China	42.30	20.00	1.00
UN average	42.30	20.00	1.00
Z. Liu, Guan, et al. (2015)	42.62	20.08	0.98
Natural gas	NCV_i $(PJ/10^8m^3)$	$CC_i(tC/TJ)$	O_i (%)
IPCC	3.44	15.30	0.99
NBS	3.89	15.32	0.99
NDRC	3.89	15.32	0.99
NC1994	3.90	15.30	0.99
NC2005	3.89	12.32	0.99
MEIC	3.89	15.16	1.00
UN-China	3.44	15.30	1.00
UN average	3.44	15.30	1.00
Z. Liu, Guan, et al. (2015)	3.89	15.32	0.99

Based on the measurements of 602 coal samples from the 100 largest coal-mining areas in China (Z. Liu, Guan, et al., 2015), the coal emission factors recommended by the IPCC and NDRC are frequently (40%) higher than the current emissions factors. The newly updated factors are now widely used in China-specific emission studies, and even being adopted by the Chinese government in its recently released report on climate change (NDRC, 2016b). This demonstrates that the emission factors collected by Z. Liu, Guan, et al. (2015) are supposed to be more accurate and suitable for China. Therefore, this study uses Z. Liu, Guan, et al. (2015)'s emission factors to calculate China's CO_2 emissions. The comparisons of different emission factors are shown in Table 3-3 and Appendix Table 1.

Table 3-4 Emission factors used in this study

No. (i)	Fossil fuel types	NCV_i $(PJ/10^4t,\ 10^8m^3)$	$CC_i(t\ CO_2/TJ)$
1	Raw coal	0.21	96.51

2	Cleaned coal	0.26	96.51
3	Other washed coal	0.15	96.51
4	Briquettes	0.18	96.51
5	Coke	0.28	115.07
6	Coke oven gas	1.61	78.80
7	Other gas	0.83	78.80
8	Other coking products	0.28	100.64
9	Crude oil	0.43	73.63
10	Gasoline	0.44	69.30
11	Kerosene	0.44	71.87
12	Diesel oil	0.43	74.07
13	Fuel oil	0.43	77.37
14	Liquefied petroleum gas	0.51	63.07
15	Refinery gas	0.47	73.33
16	Other petroleum products	0.43	74.07
17	Natural gas	3.89	56.17

Z. Liu, Guan, et al. (2015) only reported the emission factors of three primary fossil fuels (i.e. raw coal, crude oil, and natural gas), this study estimates the emissions factors of other 14 secondary fossil fuels by scaling them down according to the ratio of the updated primary fossil fuels' emission factors to those of NDRC. This study uses the ratio of raw coal, crude oil to update emission factors of coal-related, oil-related fuels, respectively. Emission factors for 17 fossil fuels are shown in Table 3-4. As for the oxygenation efficiencies, this study considers different values for fossil fuels used in different sectors (NDRC, 2011a), as the combustion technology levels of sectors are different in China. Detailed oxygenation efficiencies are presented in Appendix Table 2.

As for the emission factors of cement production, the emission factor is collected from the previous study on China's cement process (Z. Liu, Guan, et al., 2015), which is 0.2906 $t\,CO_2/t$. The value is 41.7% lower than the IPCC default value (0.4985).

3.4. National and provincial activity data collection

As discussed in Section 2.2 and 2.1.3, either the sectoral-approach or the reference-approach fossil fuel consumption can be calculated based on the energy balance tables and sectoral final energy consumption tables.

The national energy balance tables and sectoral final energy consumption tables are collected from Energy statistical yearbooks. The Energy statistical yearbooks are published by NBS annually. The yearbooks present the energy production, import, export, and consumption data of the whole country, as well as some energy-related information, such the infrastructure investment, technical innovation in the energy field. The yearbooks also provide the provincial data, such as the provincial energy balance tables. The energy statistical yearbook is the only official energy data source in China.

However, China has revised its national energy statistics four times since 2000 (in 2004, 2005, 2009, and 2014's China energy statistical yearbooks). Each revision has modified the previous energy balance sheets and sectoral energy consumptions. For example, the total energy consumptions of 2011 are modified from 3,480 to 3,870 Mtce in 2014's revision, enlarged by 11.2%. Figure 3-3 shows the national CO_2 emissions calculated based on the four-revised data. The data revision in 2014 increased the national emissions by 12%. The following emission inventories compiled and analysed in this study are calculated based on the most up to date energy data published after 2014 (NBS, 2014-2016).

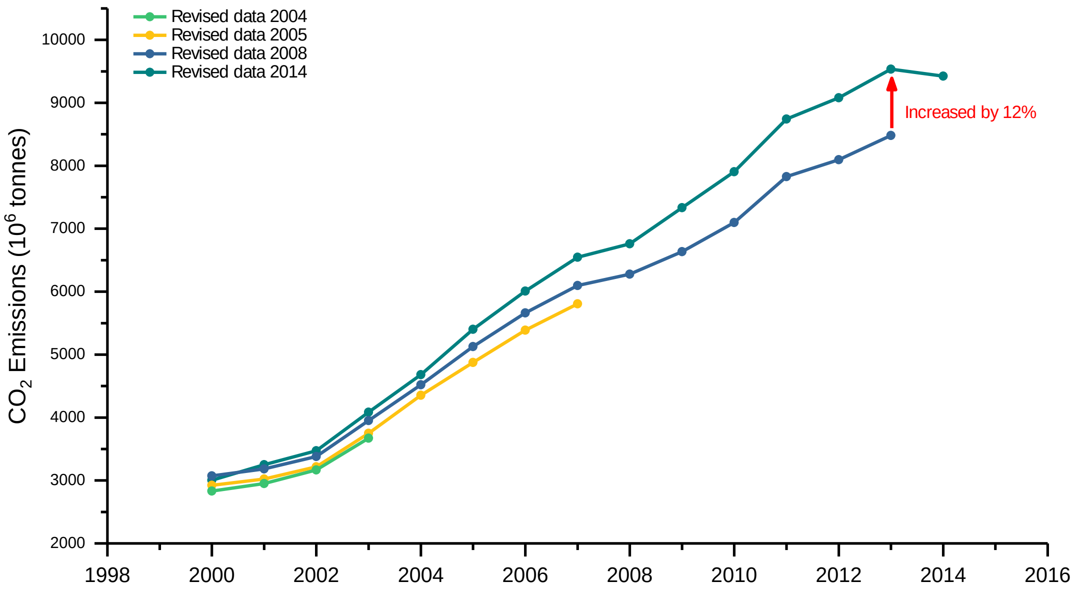

Figure 3-3 National CO_2 emissions based on four revised energy data, 2000-2015

For the provincial scale, the Energy statistical yearbooks only publish each province's energy balance table every year. Most of the provinces' industry sectoral fossil fuel consumption can be collected from the provinces' corresponding statistical yearbooks. For certain provinces (Hebei, Jiangsu, Zhejiang, Shandong, Guangxi, Hainan, Sichuan, and Guizhou) that do not have the data in their yearbooks, this study uses the provinces' economic census data 2008 (NBS, 2008) instead, which assumes the provinces' industry structures are stable during the intervening years.

As for the cement process-related emissions' calculation, this study collects the cement production of China and its provinces from the official dataset of the NBS (NBS), which are consistent with the latest China statistical yearbooks (NBS, 1998-2016).

3.5. Methods for city-level activity data collection

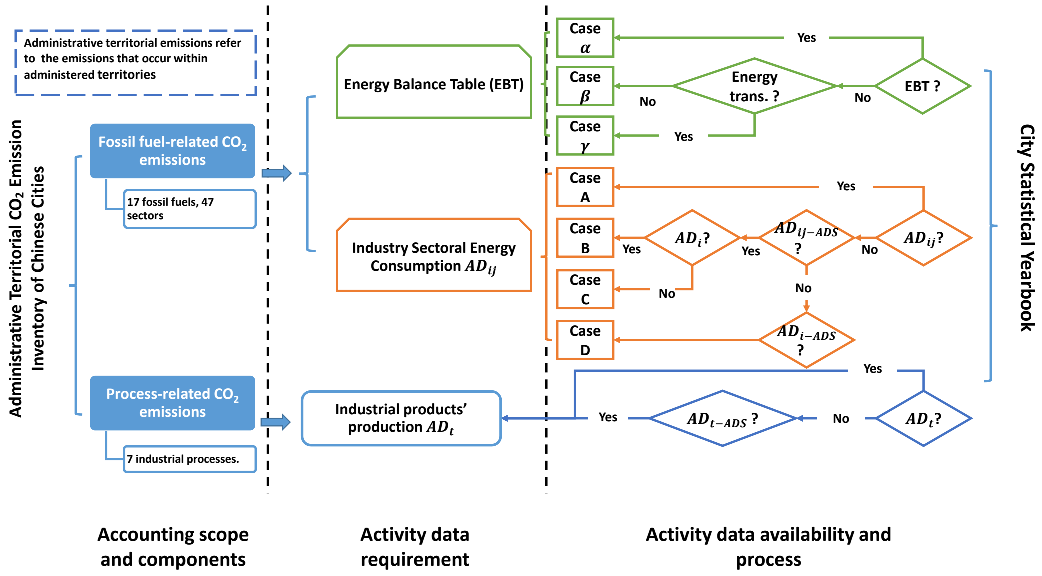

Figure 3-4 Data process framework for Chinese cities

Due to the poor data quality of Chinese cities, most cities do not compile the energy balance tables in their statistical yearbooks. This study, therefore, develops a series of methods to compile the missing energy balance tables. Figure 3-4 shows the overall methodology framework designed for the collection of energy data at city-level in China. This study only considers the sectoral approach CO_2 emissions for cities due to the frequent energy trade among cities (see discussions in section 4.3.2). Three cases for energy balance table's reckoning and four cases for sectoral energy consumption are designed. The original and other supporting data are collected from each city and their corresponding province's statistical yearbooks.

3.5.1. Energy balance tables for cities

Case α: cities with the energy balance table

Some cities compile energy balance tables in their statistical yearbooks, such as Guangzhou. This study uses the table directly for further emission calculation in this case. Among the 182 case cities analysed in this study, 17 of them (9.34%) fall into this category.

Case β: cities without the energy balance table

For cities such as Hefei and Xiamen, there is no energy balance table in their statistical yearbooks. Among the 182 case cities analysed in this study, 120 of them (65.93%) fall into this category.

In these cases, this study compiles the city's energy balance table on the basis of its corresponding provincial energy balance table ($EBT_{province}$). First, this study defines a city-province percentage p in Equation 3-2, which can be calculated using different indexes, such as industrial outputs and population. The equation reflects the percentage relation between a city and its province.

$$p = \frac{Index_{city}}{Index_{province}} \times 100\%$$ *Equation 3-2*

With the city-province percentage p, this study scales down the provincial energy balance table to the city level (see Equation 3-3). In the following calculation of a city's sectoral-approach emissions, only the data on energy transformation, loss, and final consumption will be used. Therefore, this study focuses solely on these three components.

$$EBT_{city} = EBT_{province} \times p$$ *Equation 3-3*

By using different indexes, p can indicate the different percentage types of emissions in one city based on the entire province. This study uses different city-province percentages p, to deduce the relevant items for the energy balance table in this paper. For the "Input and output of transformation" and "Loss" parts, this study uses the industrial output as the index because energy transformation departments belong to industrial sectors. For the "Final consumption" part, this study uses the corresponding outputs of each sector as the index. For the "Residential consumption" part, this study uses population as the index. The industrial output and population can be collected from city's statistical yearbook.

Case γ: cities without the energy balance table, but with "Energy transformation input and output"

Some cities do not have an energy balance table in their statistical yearbooks but have compiled a table of "Energy transformation input and output", such as Huangshi in Hubei province. Such a transformation table gives detailed information of energy transformation of the city, this study, therefore, modifies the transformation part of the deduced energy balance table with the table of transformation. Among the 182 case cities analysed in this study, 45 of them (24.73%) fall into this category.

Case β and Case γ method verification

In order to verify the methods used to deduce the cities' energy balance table (i.e. Case β, Case γ), this study applies the Case α, Case β, and Case γ methods to calculate the emissions of 13 cities, which have energy balance tables (Tangshan, Hohhot, Wuhai, Tongliao, Jixi, Weifang, Xinxiang, Changsha, Hengyang, Shaoyang, Chenzhou, Guangzhou, Yangjiang), and compares the results. The comparisons show that the difference between emissions from Case α and Case β method falls in (-5.24%, 9.86%), while the difference between emissions from Case α and Case γ fall in (-4.86%, 7.92%). The tiny gaps could verify the method developed for cities' data collection are robust and validated.

3.5.2. Sectoral fossil fuel consumptions for cities

Following the methods below, this study reckons the industrial sectoral energy consumption of cities with different data qualities.

Case A: cities with industry sectoral fossil fuel consumption (AD_{ij})

For some cities, such as Tangshan, the sectoral energy consumption of industry (AD_{ij}) is provided in the statistical yearbook. This study uses the data directly. Among the 182 case cities analysed in this study, 10 of them (5.49%) fall into this category.

Case B: cities with sectoral fossil fuel consumption of industrial enterprises above-designated size (AD_{ij-ADS}) and total fossil fuel consumption of industry (AD_j)

For cities such as Guangzhou, there are sectoral fossil fuel consumption of industrial enterprises above designated size (AD_{ij-ADS}) and total fossil fuel consumption of the whole industry (AD_j) in the statistical yearbook. The enterprise above designated size (ADS) usually refers to the enterprise with annual main business turnover above 5 million yuan. Among the 182 case cities analysed in this study, 26 of them (14.29%) fall into this category.

In this case, this study expands AD_{ij-ADS} by AD_j to obtain AD_{ij} in Equation 3-4.

$$AD_{ij} = \frac{AD_{ij-ADS}}{\sum_i AD_{ij-ADS}} \times AD_j \qquad \textit{Equation 3-4}$$

Case C: cities with sectoral fossil fuel consumption of industry above designated size (AD_{ij-ADS}) only

These cities are the most typical types in terms of data collection for Chinese cities. 75.82% (138 of 182) cities are classified as this case; these include Hefei and Xiamen. To calculate the sectoral fossil fuel consumption of industry (AD_{ij}) in these cities, this study expands AD_{ij-ADS} to AD_{ij} by the whole industry to the ADS industry (above the designated size) multiplier m (see Equation 3-5).

$$AD_{ij} = AD_{ij-ADS} \times \frac{O_{industry}}{O_{ADS}} \qquad \textit{Equation 3-5}$$

$O_{industry}/O_{ADS}$, which is the ADS multiplier (m), refers to the multiple of industrial output to that of the industry above the designated size.

Note that the total fossil fuel consumption of industry calculated in this manner can be different with the deduced energy balance table. This study uses the consumption calculated by the ADS multiplier as more accurate data, and modify the relevant data in the deduced energy balance table. Because the consumption calculated by the ADS multiplier is compiled by sectors, it is assumed to be more accurate.

Case D: cities with total fossil fuel consumption of industry above designated size (AD_{j-ADS}) only

For cities such as Weifang and Huangshi, there is only total fossil fuel consumption of industry above the designated size (AD_{j-ADS}) in the statistical yearbooks. Among the 182 case cities analysed in this study, only 8 of them (4.40%) fall into this category.

In this case, this study first scales up AD_{j-ADS} to AD_j by the ADS multiplier m and then divide AD_j into each sector by the sectoral comprehensive energy consumption of the industry above the designated size (AD^*_{i-ADS}) (refer to Equation 3-6). If one city does not have AD^*_{i-ADS}, this study uses the sectoral industry output instead.

$$AD_{ij} = AD_{j-ADS} \times \frac{O_{industry}}{O_{ADS}} \times \frac{AD^*_{i-ADS}}{\sum AD^*_{i-ADS}}$$ *Equation 3-6*

The formula $AD^*_{i-ADS}/\sum AD^*_{i-ADS}$ can be seen as the sectoral ratio used for dividing the city's total industrial fossil fuel consumption. The ratio can also be calculated as the city's AD_{ij} of nearby inventorying year, or the corresponding province's AD_{ij}, assuming that the city shares a similar sector structure with its province.

Case B, Case C, and Case D method verification

Similarly, with the verification of the energy balance table's estimation, this study verified the three cases defined for sectoral fossil fuel consumption estimation as well. This study applies the Case A, Case B, Case C, and Case D methods to calculate the emissions of 10 cities, which have sectoral fossil fuel consumption, and compares the results. The comparisons show that the emissions calculated by Case A and Case B method are almost the same with ±0.5%'s gap, while the difference between emissions from Case A and Case C fall in (-2.45%, 3.81%). The emissions calculated with Case D have the largest discrepancies with the results from Case A: (-8.89%, 9.71%).

3.5.3. Industry products' production

Data collection for the products' production is much easier and universal. Every city has the "Production of industrial products" table in its statistical yearbook. A portion of the production is derived from industrial enterprises above the designated size. Expanding the production above the designated size (AD_{t-ADS}) by the city's ASD multiplier m defined above, the total production of each industrial product (AD_t) can be obtained, shown in Equation 3-7.

$$AD_t = AD_{t-ADS} \times m$$ *Equation 3-7*

3.5.4. Verification

In order to overall verify the method developed for city-level data collection, this study applies the method to 5 selected cities firstly and compares the fossil fuel-related CO_2 emissions with previous studies. Fossil fuels contribute about 90% of the total CO_2 emissions. Therefore, the comparison of the fossil fuel-related CO_2 emissions with other research can be a validation. In the CHRED with 1km resolution built by Chinese Academy for Environmental Planning (CAEP), they estimated few cities' fossil fuel-related CO_2 emissions based on energy consumption data collected in a bottom-up way based on industrial facility data and other supporting information (B. Cai, 2011;2012b; B. Cai et al., 2014b; J. Wang, Cai, et al., 2014). The 5 cities, Hefei, Xiamen, Weifang, Huangshi, and Guangzhou, contain all the different case defined above, see Table 3-5. The difference of CO_2 emissions calculated in this study and CHRED's research is within ±10%. The tiny difference testifies the city-level data collection methods developed in this study are feasible.

Table 3-5 Validation of the city-level data collection methods

Cities	This study	CHRED-CAEP	Difference	Case type
Hefei	30.22	33.23	-9.06%	βC
Xiamen	11.82	12.67	-6.66%	βC
Weifang	60.17	57.18	5.24%	αD
Huangshi	19.65	20.61	-5.25%	γD
Guangzhou	96.13	96.67	-0.56%	γB

3.6. Summary

This chapter introduces the CO_2 emission accounts methods developed for China and its regions. This study adopts the IPCC administrative territorial scope to calculate the CO_2 emissions for China and its regions. The CO_2 emissions estimated in the following chapters include both the scope 1 fossil fuel-related and scope 1 process-related CO_2 emissions induced within one administrative unit's boundary.

The fossil fuel-related CO_2 emissions inventory are constructed as two different approaches: the sectoral and reference approach. The two approach emission inventories are designed and constructed based on China's energy statistical system and data layout.

This chapter also collects the parameters and activity data for the emission estimations in the following chapters. The emission factors are collected from Z. Liu, Guan, et al.

(2015), which are supposed to be more accurate and suitable for China. Then the activity data (fossil fuel consumption and cement production) for China and its province's CO_2 emission accounts are collect in section 3.4. The national and provincial activity data are collected from the statistical yearbooks published by the NBS. Due to the poor data quality within city records, lots of necessary data for city-level emission accounts are missing, such as the energy balance table and sectoral fossil fuel consumption. Aiming at this research gap and data limitation, this chapter develops a series of methods to handle the deficient city-level activity data (see section 3.5). Three cases and four cases are defined to estimate the missing energy balance table and sectoral fossil fuel consumption for cities, respectively. The validation of the methods shows that the uncertainty for energy balance table's estimation fall between -5% and 10%, while that for sectoral fossil fuel consumption's estimation fall is ±9%. A verification analysis of the developed methods is conducted by comparing the cities' emissions with a bottom-up approach emission database. The results show that the difference between the two sources' CO_2 emissions is within ±10%. The tiny difference testifies the city-level data collection methods developed in this study are feasible.

Chapter 4 Emissions in the whole China and by province

By employing emission calculation and inventory construction methods, this chapter examines the CO_2 emission inventories for China and its 30 provinces (excluding Tibet, Hong Kong, Macao and Taiwan). The national emission inventories cover 2000 to 2015, while the provincial inventories cover the period 1997 to 2015 due to data availabilities. Emissions from Tibet and its cities will be examined in Chapter 7, as an important supplement to national and provincial emission inventories.

Section 4.1 examines both the sectoral- and reference-approach national CO_2 emissions from 2000 to 2015. The per capita emissions and emission intensities are discussed as well. In section 4.2, a similar analysis is conducted at the provincial level. 30 provinces' contributions to 2015 CO_2 emissions are also discussed in section 4.2.1 to present the geographical distribution characteristics of provincial CO_2 emissions. Section 4.3, contains a discussion of the uncertainties of the estimated national and provincial CO_2 emissions by comparing the emission estimates with other existing emission database and conducting the Monte Carlo simulations.

4.1. National CO_2 emissions

Figure 4-1 shows the overall CO_2 emissions of China from 2000 to 2015, including both sectoral- and reference-approach emissions.

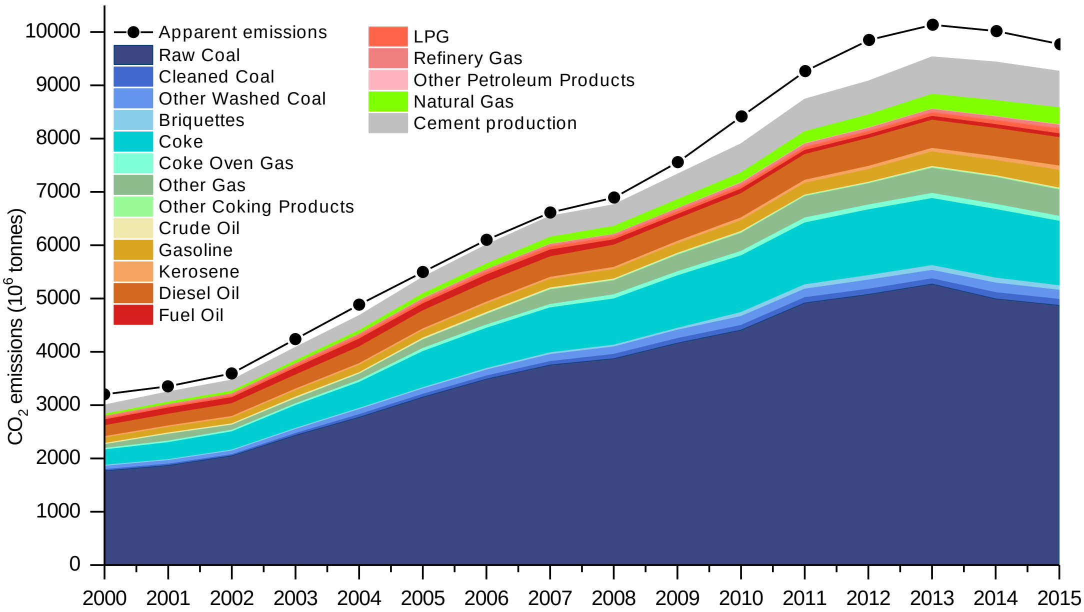

Figure 4-1 National CO_2 emissions, 2000-2015

4.1.1. National sectoral-approach CO_2 emissions

Appendix Table 3 presents the sectoral-approach national CO_2 emissions by fossil fuel type. During the past 16 years, the total CO_2 emissions increased from 3,003 to 9,265 Mt with an average increase of 7.8% per year. The rapid CO_2 emissions growth can be divided into several periods, shown in Figure 4-2.

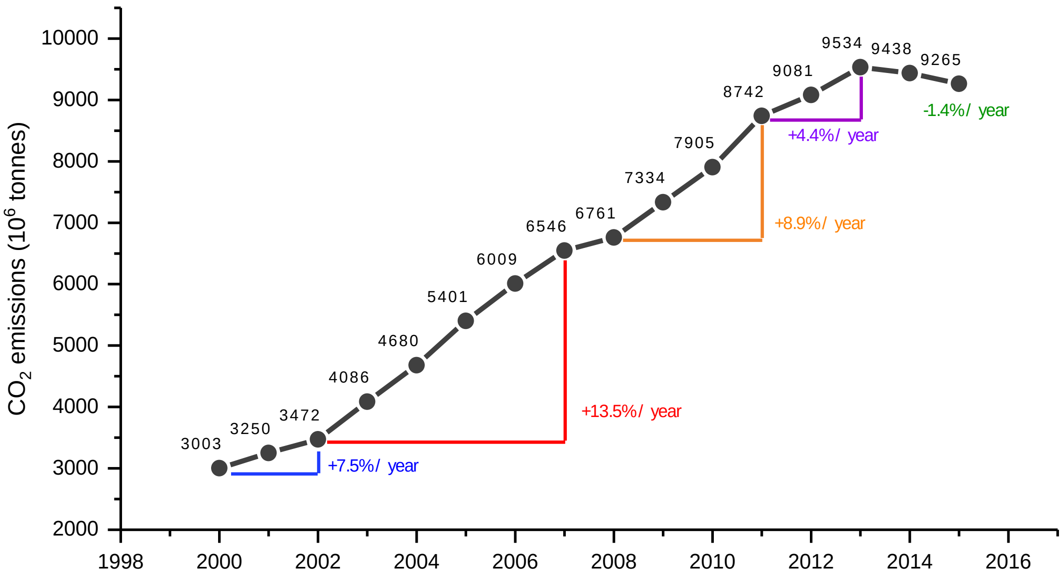

Figure 4-2 CO_2 emissions growth in China during 2000-2015

- Pre-WTO (2000-2002): Before China joined the WTO in 2002, China's CO_2 emissions increased steadily from 3,003 in 2000 to 3,472 Mt in 2002 at an average rate of 7.5% per year;

- Pre-financial crisis (2002-2007): CO_2 emissions almost doubled during the 6 years after China joined the WTO. Emissions increased from 3,472 in 2002 to 6,546 Mt in 2007 at an average rate of 13.5% per year;
- Post-financial crisis (2008-2013): Influenced by the global financial crisis in 2007 and 2008, the total emissions of China remained stable in these two years with little increase (215 Mt, 3.3%). After the financial crisis, China's emissions increased rapidly again until 2011. The total emissions growth during these four years was 1,981 Mt or 29.3%. Since 2011, China's emissions growth has slowed. The average rate of increase from 2011 to 2013 was only 4.4%, even lower than the pre-WTO rate;
- Emissions peak and after (2013-2015): according to this study's analysis, China's CO_2 emissions peaked in 2013, at 9,534 Mt. Since then there has been a slight decrease in growth rate of 1.4% per year.

Economic growth has been the major contributor to emissions growth in China. According to Guan et al. (2009), per capita GDP drove 37% of the emission increase between 2002 and 2005. Between 2007 and 2013, the 40.9% increase in Chinese emissions was also driven by strong economic growth. The possible driver for the emission decrease since 2013 in China may be the changes in industrial structure and further decreases in both the share of fossil fuel derived from coal and energy intensity (Guan et al.).

Emissions by fossil fuels and sectors

The structure of energy utilization in China has been very stable over the past 15 years. Based on natural resource endowments of "rich coal, deficient oil, and lean gas", coal and its related secondary fossil fuels make the great proportion of total energy consumption in China, representing an average of 70.0% over the period. Crude oil's share in the total energy consumption decreased from 22.0% to 18.3%, whereas the share of natural gas increased from 2.2% to 5.9% between 2000 and 2015. This can be illustrated in the fossil fuel mix in China's emission structure as well.

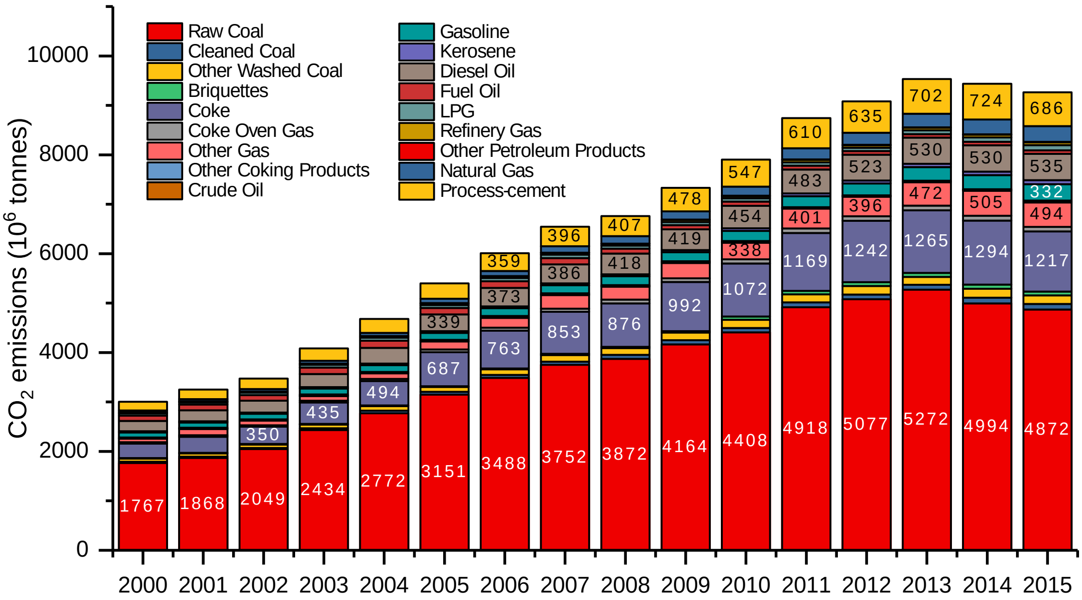

Figure 4-3 National sectoral-approach CO_2 emissions by fossil fuels, 2000-2015

Figure 4-3 shows the fossil fuel mix changes in China's CO_2 emissions. In 2000, raw coal and its related products contributed 75.3% (or 2,261 Mt) of total emissions. The percentage first increased to 79.5% (or 5,829 Mt) in 2009, then decreased to 76.1% (or 7,053 Mt) in 2015. Raw coal's proportion (the red module in Figure 4-3) in the energy mix decreased slightly from 58.8% (or 1,767 Mt) in 2000 to 52.6% (or 4,872 Mt) in 2015.

Meanwhile, the CO_2 emissions from natural gas (the dark blue module in Figure 4-3) increased almost ten times from 39 (or 1.3%) in 2000 to 317 (or 3.4%) Mt in 2015. The cement process contributes about 6.5% of the total emissions over the period.

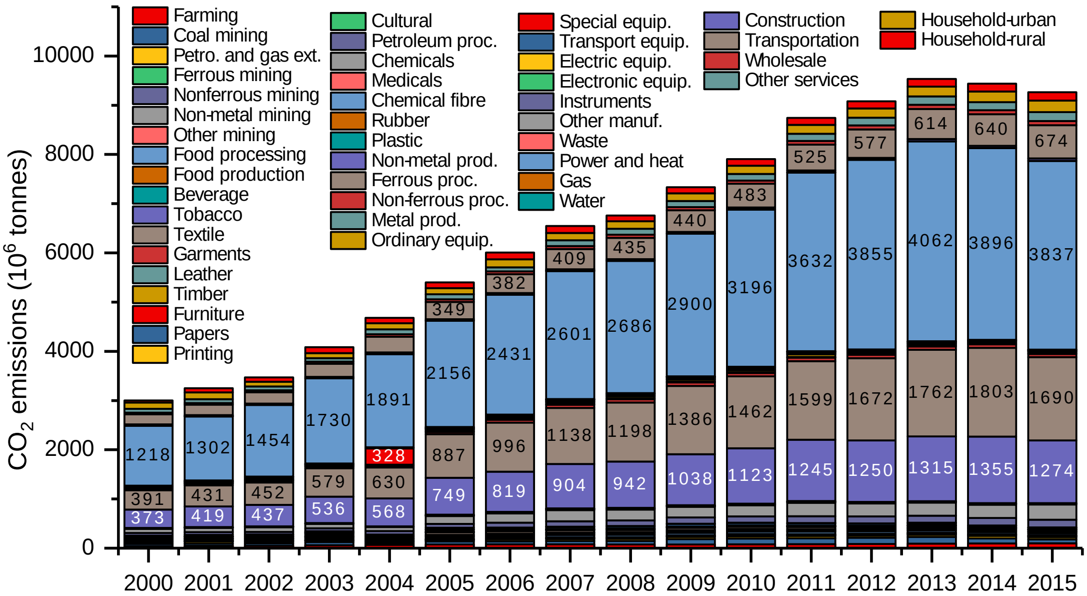

Figure 4-4 National sectoral-approach CO_2 emissions by sector, 2000-2015

In terms of sectors, this study finds that manufacturing is the biggest contributor to CO_2 emissions. In 2015, the 39 manufacturing sectors emitted 7,774 Mt (or 83.9%) of CO_2. The service-sectors (Transportation, Wholesale, and Others) contributed 10.2% (or 943 Mt) of the total CO_2 emissions. The remaining 5.9% emissions were generated by Farming (1.1%, or 98 Mt), Construction (0.5%, or 47 Mt), and Household energy consumptions (4.4%, or 404 Mt).

Among the 39 manufacturing sectors, the overwhelming proportion of emissions are from three sectors: “Power and heat”, “Ferrous proc.”, and “Non-metal prod.”. The three sectors produced 6,801 Mt (or 73.4%) of the entire national emissions in 2015. Particularly, the “Power and heat” sector alone emitted 3,837 Mt CO_2 in 2015, representing a percentage of 41.4%. The emissions induced in the “Power and heat” sector comes primarily from the burning of raw coal in power plants for electricity and heat generation.

Similar to the fossil fuel mix, the sector mix in emissions changed slightly during the past 15 years as well. The emissions from “Farming” sector decreased continuously from 1.4% in 2000 to 0.9% in 2011 and 2012, then increased to 1.1% in 2015. At the same time, emissions from manufacturing sectors increased from 81.7% in 2000 to 86.4% in 2011, then decreased to 83.9% in 2015. The emissions from Construction, Services, and Household remained stable at around 0.5%, 9.3%, and 4.3% respectively over that period of time.

Per capita CO_2 emissions and CO_2 emission intensity

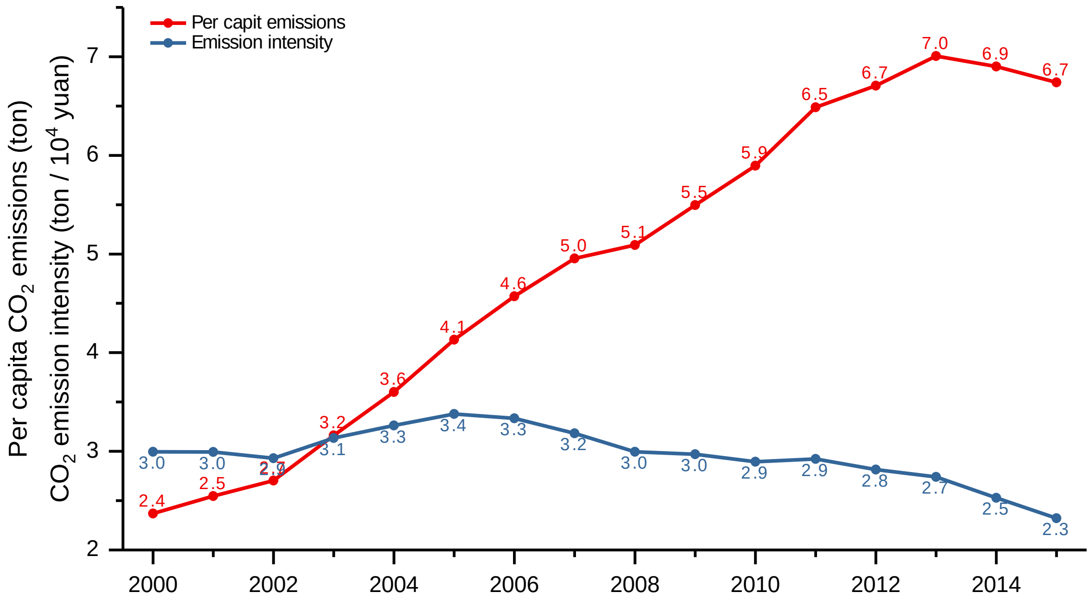

Figure 4-5 China's per capita CO_2 emissions and CO_2 emission intensity, 2000-2015

Based on the CO_2 emissions data, this study calculates the per capita CO_2 emissions and CO_2 emission intensity of the country, shown in Figure 4-7. The per capita CO_2 emissions are calculated as total emissions divided by the national population in Equation 4-1.

Per capita emissions = Total emissions / Population *Equation 4-1*

CO_2 emission intensity is defined as emissions over GDP in Equation 4-2.

Emission intensity = Total emissions / GDP *Equation 4-2*

This study uses GDP at a constant price of 2000 to eliminate the influence of inflation. Both the population and GDP data were collected from NBS .

A similar trend to the total emissions can be seen in the per capita CO_2 emissions: they firstly increased rapidly from 2.7 in 2002 to 6.5 tonnes in 2011, then peaked in 2013 at 7.0 tonnes. The per capita emissions decreased slightly to 6.7 tonnes in 2015 due to the decline in total emissions after 2013.

Meanwhile, China's CO_2 emission intensity has continued to decrease since 2005. The intensity has decreased by 32.4% from 3.4 to 2.3 tonnes per 10 thousand yuan during the past 10 years. The average reduction rate was -3.8% per year. The Chinese government has promised to reduce national emission intensity by 40-45% and 60-65% by 2020 and 2030, respectively, compared with the 2005 level (NDRC, 2014; The Chinese Government, 2015). Following the current trend of decreasing emission intensity (-3.8% per year), China can easily achieve its target. The estimated emission intensities in 2020 and 2030 will be 2.0 (or 41.2% off) and 1.3 (or 61.8% off) tonnes respectively.

Emissions prediction until 2030

Despite China's CO_2 emissions showed decreasing in 2014 and 2015, it is still too early to claim China's emissions have peaked in 2013. Mi, Wei, et al. (2017) believe that China's emissions step into a "new normal" phase, as it will grow in a manageable and relatively balanced manner.

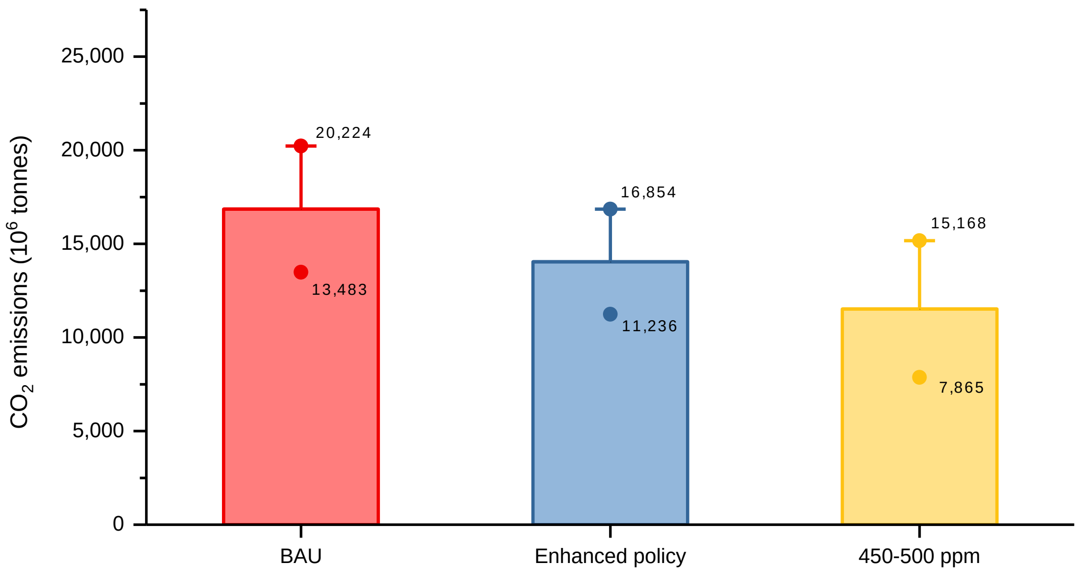

Figure 4-6 CO_2 emissions prediction until 2030

Previous studies applied the scenario analysis to predict China's CO_2 emissions until 2030, which is the target year of the "60-65%" emission intensity reduction policy (H. Li & Qi, 2011; Mi, Wei, et al., 2017). Grubb et al. (2015) defined three scenarios: Business as usual (BAU), Enhance policy, and 450-500 ppm scenario based on an extensive review of "*89 separate scenarios produced with different modelling platforms*" in the previous studies. Under the BAU scenario, there are no additional emission control policies being implemented. The Enhanced policy scenario assumes that some additional climate policies being designed and conducted, while the strongest emission control policies are taken under the 450-550 ppm scenario to "*achieve* *stabilisation of atmospheric CO_2 at 450-550 ppm in 2100, consistent with a roughly 50% or greater chance of keeping global temperature rise to within about 2 ℃ above pre-industrial levels (page S18)*" (Grubb et al., 2015). Grubb et al. (2015) claimed that China's 2030 CO_2 emissions will increase by 43% to 114%, 19% to 79%, and -19% to 61% compared the 2013/2014 level under the BAU, Enhanced policy, and 450-500 ppm scenarios, respectively.

Using the scenarios defined by Grubb et al. (2015), this study predicts China's CO_2 emissions until 2030, shown in Figure 4-6. The figure shows that the 2030 CO_2 emissions span a range of 13,483-20,224, 11,236-16,854, 7,865-15,168 Mt CO_2 under the BAU, Enhanced policy, and 450-500 ppm scenarios, respectively.

4.1.2. National reference-approach CO_2 emissions

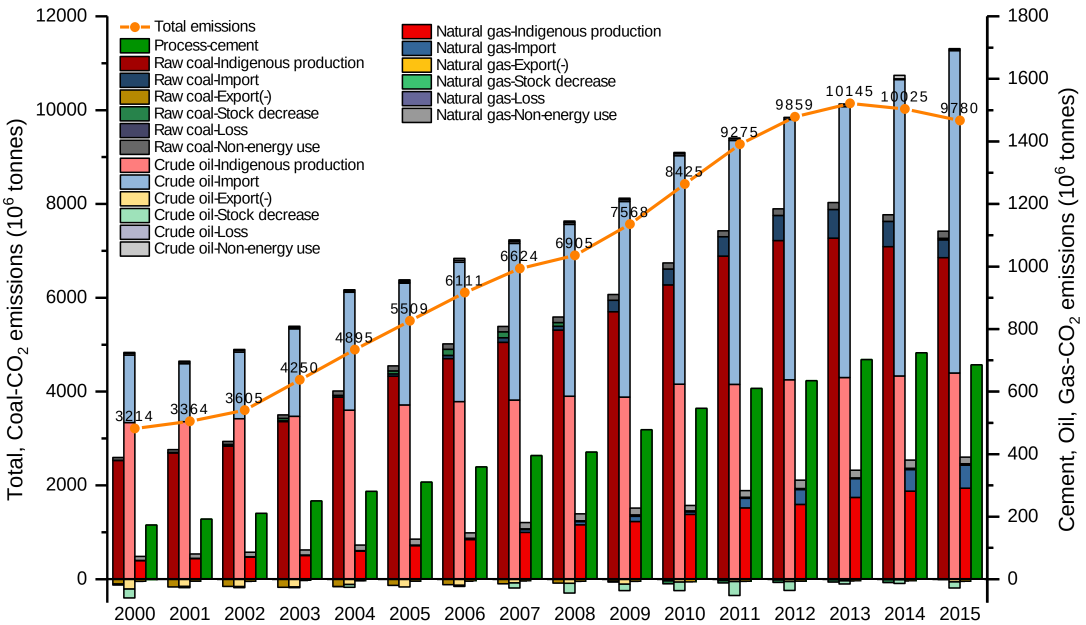

Figure 4-7 National reference-approach CO_2 emissions, 2000-2015

This study calculates the national reference-approach CO_2 emissions from 2000 to 2015, shown in Figure 4-7 and Appendix Table 4. As with the national sectoral emissions, the reference-approach CO_2 emissions of China also increased rapidly between 2002 and 2013, at an average increasing speed of 9.9% per year. Emissions peaked in 2013, at 10,145 Mt. Then the reference-approach CO_2 emissions declined slightly from 10,145 to 9,780 Mt between 2013 and 2015.

The reference-approach CO_2 emissions reflect the characteristics of China's primary fossil fuels' supply. As shown in Figure 4-7, the reference-approach CO_2 emissions from raw coal followed a similar trend to that of the total emissions, also peaking in 2013. Raw coal indigenous production is the major source of coal used in China, taking a percentage of 96.5% of the total coal consumption in 2015. Only 5% of the raw coal used in China was imported from other countries. In the meantime, due to increasing imports, the emissions share from imported crude oil as a portion of the total crude oil-related emissions, increased from 33.3% in 2000 to 62.3% in 2015. Only 39.8% of the crude oil consumption was produced domestically in China in 2015. As for natural gas, 87.6% was produced domestically and 22.2% was imported from other countries. 6.3% of the total natural gas was used as raw material (non-energy use) in chemical processes.

Reference-approach CO_2 emissions can be used to validate sectoral emissions. This study compares the differences between the reference-approach and sectoral-approach emissions in section 4.3.2 below.

4.2. Provincial CO_2 emissions

This study also complies both the sectoral- and reference-approach CO_2 emissions for China's 30 provinces from 1997 to 2015.

4.2.1. Sectoral-approach CO_2 emissions of 30 provinces

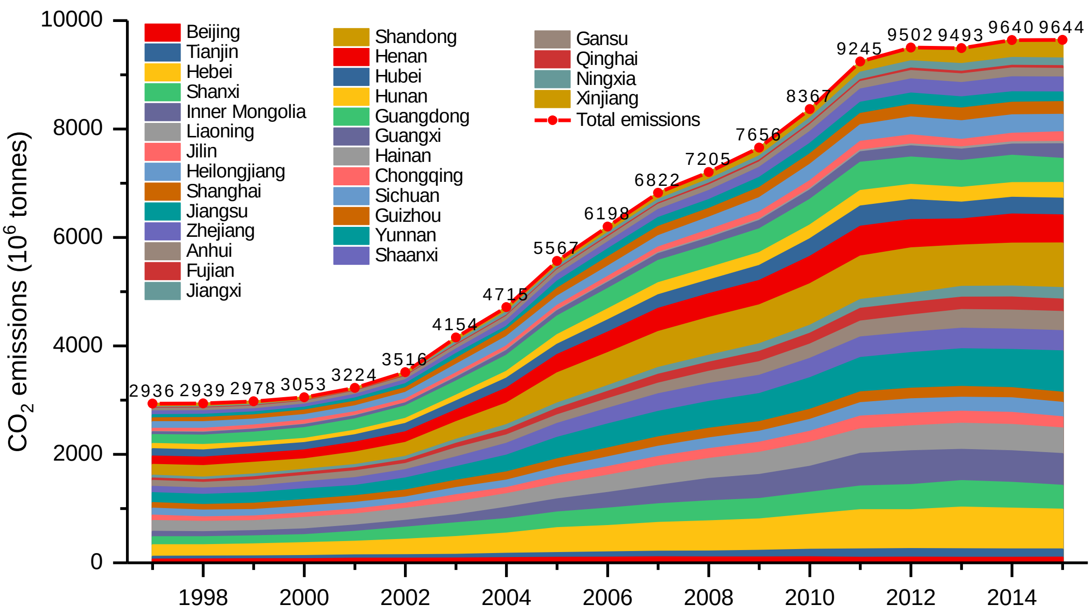

Figure 4-8 Provincial sectoral-approach CO_2 emissions, 1997-2015

Figure 4-8 presents the sectoral-approach CO_2 emissions of 30 provinces. The aggregated provincial emissions increased by 228.5% over the period, from 2,936 to 9,644 Mt. Among the 30 provinces, Shandong emitted the most CO_2 cumulatively, 10,061 Mt (or 8.6%). The four provinces with the next highest cumulative emissions were Hebei, Jiangsu, Guangdong, and Henan, which emitted 9,070 (or 7.8%), 8,084 (or 6.9%), 6,647 (or 5.7%), and 6,637 (or 5.7%) Mt CO_2, respectively. The data on emissions for all 30 provinces over 1997–2015 are presented in Appendix Table 5.

Figure 4-9 shows the locations of the provinces. Provinces in northern and eastern China have higher CO_2 emissions, while provinces in central and western China have lower emissions.

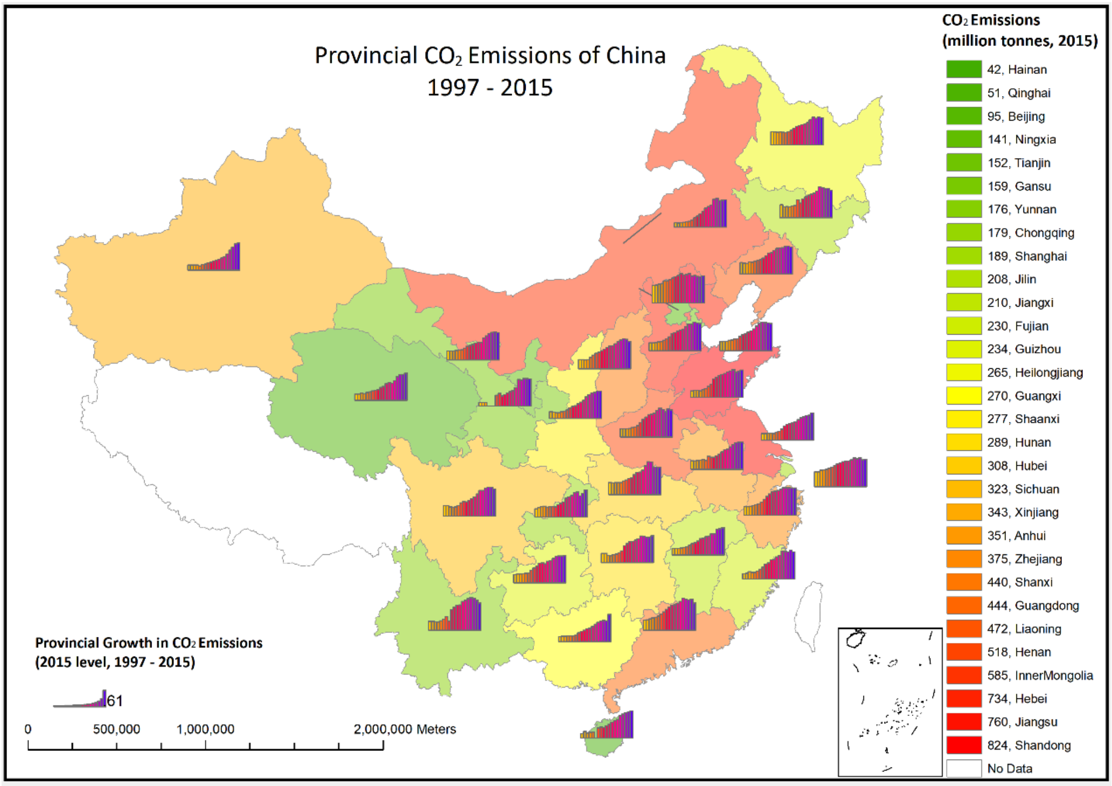

Figure 4-9 Provincial sectoral-approach CO_2 emissions (map)

In order to have a deep understanding of Chinese provinces' emission and emission-socioeconomic characteristics, the following sections discuss emissions by different fossil fuels and sectors and calculates the per capita emissions and emission intensity.

<u>*Emissions by fossil fuels and sectors*</u>

As with the fossil fuel mix in national emissions, coal and its related secondary fuels contribute the most to the provincial aggregated CO_2 emissions, shown in Figure 4-10. In 2015, coal-related fuels contributed 75.4% (or 7,276 Mt) to the total emissions, while oil- and gas-related emissions only accounted for percentages of 13.5% (or 1,302 Mt) and 4.0% (382 Mt). The process-related emissions in the cement production industry emitted 684 Mt CO_2 in 2015, taking a percentage of 7.1%.

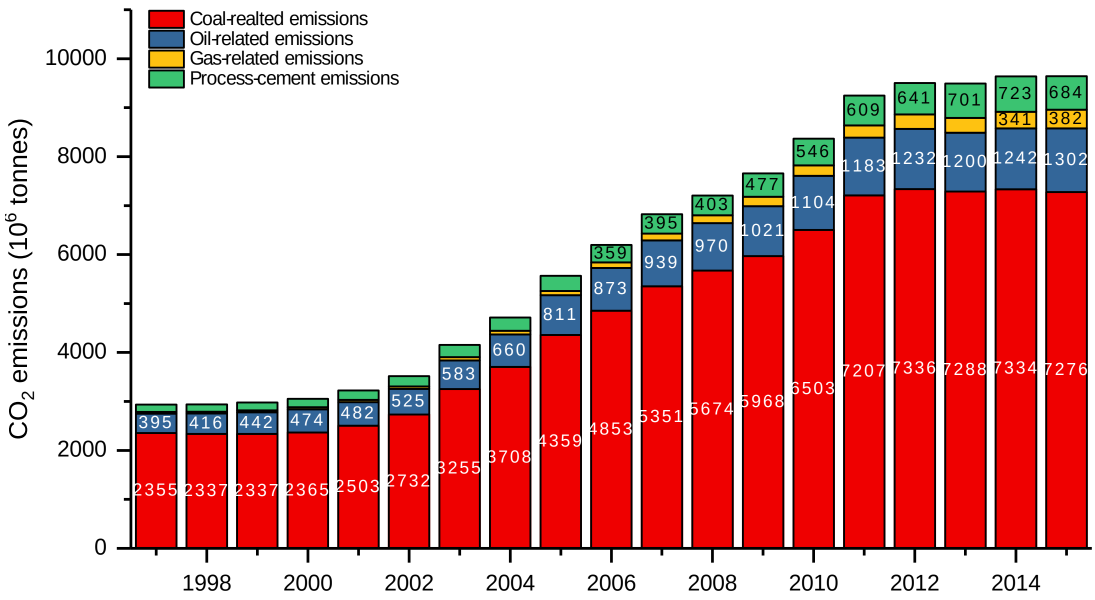

Figure 4-10 Provincial CO_2 emissions by fossil fuels, 1997-2015

Several provinces that contributed most to emissions of each fossil fuel type in 2015 are presented in Figure 4-11, Figure 4-12, Figure 4-13, and Figure 4-14.

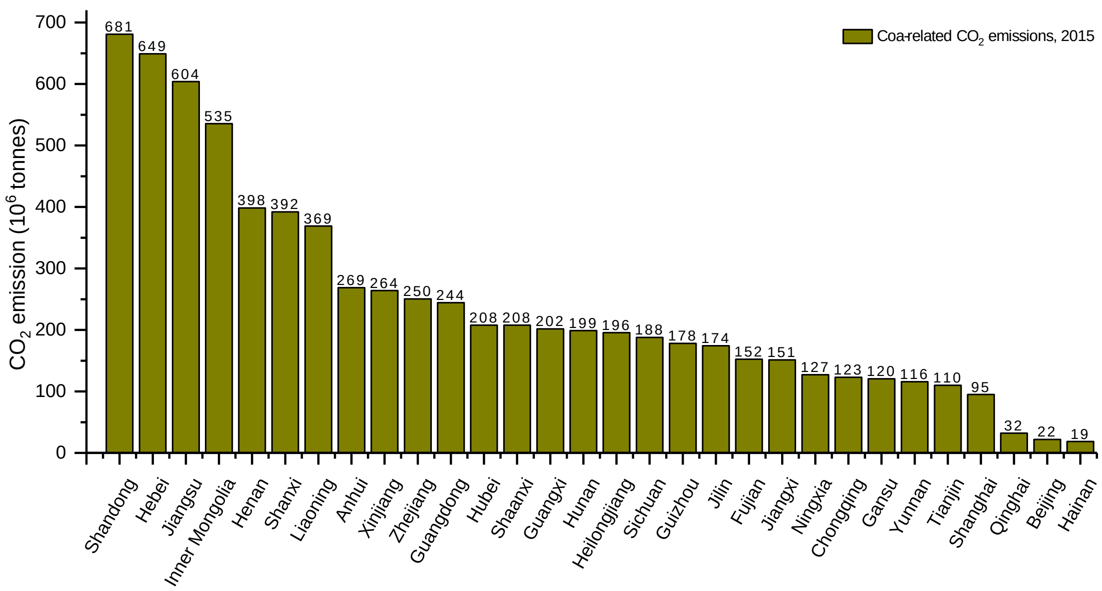

Figure 4-11 The coal-related CO_2 emissions of each province, 2015

Shandong (681 Mt, 9.4%), Hebei (649 Mt, 8.9%), Jiangsu (604 Mt, 8.3%), Inner Mongolia (535 Mt, 7.4%), Henan (398 Mt, 5.5%), and Shanxi (392 Mt, 5.4%) contributed the most to coal-related CO_2 emissions in 2015. These provinces are either coal bases or manufacturing provinces.

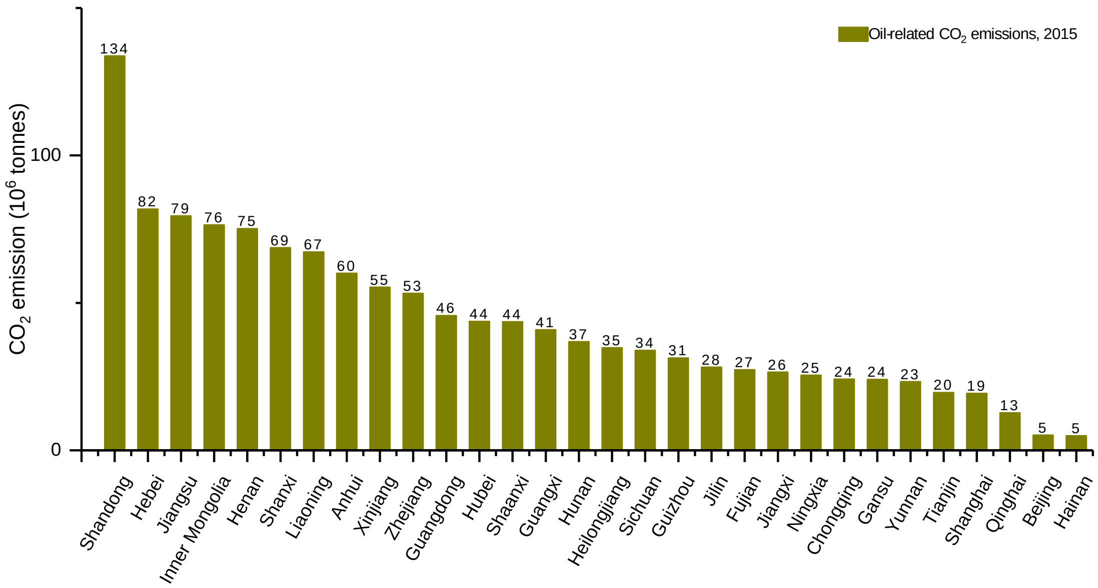

Figure 4-12 The oil-related CO_2 emissions of each province, 2015

Coastal Guangdong (134, 10.3%), Shandong (82 Mt, 6.3%), Liaoning (79 Mt, 6.1%), Shanghai (76 Mt, 5.9%), Zhejiang (75 Mt, 5.8%), and Jiangsu (69 Mt, 5.3%) have more developed shipping industries; more oil was consumed in these provinces, resulting in huge CO_2 emissions.

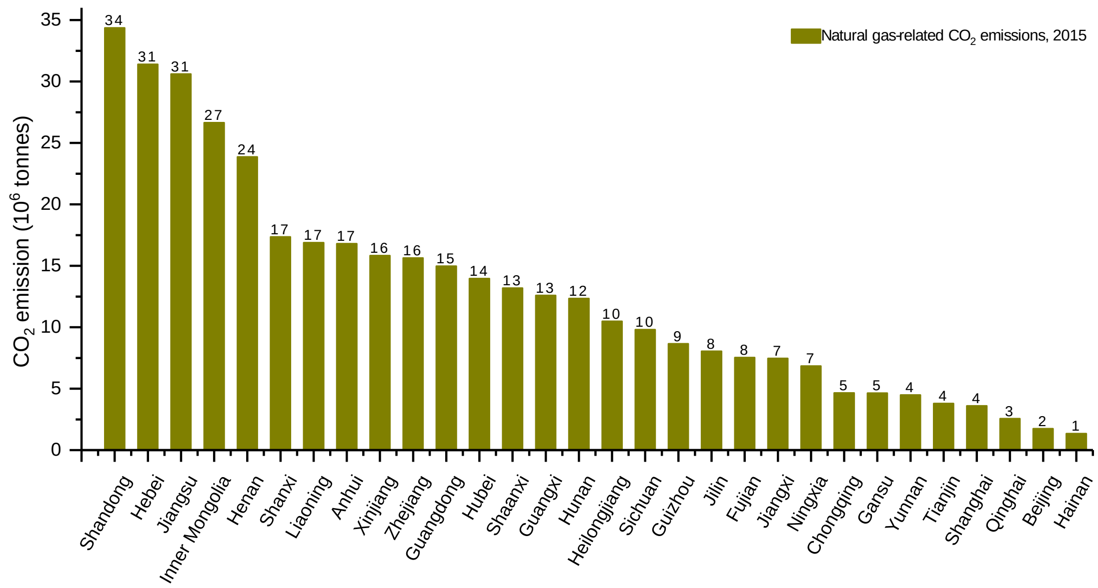

Figure 4-13 The natural gas-related CO_2 emissions of each province, 2015

Jiangsu (34 Mt, 9.0%), Xinjiang (31 Mt, 8.2%), Beijing (31 Mt, 8.0%), and Sichuan (27 Mt, 7.0%) consumed high levels of natural gas in 2015. Sichuan and Xinjiang have the main natural gas fields. Jiangsu and Beijing are the most developed provinces in China and are exploring cleaner energy utilization pathways, such as replacing coal gas with natural gas in residential energy consumption.

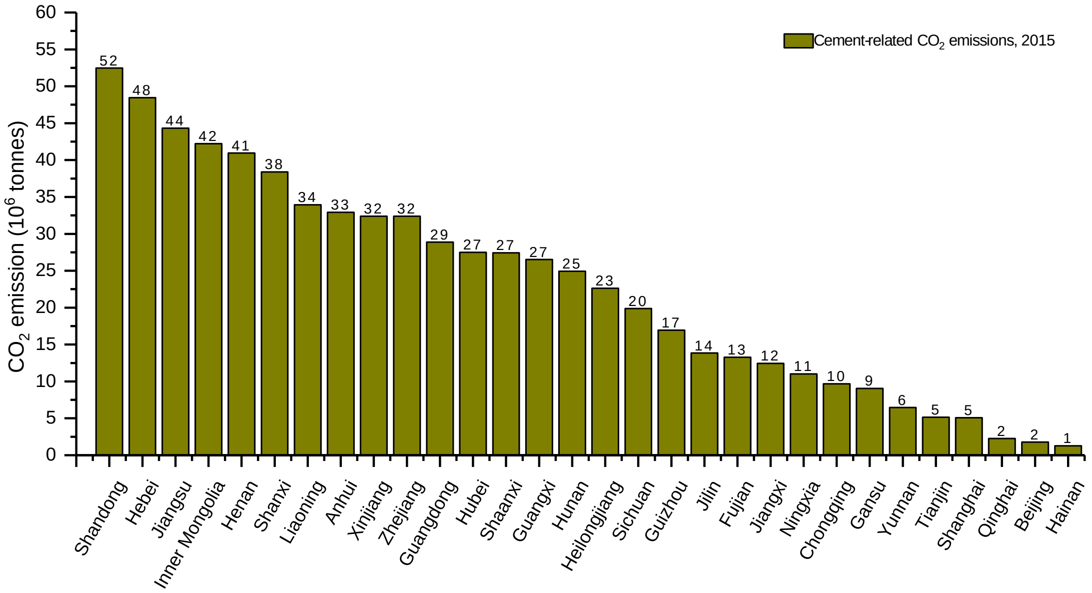

Figure 4-14 The cement-related CO_2 emissions of each province, 2015

Jiangsu (52 Mt, 7.7%), Henan (48 Mt, 7.1%), Shandong (44 Mt, 6.5%), Guangdong (42 Mt, 6.2%), Sichuan (41 Mt, 6.0%), and Anhui (38 Mt, 5.6%) were the main contributors of process-related CO_2 emissions due to their high cement productions.

Provinces that contributed most to CO_2 emissions of selected industry sectors in 2015 are presented in Figure 4-15 to Figure 4-24. The sectors' categories correspond to Table 3-2. Note that "Others" in Figure 4-24 includes "Farming" and "Household energy consumption". This study lists "Coal mining" and "Ferrous proc." separately from the categories "Energy production" and "Heavy manufacturing" due to the high proportion of the total emissions they generate.

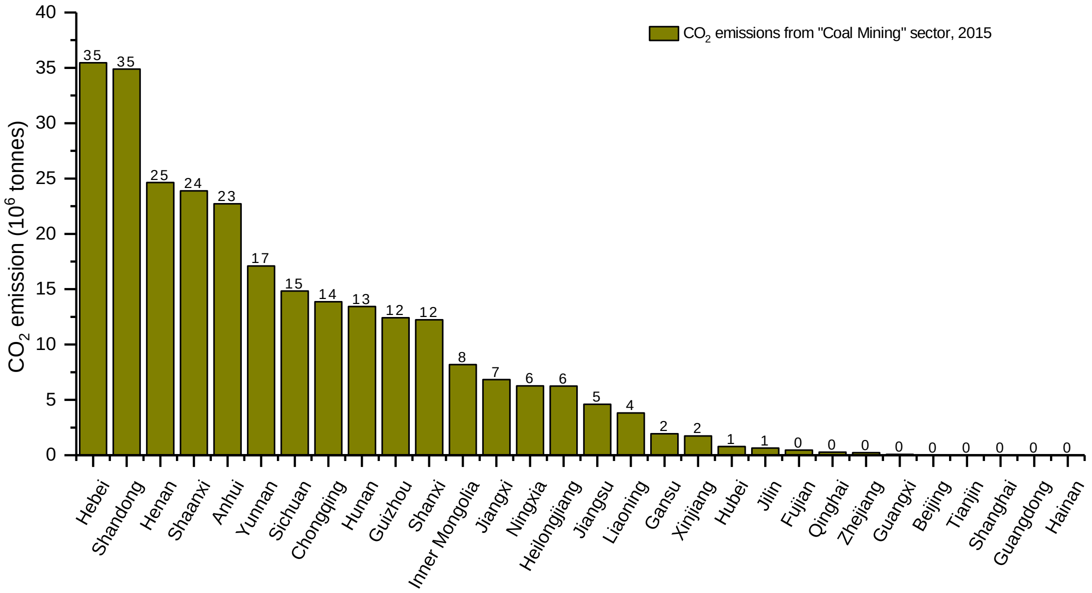

Figure 4-15 Provincial CO_2 emissions from "Coal mining" sector, 2015

Hebei (35 MT, 13.3%), Shandong (35 Mt, 13.0%), Henan (25 Mt, 9.2%), and Shaanxi (24, 8.9%) contributed the most to coal mining-related CO_2 emissions in 2015. These provinces are either coal bases (Henan and Shaanxi) or manufacturing provinces which have more coal processing enterprises (Hebei and Shandong).

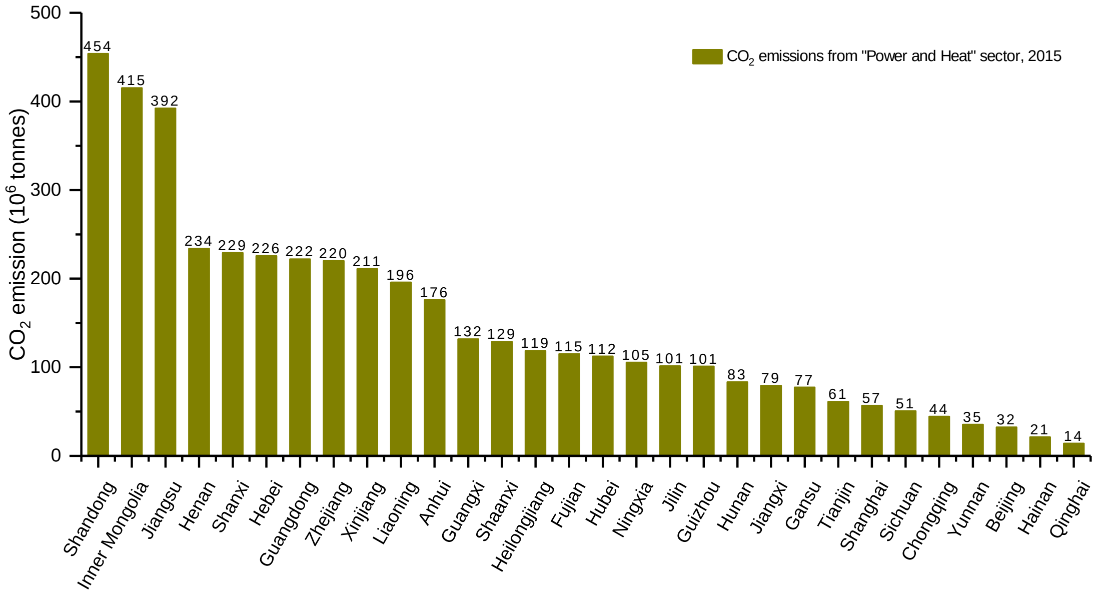

Figure 4-16 Provincial CO_2 emissions from "Power and heat" sector, 2015

Shandong (454 Mt, 10.2%), Inner Mongolia (415 Mt, 9.3%), Jiangsu (392 Mt, 8.8), Henan (234 Mt, 5.3%), and Shanxi (229 Mt, 5.2%) contributed a large proportion of CO_2 emissions in the "Power and heat" sector in 2015. These provinces emitted CO_2 from power plants to generate electricity and heat for themselves as well as nearby regions.

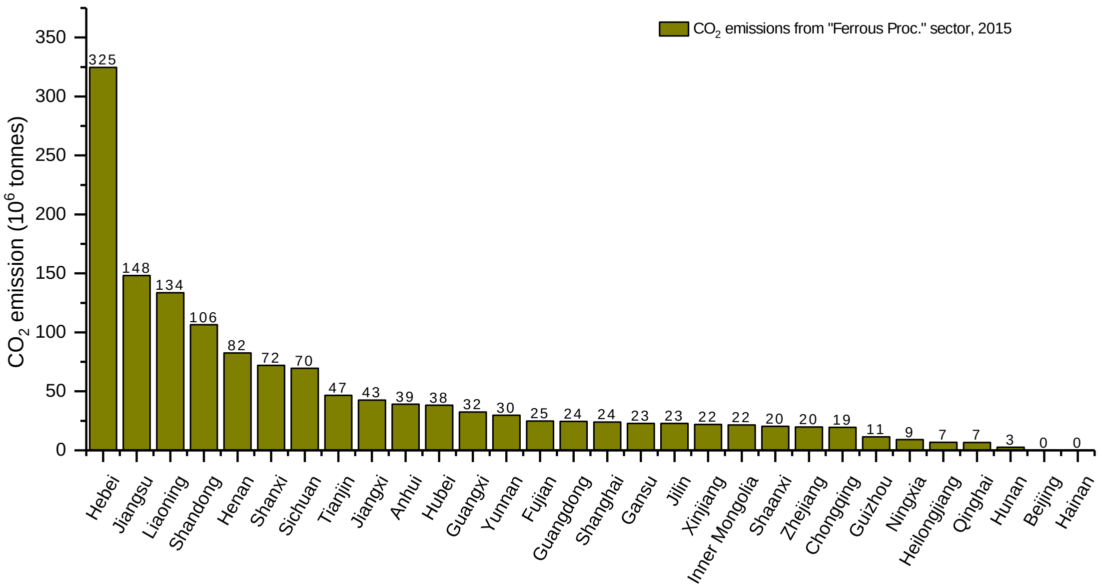

Figure 4-17 Provincial CO_2 emissions from "Ferrous proc", 2015.

As for the CO_2 emission from ferrous processing industries, Hebei province contributed 22.8% (or 325 Mt), Jiangsu and Liaoning province contributed another 10.4% (or 148 Mt) and 9.4% (or 134 Mt) in 2015 respectively. Tangshan city, located in Hebei, is the biggest iron and steel manufacturing base in China. A large amount of coke is consumed in the steel mills (belonging to the ferrous processing sector) in Tangshan, Hebei, which induced huge CO_2 emissions.

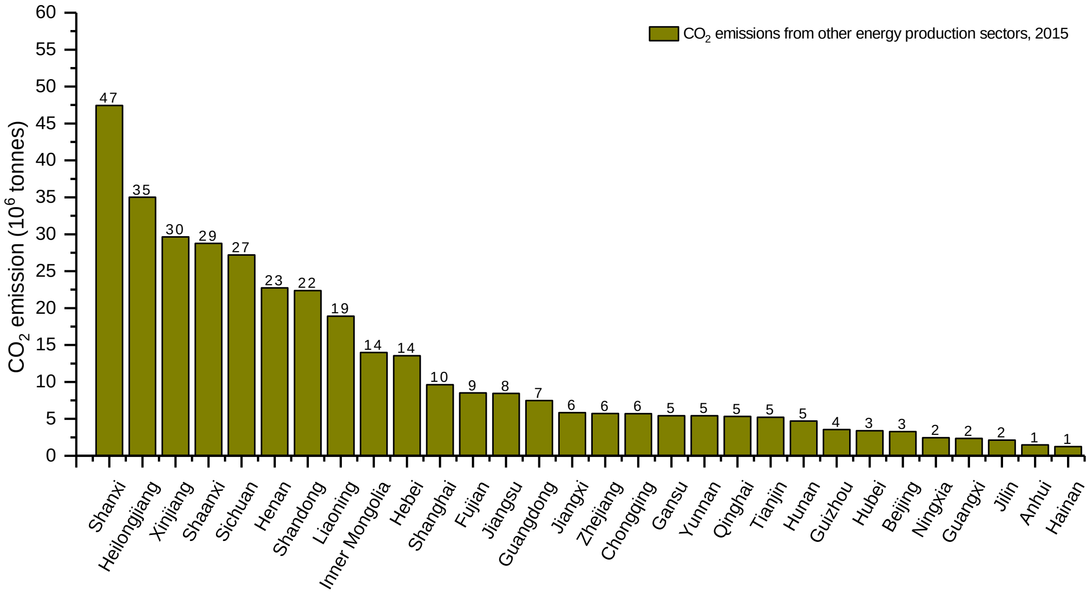

Figure 4-18 Provincial CO_2 emissions from other energy production sectors. 2015

Shanxi (47 Mt, 13.3%), Heilongjiang (35 Mt, 9.8%), Xinjiang (30 Mt, 8.3%), and Shaanxi (29 Mt, 8.1%) were the provinces that contributed the most to the national CO_2 emission from other energy production in 2015.

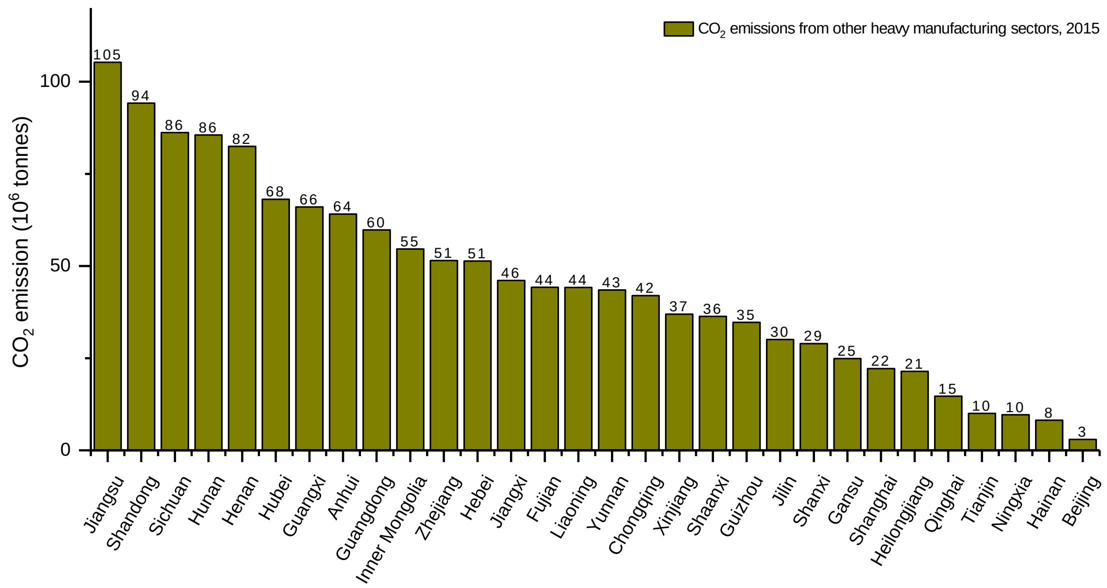

Figure 4-19 Provincial CO_2 emissions from other heavy manufacturing sectors. 2015

Jiangsu (105 Mt, 7.7%), Shandong (94 MT, 6.9%), Sichuan (86 Mt, 6.3%), Hunan (86 Mt, 6.2%), and Henan (82 Mt, 6.0%) contributed the most to other heavy manufacturing-related emissions.

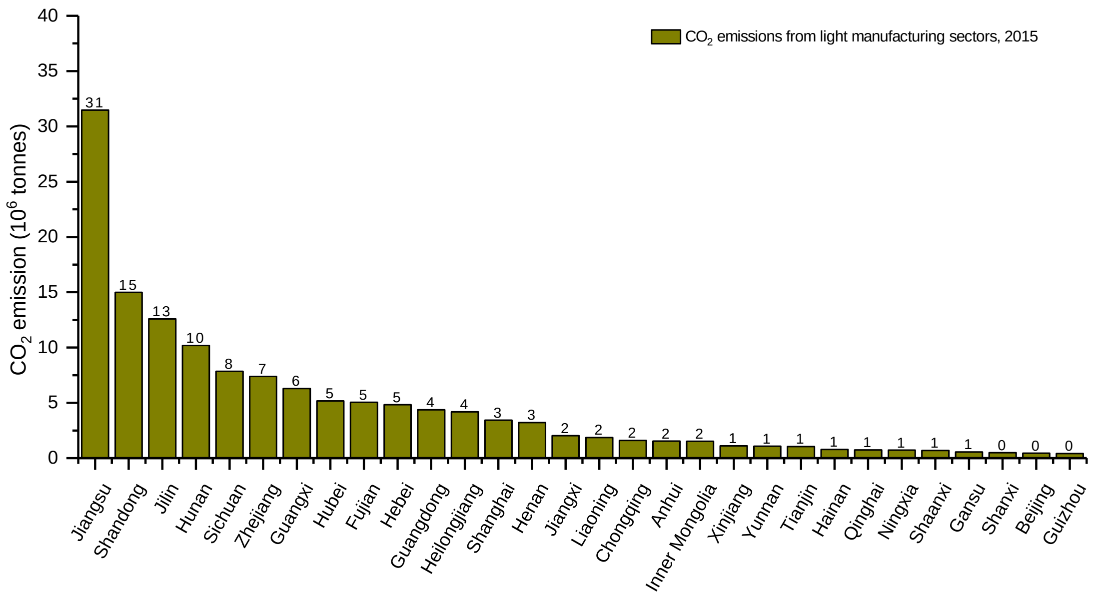

Figure 4-20 Provincial CO_2 emissions structure from light manufacturing sectors, 2015

Jiangsu (31 Mt, 22.9%), Shandong (15 MT, 10.9%), Jilin (13 Mt, 9.1%), and Hunan (10 Mt, 7.4%) contributed the most to light manufacturing-related emissions.

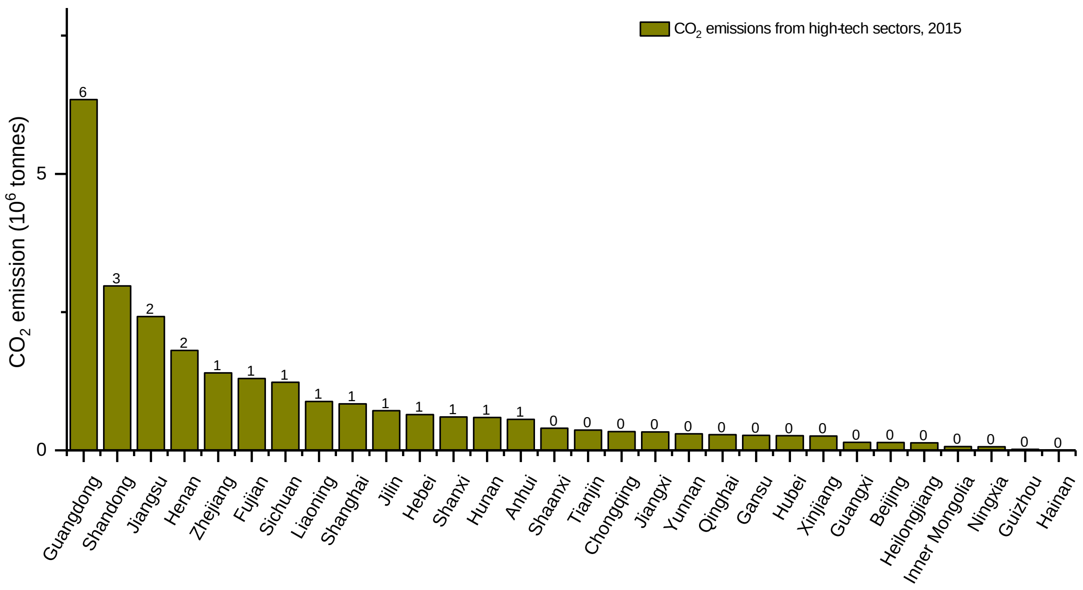

Figure 4-21 Provincial CO_2 emissions from high-tech industries, 2015

In terms of the contribution of high-tech industries to overall emissions, Guangdong province was responsible for the largest percentage in 2015 (6 Mt, 24.7%). Shenzhen and Zhuhai city (located in Guangdong province) have the most developed high-tech industries in China, such as electronic and telecommunications equipment manufacturing.

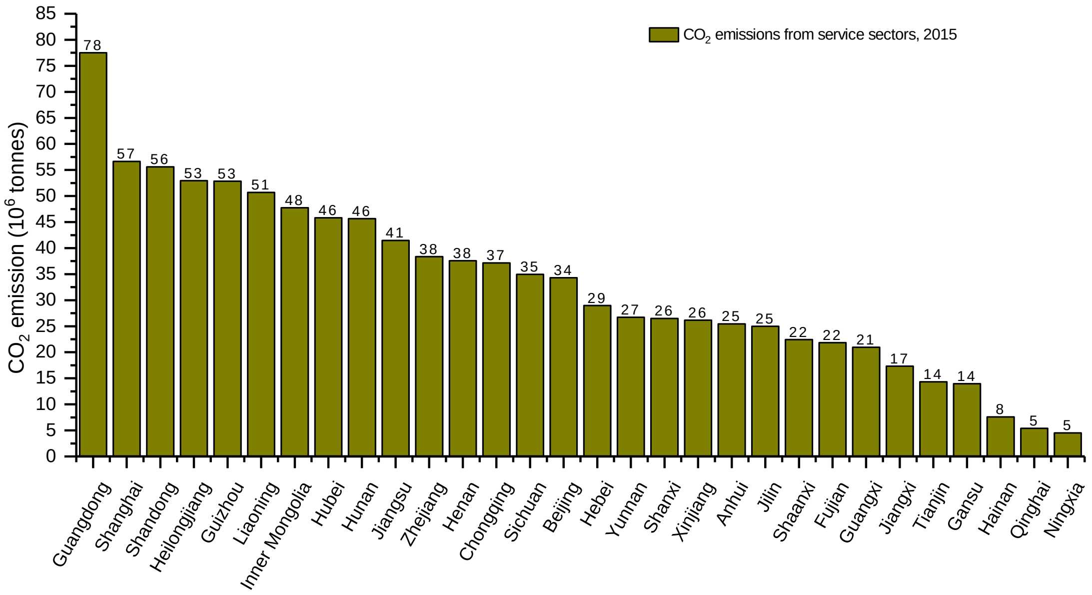

Figure 4-22 Provincial CO_2 emissions from service sectors, 2015

Guangdong (78 Mt, 7.8%), Shanghai (57 Mt, 5.7%), Shandong (56 Mt, 5.6%), Heilongjiang (53 Mt, 5.3%), and Guizhou (53 Mt, 5.3%) have more developed tertiary industries, and therefore, more service-related CO_2 emissions were induced in these provinces in 2015 compared with other provinces.

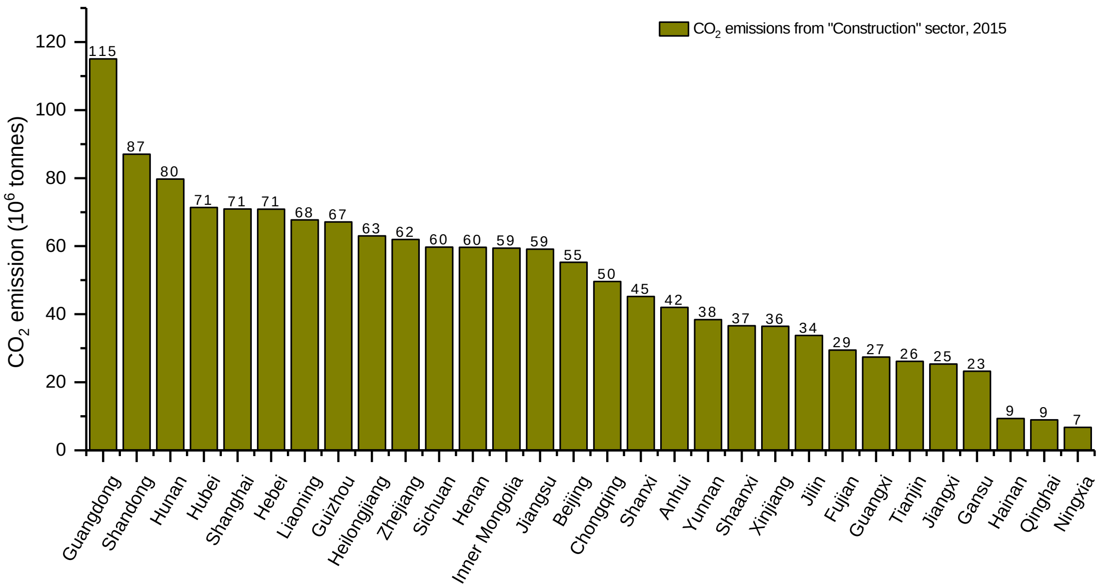

Figure 4-23 Provincial CO_2 emissions from "Construction" sector, 2015

In terms of the contribution of the construction sectors to overall emissions, Guangdong province was responsible for the largest percentage in 2015 (115 Mt, 7.7%), followed by Shandong (87 MT, 5.9%) and Hunan (80 Mt, 5.4%).

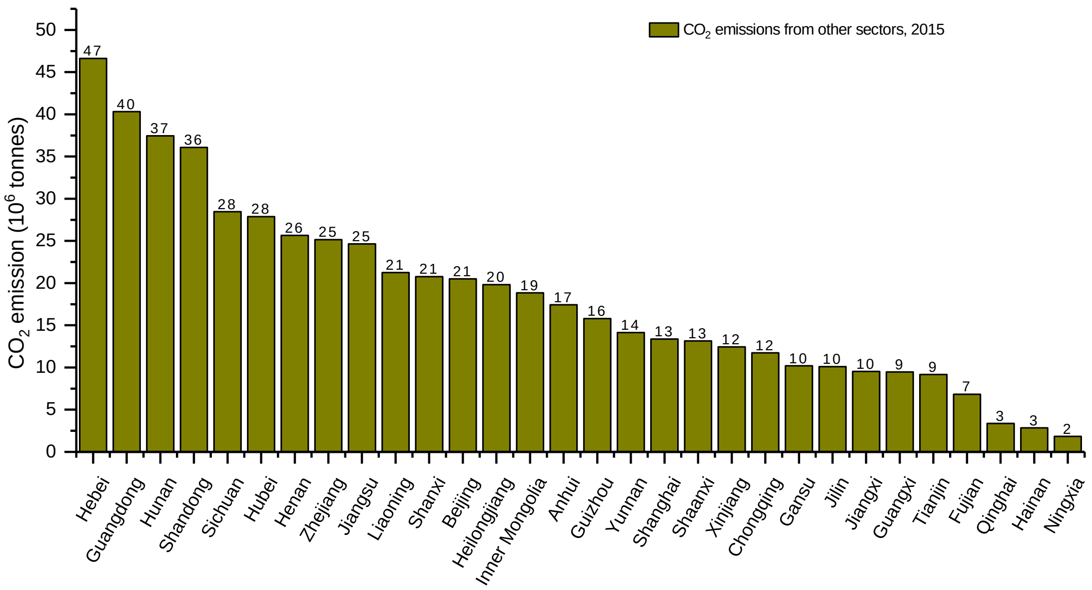

Figure 4-24 Provincial CO_2 emissions from other sectors, 2015

As for other sectors, Hebei (47 MT, 8.4%), Guangdong (40 MT, 7.3%), Hunan (37 Mt, 6.7%), and Shandong (36 Mt, 6.5%) are the top four contributors in 2015.

To analyse the emission characteristics of different provinces, this study has calculated the 2015 per capita CO_2 emissions and CO_2 emissions intensity as examples (see Figure 4-25 and Figure 4-26).

Per capita CO_2 emissions in 2015

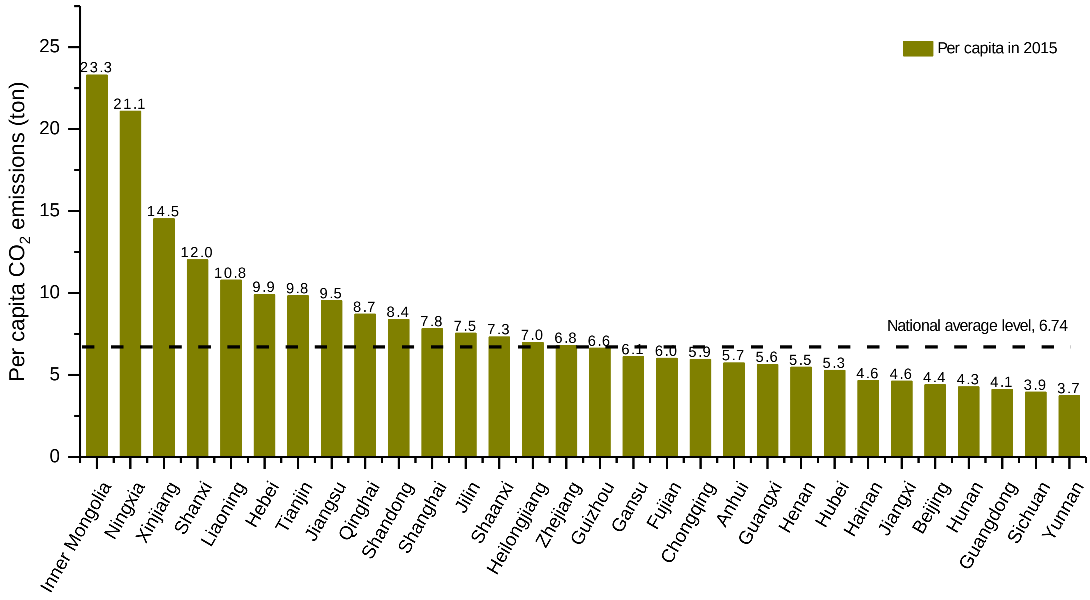

Figure 4-25 Per capita emissions of provinces in 2015
Population data source: NBS

As discussed above, the national average CO_2 emissions per capita in 2015 were 6.74 tonnes per person. The emissions per capita varied among provinces due to the regional development distinction in China. One half (15) of 30 provinces had CO_2 emissions per capita above the national level in 2015.

The top four provinces were Inner Mongolia, Ningxia, Xinjiang, and Shanxi. All four provinces are primary energy producers, with many large coal mines/oil fields, and the energy consumption per capita is much higher here as compared with the national average. The top four provinces had per capita CO_2 emissions above 10 tonnes. Mongolia and Ningxia host the China Shenhua Energy Company Limited (the nation's largest energy company), and Shanxi is the base for the China National Coal Group Corporation (the second largest energy company). The two enterprises are the only two energy enterprises in China among the 112 central enterprises (i.e., firms under government control) updated in 2015 (State-owned Assets Supervision and Administration Commission of the State Council, 2015). Central enterprises are normally pillars of economic growth, with high output and added value. Karamay oil field, located in Xinjiang, is the first ten-million-ton oil field in west China. Thus, these three provinces have higher CO_2 emissions per capita.

The second group included nine provinces: Liaoning, Hebei, Tianjin, Jiangsu, Qinghai, Shandong, Shanghai, Jilin, and Shaanxi. These are either primary energy suppliers (such as Shaanxi and Qinghai) or bases for heavy industry (such as Liaoning, Hebei, Shandong, and Jilin). The third group included five provinces: Heilongjiang, Zhejiang, Guizhou, Gansu, and Fujian. The CO_2 emissions per capita of these provinces were near the national average (6.0 to 7.0).

The remaining 12 provinces belonged to the last group. Some of these provinces are located in central and southwest parts of China, with primary industry as their pillar economy; others are among the most developed provinces with highly developed service industries (such as Beijing and Guangdong). Yunnan and Sichuan had the lowest CO_2 emissions per capita, 3.7 and 3.9 tonnes, respectively.

More detailed per capita CO_2 emissions of the 30 provinces from 2000 to 2015 are shown in Appendix Table 7.

CO_2 emissions intensity in 2015

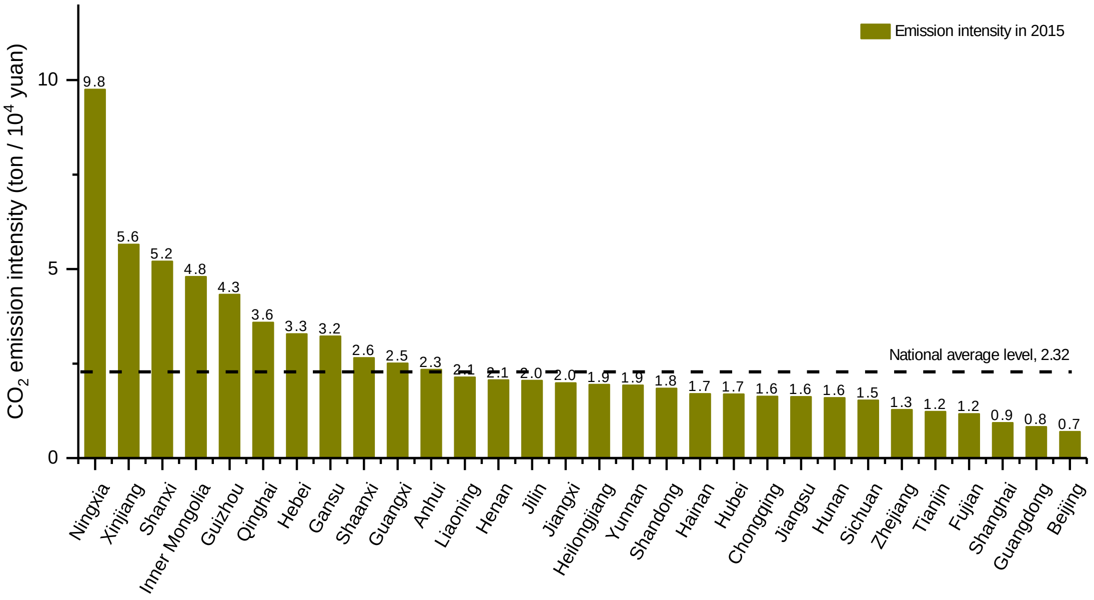

Figure 4-26 Emission intensity of provinces in 2015

Note: emission intensities are calculated based on the constant price of 2000, GDP data source: NBS

The national average CO_2 emission intensity in 2015 was 2.32 tonnes per 10 thousand yuan. 11 of the 30 provinces had an emission intensity above the national level in 2015.

As shown in Figure 4-26, the distribution of CO_2 emission intensity was similar to that of CO_2 emissions per capita. The provinces in the north and northwest had higher emission intensities, whereas the provinces in the central and southeast areas had lower intensities. The differences in emission intensities among these provinces reflect differences in their natural resource endowments as well as their industrial structures. As mentioned above, the provinces in north and northwest have more coal mines (such as Shanxi and Inner Mongolia) and oil fields (such as Xinjiang). Therefore, the industries of energy production and transformation are the pillar industries of the local economy, including coal mining and dressing, coking and petroleum processing. These industries are all high energy intensity, and huge amounts of primary fossil fuels are consumed in these provinces for energy transformation and final consumption.

By contrast, the more developed provinces in eastern and southern China have lower CO_2 emission intensities, such as Beijing (0.7), Guangdong (0. 8), and Shanghai (0.9). These more developed provinces have more service sectors, which are less energy dependent.

More detailed figures for CO_2 emissions intensities of 30 provinces from 2000 to 2015 are shown in Appendix Table 8.

4.2.2. Reference-approach CO_2 emissions of 30 provinces

Figure 4-27 and Appendix Table 6 show the provincial reference-approach emissions.

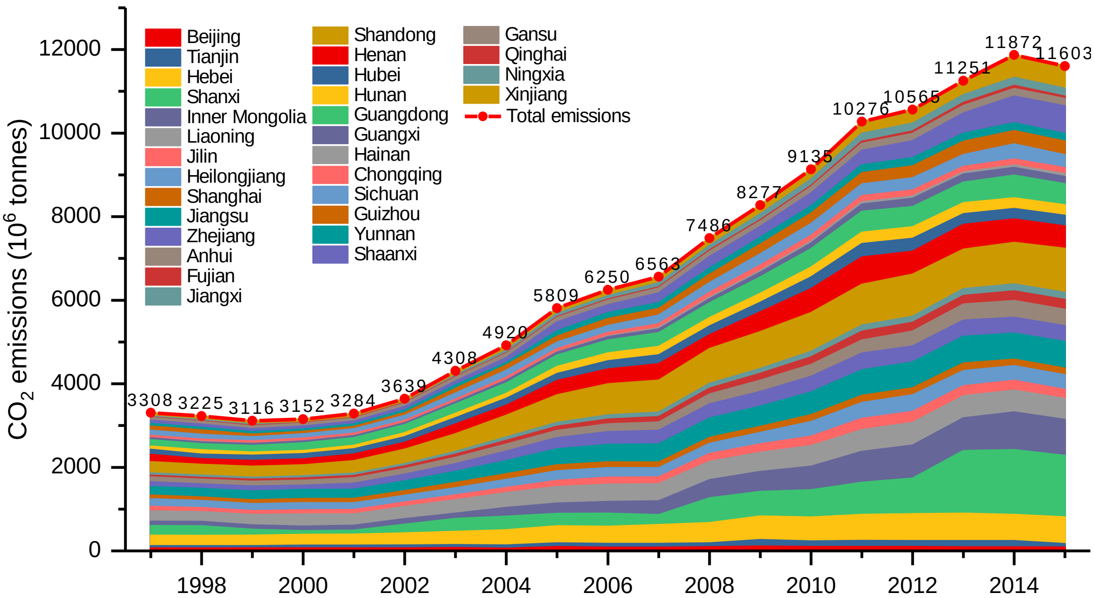

Figure 4-27 Provincial reference-approach CO_2 emissions, 1997-2015

Due to frequent energy trade among Chinese provinces, especially in secondary fossil fuels, the provincial reference emissions cannot reflect the real CO_2 emissions within one provincial boundary. However, the provincial aggregated reference-approach emissions can be a validation of the total national emissions. For data completeness and transparency this study calculates the provincial reference-approach emissions. Figure 4-27 shows that the provincial aggregated reference-approach emissions peaked in 2014 at 11,872 Mt.

The reference-approach CO_2 emissions are calculated using the reference-approach fossil fuel, all of the primary fuels transformed into secondary energy are included in the energy consumption of the province. Hence, the CO_2 emissions of the energy-producing provinces are much higher. For example, Shanxi, Shandong, and Inner Mongolia, the top three reference-emitters, emitted 1,474 (or 12.7%), 1,052 (or 9.1%), and 859 Mt (or 7.4%) of the reference emissions in 2015. In the sectoral-approach, these three provinces only emitted 440 (or 4.6%), 824 (or 8.5%), and 585 Mt (or 6.1%) in 2015. More comparisons between the two approach emissions are discussed below in section 4.3.2.

4.3. Comparisons and uncertainties

4.3.1. Comparisons with other emission datasets

This study compares emissions with estimates from other research institutes, shown in Figure 4-28. The sectoral-approach national CO_2 emissions by this study are the lowest among the estimates. The Global Carbon Budget (GCB) has the highest value until EDGAR passed it since 2012. This study's national sectoral-approach CO_2 emissions are 9% to 18% lower than the highest value. This is mainly caused by the lower emission factors used in this study compared with others. This study's results are 1-3% higher than BP and MEIC's since 2013. Even considering the emissions from BP and MEIC not including the cement-related emissions, they have closer results with this study compared with other emission estimations. This study's estimates are highly consistent with the newly published official emission inventory. The Chinese government published the greenhouse gas emission inventories of China in the "First Biennial Update Report on Climate Change" (NDRC, 2016b). In the report, the fossil fuel-related CO_2 emissions in 2012 were 8,688 Mt (the blue points in Figure 4-28), only 2.79% higher than this study's estimates (national sectoral emissions, 8,446 Mt). This tiny difference falls within the uncertainty range of the NDRC inventories (±5%).

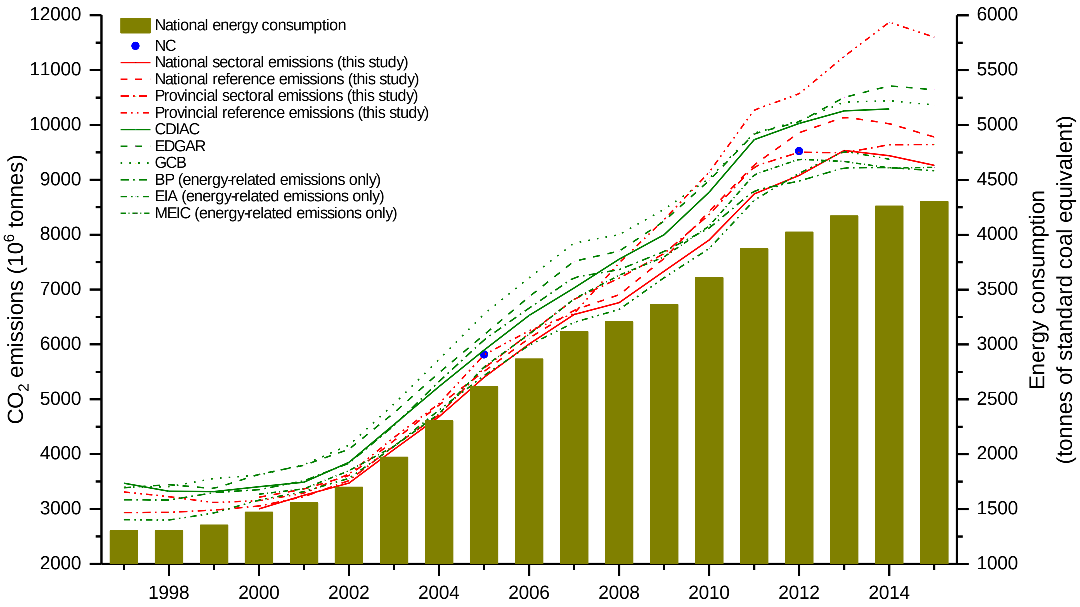

Figure 4-28 Emissions comparisons with other estimates

Data source: National energy consumption (NBS, 2016a), NC1994 (NDRC, 2004), NC2005 (NDRC, 2013c), CDIAC (Boden et al.), EDGAR (Olivier et al., 2016); Global Carbon Project (Le Quéré et al., 2016); BP (BP, 2017); EIA (EIA). MEIC (Yu Lei, Zhang, He, et al., 2011; Q. Zhang, Streets, et al., 2009). Note that emissions by NC2005 include CO_2 emissions from lime and glass production as well, emissions by MEIC, BP and EIA include the energy-related emissions only.

In addition, from the aspect of format, the existing emission estimates only present the total emissions of the whole country, or emissions from three fossil fuel categories at most (solid, liquid, and gas). This study provides the fossil fuel-related CO_2 emissions from 46 socioeconomic sectors and 17 fuels to give detailed demonstrations of China's emission statue as well as its provinces. Thus, this study can be a more detailed supplement to the existing emission estimates and the official emission inventories.

4.3.2. Comparisons of the two approach inventories

The difference between the sectoral- and reference-approach emission inventories lays in the calculation method of fossil fuel consumptions (see section 3.2). The process-related emissions from the two approaches are exactly the same. The sectoral emissions are calculated from the energy consumption aspect while the reference emissions are calculated via the energy production and trade data. The reference approach assumes that all the carbon elements from the primary energy sources (excluding the transport loss and non-energy usage part) are converted into CO_2 emissions. IPCC (2006) suggests calculating the reference emissions for one country as a validation of the sectoral emissions. Therefore, this study calculates both the sectoral and reference emission for China and its provinces. The red lines in Figure 4-28 compare the sectoral and reference emissions.

The reference emissions are 1% to 7% higher than the sectoral emissions. The differences between the two approaches can be explained from three aspects. First, the energy loss during energy transformation process is not excluded from the reference energy consumption. Second, only transport loss and non-energy usage of primary energy sources are excluded from the total consumption in the reference approach. Those of secondary energy sources were not removed. Third, there is roughly 1.2% statistical difference between the energy production and consumption data in China's energy balance table (NBS, 2016a).

As discussed above, the reference emissions are calculated with the data of primary fossil fuels only, while the emissions embodied in the secondary fossil fuels cannot be reflected. Due to the frequent energy trade among Chinese provinces, especially the secondary energy types, the provincial reference emissions cannot reflect the real CO_2 emissions within one provincial boundary. The CO_2 emissions of the energy-producing provinces are much higher. For example, the reference-approach CO_2 emissions of Shanxi, Shandong, and Inner Mongolia were 1,474 (or 12.7%), 1,052 (or 9.1%), and 859 Mt (or 7.4%) in 2015, however, the sectoral-approach CO_2 emissions of these three provinces were only 440 (or 4.6%), 824 (or 8.5%), and 585 Mt (or 6.1%). Considering the data completeness and transparency, this study complies the provincial reference emission inventories as well.

4.3.3. Uncertainties analysis with Monte Carlo simulation

Analysing uncertainty is an important tool for improving emission inventories that contain uncertainty (Jonas et al., 2014; L. Shen et al., 2014). Different methods are used to analyse the uncertainty of emissions, Jonas et al. (2010) described four relevant uncertainty terms and six techniques that can be used to analyse uncertain emission changes. Monte Carlo simulation is one of them and is recommended by IPCC (2006), widely used in previous research (Lang et al., 2014). This study employs the Monte Carlo simulation to calculate the uncertainties of the estimated CO_2 emissions.

Considering the small amounts and low uncertainties of the process-related emissions in cement production (Z. Liu, Guan, et al., 2015; Y. Zhao et al., 2011), this study only calculates the uncertainties from fossil fuel-related emissions. The uncertainties of emission estimates are caused by many reasons, as the fossil fuel-related CO_2 emissions are calculated as fossil fuel consumption (activity data) multiplied by the emission factors, the uncertainties should be "*derived for the component parts such as emission factors, activity data and other estimation parameters (Volume 1, Chapter 3, Page 6)*" (IPCC, 2006). This study quantifies both the uncertainties of the emissions from the emission factors and fossil fuel consumption with the Monte Carlo simulation.

Uncertainties from the emission factors

As introduced above in section 3.3, this study adopts the emission factors from Z. Liu, Guan, et al. (2015). However, the emission factors of China's fossil fuel combustions may have large variations as discussed in subsequent studies (such as Olivier et al. (2015); Le Quéré et al. (2015); Korsbakken et al. (2016a); Jackson et al. (2016)). To quantitatively characterize the range of emission factor, this study summarises the emission factors (NCV_i , CC_i , and O_i) from seven other sources: IPCC, NBS, NDRC, NC1994, NC2005, MEIC, UN-China, and UN-average (shown in Appendix Table 1).

It is found that the fuels' net caloric values vary a larger range than those of carbon contents and oxygenation efficiencies. Taking raw coal as an example, the Coefficient of Variation (CV, the standard deviation divided by the mean) of raw coal's net caloric value is 15%, while the CV of carbon content and oxygenation efficiency is 2% and 4% respectively. The CV of raw coal's comprehensive emission factor ($NCV_i \times CC_i \times O_i$) is, therefore, 18%. The emission factor of coal-related fuels varies in a wider range than those of oil-related fuels and the natural gas. The average CV of coal-related fuels is 18%, while that for the oil-related fuels and natural gas is 4% and 5% respectively. Among the emission factors from eight sources, the IPCC and UN-average have the higher values, while Z. Liu, Guan, et al. (2015) (used in this study), MEIC and NC1994 have the lower values.

Uncertainties from the activity data

Due to the poor quality of China's fossil fuel data, the consumption data also has large uncertainties. According to the previous literature, the fossil fuels consumed in electricity generation sector have a CV of 5% (Y. Wu et al., 2010; Yu Zhao et al., 2008), while the fossil fuels consumed in other industry and construction sector have a CV of

10% (IPCC, 2006; Q. Zhang et al., 2007). The CV of fossil fuel consumed in the transportation sector is 16% (Karvosenoja et al., 2008), while residential and primary industry fossil fuels usage even has a higher CVs of 20% (IPCC, 2006) and 30% (S. X. Wang et al., 2008) respectively. The uncertainties in China's fossil fuel data has been addressed and discussed by Guan et al. (2012b) previously. Possible reasons include the opaqueness in China's statistical systems, especially on the "*statistical approach on data collection, reporting and validation (Page 673)*" (Guan et al., 2012b); and the dependence of China's statistics departments with other government departments. As a result, China's national fossil fuel consumption is smaller than the provincial aggregated data. Despite that China enlarged its 2000-2013 national energy data in 2014 (presented in section 3.4), there is still roughly 5% gap between the latest national and provincial aggregated energy data.

Monte Carlo Simulation

This study employs the Monte Carlo simulation to propagate the uncertainties induced by both fossil fuel consumption and emission factors to provide the uncertainty estimates for entire emission inventories (IPCC, 2006). According to the Monte Carlo technique, this study first assumes normal distributions (probability density functions) for both activity data (fossil fuel consumption) and emission factors with CVs discussed above (Z. Liu, Guan, et al., 2015; Y. Zhao et al., 2011). Random sampling on both the activity data and emission factors are then conducted for 100,000 times and generated 100,000 estimations on the CO_2 emissions. The uncertainty range, therefore, is 97.5% confidential intervals of the estimations. The above simulation is conducted in MATLAB R2014a.

Uncertainties of the national emissions

This study finds that the uncertainties of the entire CO_2 emissions inventories are roughly (-15%, 25%) at a 97.5% confidential level. Figure 4-29 and Appendix Table 9 show the uncertainties in the national emission inventories from 2000 to 2015. The above ranges, e.g., (-15%, 25%), reflect the uncertainties from both emission factor and activity data. In particular, concerning the continuous debate on the emission factor of fossil fuel combustion in China (Jackson et al., 2016; Korsbakken et al., 2016a; Le Quéré et al., 2015; Olivier et al., 2015), this study incorporates 8 emission factors from independent sources to represent the uncertainty of emission factors. In order to separate the uncertainty induced by emission factor and activity data, this study then conducts the Monte Carlo simulations by assuming the CV of one of them is 0. The results show that uncertainties from the emission factors in 2015 are (-15.8%, 23.7%), while the uncertainties from the activity data are (-1.4%, 9.2%). This implies the emission factors of fossil fuels induce higher uncertainty in the final estimation.

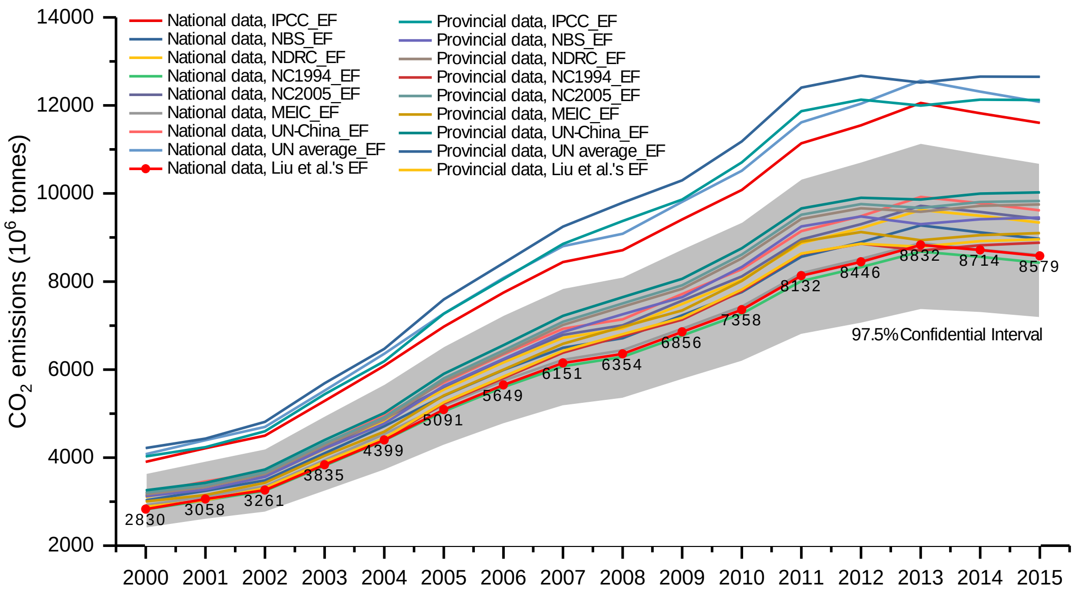

Figure 4-29 Uncertainties in the national emission accounts, 2000-2015

In Figure 4-29, the grey area indicates the 97.5% confidential interval of China's CO_2 emission estimations of this study. The lines present China's CO_2 emission calculated based on the national/provincial aggregated energy data and 8 different emission factors. The figure shows that emissions calculated based on emission factors from Z. Liu, Guan, et al. (2015), NBS, NDRC, NC1994, NC2005, MEIC, and UN-China's fall in the 97.5%

confidential interval. Emissions calculated based on the IPCC and UN-average emissions factors are 10% larger than the upper bound of the 97.5% confidential interval due to their high emission factor value, while the emissions calculated based on the emission factors from Z. Liu, Guan, et al. (2015), NC1994, and MEIC have relatively low values. In addition, the emissions calculated based the provincial aggregated energy data are about 5% higher than that based on national data due to the difference in the national and provincial data.

4.4. Summary

The accurate account of CO_2 emissions is the foundation of any emission analysis and further reduction actions. However, CO_2 emission accounts for China are not well documented. There is no annual, officially published emission report in China. The Chinese government has only published national CO_2 emissions three times: in 1994 (NDRC, 2004), 2005 (NDRC, 2013c), and 2012 (NDRC, 2016b). All the previous studies calculated China's emissions individually, making the emissions inconsistent and incomparable with each other. Also, the China's emission published by research institutions (CDIAC, EDGAR, et.al) exist huge discrepancies. The discrepancies among different estimates are approximately equal to Japan's total emissions in 2011, which was the 5th top-emitter in the world. Furthermore, all the existing datasets only present the national total CO_2 emissions. There are scarcely any open-access datasets providing the CO_2 emission inventories constructed according to fossil fuel types and industrial sectors for China and its 30 provinces.

This chapter, for the first time presents the national and provincial CO_2 emission of China from 1997 to 2015. An open-access database "ceads.net" is built based on this PhD study. CEADs is the first open-access emission database providing self-consistent and transparent data for China. Detailed methods and data sources are summarised previously in Chapter 3.

Section 4.1 examines both the sectoral- and reference-approach national CO_2 emissions from 2000 to 2015. The emissions show that during the past 16 years, the total CO_2 emissions increased from 3,003 to 9,265 Mt with an average increase of 7.8% per year. The detailed analysis of fossil fuels finds that coal and its related products in the primary contributor of China's CO_2 emissions, accounts for more than 75%. As for the aspect of sector analysis, this chapter finds that manufacturing is the biggest contributor to

CO_2 emissions. In 2015, the 39 manufacturing sectors emitted 83.9% of CO_2, followed by the service-sectors (10.2%), farming (1.1%), construction (0.5%), and household energy consumptions (4.4%). Among the 39 manufacturing sectors, the overwhelming proportion of emissions are from three sectors: "Power and heat", "Ferrous proc.", and "Non-metal prod.".

The calculation of per capita emission and emission intensity finds that the per capita emissions firstly increased rapidly from 2.7 in 2002 to 6.5 tonnes in 2011, then peaked in 2013 at 7.0 tonnes, while the emission intensity has continued to decrease since 2005 at an average reduction rate of 3.8% per year. Then the scenario analysis finds that the 2030 CO_2 emissions will span a range of 13,483-20,224, 11,236-16,854, 7,865-15,168 Mt CO_2 under the BAU, Enhanced policy, and 450-500 ppm scenarios, respectively.

In section 4.2, a similar analysis is conducted at the provincial level. 30 provinces' contributions to 2015 CO_2 emissions are also discussed in section 4.2.1 to present the geographical distribution characteristics of provincial CO_2 emissions. Among the 30 provinces, Shandong emitted the most CO_2 cumulatively, 10,061 Mt (or 8.6%). The four provinces with the next highest cumulative emissions were Hebei, Jiangsu, Guangdong, and Henan, which emitted 9,070 (or 7.8%), 8,084 (or 6.9%), 6,647 (or 5.7%), and 6,637 (or 5.7%) Mt CO_2, respectively. Provinces in northern and eastern China have higher CO_2 emissions, while provinces in central and western China have lower emissions.

In section 4.3, this chapter discusses the uncertainties of the estimated national and provincial CO_2 emissions by compare the emission estimates with other existing emission database and conducing the Monte Carlo simulations. The results show that this study's estimates are highly consistent with the newly published official emission inventory 2012 in NC2012 (NDRC, 2016b). The two estimates are only with 2.79% difference. The Monte Carlo simulation finds that the uncertainties of the entire CO_2 emissions inventories are roughly (-15%, 25%) at a 97.5% confidential level. Compared with the activity data (-1.4%, 9.2%), emission factors of fossil fuels have a higher uncertainty (-15.8%, 23.7%).

Chapter 5 Analysis of CO_2 emissions from key industry/fuel in China

In the previous Chapter (Chapter 4: Emissions), this study examined the overall emission characteristics of China and its 30 provinces. However, if the country wants to reduce its CO_2 emissions effectively and efficiently, further detailed emission reduction policies should be made aiming at the highly-emitting industries or fossil fuels. This chapter uses the lime industry and petroleum coke as cases to discuss the industry/fuel-specific emission characteristics. Emission-reducing policies are also proposed based on the industry/fuel-specific analysis. The lime industry is the second largest source of industrial process emissions, while petroleum coke (a non-environmentally friendly energy source) is gradually replacing other power fuels in China's industrial enterprises and power plants in recent years. Both of the emissions from the lime industry and petroleum coke combustion have not been well analysed previously. This chapter is the first one filling the research gap, can be referred to discuss the emissions and reduction policies of other industry processes/fossil fuels in the future.

In section 5.1, this study analyses the CO_2 emissions from lime industry in China. Lime is the second largest source of greenhouse gas emissions from industrial processes after the cement production. According to the 2005 national greenhouse gas inventory (NDRC, 2013c), lime process emitted 15.1% of the total process emissions, followed by the cement process (72.4%). The remaining industrial processes contributed accumulated 12.5% of the total process emissions only. However, most of the previous studies on China's process-related emissions focused on the cement production only, there is still no research aiming at the lime industry process-related emissions. This Chapter fills the research gap by examining the 2001-2012 CO_2 emissions from China's lime industry.

In section 5.2, this study discussed the fast-growing emissions induced by petroleum coke consumption in China. The petroleum coke is a non-environmentally friendly fossil fuel source, it is gradually replacing other power fuels in China's industrial enterprises and power plants. The consumption petroleum coke is increasing fast. Petroleum coke has high emission factors and thus emits more greenhouse gases and air pollutants than even raw coal. This chapter, for the first time, examines the rapid growth of petroleum coke consumption in China since 2010 by industry sector and region and then estimates the petroleum coke-related emissions. The increased use of petroleum coke will increase the urgency for the development of climate change mitigation and emissions reduction measures in China. Several possible policy suggestions for petroleum coke management and emissions control are proposed in this chapter as well.

5.1. Emissions from China's Lime industry

The greenhouse gases emitted from China's lime production are considerably high and account for a large percentage of both China's industrial emissions and global lime emissions (European Commission, 2015). According to NDRC (2013c), lime production is the second largest industrial process emission source in China after cement production (see Table 5-1). Based on the estimates, greenhouse gas emissions from the lime production process amount to 85.62 Mt CO_2-eq (15.06%) in 2005.

Table 5-1 Greenhouse gas emissions in China, 1994 and 2005

Items	1994		2005	
	Greenhouse gas emissions	Percentage	Greenhouse gas emissions	Percentage
Unit	10^6 tonnes CO_2 equivalent			
National total emissions	2665.99	100.00%	5975.57	100.00%
Industry energy use	1223.02	45.87%	2114.03	35.38%
Industrial process	277.98	10.43%	568.60	9.52%
Other	1164.99	43.70%	3292.94	55.11%
	Greenhouse gas emissions	Percentage	Greenhouse gas emissions	Percentage
Industrial process emissions	277.98	100.00%	568.60	100.00%
Cement process	157.78	56.76%	411.67	72.40%
Lime process	93.56	33.66%	85.62	15.06%
Steel process	22.68	8.16%	46.95	8.26%
Calcium carbide process	3.97	1.43%	10.32	1.81%
Other	0.00	0.00%	14.04	2.47%

Data source: NDRC (2004;2013c)

More importantly, China has produced the majority of total emissions from global lime production in recent years (see Figure 5-1). The percentage increased from 29.45% in 1970 to 64.86% in 2009. In 2009, greenhouse gas emissions from China's lime production process (142.50 Mt CO_2-equivalent) were greater than the total national emissions from certain developed countries, such as Finland (128.97) or Greece (117.16 CO_2-equivalent) (European Commission, 2015).

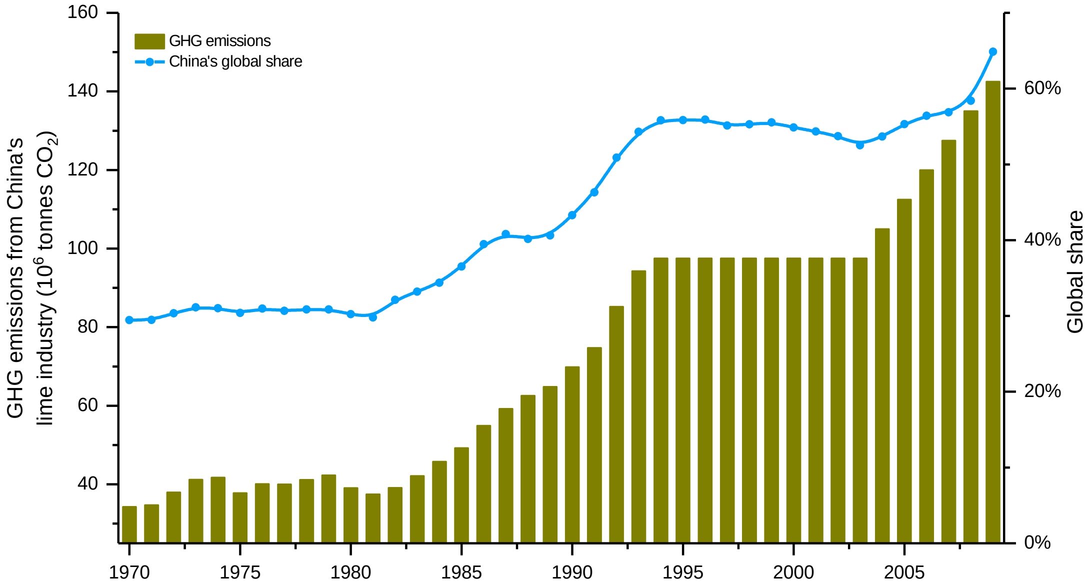

Figure 5-1 Greenhouse gas emissions from China's lime industry and global share
Data source: EDGAR (European Commission, 2015)

However, the emissions from China's lime production are poorly understood, and comprehensive studies on the emissions from the lime industry in China are rarely conducted. In a search of 297 international peer-reviewed publications from SCI indexed database in most recent 10 years (2004-2014) using the keywords "carbon emissions", "industrial process" and "China", only 73 articles relevant to industrial production were found, and none of them was related to lime production. When using the keywords "CO_2 emissions industry China," 82 journal articles on industrial production were found, but none were related to lime production in China (see Table 5-2). This literature review shows that most of the previous studies have focused on greenhouse gases emitted from fossil fuel combustion or cement production (L. Chen, Yang, et al., 2013; Z. M. Chen, Chen, et al., 2013; Guan et al., 2012b; Z. Liu, Geng, et al., 2012; L. Shen et al., 2014; K. Wang, Wang, et al., 2007; J.-H. Xu, Fleiter, et al., 2014; J. Yang et al., 2014), whereas limited studies have addressed emissions from lime production in China. From the global view, only a few studies have addressed emissions from lime industry. However, these studies mostly focused on the industrial process and technique, such as the environmental impact of the lime production process (Sagastume Gutiérrez et al., 2012) and emissions from different lime kilns (Miner et al., 2002). There is still no research related to CO_2 emissions accounting for lime production. Thus, there is a research gap in understanding and quantification of CO_2 emissions from lime production.

Table 5-2 Previous studies on China's lime-related emissions

Sectors	Carbon emissions industry China		CO_2 emissions industry China	
Cement	14	19.18%	17	20.73%
Power	10	13.70%	13	15.85%
Iron & Steel	9	12.33%	11	13.41%
Transportation	8	10.96%	8	9.76%
Construction	7	9.59%	4	4.88%
Chemical	3	4.11%	3	3.66%
Dyeing & Textile	2	2.74%	1	1.22%
Mining	2	2.74%	0	0.00%
Metal	1	1.37%	1	1.22%
Manufacture	1	1.37%	0	0.00%
Non-ferrous metal	1	1.37%	4	4.88%
Plate glass	1	1.37%	1	1.22%
Other	14	19.18%	20	24.39%
Total relevant articles	73	100.00%	82	100.00%

In order to fill the relevant research gap, this chapter estimates CO_2 emissions based on three system boundaries: process emissions (scope 1 direct CO_2 emissions caused by the process), fossil fuel combustion emissions (scope 1 direct emissions caused by fossil fuel combustion) and scope 2 indirect emissions (CO_2 emissions caused by electricity consumption). This is the first analysis that quantifies CO_2 emissions from China's lime production in terms of production process emissions and energy-related emissions. Due to data availability, this chapter only discusses the emissions from China's lime industry at the national level. This chapter contributes to filling current research gap and provide a practical implication for the global low carbon development. The research can be referred by other developing countries with no systematic emission data in industrial processes.

5.1.1. Calculation scope and methods for lime industry

This study calculates the process-related CO_2 emissions of China's lime industry. This study also examines the fossil fuel- and electricity-related CO_2 emissions of the industry of the year 2012 to give a more detailed illustration. The process-related emissions refer to CO_2 emissions from the thermal decomposition of limestone, as discussed in section 2.1.2). The CO_2 emitted during the burning of fuel in lime kilns should be counted as fossil fuel-related emissions. Because all of the electricity consumed by the industry is purchased from power plants, the emitted CO_2 from electricity consumption should be counted as scope 2 indirect emissions (Y. Wang et al., 2013).

The process-related emissions from lime industry are calculated similarly as the cement-related emissions in Equation 2-4 (see section 2.1.3 for more details). The activity data AD_t is lime productions instead, which are collected from the Almanac of the Chinese Building Materials Industry, shown in Table 5-4. Data of lime production is compiled by the Chinese Lime Association, the only institution that records the production, and their figures are based on the demand of downstream consumer sectors (Editorial board of Almanac of China Building Materials Industry, 2002-2013). According to the IPCC (2006), in the absence of country-specific data, the default emission factor (EF_t) for the processing of lime is 0.75 ton CO_2/ton lime produced. However, in the NDRC (2011a), the default emission factors for lime processing is 0.683 ton CO_2/ton lime produced, which is 8.93% smaller than the emission factor recommended by the IPCC. This study adopts the emission factor recommended by the NDRC because it is more relevant to Chinese practical circumstances/experience.

According to the Almanac of the Chinese Building Materials Industry (Editorial board of Almanac of China Building Materials Industry, 2002-2013), only coal is used as a fuel during the lime production process. Therefore, the fossil fuel-related emissions of lime industry refer to coal-related emissions. This study uses Equation 2-3 to estimate the coal-related CO_2 emissions (see section 2.1.3 for more details). The coal combusted in the lime kilns could be deduced based on the economic and technical indexes of different lime kilns (see Table 5-6). This study adopts 1.83 tonnes CO_2/ton as the emission factor ($NCV_i \times CC_i \times O_{ij}$ in Equation 2-3) for coal used in China's lime industry, see Table 3-4. The average oxygenation efficiency for coal is 92%, which is collected from Z. Liu, Guan, et al. (2015)'s research as well.

As for the scope 2 indirect emissions from purchased electricity, Equation 5-1 is used.

$$CE_{ele} = AD_{ele} \times EF_{ele} \qquad \textit{Equation 5-1}$$

where CE_{ele} represents the scope 2 indirect CO_2 emissions from electricity consumption; AD_{ele} represents the purchased electricity consumption in China's lime industry; and EF_{ele} represents the emissions factors of the power grids.

The electricity consumed during the industrial process could be calculated based on the economic and technical indexes of different lime kilns (see Table 5-7). As for the emission factor (EF_{ele}), this study adopts the weighted average of the emissions factors from regional power grids, including the North China Grid, Northeast China Grid, East China Grid, Centre China Grid, Northwest China Grid, and South China Grid. The emission factors of different power grids are collected from the NDRC (2013b). The weights are calculated based on the electricity consumption of different grids in 2012, which are collected from the Editorial board of China Electric Power Yearbook (2013). Table 5-3 shows the emission factors and weights of different power grids. The weighted emission factor of electricity is 0.9402 ton CO_2/mWh.

Table 5-3 Emission factors and weights of different power grids

Gird	Emission factor (tonnes CO_2/mWh)	Weight (%)
North China Grid	1.0302	24.67%
North-east China Grid	1.1120	6.78%
East China Grid	0.8100	24.34%
Centre China Grid	0.9779	18.17%
Northwest China Grid	0.9720	9.24%
South China Grid	0.9223	16.81%

Data source: Emission factors are collected from the “2013 Baseline emission factors for regional power grids in China” (NDRC, 2013b), and the grids’ weight are collected from the China Electric Power Yearbook 2013 (Editorial board of China Electric Power Yearbook, 2013).

5.1.2. Lime-related CO_2 emissions and implications

Process-related emissions

The estimated process-related CO_2 emissions from China’s lime production from 2001 to 2012 are shown in Table 5-4.

Table 5-4 Process-related CO_2 emissions from China’s lime production, 2001-2012

Year	Lime production (Mt)	Emission factor for lime (ton CO_2/ton lime)	CO_2 emissions from process (Mt)
2001	130.00	0.683	88.79
2002	132.00	0.683	90.16
2003	135.73	0.683	92.70
2004	143.28	0.683	97.86
2005	154.30	0.683	105.39
2006	162.60	0.683	111.06
2007	171.10	0.683	116.86
2008	178.10	0.683	121.64
2009	187.00	0.683	127.72
2010	170.00	0.683	116.11
2011	205.50	0.683	140.36
2012	207.50	0.683	141.72

Beginning in 2004, the rapid growth of process CO_2 emissions occurred in China's lime industry because of increased lime production. The average annual growth rate from 2004 to 2009 was 5.49%. Subsequently, the CO_2 emissions dropped by 9.09%. The emissions in 2009 were 127.72 Mt and dropped to 116.11 Mt in 2010, which was remarkable compared with the previous 5.45% growth. A similar phenomenon also occurred for the emissions from the cement industry, and to explore the causes, this study divides the total emissions into five downstream consumer sectors.

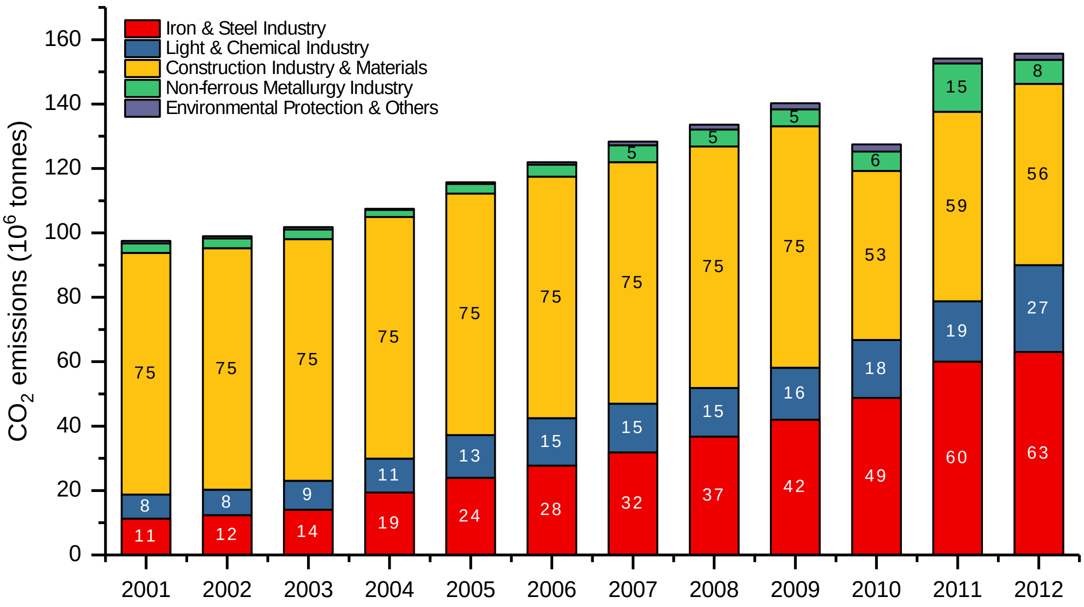

Figure 5-2 Process CO_2 emissions caused by downstream sectors' lime consumption, 2001-2012

There are several downstream consumer sectors of the lime industry (Editorial board of Almanac of China Building Materials Industry, 2002-2013), including the following five consumer sectors: iron and steel industry, light and chemical industry, construction industry and materials, non-ferrous metallurgy industry and environmental protection and others. Based on the lime consumed in different sectors, this research divides the total process CO_2 emissions into these five consumer sectors (see Figure 5-2).

As shown in Figure 5-2, the "Construction Industry and Materials" sector should account for the majority of CO_2 emissions because of the long-term high demand for lime. The "Iron and Steel Industry" sector quickly increased from 11.54% to 40.48% over the past 12 years and surpassed the "Construction Industry and Materials" sector to become the largest lime consuming sector beginning in 2011.

The emissions decreased in 2010, this phenomenon may have been caused by the global financial crisis in 2008 (Editorial board of Almanac of China Building Materials

Industry, 2002-2013). The financial crisis caused global international exports to rapidly decrease. As a result, China was exposed to a deep-rooted structural imbalance in domestic industry, in particular during the global economy slowing down in the second half of 2008. The downstream industries of the lime industry, especially construction (Figure 5-2 shows that most of the decrease occurred in the "Construction Industry and Materials" sector), experienced serious problems, such as excess capacity, industry decentralisation, low-quality products, and lack of core competitiveness (X. Dong, Wei, et al., 2010; Y. Li et al., 2012). Such problems caused a decrease in production in downstream industries, and lime industry is directly related to its downstream industries. Therefore, there appeared a decrease in lime production in 2010, which lead a quick drop in CO_2 emitted from lime industry.

Fossil fuel-related emissions in 2012

This study uses the year 2012 as an example to estimate the CO_2 emissions from fossil fuel combustion in China's lime production. There are seven types of lime kilns widely use in China's lime industry: rotary kiln, Maerz lime kiln, shaft kiln, Finikas lime kiln, air shaft kiln, mechanical shaft kiln, and Sinopec shaft kiln (Editorial board of China Electric Power Yearbook, 2013). The environmental impacts (unit coal consumption and unit electricity consumption) of the seven types' kilns are presented in Table 5-5.

Table 5-5 Production and energy intensities of lime kilns, 2012

Limekilns	Unit coal consumption (Kg/ton)	Unit electricity consumption (kWh/ton)	Lime production (Mt)
Rotary kiln	153.00	42.97	33.20
Maerz lime kiln	122.00	54.57	6.23
Shaft kiln	127.00	44.73	6.23
Finikas lime kiln	135.00	52.68	12.45
Air shaft kiln	163.00	41.04	4.15
Mechanical shaft kiln	149.73	17.63	16.60
Sinopec shaft kiln	151.00	6.97	33.20
Others	147.54	13.65	95.45
Total			207.50

Data source: Editorial board of China Electric Power Yearbook (2013)

First, this study distributes the total production (207.50 Mt in 2012) into seven types of lime kilns based on their production percentages. Then, this study calculates the coal consumed by each type of kiln. Finally, using the emission factors discussed above, the CO_2 emissions from fossil fuel combustion from China's lime production are estimated in Table 5-6. In 2012, CO_2 emissions from fossil fuel combustion in China's lime production accounted for 55.95 Mt.

Table 5-6 Fossil fuel-related CO_2 emissions from China's lime industry, 2012

Limekiln	Lime production	Coal-consumption	Fossil fuel combustion emissions
Rotary kiln	33.20	5.08	9.30
Maerz lime kiln	6.23	0.76	1.39
Shaft kiln	6.23	0.79	1.45
Finikas lime kiln	12.45	1.68	3.07
Air shaft kiln	4.15	0.68	1.24
Mechanical shaft kiln	16.60	2.49	4.56
Sinopec shaft kiln	33.20	5.01	9.17
Others	95.45	14.08	25.77
Total / Average	207.50	30.57	55.95

Unit: Mt

Electricity-related emissions in 2012

Using the activity data from the Almanac of the Chinese Building Materials Industry 2013 (Editorial board of Almanac of China Building Materials Industry, 2002-2013) and power grid emission factors recommended by the NDRC (2011a), the electricity-related emissions from China's lime production are estimated in Table 5-7.

Table 5-7 Scope 2 CO_2 emissions for China's lime production, 2012

Limekilns	Lime production	Electricity consumption	Electricity-related emissions
Rotary kiln	33.20	1426604.00	1.34
Maerz lime kiln	6.23	339698.25	0.32
Shaft kiln	6.23	278444.25	0.26
Finikas lime kiln	12.45	655866.00	0.62
Air shaft kiln	4.15	170316.00	0.16
Mechanical shaft kiln	16.60	292658.00	0.28
Sinopec shaft kiln	33.20	231404.00	0.22
Others	95.45	1302892.50	1.22
Total	207.50	4697883.00	4.42

Unit: Mt (lime production and electricity-related emissions), mWh (electricity consumption)

The electricity-related CO_2 emissions from China's lime production were 4.42 Mt in 2012.

Above all, the process, fossil fuel- and electricity-related CO_2 emissions from China's lime production in 2012 were 206.51 Mt, with 68.63% contributed by the industrial process, namely, process emissions. The electricity-related indirect emissions from electricity consumption only accounted for 2.14% of the total.

Emission intensities of lime kilns in 2012

Using the emissions from each lime kilns, this study calculates the CO_2 emission intensity (tonnes CO_2 emission when producing one-ton lime) from each type of lime kiln (see Table 5-8). The CO_2 emission intensity ranged widely from 1.42 to 1.55 tonnes CO_2 / ton lime produced. When producing one ton of lime, if the total CO_2 emissions from a lime kiln are less than 1.50 tonnes, this study defines the lime kiln as an environmentally advanced kiln. As shown in Table 5-8, the environmentally advanced kilns include the Maerz lime kiln, Shaft kiln, Mechanical shaft kiln, and Sinopec shaft kiln because these kilns are more efficient and environmentally friendly when producing lime, and they are currently the most advanced technology. Therefore, among the total emissions, the amount contributed by the Maerz lime kiln, Shaft kiln, Mechanical shaft kiln, and Sinopec shaft kiln, denoted as the environmentally advanced lime kilns, was 61.27 Mt or 29.67%.

Table 5-8 Emission intensities of lime kilns, 2012

Lime kilns	Lime production	Total CO_2 emissions	Emission intensity
Rotary kiln	33.20	34.66	1.53
Maerz lime kiln	6.23	6.29	1.48
Shaft kiln	6.23	6.23	1.46
Finikas lime kiln	12.45	12.81	1.51
Air shaft kiln	4.15	4.39	1.55
Mechanical shaft kiln	16.60	16.46	1.45
Sinopec shaft kiln	33.20	32.29	1.42
Others	95.45	93.40	1.43
Total	207.50	206.51	1.46

Unit: Mt (lime production), ton/ton (emission intensity)

5.1.3. Discrepancies and uncertainty in lime-related emissions

Process-related emissions from China's lime production are estimated by a number of different organisations. A comparison of different estimates that were used to determine the discrepancies and perform the uncertainty analyses is shown in Figure 5-3.

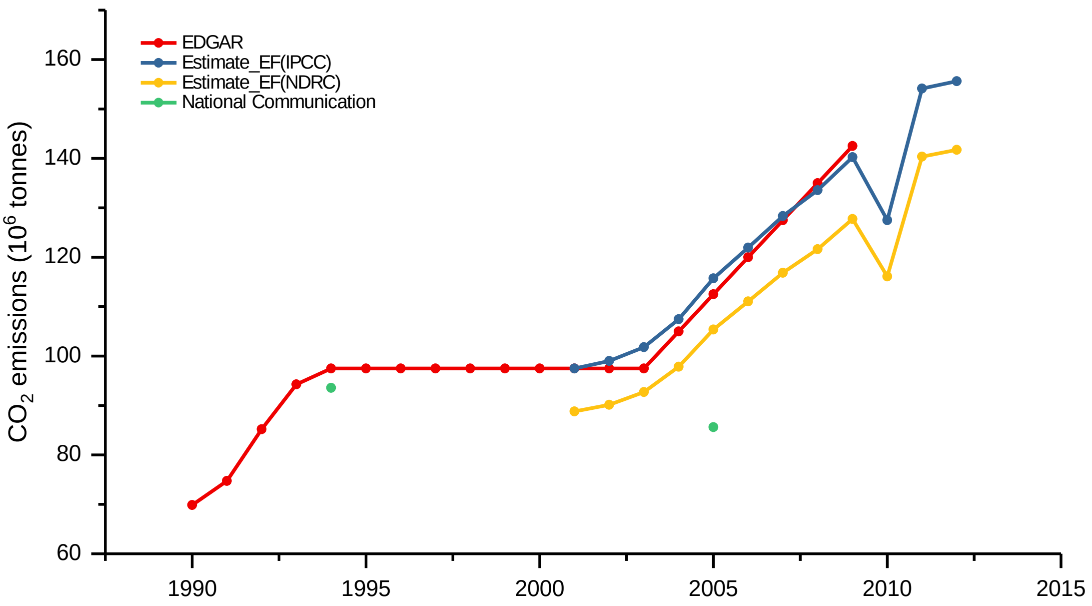

Figure 5-3 Comparison of different estimates of process CO_2 emissions

In Figure 5-3, the estimates by this study are shown by the blue and yellow lines. The blue line was calculated using the IPCC emission factor, whereas the yellow line was calculated using the NDRC emission factor. There is an 8.93% difference between the two lines. The estimate from the EDGAR (European Commission, 2015) (blue line) is nearly identical to the estimates using the IPCC emission factor, with only a small difference of 1.20%.

The two green points in 1994 and 2005 are recorded by NC1994 and NC2005 (NDRC, 2004;2013c). In the national communications, the process-related CO_2 emissions in 1994 are similar to the estimate from EDGAR (93.56 Mt). In 2005, however, there is a gap between the national communication and our estimate using the NDRC emission factor by 19.77 Mt. This gap is attributable to the difference in activity data because the two estimates use the same emission factor.

According to the national communications for the period from 1994 to 2005, the process-related CO_2 emissions from China's lime production decreased slightly. During the same period, however, process-related CO_2 emissions from all industries doubled because of economic and production growth (see Figure 5-3). Therefore, this study believes that the measurement standard for lime production used in the national communications should be different from that of other estimates. In the study of uncertainty, this study regards the estimates from the national communications as statistically abnormal values and will exclude them in the analysis of uncertainty in the following section.

Lacking coefficients of variation and distribution of the two factors (activity data and emission factors) of lime industry, the Monte Carlo simulation cannot be used. Therefore, this study adopts methodologies and recommendations from the "Guide to the expression of uncertainty in measurement (JCGM)" (JCGM, 2010) to evaluate the uncertainty of the estimates.

First, different estimates are not obtained from repeated observations, and the Type B standard uncertainty is evaluated by "scientific judgment using the relevant information available" (JCGM, 2010); Second, a uniform or rectangular distribution is assumed for different estimates of process CO_2 emissions from China's lime production because of the absence of specific information on the probability distribution; Third, the upper and lower limits are assumed to be the maximum and minimum estimates of process CO_2 emissions from lime production; specifically, if the maximum and minimum estimates of process CO_2 emissions from lime production by different organisations are denoted as a_+ and a_-, then the probability that the actual process CO_2 emissions from lime production lie within the interval $[a_-, a_+]$ is assumed to be equal to one (the probability that the actual CO_2 emissions from lime production lie outside this interval is essentially zero) (JCGM, 2010); Forth, the process CO_2 emissions from China's lime production are assumed to be uncorrelated; Finally, according to this analysis, the estimates using the NDRC emission factor can be used as the expected value for the actual process CO_2 emissions from China's lime production and is denoted as x'.

According to (JCGM, 2010), the upper and lower bounds a_+ and a_- for the quantity X_i may not be symmetric with respect to the best estimate x'; specifically, if the lower bound is written as $a_- = x' - b_-$ and the upper bound is written as $a_+ = x' + b_+$, then $b_- \neq b_+$ because in this case, x' (assumed to be the best estimate of X_i) is not at the centre of the interval $[a_-, a_+]$; therefore, the probability distribution of X_i cannot be uniform throughout the interval. However, there may not be enough information available to choose an appropriate distribution, and different models will produce different expressions for the variance. In the absence of such information, the simplest approximation is as Equation 5-2.

$$u^2(x_i) = \frac{(b_+ + b_-)^2}{12} = \frac{(a_+ - a_-)^2}{12}$$ *Equation 5-2*

Based on the above assumptions and methodology from JCGM, this study adopts Equation 5-2 to measure the variances associated with the best estimates of process CO_2 emissions for China's lime production.

The Type B standard uncertainty can be calculated by Equation 5-3 (JCGM, 2010).

$$u = \sqrt{\frac{(b_{+}+b_{-})^2}{12}} = \sqrt{\frac{(a_{+}-a_{-})^2}{12}} \qquad \textit{Equation 5-3}$$

The relative uncertainty of the best estimate x' is defined by Equation 5-4.

$$u^{rel} = \mathrm{u}/x' \times 100\% \qquad \textit{Equation 5-4}$$

The standard and relative uncertainty of the best estimate of process CO_2 emissions of China's lime industry are shown in Table 5-9.

Table 5-9 Uncertainties of lime process-related CO_2 emissions

Year	EDGAR	EF-IPCC	EF-NDRC (x')	u	u^{rel} (%)
2001	97.50	97.50	88.79	2.51	2.83%
2002	97.50	99.00	90.16	2.55	2.83%
2003	97.50	101.80	92.70	2.63	2.83%
2004	105.00	107.46	97.86	2.77	2.83%
2005	112.50	115.73	105.39	2.98	2.83%
2006	120.00	121.95	111.06	3.14	2.83%
2007	127.50	128.33	116.86	3.31	2.83%
2008	135.00	133.58	121.64	3.86	3.17%
2009	142.50	140.25	127.72	4.27	3.34%
2010		127.50	116.11	3.29	2.83%
2011		154.13	140.36	3.97	2.83%
2012		155.63	141.72	4.01	2.83%

Unit: Mt

As Table 5-9 shows, the relative uncertainty of the estimates using the NDRC emission factor is between 2.83% and 3.34%, and the analysis on discrepancies indicates that this uncertainty is a product of variations in the emission factors and activities data.

Firstly, the largest component of the uncertainty lies in emission factor. The emission factor for lime process ranges from 0.683 to 0.75 ton CO_2/ton lime produced (IPCC, 2006; NDRC, 2011a). This uncertainty embodied in the two estimates using different emission factors, the green line and red line. In additional, lime production data is another challenge of accounting the lime emissions in China. Comparing to other industries (e.g. cement, steel) (Gregg et al., 2008b; Price et al., 2002), a large portion of lime are produced in small lime mills in China, and their lime productions are usually not recorded in the published statistics. Different organises use data from different sources. This is the major reason for the discrepancies of the estimate from EDGAR and the calculation using IPCC emission factor, since both the two estimates use emission factor from IPCC. The similar uncertainty also embodied in China's coal-related CO_2 emissions (Pan et al., 2013).

5.2. Emissions from China's Petroleum coke combustion

China is trying its best to optimise its energy structure towards a low-carbon path by proposing several policies to control energy/coal consumption recently (Guan et al., 2016). After implementing a series of energy/emissions control policies, the coal share in China decreased from 72.5% in 2007 to 65.6% in 2014. Additionally, the oil shares decreased from 22.0% in 2000 to 17.4% in 2014. Simultaneously, China strived to develop renewable and clean energies, such as natural gas, hydropower, and nuclear power. Renewable and clean energies now contribute 17.0% of overall energy consumption and have almost doubled since 2000 (9.5%) (NBS, 2016a). However, a few industrial enterprises and power plants have recently begun to use cheap but environmentally unfriendly energy sources, especially petroleum coke.

According to the IPCC guidelines, *"petroleum coke is defined as a black solid residue, obtained mainly by cracking and carbonizing of petroleum derived feedstocks, vacuum bottoms, tar and pitches in processes such as delayed coking or fluid coking. It consists mainly of carbon (90 to 95 percent) and has a low ash content. It is used as a feedstock in coke ovens for the steel industry, for heating purposes, for electrode manufacture and for production of chemicals"* (IPCC, 2006). According to a previous study that compared emissions factors (EIA, 2014), petroleum coke emits 2.21 times the CO_2, 6.15 times the CH_4, and 5.48 times the N_2O emitted by lignite coal during combustion. Lignite coal is primarily used as thermal coal in power plants and industrial boilers in China. Therefore, petroleum coke is a more carbon- and pollution-intensive energy source, even when compared with raw coal and crude oil. The use of petroleum coke, especially for combustion, degrades the local air quality and threatens residents' health (Andrews et al., 2014).

Because of its relatively small consumption amount, petroleum coke was not listed as a separate energy type in China's energy statistics system until 2010 (NBS, 2011-2015) and was previously included in other petroleum products. Figure 5-4 presents the production, import and consumption of petroleum coke in China since 2010. Petroleum coke production and consumption have increased rapidly in China. From 2010 to 2014, the production of petroleum coke increased by 32.31%, and its use in industrial final combustion increased by 159.32%, as it was used in kiln stoves/boilers to provide power. The Chinese government has not yet recognized the hazard posed by the widespread use of petroleum coke. Indeed, in the "10 key energy conservation projects during the 11th five-year plan (2006-2010)", the use of petroleum coke as a replacement for fuel oil (burnt in oilfield exploitation) and heavy oil (used in the production of construction materials) is actually encouraged (NDRC, 2006a). Only in the "Air pollution prevention and control action plan", which was published in 2013 (MEP, 2013), did the government first intensify its controls on the import of high-sulphur petroleum coke. However, this policy was issued without any detailed measures.

In this section, the study analyses the production, consumption and the related emissions of petroleum coke in China, as well as the reduction policies.

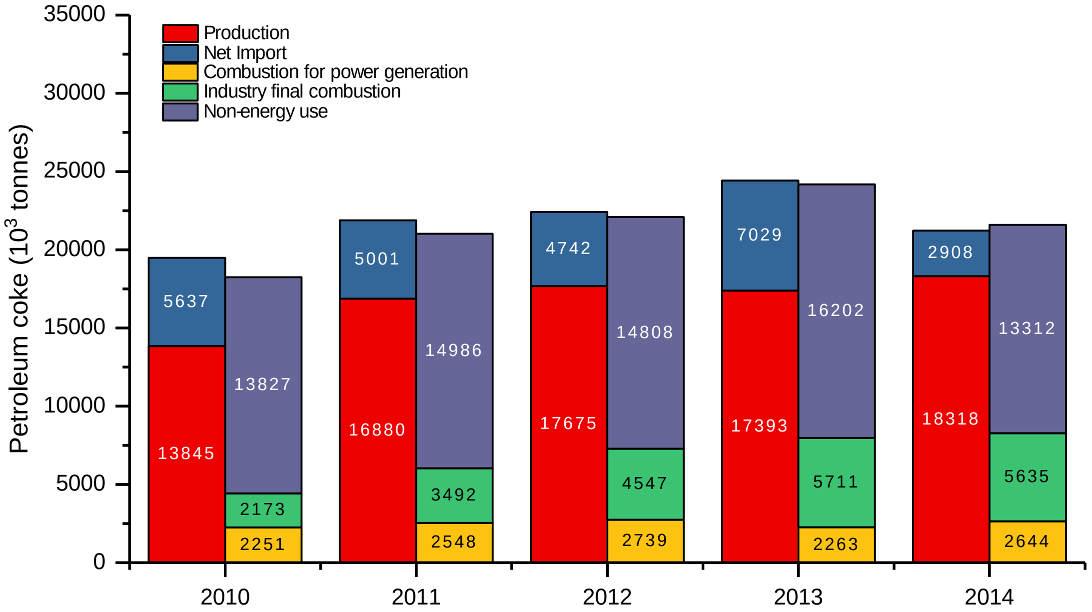

Figure 5-4 Petroleum coke production, import, and consumption of China, 2010-2014
Data source: NBS (2015b)

5.2.1. Production and imports of petroleum coke

Production

Petroleum coke is a by-product produced by petroleum refineries. Heavy crude produces more petroleum coke than light crude (Gordon et al., 2015). The national overall petroleum coke production in 2014 was 18,318 thousand tonnes. China's petroleum coke production increased by 32.31% (4,473 thousand tonnes) from 2010 to 2014, probably because of long-term engineering service contracts between China and

Iraq, which started in 2003, and the oil exploration agreements between China's national petroleum corporation and Abu Dhabi's national oil company, which were signed in 2014 (Khoudouri, 2014).

Petroleum refineries are concentrated in several primary oilfields or petrochemical bases in China. Taking the year 2014 as an example, the red dots in Figure 5-5 show the petroleum production of a few primary oilfields, with larger dots representing higher productions. Shengli oilfield in Dongying, Shandong province, is the largest petroleum coke producer. It produced 4,611 thousand tonnes of petroleum coke in 2014, accounting for 25.17% of the national overall production. Guangdong (Maoming petrochemical base, 1,964 thousand tonnes), Jiangsu (Jiangsu oilfield, 1,760), Liaoning (Liao river oilfield, 1,627), Xinjiang (Karamay oilfield, 1,563), and Tianjin (Dagang oilfield, 1,070) also produced large quantities of petroleum coke. These top 6 oilfields (petrochemical bases) produced 68.75% of the total petroleum coke in 2014.

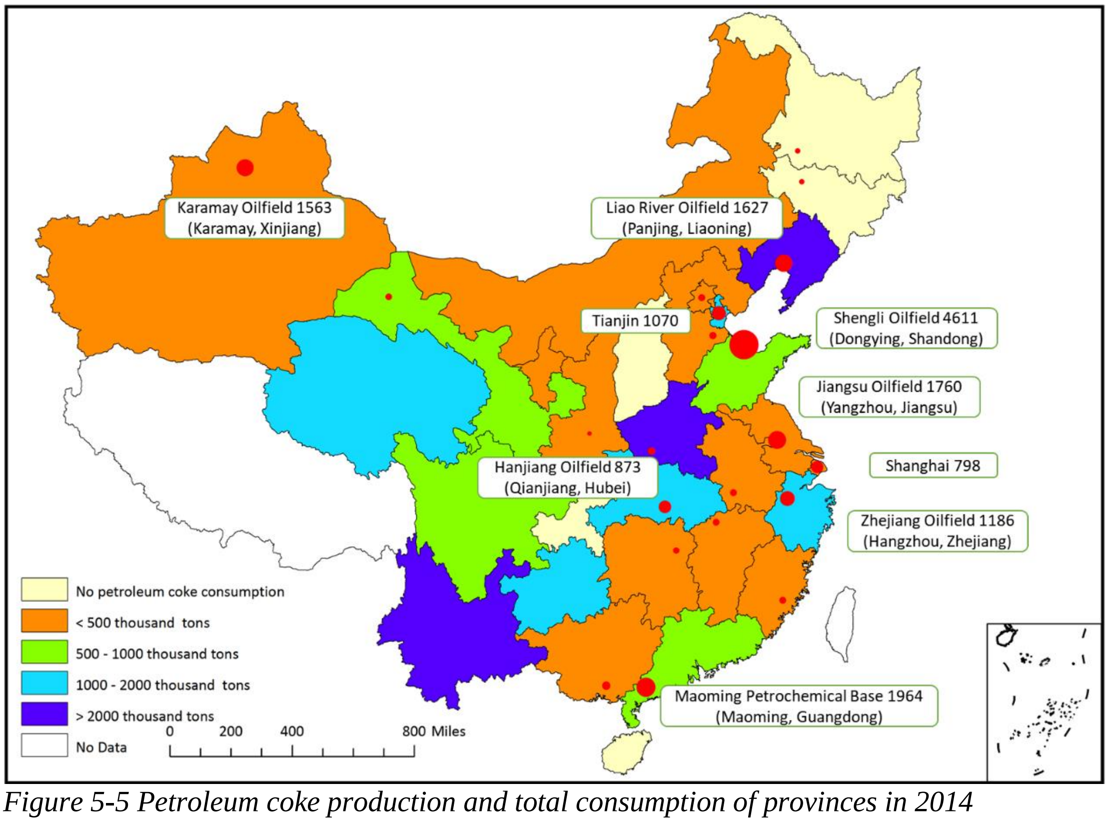

Figure 5-5 Petroleum coke production and total consumption of provinces in 2014
Data source: NBS (2015b)

Figure 5-6 shows that the increasing petroleum coke production in China can be primarily attributed to Shandong province (i.e., the Sinopec Shengli oilfield company in Dongying). Shandong increased its petroleum coke output by 3,332 thousand tonnes during the five-year study period, accounting for 74.49% of the national increase. In other provinces, production either remained stable or increased only slightly.

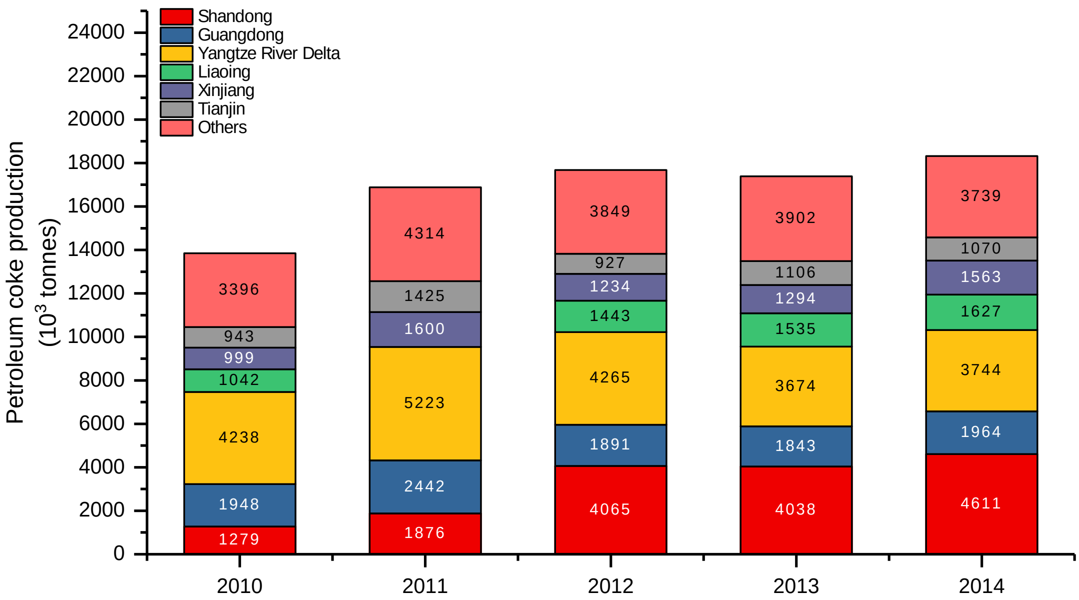

Figure 5-6. Petroleum coke production by 6 primary regions, 2010-2014
Note: Here, the Yangtze River Delta includes Shanghai, Jiangsu, and Zhejiang provinces. Because of the poor data quality of some of China's regions, there is no import data for Liaoning in 2011 (shown as 0 ton here). Compared with the data from similar years, this study assumes that Liaoning produced approximately 1,200 thousand tonnes of petroleum coke in 2011. Data source: NBS (2011-2015)

Import

The import volume of petroleum coke fluctuated widely. China imported roughly 7,500 thousand tonnes of petroleum coke per year before 2013, representing approximately 50% of its local production. Subsequently, the imports increased to 9,349 thousand tonnes in 2013 and then suddenly dropped to 5,888 thousand tonnes in 2014. About 50% of the imported petroleum coke was from the USA (Table 5-10). China is the third-largest consumer of petroleum coke produced in the USA (10%-20%), followed by India and Japan (EIA, 2016).

Among the 5,350 thousand tonnes of petroleum coke imported in 2014, 85.56% (4,578 thousand tonnes) was imported by Shandong. However, although Shandong imported a large amount of petroleum coke, this study cannot conclude that all of the imported petroleum coke was consumed in Shandong province. Indeed, Shandong province consumed just 708 thousand tonnes of petroleum coke. Together with that produced in Shandong, most of the imported petroleum coke was transported to other provinces

(5,995 thousand tonnes in total). Therefore, Sinopec Shengli Oilfield Company in Shandong is the primary petroleum coke production and transhipment base in China.

Table 5-10 Petroleum coke imported by China and exported by the USA

Year	USA exports (thousand barrels)			China imports (10 thousand tonnes)		
	To China	Total export	Percentage	From USA	Total import	Percentage
2010	15,158	163,868	9.25%	206.14	773.86	26.64%
2011	24,771	182,222	13.59%	336.89	811.05	41.54%
2012	26,179	184,167	14.21%	356.03	703.38	50.62%
2013	38,434	191,219	20.10%	522.70	934.9	55.91%
2014	20,845	197,491	10.55%	283.49	535.01	52.99%
2015	18,358	196,482	9.34%	249.67	588.76	42.40%

Data source: USA's exports (EIA, 2016); China's imports from the USA were calculated based on a unit conversion factor (0.136 tonnes of oil equivalent per barrel) (Society of petroleum engineers); China's total imports were obtained from China's energy statistical yearbooks (NBS, 2011-2015)

5.2.2. Consumption of petroleum coke

The increasing production and imports lead to a sharp increase in petroleum coke consumption. In total, China consumed 21,591 thousand tonnes of petroleum coke in 2014, increasing from 18,250 thousand tonnes in 2010. Generally, petroleum coke is used in the following two ways in China, see Figure 5-7.

- Over 60% of the petroleum coke is consumed as a raw material, i.e., for a non-energy use, such as in the smelting of steel or aluminium and the manufacturing of graphite;
- Less than 40% of the petroleum coke is combusted in industrial kiln stoves/boilers and in power plants as fuel.

Although most of the petroleum coke was used as a raw material (13,312 thousand tonnes in 2014, accounting for 61.66% of the overall consumption), the additional 3,341 thousand tonnes consumed is primarily attributable to combustion. Petroleum coke combustion increased by 87.16% (3,855 thousand tonnes) from 2010 to 2014. This growth rate is remarkably high compared with those of total energy and raw coal. Indeed, total energy combustion increased by 31.43% (from 2,869 to 3,770 Mt of standard coal equivalent according to calorific value calculations), whereas raw coal combustion increased by 24.15% (from 2,358 to 2,928 Mt).

Consumption by sectors

Petroleum coke combustion is presented by sector in Figure 5-7. For clarity, this study divides the petroleum coke consumption by sector into two parts according to the method of consumption: “Input as industrial material (non-energy use)” and “Burning consumption”. The “Non-metal prod.” sector consumed most of the petroleum coke in 2014 (65.41%), followed by the “Power and heat” sector (12.77%), “Petroleum proc.” sector (9.09%), “Non-ferrous proc.” sector (8.02%), “Chemicals” sector (2.45%), and “Ferrous proc.” sector (2.17%). Other industries include “Nonferrous mining”, “Beverage”, “Paper”, “Metal prod.”, “Electric equip.”, and others.

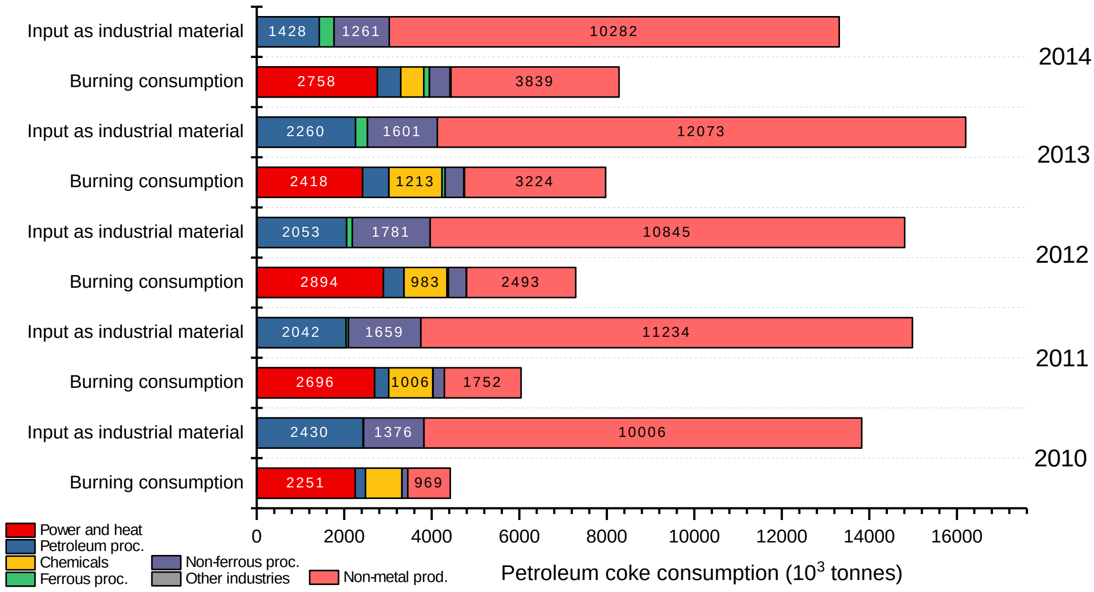

Figure 5-7 Petroleum coke consumption by sector in China, 2010-2014
Data source: NBS (2015b)

The raw material input of petroleum coke fluctuated slightly during the five-year study period and even appeared to decrease (17.84%) in 2014. This was likely the result of China’s temporary economic slowdown (Cashin et al., 2017), during which some industrial enterprises reduced their production. As a raw material, in China, petroleum coke is primarily used in the “Non-metal prod.” sector to produce graphite, accounting for 77.24% of the total material input in 2014. The “Petroleum proc.” sector used 1,428 thousand tonnes of petroleum coke, whereas 1,261 thousand tonnes were used as prebaked anodes to electrolyze aluminium in the “Non-ferrous proc.” sector. The remaining 340 thousand tonnes were used in the “Ferrous proc.” sector for steelmaking.

During this period, the burning consumption of petroleum coke increased at an alarming rate. The amount doubled from 2,173 thousand tonnes in 2010 to 5,711 thousand tonnes in 2013 and finally to 5,635 thousand tonnes in 2014. Among the 6-petroleum coke-consuming sectors, “Non-metal prod.” burnt 3,839 thousand tonnes in 2014, representing an increase of 296.18% since 2010. The petroleum coke combusted in power plants for electricity and heat generation remained stable at approximately 2,500 thousand tonnes throughout the five-year period. As a raw material utilized in industrial processes, the non-energy uses of petroleum coke emit little greenhouse gases or air pollutants. In contrast, combustion emits large quantities of carbon, nitrogen, and oxidized sulphur. Therefore, the combustion of petroleum coke is the primary emissions source and should be considered as a key regulatory target.

As discussed above, the raw material input of petroleum coke decreased in 2014 as some industrial enterprises reduced their production, whereas the combustion of petroleum coke in industrial enterprises (excluding combustion in power plants) increased rapidly (i.e., by 159.32% since 2010). This trend strongly suggests that industrial enterprises are replacing other fuel types with petroleum coke, probably because of petroleum coke’s price advantage. The price of coal in China increased from 200 (2005) to 1,000 yuan per ton (2008). In contrast, the price of petroleum coke imported from the USA is 25% cheaper than the coal price in 2008 (T. Wang, 2015). China’s government should pay close attention to this “replacement” fuel, as its use does not fit with the country’s energy mix optimization strategy and low-carbon development plans.

Consumption by provinces

Taking 2014 as an example (Figure 5-5). In 2014, the top five petroleum coke-consuming provinces were Henan (3,850 thousand tonnes, 17.83%), Yunnan (3,419, 15.83%), Liaoning (2,088, 9.67%), Qinghai (1,867, 8.65%), and Guizhou (1,788, 8.28%). Heilongjiang, Jilin, Shanxi, and Chongqing consumed no petroleum coke. Although most of the petroleum coke is used as a raw material in industrial processes, that which is used for burning is the relatively important part in terms of emissions. Figure 5-8 highlights the distribution of the burning consumption and industry final consumption of petroleum coke. The industry final consumption refers to the petroleum coke burnt in industrial kiln stoves/boilers to provide power, excluding combustion in power plants. The burning consumption is equal to industry final consumption plus that burnt in power plants for electricity and heat generation.

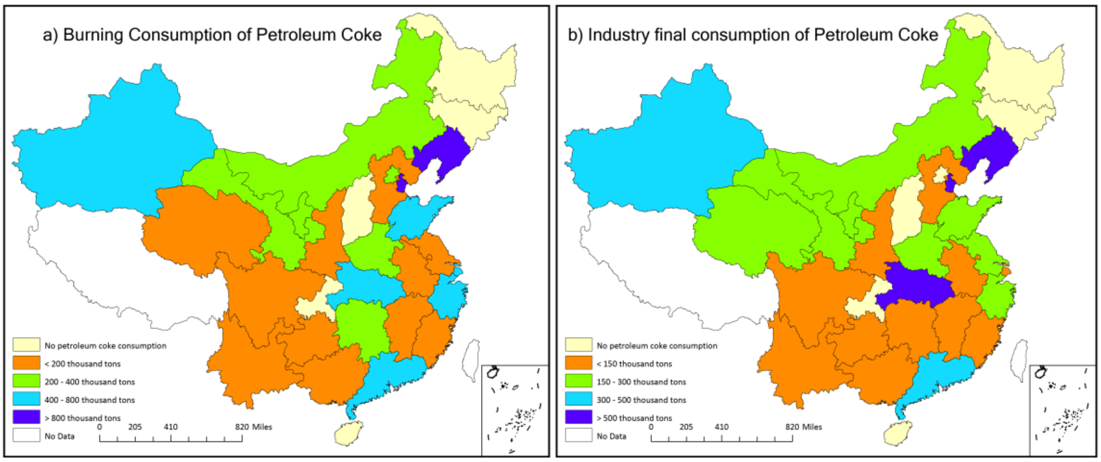

Figure 5-8 Petroleum coke combustion by province in 2014
Data source: NBS (2015b)

Liaoning (1,127 thousand tonnes) and Tianjin (1,092) burnt the most petroleum coke, followed by Guangdong (716), Zhejiang (677), Shandong (576), Xinjiang (441), Shanghai (421), and Henan (347). These eight super-burning-consumption provinces (dark-blue and light-blue regions in Figure 5-8-a) contributed 65.20% of the overall burning consumption in China. Unlike other super-burning-consumption provinces, Liaoning, Hubei, and Xinjiang only burnt petroleum in industrial boilers, contributing 20.01%, 10.53%, and 7.82% of the overall industrially burnt petroleum coke in 2014, respectively. Guangdong also burnt a large quantity of petroleum coke in industrial boilers (307 thousand tonnes, 5.45%). As discussed above, in China, industrial boilers are usually not equipped with denitration systems, and therefore, the provinces with high levels of industrial petroleum coke combustion should be subjected to more scrutiny.

Only 10 provinces burnt petroleum coke in power plants. Tianjin burnt 576 thousand tonnes of petroleum coke in 2014, followed by Zhejiang (412), Guangdong (409), Shandong (310), Shanghai (278), Beijing (258), Henan (173), Fujian (108), Hunan (89), and Jiangxi (32) (Figure 5-9). Although the overall combustion in power plants remained steady over the study period, Fujian, Hunan, and Jiangxi started using petroleum coke to generate electricity and heat in 2012, and Guangdong increased its petroleum coke usage in power plants. These are not positive changes and should be strictly controlled. By focusing on the top burning consumption provinces, especially Liaoning and Tianjin, China's government should be able to manage and control the petroleum coke consumption effectively.

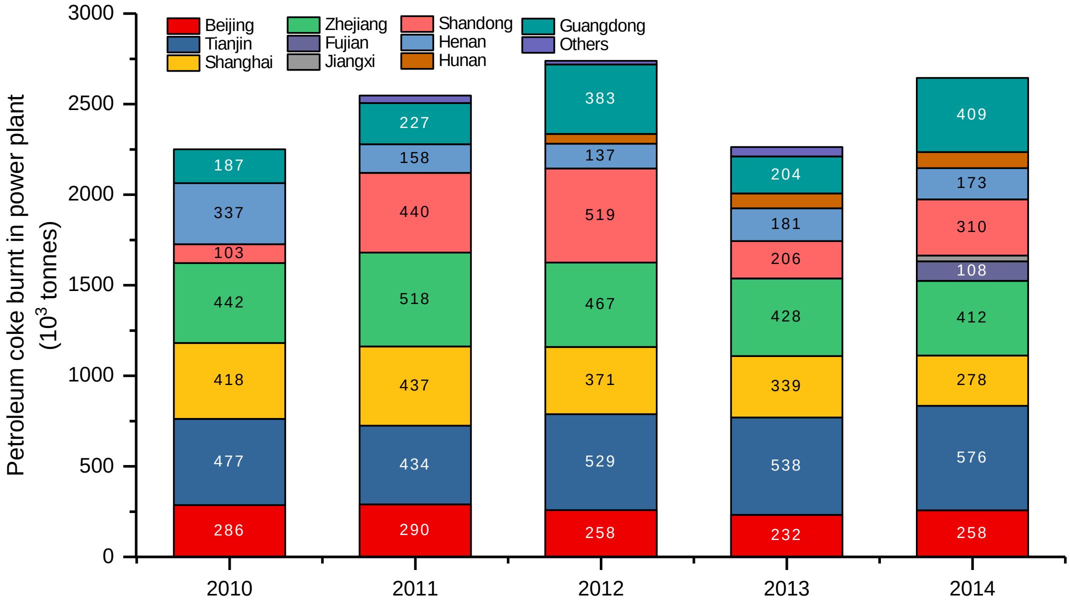

Figure 5-9 Petroleum coke burnt in power plants for electricity and heat generation by provinces, 2010-2014
Data source: NBS (2011-2015)

5.2.3. Calculation scope and methods for petroleum coke

To elucidate the adverse effects of China's growing petroleum coke consumption on the climate and air quality, this study estimates the CO_2, CH_4, and N_2O emissions from petroleum coke combustion in this country. All three gases are considered greenhouse gases. CH_4 and N_2O are also classified as air pollutants.

Different from Equation 2-3 used for CO_2 emission calculation, this study considers control measures for air pollutants emissions, see Equation 5-5.

$$CE_{petrocoke} = AD_{petrocoke} \times NCV \times \mathrm{CC} \times \mathrm{O} \times ECR \qquad \textit{Equation 5-5}$$

where $AD_{petrocoke}$ means Activity Data, refers to petroleum coke burning consumption. The consumption data of petroleum coke ($AD_{petrocoke}$) are collected from China and its 30 provinces' energy balance tables 2010-2014 (NBS, 2011-2015). Considering the statistical gap between China's national and regional energy data (Guan et al., 2012b), this study scales down the provincial data to match the national data.

Similar to Equation 2-3, NCV, CC, and O in Equation 5-5 have the same meaning. NCV means Net Calorific Value, refers to the heat released during per physical unit of petroleum coke combustion; CC is the CO_2, CH_4, and N_2O emissions while per Joule heat releasing. As not all of the fossil fuel could be fully combusted in boilers, an oxygenation efficiency O is timed in the equation, which refers to the boilers' oxidation ratio of petroleum coke. Because no research has specifically focused on China's petroleum coke emissions factors to date, this study adopts the IPCC's default values. The NCV of petroleum coke is 32.5 TJ/Gg. The CC values of CO_2, CH_4, and N_2O are 97,500, 3, and 0.6 Kg/TJ, respectively. The default oxygenation efficiency is 1.

ECR in Equation 5-5 refers to Emission Control Ratio. Because most of the power plants in China have been equipped with denitration systems (low-NO_x boilers), this study assigns a control ratio of 70% to the estimated N_2O emissions from petroleum coke burnt in power plants equipped with low-NO_x boilers. The 70% control ratio means that 30% of the N_2O emissions can be removed by the denitration system. According to the literature, currently, such denitration systems are installed in approximately 75% of power plants in China (B. Zhao et al., 2013). Thus, the ECR for power plants is 52.5%. In contrast, industrial boilers usually have small power capacities; thus, it is uneconomical to install denitration systems on them. Consequently, the installation rate of denitration equipment on industrial boilers is quite low. Therefore, this study assumes that N_2O emissions from petroleum coke burnt in industrial boilers are not controlled (B. Zhao et al., 2013), and as a result, the ECR is 1.

5.2.4. Petroleum coke-related emissions and implications

Similar to the consumption growth, petroleum coke-related emissions increased by 87% during the five-year study period, as demonstrated by Figure 5-10. This is remarkably high compared to the 19.41% growth rate of total CO_2 emissions in China and the overall slight decline that occurred in 2014 (Shan, Liu, Liu, et al., 2016). Taking 2014 as an example, the total petroleum coke-related CO_2 emissions were 26.23 Mt, 68.06% of which (17.85 Mt) were produced by industrial boilers. The rest of the emissions (31.94%, 83.79 Mt) were contributed by power plants. Because of their relatively low emissions factors, CO_2 and CH_4 emissions totalled only 807.17 tonnes, and an additional 136.95 tonnes of N_2O was emitted from petroleum coke burning. Power plants contributed only 19.77% (27.07 tonnes) of the total N_2O emissions because of their denitration systems. Thus, most of the N_2O (109.87 tonnes) was emitted from industrial boilers.

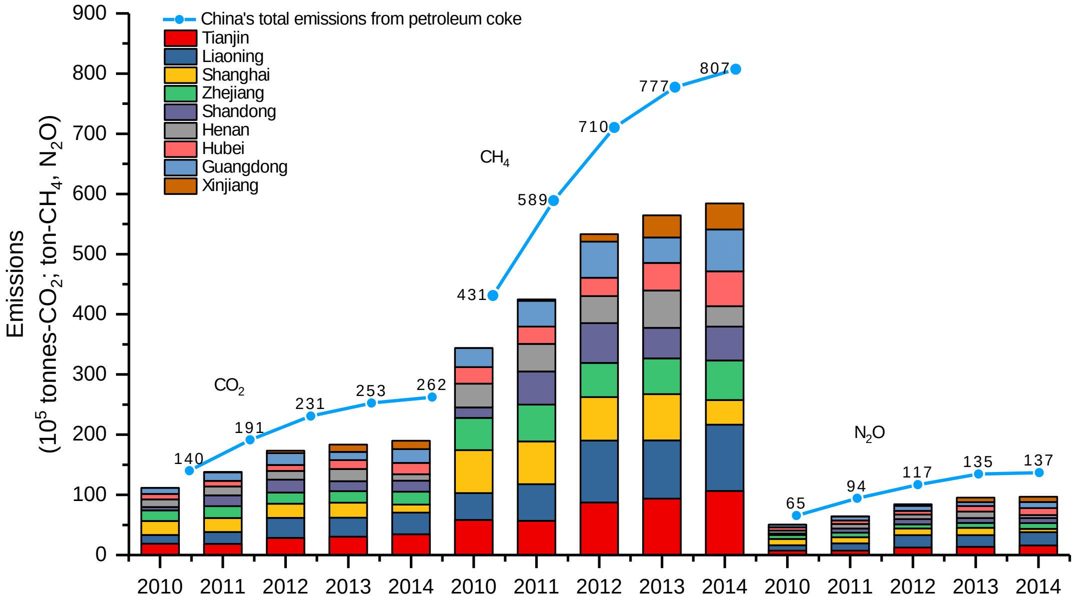

Figure 5-10 Petroleum coke-related CO_2, CH_4, N_2O emissions, 2010-2014

Similar to the consumption distribution, the emissions levels were attributable to the few main petroleum coke-consuming provinces, especially Liaoning and Tianjin. Take CO_2 emissions as an example: Liaoning and Tianjin contributed 13.62% and 13.20%, respectively, of the total CO_2 emissions in 2014. In contrast, the contributions of Shanghai and Zhejiang decreased from 12% to 5% over the five-year study period, while in Xinjiang, CO_2 emissions increased rapidly from 0% to 5.32%. Detailed emissions results are shown in Table 5-11.

Table 5-11 Petroleum coke-related CO_2, CH_4, and N_2O emissions, 2010-2014

		China	TJ	LN	SH	ZJ	SD	HN	HB	GD	XJ	Others
CO_2	2010	140	19	14	23	17	6	13	9	10	0	9
	2011	191	18	20	23	20	18	15	9	14	1	9
	2012	231	28	33	23	18	22	15	10	20	4	8
	2013	253	30	32	25	19	17	20	15	14	12	7
	2014	262	35	36	13	21	18	11	19	23	14	8
CH_4	2010	431	58	45	72	54	17	40	27	32	0	28
	2011	589	57	61	71	61	55	46	29	43	2	28
	2012	710	87	103	72	57	66	45	30	60	13	25
	2013	777	94	97	77	60	51	62	46	42	37	23
	2014	807	107	110	41	66	56	34	58	70	43	25
N_2O	2010	65	7	9	10	7	3	5	5	5	0	4
	2011	94	7	12	10	7	7	8	6	7	0	4
	2012	117	13	21	11	7	8	8	6	8	3	6
	2013	135	14	19	12	8	8	11	9	7	7	6
	2014	137	16	22	6	9	8	5	12	10	9	7

Note: Province abbreviations are TJ (Tianjin), LN (Liaoning), SH (Shanghai), ZJ (Zhejiang), SD (Shandong), HN (Henan), HB (Hubei), GD (Guangdong), and XJ (Xinjiang). Unit: 100 thousand tonnes (CO_2), ton (CH_4 and N_2O)

Furthermore, unlike the coal used as a raw material input, which does not emit any CO_2 (Peters et al., 2006), the consumption of petroleum coke for non-energy uses likely results in the emission of greenhouse gases and air pollutants. For example, when petroleum coke is used as a prebaked anode in electrolytic aluminium production (i.e., the SPNM sector), 10%-20% of its sulphur is converted into SO_2 and is emitted into the air (Y. Zhao et al., 2010). Because of the lack of accurate escape ratios and emissions factors, this study could not estimate the exact emissions from non-energy uses of petroleum coke. Thus, the actual petroleum coke-related emissions are higher than the values estimated above. As greenhouse gas and air pollutant emissions are highly related to physical consumption, they could be controlled effectively by managing the consumption and production of petroleum coke.

To manage and control petroleum coke consumption and its related emissions in China, more attention should be focused on the key industrial sectors and top-consuming provinces. China’s government should strongly restrict the production and import of high-sulphur petroleum coke. Additionally, burning petroleum coke to provide power should be discouraged. In 2013, the U.S. Environmental Protection Agency stopped issuing new licenses for petroleum coke burning in that country; this strategy may work for China as well. Furthermore, all power plants and industrial kiln stoves/boilers should be equipped with more efficient decontamination systems, especially for desulfurization and denitrification. As discussed above, the installation rate of the low-NO_x boiler in power plants is currently only 70%, and the equipment can only decontaminate 30% of the total NO_x emissions; in addition, no decontamination equipment is installed on industrial boilers for economic reasons. Finally, because the non-energy use of petroleum coke will also emit greenhouse gases and air pollutants, the development of advanced industrial processes and the clean utilization of petroleum coke are urgently needed.

5.3. Summary

The CO_2 emissions from China's lime industry are considerably high and account for a large percentage of both global lime emissions and China's industrial emissions. However, most studies have only focused on the CO_2 emissions from fossil fuel combustion and cement production, and only limited number of studies have analysed the environmental impact of lime production. This chapter fills the gap in the literature by presenting for the first time an analysis of CO_2 emissions from China's lime production from 2001 to 2012. This chapter estimates the process emissions, fossil fuel combustion emissions, and scope 2 indirect emissions from China's lime industry. The estimations showed that the process emissions increased rapidly from 88.79 to 141.72 Mt from 2001 to 2012, and fossil fuel combustion/scope 2 electricity-related emissions in 2012 accounted for 55.95 and 4.42 Mt, of which 29.67% were contributed by environmentally advanced lime kilns. In 2012, the total CO_2 emissions from China's lime production were 206.51 Mt, with 68.63% contributed by the industrial process or process emissions. Scope 2 indirect emissions from electricity consumption were only 2.14%. This chapter also analyses the discrepancies and uncertainties of different estimates. The results showed that the estimates using the NDRC emission factor are the closest to the actual process CO_2 emissions from China's lime production, and the uncertainty of the estimates, which was produced by differences in the emission factors and activities data, is between 2.83% and 3.34%.

The results have global impacts. With the total emission of 206.51 Mt CO_2, emission from lime production is equivalent to the total emission from some developing countries, such as Thailand (258 Mt, global top 24^{th}), Kazakhstan (257 Mt, global top

25th), Egypt (228 Mt, global top 26th), and Malaysia (216 Mt, global top 27th) (Olivier et al., 2016).

Despite the high emissions, little attention has been paid to the mitigation of CO_2 emission from lime industry. Cleaner production, efficiency improvement as well as energy saving in lime production need to be addressed with the same priority as the mitigation strategy in energy sectors, so that the low carbon development can be achieved at the national and global level.

As for the petroleum coke consumption, evidence indicates that petroleum coke is gradually replacing other power fuels in China's industrial enterprises because of its current price advantage. This chapter presents China's production and consumption of petroleum coke by sector and region from 2010 to 2014 for the first time. The results show that production increased by 32.31% (4,473 thousand tonnes), primarily because of activities in Shandong province (3,332 thousand tonnes). Shandong, Guangdong, Jiangsu, and Liaoning were consistently the major producers of petroleum coke in China. The total consumption of petroleum coke has increased by 18.30% since 2010, and over 60% of the total consumption is as a raw material in industrial processes. The other 40% is burnt in power plants and industrial kiln stoves/boilers. This usage is the major source of emissions and should be considered as a key regulatory target. The combustion consumption of petroleum coke is focused in the "Non-metal prod." and "Power and heat" sectors and in Liaoning and Tianjin provinces. The consumption of industrial kiln stoves/boilers increased by approximately 159.32% during the past five years, reaching 8,279 thousand tonnes in 2014.

Because of the increased petroleum coke consumption in China, GHG and air pollutant emissions are increasing annually. Petroleum coke-related CO_2 emissions in 2014 were as high as 26.2 million tonnes, whereas those of CH_4 and N_2O were 807 and 137 tonnes, respectively. Apart from the largest emissions contributors, Liaoning and Tianjin, Xinjiang exhibited rapid growth in its emissions levels over the five-year study period. As a result, if no measures are taken, China will face increasingly serious challenges in dealing with climate change and environmental issues. Several possible policy suggestions for petroleum coke management and emissions control are proposed in this chapter, such as strongly restricting the production and import of high-sulphur petroleum coke; discouraging burning petroleum coke to provide power; equipping more efficient decontamination systems for power plants and industrial kiln stoves/boilers; developing the advanced industrial processes and the clean utilization of petroleum coke.

Chapter 6 Emissions and low-carbon development in Chinese cities

In order to fulfil the series of ambitious commitments of climate change mitigation and emission reduction in the most cost-effective way, policymakers of China seek to characterize the sources of CO_2 in as much detail as possible. Urbanization and industrialisation have been a major driver of economic growth in China, and as elsewhere (Satterthwaite, 2008), cities produce most (85%) of China's CO_2 emissions (Dhakal, 2010). For these reasons, Chinese cities play an increasingly important role in efforts to reduce CO_2 emissions (Huang et al., 2013). For example, the "Energy Quota Allocation and Trading Scheme" to be implemented nationwide in 2017 (Guan et al., 2016) will monitor and control firm-level energy consumption and CO_2 emissions as part of an emission peak by 2030. However, the success of the scheme depends upon the cooperation of city-level governments, where many officials are concerned about the economic impacts of energy and emissions constraints.

As discussed in the literature review section 2.3, yet there have been very few studies that assess emissions at the level of individual cities (Auffhammer et al., 2016; G. Chen et al., 2016; Creutzig et al., 2015; Dodman, 2009; Ramaswami et al., 2008). "*Only approximately 45% of prefecture-level cities in China have emission estimates with different levels. The CO_2 emission data available for prefecture-level cities are scarce (page 198)*" (Q. Chen et al., 2017). Most of the existing studies have focused only on larger cities, such as the four-municipality cities and a few provincial capital cities with consistent and systematic energy statistics, and the emissions from specific industry sectors reported in surveys, such as industrial energy consumption, transportation, household energy consumption, commercial energy consumption, and industrial processes. This makes the results geographically narrow, inconsistent in scope, and impossible to compare across studies.

Despite some previous studies discussed the potential of low-carbon transitions for cities, but most of them focused on one or two individual cities, such as Sharp et al. (2011), Romero Lankao (2007). L. X. Zhang et al. (2011), and Gielen et al. (2001). However, under the view of national industrialisation and globalization, the city-level low-carbon roadmaps should be discussed based on hundreds of cities at different industrial stages and development pathways.

In this chapter, the study firstly constructs the comprehensive and self-consistent inventories for 182 Chinese cities in section 6.1. The study then clusters the cities into five groups at different industrialisation stage and development pathways in section 6.2. The potential for emissions reductions among the five city groups are quantified under a range of technological scenarios in section 6.3. The results reveal the extent to which different policies may reduce emissions while substantially maintaining the current industrial structure and energy mix of cities and thereby minimize economic impacts.

6.1. Emission accounts of the 182 case cities

6.1.1. Selection of the 182 case cities

After a comprehensive audit of China's 334 prefecture-level administrative cities, this study finds that 182 of them have energy data of different details in 2010. Followed the series method developed for city-level CO_2 emissions accounts (described in section 3.5), this study constructs the administrative territorial-based emission inventories for these cities.

Figure 6-1 Cities' spatial distributions and their correspondent provinces

Note: The numbers in the brackets represent the cities, which are the same as city number in Appendix Table 10

The 182 cities cover 62% of the total population as well as 77% of national GDP in 2010. Most of the 182 cities are located in the eastern half of the country, shown in Figure 6-1. Yet population and socio-economic development vary tremendously among these cities: from 0.2 million people living in Jiayuguan (northwest China) to 28.7 in Chongqing (southwest) and from per capita GDP of just ¥9,068 in Fuyang (central) to ¥175,125 in Ordos (north). The socioeconomic data of the 182 cities are shown in Appendix Table 10.

6.1.2. CO_2 emissions of the 182 case cities

Total CO_2 emissions for 182 Chinese cities in 2010 are 7,610 Mt. Figure 6-2 shows the total CO_2 emissions and per capita emissions of the 182 cities. Note that "cities" in China are sub-provincial entities, but are not entirely urban environments. The detailed emissions and related data of the 182 cities are shown in Appendix Table 10.

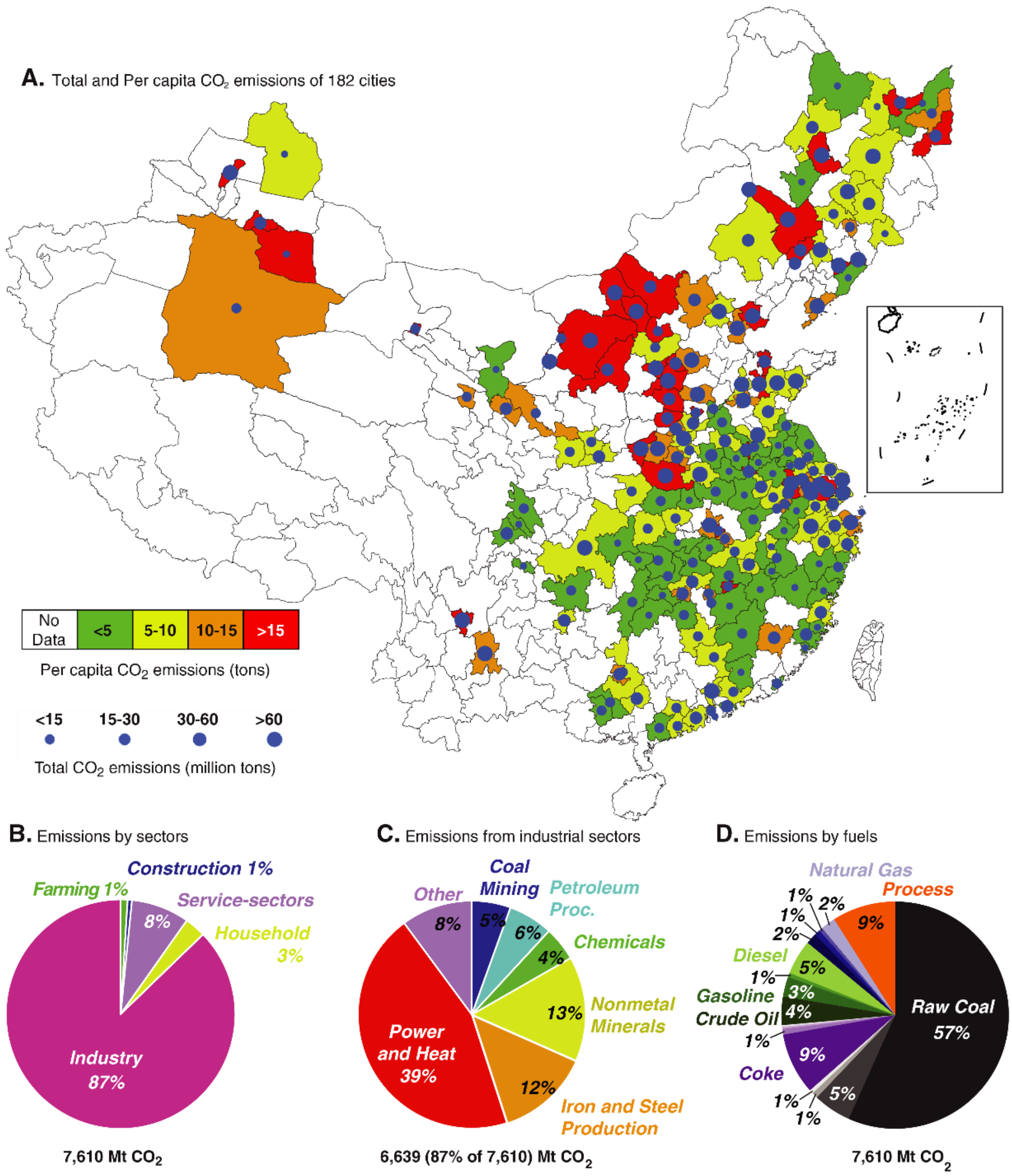

Figure 6-2 Total and per capita CO_2 emissions of 182 cities, 2010

The blue circles show the total CO_2 emissions of cities. The top-emitting cities represent a disproportionately large fraction of the total emissions from the 182 cities. The top five emitting cities (Tangshan, Shanghai, Suzhou (js), Nanyang, and Chongqing) accounted for 11% of the total emissions in 2010. More high-emitting cities can be found in northern and eastern China compared with other regions. Colours in Figure 6-2A indicate CO_2 and our estimates of CO_2 emissions per capita, ranging from <5 tonnes of CO_2 per person (green) to >15 tonnes per person (red; see also Figure 6-2), with a minimum of 1 ton in Fuzhou (Jiangxi province, southeast), a maximum of 104 tonnes in Karamay (far northwest), and an average of 8.9 tonnes. Higher levels of per capita emissions prevail in the north and east similar to the total emissions (Figure 6-2A).

Compared with western countries, this study finds that Chinese cities have relatively lower per capita CO_2 emissions. For example, the average per capita CO_2 emissions of Australia, USA, Canada, and The Netherlands are 25.8, 23.6, 22.7, and 12.7 tonnes respectively in 2007 (Hoornweg et al., 2011), much higher than China's average level (8.9 tonnes). Per capita CO_2 emissions of mega cities from developed countries are also much higher than those in China. Rotterdam, Denver, Sydney have per capita CO_2 emissions of 29.8 (2005), 21.5 (2005), 20.3 tonnes (2006) respectively (Hoornweg et al., 2011), while Beijing, Shanghai, Tianjin, Chongqing and Guangzhou, known as the most developed megacities in China, have per capita CO_2 emissions of 5.5, 8.3, 10.5, 5.1 and 9.7 tonnes in 2010, respectively. The high per capita CO_2 emissions are usually driven by massive economic activities (Panayotou, 2016; S. Wang, Li, et al., 2016). Therefore, the per capita GDP of the western cities are higher than Chinese cities as well. The highest per capita GDP of the 182 case cities are 175[8] (Ordos) and 121[9] thousand yuan (Karamay), while the per capita GDP of San Francisco, Washington DC, Boston, and New York are as high as 86.5, 85.5, 80.5, and 73.3 thousand US dollars in 2008, respectively (PWC, 2009).

The pie charts in Figure 6-2B-D show the emissions of all 182 cities from sectors and fossil fuels/processes. Industrial sectors (Figure 6-2C) make up the largest share of emissions (6,639 Mt CO_2, or 87% of the cities' total), especially power and heat production, iron and steel production, non-metal minerals (cement, glass, ceramics). Non-industrial sectors (Figure 6-2B) make up the remaining 12% (971 Mt CO_2), with two-thirds of emissions from farming and direct energy use in rural areas. Service sectors (including transportation, wholesale, et al, 8%), and residents (including both urban and rural regions, 3%) contribute one-tenth of total CO_2 emissions. Figure 6-2D shows that burning of coal is the source of 74% (especially raw coal (57%) and coke (9%)) of the cities' total emissions, with oil and natural gas combustion representing

[8] 25.7 thousand US dollars (1 US dollar roughly equals to 6.8 Chinese yuan in 2008)
[9] 17.8 thousand US dollars (1 US dollar roughly equals to 6.8 Chinese yuan in 2008)

just 15% and 2%, respectively, and the remaining 9% from industrial processes (cement production).

The detailed investigation of cities' emissions by sectors and fuels helps in understanding the large range in cities' carbon intensity (i.e. CO_2 per unit of GDP): Cities such as Beijing and Shenzhen, whose emission intensities are just 73 and 40 kg CO_2 per 1,000 yuan, respectively, have small manufacturing and energy sectors (20% and 44% of their GDP, respectively) and larger service sectors (75% and 53%, respectively). In contrast, cities such as Maanshan, Tangshan and Panzhihua have iron and steel production as their "pillar" industries (21%, 27%, and 31% of their GDP, respectively), with correspondingly high carbon intensities: 684, 434 and 1550 kg CO_2 per ¥1,000, respectively. Similarly, cities where energy production and mining of natural resources are dominant industries, such as Hegang, emissions intensities are especially high because the activities are emissions-intensive but produce low value-added energy products (such as cleaned coal, coke, and electricity). Hegang's carbon intensity is 1,719 kg per 1,000 yuan.

6.2. City industrialisation and low-carbon development

6.2.1. Cluster analysis

Recognizing the characteristic and industrial-development differences of Chinese cities (section 1.5.3 and Figure 1-3), this study uses cluster analysis (Edwards et al., 1965; Eisen et al., 1998; Ketchen Jr et al., 1996; Lorr, 1983) to classify the cities into five distinct groups based on their GDP and industrial output/industry structure.

Cluster analysis has been widely used in econometrics (Ketchen Jr et al., 1996; Lorr, 1983) and other interdisciplinary studies (Eisen et al., 1998) to classify a set of samples into distinct groups based on a set of measured variables (Edwards et al., 1965). The basic rationale of cluster analysis is grouping samples with similar attributes. The samples within the groups will be close together geometrically, while the statistical distance between groups will be farther. The statistical distance is measured by distance metrics, such as Euclidean distance, Manhattan distance, and Minkowski distance.

K-means algorithm is one of the cluster algorithms, in which the desired number of clusters could be specified in advance and then the 'best' solution will be chosen (Mathematics learning support centre, 2007). According to a previous study on the comparison of different distance metrics used in K-means algorithm, Euclidian distance metric's performance is better than others (Singh et al., 2013). Therefore, this study employs the K-means algorithm implemented using Euclidean distance metric to group cities. This study uses cities' sectoral industrial output as variables to cluster the cities. The cluster analysis is conducted in software SPSS.

The study first clusters the 182 case cities into 4 groups using each city's industry structure. The industry structures are calculated based on each cities' sectoral industrial outputs of four categories (energy production, heavy manufacturing, light manufacturing, and high-tech industry) in the following steps.

- This study firstly figures out each city's industrial output share (IO) of the four industry categories: "Energy production (IO_{EP})", "Heavy manufacturing (IO_{HM})", "Light manufacturing (IO_{LM})", and "High-tech industry (IO_{HT})". Taking Beijing as an example, $IO_{EP} - Beijing$ equals to the energy productions' industrial outputs divided by Beijing's total industrial outputs (28%). $IO_{HM} - Beijing$, $IO_{LM} - Beijing$, and $IO_{HT} - Beijing$ are 37%, 11%, and 24% respectively in 2010. This means 28% of Beijing's industrial outputs are contributed by energy productions, and 24% contributed by high-tech industries.
- Then the study sorts the cities according to their sectors' industrial output share from small to large and gets the cities' rankings of each industry category. Taking Beijing as an example, $IO_{HT} - Beijing$ ranks 124 of the total 182 case cities, while $IO_{HM} - Beijing$ ranks 52, which implies Beijing has more high-tech rather than heavy manufacturing industries compared with other case cities.
- Finally, the study changes the rankings into percentiles (IO'). Beijing's high-tech industry share is ahead of 90.11% case cities ($IO'_{HT} - Beijing = \frac{124}{182} \times 100\% = 90.11\%$).

The cluster analysis results show that Group 1 includes 22 cities with more energy production enterprises; group 2 includes 41 cities with higher rankings in heavy manufacturing; group 3 includes 65 cities relied more on light manufacturing. The remaining 54 cities are grouped together in group 4 (high-tech).

As the cluster analysis is operated based on mathematical relationships, the results can be adjusted slightly based on some other information and the cities' actual situations. For example, Xianyang is previously classified in group 4, which indicates it has more high-tech industries. However, after examining the industry structure of Xianyang, this study finds that the city relies more on the energy productions. The ranking percentage of its energy production sectors is 88%, and the industrial output of its energy production sectors are as high as 50,398 million yuan. Therefore, this study moves Xianyang to the energy group. The similar changes are made to Taiyuan, Hohhot, Fuxin and Hebi as well.

Following the cities' industrialisation process, the most developed high-tech cities will further develop to service-based cities. These service cities may go through every stage of the industrialisation process in the past decades, they have now successfully transited their "pillar" industry to service sectors with low emission intensity. They present sophisticated and practical roadmaps of economic structure optimization and low-carbon development. Therefore, this study extracts these service-based cities from the previous high-tech group to make up a new group. In this study, the service-based cities are defined as high-tech cities with service sectors' share in GDP over 50.63%. The 50.63% boundary is calculated as the high-tech cities' average service sectors' share in GDP (Ramaswami, Jiang, et al., 2017). There are 8 cities in the service-based city group: Beijing, Shanghai, Nanjing, Jinan, Wuhan, Guangzhou, Shenzhen, and Xi'an.

In this way, the 182 case cities are finally clustered into 5 city groups with different pillar industries describing their industrialisation stages and development pathways. This study names the city groups after their pillar industries: 25 energy cities, 51 heavy manufacturing cities, 67 light manufacturing cities, 24 high-tech cities, and 8 service-based cities, see Figure 6-3 and Appendix Table 10.

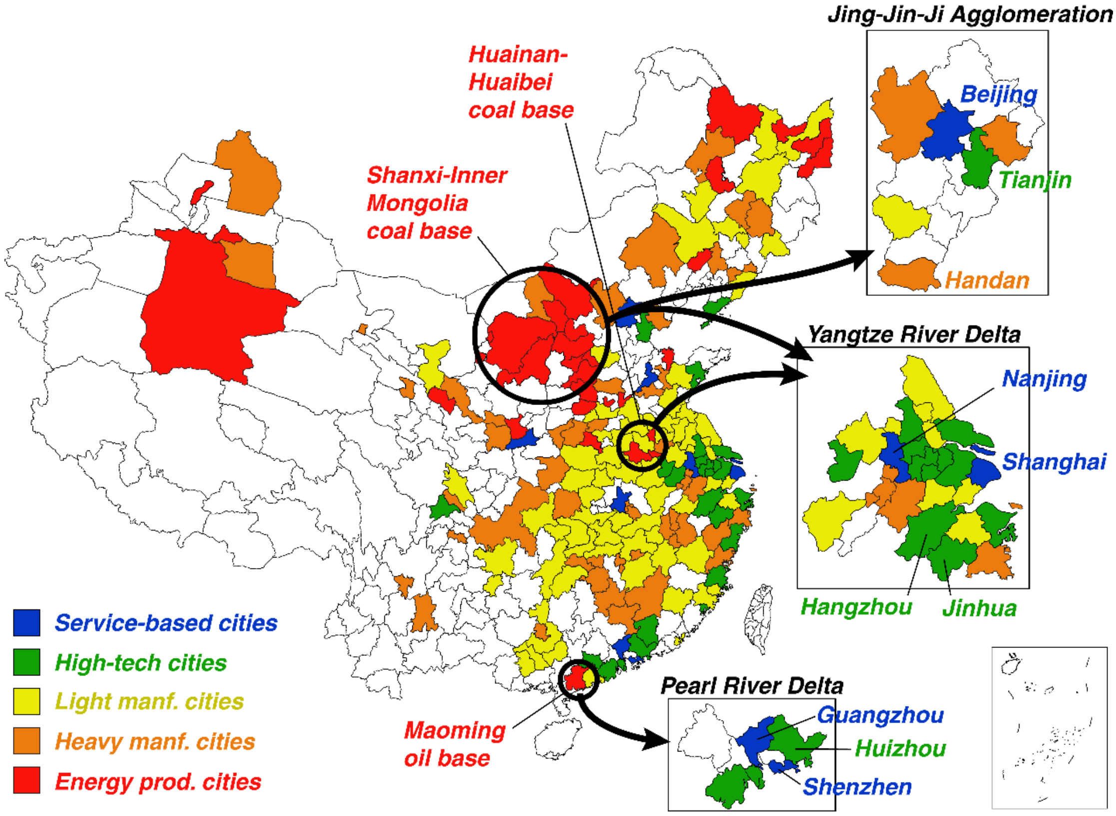

Figure 6-3 City clusters

6.2.2. Discrepancies among city clusters

Figure 6-4.A shows the emission intensity's mean values and standard deviations of the five city groups. The bars in Figure 6-4.A present the mean value of the variables, the lines above the bars show the +1 standard deviation of the variables.

The average emissions intensity of energy production cities is 0.47 ton CO_2 per ¥1,000, 0.31 ton CO_2 per ¥1,000 in heavy manufacturing cities, 0.23 ton CO_2 per ¥1,000 in light manufacturing cities, 0.15 ton CO_2 per ¥1,000 in high-tech cities, and 0.11 ton CO_2 per ¥1,000 in service-based cities. This study finds that among the five city groups, the energy production cities have the highest average emission intensity, while the service-based cities have the lowest value. The standard deviations of the energy production and heavy manufacturing cities' emission intensity are the largest among the five city groups (0.34 and 0.30 ton CO_2 per ¥1,000, respectively). The standard deviations of high-tech and service-based cities' emission intensities are relatively small, which are 0.08 and 0.07 ton CO_2 per ¥1,000, respectively.

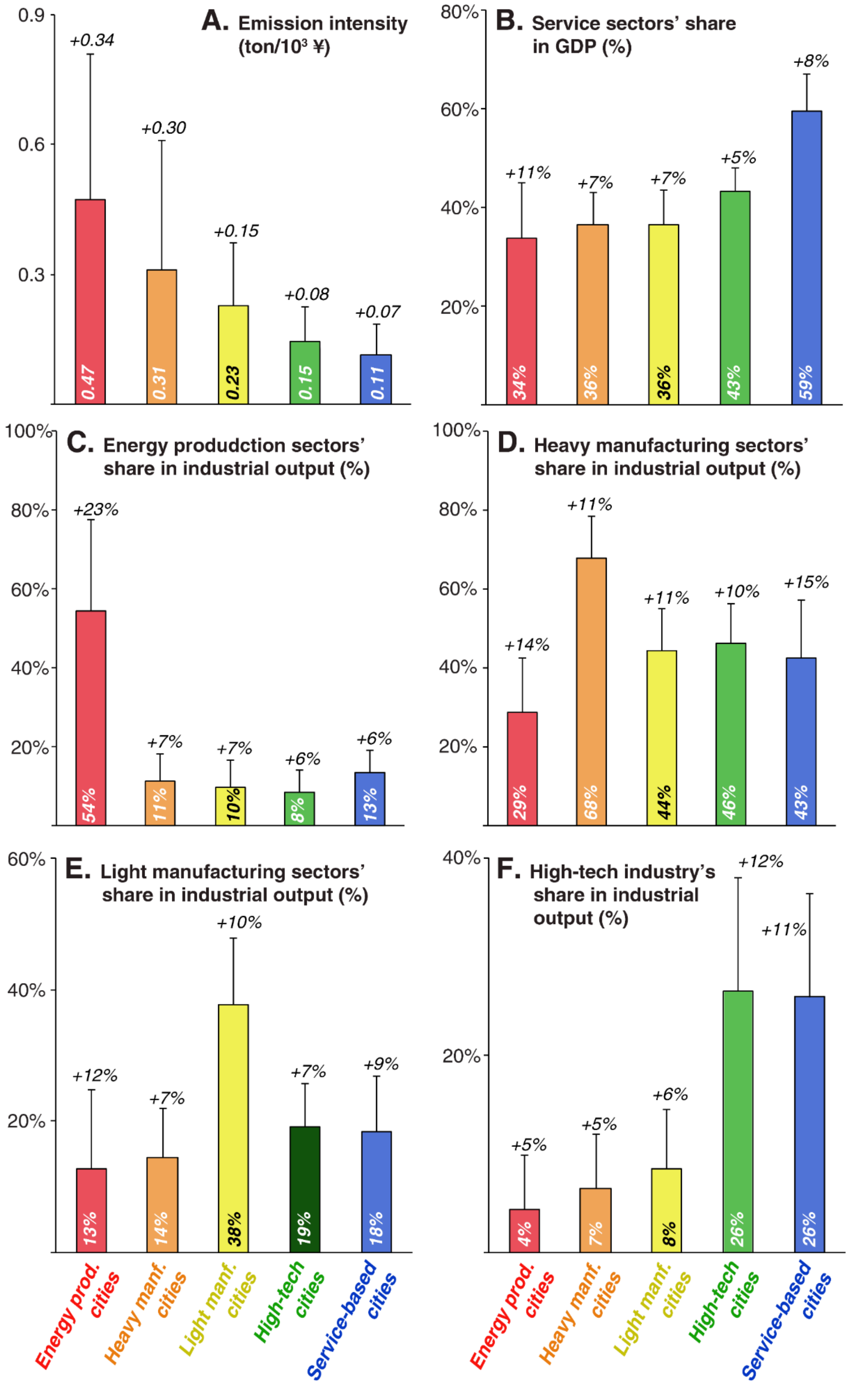

Figure 6-4 Mean and standard deviation of emission intensity and economic structure of each city group

Such a difference in city groups' energy intensity is determined by the cities' economic structures. The energy production and heavy manufacturing cities have more energy-insensitive sectors, which emit high CO_2 with low economic outputs. On the contrary, high-tech and service-based cities rely more on the high-tech industries and service sectors. This leads them to lower emission intensities. The economic structures of the five city groups are shown in Figure 6-4.B-F.

Figure 6-4.B-F and related z-test below of mean values define the pillar industry of each city group. A city group's pillar industry has the highest share in economic structure compared with other city groups. For example, the service sectors' average share in GDP of the service-based cities (59%) is significant higher than those of energy production (34%), heavy manufacturing (36%), light manufacturing (36%), and high-tech cities (43%). Similarly, the energy production sectors' average share in energy production cities (54%) is the highest among the five city groups.

6.2.3. Z-test of the discrepancies

In order to validate discrepancies among the city groups, this study applies the z-test to compare each city group's average emission intensity and economic structures, shown in Figure 6-5 and Table 6-1.

Figure 6-5.A shows that the emission intensity of energy production cities is significantly higher than that of the light manufacturing, high-tech, and service-based cities at the 0.05 level. While the heavy manufacturing cities have a higher average emission intensity compared with high-tech and service-based cities. The average emission intensities of light manufacturing, high-tech, and service-based cities have no significant difference. This is determined by the cities' pillar industry and economic structures. Energy production and heavy manufacturing cities have more energy-intensive enterprises. On the contrary, the high-tech and service-based cities rely more on high-tech industries and service sectors.

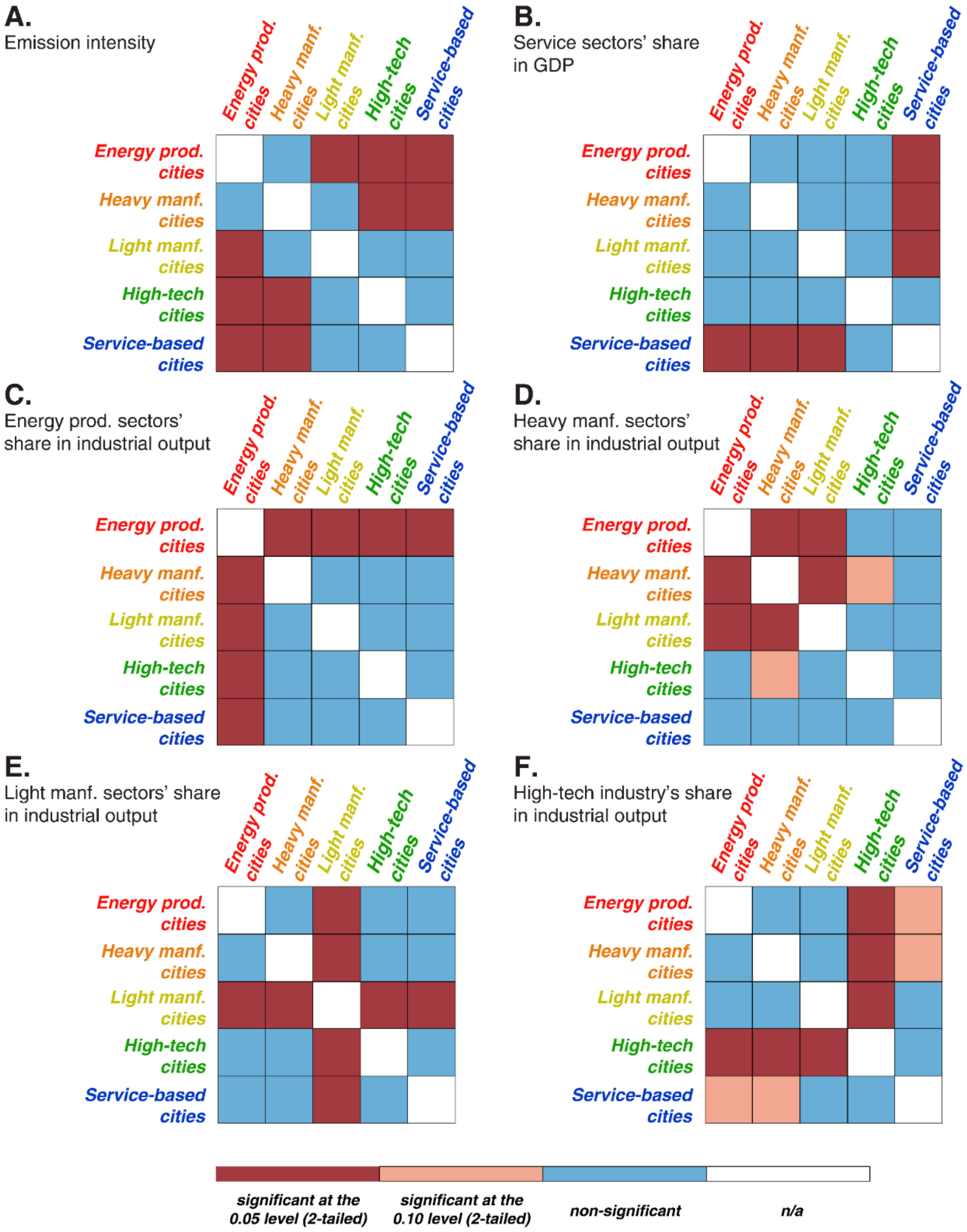

Figure 6-5 Mean test (z-test) results of the five city group

In Figure 6-5.B, the service sectors' average share in GDP of the service-based cities is significantly higher than those of the energy production, heavy manufacturing, and light manufacturing cities. The service sectors' average share in GDP of other city groups have no significant difference. Similar results can be found in the z-test of energy production sectors (Figure 6-5.C), light manufacturing sectors (Figure 6-5.E), and high-tech industries (Figure 6-5.F). As for the z-test of the heavy manufacturing sectors, we find that the sectors' average share in economic structure is significantly different with those of energy production, light manufacturing, and high-tech cities (at 0.10 level). What's more, the sectors' average share is also significantly different between the energy production and light manufacturing cities.

Table 6-1 Mean test (z-test) results of the five city groups

Index	City groups	z	P(Z<=z) one-tail	P(Z<=z) two-tail
CO_2 emission intensity	Service & High-tech cities	-0.221	0.413	0.825
	Service & Light manf. cites	-0.951	0.171	0.341
	Service & Heavy manuf. cities	-2.033	0.021*	0.042*
	Service & Energy prod. cities	-3.137	0.001*	0.002*
	High-tech & Light manf. cities	-1.013	0.156	0.311
	High-tech & Heavy manuf. cities	-2.31	0.010*	0.021*
	High-tech & Energy prod. cities	-3.495	0.000*	0.000*
	Light & Heavy manuf. cities	-1.631	0.051**	0.103
	Light manuf. & Energy prod. cities	-2.982	0.001*	0.003*
	Heavy manuf. & Energy prod. cities	-1.481	0.069**	0.139
Service sectors' share in GDP	Service & High-tech cities	1.435	0.076**	0.151
	Service & Light manf. cites	2.063	0.020*	0.039*
	Service & Heavy manuf. cities	2.177	0.015*	0.029*
	Service & Energy prod. cities	2.107	0.018*	0.035*
	High-tech & Light manf. cities	1.049	0.147	0.294
	High-tech & Heavy manuf. cities	1.258	0.104	0.208
	High-tech & Energy prod. cities	1.165	0.122	0.244
	Light & Heavy manuf. cities	0.299	0.382	0.765
	Light manuf. & Energy prod. cities	0.425	0.335	0.671
	Heavy manuf. & Energy prod. cities	0.205	0.419	0.838
Energy prod. sectors' share in industrial output	Service & High-tech cities	0.585	0.279	0.558
	Service & Light manf. cites	0.304	0.381	0.761
	Service & Heavy manuf. cities	0.287	0.387	0.774
	Service & Energy prod. cities	-3.529	0.000*	0.000*
	High-tech & Light manf. cities	-0.505	0.307	0.614
	High-tech & Heavy manuf. cities	-0.499	0.309	0.618
	High-tech & Energy prod. cities	-4.846	0.000*	0.000*
	Light & Heavy manuf. cities	-0.021	0.492	0.983
	Light manuf. & Energy prod. cities	-4.921	0.000*	0.000*
	Heavy manuf. & Energy prod. cities	-4.816	0.000*	0.000*
Heavy manuf. sectors' share in industrial output	Service & High-tech cities	0.139	0.445	0.889
	Service & Light manf. cites	0.397	0.346	0.691
	Service & Heavy manuf. cities	-1.593	0.056**	0.111
	Service & Energy prod. cities	1.410	0.079**	0.158
	High-tech & Light manf. cities	0.160	0.437	0.873
	High-tech & Heavy manuf. cities	-1.877	0.030*	0.061**
	High-tech & Energy prod. cities	1.631	0.051**	0.103
	Light & Heavy manuf. cities	-4.678	0.000*	0.000*
	Light manuf. & Energy prod. cities	2.034	0.021*	0.042*
	Heavy manuf. & Energy prod. cities	5.516	0.000*	0.000*
Light manuf. sectors' share in industrial output	Service & High-tech cities	-0.283	0.388	0.777
	Service & Light manf. cites	-2.068	0.019*	0.039*
	Service & Heavy manuf. cities	0.312	0.378	0.755
	Service & Energy prod. cities	0.196	0.422	0.845
	High-tech & Light manf. cities	-2.992	0.001*	0.003*
	High-tech & Heavy manuf. cities	1.037	0.150	0.300

	High-tech & Energy prod. cities	0.700	0.242	0.484
	Light & Heavy manuf. cities	4.825	0.000*	0.000*
	Light manuf. & Energy prod. cities	3.473	0.000*	0.001*
	Heavy manuf. & Energy prod. cities	-0.150	0.440	0.881
High-tech industry's share in industrial output	Service & High-tech cities	1.463	0.072**	0.144
	Service & Light manf. cites	1.681	0.046*	0.090**
	Service & Heavy manuf. cities	1.801	0.036*	0.072**
	Service & Energy prod. cities	2.481	0.007*	0.013*
	High-tech & Light manf. cities	2.481	0.007*	0.013*
	High-tech & Heavy manuf. cities	2.830	0.002*	0.005*
	High-tech & Energy prod. cities	0.505	0.307	0.613
	Light & Heavy manuf. cities	0.784	0.216	0.433
	Light manuf. & Energy prod. cities	0.341	0.366	0.733
	Heavy manuf. & Energy prod. cities	1.463	0.072**	0.144

Note: The Z Critical one-tail value is 1.645, while the Z Critical two-tail value is 1.960
* significant at the 0.05 level
** significant at the 0.10 level

Above all, the z-test for the mean value between city groups verifies the classification of cities. The pillar industry of one city group is significantly higher than the others.

6.2.4. The industrialisation stages of city clusters and their dependent relationship

As shown in Figure 6-3, colours on the map indicate the categorization of each of 182 cities into energy production cities (red), heavy manufacturing cities (orange), light manufacturing cities (yellow), high-tech cities (green), and service-based cities (blue). Black circles and areas indicate the location of coal and oil bases and common city cluster destinations for their energy exports. Most service-based and high-tech cities (blue and green in Figure 6-3, respectively) are located in east and south China, 21 of the 32 gathered into three city clusters (see map insets of Beijing-Tianjin-Hebei (the capital circle Jing-Jin-Ji), the Yangtze River Delta, and the Pearl River Delta). In contrast, the 32 energy production cities (red in Figure 6-3) are congregated in the west and north China due to the location of fossil resources (main coal) in those regions. The heavy and light industry cities (orange and yellow in Figure 6-3, respectively) are more widely dispersed, but with a large concentration in central China.

Compared with the other four groups, energy cities emit more CO_2 but make only a small contribution to their GDP. The average emission intensity of the energy city group is 0.47 ton/thousand yuan. Energy production industries consume large amounts of fossil fuels but produce low value-added energy products (such as cleaned coal, coke, and electricity). On the other hand, heavy and light manufacturing cities have lower average emission intensities of 0.31 and 0.23, respectively. As there are relatively few large energy consuming enterprises in the high-tech and service-based cities, their average emission intensities are the lowest among the five city groups (0.15 and 0.11 ton/thousand yuan respectively).

Yet none of the different types of cities is independent of the others, and there is evidence of a division of labour among the city groups. For example, although none of the three major city clusters highlighted in Figure 6-3 contains cities where energy production is the pillar industry, each cluster is supported by energy imported from nearby energy-production centres: the Pearl River Delta cities are supported by Maoming oil base, the Jing-Jin-Ji region obtains power from the Shanxi-Inner Mongolia coal base, and the Yangtze River Delta cities are supported by both the Huainan-Huaibei and Shanxi-Inner Mongolia coal bases (black circles and arrows in Figure 6-3). Production and consumption activities of the major city clusters are similarly supported by emissions-intensive activities of outer lying heavy and light industry cities (K. Feng et al., 2013; Mi et al., 2016). Such energy and emission-intensive products' supports between cities can be demonstrated through coal moving.

Figure 6-6 shows the coal moving between China's 10 primary production base and 10 consumption regions. Based on the "proximity principle" in energy usage, coal is usually consumed in cities near the source area, rather than delivered to distant cities in order to reduce the overall transportation cost. For example, 89% (or 99 Mt) of the coal produced in Huainan-Huaibei coal base, which is located in Anhui, are used in Yangtze River Delta. 85% (or 739 Mt) of the coal used in Jing-Jin-Ji region and north China are produced in the nearby Shanxi-Inner Mongolia coal base.

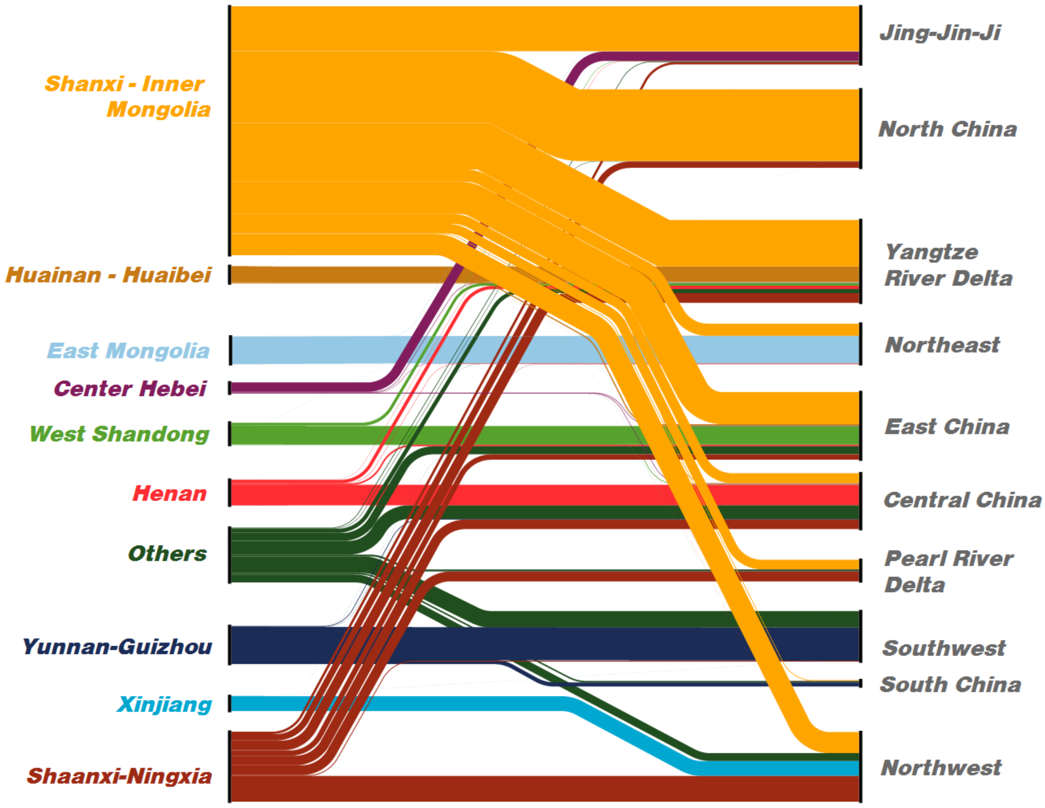

Figure 6-6 Raw coal moving between regions in 2010

Note: the Yangtze river delta includes Anhui province and the Pearl River delta refers to Guangdong province in this figure. Data source: China coal industry yearbook 2011 (Pan et al., 2013; State Administration of Coal Mine Safety, 2011)

In other words, there is a division of labour among the cities, in that the heavy-intensity industry cities emit CO_2 for production and consumption activities of nearby megacities. This is determined by regional natural resource endowment but also a policy outcome. For example, megacities, such as Beijing are outsourcing their pollution to lower-income cities nearby under the current $PM_{2.5}$ policies (MEP, 2013), which includes moving out heavy polluting industries, especially energy production and steelmaking industries (China Daily, 2005). The megacities then import electricity and other products from the nearby manufacturing cities. Mi et al. (2016)'s previous research on 13 cities' consumption-based emissions shows that Beijing only produced 57% of its total consumption-based CO_2 emissions in 2007. Meanwhile, Shijiazhuang and Tangshan nearby are typical production-based cities, whose production-CO_2 emissions are 1.85 and 1.80 times of their consumption-based emissions, respectively.

6.3. Emission reductions based on realizing efficiency potentials

6.3.1. Efficiency gain is a practical and effective way to reduce the cities' CO_2 emissions in the short run

In the latest national scheme on addressing climate change, China's government put forward nine measures to control greenhouse gas emissions (NDRC, 2014). The first place is "industry structure optimisation", which encouraging the cities removing their energy-intensive industries out of the city boundary.

However, considering the difference in cities' economic structure and development pathways, this study notes that simply removing energy-insensitive industries may in the short-run bring serious economic harm to the energy production- and heavy-industry based cities, as well as impacting the more developed city clusters relying on them. For example, Yangquan and Shuozhou, two coal bases in Shanxi Province and support the Jing-Jin-Ji region, have coal mining and process as their pillar industry, accounting for 82% and 81% of their total industrial output, respectively. They produced 57.2 and 160.0 Mt' raw coal, totally accounting for 7% of the whole national production (3235 Mt) in 2010. Policies targeting industrial structure will contribute to cut their coal production, but at the same time impacting their economies, and subsequently impacting the whole Jing-Jin-Ji area, at least in the short run. That is, of course, no argument for not continuing with a decarbonisation of the economy but rather points towards finding low-carbon policies while providing income for current fossil fuel and heavy manufacturing based regions and securing cheap energy provision for high value-added cities, in the short run.

Although it would be costly and disruptive for energy and heavy industry-based cities to reorganize their industrial structure in the short term (e.g., by closing or relocating emissions-intensive industries), more affluent, service-based cities might be able to quickly outsource their more emissions-intensive industries without economic hardship. However, such outsourcing by highly-developed cities could increase overall emissions; by virtue of their level of development, such cities often have more advanced technologies in place, and outsourcing would thus tend to move carbon-intensive, heavy polluting industries to less developed regions with less efficient technologies. For example, Shougang Corporation, one of the largest steelmaking companies in China, has moved progressively from Beijing to Hebei province (mainly to Tangshan) since 2010 (China Daily, 2005). Beijing's CO_2 emissions decreased by 7.6 Mt during 2010 to 2015, but emissions in Hebei province increased by 87.1 Mt during the same period (CEADs; Shan, Liu, Liu, et al., 2016), and Shougang Corporation is one of the main causes of the increase. Whereas the emissions intensity of iron and steel production in Beijing was 1.4 tonnes per thousand yuan in 2007, the intensity of the same sector in Tangshan (Hebei) was 2.6 tonnes per thousand yuan in 2010 - 86% higher.

Although a few affluent cities have reduced the proportion of coal in their energy mix (e.g., Beijing has reduced its coal consumption by 61%, or 18.2 million tonnes 2007-2015 (MEP, 2013; NBS, 2016a)) through a combination of increased renewables and natural gas, China's large stocks of cheap coal and equally large fleet of young, coal-burning power plants (S. J. Davis et al., 2014) are daunting economic barriers to radical near-term shifts in the Chinese energy mix.

On the other hand, efficiency gains could be a practical and effective way to reduce CO_2 emissions. A previous study at the national level found that energy efficiency improvement in China reduced its emissions by 50-60% in the early 2000s (Peters et al., 2007). As industry sectors are the main contributor of CO_2 emissions, efficiency gains of industries would lead to a decline in CO_2 emissions intensity effectively in the short run while industry structure (i.e., development pathway) remain unchanged.

6.3.2. Emission-Lorenz curve of the manufacturing city-sectors

In order to disclose the distribution relationship of the CO_2 emissions and the city-sectors' per industrial output emissions, this study borrows the concept of the Lorenz curve to plot the Emission-Lorenz curve of Chinese manufacturing-based city-sectors. The Lorenz curve "*plots the percentage of total income earned by various portions of the population when the population is ordered by the size of their incomes (page 1037)*" (Gastwirth, 1971). As each city has 39 manufacturing sectors, there are 7098-manufacturing city-sectors totally. The terminology of "city-sector" refers to each sector of each city, for example, the sector "Coal Mining and Dressing" of Beijing is a city-sector, while the sector "Food Processing" of Shanghai is another.

Figure 6-7.A presents the Emission-Lorenz curve of the 7098-manufacturing city-sectors. The Y-axis of the figure shows the percentage of the city-sectors' cumulative

CO_2 emissions when the city-sectors are ordered by their per industrial output CO_2 emissions ascendingly. The curve is below the 1:1 line and shows that the top 2.5% of the 7098-manufacturing city-sectors in per industrial output emissions contribute 70% of total CO_2 emissions.

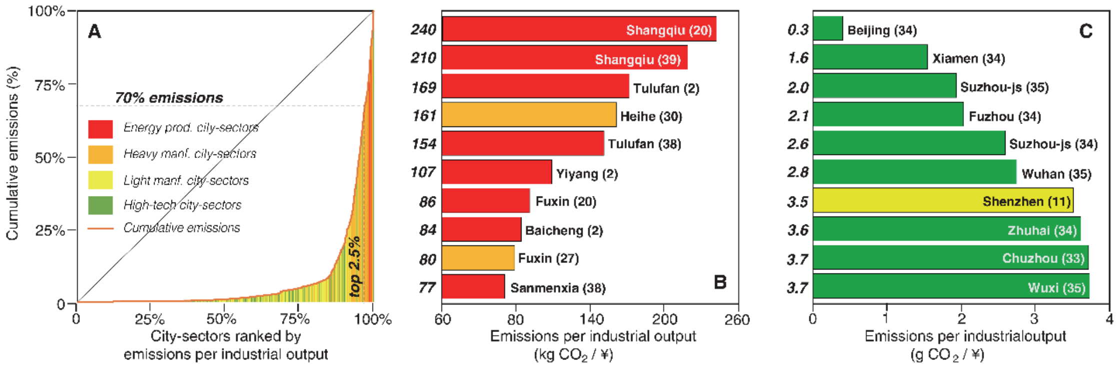

Figure 6-7 Emission-Lorenz curve of city sectors and top- emitters, 2010

Figure 6-7.B presents the top 10 manufacturing city-sectors in per industrial output emissions, which are the “super-emitting city-sectors. The numbers alongside the Y-axis in Figure 6-7.B are the per industrial output emissions of the city-sectors. The numbers in the bracket after the cities’ name present the sectors of the cities, which are consistent with sectors’ ID number (consistent with Table 3-2). The colours of the bars present the city-sectors’ categories (red: energy production, Orange: heavy manufacturing, Yellow: light manufacturing, Green: high-tech industry). For example, Shangqiu (20) in Figure 6-7.B refers to the “Petroleum Processing and Coking” sector of Shangqiu, belongs to energy production (red). The figure shows that all of the top 10 “super-emitting” city-sectors belong to the energy production or heavy-manufacturing sectors. While the bottom 10 “super-emitting” city-sectors shown in Figure 6-7.C belong to high-tech or light-manufacturing sectors. For example, Beijing (34) in figure C refers to the “Electronic and Telecommunications Equipment” sector of Beijing, belongs to high-tech industry (green). Similar rules are also shown in Figure 6-7.A, the Emission-Lorenz curve. The city-sectors with higher per industrial output emissions are redder (nearer to the 100% in X-axis) than the ones with lower values (nearer to the 0% in X-axis).

This implies that relatively small number of high per industrial output emission city-sectors contribute the major part of the cumulative CO_2 emissions. Policies targeting the relatively small number of “supper-emitting” city-sectors may substantially reduce the overall CO_2 emissions.

6.3.3. CO_2 emission reduction capacities via technical improvement

This study next examines the potential for emissions reductions targeting the relatively small number of "super-emitting" city-sectors through scenarios of specific technological improvement. This study identifies three levels of "super-emitters" of those city-sectors based on the city-sectors' per industrial output emissions (D. Tong et al., 2018):

- The level 1 super-emitters have the per industrial output emissions 2σ above the sector mean;
- The level 2 super-emitted have the per industrial output emissions 1σ above the sector mean;
- The level 3 super-emitters have per industrial output emissions greater than the sector mean.

The level 1 super-emitters represent the most carbon-intensive city-sectors. The small amount of "super-emitting" city-sectors represent a disproportionately large fraction of the total emissions. This study then defined three scenarios showing different levels of technical improvements.

- Scenario #1: level 1 "super-emitting" city-sectors reach the current national sector average emissions intensity;
- Scenario #2: level 2 super-emitters reach the current sector average;
- Scenario #3: level 3 super-emitters reach the current sector average.

The scenario # 3, which targets at the level 3 super-emitters, is the strongest scenario. The strongest technical improvement policies are taken to all the super-emitters with per industrial output emissions greater than the sector's average level. Meanwhile, the scenario #1 is the weakest among the three scenarios.

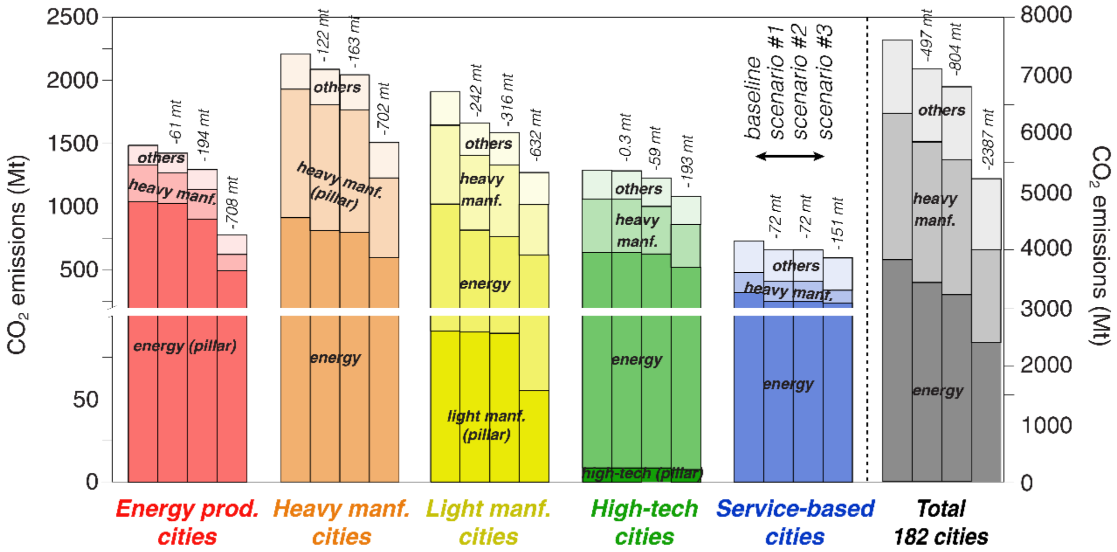

Figure 6-8 Emissions of city groups under three reduction scenarios, 2010

Figure 6-8 shows the CO_2 emission of the five city clusters under the 3 scenarios' technical improvements. The numbers overtop each of the scenario bars in the figure represent the potential reductions in CO_2 emissions under the scenarios compared with the baseline. The four sections of each bar (showing as colours with different saturations) show the CO_2 emissions of the pillar industry, energy production sectors, heavy manufacturing sectors, and other sectors.

As discussed above, the pillar industries contribute the most to the cities' economic growth. The cities should develop their pillar industries in the short run in order to gain economic welfare. Therefore, the pillar industries are the main targeting sectors for technical improvement to achieve emission reductions. Under scenario #3, when the strongest technical improvement policies are applied, reductions to cities' "pillar" industries alone could bring avoid emissions of 544 Mt CO_2 in energy production cities, 388 Mt CO_2 in heavy manufacturing cities, 36 Mt CO_2 in light manufacturing cities, and 1 Mt CO_2 in high-tech cities, or 52%, 38%, 40%, and 11%, respectively, of those cities pillar industry emissions. If scenario #2 is applied to the cities' "pillar" industries, the emission reductions to energy production, heavy manufacturing, light manufacturing, and high-tech cities are 140, 47, 1, and 0 Mt or 13%, 5%, 2% and 0%, respectively. Similarly, the scenario #1, the weakest technical improvement scenario may bring 15 Mt or 1%, 17 Mt or 2%, 1 Mt or 1%, and 0 Mt or 0% emission reduction to the energy production, heavy manufacturing, light manufacturing, and high-tech cities' pillar industries, respectively.

Apart from the pillar industry, energy production and heavy manufacturing sectors contribute the most to one city's total CO_2 emissions due to their energy-intensive feature and high emission intensities. Therefore, this study also estimates the emission reduction capacities when the 3 scenarios are applied to each city cluster's energy production and heavy manufacturing sectors. The results show that the strongest technical improvement scenario #3 will bring 313 Mt or 34%, 367 Mt or 39%, 117 Mt or 19%, and 85 Mt or 25% emission reduction to the heavy manufacturing, light manufacturing, high-tech, and service-based cities' energy production sectors, respectively. Meanwhile, the scenario #2 will bring 116 Mt or 13%, 258 Mt or 28%, 15 Mt or 3%, and 71 Mt or 21% emission reduction to the heavy manufacturing, light manufacturing, high-tech, and service-based cities' energy production sectors, respectively. The weakest technical improvement scenario #1 will bring 104 Mt or 11%, 205 Mt or 22%, 0 Mt or 0%, and 71 Mt or 21% emission reduction to the heavy manufacturing, light manufacturing, high-tech, and service-based cities' energy production sectors, respectively.

The scenario analysis of the city clusters' heavy manufacturing sectors shows that the strongest technical improvement scenario #3 will bring 165 Mt or 57%, 229 Mt or 36%, 75 Mt or 19%, and 66 Mt or 35% emission reduction to the energy production, light manufacturing, high-tech, and service-based cities' heavy manufacturing sectors, respectively. Meanwhile, the scenario #2 will bring 54 Mt or 19%, 56 Mt or 9%, 43 Mt or 11%, and 1 Mt or 0% emission reduction to the energy production, light manufacturing, high-tech, and service-based cities' heavy manufacturing sectors, respectively. The weakest technical improvement scenario #1 will bring 46 Mt or 16%, 37 Mt or 6%, 0 Mt or 0%, and 0 Mt or 0% emission reduction to the energy production, light manufacturing, high-tech, and service-based cities' heavy manufacturing sectors, respectively.

Compared with the five city clusters, this study finds that the energy production cities have the largest overall emission reduction capacities. Taking the scenario #3 as an example, the total scenario #3 emission reduction capacities of the energy production cities are 708 Mt or 48%, while the emission reduction capacities of heavy manufacturing, light manufacturing, high-tech, and service-based cities are 702 Mt or 32%, 632 Mt or 33%, 193 Mt or 16%, and 151 Mt or 19%, respectively.

Above all, if scenario #3 technical improvement is applied to all the cities' "pillar", energy production, and heavy manufacturing industries, the overall emission reductions are 2,387 Mt CO_2 or 31% of the cities' current emissions. Detailed emissions under three scenarios are shown in Table 6-2.

Table 6-2 Emissions of city groups under three reduction scenarios, 2010

City groups	Scenario	Energy prod.	Heavy manufacturing	Light manufacturing	High-tech	Farming, construction, services, and household	Total
Energy production cities	Baseline	1037.26	291.28	28.16	4.71	123.97	1485.37
	Scenario #1	1022.23	245.35	28.16	4.71	123.97	1424.42
	Scenario #2	897.47	236.99	28.16	4.71	123.97	1291.30
	Scenario #3	493.63	126.42	28.16	4.71	123.97	776.89
Heavy manufacturing cities	Baseline	912.60	1017.10	48.24	4.76	225.90	2208.61
	Scenario #1	808.38	999.65	48.24	4.76	225.90	2086.94
	Scenario #2	796.62	970.20	48.24	4.76	225.90	2045.73
	Scenario #3	599.36	628.84	48.24	4.76	225.90	1507.11
Light manufacturing cities	Baseline	928.88	629.15	90.87	7.22	246.99	1903.10
	Scenario #1	723.50	592.64	90.34	7.22	246.99	1660.68
	Scenario #2	670.52	572.87	89.37	7.22	246.99	1586.97
	Scenario #3	562.16	399.96	54.86	7.22	246.99	1271.18
High-tech industry cities	Baseline	607.05	393.85	53.46	8.28	157.55	1220.18
	Scenario #1	607.00	393.57	53.46	8.27	157.55	1219.84
	Scenario #2	591.56	350.45	53.46	8.27	157.55	1161.29
	Scenario #3	489.64	318.66	53.46	7.39	157.55	1026.68
Service-based cities	Baseline	341.79	190.15	23.02	20.94	216.45	792.36
	Scenario #1	270.51	189.75	23.02	20.94	216.45	720.68
	Scenario #2	270.51	189.55	23.02	20.94	216.45	720.48
	Scenario #3	256.67	123.91	23.02	20.94	216.45	640.99
Total (all 182 cities)	Baseline	3827.57	2521.53	243.75	45.90	970.86	7609.62
	Scenario #1	3431.63	2420.95	243.22	45.90	970.86	7112.56
	Scenario #2	3226.69	2320.05	242.26	45.90	970.86	6805.76
	Scenario #3	2401.45	1597.79	207.74	45.01	970.86	5222.86

Unit: Mt

6.4. Summary

Being the basic units for human activities (Guan et al., 2017), and the main consumers of energy and emitters of CO_2 (80%+) throughout the world (Satterthwaite, 2008; Yufei Wang et al., 2015), cities are the core to global climate change mitigation. In China, 85% emissions are contributed by cities, which is higher than that of the United States (80%) and Europe (69%) (Dhakal, 2009;2010). For these reasons, Chinese cities play an increasingly important role in efforts to reduce CO_2 emissions (Huang et al., 2013). The newly launched nation-wide Emission Trading Shame will monitor and control China's emissions at city/firm level. Detailed analyses of Chinese cities' features are urgently needed by the country. However, there is still no self-consistent and transparent emission database designed for extensive Chinese cities. Previous studies focused on several mega cities or city clusters only (Q. Chen et al., 2017). This chapter investigates the emissions from 182 generic cities in China, complies the self-consistent emission inventories for them. The scope and calculation methods are consistent with the emission inventories constructed for the nation and provinces. Detailed methods and data sources are summarised in Chapter 3.

Section 6.1 finds that the total CO_2 emissions for 182 Chinese cities in 2010 are 7,610 Mt. The top-emitting cities represent a disproportionately large fraction of the total emissions from the 182 cities. The top five emitting cities (Tangshan, Shanghai, Suzhou (js), Nanyang, and Chongqing) accounted for 11% of the total emissions in 2010. More high-emitting cities can be found in northern and eastern China compared with other regions. By comparing with western countries, this study finds that Chinese cities have relatively lower per capita CO_2 emissions averagely.

Then section 6.2 applied the cluster analysis to group the 182 cities into 5 groups with different pillar industries describing their different industrialisation stages and development pathways. The results shows that, compared with the other four groups, energy cities emit more CO_2 but make only a small contribution to their GDP. On the other hand, heavy and light manufacturing cities have lower average emission intensities of 0.31 and 0.23, respectively. This study also finds the dependecne relationships among Chinese cities. The most developed cities in China are supported by nearbly manfacturing cities. In turn, the manufacturing cities are heavily replied on the energy centres nearby. In other words, there is a division of labour among the cities, in that the heavy-intensity industry cities emit CO_2 for production and consumption activities of nearby megacities. This is determined by regional natural resource availability but also a policy outcome.

Based on the sectoral analysis of the case cities, section 6.3 finds that updating and improving technologies might reduce emissions while leaving unchanged the industrial structure of individual cities - and thus their respective roles in the existing Chinese economy. This study explores the city-level emissions reductions under three scenarios of technological progress to show that substantial reductions are possible by updating a disproportionately small fraction of existing infrastructure. If scenario #3 technical improvement (the strictest scenario) is applied to the super-emitting city sectors, the overall reductions are 2,387 Mt CO_2 or 31% of the 182 cities' emissions in 2010.

Although the levelling off China's CO_2 emissions in recent years is a tremendous watershed in the global effort to avoid dangerous climate change, the progress reflects sweeping policies to improve the country's industrial technologies and energy systems. However, further progress will increasingly depend upon policies that differentiate among cities according to their economic structure, level of development, and infrastructure, and are carefully crafted to target the largest and most cost-effective emissions reductions.

Chapter 7 Emissions from Tibet and its cities

This Chapter examines the CO_2 emissions from Tibet and its cities. Due to data lacking, the emission from Tibet is still vacant. Unlike the nation and provinces with consistent and systematic energy statistics, Tibet is not included in China's energy statistical system. China's National Bureau of Statistics releases national and provincial energy data in its annual "China Energy Statistical Yearbook". The yearbook is the only official energy report in China (NBS, 2016a). There is no Tibet's energy data in the yearbook. Previous studies on China's national/provincial inventory excludes Tibet (Z. Liu, Guan, et al., 2015; Shan, Liu, Liu, et al., 2016; S. Wu et al., 2017), as well as analysis on China's energy consumption and greenhouse gas emissions (J.-L. Fan et al., 2016; J.-L. Fan et al., 2015; Miao Wang & Feng, 2017; S. Wang, Fang, et al., 2016). This chapter fills in this research gap by examining the CO_2 emissions from Tibet and its cities in 2014. The emission-socioeconomic indexes such as per capita emissions and emission intensities of Tibet and its cities are also discussed in this chapter.

The Tibet Autonomous Region is one of China's 34 provincial-level divisions. It is located in the most south-westerly part of China and is China's second largest province. Tibet is a vast territory with a sparse population. Its administrative area is 1.2 million km^2 and accounts for one-eighth of the country's geographic expanse; however, its 2014 population constitutes only 0.23% of China's population (3.18 million). Tibet is a typical agriculture-based autonomous region, and its primary industry contributed over 45% to the economy in the early 1990s. After years of development, Tibet now has a tertiary industry as a foundational economic driver, and this tertiary industry contributed 53.5% to total GDP in 2014. Even so, the primary industry remains the largest sector in Tibet, and 43.7% of the working population work in the primary industry. The secondary industry, which includes manufacturing and construction, is the smallest segment of Tibet's national economy; it employs only 14.7% of Tibet's working population. The secondary industry's GDP in 2014 was 33.68 billion yuan, which is quite small compared with China's national GDP of 27,176.45 billion yuan (0.12%) (NBS, 2015c).

Due to its small scale of energy-intensive industries, Tibet consumes very little energy every year and its consumption of conventional fossil fuels is particularly low. Moreover, because it is covered primarily by forests, lakes, and other natural ecological reserves, Tibet has large carbon sink capacities. For example, Tibet's forests covered 14%+ of its total area in 2015, and its forest stock is 2.09 billion m^3, ranking at the top of Chinese provinces (The State Council Information Office of China, 2015). The forests' ecosystem will absorb 50.65 Mt of carbon every year (NEA, 2014). Tibet's carbon sink function is larger than its human-induced carbon emissions.

Despite its small amount of energy consumption and emissions, the study on Tibet's energy consumption and emission have great significant as well. Tibet is an important component of China, it is at a very early stage of industrialisation. The study on Tibet's energy consumption and emissions will help Tibet to realize low-carbon and sustainable development from its initial industrialisation stage. Tibet's low-carbon development have great referential significant to other developing countries at similar early industrialisation stage. Therefore, both Chinese central government and local government have taken actions on Tibet's emission reduction and climate change mitigation. In the "Tibet action on climate change and emission reduction during 2014-2015" issued by Tibet autonomous region government (2014), the energy consumption intensity (energy consumption per GDP) in 2015 are required to decrease by 2.09% compared with 2014, while the CO_2 emissions are required to keep stable with 2010. In the assessment of each province's emission intensity (CO_2 emissions per GDP) reduction by the NDRC (2015), Tibet had the worst performance among China's 31 provinces.

Given the targets of emission reduction in Tibet autonomous region, a quantitative measure of Tibet's regional CO_2 emissions is urgently needed. However, few studies have focused on Tibet's energy consumption. Only three English-language papers could be found covering Tibet's energy consumption on the Web of Science (G. Liu et al., 2008; Ping et al., 2011; Jin Zhang et al., 2015), and eleven Chinese documents (G. Cai et al., 2006a;2006b; Pei et al., 2007; Tang et al., 2015; Changgui Wang, 2006a;2006b; D. Wang, 1985; Yuqun Wang, Basang, et al., 2007; T. Yang et al., 2015; Yao, 2013; J. Zhao et al., 2016) were found on China's National Knowledge Infrastructure (CNKI) datasets. Most of these papers discussed Tibet's sustainable energy development and its carbon sink function, as well as emissions from biomass fuels (Q. Xiao et al., 2015). J. Zhao et al. (2016) is the only study that has discussed Tibet's human-induced CO_2 emissions so far. These authors estimate the fossil fuel consumption in Tibetan industries and calculate the related CO_2 emissions for the year

2014. Inconsistent with the national/provincial CO_2 emissions estimated above, this study calculates the territorial-based emission of Tibet and its cities. There are seven cities in the Tibet Autonomous Region: Lhasa City, Qamdo City, Xigaze City, Shannan Region, Nagqu Region, Ngari Region, and Nyingchi Region. The quantitative measure of Tibet's regional CO_2 emissions will provide solid data support for Tibet's actions on climate change and emission reductions.

7.1. Calculation scope and methods for Tibet and its cities

7.1.1. Calculation scope and methods

This study considers both the fossil fuel- and process- (cement) related CO_2 emissions for Tibet emission accounts. The emissions calculation methods for Tibet are the same with the methods used for the national/provincial emission estimating, see section 2.1.3. Unlike provinces with consistent energy statistics, the activity data (fossil fuel consumption and cement production) can be collected from the energy balance tables in China energy statistical yearbooks or China statistical yearbooks, only limited information about Tibet's fossil fuel consumption can be found online. Thus, this study estimates fossil fuel consumption for Tibet and its seven cities in a bottom-up approach, collects the consumption of specific energy types of Tibet from multiple sources, such as government reports, news reports, and literature.

7.1.2. Activity data collection

Cement production

Data regarding cement production in Tibet for 2014 was collected from the Tibet statistical yearbook 2015 (Tibet Bureau of Statistics, 2015). In 2014, Tibet produced a total of 3,422.48 thousand tonnes of cement. According to the "Tibet 12^{th} Five-year Plan for Building Materials Industry" (Tibet autonomous region government, 2011), there are only 7 cement manufacturing companies in Tibet; see Table 7-1. This study uses Tibet's 2014 cement production to scale each plant's production and total up by regions. Then, the cement productions for each city are shown in Table 7-2.

Table 7-1 Cement plants in Tibet and their production, 2010

Cement plants	Location	Production
Tibet Gao Zheng Building Materials Corporation	Lhasa	86.41
Tibet Gao Zheng (Group) Co., Ltd (Qamdo)	Qamdo	9.50
Tibet Gao Zheng (Group) Co., Ltd (Ngari)	Ngari	4.42
Tibet Gao Zheng (Group) Co., Ltd (Markam)	Qamdo	2.00
Lhasa Dongga Cement Plant	Lhasa	9.23
Huaxin Cement (Tibet) Co., Ltd	Shannan	69.41
Shannan Yalong Cement Co., Ltd	Shannan	5.00
Lhasa Yuanda Building Materials Co., Ltd	Lhasa	9.95
Xigaze Xuelian Cement Plant	Xigaze	11.00
Tibet Jinhada Cement Co., Ltd	Lhasa	9.00
Xigaze Gao Zheng Cement Plant	Xigaze	3.20

Unit: 10 thousand tonnes

Industrial coal consumption

As the abundant hydropower in Tibet, electricity from hydropower station plays the dominant part in Tibet industrial and residential energy consumption, which also suppress the fossil fuel usage in Tibet. Coal only takes a small proportion of Tibet's energy mix. There are no official reports on Tibet's coal consumption statistics. Approximately 85% of Tibet's coal consumption is associated with cement plants to provide power; the remaining 15% is used for restaurants and residences (J. Zhao et al., 2016). Therefore, this study uses Tibet's cement production to estimate coal consumption in Equation 7-1.

$$CC_{total} = \frac{CC_{cement}}{85\%} = \frac{CP_{clinker} \times uCC_{clinker}}{85\%} \qquad \textit{Equation 7-1}$$

where CC_{total} indicates total coal consumption in Tibet; CC_{cement} presents the coal consumption for cement production in Tibet; $CP_{clinker}$ means cement-clinker production in Tibet; $uCC_{clinker}$ is the coal consumption for the unit cement clinker output. As there is no cement-clinker production in Tibet's statistical yearbook, this study uses the national cement-clinker production ratio to estimate Tibet's cement production. According to "The 12th Five-year Plan for Building Materials Industry" (MIIT, 2011), the national new dry cement-clinker production in 2010 was 1260.00 Mt, taking 81% of overall cement clinker. Thus, total cement-clinker production in 2010 is estimated as 1555.56 (=1260/81%) Mt. At the same time, the national total cement production is 1880.00 Mt, which means that the average cement-clinker production ratio is approximately 82.74% (=1555.56Mt/1880.00Mt) in China. This study uses the national average ratio to estimate Tibet's cement-clinker production as 2831.85 (=3422.48×82.74%) thousand tonnes in 2014. According to the same report, average coal consumption of cement-clinker production is 160 kilograms per ton clinker production in China. This study adopts the national average value and calculate the entirety of Tibet's coal consumption as 533.05 (=2831.85×160/85%/1000) thousand tonnes of coal.

Residential coal consumption

Among the total coal consumption, 453.10 thousand tonnes are consumed in cement plants and the remaining 79.95 thousand tonnes are consumed for residential usage. This study allocates the residential consumption of coal to each city based on its population in 2014. The populations of each administrative division are collected from the 6th national population census (NBS, 2012), see Table 7-2.

Table 7-2 Cement production, coal consumption, and the population of each city in Tibet, 2014

Division	Cement production (10^3 tonnes)	Coal consumption for cement production	Populati on	Residential coal consumption (10^3 tonnes)	Coal consumption
Lhasa	1,789.80	236.95	559.42	14.90	251.85
Qamdo	179.62	23.78	657.51	17.51	41.29
Shannan	1,162.22	153.87	328.99	8.76	162.63
Xigaze	221.79	29.36	703.29	18.73	48.09
Nagqu	0.00	0.00	462.38	12.31	12.31
Ngari	69.04	9.14	95.47	2.54	11.68
Nyingchi	0.00	0.00	195.11	5.20	5.20
Total	3,422.48	453.10	3,002.17	79.95	533.05

Diesel consumption in thermal power plants

The total thermal power generation of Tibet was 149 million kWh in 2014 (NBS, 2016a). The State Grid Tibet Electricity Power Company Limited has two thermal power plants in Tibet: the Ngari thermal plant and the Dongga (Lhasa) thermal plant. The Ngari thermal plant has four 2,500 kW diesel generating sets (State Grid Tibet Electricity Power Company Limited, 2015), and the total installed capacity of the Ngari thermal plant is 10 thousand kW. The Dongga (Lhasa) thermal plant has six 11,500 kW diesel generating sets before 2010, China's Huaneng Group invested in another nine 11,500 kW sets in 2010, bringing the total installed capacity of the Dongga (Lhasa) thermal plant to 172.5 thousand kW. Therefore, this study assumes that the electricity generated by the Ngari thermal plant was 8.16 million kWh in 2014, whereas the electricity generated by the Dongga thermal plants in Lhasa was 140.84 million kWh.

The fuel consumption of the diesel generating set is approximately 190-250 g/kWh (Bao et al., 2014; Weifang Chengfeng Power Equipment CO. Ltd.; W. Xiao, 2001), which means that in producing 1 kWh electricity, the generating set will combust 190-250 grams of diesel oil. Considering the low combustion efficiency in the plateau, this study adopts a high threshold value of 250 g/kWh. In this manner, this study calculates that the Dongga (Lhasa) thermal plant burned 35.21 (=140.84mkWh×250g/kWh/1000) thousand tonnes of diesel oil in 2014, whereas the Ngari thermal plant burned 2.04 (=8.16mkWh×250g/kWh/1000) thousand tonnes.

Other refined oil consumption in transportation sector

Tibet consumed approximately 745 thousand tonnes of refined oil in 2012, which consists mainly of diesel oil in road transportation and thermal power plants (410 thousand tonnes), gasoline in road transportation (310 thousand tonnes), diesel oil in railway transportation (10 thousand tonnes), and kerosene in air transportation (15 thousand tonnes). Among the 745 thousand tonnes of consumption, 600 thousand tonnes were sold by China's National Petroleum Corporation (CNPC) (J. Zhao et al., 2016). In 2014, CNPC sold 786.30 thousand tonnes of petroleum products in Tibet (NDRC, 2016a). This study estimates total petroleum product consumption at 976.32 (=786.30/600×745) thousand tonnes in 2014, including diesel oil burned in thermal power plants, which were identified previously as the 37.25 thousand tonnes calculated above. The consumption levels of diesel oil for road transportation, diesel oil for railway transportation, gasoline for road transportation, and kerosene for air transportation are estimated as 500.06, 13.11, 406.26, and 19.66 thousand tonnes, respectively.

This study allocates diesel oil and gasoline consumption in road transportation to each city according to cities' tertiary industry GDP (including transport, storage and post as dominating contributors). The diesel oil consumed for railway transportation and kerosene for air transportation are calculated in Lhasa due to Lhasa's dominant volume of freight traffic and passengers in Tibet (see Table 7-3).

Table 7-3 GDP and oil consumption in Tibet and its cities, 2014

Division	Tertiary industry GDP	Diesel oil (road)	Diesel oil (thermal)	Diesel oil (railway)	Gasoline (road)	Kerosene (air)
Lhasa	206.76	212.00	35.21	13.11	172.23	19.66
Qamdo	48.73	49.96	-	-	40.59	-
Shannan	43.74	44.85	-	-	36.44	-
Xigaze	70.11	71.89	-	-	58.40	-

Nagqu	50.05	51.32	-	-	41.69	-
Ngari	17.57	18.02	2.04	-	14.64	-
Nyingchi	50.74	52.03	-	-	42.27	-
Total	487.70	500.06	37.25	13.11	406.26	19.66

Unit: GDP 10^8 yuan, energy consumption 10^3 tonnes

Residential gas usage (natural gas and LPG)

The "Gas Tibet" project was launched by Qinghai Oilfield, CNPC in 2010 to bring natural gas to Lhasa for the first time. Natural gas consumption increased 10 times in the last three years (Ren et al., 2014). The total natural gas supplied to Lhasa reached 160 thousand m^3 in 2014. In addition, Tibet also consumed a small amount of liquefied petroleum gas (LPG) in its urban area, approximately 62.48 thousand tonnes in 2014 (NBS, 2016a), which are all assumed to be consumed in Lhasa's urban households.

In summary, the levels of conventional energy consumption and cement production in Tibet and its cities in 2014 are shown in Table 7-4. The activity data are prepared for CO_2 emissions estimation in the following section.

Table 7-4 Energy consumption and cement production of Tibet and its cities, 2014

Division	Cement	Coal	Diesel	Gasoline	Kerosene	LPG	Natural gas
Lhasa	1,789.80	251.85	260.32	172.23	19.66	62.48	160.00
Qamdo	179.62	41.29	49.96	40.59	-	-	-
Shannan	1,162.22	162.63	44.85	36.44	-	-	-
Xigaze	221.79	48.09	71.89	58.40	-	-	-
Nagqu	-	12.31	51.32	41.69	-	-	-
Ngari	69.04	11.68	20.06	14.64	-	-	-
Nyingchi	-	5.20	52.03	42.27	-	-	-
Total	3,422.48	533.05	550.42	406.26	19.66	62.48	160.00

Unit: cement, coal, diesel, gasoline, kerosene, LPG 10^3 tonnes, natural gas 10^3 m^3

7.2. CO_2 emissions of Tibet

7.2.1. CO_2 Emissions in 2014

In 2014, Tibet emitted a total of 5.52 Mt of CO_2 related to fossil fuel combustion and cement production (see Table 7-5). These emissions were relatively small both in their absolute amounts and in terms of the proportion of national emissions (9,438.45 Mt), which stands at 0.06% of China’s total emissions (CEADs). The small emissions amount results from Tibet’s limited industry but also from its renewable-dominant energy structure. Tibet is rich in renewable energy, such as hydro energy, wind power, and solar energy (Tang et al., 2015). In fact, 3.24 billion kWh of the electricity generated in Tibet was from renewable energies in 2014, accounting for 89.94% of total electricity generation. Hydro energy contributed 80.64% of this amount (2.90 billion kWh). Only 10.06% (0.36 billion kWh) of electricity was generated in fire-powered plants. Tibet’s renewable energy proportion in the energy mix was much higher than the national average level of 11.30% in 2014.

Table 7-5 CO_2 emissions from Tibet in 2014

	Coal	Diesel	Gasolin e	Kerose ne	LPG	Natural gas	Cement process
Cement	829.17	-	-	-	-	-	994.57
Power plants	-	117.34	-	-	-	-	-
Road transport	-	1,575.19	1,210.65	-	-	-	-
Rail transport	-	41.30	-	-	-	-	-
Air transport	-	-	-	60.75	-	-	-
Resident	146.31	-	-	-	197.44	345.60	-
Tibet-total	975.48	1,733.82	1,210.65	60.75	197.44	346	994.57

Unit: Mt

Apart from non-fossil fuel energies, diesel and gasoline consumption are Tibet's main sources of energy-related emissions (see Figure 7-1-a). These two energy types contributed 31.42% (1.73 Mt) and 21.94% (1.21) to total CO_2 emissions, respectively, in 2014. In addition, coal is responsible for only 975.48 thousand tonnes of CO_2, accounting for 17.68% of total emissions primarily because of Tibet's simple energy structure. This is significantly different from China's overall emission structure and from the structures in other provinces: coal and its related products dominate energy consumption (65.60%) and CO_2 emissions (77.21%) and is burned mainly in coal-based fire-powered plants for power. In Tibet, as discussed above, coal is consumed exclusively in cement plants and for residential usage, the only two fire-powered plants are diesel-based power plants. This is a result of Tibet's limited coal sources and low coal production. Almost all the coal used in Tibet are imported from its nearby provinces. In 2014, 625.5 thousand tonnes of coal are imported to Tibet according to "China Coal Industry Yearbook 2014" (China Coal Information Institute, 2014). Considering the factor of stock changing and statistical error, our estimation of 533.05 thousand tones' coal consumption is relatively accurately.

The cement process is another large contributor to Tibet's CO_2 emissions, accounting for 18.02% (994.57 thousand tonnes) in 2014. This percentage is much higher than the national average level of 7.67% in 2014.

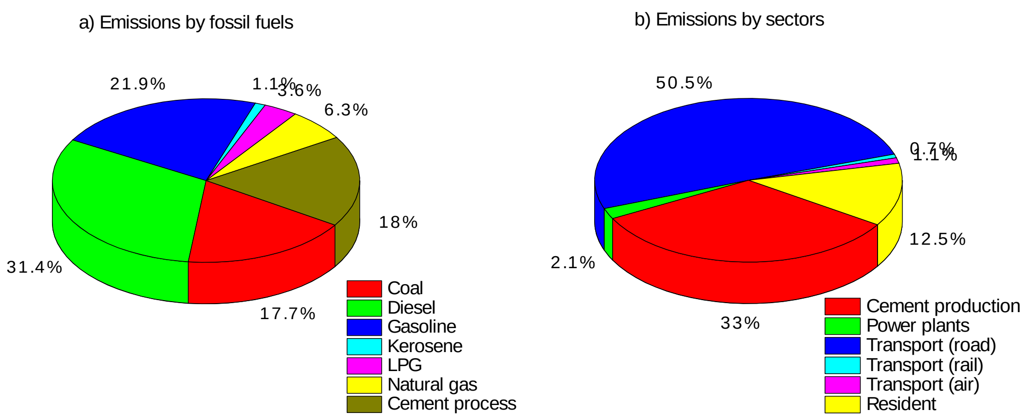

Figure 7-1 CO_2 emissions by fossil fuel types and sectors in Tibet, 2014

From the sectorial perspective, transportation and cement production are two primary contributors to CO_2 emissions (Figure 7-1-b). Indeed, 50.48% (2.79 Mt) of total emissions are associated with road transportation, which is mainly induced by gasoline usage in private cars and passenger coaches and by diesel used in cargo trucks. Cement production contributed 33.05% (1.82 Mt) to total emissions. The cement production emissions include two parts: emissions from the cement process (994.57 thousand tonnes), which is the same as the cement process in Figure 7-1-a; and emissions from coal combustion in cement plants for power (829.17 thousand tonnes). The remaining 16.47% of CO_2 emissions are associated with air transportation, rail transportation, power plants and residential consumption.

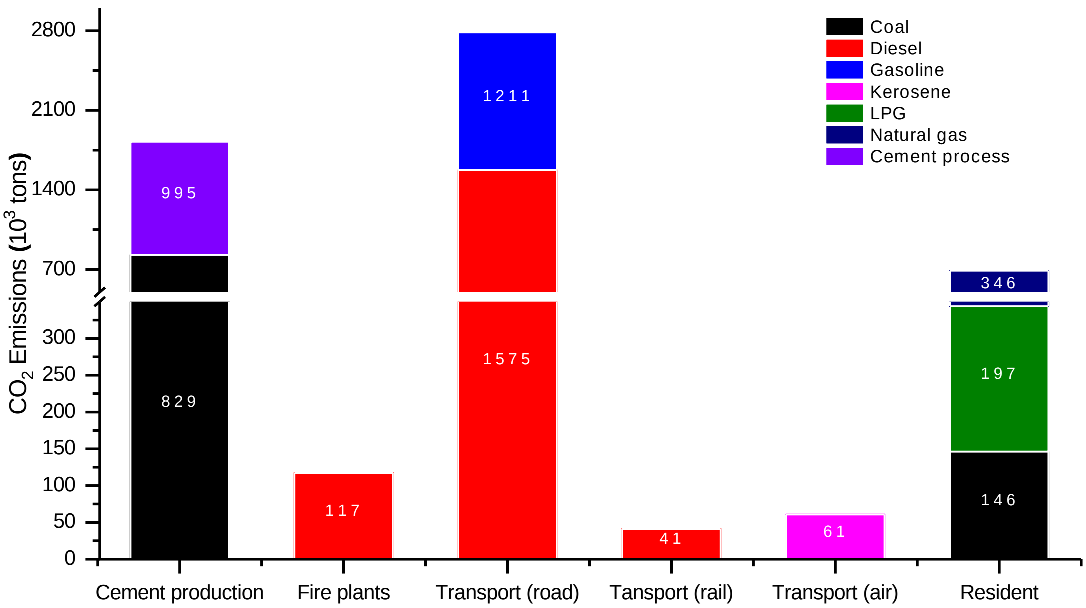

Figure 7-2 Tibet CO_2 emissions, 2014

Figure 7-2 provides a detailed illustration of energy structures in different sectors' CO_2 emissions. This figure shows that in road transportation, 56.54% emissions are from diesel consumption (mainly used in cargo trucks). The remaining 55.54% is induced by gasoline combustion in private cars and passenger coaches. Apart from electricity, residents in Tibet consumed a substantial amount of LPG, which contributes 28.64% of the total residential emissions. LPG and natural gas (50.13%) are consumed only in Lhasa City, having benefited from the "Gas Tibet" project since 2010 (Ren et al., 2014). Households in rural and less-developed areas (particularly Nagqu, Ngari, and Nyingchi) use coal as their main energy source for heating and cooking due to the lack of electricity and gas. This segment of coal consumption emitted 146.31 thousand tonnes of CO_2 in 2014.

Tibet's per capita CO_2 emissions are 1.74 tonnes and its emission intensity is 0.60 ton per thousand yuan in 2014. Per capita CO_2 emissions in Tibet are remarkably lower than the national level of 6.7 tonnes (section 4.1.1). Tibet is one of the least developed provinces in China, as most of its residents continue to maintain a farming-based lifestyle, which consumes less energy than urban lifestyles. However, Tibet's emission intensity is much higher than the national level of 0.15 ton per thousand yuan because of the low combustion heat value in the plateau, backward production technologies in industrial system and Tibet's simple industrial structure. Heavy industries account for the lion's share of the 58.86% in Tibet's overall industrial output. Cement production is the primary contributor, accounting for 34.05% of heavy industrial output. Tibet's emission intensity is close to Ningxia's (0.52 ton per thousand yuan) due to the nearby geographical location and similar simple industry structure.

7.2.2. Historical CO_2 emissions growth of Tibet

Based on the CO_2 emissions in 2014, this study estimates Tibet's time-series emissions from 2003 to 2013 with its energy consumption/cement production increasing rate. The cement process-, LPG-, and natural gas-related emissions are calculated with their own historical emissions (NBS, 2016a). The emissions from coal consumption are calculated based on the cement production increasing rate (NBS, 2016b). The refined oil consumption in Tibet increased 13% per year steadily (Tibet autonomous region government, 2007), this study uses the ratio to estimate Tibet's CO_2 emissions from diesel, gasoline, and kerosene.

The results find that Tibet's CO_2 emissions in 2003 are about 1,300 thousand tonnes, and then increased smoothly at a speed of 14+% per year, see Table 7-6. With the growth rate of 15%, this study estimates Tibet's CO_2 emissions in 2015 as 6,346 thousand tonnes. However, benefited from the "Gas Tibet" project, the natural gas consumption in Tibet increased sharply in 2015, reached 13,460 thousand m^3 (China Energy Web, 2016; NBS, 2016a). Considering this, Tibet's total CO_2 emission would surpass 35,000 thousand tonnes in 2015.

Table 7-6 Tibet's historical CO_2 emissions, 2000-2014

Year	Cement	Coal	Diesel	Gasoline	Kerosene	LPG	Natural gas	Tota l
2003	258	253	452	316	16	3	0	1298
2004	279	274	511	357	18	2	0	1440
2005	399	391	577	403	20	5	0	1795
2006	484	475	652	455	23	15	0	2105
2007	464	455	737	515	26	26	0	2222
2008	490	480	833	581	29	26	0	2439
2009	552	541	941	657	33	26	0	2750
2010	637	625	1063	743	37	17	0	3122
2011	683	670	1202	839	42	78	0	3513
2012	833	817	1358	948	48	82	0	4086
2013	860	844	1534	1071	54	64	281	4709
2014	995	975	1734	1211	61	197	346	5518

Unit: Mt

7.3. CO_2 emissions of Tibet's cities in 2014

The CO_2 emissions of 7 of Tibet's cities in 2014 are shown in Figure 7-3 and Table 7-7. The figure shows that Lhasa contribute over half (53%) of Tibet's CO_2 emissions in 2014, followed by Shanna (18%) and Xigaze (10%).

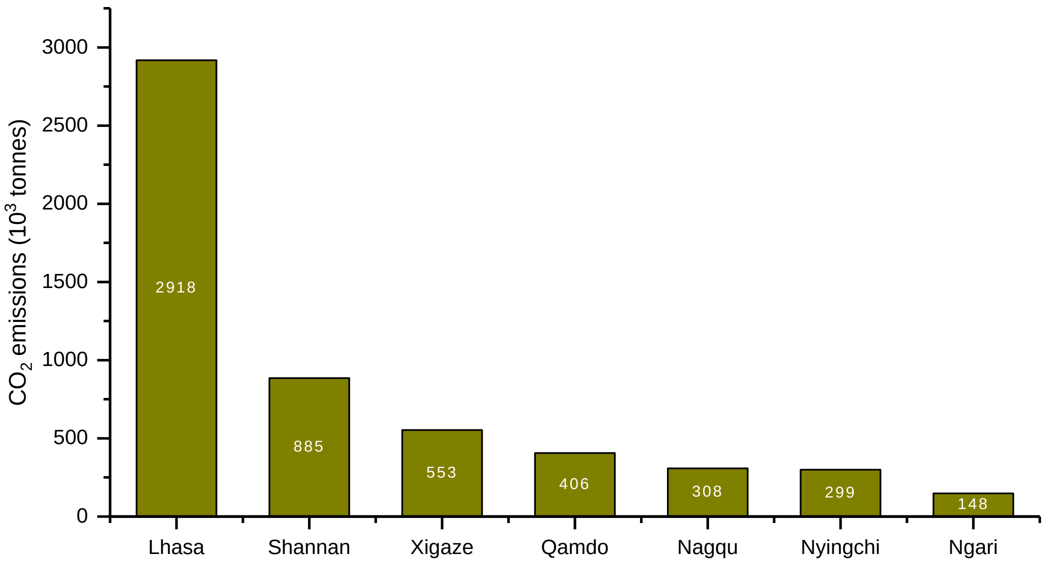

Figure 7-3 Total CO_2 emissions from seven cities in Tibet, 2014

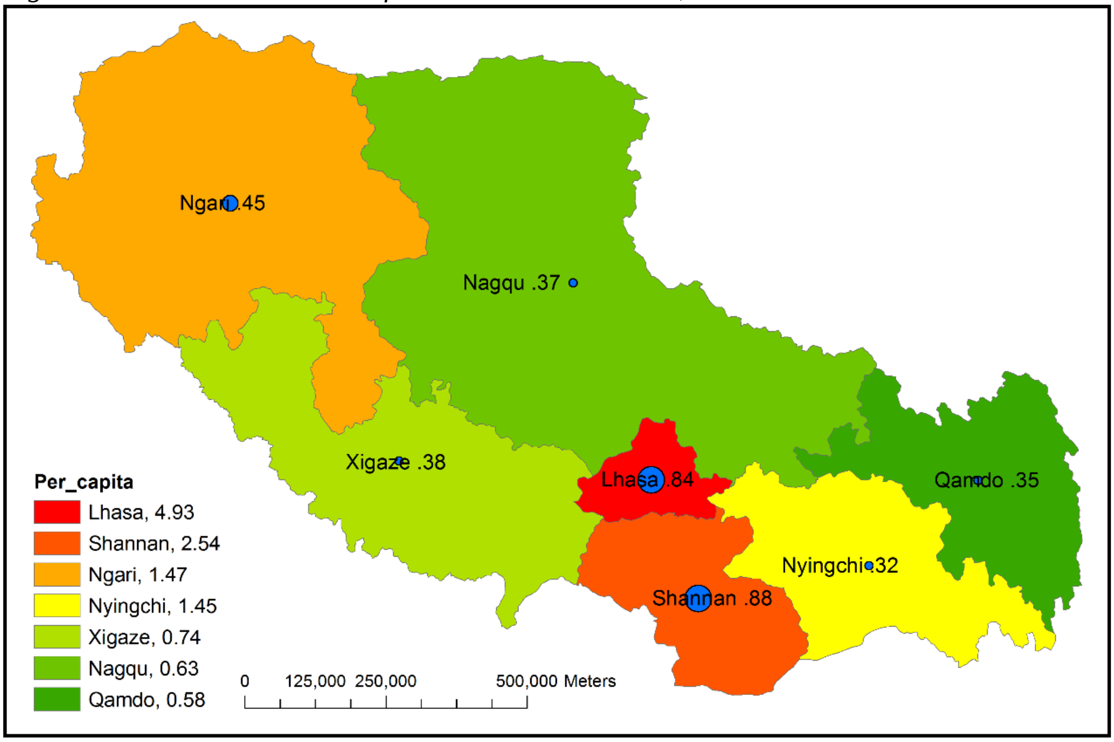

Figure 7-4 Per capita CO_2 emissions and intensities from seven cities in Tibet, 2014

The colours of the map show the per capita emissions (CO_2 emissions/population, in ton) of each city. Greener city has a lower per capita emission while redder city has a higher one. The Blue circles represent emissions intensity (CO_2 emissions/ total GDP) for each city, bigger circle refers to a higher emission intensity. The numbers on the map show the emission intensity of each city (in ton per thousand yuan), for example, the emission intensity of Lhasa is 0.84 ton per thousand yuan.

Table 7-7 CO_2 emissions from Tibet's 7 cities, 2014

City	Sector	Coal	Diesel	Gasoline	Kerosene	LPG	Natural gas	Cement
Lhasa	Cement	433.62	-	-	-	-	-	520.12
	Power plants	-	110.91	-	-	-	-	-
	Road transport	-	667.80	513.25	-	-	-	-
	Rail transport	-	41.30	-	-	-	-	-
	Air transport	-	-	-	60.75	-	-	-
	Resident	27.27	-	-	-	197.44	345.60	-
	Sub-total	460.89	820.01	513.25	60.75	197.44	345.60	520.12
Qamdo	Cement	43.52	-	-	-	-	-	52.20
	Power plants	-	-	-	-	-	-	-
	Road transport	-	157.37	120.96	-	-	-	-
	Rail transport	-	-	-	-	-	-	-
	Air transport	-	-	-	-	-	-	-
	Resident	32.04	-	-	-	-	-	-
	Sub-total	75.56	157.37	120.96	-	-	-	52.20
Shannan	Cement	281.58	-	-	-	-	-	337.74
	Power plants	-	-	-	-	-	-	-
	Road transport	-	141.28	108.59	-	-	-	-
	Rail transport	-	-	-	-	-	-	-
	Air transport	-	-	-	-	-	-	-
	Resident	16.03	-	-	-	-	-	-
	Sub-total	297.61	141.28	108.59	-	-	-	337.74
Xigaze	Cement	53.73	-	-	-	-	-	64.45
	Power plants	-	-	-	-	-	-	-
	Road transport	-	226.45	174.03	-	-	-	-
	Rail transport	-	-	-	-	-	-	-
	Air transport	-	-	-	-	-	-	-
	Resident	34.28	-	-	-	-	-	-
	Sub-total	88.00	226.45	174.03	-	-	-	64.45
Nagqu	Cement	-	-	-	-	-	-	-
	Power plants	-	-	-	-	-	-	-
	Road transport	-	161.66	124.24	-	-	-	-
	Rail transport	-	-	-	-	-	-	-
	Air transport	-	-	-	-	-	-	-
	Resident	22.53	-	-	-	-	-	-
	Sub-total	22.53	161.66	124.24	-	-	-	-

Ngari	Cement	16.73	-	-	-	-	-	20.06
	Power plants	-	6.43	-	-	-	-	-
	Road transport	-	56.76	43.63	-	-	-	-
	Rail transport	-	-	-	-	-	-	-
	Air transport	-	-	-	-	-	-	-
	Resident	4.65	-	-	-	-	-	-
	Sub-total	21.37	63.19	43.63	-	-	-	20.06
Nyingchi	Cement	-	-	-	-	-	-	-
	Power plants	-	-	-	-	-	-	-
	Road transport	-	163.89	125.96	-	-	-	-
	Rail transport	-	-	-	-	-	-	-
	Air transport	-	-	-	-	-	-	-
	Resident	9.52	-	-	-	-	-	-
	Sub-total	9.52	163.89	125.96	-	-	-	-

Unit: thousand tonnes

Table 7-7 shows that over half of Tibet's CO_2 emissions come from Lhasa City. Lhasa is the capital and the largest and most developed city in Tibet, contributing 37.73% to Tibet's economic growth in 2014. Therefore, Lhasa has the most complex emission structure of all the cities, as shown in Figure 7-5. Like Tibet's emission structure, approximately 83% of Lhasa's emissions are from cement production (38.28% or 953.73 thousand tonnes) and road transportation (44.54% or 1.11 Mt). Lhasa is the largest cement production base in Tibet, with four cement plants, and produces 52.30% of Tibet's total cement production. Lhasa is also the entrepot of Tibet, with high volumes of passenger and freight traffic. As discussed above, LPG and natural gas are used in Lhasa's urban households, and these two energy types account for 95.22% of Lhasa's CO_2 residential emissions. This percentage is substantially higher than China's average level of 37.90% in 2014 (NBS, 2016a).

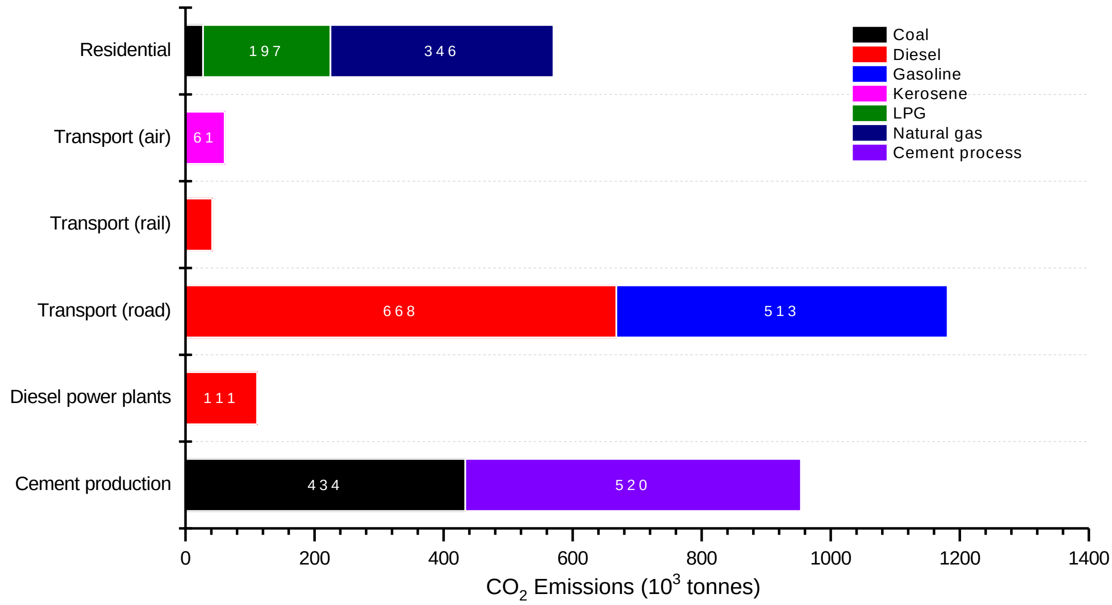

Figure 7-5 Lhasa CO_2 emissions, 2014

The Shannan region is another large CO_2 emitting region in Tibet, accounting for 16 % of emissions. Most of its CO_2 emissions are also related to cement production (69.96%, 619.32 thousand tonnes) and road transportation (28.23%, 249.87thousand tonnes). Lhasa and Shannan have the highest per capita emissions and emission intensities among Tibet's cities. The per capita emissions of the two divisions are 4.93 and 2.54 tonnes, respectively. The value is close to that of Sichuan province (4.19 tonnes) and Yunnan province (4.14 tonnes), areas that are contiguous to Tibet. The emission intensity of Lhasa and Shannan is 0.84 and 0.88 tonnes per thousand yuan, respectively. The high emission intensity is caused by a large amount of cement production in these administrative divisions.

Nagqu and Nyingchi regions are the only two divisions with no cement production in Tibet. These two cities' emission intensities are therefore the lowest (0.37 and 0.32, respectively). Nagqu is a pure pasturing zone: 73.99% of its area (333.33 thousand km^2) is the meadow. Nyingchi is a typical mountainous region in Tibet: the Himalayas and the Nyenchen Tanglha Mountains run through it. Nyingchi's forest coverage rate is 46.0%, and 80% of Tibet's forest is in Nyingchi. There is very little industry in Nagqu and Nyingchi regions.

7.4. Policy implications on Tibet emission control

The detailed analysis of Tibet's emission characteristics implies that possible measures regarding Tibet's CO_2 emissions reduction could be taken as follows.

Despite Tibet's per capita emissions is much lower than the national average level, there is a certain amount of scattered coal combusted by households in Tibet's rural regions. Tibet should replace residential coal usage in rural and less-developed regions by natural gas. The "Gas Tibet" project has met with huge success in Lhasa city during the past three years and increased its natural gas consumption by 10 times. This study suggests that the project should be continued and expanded to other administrative divisions in Tibet. Coal is more carbon-intensive energy type than natural gas, and replacing coal with natural gas in residential usage could thus reduce Tibet's CO_2 emissions effectively.

Considering the emission intensity in Tibet is relatively high, Tibet should improve its industrial production process. As the only energy-intensive industrial process in Tibet, cement production contributes substantially to emissions each year, although Tibet's cement production is relatively limited compared with other regions in China. Measures such as improving the energy combustion efficiency/combustion heat value, reducing the unit energy consumption in cement production could lower Tibet's emission intensity.

Tibet could weed out the behindhand generator sets in the diesel-power plant, i.e. the generator sets with power capacity and high unit energy consumption. For example, this study suggests replacing the four 2,500 kW diesel generating sets in the Ngari thermal plant by 11,500 kW or more advanced sets. The advanced sets have lower unit energy consumption.

Tibet could maintain the development of renewable energies. Notably, Tibet has abundant water resources and thereby great potential to develop its renewable energy, particularly via hydropower. As Tibet has developed its hydropower capability, Tibet's green electricity generation increased rapidly from 1.72 in 2010 to 3.24 billion kWh in 2014. The percentage of total electricity generation also increased from 81.81% to 89.94% during the same period. Although energy consumption and CO_2 emissions in Tibet are much lower than in other provinces, Tibet's role in national climate change mitigation should not be underestimated. Because of its high potential capacity of hydropower, Tibet is more likely to act as the electricity exporter and to ease electricity shortage and decrease energy consumption in other regions. Tibet should continue this increasing trend and develop its renewable energies in the future. Despite all this, conventional fossil fuels would still play an important role in Tibet's energy structure. Booming infrastructure development in Tibet, particularly in road construction, would directly bring about a rise in diesel and gasoline consumption, thereby increasing emissions. Tibet's energy and emission structure would be more likely to change in the future.

7.5. Summary

Tibet's autonomous region has always been missing from energy statistics and CO_2 emissions accounting. Previous studies on China's national and provincial emissions accounting typically ignore Tibet due to the lack of data and its relatively low emissions. Despite its small amount of energy consumption and emissions, the study on Tibet's energy consumption and emission have great significant as well. Tibet is an important component of China, it is at the very initial stage of industrialisation. The study on Tibet's energy consumption and emissions will help Tibet to realize low-carbon and sustainable development from its initial industrialisation stage. Tibet's low-carbon development are a significant benchmark for other developing countries at similar early industrialisation stage.

This chapter, for the first time, estimates Tibet's energy consumption according to limited online documents and calculates the fossil fuel- and process-related CO_2 emissions of Tibet and its seven cities in 2014.

This chapter finds that Tibet emitted 5.52 million tonnes of CO_2 in 2014; 18% of these emissions are associated with the cement production's process emissions, and the remaining 82% from fossil fuel combustion. Diesel and gasoline are two dominating energy types in Tibet's emission structure. Approximately 90% of Tibet's CO_2 emissions in 2014 are associated with cement production and road transportation. The per capita emission of Tibet in 2014 was 1.74 tonnes, which is remarkable lower than the national average level, whereas the emission intensity of Tibet is relatively high, at 0.60 ton per thousand yuan in 2014. Lhasa City and the Shannan region are two large CO_2 contributors among the seven cities in Tibet. They also have the highest per capita emissions and emission intensities. The Nagqu and Nyingchi regions emit little CO_2 every year as a result of their farming/pasturing-dominated economies.

The detailed analysis of Tibet's emission characteristics implies that several possible measures regarding Tibet's CO_2 emissions reduction could be taken, such as replacing residential coal usage in rural and less-developed regions by natural gas; improving the cement production process in Tibet; weeding out the behindhand generator set in the diesel-power plant by more advanced sets; maintaining the development of renewable energies, particularly the hydropower.

Chapter 8 Conclusions

China, the world's second-largest economy, has witnessed a miracle in its economic growth. With lifestyle changes and rapid economic growth, its energy consumption has also increased rapidly, leading to very high greenhouse gas emissions. Indeed, China's total CO_2 emissions have quadrupled during the past two decades (Olivier et al., 2016), making China the world leading energy consumer and CO_2 emitter. Despite the fact that China's per capita emissions are still below the global average level, the country - with a population of more than 1.3 billion people - is now consuming 20% of global primary energy every year and accounts for 28% of the global emissions. Consequently, China is playing an increasingly important role in global emission reduction and climate change mitigation.

This PhD thesis compiles the time-series CO_2 emission inventories for China and its provinces from 1997 to 2015. The multi-scale emissions inventories are constructed in a uniform format based on 46 socio-economic sectors and 17 fossil fuels. This PhD thesis also examines the emission characteristics of key industries in China, such as the lime industry and petroleum coke combustion. CO_2 emissions from Tibet and its cities are discussed separately using a different method.

Being the basic units for human activities and major contributors to emissions, cities are major components in the implementation of climate change mitigation and CO_2 emission reduction policies. Increasing attention has now been paid to city-level emission reduction and climate change mitigation in China. This study develops a series of methods to compile CO_2 emission inventories for cities with different data availabilities and examines the emissions characteristics of hundreds of cities in China.

Furthermore, possible emission reduction capacities and low-carbon roadmaps for Chinese cities at different stages of industrialisation and development have been designed and discussed. The low-carbon roadmaps might be relevant to other developing countries as well.

8.1. Contributions to the scholarship and policy

This study has great real-world significance and has filled in several research gaps in China's emission accounts and cities' low-carbon development. The research also provides solid and robust data support for future academic research on China's emission topics and emission reductions policy-making in China.

First of all, this study provides the first open-access China emission database providing the multi-scale CO_2 emission inventories (by 46 socioeconomic sectors and 17 fossil fuels) for China. This study constructs the IPCC administrative territorial CO_2 emission inventories for China, its provinces and cities. The national and provincial emissions are a time-series from 1997 to 2015. The multi-scale emission inventories have the uniform formatting, which illustrates the CO_2 emissions from 46 socioeconomic sectors and 17 fossil fuel types. All data have been uploaded to China Emission Accounts and Datasets (www.ceads.net) for free download. This is the first open-access database providing free emission inventories of China. All the previous emission databases only provide the total emissions of the country, rather than detailed inventories by sectors and fossil fuels. The uniformly formatted time-series of national, provincial and city-specific emission inventories have been utilised by other scholars to conduct further China emissions-related research (Duan et al., 2018; K. Fang et al., 2017; Q. He et al., 2017; S. Liang et al., 2017; J. Meng et al., 2017; Mi, Meng, Guan, Shan, Liu, et al., 2017; Mi, Meng, Guan, Shan, Song, et al., 2017; Mi, Wei, et al., 2017; Ou et al., 2017; Shao et al., 2016; Shao et al., 2018; Zhen Wang, Xiao, et al., 2017; Zhaohua Wang et al., 2018; Wen et al., 2017; Wiedenhofer et al., 2016; Zengkai Zhang et al., 2018; Heran Zheng et al., 2018). The author's data has been re-used and cited by more than 50 times according to the Web of Science searching. The accurate accounts of China's CO_2 emissions provide robust data support for policy-making and assessment.

Secondly, this study analyses the detailed emission characteristics of China, its provinces, and cities. Based on the emission inventories by sectors and fuels, this study identifies the major sector/fuel contributors to the country/provinces/cities' CO_2 emissions. More specific and efficient emission control policies targeting these major contributors are discussed based on the analysis. Also, this study examines the CO_2 emissions from China's selected key industries, i.e. lime and petroleum coke, to disclose the sector- and fuel-specific emission features in China. This is the first study to account and analyse the CO_2 emission of the lime industry and petroleum coke consumption. The detailed emission analysis provides possible emission control policies for these key industries in China. What's more, this study fills in the research blank of Tibet's emission accounts by estimating the energy consumption and CO_2

emissions of Tibet and its seven cities. Such a Tibet-related study provides an important supplement to national and provincial emissions data.

Thirdly, this study is the first one developing a series of methods to calculate Chinese cities' emission inventories in a top-down approach. This study fills in the research gap that there is no top-down emission inventory construction designed for Chinese cities. Then this study applies the methods to 182 Chinese cities and constructs the emission inventories of them. The city-level emission features of China are examined and analysed. Such top-down approach emission inventories of cities can be further cross-validated with the existing bottom-up approach emissions, in order to clearly and accurately figure the emissions of Chinese cities.

Fourthly, the self-consistent emission accounting framework designed in this study provide reference for other developing countries without integrated emission accounts. Despite the quality of emission data has been formally required by the "Paris Agreement" (UNFCCC, 2015), the capacities of inventorying emissions in developing countries are still scarce, especially in Asia and Africa. Among the 37 developing countries in Asia, only 17 of them have relatively high inventorying capacities (Umemiya et al., 2017). The other 20 Asian countries, such as Yemen, North Korea, Kazakhstan, Laos, Cambodia, have limited inventorying capacities. This is mainly caused by their poor statistical system (DeFries et al., 2007). This PhD study on China's multi-scale emission accounts provide a series of methods to deal with the lack of data, which are applicable to other developing countries with similar limited data accessibilities.

Fifthly, based on the cities' emission inventories and socioeconomic indexes, this study analyses the different industrialisation stages and development pathways of Chinese cities. Sectoral-based low-carbon roadmaps are designed for the cities considering their existing development pathways. The city-level low-carbon analysis provides feasible and practical guidance to local governments in China to achieve the balance of economic growth and carbon emission control.

Furthermore, as the 330+ Chinese cities are at various industrialisation levels, from the earliest stage of industrialisation (such as the rural area in Tibet and Xinjiang province) to the post-industrialisation stage (such as Beijing, Shanghai), the cross-section analysis of China's cities may disclose the emissions characteristics of the whole industrialisation process. The emission reduction roadmaps designed in this study for cities at different industrialisation stages also provide references for other developing countries at similar stages of industrialisation (Gouvello, 2010; Ockwell et al., 2008).

8.2. Summary of work and key findings

This study closes the research gaps defined in Chapter 2, section 2.4 by: 1) compiles consistent and transparent multi-scale emission inventories for China; 2) examines the emissions from the lime industry and petroleum coke consumption in China; 3) discusses the emissions from Tibet and its cities; 4) analyses the CO_2 emissions of 182 cities as well as their low-carbon pathways.

8.2.1. Multi-scale emissions of China

In Chapter 4 this study presents calculations made in relation to the IPCC administrative territorial-based CO_2 emissions of China and its provinces from 1997 to 2015. This study includes both fossil fuel-related emissions and process-related emissions induced in cement production in China. Both sectoral- and reference-approach inventories have been compiled. Sectoral-approach emission inventories were constructed to comprise 17 fossil fuels and 46 socio-economic sectors. Reference-approach emissions, calculated based on fossil fuel production data, have validated the sectoral-approach emission inventories. The accuracy of these emission estimates and comparisons with other existing inventories have also been discussed in this study.

This study finds that China's total CO_2 emissions increased from 3,003 to 9,265 Mt with an average increase of 7.8% per year during 2000 to 2015. Emissions peaked in 2013 at 9,534 Mt. Coal and related fossil fuels are the major energy sources used in China, as well as the largest emissions contributor. In 2015, coal-related fossil fuels emitted 7,053 Mt (or 76.1%) CO_2 emissions. In terms of sectors, manufacturing ("Power and heat", "Ferrous proc.", and "Non-metal prod.") sectors contributed the most to the total CO_2 emissions.

This study calculates China's per capita CO_2 emissions and emission intensities from 2000 to 2015. The results show that per capita emissions have followed the same trend as the total emissions, also peaking in 2013 at 7.0 tonnes per person. Emission intensity has been decreasing since 2005. The current emissions intensity is 2.3 tonnes per 10 thousand yuan (at 2000 constant price).

As for provincial emissions, the results show that among the 30 provinces, Shandong emitted the most CO_2 cumulatively, 10,061 Mt (or 8.6%). The four provinces with the next highest cumulative emissions were Hebei, Jiangsu, Guangdong, and Henan, which emitted 9,070 (or 7.8%), 8,084 (or 6.9%), 6,647 (or 5.7%), and 6,637 (or 5.7%) Mt CO_2, respectively. Provinces in northern and eastern China have higher CO_2 emissions, while provinces in central and western China have lower emissions.

The per capita emissions and emission intensities of each province are also presented in this study. The results show that the per capita CO_2 emissions and emission intensity vary significantly between provinces due to differences in regional development in China. The provincial per capita CO_2 emissions varied from 3.7 to 23.3 tonnes per person in 2015; half of the 30 provinces had per capita CO_2 emissions above the national average level of 6.7 tonnes. At the same time, the provincial emission intensity varied from 0.7 to 9.8 tonnes per 10 thousand yuan, with the national level at 2.3 tonnes.

This study uses 2015 as an example to show each province's emission contributions to each fossil fuel/sector. The results show that Shandong, Hebei, Jiangsu, Inner Mongolia, Henan, and Shanxi contributed the most to coal-related CO_2 emissions in 2015. These provinces are either coal bases or manufacturing provinces. Coastal Guangdong, Shandong, Liaoning, Shanghai, Zhejiang, and Jiangsu have more developed shipping industries; more oil was consumed in these provinces, resulting in huge CO_2 emissions. Jiangsu, Xinjiang, Beijing, and Sichuan consumed high levels of natural gas in 2015. As for the aspect of sectors, this study finds that Jiangsu, Henan, Shandong, Guangdong, Sichuan, and Anhui were the main contributors to process-related CO_2 emissions due to their high cement productions. Hebei, Shandong, Henan, and Shaanxi contributed the most to coal mining-related CO_2 emissions in 2015. These provinces are either coal bases (Henan and Shaanxi) or manufacturing provinces which have more coal processing enterprises (Hebei and Shandong). Shandong, Inner Mongolia, Jiangsu, Henan, and Shanxi contributed a large proportion of CO_2 emissions in the "Power and heat" sector in 2015. These provinces emitted CO_2 from power plants to generate electricity and heat for themselves as well as nearby regions. As for the CO_2 emission from ferrous processing industries, Hebei province contributed 22.8%, Jiangsu and Liaoning province contributed another 10.4% and 9.4% in 2015 respectively. Shanxi, Heilongjiang, Xinjiang, and Shaanxi were the provinces that contributed the most to the national CO_2 emission from other energy production in 2015. Jiangsu, Shandong, Sichuan, Hunan, and Henan contributed the most to other heavy manufacturing-related emissions. Jiangsu, Shandong, Jilin, and Hunan contributed the most to light manufacturing-related emissions. In terms of the contribution of high-tech industries to overall emissions, Guangdong province was responsible for the largest percentage in 2015. Guangdong, Shanghai, Shandong, Heilongjiang, and Guizhou have more developed tertiary industries, and therefore, more service-related CO_2 emissions were induced in these provinces in 2015 compared with other provinces. In terms of the contribution of the construction sectors to overall emissions, Guangdong province was responsible for the largest percentage in 2015, followed by Shandong and Hunan.

The comparison and uncertainty analysis of the emission estimates find that this study's estimates are highly consistent with the newly published official emission inventory 2012 in NC2012 (NDRC, 2016b). The two estimates are only with 2.79% difference. The Monte Carlo simulation finds that the uncertainties of the entire CO_2 emissions inventories are roughly (-15%, 25%) at a 97.5% confidential level. Compared with the activity data (-1.4%, 9.2%), emission factors of fossil fuels have a higher uncertainty (-15.8%, 23.7%).

8.2.2. Emissions of lime industry in China

This study presents an analysis of CO_2 emissions from China's lime industry, which is the second large source of process-related emissions in China, for the first time. This study estimates the process-related emissions, fossil fuel combustion emissions, and scope 2 indirect emissions from purchased electricity consumption.

The results show that the process-related CO_2 emissions of lime industry in China increased rapidly from 88.79 to 141.72 Mt from 2001 to 2012, and the fossil fuel-related emissions in 2012 accounted for 55.95 Mt. The scope 2 emissions amounted to 4.42 Mt, among which 18.10% were contributed by environmentally advanced lime kilns.

In 2012, the total CO_2 emissions from China's lime production were 202.69 Mt, with 69.92% contributed by the industrial process or process emissions. Scope 2 indirect emissions from electricity consumption were only 2.18%. Among the total emissions in 2012, 61.27 Mt or 29.67% were contributed by the environmentally advanced lime kilns.

The emission accounts of China's lime industry have significant global impacts. With the total emission of 202.69 Mt CO_2, emission from lime production is equivalent to the total emission from some developed countries. However, little attention has been paid to the mitigation of CO_2 emission from lime industry. Cleaner production, efficiency improvement as well as energy saving in lime production need to be addressed with the same priority as the mitigation strategy in energy sectors, so that the low carbon development can be achieved at the national and global level.

8.2.3. Emissions of petroleum coke consumption growth in China

Evidence indicates that petroleum coke is gradually replacing other power fuels in China's industrial enterprises because of its current price advantage. This study presents China's production and consumption of petroleum coke by sector and region from 2010 to 2014 for the first time.

The results show that petroleum coke production increased by 32.31% (or 4,473 thousand tonnes), primarily because of activities in Shandong province (3,332 thousand tonnes). Shandong, Guangdong, Jiangsu, and Liaoning were consistently the major producers of petroleum coke in China. The total consumption of petroleum coke has increased by 18.30% since 2010, and over 60% of the total consumption is as a raw material in industrial processes. The other 40% is burnt in power plants and industrial kiln stoves/boilers. This usage is the major source of emissions and should be considered as a key regulatory target. The combustion consumption of petroleum coke is focused in the “Non-metal prod.” and “Power and heat” sectors and in Liaoning and Tianjin provinces. The consumption in industrial kiln stoves/boilers increased by approximately 159.32% during the past five years, reaching 8,279 thousand tonnes in 2014.

Because of the increased petroleum coke consumption in China, the greenhouse gas and air pollutant emissions are increasing annually. Petroleum coke-related CO_2 emissions in 2014 were as high as 26.2 Mt, whereas those of CH_4 and N_2O were 807 and 137 tonnes, respectively. Apart from the largest emissions contributors, Liaoning and Tianjin, Xinjiang exhibited rapid growth in its emissions levels over the five-year study period. As a result, if no measures are taken, China will face increasingly serious challenges in dealing with climate change and environmental issues.

To manage and control petroleum coke consumption and its related emissions in China, more attention should be focused on the key industrial sectors and top-consuming provinces. China's government should strongly restrict the production and import of high-sulphur petroleum coke. Additionally, burning petroleum coke to provide power should be discouraged.

8.2.4. Emissions of Tibet and its cities

Tibet's autonomous region has always been absenting in energy statistics and CO_2 emissions accounting. Previous studies on China's national and provincial emissions accounting typically ignore Tibet. This study estimates the Tibet's energy consumption according to limited online documents and calculates the fossil fuel- and process-related CO_2 emissions of Tibet and its seven cities in 2014 for the first time.

The results show that Tibet emitted 5.52 Mt of CO_2 in 2014; 18% of these emissions were associated with the cement production's process-related emissions, and the remaining 82% from fossil fuel combustion. Diesel and gasoline are two dominating fossil fuel types used in Tibet's energy structure. Approximately 90% of Tibet's CO_2 emissions in 2014 were associated with cement production and road transportation. The per capita emission of Tibet in 2014 was 1.74 tonnes, which was remarkable lower than the national average level, whereas the emission intensity of Tibet is relatively high, at 0.60 ton per thousand yuan in 2014.

As for the city-level emissions, Lhasa city and the Shannan region were two large CO_2 contributors among the seven cities in Tibet. They also had the highest per capita emissions and emission intensities. The Nagqu and Nyingchi regions emit little CO_2 every year as a result of their farming/pasturing-dominated economies.

The detailed analysis of Tibet's emission characteristics implies that several possible measures regarding Tibet's CO_2 emissions reduction could be taken, such as "replacing residential coal usage in rural and less-developed regions by natural gas"; "improving the cement production process in Tibet"; "weeding out the behindhand generator set in the fire-power plant by more advanced sets"; "maintaining the development of renewable energies, particularly the hydropower".

8.2.5. City-level emission accounts and reduction capacities in China

As national efforts to reduce CO_2 emissions intensify, policymakers are in need of increasingly specific, subnational information about the sources of CO_2 and the potential reductions and economic implications of different possible policies. This is particularly true in China, a large and economically-diverse country that has rapidly industrialized and urbanized, and which has pledged under the Paris Agreement that its emissions will peak by 2030.

This study presents city-level estimates of CO_2 emissions for 182 Chinese cities. The CO_2 emissions calculated for Chinese cities have the same scope and formats as the national and provincial emissions. The emission inventories are compiled by 17 different fossil fuels and cement industrial process.

This study finds that more affluent cities have systematically lower emissions per unit GDP that is supported by imports from less affluent, industrial cities located nearby. In turn, clusters of industrial cities are supported by nearby centres of coal or oil extraction. Whereas policies directly targeting manufacturing and electric power infrastructure would drastically undermine the GDP of the industrial cities, consumption-based policies might allow emissions reductions to be subsidized by those with greater ability to pay.

In particular, the sector-based analysis of each city in this study suggests that technological improvements could be a practical and effective means of reducing emissions while maintaining growth and the current economic structure and energy system. This study explores the city-level emissions reductions under three scenarios of technological progress to show that substantial reductions are possible by updating a disproportionately small fraction of existing infrastructure. If scenario #3 technical improvement (the strictest scenario) is applied to the super-emitting city sectors, the overall reductions are 2,400 Mt CO_2 or 31% of the 182 cities' emissions in 2010.

Therefore, this study suggests that China's near-term goals of reducing its emissions intensity may be feasibly accomplished by targeted technological improvements, buying time for the longer-term strategies of shifting to non-fossil energy and a more service-based economy. Moreover, improving and optimizing the energy and carbon efficiency of industrial production processes and operations could help lower the costs of advanced technologies and thus facilitate their deployment in less-developed cities and countries beyond China.

8.3. Methodological innovation

This PhD study has adopted the IPCC administrative territorial-based emission accounts method as the primary method to describe the multi-scale CO_2 emissions of China. However, this study has developed the technique so as to be better applied in China. The methodological innovation is summarised in the following two sections.

8.3.1. Inventories based on China's energy statistical system

So as to be in line with China's energy statistical system, the sectoral-approach emission inventories comprise 17 fossil fuel types and 46 socio-economic sectors. Such an inventory layout is applied to both the national/provincial and city-level emission inventory construction in this study.

There are 27 kinds of fossil fuels in China's official energy statistics; this study merges them into 17 when calculating the fossil fuel-related CO_2 emissions, due to some fossil fuels' small share of consumption and similarity with other fossil fuels.

As for the sectors' setting, this study adopts the sector classification used in China's System of National Accounts. The CO_2 emissions from fossil fuel consumption in final consumption sectors are allocated directly to their corresponding sectors. The CO_2 emissions induced by fossil fuel combustion in the power plants (i.e., inputs as energy transformations) are allocated to the sector "Power and heat". The process-related CO_2 emissions are allocated to their corresponding manufacturing sectors as well. For example, the emissions from cement and lime production are allocated to the "Non-metal prod." sector; the emissions from ammonia and soda ash production are allocated to the "Chemicals" sector; the emissions from ferrochromium, silicon metal, and ferro-unclassified production are allocated to the "Ferrous proc." sector. Thus, the sectoral approach fossil fuel consumption is constructed across 46 socioeconomic sectors.

8.3.2. City-level CO_2 emission accounts

Accurate accounts of cities' CO_2 emissions are considered a fundamental step for further analysis of the emission-economic nexus, as well as mitigation action proposals. However, due to the poor data quality of Chinese cities, most cities do not have consistent energy statistics. This study, therefore, develops a series of methods to compile the missing energy data. Three cases dealing with the energy balance table and four cases with the sectoral energy consumption from industry sectors are developed in this study.

In order to verify the method developed for city-level data collection, this study applies the method to 5 selected cities (Hefei, Xiamen, Weifang, Huangshi, and Guangzhou) and compares the CO_2 emissions with CHRED built by the Chinese Academy for Environmental Planning. The 5 cities contain all the different cases. The CHRED estimates cities' CO_2 emissions based on energy consumption data collected in a bottom-up way based on industrial facility data and other supporting information. The difference between CO_2 emissions calculated in this study and CHRED's research is within ±10%. The tiny difference testifies that the city-level data collection methods developed in this study are feasible.

By applying this methodology to cities, future research can calculate the time-series CO_2 emissions of hundreds of other Chinese cities. This knowledge will be helpful for understanding energy utilization and identifying key emission contributors and drivers, given cities' various socioeconomic settings and industrialisation phases.

8.4. Limitations and future research

8.4.1. Limitations

This PhD thesis has limitations and shortcomings in terms of data collection and methodology. In the following section, the author discusses these limitations and proposes future research.

Firstly, the national and provincial CO_2 emissions estimated in this study have the following limitations:

- This study uses the national average emission factors of fossil fuels and cement production when calculating the provincial CO_2 emissions in the current version. The emission factors should be different in different regions considering the discrepancy in energy quality and cement production technology;
- In the current version, this study uses the sectoral fossil fuel consumption structure in 2008 to estimate that of the intervening years for 8 specific

provinces. Such a replacement had little effect on the total emissions but increased the uncertainties with regards to provincial sectoral emissions;

- This study has only considered emissions from cement production in the current process-related emissions accounts. The latest official emission inventory in 2012 (NDRC, 2016b) includes another nine processes such as glass, lime, steel production.

Considering the limitations discussed above, additional uncertainties should be taken into consideration when re-using the emission data in the future, such as "lack of completeness", "lack of data", "measurement error". These uncertainties are very small and difficult to quantify; however, they are also essential parts of the inventories' uncertainties.

- Lack of completeness: this study has only considered fossil fuel-related emissions and cement-related emissions. Emissions from other sources are not taken into account, such as "agriculture", "land-use change and forestry", "waste disposal", and other industrial processes;
- Lack of data: as discussed above, data on the sectoral fossil fuel consumption of 8 provinces is not available. This study uses the sectoral fossil fuel consumption structure in 2008 to estimate that of the intervening years. Also, the emission factors for secondary fossil fuels were estimated based on the primary fossil fuel emission factors' ratio;
- Measurement error: the *"measurement error is random or systematic, results from errors in measuring, recording and transmitting information; inexact values of constants and other parameters obtained from external sources (Volume 1, Chapter 3, Page 11)"* (IPCC, 2006). Measurement errors might be generated during the collection of energy statistics and emission factors.

As for the analysis of the lime-related CO_2 emissions (Chapter 5, section 5.1), this study only examines the national level emissions from China' s lime industry. This is fully restricted by the data availability of China's lime production. There is no regional lime production in China, only the national total production can be collected.

The study also has some limitations with regards to city-level emission accounts. This study compiles the city-level energy balance table by scaling down the provincial table with city-province percentages (Chapter 3, section 3.5). By using the distinct city-province percentages for different sectors, the compiled city-level table may not be balanced. Also, choosing different indexes for the city-province percentages may lead to different city-level energy balance tables.

In the analysis of super-emitting city-sectors (Chapter 6, section 6.3), this study has assumed that all the cities share similar production structures within the same sector. However, this is unrealistic. Taking the sector "Non-metal prod." as an example, this sector includes numerous different industrial processes, such as glass, cement, lime, and ceramics. The emission intensities of these sub-sector industrial processes are distinct from one another. This could lead to a broad range of sectoral emission intensities in different cities. In other words, the differences in sectoral emission intensity of cities are not solely induced by the inter-city technical abilities.

8.4.2. Future work

In the future, the author will firstly improve the accuracy of China's emission accounts, and then apply the crosscutting social-economic methods and big data technology to investigate the carbon emissions and other environmental indicators for 330+ Chinese cities. The insight analysis of China's overall and regional emissions would provide more data support of the low-carbon development of China.

The future research will also use the environmental economic methods to examine the environmental impacts via the "triangular trade" chain of production among Chinese cities, and explore how to better link the resource providers (energy production cities), manufacturers (heavy/light/high-tech manufacturing cities) and end consumers (high-tech/service-based cities) to achieving the balance of emission reduction and economic growth, i.e. low-carbon roadmaps. Considering the huge discrepancies of Chinese cities' industrialisation stages and development pathways, the city-level low-carbon research of China would provide reference for other developing countries at similar industrialisation stages. Detailed future research plans are discussed below.

Improving the accuracy of multi-scale China's emission accounts

The limitations of current emission accounts of China discussed above are mainly the result of poor data quality. The results analysed in this study is based on the most comprehensive data the author could find. In the future, the author will focus on improving China's data quality and the accuracy of China emission accounts. Some possible fields are:

- To specify the emission factors of each province / industrial sector to achieve more accurate regional / sectoral emission inventories for China;
- To collect more detailed data for 8 provinces with no sectoral energy data currently (Hebei, Jiangsu, Zhejiang, Shandong, Guangxi, Hainan, Sichuan, and Guizhou) through in-depth investigations;
- To extend the scope of the emission inventories to include more industrial processes.

Based on the more accurate emission data, the author will apply economic models and scenario analysis (Riahi et al., 2017) to discuss how China's CO_2 emissions will look like in the future. Some comparative analysis of China and other countries' emissions will also be conducted. The prediction and comparative analysis of China's emissions would provide more data support of the future low-carbon development of China, as well as other developing countries.

City-level emissions and emission-socioeconomic analysis

In the future, the time-series emission inventories of 330+ Chinese cities will be constructed to present the more detailed emission characteristics of China at city-level. The author will verify the top-down inventories with bottom-up emissions and satellite data (B. Cai, 2011;2012b; B. Cai et al., 2014b; J. Wang, Cai, et al., 2014). The top-down inventories, bottom-up emissions, and satellite data will be integrated to build multi-resolution emission accounts of Chinese cities in order to construct the carbon emission distributions with high spatial resolution and further evaluate the human-induced emission characteristics.

With the emission data, the author will then analyse the emission drivers and its geospatial features of cities/city clusters in China. The identification and quantification of the socioeconomic factors contributing to CO_2 emission growth can be essential not only for carbon mitigation and natural impact control, but also for making recommendations regarding sustainable development. Up to date, there have been some studies on the socioeconomic drivers of the national and provincial CO_2 emissions in China employing the IDIA-LMDI (Chong et al., 2012; L. C. Liu et al., 2007b; Z. Liu, 2016b; S.-C. Xu, He, et al., 2014; W. Zhang, Li, et al., 2016). However, there is still no such studies at city-level. In the future work, the IDA-LMDI technique (B. W. Ang, 2004; Z. Liu, Geng, et al., 2012) will be used in this study to explore the drivers of emissions growth in Chinese cities.

What's more, the future work will construct the Inclusive Emission-Wealth Index for cities in China based on the Inclusive Wealth Index (IWI). IWI presents the big picture: measuring countries' wealth in terms of progress, well-being and long-term sustainability. It provides important insights into long-term economic growth and human well-being. "*Built up at the confluence of welfare, development and sustainability economics, the indicator has been designed to bring information about the wealth of nations and their sustainability, in a comprehensive way (page 185)"* (Roman et al., 2016). In the proposed study, the author will link the CO_2 emission data with the IWI as one sustainability index and apply the Inclusive Emission-Wealth Index to city-level in China, aiming at measuring a city's capacity to create and maintain human well-being and sustainable development over time.

Environmental impacts of the triangular trade between city clusters in China

Based on the previous study in this PhD thesis, the 330+ cities in China can be clustered as Resource Providers (energy production cities), Manufacturers (heavy/light/high-tech manufacturing cities), and End Consumers (service-based cities). They form a kind of triangular trade chain.

From a consumerist point of view, the way of end consumers' consumption would largely impact on resources depletion and local ecosystem degradation in resource providers, manufacturers, and even the global environmental changes. Therefore, if their mutually dependent interests are to meet each other in a context of sustainability, there is an urgent need to examine the environmental impacts via this triangular chain of production, and explore how to better link resource providers, manufacturers and end consumers in analysis and dialogue. This "Triangular Approach" can provide an alternative means of structuring dialogue and cooperation among resource providers, manufacturers and end consumers – is one possible conceptual framework to achieving low-carbon development in China and its cities.

Therefore, the future research will analyse the impact of the developed cities' imports from manufacturing cities and manufacturing cities' imports from resources providing cities by using: indicators of material flow e.g. energy, metal, and other industrial products, to conduct a path analysis throughout the whole trade chain to illustrate the physical material flows via trade among resource providers, manufacturers, and end consumers; indicators of carbon and water footprints to assess the induced impacts in resource providers and manufacturers.

Above all, in the future, the author will follow this PhD research, apply the crosscutting social-economic methods to investigate the carbon emissions and other environmental indicators of China and its cities. The future work will provide more accurate and robust data support of the low-carbon policy-making in China. Specific low-carbon research and dependence relationships will be analysed for Chinese cities, as well as other developing countries at similar industrialisation stages.

Appendix 1: Tables

Appendix Table 1 Emission factors from 8 sources

Emission factor sources		IPCC	NBS	NDRC	NC 1994	NC 2005	MEIC	UN-China	UN average	Liu et al.'s nature	Average value	CV
NCV_i	Raw Coal	0.28	0.21	0.21	0.21	0.22	0.19	0.21	0.29	0.21	0.23	15%
	Cleaned Coal	0.27	0.26	0.23	0.24	0.23	0.26	0.21	0.29	0.26	0.25	9%
	Other Washed Coal	0.27	0.15	0.23	0.21	0.23	0.15	0.21	0.29	0.15	0.21	23%
	Briquettes	0.26	0.18	0.17	0.20	0.17	0.18	0.21	0.29	0.18	0.20	20%
	Coke	0.28	0.28	0.28	0.28	0.28	0.28	0.26	0.26	0.28	0.28	3%
	Coke Oven Gas	1.88	1.63	1.74	1.63	1.74	1.67	1.88	1.88	1.61	1.74	6%
	Other Gas	1.88	0.84	1.58	0.84	1.58	0.52	1.88	1.88	0.83	1.31	39%
	Other Coking Products	0.43	0.28	0.28	0.28	0.28	0.42	0.43	0.43	0.28	0.35	21%
	Crude Oil	0.42	0.42	0.43	0.42	0.43	0.42	0.42	0.42	0.43	0.42	1%
	Gasoline	0.44	0.43	0.45	0.45	0.45	0.43	0.45	0.45	0.44	0.44	2%
	Kerosene	0.44	0.43	0.45	0.45	0.45	0.43	0.43	0.43	0.44	0.44	2%
	Diesel Oil	0.43	0.43	0.43	0.45	0.43	0.43	0.42	0.42	0.43	0.43	2%
	Fuel Oil	0.40	0.42	0.40	0.40	0.40	0.42	0.40	0.40	0.43	0.41	2%
	LPG	0.47	0.50	0.47	0.47	0.47	0.50	0.46	0.46	0.51	0.48	4%
	Refinery Gas	0.50	0.46	0.46	0.40	0.46	0.46	0.42	0.42	0.47	0.45	6%
	Other Petroleum Products	0.40	0.42	0.45	0.40	0.45	0.42	0.42	0.42	0.43	0.42	4%
	Natural Gas	3.44	3.89	3.89	3.90	3.89	3.89	3.44	3.44	3.89	3.74	6%
CC_i	Raw Coal	25.80	26.37	26.37	24.26	25.83	25.80	25.80	25.80	26.32	25.82	2%
	Cleaned Coal	26.80	25.41	25.41	26.35	27.82	25.80	26.80	26.80	26.32	26.39	3%
	Other Washed Coal	26.80	25.41	25.41	24.26	27.82	25.80	26.80	26.80	26.32	26.16	4%
	Briquettes	25.80	33.56	33.56	24.26	33.56	25.80	25.80	25.80	26.32	28.27	13%
	Coke	29.20	29.42	29.42	29.50	28.84	25.52	29.20	29.20	31.38	29.08	5%
	Coke Oven Gas	12.10	13.58	13.58	20.00	14.00	15.16	12.10	12.10	21.49	14.90	22%

	Other Gas	12.10	12.20	12.20	12.10	12.20	15.16	12.10	12.10	21.49	13.52	22%
	Other Coking Products	25.80	29.50	29.50	25.80	20.00	19.91	25.80	25.80	27.45	25.51	13%
	Crude Oil	20.00	20.08	20.08	20.00	20.08	19.91	20.00	20.00	20.08	20.03	0%
	Gasoline	18.90	18.90	18.90	18.90	18.90	19.91	18.90	18.90	18.90	19.01	2%
	Kerosene	19.50	19.60	19.60	19.60	19.60	19.91	19.50	19.50	19.60	19.60	1%
	Diesel Oil	20.20	20.20	20.20	20.20	20.20	19.91	20.20	20.20	20.20	20.17	0%
	Fuel Oil	21.10	21.10	21.10	21.10	21.10	19.91	21.10	21.10	21.10	20.97	2%
	LPG	17.20	17.20	17.20	17.20	17.20	19.91	17.20	17.20	17.20	17.50	5%
	Refinery Gas	15.70	18.20	18.20	15.70	18.20	19.91	15.70	15.70	20.00	17.48	10%
	Other Petroleum Products	20.00	20.00	20.00	20.00	20.00	19.91	20.00	20.00	20.20	20.01	0%
	Natural Gas	15.30	15.32	15.32	15.30	15.32	15.16	15.30	15.30	15.32	15.29	0%
O_i	Raw Coal	0.98	0.94	0.94	0.90	0.92	1.00	1.00	1.00	0.92	0.95	4%
	Cleaned Coal	0.98	0.98	0.98	0.90	0.92	1.00	1.00	1.00	0.92	0.96	4%
	Other Washed Coal	0.98	0.98	0.98	0.90	0.92	1.00	1.00	1.00	0.92	0.96	4%
	Briquettes	0.98	0.90	0.90	0.90	0.90	1.00	1.00	1.00	0.92	0.94	5%
	Coke	0.98	0.93	0.93	0.97	0.93	1.00	1.00	1.00	0.92	0.96	3%
	Coke Oven Gas	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	0.92	0.99	2%
	Other Gas	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	0.92	0.99	2%
	Other Coking Products	0.99	0.93	0.93	0.97	0.93	1.00	1.00	1.00	0.92	0.96	3%
	Crude Oil	0.99	0.98	0.98	0.98	0.98	1.00	1.00	1.00	0.98	0.99	1%
	Gasoline	0.99	0.98	0.98	0.98	0.98	1.00	1.00	1.00	0.98	0.99	1%
	Kerosene	0.99	0.98	0.98	0.98	0.98	1.00	1.00	1.00	0.98	0.99	1%
	Diesel Oil	0.99	0.98	0.98	0.98	0.98	1.00	1.00	1.00	0.98	0.99	1%
	Fuel Oil	0.99	0.98	0.98	0.98	0.98	1.00	1.00	1.00	0.98	0.99	1%
	LPG	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	0.98	0.99	1%
	Refinery Gas	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	0.98	0.99	1%
	Other Petroleum Products	0.99	0.98	0.98	0.98	0.98	1.00	1.00	1.00	0.98	0.99	1%
	Natural Gas	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	0.99	0.99	0%
EF_i	Raw Coal	2.61	1.90	1.90	1.67	1.94	1.80	1.98	2.77	1.83	2.05	18%
	Cleaned Coal	2.57	2.41	2.12	2.13	2.17	2.49	2.05	2.88	2.31	2.35	11%

Other Washed Coal	2.57	1.41	2.12	1.66	2.17	1.46	2.05	2.88	1.33	1.96	26%
Briquettes	2.39	1.97	1.93	1.60	1.93	1.68	1.98	2.77	1.60	1.98	18%
Coke	2.96	2.85	2.85	2.99	2.79	2.66	2.82	2.82	2.96	2.86	3%
Coke Oven Gas	8.26	8.04	8.55	11.84	8.85	9.30	8.34	8.34	11.67	9.24	15%
Other Gas	8.26	3.73	6.98	3.70	6.98	2.91	8.34	8.34	6.02	6.14	33%
Other Coking Products	4.03	2.86	2.86	2.61	1.94	3.05	4.07	4.07	2.59	3.12	23%
Crude Oil	3.07	3.02	3.08	3.01	3.08	3.05	3.10	3.10	3.10	3.07	1%
Gasoline	3.05	2.93	3.04	3.04	3.04	3.14	3.11	3.11	2.99	3.05	2%
Kerosene	3.10	3.04	3.15	3.15	3.15	3.14	3.09	3.09	3.10	3.11	1%
Diesel Oil	3.15	3.10	3.15	3.25	3.15	3.11	3.15	3.15	3.12	3.15	1%
Fuel Oil	3.09	3.17	3.05	3.05	3.05	3.05	3.13	3.13	3.26	3.11	2%
LPG	2.95	3.13	2.95	2.95	2.95	3.66	2.87	2.87	3.15	3.06	8%
Refinery Gas	2.82	3.04	3.04	2.29	3.04	3.36	2.41	2.41	3.38	2.87	14%
Other Petroleum Products	2.90	3.01	3.24	2.89	3.24	3.05	3.12	3.12	3.12	3.08	4%
Natural Gas	1.91	2.17	2.17	2.17	2.17	2.16	1.93	1.93	2.16	2.08	5%

Unit: NCV_i $PJ/10^4 tonnes,\ 10^8 m^3$, CC_i $tonne\ C/TJ$, O_i %, EF_i $tonnes\ CO_2/tonnes,\ 10^4 m^3$

Appendix Table 2 Oxygenation efficiencies

Sectors	Raw Coal	Cleaned Coal	Other Washed Coal	Briquettes	Coke	Coke Oven Gas	Other Gas	Other Coking Products	Crude Oil	Gasoline	Kerosene	Diesel Oil	Fuel Oil	LPG	Refinery Gas	Other Petroleum Products	Natural Gas
Farming	83%	83%	83%	83%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Coal mining	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Petro. and gas ext.	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Ferrous mining	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Nonferrous mining	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Non-metal mining	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Other mining	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Food processing	80%	80%	80%	80%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Food production	80%	80%	80%	80%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Beverage	80%	80%	80%	80%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Tobacco	80%	80%	80%	80%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Textile	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Garments	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Leather	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Timber	80%	80%	80%	80%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Furniture	80%	80%	80%	80%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Papers	80%	80%	80%	80%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Printing	80%	80%	80%	80%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Cultural	80%	80%	80%	80%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%

Petroleum proc.	83%	83%	83%	83%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Chemicals	85%	85%	85%	85%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Medicals	85%	85%	85%	85%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Chemical fibre	85%	85%	85%	85%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Rubber	85%	85%	85%	85%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Plastic	85%	85%	85%	85%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Non-metal prod.	90%	90%	90%	90%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Ferrous proc.	84%	84%	84%	84%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Non-ferrous proc.	84%	84%	84%	84%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Metal prod.	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Ordinary equip.	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Special equip.	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Transport equip.	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Electric equip.	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Electronic equip.	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Instruments	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Other manuf.	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Waste	87%	87%	87%	87%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Power and heat	87%	87%	87%	87%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Gas	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Water	82%	82%	82%	82%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Construction	83%	83%	83%	83%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Transportation	74%	74%	74%	74%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Wholesale	74%	74%	74%	74%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%

Other services	74%	74%	74%	74%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Household-urban	74%	74%	74%	74%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%
Household-rural	74%	74%	74%	74%	89%	91%	91%	89%	96%	96%	96%	96%	96%	97%	97%	96%	98%

Unit: %

Appendix Table 3 National sectoral-approach CO_2 emissions, 2000-2015

Fuels	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total	3003	3250	3472	4086	4680	5401	6009	6546	6761	7334	7905	8742	9081	9534	9438	9265
Raw Coal	1767	1868	2049	2434	2772	3151	3488	3752	3872	4163	4408	4918	5077	5272	4994	4872
Cleaned Coal	25	25	21	34	51	54	59	66	80	87	88	98	98	98	117	112
Other Washed Coal	62	67	68	74	95	98	113	133	140	156	166	161	172	160	180	172
Briquettes	10	11	12	14	14	15	19	23	25	27	68	73	76	81	85	77
Coke	296	326	350	435	494	687	763	853	876	992	1072	1169	1242	1265	1294	1217
Coke Oven Gas	28	29	30	34	40	58	63	61	78	77	84	93	91	96	98	93
Other Gas	69	128	93	94	113	160	197	276	262	311	337	401	396	472	505	493
Other Coking Products	4	4	5	6	7	7	9	11	13	16	16	16	13	16	15	17
Crude Oil	20	20	21	25	23	26	29	25	20	20	20	14	16	17	17	20
Gasoline	102	105	111	122	137	142	158	161	180	180	203	222	239	274	286	332
Kerosene	26	27	28	29	32	33	35	38	39	44	53	55	59	66	71	81
Diesel Oil	206	221	240	265	315	339	373	386	418	419	454	483	523	530	530	535
Fuel Oil	107	116	112	131	147	130	136	127	99	86	84	77	71	72	72	69
LPG	45	43	49	55	61	62	67	71	64	65	67	70	69	78	89	105
Refinery Gas	23	23	23	24	27	31	32	34	36	41	44	48	49	51	55	58
Other Petroleum Products	0	2	2	2	4	7	4	6	5	6	11	10	9	8	9	10
Natural Gas	39	44	47	57	66	90	103	129	149	166	183	224	245	276	299	317
Process-cement	173	192	211	251	281	311	359	396	407	478	547	610	635	702	724	686

Unit: Mt

Appendix Table 4 National reference-approach CO_2 emissions, 2000-2015

Items		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Raw Coal	Indigenous production	2533	2692	2837	3357	3884	4327	4702	5050	5312	5700	6273	6888	7218	7272	7088	6855
	Import	4	5	21	21	35	49	71	96	81	246	341	414	537	609	542	380
	Export (-)	-101	-165	-154	-172	-159	-131	-116	-97	-83	-41	-35	-27	-17	-13	-10	-10
	Stock decrease	-24	4	15	50	0	65	128	130	76	-19	-64	-53	-53	-48	-61	34
	Loss	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Non-energy use	58	62	64	76	94	107	115	115	120	124	130	128	140	151	141	153
	Raw coal total	2354	2475	2655	3180	3665	4203	4670	5064	5267	5761	6386	7094	7546	7668	7418	7106
Crude Oil	Indigenous production	501	504	513	521	540	557	568	573	585	582	624	623	638	645	650	659
	Import	216	185	213	280	377	390	446	501	550	626	730	780	833	866	948	1031
	Export (-)	-32	-23	-24	-25	-17	-25	-19	-12	-13	-16	-9	-8	-7	-5	-2	-9
	Stock decrease	-28	-4	-3	-2	-9	2	-3	-16	-31	-21	-27	-45	-28	-10	-12	-19
	Loss	6	6	6	5	5	5	6	6	6	6	6	5	5	7	3	3
	Non-energy use	3	3	3	3	3	3	6	5	4	5	5	2	1	3	11	4
	Crude oil total	649	653	691	766	883	916	979	1035	1080	1161	1307	1343	1428	1486	1569	1655
Natural Gas	Indigenous production	59	66	71	76	90	107	127	150	174	184	207	228	239	261	282	291
	Import	0	0	0	0	0	0	2	9	10	17	8	31	47	60	69	74
	Export (-)	-7	-7	-7	-4	-5	-6	-6	-6	-7	-7	-9	-7	-6	-6	-6	-7
	Stock decrease	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Loss	1	1	1	1	2	2	2	2	3	5	4	3	4	3	4	4
	Non-energy use	12	14	14	16	18	19	17	20	23	22	17	21	27	25	26	21
	Natural gas total	38	44	48	54	65	79	103	130	151	168	186	227	250	288	314	332
Process	Cement	173	192	211	251	281	311	359	396	407	478	547	610	635	702	724	686

Total apparent CO_2 emissions	3214	3364	3605	4250	4895	5509	6111	6624	6905	7568	8425	9275	9859	10145	10025	9780

Unit: Mt

Appendix Table 5 Provincial sectoral-approach CO_2 emissions, 1997–2015

Provinces	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Beijing	62	63	67	68	77	78	82	88	92	97	103	99	100	103	94	97	93	92	95
Tianjin	51	52	53	58	60	65	66	78	89	96	103	110	122	137	152	158	157	155	152
Hebei	212	211	223	237	251	284	329	374	459	487	529	554	578	647	725	714	769	752	734
Shanxi	149	148	146	148	184	221	252	268	290	320	345	371	375	407	439	466	488	476	440
Inner Mongolia	97	92	97	106	116	127	149	207	241	291	340	411	445	477	598	622	576	582	585
Liaoning	201	191	184	213	206	221	237	250	280	318	362	371	407	446	455	461	482	484	472
Jilin	99	83	84	83	89	92	134	112	143	159	171	179	186	202	234	230	222	223	208
Heilongjiang	129	124	122	125	121	118	130	140	158	179	187	197	203	218	247	269	257	269	265
Shanghai	103	104	116	118	123	128	137	149	159	165	175	178	179	187	200	195	201	188	189
Jiangsu	184	187	194	199	192	220	251	312	396	441	469	497	516	580	633	656	694	705	760
Zhejiang	115	115	121	131	143	156	178	218	256	290	325	330	338	359	379	377	379	375	375
Anhui	109	106	113	119	127	113	168	154	157	176	198	225	252	262	291	318	343	350	351
Fujian	44	47	60	56	56	67	83	100	124	135	161	166	188	199	237	232	229	243	230
Jiangxi	52	51	51	53	58	63	76	89	96	109	127	130	142	148	164	164	197	202	210
Shandong	199	213	214	195	233	259	325	398	557	606	663	698	718	767	801	842	762	790	824
Henan	154	156	157	162	181	194	216	278	336	379	426	436	451	505	549	521	484	535	518
Hubei	134	133	135	137	135	154	165	182	189	225	250	254	275	324	374	368	309	310	308
Hunan	98	99	81	77	85	92	105	125	178	203	223	227	239	255	286	282	271	270	289
Guangdong	165	173	185	200	210	231	262	297	342	376	410	417	438	472	521	505	497	504	444
Guangxi	51	52	52	56	56	57	67	87	99	113	128	133	152	172	192	205	210	208	270
Hainan	7	10	8	9	9	N/A	16	17	16	19	22	25	27	29	35	37	39	41	42
Chongqing	55	64	69	71	65	70	68	68	82	90	99	126	133	141	160	165	140	156	179
Sichuan	123	123	109	105	109	124	157	175	170	190	208	230	263	304	303	331	343	341	323

Guizhou	72	78	77	81	83	86	110	129	146	170	172	163	185	192	211	230	233	231	234
Yunnan	58	57	55	53	61	72	89	59	133	150	161	164	187	194	205	212	206	195	176
Shaanxi	69	66	59	59	68	76	86	108	122	129	148	165	186	219	244	262	266	277	277
Gansu	50	51	52	54	56	59	67	78	84	89	98	103	101	126	139	153	160	164	159
Qinghai	12	12	14	12	15	16	18	19	20	24	26	32	33	32	37	45	48	48	51
Ningxia	17	18	17	N/A	N/A	N/A	55	66	52	59	66	75	80	95	137	135	143	143	141
Xinjiang	63	64	62	65	54	70	77	90	101	114	125	137	157	168	203	252	293	329	343
Total	2936	2939	2978	3053	3224	3516	4154	4715	5567	6198	6822	7205	7656	8367	9245	9502	9493	9640	9644

Unit: Mt

Appendix Table 6 Provincial reference-approach CO_2 emissions, 1997–2015

Provinces	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Beijing	61	60	61	63	62	64	69	54	95	81	80	92	108	97	95	96	87	89	83
Tianjin	57	56	57	67	67	69	72	79	90	90	90	93	156	134	149	143	151	150	82
Hebei	249	247	252	258	267	290	321	366	409	409	454	482	564	569	623	642	658	625	639
Shanxi	231	232	142	88	93	208	308	323	296	314	238	594	590	654	766	855	1499	1554	1474
Inner Mongolia	107	101	103	111	118	132	126	210	247	278	329	438	477	562	741	789	784	903	859
Liaoning	244	237	249	290	272	294	320	356	398	417	411	436	457	495	524	543	530	521	502
Jilin	109	94	95	96	103	105	116	124	147	164	162	191	202	226	265	265	237	235	219
Heilongjiang	184	171	165	172	163	164	172	193	228	231	222	239	275	352	381	393	363	350	348
Shanghai	87	87	93	101	106	109	124	134	142	138	132	144	142	161	171	169	182	157	162
Jiangsu	203	203	208	216	217	232	268	314	387	420	436	462	486	546	613	620	638	621	634
Zhejiang	117	109	121	100	148	163	184	232	267	302	326	339	352	376	399	384	388	381	382
Anhui	116	113	115	122	129	133	150	165	172	189	197	240	273	283	315	356	387	402	393
Fujian	42	43	49	54	54	62	75	87	99	113	129	137	162	180	210	209	204	229	234
Jiangxi	57	51	48	52	53	56	68	83	90	101	107	115	117	134	145	146	162	165	170
Shandong	265	261	260	261	303	346	424	518	662	746	766	832	880	929	977	1008	944	998	1052
Henan	176	133	140	141	156	163	232	239	343	352	395	331	472	573	654	546	594	558	537
Hubei	122	111	123	128	127	135	151	169	168	200	211	212	233	280	322	311	253	252	253
Hunan	75	101	79	76	82	95	104	114	167	185	202	198	212	232	270	275	266	256	251
Guangdong	155	147	158	182	185	198	226	251	272	310	327	357	395	445	501	487	493	542	507
Guangxi	45	44	45	47	45	42	50	67	71	81	90	96	110	134	173	193	190	183	173
Hainan	3	10	3	5	5	N/A	8	6	8	15	35	36	38	45	53	54	52	59	65
Chongqing	57	55	60	61	56	58	55	64	73	84	91	120	136	138	151	149	134	145	147
Sichuan	120	118	100	104	106	114	149	170	159	168	208	234	271	284	280	290	285	360	308

Guizhou	100	105	62	61	56	69	112	123	144	168	160	195	227	247	269	287	314	320	328
Yunnan	64	61	58	54	59	63	82	60	125	141	137	150	165	176	188	195	196	188	179
Shaanxi	78	78	74	69	70	85	94	116	217	187	234	275	262	308	345	405	483	639	666
Gansu	65	67	67	71	73	79	90	100	105	110	118	126	124	145	170	174	181	180	177
Qinghai	12	12	14	13	15	16	18	20	21	24	25	32	35	37	50	59	71	75	51
Ningxia	25	29	28	N/A	N/A	N/A	38	61	74	82	98	109	140	152	191	189	188	195	193
Xinjiang	85	89	87	89	94	92	103	121	132	149	152	179	215	241	286	333	336	542	535
Total	3308	3225	3116	3152	3284	3639	4308	4920	5809	6250	6563	7486	8277	9135	10276	10565	11251	11872	11603

Unit: Mt

Appendix Table 7 Per capita CO_2 emissions of provinces, 2000-2015

Provinces	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Beijing	5.0	5.6	5.5	5.6	5.9	6.0	6.0	6.1	5.6	5.4	5.2	4.7	4.7	4.4	4.3	4.4
Tianjin	5.8	6.0	6.5	6.5	7.6	8.5	8.9	9.3	9.4	10.0	10.5	11.2	11.2	10.7	10.2	9.8
Hebei	3.6	3.8	4.2	4.9	5.5	6.7	7.1	7.6	7.9	8.2	9.0	10.0	9.8	10.5	10.2	9.9
Shanxi	4.6	5.6	6.7	7.6	8.0	8.6	9.5	10.2	10.9	11.0	11.4	12.2	12.9	13.4	13.0	12.0
Inner Mongolia	4.4	4.9	5.3	6.3	8.7	10.0	12.0	14.0	16.8	18.1	19.3	24.1	25.0	23.1	23.2	23.3
Liaoning	5.1	4.9	5.3	5.6	5.9	6.6	7.4	8.4	8.6	9.4	10.2	10.4	10.5	11.0	11.0	10.8
Jilin	3.1	3.3	3.4	5.0	4.1	5.3	5.8	6.2	6.6	6.8	7.4	8.5	8.3	8.1	8.1	7.5
Heilongjiang	3.3	3.2	3.1	3.4	3.7	4.1	4.7	4.9	5.2	5.3	5.7	6.5	7.0	6.7	7.0	7.0
Shanghai	7.3	7.3	7.5	7.8	8.1	8.4	8.4	8.5	8.3	8.1	8.1	8.5	8.2	8.3	7.7	7.8
Jiangsu	2.7	2.6	3.0	3.4	4.1	5.2	5.8	6.1	6.4	6.6	7.4	8.0	8.3	8.7	8.9	9.5
Zhejiang	2.8	3.0	3.3	3.7	4.4	5.1	5.7	6.3	6.3	6.4	6.6	6.9	6.9	6.9	6.8	6.8
Anhui	1.9	2.1	1.8	2.7	2.5	2.6	2.9	3.2	3.7	4.1	4.4	4.9	5.3	5.7	5.8	5.7
Fujian	1.7	1.6	1.9	2.4	2.8	3.5	3.8	4.5	4.6	5.1	5.4	6.4	6.2	6.1	6.4	6.0
Jiangxi	1.3	1.4	1.5	1.8	2.1	2.2	2.5	2.9	3.0	3.2	3.3	3.7	3.6	4.4	4.5	4.6
Shandong	2.2	2.6	2.8	3.6	4.3	6.0	6.5	7.1	7.4	7.6	8.0	8.3	8.7	7.8	8.1	8.4
Henan	1.7	1.9	2.0	2.2	2.9	3.6	4.0	4.6	4.6	4.8	5.4	5.8	5.5	5.1	5.7	5.5
Hubei	2.4	2.4	2.7	2.9	3.2	3.3	4.0	4.4	4.4	4.8	5.7	6.5	6.4	5.3	5.3	5.3
Hunan	1.2	1.3	1.4	1.6	1.9	2.8	3.2	3.5	3.6	3.7	3.9	4.3	4.2	4.1	4.0	4.3
Guangdong	2.3	2.4	2.6	2.9	3.3	3.7	4.0	4.2	4.2	4.3	4.5	5.0	4.8	4.7	4.7	4.1
Guangxi	1.2	1.2	1.2	1.4	1.8	2.1	2.4	2.7	2.8	3.1	3.7	4.1	4.4	4.5	4.4	5.6
Hainan	1.1	1.2	N/A	1.9	2.1	2.0	2.3	2.6	2.9	3.1	3.3	4.0	4.2	4.4	4.5	4.6
Chongqing	2.5	2.3	2.5	2.4	2.4	2.9	3.2	3.5	4.4	4.7	4.9	5.5	5.6	4.7	5.2	5.9
Sichuan	1.3	1.3	1.5	1.9	2.2	2.1	2.3	2.6	2.8	3.2	3.8	3.8	4.1	4.2	4.2	3.9
Guizhou	2.2	2.2	2.2	2.8	3.3	3.9	4.6	4.7	4.5	5.2	5.5	6.1	6.6	6.7	6.6	6.6

Yunnan	1.2	1.4	1.7	2.0	1.3	3.0	3.4	3.6	3.6	4.1	4.2	4.4	4.5	4.4	4.1	3.7
Shaanxi	1.6	1.9	2.1	2.3	2.9	3.3	3.5	4.0	4.4	5.0	5.9	6.5	7.0	7.1	7.3	7.3
Gansu	2.2	2.2	2.3	2.6	3.1	3.3	3.5	3.8	4.1	3.9	4.9	5.4	5.9	6.2	6.3	6.1
Qinghai	2.3	2.8	3.0	3.3	3.5	3.7	4.4	4.7	5.7	6.0	5.6	6.4	7.8	8.3	8.3	8.7
Ningxia	N/A	N/A	N/A	9.5	11.2	8.7	9.7	10.9	12.2	12.8	15.1	21.5	20.9	21.8	21.5	21.1
Xinjiang	3.5	2.9	3.7	4.0	4.6	5.0	5.6	6.0	6.4	7.3	7.7	9.2	11.3	12.9	14.3	14.5

Unit: tonnes

Appendix Table 8 CO_2 emission intensity of provinces, 2000-2015

Provinces	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Beijing	2.2	2.2	2.0	1.9	1.8	1.7	1.5	1.4	1.3	1.2	1.1	0.9	0.9	0.8	0.7	0.7
Tianjin	3.4	3.2	3.0	2.7	2.7	2.7	2.5	2.4	2.2	2.1	2.0	1.9	1.7	1.5	1.4	1.2
Hebei	4.7	4.6	4.7	4.9	4.9	5.3	5.0	4.8	4.6	4.4	4.3	4.4	3.9	3.9	3.6	3.3
Shanxi	8.0	9.1	9.6	9.5	8.8	8.5	8.4	7.8	7.7	7.4	7.0	6.7	6.5	6.2	5.8	5.2
Inner Mongolia	6.9	6.8	6.6	6.6	7.6	7.1	7.3	7.1	7.3	6.8	6.3	6.9	6.5	5.5	5.1	4.8
Liaoning	4.6	4.0	3.9	3.8	3.5	3.5	3.5	3.5	3.2	3.1	2.9	2.7	2.5	2.4	2.3	2.1
Jilin	4.3	4.2	3.9	5.2	3.9	4.4	4.3	3.9	3.6	3.3	3.1	3.2	2.8	2.5	2.3	2.0
Heilongjiang	4.0	3.5	3.1	3.1	3.0	3.0	3.1	2.9	2.7	2.5	2.4	2.4	2.4	2.1	2.1	1.9
Shanghai	2.5	2.3	2.2	2.1	2.0	1.9	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0	0.9
Jiangsu	2.3	2.0	2.1	2.1	2.3	2.5	2.4	2.3	2.1	2.0	2.0	1.9	1.8	1.7	1.6	1.6
Zhejiang	2.1	2.1	2.0	2.0	2.2	2.3	2.3	2.2	2.0	1.9	1.8	1.8	1.6	1.5	1.4	1.3
Anhui	4.1	4.0	3.3	4.4	3.6	3.3	3.2	3.2	3.2	3.2	2.9	2.8	2.8	2.7	2.5	2.3
Fujian	1.5	1.4	1.5	1.6	1.8	2.0	1.9	2.0	1.8	1.8	1.7	1.8	1.6	1.4	1.3	1.2
Jiangxi	2.7	2.7	2.6	2.8	2.9	2.8	2.8	2.9	2.6	2.5	2.3	2.3	2.0	2.2	2.1	2.0
Shandong	2.3	2.5	2.5	2.8	3.0	3.6	3.4	3.3	3.1	2.8	2.7	2.5	2.4	2.0	1.9	1.8
Henan	3.2	3.3	3.2	3.2	3.7	3.9	3.8	3.8	3.4	3.2	3.2	3.1	2.7	2.3	2.3	2.1
Hubei	3.9	3.5	3.7	3.6	3.5	3.3	3.5	3.4	3.0	2.9	3.0	3.0	2.7	2.0	1.9	1.7
Hunan	2.2	2.2	2.2	2.3	2.4	3.1	3.1	3.0	2.7	2.5	2.3	2.3	2.0	1.8	1.6	1.6
Guangdong	1.9	1.8	1.7	1.7	1.7	1.7	1.6	1.6	1.4	1.4	1.3	1.3	1.2	1.1	1.0	0.8
Guangxi	2.7	2.5	2.3	2.4	2.8	2.8	2.9	2.8	2.6	2.6	2.6	2.6	2.5	2.3	2.1	2.5
Hainan	1.7	1.6	N/A	2.2	2.2	1.9	2.0	2.0	2.0	2.0	1.8	2.0	1.9	1.9	1.8	1.7
Chongqing	4.0	3.3	3.3	2.9	2.5	2.7	2.7	2.5	2.8	2.6	2.4	2.3	2.1	1.6	1.6	1.6
Sichuan	2.7	2.5	2.6	3.0	3.0	2.5	2.5	2.4	2.4	2.4	2.4	2.1	2.0	1.9	1.7	1.5
Guizhou	7.9	7.4	7.1	8.2	8.6	8.7	9.1	8.0	6.9	7.0	6.4	6.1	5.9	5.3	4.7	4.3

Yunnan	2.6	2.9	3.1	3.5	2.1	4.3	4.3	4.2	3.8	3.9	3.6	3.3	3.1	2.6	2.3	1.9
Shaanxi	3.3	3.5	3.5	3.5	3.9	3.9	3.7	3.6	3.5	3.4	3.5	3.5	3.3	3.0	2.9	2.6
Gansu	5.2	4.9	4.6	4.8	5.0	4.8	4.6	4.5	4.3	3.8	4.2	4.1	4.0	3.8	3.6	3.2
Qinghai	4.6	5.0	4.8	4.8	4.6	4.3	4.7	4.4	4.7	4.5	3.7	3.8	4.1	4.0	3.7	3.6
Ningxia	N/A	N/A	N/A	13.7	14.7	10.4	10.5	10.5	10.6	10.1	10.6	13.6	12.0	11.5	10.7	9.8
Xinjiang	4.8	3.6	4.4	4.3	4.5	4.6	4.7	4.6	4.5	4.8	4.6	5.0	5.5	5.8	5.9	5.6

Unit: tonnes / 10^4 yuan, at 2000 constant price

Appendix Table 9 Uncertainties in China's CO_2 emission inventory, 2000-2015

	2015			2014			2013		
Total	8,579.48	-16%	25%	8,714.25	-16%	25%	8,832.11	-17%	26%
Farming and household	501.79	-24%	7%	471.00	-24%	8%	447.65	-25%	9%
Coal mining	80.21	-17%	44%	104.11	-18%	45%	133.40	-20%	47%
Ferrous proc.	1,690.19	-20%	18%	1,802.73	-20%	18%	1,761.64	-20%	18%
Non-metal prod.	588.38	-15%	45%	630.48	-16%	44%	612.41	-18%	44%
Power and heat	3,836.69	-22%	43%	3,896.40	-22%	44%	4,061.84	-22%	44%
Other industry	893.06	-21%	17%	878.06	-21%	17%	904.29	-21%	19%
Construction	46.75	-8%	16%	44.67	-9%	18%	43.41	-9%	16%
Service sectors	942.41	-9%	1%	886.80	-9%	2%	867.46	-8%	3%
	2012			2011			2010		
Total	8,445.86	-17%	27%	8,131.52	-16%	27%	7,357.66	-16%	27%
Farming and household	420.75	-24%	11%	403.22	-24%	12%	379.41	-23%	14%
Coal mining	125.02	-21%	47%	121.02	-21%	48%	114.71	-22%	49%
Ferrous proc.	1,671.54	-19%	17%	1,598.55	-19%	18%	1,461.94	-19%	17%
Non-metal prod.	615.69	-17%	45%	634.67	-17%	45%	576.41	-17%	46%
Power and heat	3,854.76	-22%	45%	3,632.18	-22%	45%	3,195.80	-22%	45%
Other industry	905.63	-20%	21%	956.52	-20%	22%	909.60	-18%	23%
Construction	38.73	-9%	17%	39.29	-9%	17%	37.01	-9%	17%
Service sectors	813.74	-8%	3%	746.06	-8%	3%	682.79	-7%	4%
	2009			2008			2007		
Total	6,855.94	-16%	28%	6,354.18	-16%	28%	6,150.74	-16%	28%
Farming and household	352.88	-22%	17%	343.75	-22%	18%	367.35	-19%	20%
Coal mining	110.29	-21%	50%	70.49	-19%	46%	68.10	-20%	47%
Ferrous proc.	1,385.81	-19%	17%	1,198.09	-19%	17%	1,138.08	-19%	17%
Non-metal prod.	560.49	-18%	46%	534.99	-19%	44%	507.90	-18%	46%

Power and heat	2,899.73	-22%	45%	2,685.75	-22%	46%	2,601.00	-22%	45%
Other industry	884.65	-18%	24%	873.16	-19%	23%	849.16	-19%	23%
Construction	32.41	-8%	18%	29.57	-9%	18%	31.20	-9%	17%
Service sectors	629.68	-8%	5%	618.38	-7%	5%	587.95	-7%	6%
	2006			2005			2004		
Total	5,649.31	-16%	28%	5,090.53	-16%	28%	4,399.41	-16%	29%
Farming and household	381.73	-16%	21%	318.16	-18%	26%	300.39	-17%	27%
Coal mining	59.38	-20%	47%	61.41	-17%	40%	31.60	-16%	45%
Ferrous proc.	996.18	-19%	16%	886.69	-19%	15%	630.23	-19%	15%
Non-metal prod.	459.55	-18%	46%	438.82	-17%	49%	286.65	-13%	44%
Power and heat	2,431.26	-22%	46%	2,156.15	-22%	46%	1,890.84	-22%	45%
Other industry	768.58	-19%	23%	695.59	-21%	22%	763.06	-20%	30%
Construction	30.91	-10%	18%	28.41	-10%	18%	26.01	-11%	19%
Service sectors	521.71	-7%	7%	505.30	-6%	7%	470.63	-6%	7%
	2003			2002			2001		
Total	3,835.08	-16%	29%	3,261.45	-16%	29%	3,058.05	-15%	29%
Farming and household	283.33	-16%	27%	238.64	-18%	29%	271.11	-19%	30%
Coal mining	64.63	-28%	30%	46.87	-19%	46%	46.48	-18%	45%
Ferrous proc.	578.84	-17%	16%	451.72	-18%	17%	430.91	-18%	17%
Non-metal prod.	284.96	-18%	47%	226.55	-15%	45%	226.60	-15%	45%
Power and heat	1,729.75	-22%	46%	1,453.73	-22%	45%	1,301.92	-22%	45%
Other industry	490.39	-17%	19%	476.41	-18%	18%	440.09	-18%	18%
Construction	22.21	-11%	21%	21.14	-11%	21%	20.45	-11%	21%
Service sectors	380.98	-6%	8%	346.40	-6%	8%	320.50	-5%	9%
	2000								
Total	2,829.94	-15%	29%						

Farming and household	216.68	-17%	33%		
Coal mining	43.76	-18%	44%		
Ferrous proc.	390.58	-17%	16%		
Non-metal prod.	199.94	-15%	44%		
Power and heat	1,217.53	-22%	45%		
Other industry	427.08	-18%	19%		
Construction	20.29	-12%	23%		
Service sectors	314.07	-5%	8%		

Note: 1) The first number of each year refers to the emission estimates, in Mt. 2) The percentages followed indicate the 97.5% Confidence Interval around the central estimate.

Appendix Table 10 Emission-Socioeconomic indexes of 182 cities in 2010

No.	City	Area (km^2)	Population (10^3)	Per capita GDP (yuan)	Industry output (billion Yuan)	Total CO_2 emissions (Mt)	Emission intensity (tonnes/thousand Yuan)	Per capita Emissions (tonnes)	Per GDP Emission (tonnes/thousand Yuan)	City Group
1	Beijing	16411	18584	75943	1370	102.62	0.07	0.07	5.52	Service
2	Tianjin	11760	12637	72994	1675	132.01	0.08	0.14	10.45	High-tech
3	Shijiazhuang	15848	10028	33915	566	119.54	0.21	0.35	11.92	Light
4	Tangshan	13472	7525	59389	755	194.02	0.26	0.43	25.78	Heavy
5	Handan	12062	9033	26143	411	129.57	0.32	0.55	14.34	Heavy
6	Zhangjiakou	36873	4292	22517	89	53.16	0.59	0.55	12.39	Heavy
7	Taiyuan	6963	3540	50225	199	86.99	0.44	0.49	24.57	Energy
8	Yangquan	4570	1346	31898	54	32.99	0.61	0.77	24.51	Energy
9	Changzhi	13896	3329	27642	143	57.41	0.40	0.62	17.24	Energy
10	Jincheng	9425	2259	32337	85	34.63	0.41	0.47	15.33	Energy
11	Shuozhou	11066	1630	41107	83	27.16	0.33	0.41	16.66	Energy
12	Jinzhong	16392	3147	24275	103	60.65	0.59	0.79	19.28	Energy
13	Xinzhou	25117	3082	14193	39	24.17	0.61	0.55	7.84	Energy
14	Hohhot	17224	2788	66929	119	69.00	0.58	0.37	24.75	Energy
15	Baotou	27768	2610	94269	241	119.20	0.49	0.48	45.66	Heavy
16	Wuhai	1754	510	76653	55	21.65	0.40	0.55	42.42	Energy
17	Chifeng	90021	4335	25059	127	38.05	0.30	0.35	8.78	Heavy
18	Tongliao	59535	3084	38157	181	61.21	0.34	0.52	19.85	Light
19	Erdos	86752	1509	175125	268	131.56	0.49	0.50	87.17	Energy
20	Ulanqab	54492	2134	26604	68	43.15	0.64	0.76	20.22	Energy
21	Shenyang	12980	8046	62357	961	63.36	0.07	0.13	7.87	Heavy

22	Dalian	12574	6638	77704	770	73.86	0.10	0.14	11.13	High-tech
23	Benxi	8411	1700	50612	151	67.02	0.44	0.78	39.43	Heavy
24	Dandong	15290	2438	29893	87	10.09	0.12	0.14	4.14	Light
25	Fuxin	10355	1820	20819	45	34.82	0.78	0.92	19.13	Energy
26	Changchun	20604	7577	43936	588	61.15	0.10	0.18	8.07	Heavy
27	Jilin	27126	4341	41479	210	41.32	0.20	0.23	9.52	Heavy
28	Siping	14080	3398	22942	104	21.80	0.21	0.28	6.42	Light
29	Liaoyuan	5140	1238	33137	59	18.44	0.31	0.45	14.90	Light
30	Baicheng	25745	2026	21973	26	7.61	0.29	0.17	3.76	Light
31	Yanbian	43474	2185	24448	55	14.34	0.26	0.27	6.56	Light
32	Harbin	53068	9918	36951	230	68.93	0.30	0.19	6.95	Light
33	Qiqihaer	42469	5399	16309	83	45.61	0.55	0.52	8.45	Heavy
34	Jixi	22531	1900	22083	29	44.11	1.53	1.05	23.22	Energy
35	Hegang	14659	1089	23044	28	43.15	1.52	1.72	39.62	Energy
36	Shuangyashan	23209	1512	26215	36	18.84	0.52	0.48	12.46	Energy
37	Daqing	21219	2800	103576	329	106.80	0.32	0.37	38.14	Energy
38	Yichun(hlj)	32759	1271	15924	19	8.37	0.43	0.41	6.59	Light
39	Jiamusi	32704	2530	20254	31	11.45	0.36	0.22	4.53	Light
40	Heihe	82164	1741	14994	9	6.62	0.70	0.25	3.80	Energy
41	Shanghai	6340	22565	76074	3011	187.49	0.06	0.11	8.31	Service
42	Nanjing	6587	8012	64037	861	141.08	0.16	0.27	17.61	Service
43	Wuxi	4627	6286	92166	1297	73.77	0.06	0.13	11.74	High-tech
44	Xuzhou	11259	8632	34084	511	78.56	0.15	0.27	9.10	Light
45	Changzhou	4372	4523	67327	740	48.17	0.07	0.16	10.65	High-tech
46	Suzhou	8488	9919	93043	2465	172.99	0.07	0.19	17.44	High-tech

47	Nantong	8001	7309	47419	738	42.02	0.06	0.12	5.75	High-tech
48	Lianyungang	7500	4422	26987	194	20.00	0.10	0.17	4.52	Light
49	Huaian	10072	4810	28861	244	23.70	0.10	0.17	4.93	Light
50	Yancheng	16972	7373	31640	394	24.86	0.06	0.11	3.37	Light
51	Yangzhou	6591	4478	49786	575	31.40	0.05	0.14	7.01	High-tech
52	Zhenjiang	3847	3141	63280	419	44.24	0.11	0.22	14.09	High-tech
53	Taizhou(js)	5787	4644	44118	492	25.37	0.05	0.12	5.46	Light
54	Suqian	8555	4724	22525	114	6.50	0.06	0.06	1.38	Light
55	Hangzhou	16596	8520	69828	1108	84.56	0.08	0.14	9.93	High-tech
56	Ningbo	9816	7443	69368	1062	102.10	0.10	0.20	13.72	High-tech
57	Wenzhou	11786	7830	37359	449	29.54	0.07	0.10	3.77	High-tech
58	Jiaxing	3915	4411	52143	510	37.40	0.07	0.16	8.48	Light
59	Huzhou	5818	2872	45323	267	24.37	0.09	0.19	8.48	Light
60	Shaoxing	8279	4383	63770	680	39.11	0.06	0.14	8.92	Light
61	Jinhua	10941	5289	39897	341	43.15	0.13	0.20	8.16	High-tech
62	Zhoushan	1440	968	66581	98	6.13	0.06	0.10	6.34	Heavy
63	Taizhou(zj)	9411	5893	41172	363	30.81	0.08	0.13	5.23	Heavy
64	Lishui	17298	2119	31296	114	8.97	0.08	0.14	4.23	Heavy
65	Hefei	7047	4930	54796	380	34.06	0.09	0.13	6.91	High-tech
66	Wuhu	3317	2295	48306	225	28.59	0.13	0.26	12.46	Heavy
67	Bengbu	5941	3614	17621	77	12.36	0.16	0.19	3.42	Heavy
68	Huainan	2585	2317	26049	79	53.28	0.68	0.88	22.99	Energy
69	Maanshan	1686	1289	62942	136	55.43	0.41	0.68	43.02	Heavy
70	Huaibei	2741	2069	22309	88	38.60	0.44	0.84	18.66	Energy
71	Tongling	1113	724	64496	110	18.90	0.17	0.41	26.13	Heavy

72	Anqing	15318	5311	18604	132	18.20	0.14	0.18	3.43	Light
73	Huangshan	9807	1484	20846	33	1.58	0.05	0.05	1.06	Light
74	Chuzhou	13523	3998	17400	105	11.36	0.11	0.16	2.84	Light
75	Fuyang	9775	7960	9068	70	13.02	0.19	0.18	1.64	Energy
76	Suzhou	9787	6542	9945	68	20.68	0.31	0.32	3.16	Light
77	Chaohu	9394	3897	16158	83	20.07	0.24	0.32	5.15	High-tech
78	Lu'an	17976	5612	12047	83	8.37	0.10	0.12	1.49	Light
79	Bozhou	8374	4970	10318	32	6.92	0.21	0.13	1.39	Light
80	Xuancheng	12323	2533	20754	107	11.69	0.11	0.22	4.62	Heavy
81	Fuzhou	13066	6993	44667	455	37.99	0.08	0.12	5.43	High-tech
82	Xiamen	1573	3531	58337	369	11.85	0.03	0.06	3.36	High-tech
83	Putian	4119	2819	30161	127	6.86	0.05	0.08	2.43	Light
84	Quanzhou	11015	8000	44563	626	39.52	0.06	0.11	4.94	Light
85	Nanping	26308	2773	26279	78	7.49	0.10	0.10	2.70	Light
86	Longyan	19063	2561	38698	118	33.57	0.29	0.34	13.11	Light
87	Ningde	13452	2931	25200	92	10.32	0.11	0.14	3.52	Heavy
88	Nanchang	7402	5027	43769	277	39.95	0.14	0.18	7.95	Light
89	Jingdezhen	5256	1583	29155	69	12.08	0.18	0.26	7.63	Heavy
90	Pingxiang	3824	1852	28106	120	25.97	0.22	0.50	14.03	Heavy
91	Jiujiang	18823	4721	21862	150	24.93	0.17	0.24	5.28	Light
92	Xinyu	3178	1137	55492	120	29.37	0.24	0.47	25.82	Heavy
93	Yingtan	3560	1121	30769	118	4.80	0.04	0.14	4.28	Heavy
94	Ganzhou	39379	8405	13322	127	15.16	0.12	0.14	1.80	Heavy
95	Ji'an	25283	4813	14969	113	9.62	0.08	0.13	2.00	Light
96	Yichun(jx)	18669	5412	16075	124	24.57	0.20	0.28	4.54	Light

97	Fuzhou	18820	3917	16083	73	4.05	0.06	0.06	1.03	Light
98	Shangrao	22791	6557	13741	118	17.16	0.15	0.19	2.62	Heavy
99	Jinan	8177	6746	57966	449	64.88	0.14	0.17	9.62	High-tech
100	Qingdao	10978	8608	65827	1066	84.73	0.08	0.15	9.84	High-tech
101	Zibo	5965	4522	63397	774	89.25	0.12	0.31	19.74	Heavy
102	Dongying	7923	2027	116448	604	51.08	0.08	0.22	25.20	Energy
103	Weifang	16140	9019	34273	753	67.88	0.09	0.22	7.53	Light
104	Taian	7762	5487	37390	377	63.95	0.17	0.31	11.65	Heavy
105	Linyi	17191	10048	23886	459	59.51	0.13	0.25	5.92	Light
106	Heze	12239	8268	14841	253	20.69	0.08	0.17	2.50	Light
107	Zhengzhou	7446	8090	49947	591	76.34	0.13	0.19	9.44	Heavy
108	Luoyang	15200	6488	35762	413	66.97	0.16	0.29	10.32	Heavy
109	Pingdingshan	7904	4904	26730	200	59.65	0.30	0.46	12.16	Energy
110	Hebi	2182	1504	28531	99	23.86	0.24	0.56	15.86	Energy
111	Xinxiang	8169	5614	21196	217	32.42	0.15	0.27	5.78	Light
112	Jiaozuo	4071	3483	35767	289	37.71	0.13	0.30	10.83	Light
113	Puyang	4266	3559	21787	139	16.92	0.12	0.22	4.75	Energy
114	Xuchang	4996	4311	30536	250	29.83	0.12	0.23	6.92	Light
115	Sanmenxia	10496	2232	39176	204	112.70	0.55	1.29	50.49	Heavy
116	Nanyang	26509	10203	19145	250	155.74	0.62	0.80	15.26	Light
117	Shangqiu	10704	7582	15085	136	46.87	0.34	0.41	6.18	Light
118	Xinyang	18847	6447	16936	112	19.77	0.18	0.18	3.07	Light
119	Zhoukou	11959	9489	12944	150	44.65	0.30	0.36	4.71	Light
120	Zhumadian	15083	7464	14117	114	71.54	0.63	0.68	9.58	Light
121	Wuhan	8494	9440	58961	642	101.41	0.16	0.18	10.74	Service

122	Huangshi	4586	2428	28427	120	29.98	0.25	0.43	12.35	Heavy
123	Shiyan	23680	3464	21267	128	20.14	0.16	0.27	5.81	Heavy
124	Yichang	21084	4053	38181	212	25.00	0.12	0.16	6.17	Heavy
125	Xiangyang	19724	5500	27969	230	21.98	0.10	0.14	4.00	Light
126	Ezhou	1594	1042	37943	63	24.16	0.38	0.61	23.19	Heavy
127	Jinmen	12404	2862	25509	120	26.07	0.22	0.36	9.11	Light
128	Jinzhou	14092	5692	14707	90	11.89	0.13	0.14	2.09	Light
129	Xianning	9861	2463	21129	63	11.07	0.17	0.21	4.50	Light
130	Suizhou	9636	2185	18381	51	3.22	0.06	0.08	1.47	Light
131	Enshizhou	24111	2766	12696	23	8.24	0.36	0.23	2.98	Light
132	Changsha	11816	6844	66443	417	52.97	0.13	0.12	7.74	Light
133	Xiangtan	5015	2766	32321	150	32.07	0.21	0.36	11.60	Heavy
134	Hengyang	15299	6956	20419	188	15.38	0.08	0.11	2.21	Heavy
135	Shaoyang	20830	6948	10468	71	14.61	0.21	0.20	2.10	Light
136	Yueyang	15087	5476	28110	278	21.41	0.08	0.14	3.91	Light
137	Changde	18190	5618	26551	126	23.51	0.19	0.16	4.18	Light
138	Zhangjiajie	9516	1493	16238	11	4.60	0.42	0.19	3.08	Light
139	Yiyang	12144	4230	16839	81	15.28	0.19	0.21	3.61	Light
140	Chenzhou	19699	4505	24015	144	28.75	0.20	0.27	6.38	Heavy
141	Huaihua	27624	4696	14371	70	15.26	0.22	0.23	3.25	Light
142	Xiangxi	15462	2531	11991	27	3.64	0.14	0.12	1.44	Heavy
143	Guangzhou	7434	10372	103625	1383	100.50	0.07	0.09	9.69	Service
144	Shaoguan	18463	2971	22995	77	22.73	0.29	0.33	7.65	Heavy
145	Shenzhen	1992	8965	106880	1853	38.65	0.02	0.04	4.31	Service
146	Zhuhai	1711	1498	80697	298	13.00	0.04	0.11	8.68	High-tech

147	Shantou	2064	5123	23600	190	24.43	0.13	0.20	4.77	Light
148	Jiangmen	9568	4209	37313	383	30.94	0.08	0.20	7.35	High-tech
149	Maoming	11458	6227	23961	136	27.80	0.20	0.19	4.46	Energy
150	Huizhou	11343	3986	43397	391	23.59	0.06	0.14	5.92	High-tech
151	Heyuan	15642	2915	16301	83	9.41	0.11	0.20	3.23	High-tech
152	Yangjiang	7946	2397	26694	69	15.83	0.23	0.25	6.61	Light
153	Zhongshan	1800	2523	73348	502	17.21	0.03	0.09	6.82	High-tech
154	Yunfu	7779	2446	16391	47	17.86	0.38	0.45	7.30	High-tech
155	Nanning	22112	7026	25622	129	23.38	0.18	0.13	3.33	Light
156	Liuzhou	18617	3734	35230	239	48.95	0.20	0.37	13.11	Heavy
157	Guigang	10602	4346	12531	47	36.76	0.78	0.67	8.46	Light
158	Laibin	13411	2204	18369	37	21.15	0.57	0.52	9.59	Light
159	Chongqing	82829	28720	27596	914	147.50	0.16	0.19	5.14	Heavy
160	Chengdu	12132	11444	48510	581	41.63	0.07	0.07	3.64	High-tech
161	Zigong	4373	2810	23053	111	11.53	0.10	0.18	4.10	Heavy
162	Panzhihua	7440	1233	42499	95	81.23	0.85	1.55	65.88	Heavy
163	Deyang	5911	3636	25335	160	12.23	0.08	0.13	3.36	Heavy
164	Mianyang	20249	4788	20053	127	16.57	0.13	0.17	3.46	Light
165	Guizhou	8034	4305	26057	106	40.44	0.38	0.36	9.39	Light
166	Zunyi	30762	6141	14799	79	23.61	0.30	0.26	3.84	Light
167	Kunming	21015	6320	33550	244	80.90	0.33	0.38	12.80	Heavy
168	Xi'an	10108	8454	38341	313	55.72	0.18	0.17	6.59	Service
169	Baoji	18131	3736	26124	132	26.56	0.20	0.27	7.11	Heavy
170	Xianyang	10196	4888	22477	134	26.78	0.20	0.24	5.48	Energy
171	Yulin	43578	3347	52480	196	54.08	0.28	0.31	16.16	Energy

172	Lanzhou	13086	3236	34009	159	43.07	0.27	0.39	13.31	Energy
173	Jiayuguan	2935	221	83425	52	22.85	0.44	1.24	103.43	Heavy
174	Baiyin	21158	1760	17680	43	22.00	0.51	0.71	12.50	Heavy
175	Wuwei	33238	2154	10621	18	4.90	0.28	0.21	2.27	Light
176	Xining	7655	2210	28428	75	28.01	0.37	0.45	12.67	Heavy
177	Yinchuan	9025	1853	41520	94	95.48	1.02	1.24	51.52	Energy
178	Urumchi	13788	3110	43039	167	58.99	0.35	0.44	18.97	Energy
179	Karamay	9548	586	121387	133	61.14	0.46	0.86	104.32	Energy
180	Aletai	117972	602	22406	8	4.52	0.57	0.33	7.50	Heavy
181	Bayinguoleng	471526	1363	46955	56	17.96	0.32	0.28	13.18	Energy
182	Tulufan	69759	613	29828	4	11.10	2.99	0.61	18.11	Heavy

Data source: socioeconomic data of cities (NBS, 2011a).

Appendix 2: Jointly-authored publications used in this thesis

Chapter 3, section 3.5: Methods for city-level activity data collection

> **<u>Shan, Y.</u>**, Guan, D.*, Liu, J., Mi Z., Liu, Z., Liu, J.*, Schroeder, H., Cai B., Chen, Y., Shao, S., & Zhang, Q. (2017). Methodology and applications of city level CO_2 emission accounts in China. **Journal of Cleaner Production** (IF=5.715), *161, 1215-1225*. DOI: 10.1016/j.jclepro.2017.06.075

In this jointly-authored publication, this PhD author led the overall research, designed the city-level emission calculation method, analysed the results, and wrote the paper. G.D. and L.J. designed the research. M.Z., L.Z., S.H. revised the paper with comments. C.B. and Z.Q. provided the bottom-up emission database for verification. C.Y. and S.S. contribute to the raw data collection. This PhD author contribute over 85% of this publication.

Chapter 4, section 4.2.2: Reference-approach CO2 emissions of 30 provinces

> **<u>Shan, Y.</u>**, Liu, J.*, Liu, Z., Xu, X., Shao, S., Wang, P., & Guan, D.* (2016). New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors. **Applied Energy** (IF=7.182), *184, 742-750*. DOI: 10.1016/j.apenergy.2016.03.073

In this jointly-authored publication, this PhD author led the overall research, collected the raw data, calculated the provincial emission data, analysed the results, and wrote the paper. L.J. and G.D. designed the research. L.Z., X.X., S.S., W.P. revised the paper with comments. This PhD author contribute over 80% of this publication.

Chapter 4, section 4.3: Comparisons and uncertainties

> **<u>Shan, Y.</u>**, Guan, D.*, Zheng, H., Ou, J., Li, Y.*, Meng, J., Mi, Z., Zhu, L.*, & Zhang, Q. (2017). China CO_2 emission accounts 1997-2015. **Scientific Data** (IF=4.836), *5, 170201*. DOI: 10.1038/sdata.2017.201

In this jointly-authored publication, this PhD author led the project, collected and assembled the data, and prepared the manuscript. G.D. designed the research. Z.H. collected the raw data. O.J., L. Y., M. J., M. Z., L. Z., and Z.Q. revised the manuscript and participated in the construction of the database. This PhD author contribute over 85% of this publication.

Chapter 5, section 5.1: Emissions from China's Lime industry

Shan, Y., Liu, Z.*, & Guan, D. (2016). CO_2 emissions from China's lime industry. **Applied Energy** (IF=7.182), *166, 245-252*. DOI: 10.1016/j.apenergy.2015.04.091

In this jointly-authored publication, this PhD author led the overall research, collected the raw data, calculated the emission data from China's lime industry, analysed the results, and wrote the paper. L.Z. designed the research. G.D. revised the paper with comments. This PhD author contribute over 90% of this publication.

Chapter 5, section 5.2: Emissions from China's Petroleum coke combustion

Shan, Y., Guan, D.*, Meng, J., Liu, Z., Schroeder, H., Liu, J., & Mi, Z. Rapid growth of petroleum coke consumption and its related emissions in China. ***Applied Energy*** *(IF=7.182), in press*

In this jointly-authored publication, this PhD author led the overall research, collected the raw data, analysed the results, and wrote the paper. This PhD author contribute over 90% of this publication. The paper is now accepted by Applied Energy.

Chapter 6: Emissions and low-carbon development in Chinese cities

Shan, Y., Guan, D.*, Hubacek, K., Zheng, B., Davis, S.J.*, Jia, L., Liu, J., Liu, Z., Fromer, N., Mi, Z., Meng, J., Deng, X., Li, Y.*, Lin, J., Schroeder, H., Weisz, H., & Schellnhuber H.J. City-level climate change mitigation in China. ***Science Advances****, in press*

In this jointly-authored publication, this PhD author led the overall research, collected the city-level raw data, analysed the results, and wrote the paper. This

PhD author contribute over 80% of this publication. The paper is now accepted by Science Advance.

Chapter 7: Emissions from Tibet and its cities

> **<u>Shan, Y.</u>**, Zheng, H., Guan, D.*, Li, C., Mi, Z., Meng, J., Schroeder, H., Ma, J., & Ma, Z. (2017). Energy consumption and CO_2 emissions in Tibet and its cities in 2014. **Earth's Future** (IF=4.938), *5, 854-864*. DOI: 10.1002/2017EF000571

In this jointly-authored publication, this PhD author led the overall research, designed the method, calculated the emission data from Tibet, analysed the results, and wrote the paper. Z.H. and M.J. collected the raw data. G.D. designed the research. L.C. provided the Tibet's coal production and consumption data. M.Z., M.J., S.H., and M.Z. revised the paper with comments. This PhD author contribute over 85% of this publication.

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Methodology and applications of city level CO_2 emission accounts in China

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ABSTRACT

China is the world's largest energy consumer and CO_2 emitter. Cities contribute 85% of the total CO_2 emissions in China and thus are considered as the key areas for implementing policies designed for climate change adaption and CO_2 emission mitigation. However, the emission inventory construction of Chinese cities has not been well researched, mainly owing to the lack of systematic statistics and poor data quality. Focusing on this research gap, we developed a set of methods for constructing CO_2 emissions inventories for Chinese cities based on energy balance table. The newly constructed emission inventory is compiled in terms of the definition provided by the IPCC territorial emission accounting approach and covers 47 socioeconomic sectors, 17 fossil fuels and 9 primary industry products, which is corresponding with the national and provincial inventory. In the study, we applied the methods to compile CO_2 emissions inventories for 24 common Chinese cities and examined uncertainties of the inventories. Understanding the emissions sources in Chinese cities is the basis for many climate policy and goal research in the future.

1. Introduction

Cities are the main consumers of energy and emitters of CO_2 throughout the world. The International Energy Agency (IEA) (2009) estimates that CO_2 emissions from energy use in cities will grow by 1.8% per year between 2006 and 2030, with the share of global CO_2 emissions rising from 71% to 76%. As a result of urbanization, the world's urban population grew from 220 million in 1900 (13% of the world's population) to 3530 million in 2011 (52% of the world's population) (Kennedy et al., 2015). Cities are major components in the implementation of climate change adaption and CO_2 emission mitigation policies. Understanding the emission status of cities is considered a fundamental step for proposing mitigation actions.

With rapid economic development, lifestyle change and consumption growth (Hubacek et al., 2011), China is now the world's largest consumer of primary energy and emitter of greenhouse gas emissions (Guan et al., 2009). According to U.S. Energy Information Administration (EIA) (2010) and British Petroleum (2011), China produces 25% of global CO_2 emissions, consumes 20% of global primary energy. Among CO_2 emission sources, 85% of China's emissions are contributed by energy usage in cities, which is much higher than that of the USA (80%) or Europe (69%) (Dhakal, 2009, 2010). An effective understanding of the energy consumption and emission status of common cities in China is urgently required to practice mitigate climate change.

There are some challenges for the compilation of greenhouse gas inventories at the city level for China. First, it is difficult to define a city's boundary for greenhouse gas emissions accounting because energy and material flows among cities may bring a large quantity of cross-boundary greenhouse gas emissions (Liang and

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Zhang, 2011; Wolman, 1965). Commercial activities are much more frequent among cities, compared with inter-provinces/nations, which leads to a great challenge. Second, data for energy consumption and industry products are incomparable and very limited for most cities in China (Liu et al., 2012b). Complete energy balance tables and energy inventories are available for Chinese megacities only (Beijing, Tianjin, Shanghai, and Chongqing), another 250 + cities of various sizes and development stages lack consistent and systematic energy statistics. Data used in previous studies are from various sources, including city statistical documents, remote sensing images, direct interviews with local governmental officials, and published reports and literature (Xi et al., 2011). Those data require systematic reviews for consistency and accuracy.

In this study, we develop a feasible methodology for constructing CO_2 emissions inventories for Chinese cities from fossil energy consumption and industrial processes, aiming at providing unified and comparable energy and emission statistics for generic Chinese cities. The emission inventories are calculated based on cities' energy balance tables, which are consistent with national and provincial emission accounts by previous studies (Liu, 2016; Liu et al., 2015). We verify the method by comparing our results with previous studies, as well as calculating the uncertainties of the estimates. We apply the method to 24 Chinese cities in this study, and identify the main contributors to the cities' CO_2 emissions.

2. Literature review of emission inventory at city level

The CO_2 emission inventory has captured both public and academic attention in recent years. Most of the previous emissions inventories were developed at the national level (Guan et al., 2008, 2012; Menyah and Wolde-Rufael, 2010; Mi et al., 2017; Peters et al., 2012), provincial level (Meng et al., 2011; Shan et al., 2016a; Yu et al., 2014), and sectoral level (Liu et al., 2012a; Shan et al., 2016b; Shao et al., 2011). Emission inventories for cities are limited (Brondfield et al., 2012; Chen and Chen, 2012; Dodman, 2009; Hasegawa et al., 2015; Hillman and Ramaswami, 2010; Hoornweg et al., 2011; Kennedy et al., 2011; Ramaswami et al., 2008).

Most city-level GHG emissions inventories were calculated using a bottom-up approach in the previous research, i.e., by using energy data from certain sector sets. The sectors set are different from study to study. Wang et al. (2012) calculated carbon emissions of 12 Chinese provincial capital cities by 6 sectors, including industrial energy consumption, transportation, household energy consumption, commercial energy consumption, industrial processes and waste. Differently, Kennedy et al. (2010) and their subsequent research (Kennedy et al., 2009, 2014) compiled carbon emissions inventories that cover electricity, heating and industrial fuels, ground transportation fuels, aviation and marine transportation, industrial processes and product use, and waste for 10 global megacities. Creutzig et al. (2015) built an energy/emission dataset including 274 cities, and present the aggregate potential for urban climate change mitigation.

Compared with global research, CO_2 emission inventory research on Chinese cities has not been well documented. Dhakal (2009) compiled emission inventories for 35 provincial capital cities in China. Liu et al. (2012b) complied the scope 1 and 2 emission inventories of four Chinese municipalities from 1995 to 2009. Scope 1 emissions include CO_2 induced from direct use of primary energy and industrial activity within territorial boundary. Scope 2 emissions refer to the out boundary purchased electricity related CO_2 emissions. Sugar et al. (2012) compiled the 2006 emission inventories of Chinese municipalities and compared the results with 10 other global mega cities.

Above all, the current emission inventories of Chinese cities are compiled by sectors, which are not consistent with each other, as well as the national/provincial inventories. The national/provincial inventories are usually compiled according to energy balance tables in China. What's more, most existing research has focused on a few specific megacities, such as four municipality cities (Beijing, Tianjin, Shanghai and Chongqing) and few provincial capital cities, which have consistent and systematic energy statistics. Accurate accounts of cities' CO_2 emissions are needed for further analysis on emission-economic nexus (Chen and Chen, 2017, 2016; Chen et al., 2015; Lu and Chen, 2016; Meng et al., 2017; Mi et al., 2016; Shao et al., 2016).

3. Methodology

3.1. Boundary and method for emissions accounting

In accordance with the guidelines from the Intergovernmental Panel on Climate Change (IPCC) regarding the allocation of GHG emissions, we consider the administrative territorial scope for each city's CO_2 emissions accounting in this study. Administrative territorial emissions refer to the emissions that occur within administered territories and offshore areas over which one region has jurisdiction (IPCC (2006)), including emissions produced by socioeconomic sectors and residence activities directly within the region boundary (Barrett et al., 2013). The CO_2 emissions inventory consists of two parts, emissions from fossil fuel consumption and from industrial processes. Detailed scope and boundary for emission accounting are shown in Table 1.

The notations and abbreviations used in the following emission calculation and data collection are gathered in Table 2.

3.2. Calculation of CO_2 emissions and inventory construction

First, we calculate the emissions from fossil fuel combustion. The emissions are calculated for 17 fossil fuels and 47 socioeconomic sectors. The 47 socioeconomic sectors are defined according to the Chinese National Administration for Quality Supervision and Inspection and Quarantine (NAQSIQ) (2011), which include all possible socioeconomic activities conducted in a Chinese city's administrative boundary (shown in SI Table S1). We include 17 fossil fuels in this paper that are widely used in the Chinese energy system (Department of Energy Statistics of National Bureau of Statistics of the People's Republic of China (NBS), 1986–2013), see Table 3.

We adopt the IPCC (2006) sectoral approach to calculate the CO_2 emissions, which is widely applied by research institutions and scholars (European Commission, 2014; Feng et al., 2013; Lei et al., 2011; Liu et al., 2014; United Nations Framework Convention on Climate Change (UNFCCC); Wiedmann et al., 2008; Zhou et al., 2010). The fossil fuel-related CO_2 emission equals to activity data (fossil fuel consumption) times emission factors, see Eq. (1).

$$CE_{energy} = \sum_i \sum_j CE_{ij} = \sum_t \sum_j AD_{ij} \times NCV_i \times EF_i \times O_{ij},\ i \in [1,17], j \in [1,47] \quad (1)$$

The subscript i and j in the equation refers to fossil fuel types and sector respectively, which are corresponding with those in Table 3 and SI Table S1. CE_{ij} represents the CO_2 emissions from fossil fuel i combusted in sector j ; AD_{ij} represents fossil fuel consumption. NCV_i (net caloric value), EF_i (emission factor), and O_{ij} (oxygenation efficiency) are emission parameters of different fossil fuels. The units of the three parameters are "$J/tonne\ fossil\ fuel\ consumption$", "$tonne\ CO_2/J$", and "%" respectively.

Both IPCC (2006) and NDRC (2011) provide default emission

Table 1
Scope definition for city CO_2 emission accounting.

Spatial boundaries	Components
In-boundary fossil fuel related CO_2 emissions	Primary-industry use (farming, forestry, animal husbandry, fishery and water conservancy) Industrial use (40 sub-sectors) Construction use Tertiary-industry use (2 sub-sectors) Residential use (Urban and Rural) Other
In-boundary process-related CO_2 emissions	CO_2 emissions from 9 industrial processes

Note: Due to the city's administrative boundary spanning both urban and rural geographies in China, the residential energy use are also consisted of 2 categories: urban and rural.

factors for fossil fuels. However, based on measurements of 602 coal samples from the 100 largest coal-mining areas in China (Liu et al., 2015), the emission factors recommended by the IPCC and NDRC are frequently higher than the real emissions factors. In this study, we adopted the newly measured emission factors, which we assume to be more accurate than the IPCC and NDRC default values (see Table 3). We considered different oxygenation efficiency for fossil fuels burnt in different sectors, as the combustion technology level of sectors are different in China.

Energy used as chemical raw material and loss during transportation are removed from the total energy consumption to avoid double counting. Emissions from electricity and heat generated within the city boundary are counted based on the primary energy input usage, such as raw coal (Peters et al., 2006). Our administrative territorial emission inventory excludes emissions from imported electricity and heat consumption from outside the city boundary, as well as the inter-city transportation energy consumption. We only focus on fossil fuel consumed within the city boundary.

In the second part, we calculate CO_2 emissions from 9 industrial processes (see Table 4). The 9 industrial processes are emission-intensive processes, contributing over 95% of the total process-related emissions in China (Shan et al., 2016b). The process-related emissions are CO_2 emitted as a result of chemical reactions in the production process, not as a result of the energy used by industry. Emissions from industrial processes are factored into the corresponding industrial sectors in the final emissions inventory. We estimate the process CO_2 emissions in Eq. (2).

$$CE_{process} = \sum_t CE_t = \sum_t AD_t \times EF_t, \quad t \in [1,9] \tag{2}$$

The subscript t in the equation refers to industrial processes, which are corresponding with those in Table 4. CE_t and EF_t represent the CO_2 emissions and emission factor for industrial process t. Most of the emission factors are collected from IPCC (2006), except that of cement production, which is collected from our previous study on China's cement process (Liu et al., 2015), shown in Table 4.

By including the emissions from fossil fuel consumption and industrial processes, the emissions inventory designed in this paper includes all administrative boundary territorial CO_2 emissions from 47 sectors, 17 energy types and 9 main industrial processes.

3.3. Activity data requirement and process

Fig. 1 shows the overall methodology framework designed for the construction of emissions inventories for Chinese cities in this study. We need the energy balance table (*EBT*), industrial sectoral fossil fuel consumption (AD_{ij}), and industrial products' production (AD_t) to calculate the CO_2 emissions from both fossil fuel

Table 2
Notations, abbreviations and their meaning used in this study.

Notations	Explanation
Subscript i	Fossil fuel type
Subscript j	Sector
Subscript t	Industrial process
CE_{ij}	CO_2 emissions from fossil fuel i combusted in sector j
CE_t	CO_2 emissions from industrial process t
AD_{ij}	Consumption of fossil fuel i in sector j
NCV_i	Net caloric value of fossil fuel i
EF_i	Emission factor of fossil fuel i
O_{ij}	Oxygenation efficiency of fossil fuel i combust in sector j
EF_t	Emission factor of industrial process t
EBT	City's energy balance table
$EBTp$	Provincial energy balance table
P	City-province percentage, which is calculated with industrial outputs and population, reflecting the percentage relation between a city and its province
ADS	Short for "Industrial enterprises above designated size"
m	ADS multiplier, refers to the multiple of the whole industrial output to that of the industry above the designated size
AD_i	Consumption of fossil fuel i of the whole industry
AD_{i-ADS}	Consumption of fossil fuel i at ADS scale
AD_{ij-ADS}	Consumption of fossil fuel i in sector j at ADS scale
AD^*_{j-ADS}	Comprehensive energy consumption of sector j at ADS scale
AD_t	Production of industrial process t

combustion and industrial processes. Generally, the data for cities can be collected from city's municipal bureau of statistics, such as Hefei Municipal Bureau of Statistics (2011) and Xiamen Municipal Bureau of Statistics (2011).

3.3.1. Energy balance table

The Energy Balance Table (*EBT*) is an aggregate summary of energy production, transformation and final consumption in one area (Qiu, 1995), which could reveal the energy flow of one region. The sectoral consumption of fossil fuels from *EBT* can be used as activity data to calculate the fossil fuel-related CO_2 emissions. Detailed illustration of *EBT* are shown in the Support Information. However, due to the poor data quality of Chinese cities, some cities don't compile *EBT* in their statistical yearbook. The following three cases cover all the possible *EBT* availabilities of Chinese cities.

3.3.1.1. Case α: city with energy balance table. Some cities compile EBT in their statistical yearbooks, such as Guangzhou (Guangzhou Municipal Bureau of Statistics, 2011). We collect the fossil fuel consumption from the table directly for emission estimation.

3.3.1.2. Case β: city without energy balance table. For cities such as Hefei and Xiamen, there is no EBT in their statistical yearbooks (Hefei Municipal Bureau of Statistics, 2011; Xiamen Municipal Bureau of Statistics, 2011). In these cases, we deduce the city's *EBT* from its corresponding provincial energy balance table (*EBTp*). First, we define a city-province percentage *P* in Eq. (3), which can be calculated using different indexes, such as industrial outputs and population. The equation reflects the percentage relation between a city and its province.

$$P = Index_{city} / Index_{province} \times 100\% \tag{3}$$

With the city-province percentage, *P*, we scale down the provincial energy balance table to the city level (see Eq. (4)). For 'Input & Output of Transformation' and 'Loss' part of *EBT*, we use the industrial output as index to calculate the city-province percentage *P*,

Table 3
Emissions parameters of fossil fuel combustion.

No. (i)	Energy types	$NCV_i(PJ/10^4\ tonnes, 10^8\ m^3)$	$EF_i(tonneCO_2/TJ)$
1	Raw coal	0.21	96.51
2	Cleaned coal	0.26	96.51
3	Other washed coal	0.15	96.51
4	Briquettes	0.18	96.51
5	Coke	0.28	115.07
6	Coke oven gas	1.61	78.8
7	Other gas	0.83	78.8
8	Other coking products	0.28	100.64
9	Crude oil	0.43	73.63
10	Gasoline	0.44	69.3
11	Kerosene	0.44	71.87
12	Diesel oil	0.43	74.07
13	Fuel oil	0.43	77.37
14	Liquefied petroleum gas	0.51	63.07
15	Refinery gas	0.47	73.33
16	Other petroleum products	0.43	74.07
17	Natural gas	3.89	56.17

because energy transformation departments belong to industry. For ‘Final consumption’ in *EBT*, we use the corresponding outputs of each sector as the indexes. For ‘Residential consumption’, we use population as the index. The industrial output and population can be collected from each city's statistical yearbook as well.

$$EBT = EBTp \times P \tag{4}$$

3.3.1.3. Case γ: city without energy balance table, but with table of “transformation usage of energy types”. Some cities do not have a *EBT* in their statistical yearbooks, but have compiled a table of “Transformation usage of energy types”, such as Huangshi (Huangshi Municipal Bureau of Statistics, 2011) in Hubei province. The transformation table presents the energy input and output during transformation process, and can be used to make our deduced *EBT* more accurate. We modify the “Input & Output of Transformation” section of the deduced city *EBT* with the table of transformation.

3.3.2. Industry sectoral energy consumption

The *EBT* counts industry as one entire component of all consumption components. However, industry is the major energy consumption component and contributes the majority of greenhouse gas emissions. In addition, industry is also the primary area for applying low carbon technologies (Liu et al., 2013). Based on the industry sectoral energy consumption, we could expend the final energy consumption of industry in *EBT* into 40 sub-sectors with corresponding to the industry classification provided by NAQSIQ (Xu, 2005). The extended energy balance table consists of 47 final consumption sectors and can provide a more detailed illustration of energy utilization for both industry and the entire city. Following the methods below, we could deduce the industry sectoral energy consumption of Chinese cities with different data qualities.

3.3.2.1. Case A: city with industry sectoral energy consumption by types (AD_{ij}). For some cities, the sectoral energy consumption by types of the whole industry is provided in the statistical yearbook. We use the data directly.

3.3.2.2. Case B: city with sectoral energy consumption by types of industry enterprises above designated size (AD_{ij-ADS}) and energy consumption by types of the whole industry (AD_i). For cities such as Guangzhou, the industrial statistics is carried on above designated size (ADS) scale, which means the statistical data in its yearbook only includes industry above designated size (Guangzhou Municipal Bureau of Statistics, 2011). The enterprise above designated size refers to the enterprise with annual main business turnover above 5 million Yuan. Guangzhou has sectoral energy consumption by types of ADS industry (AD_{ij-ADS}) and energy consumption by types of the whole industry (AD_i) in its yearbook. In this case, we expand AD_{ij-ADS} by AD_i to obtain AD_{ij} in Eq. (5).

$$AD_{ij} = AD_{ij-ADS} \Big/ AD_{ij-ADS} \times AD_i,\ i \in [1,17],\ j \in [2,41] \tag{5}$$

3.3.2.3. Case C: city with sectoral energy consumption by types of ADS industry (AD_{ij-ADS}) only. These cities are the most common types in terms of data collection for Chinese cities. They only have sectoral energy consumption by types of ADS industry (AD_{ij-ADS}) in their statistical yearbooks. Most cities are classified into this case; these include Hefei and Xiamen (Hefei Municipal Bureau of Statistics, 2011; Xiamen Municipal Bureau of Statistics, 2011). To calculate the sectoral energy consumption of the whole industry (AD_{ij}), we expand AD_{ij-ADS} to AD_{ij} by the ADS multiplier m (see Eq. (6)).

$$\begin{aligned} AD_{ij} &= AD_{ij-ADS} \times m \\ &= AD_{ij-ADS} \times O_{industry} \Big/ O_{ADS},\ i \in [1,17],\ j \in [2,41] \end{aligned} \tag{6}$$

$O_{industry}/O_{ADS}$, which is the ADS multiplier (m) in this paper, refers to the multiple of industrial output to that of the industry above the designated size.

3.3.2.4. Case D: city with total energy consumption by types of ADS industry (AD_{i-ADS}) only. For cities such as Weifang and Huangshi, we can collect only the total energy consumption by types of ADS industry (AD_{i-ADS}) from the statistical yearbooks (Huangshi Municipal Bureau of Statistics, 2011; Weifang Municipal Bureau of Statistics, 2011). In this case, we first scale up AD_{i-ADS} to AD_i by the ADS multiplier m and then divide AD_i into each sector by the sectoral comprehensive energy consumption of the ADS industry (AD^*_{j-ADS}) (refer to Eq. (7)). If one city does not have AD^*_{j-ADS}, we use the sectoral industry output instead.

$$AD_{ij} = AD_{i-ADS} \times m \times AD^*_{j-ADS} \Big/ \sum_j AD^*_{j-ADS},\ i \in [1,17],\ j \in [2,41] \tag{7}$$

AD^*_{j-ADS} in the equation refers to the comprehensive energy consumption of sector j at ADS scale. AD_{i-ADS}, as explained above, refers to the total energy consumption of fossil fuel i at ADS scale.

With these three cases, we collect and deduce the industry sectoral energy consumption by types for one city. By replacing the final energy consumption of industry in the *EBT* with the sub-sectoral detail, we obtain the extended energy balance table.

3.3.3. Industrial products' production

Data collection for the production of industrial products is much easier and universal. Every city has the “Production of industrial products” table in its statistical yearbook. A portion of the production is derived from industrial enterprises above the designated size. If we expand the production above the designated size (AD_{t-ADS}) by the city's ASD multiplier m defined above, we can obtain the total production of each industrial product (AD_t), shown in Eq. (8), in which the subscript $t \in [1,9]$ represents the different industrial products (refer to Table 4).

Table 4
CO_2 emission factors for 9 main industrial processes.

No.(t)	Industrial Processes	EF_t(tonne CO_2/tonne)
1	Ammonia production	1.5000
2	Soda Ash production	0.4150
3	Cement production	0.2906
4	Lime production	0.6830
5	Ferrochromium production	1.3000
6	Silicon metal production	4.3000
7	Ferro-unclassified production	4.0000
8	Ferrous Metals production (Coke usage as reducing agent)	3.1000
9	Nonferrous Metals production (Coke usage as reducing agent)	3.1000

$$AD_t = AD_{t-ADS} \times m, \ t \in [1, 9] \tag{8}$$

3.4. Validation

In order to verify our method, we apply this method to 5 cities firstly and compare the fossil fuel related CO_2 emissions with previous research. The fossil fuel contributes more than 90% of the total CO_2 emissions. Therefore, the comparison of fossil fuel related CO_2 emissions with other research can be a validation of our estimates. In the China High Resolution Emission Gridded Data (CHRED) with 1 km resolution built by Chinese academy for environmental planning (CAEP), they estimated few cities' fossil fuel-related CO_2 emissions based on energy consumption data collected in a bottom-up way based on industrial facility data and other information (Cai, 2011, 2012; Cai and Zhang, 2014; Wang et al., 2014). The 5 cities, Hefei, Xiamen, Weifang, Huangshi, and Guangzhou, contain all the different cases we deduce the city's data, see Table 5.

From Table 5 we can see that the difference of CO_2 emissions between our study and CAEP's research is within 10%. According to previous research, emissions from OECD countries may have an uncertainty of 5%–10%, while the uncertainty for non-CECD countries may be 10%–20% (Marland, 2008; Olivier and Peters, 2002). Therefore, we believe our estimations are relatively accurate and our method is effective and reliable.

4. Inventory construction and uncertainty of 24 cities

In this paper, we apply our method to 24 cities and compile the CO_2 emissions inventory for 2010. These 24 cities, which cover all the possible situations for data collection cases discussed above (see SI Table S3), are in different sociometric developmental stages. Per capita GDP of the 24 cities varies from 14.80 thousand Chinese Yuan (Zunyi) to 106.88 thousand (Shenzhen). 9 of the 24 case cities are provincial capital cities, which are larger and more affluent than the other 15 non-capital cities generally. Fig. 2 shows the locations and total CO_2 emissions of these 24 case cities.

Table 6 shows socioeconomic indexes of the 24 case cities. All necessary activity data were collected from each city's statistical yearbook. Detailed data source of this study is shown in the Support Information. We present the data collection and calculation results in SI section 3 and 4, Tables S3–S6. We have included all data used and our results online at our database: http://www.ceads.net (free to download after registration).

4.1. Results

In 2010, total CO_2 emissions of the 24 cities varied widely from 4.86 to 104.33 million tonnes. Tangshan and Guangzhou belong to the highest emission class, with more than 100 million tonnes, followed by Handan, Hohhot, and Weifang, Shenyang, Xi'an, and Changsha which have between 50 and 100 million tonnes. All these eight cities have heavy-intensity industries, such as coal mining and manufacturing. The third emission class includes all cities with CO_2 emissions between 25 and 50 million tonnes, i.e., Jixi, Shenzhen, Nanchang, Hefei, Chengdu, Huangshi, and Zunyi. The remaining cities belong to the lowest emissions class; these include cities with less heavy-intensity manufacturing industry/more developed service industry (i.e., Yichang, Nanning, Xiamen, and Suqian) and cities located in more remote areas with a smaller population and smaller GDP (i.e., Dandong, Nanping, Baicheng, Zhoushan, and Wuwei) compared with the other three classes.

If we divide the total CO_2 emissions by the population, we obtain the CO_2 emissions per capita of the 24 case cities (shown in Table 6). We find that, among the 24 case cities, the CO_2 emissions per capita in Hohhot is the highest, with 29.67 tonnes, followed by Jixi (22.84 tonnes), Shenzhen (14.69 tonnes), and Tangshan (14.20 tonnes). The four cities with the lowest CO_2 emissions per capita are Suqian (1.18) Nanping (2.38), Chengdu (2.53 tonnes), and Wuwei (2.54). In the same way as the total CO_2 emission distribution, cites with coal mines and heavy-intensity industry have high CO_2 emissions as well as high CO_2 emissions per capita, such as Jixi, Hohhot and Tangshan. Cities located in remote areas and in less developed stages have lower CO_2 emissions per capita as well as less CO_2 emission.

4.2. Uncertainty analysis

Analysing uncertainty is an important tool for improving emission inventories that contain uncertainty (Jonas et al., 2014; Shen et al., 2014). Different methods are used to analyse the uncertainty of emissions, Jonas et al. (2010) describe four relevant uncertainty terms and six techniques that can be used to analyse uncertain emission changes. In this study, we employ Monte Carlo simulations to calculate the uncertainties of 20 Chinese cities' CO_2 emissions, which is recommended by IPCC (Intergovernmental Panel on Climate Change (IPCC), 2006) and widely used in previous research (Lang et al., 2014).

As the CO_2 emission is calculated as product of activity data and emission factors, therefore uncertainty comes from two parts: activity data (fossil fuel consumption) and emission factors. According to Monte Carlo analysis, we should assume individual probability density functions for the two variables firstly, then simulate the CO_2 emissions values with the assumed functions for many times (Penman, 2000). Industrial processes emit much less CO_2 (9.89% of the total CO_2 emissions) compared with fossil fuel combustion. What's more, emissions from industrial process are generally with less uncertainties (Liu et al., 2015; Zhao et al., 2011). Therefore, we only consider uncertainty from fossil fuel consumption in this study. We calculate the uncertainty of both the overall CO_2 emissions and sub-sectors' emissions of the 24 city cases in this study.

We assume normal distributions for both activity data and emission factors (Liu et al., 2015; Zhao et al., 2011). The coefficients of variation (CV, the standard deviation divided by the mean) of different emission factors and fossil fuel consumptions are chosen from previous literature, see Table 7. We repeat the simulation procedure for 20,000 times in Monte Carlo analysis. Table 8 shows the total uncertainties of 24 cities' emissions in 2010 with 95% Confidence Interval.

The average uncertainty of total CO_2 emissions of the 24 case cites is from −4% to 4%, falling in the range of 10%–20% for non-OECD countries (Marland, 2008; Olivier and Peters, 2002). This

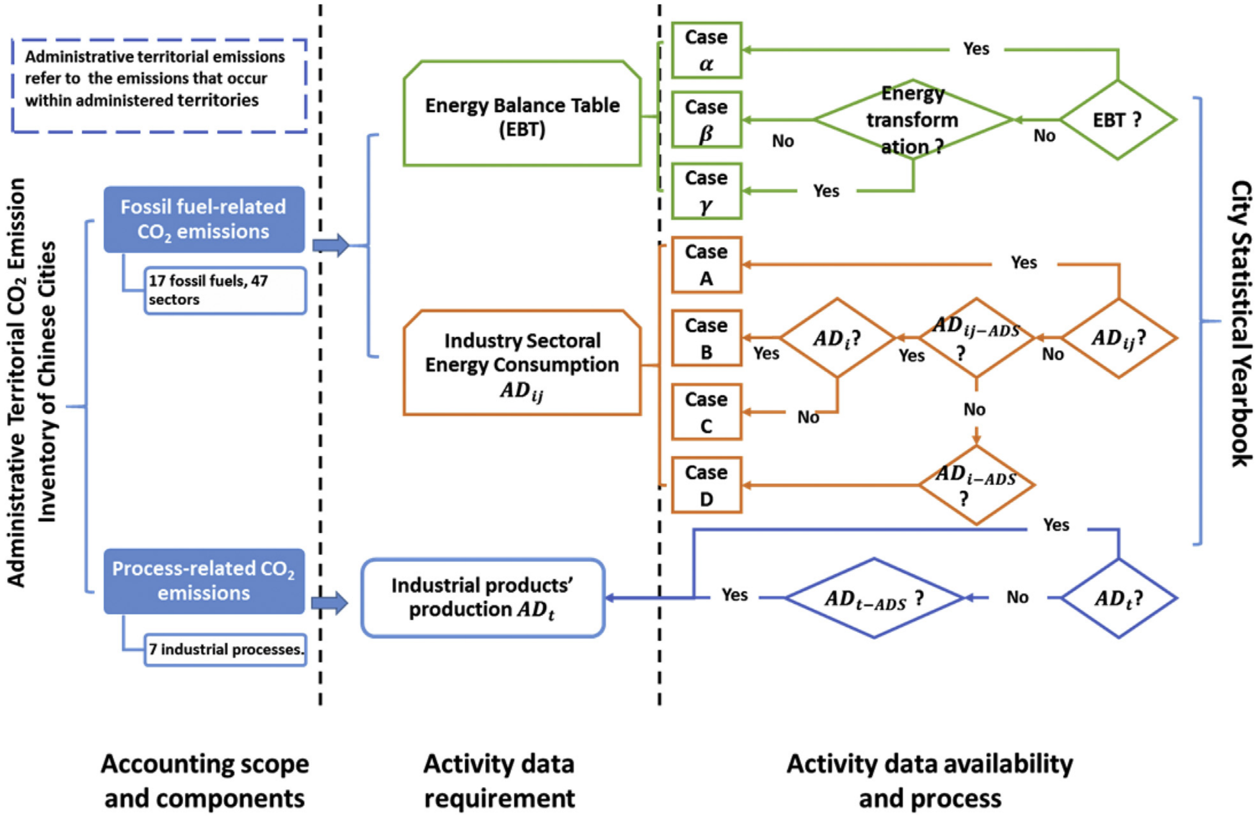

Fig. 1. *CO_2 emissions inventory construction framework for Chinese cities*. The subscript "ADS" is short for "above designated size". AD_{ij-ADS}/AD_{i-ADS} refers to sectoral/total consumption of fossil fuel *i* in industry above designated size (see section "3.3.2 Industry sectoral energy consumption" for more details).

illustrates that our estimations are relatively accurate and realisable. Among the 24 cities, CO_2 emissions of Shenzhen have the smallest uncertainty (−2%, 2%), while emissions of Jixi have the highest uncertainty (−6%, 6%). As the largest contributor of CO_2 emissions (39.19% of the total emissions averagely of the 24 cities in this study), the emissions from electricity generation sector has the largest uncertain averagely (−6%, 6%) among different sectors. This is caused by large amount of coal combusted in coal-fired power plant, uncertainty of coal's emission factor is the highest among energy types, despite the fossil fuel consumption in electricity generation sector has a low uncertainty. In contrast to power plant, CO_2 emission from service sector (transportation and territorial industries) have the lowest uncertainty averagely (−2%, 2%). Much oil and gas are used in these sectors compared with power plant, which have lower uncertainties of emission factor. Detailed uncertainties by sectors are shown in SI Table S6.

5. Discussion

5.1. Emissions of different fossil fuel types and industrial process

Fig. 3 shows the energy type distribution for the CO_2 emissions inventory in 2010. Raw coal is the largest primary source of emissions among the 17 fossil fuel types, with an average percentage of 58.2%. The high CO_2 emissions are induced by the large consumption and high carbon content of raw coal (Pan et al., 2013). Coal is the largest primary energy source in China. About 70% of the total energy used in China comes from coal in 2010 (NBS (2016)).

For example, Jixi is one of the coal bases in China and produced 20.46 million tonnes raw coal in 2010. Coal and its related products (cleaned coal, other washed coal, briquettes, and coke) become the primary energy types in Jixi. In 2010, 42.28 million tonnes of CO_2 emissions were produced by coal and combustion of coal products; this is of 97.84% of Jixi's total emissions. Similar to Jixi, Inner Mongolia province is also a main coal base in China. As the provincial capital city of Inner Mongolia, Hohhot uses coal and coal products as the main energy types as well. In 2010, Hohhot produced 6.01 million tonnes raw coal, 0.60 million tonnes coke, and generated 35.26 billion watt-hour electricity in fire power plant in 2010. Coal and coal-related products contributed 57.57 million tonnes of CO_2 emissions (84.34%) to Hohhot's total CO_2 emissions.

In addition to coal, diesel oil is another important source of CO_2 emissions, with an average percentage of 8.31%. Diesel oil is widely used most types of transportation, such as oversize vehicle and ship. Among the 24 cities, Shenzhen, Zhoushan, Guangzhou, and Xiamen have a much higher percentage of diesel use (32.34%, 22.64%, 14.79%, and 13.57% respectively) than the average percentage Diesel oil is widely used by truck and cargo shippers. These four cities are located in the south and on the southeast coast of China; they are important ports. The freight and transportation industry is more developed in these cities than others. Take Shenzhen as an example, there are 172 berths in Shenzhen harbour with 79 berths over 10 thousand tonnes class, the cargo handled at seaports are 220.98 million tonnes in 2010. The waterways and highway freight traffic in 2010 are 198.47 and 58.59 million tonnes, taking a percentage of 1.38% and 0.70% over the whole Chinese 300 + cities. Therefore, the diesel oil and Transportation sectors has a higher percentage of these cities' total CO_2 emissions compared with other cities (also see Sect. 5.2).

Industrial processes also contribute much to a city's total CO_2 emissions. The total CO_2 emissions produced during the industrial process of the 24 case cities are 92.10 million tonnes, which is 9.89%

Table 5
Validation of fossil fuel-related CO_2 emission estimations.

	Our estimation	CAEP	Difference between two results	Case type
Hefei	30.22	33.23	-9%	β, C
Xiamen	11.82	12.67	-7%	β, C
Weifang	60.17	57.18	5%	α, D
Huangshi	19.53	20.61	-5%	γ, D
Guangzhou	96.13	96.67	-1%	γ, B

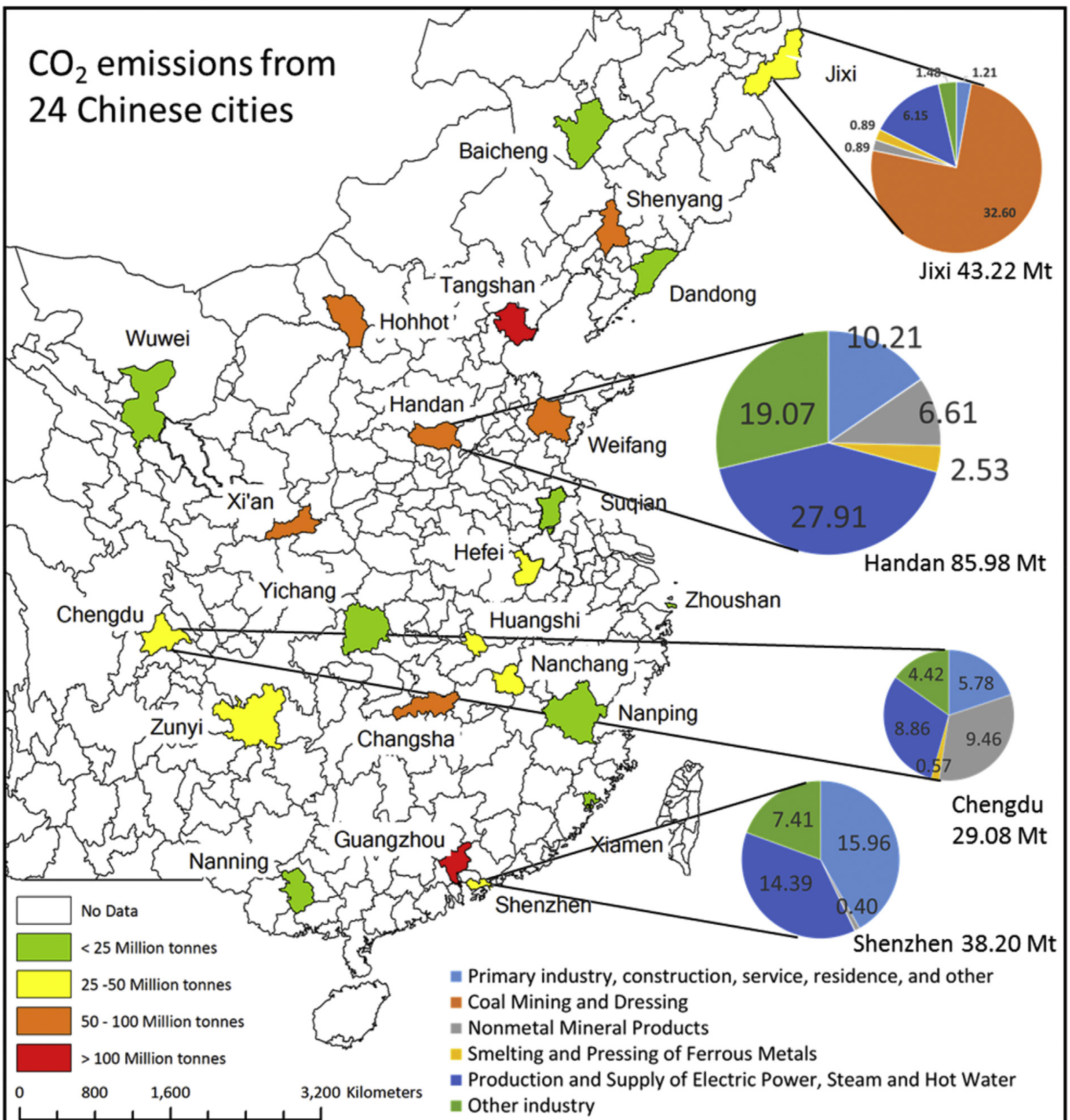

Fig. 2. CO_2 emissions of the 24 case cities, 2010, million tonnes.

Table 6
Socioeconomic-emission indexes of 24 cities.

City	Location	Per capita GDP (10^6 Yuan)	CO_2 emission (Mt)	Per capita emissions (t)	CO_2 intensity (t/10^3 Yuan)
Hefei	Provincial capital, Central east	54,796	32.49	6.56	0.12
Nanping	Southeast	26,279	7.49	2.38	0.10
Xiamen	Southeast	58,337	11.82	6.57	0.06
Wuwei	Northwest	10,621	4.86	2.54	0.21
Guangzhou	Provincial capital, South	103,625	100.50	12.47	0.09
Shenzhen	South	106,880	38.20	14.69	0.04
Nanning	Provincial capital, Southwest	25,622	23.30	3.30	0.13
Zunyi	Southwest	14,799	26.53	3.38	0.29
Handan	Central north	26,143	85.98	8.92	0.36
Tangshan	Central north	59,389	104.33	14.20	0.23
Jixi	Northeast	22,083	43.22	22.84	1.03
Huangshi	Central	28,427	26.75	10.28	0.39
Yichang	Central	38,181	25.00	6.26	0.16
Changsha	Provincial capital, Central	66,443	52.89	8.11	0.12
Baicheng	Northeast	21,973	7.41	3.65	0.17
Suqian	Central east	22,525	6.45	1.18	0.06
Nanchang	Central	43,769	36.62	7.29	0.17
Dandong	Northeast	29,893	9.07	3.76	0.12
Shenyang	Northeast	62,357	62.82	8.73	0.13
Hohhot	Provincial capital, North	66,929	68.25	29.67	0.37
Weifang	Central east	34,273	66.37	7.59	0.21
Xi'an	Provincial capital, Central west	38,341	55.76	7.12	0.17
Chengdu	Provincial capital, Southwest	48,510	29.08	2.53	0.05
Zhoushan	Central east	66,581	6.13	6.32	0.10

of the total CO_2 emissions. For example, there are many manufacturing industries in Tangshan, particularly 'non-metal mineral products' and 'smelting and pressing of ferrous metals'. The production of cement, iron, and steel in 2010 are 37.32 Mt, 65.67 Mt and 68.32 million m^3. Therefore, the industrial process contributes greatly to Tangshan's total CO_2 emissions. The CO_2 emissions from Tangshan's industrial process in 2010 were 18.80 million tonnes (18.01%), which is much higher than the average level. Changsha (10.32 tonnes), Yichang (9.87 tonnes), and Huangshi (7.22 tonnes) are similar manufacturing cities.

5.2. Emissions of different sectors

We summarise the CO_2 emissions of 47 socioeconomic sectors

Table 7
Coefficient of variance (CV) of different emission factors and fossil fuel consumptions.

CV of emission factor (Liu et al., 2015)		CV of fossil fuel consumption (Zhao et al., 2011)	
		Electricity generation sector	5% (Wu et al., 2010; Zhao et al., 2008)
Coal-related fossil fuel	3%	Other industries, construction	10% (Zhang et al., 2007)
Oil-related fossil fuel	1%	Residential fossil fuel use	20% (IPCC (2006))
Gas-related fossil fuel	2%	Transportation sector	16% (Karvosenoja et al., 2008)
		Primary industry	30% (Wang and Zhang, 2008)

Table 8
Uncertainties of 24 Chinese cities' CO_2 emissions in 2010 (million tonnes).

City	Uncertainty	City	Uncertainty
Hefei	30.22 (−4%, 4%)	Yichang	15.12 (−4%, 4%)
Nanping	5.92 (−4%, 4%)	Changsha	42.57 (−3%, 3%)
Xiamen	11.82 (−4%, 4%)	Baicheng	7.41 (−5%, 5%)
Wuwei	4.36 (−5%, 5%)	Suqian	5.00 (−3%, 3%)
Guangzhou	96.13 (−3%, 3%)	Nanchang	35.03 (−5%, 5%)
Shenzhen	38.20 (−2%, 2%)	Dandong	8.32 (−4%, 4%)
Nanning	17.06 (−4%, 4%)	Shenyang	61.01 (−4%, 3%)
Zunyi	22.53 (−5%, 5%)	Hohhot	65.12 (−5%, 5%)
Handan	81.91 (−4%, 4%)	Weifang	60.17 (−4%, 4%)
Tangshan	85.54 (−5%, 5%)	Xi'an	54.42 (−4%, 4%)
Jixi	42.85 (−6%, 6%)	Chengdu	23.13 (−3%, 3%)
Huangshi	19.53 (−4%, 4%)	Zhoushan	6.13 (−4%, 3%)

Note: The percentages in the parentheses indicate the 95% Confidence Interval around the central estimate.

into 9 key sectors in Fig. 3 in order to present sectoral contribution clearly. We also present four typical cities' sector share in Fig. 2. Industry sectors are the primary resources that contribute to a city's CO_2 emissions. Approximately 80.80% of the total CO_2 emissions are contributed by industry sectors, on average. Among the 40 sub-industry sectors defined in this paper, the "Electricity generation" sector produces the most CO_2 emissions, generating 39.19% of the total CO_2 emissions, on average. This generation is caused by the huge quantities of electricity generated in coal-fired power plants.

The "non-metal mineral products" sector contributes a lot of CO_2 emissions to the total emissions as well, taking a percentage of 12.80% averagely. This sector includes all the CO_2 emissions during non-metal mineral production, such as cement and lime. Tangshan (20.41 Mt), Changsha (14.98 Mt), Nanning (9.63 Mt), Huangshi (9.52 Mt), and Chengdu (9.46 Mt) have high CO_2 emissions in the "non-metal mineral products" sector compared with other cities. As discussed above, the cement production of Tangshan in 2010 is 37.32 Mt. Changsha (20.70 Mt), Nanning (11.87 Mt), Huangshi (14.49 Mt), and Chengdu (10.39 Mt) also produced more cement in 2010.

"Coal Mining and Dressing" sector is the third largest industrial source of CO_2 emissions (7.67% averagely), especially for Jixi (75.43%). This finding is because Jixi is a major coal-producing area in China, as discussed above. Large quantities of fossil fuels are consumed in mines to produce and wash coal and produce coke.

In addition, there are many "Smelting and pressing of ferrous Metals" industries in Tangshan and Handan. Tangshan produced 65.67 Mt iron and 68.32 million m^3 steel, while Handan produced 33.22 Mt iron and 36.84 Mt steel in 2010. The large production brings the two cities large CO_2 emissions of these sector (26.64 Mt and 8.10 Mt respectively).

In addition to industry sectors, service sectors also greatly contribute to total CO_2 emissions. The "service sectors" in Fig. 3 includes two components: "transportation" and "wholesale services". CO_2 emissions from these two sectors generate an average of 12.23% of the emissions in the 24 cities. For Shenzhen, Guangzhou, Zhoushan, Xiamen, and Changsha, the CO_2 emissions that the service sectors contribute (33.16%, 28.39%, 25.11%, 19.18%, and18.39% respectively) are much higher than the average level. Among these five cities, Shenzhen, Guangzhou, and Zhoushan are located on the south/southeast coast of China. These cities are very important ports with high waterways and highway freight traffic, as discussed above. Xi'an and Changsha are inland transport junctions. The overall freight traffic of Xi'an and Changsha in 2010 are 343.23 and 229.47 Mt. The "transportation services" sectors of these five cities are well developed. In addition, Shenzhen has a larger share of tertiary industries. The proportion of value added by Shenzhen's

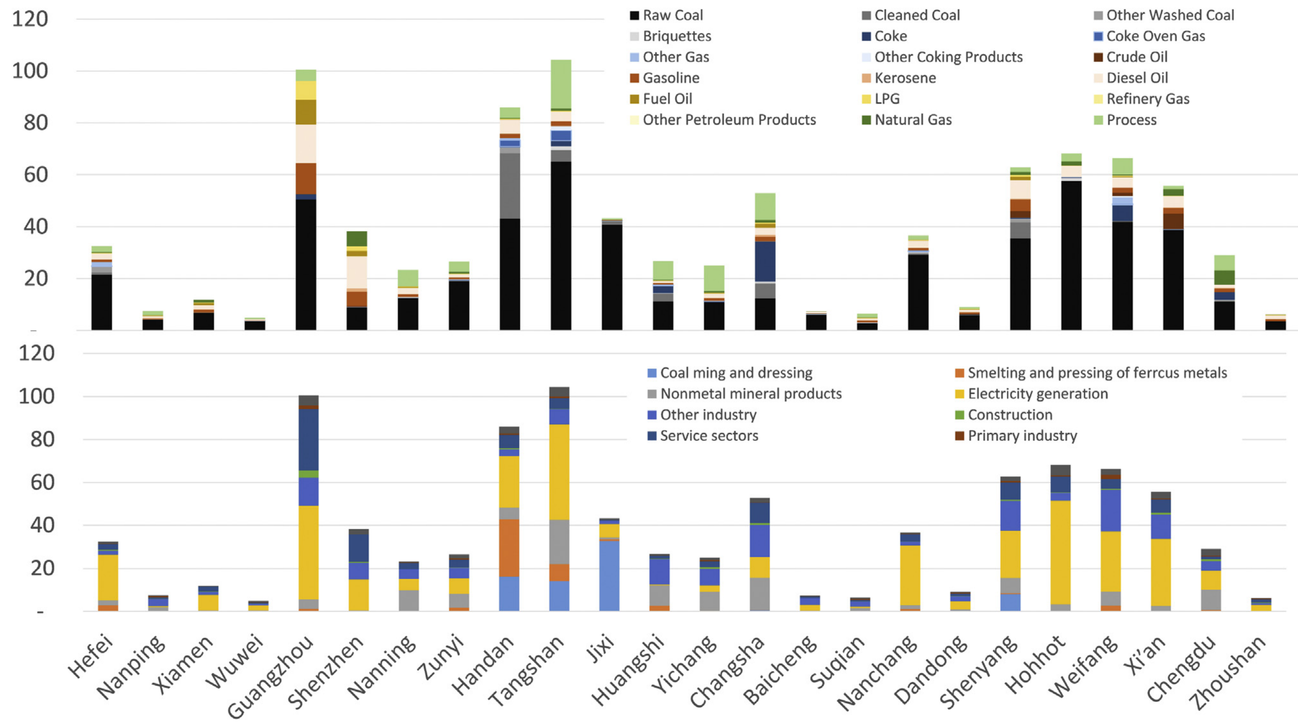

Fig. 3. CO_2 emissions by energy types and sectors (million tonnes, 2010).

tertiary industry is 52.7%, which is much higher than the national average of 44.2%. Therefore, the CO_2 emissions of Shenzhen's service departments are higher than those of other cities. The well-developed tertiary industry makes Shenzhen more affluent than other cities, the rural population of Shenzhen is 0 and per capita GDP is 106,880 Yuan in 2010, much higher than the national average level of 41,908 Yuan.

Primary industry and residential energy usage generate a small percentage of cities' CO_2 emissions in China. Based on the 20 case cities, the average percentage of the total CO_2 emissions generated by the two departments is 1.19% (primary industry) and 4.61% (residential energy usage).

5.3. Policy recommendation for emission reduction

As discussed above, coal and heavy emission intensity manufacturing industries are the primary emission sources within one city. Therefore, in order to reduce the CO_2 emissions in Chinese cities, we could take policy from two aspects. The first path is reducing the coal share in the energy mix and develop clean coal utilization strategy. The second one is reforming the industrial structure.

Reducing the coal share in the energy mix could decrease the emission intensity of one city. This is an effective way to reduce the CO_2 emissions while keep economic growing continually. Coal combustion emits more CO_2 to produce the same unit of heat compared with other energy types. Replacing coal by clearer energy types, such as nature gas, will help emission control in both Chinese cities and the whole world. In the 12th five-year plan (2011–2015) on energy, the central government proposed to control the total energy consumption and reduce coal share for the first time (NDRC, 2013). Efforts has been taken according to the government document these years and achieved initial success. The coal share in the energy mix decreased from 72.40% to 64.04% in the recent 10 years from 2005 to 2014, while the natural gas share doubled from 2.40% to 5.63%. According to the most up to data research at COP 21, the global carbon emissions decreased slightly by 2015 due to Chinese coal consumption decreasing, and renewable energy increasing globally (Le Quéré et al., 2015). Efforts should be planned and undertaken at the city level in the future. For example, we should replace coal gas with natural gas for residential use; cities with geography advantages should develop the renewable energy types, such as wind power, hydroelectricity and nuclear power. Beijing, as the capital city, has a more balanced energy mix compared with other cities. The coal and natural gas share in the energy mix is 20.41% and 21.13%, respectively, in 2014. Beijing has reduced 43% of its coal consumption (12.48 million tonnes) during 2007–2014, which is required by the "Air Pollution Prevention and Control Action Plan" (Ministry of Environmental Protection (P.R.China), 2013). Meanwhile, the consumption of natural gas increased by 144% (6.70 billion m^3). Benefit from this policy, Beijing's CO_2 emissions has remained stable since 2007 and has seen a slight decrease in recent years (Guan et al., 2016).

The other way to control CO_2 emissions in Chinese cities is reforming the industrial structure. Firstly, we should close all the non-permission coal mining and consuming enterprises, in which the kilns are usually backward and produced a lot of CO_2 emissions with low economic outputs. All the private and unregulated energy enterprises should be integrated into the corporations with the most developed and clean energy technologies. Secondly, the city government should also replace heavy emission intensity manufacturing industries with services sectors. Reviewing the emission intensity of the 24 case cities (see Table 6), we could find that cities with more heavy manufacturing industries usually have a higher emission intensity, such as Jixi, Huangshi, Hohhot, Zunyi and Tangshan. On the contrary, cities with more service sector activities have a smaller emission intensity, such as Shenzhen, Chengdu, Xiamen and Guangzhou. Through reforming the industrial structure, Chinese cities may not reduce CO_2 emissions at the expense of economic development, and achieve both environmental and social objectives.

6. Conclusion

This paper develops a feasible methodology for constructing territorial CO_2 emissions inventories for Chinese cities. By applying this methodology to cities, researchers can calculate the CO_2 emissions of any Chinese cities. This knowledge will be helpful for understanding energy utilization and identify key emission contributors and drivers given different socioeconomic settings and industrialisation phrase for different cities. Accurate accounts of cities' CO_2 emissions are considered a fundamental step for further analysis on emission-economic nexus, as well as proposing mitigation actions.

We applied this methodology to 24 cities and compiled the 2010 CO_2 emissions inventories for the cities. The results show that, in 2010, the "Production and supply of electric power, steam and hot water", "Non-metal mineral products", and "Coal mining and dressing" sectors produced the most CO_2 emissions. Additionally, coal and its products are the primary energy source in Chinese cities, with an average of 69.98%. In order to reduce the CO_2 emissions in Chinese cities, we could take policy to reduce the coal share in the energy mix and replace heavy emission intensity manufacturing industries with service sector with smaller emission intensity.

The study still contains some limitations. For example, we scale down the provincial energy balance table by using a city-province percentage. By using the different city-province percentages, the deduced table for the city may not be balanced. However, this is restrained by the data at city level. The method developed in this study is based on the most comprehensive data we can ever find. Further research will be conducted to improve the accuracy of city's emission data.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.06.075.

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New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors

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HIGHLIGHTS

- We calculate the provincial CO_2 emissions in China from 2000 to 2012 based on the "apparent energy consumption".
- During 2000 to 2012, Shandong province contributed most to national emissions accumulatively.
- Provinces located in the northwest and north had higher per capita CO_2 emissions and emission intensities.

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ABSTRACT

This study employs "apparent energy consumption" approach and updated emissions factors to re-calculate Chinese provincial CO_2 emissions during 2000–2012 to reduce the uncertainty in Chinese CO_2 emission estimates for the first time. The study presents the changing emission-socioeconomic features of each provinces as well. The results indicate that Chinese provincial aggregated CO_2 emissions calculated by the apparent energy consumption and updated emissions factors are coincident with the national emissions estimated by the same approach, which are 12.69% smaller than the one calculated by the traditional approach and IPCC default emission factors. The provincial aggregated CO_2 emissions increased from 3160 million tonnes in 2000 to 8583 million tonnes in 2012. During the period, Shandong province contributed most to national emissions accumulatively (with an average percentage of 10.35%), followed by Liaoning (6.69%), Hebei (6.69%) and Shanxi provinces (6.25%). Most of the CO_2 emissions were from raw coal, which is primarily burned in the thermal power sector. The analyses of per capita emissions and emission intensity in 2012 indicates that provinces located in the northwest and north had higher per capita CO_2 emissions and emission intensities than the central and southeast coastal regions. Understanding the emissions and emission-socioeconomic characteristics of different provinces is critical for developing mitigation strategies.

1. Introduction

China's economy has developed rapidly since joining the WTO in 2001. The nation's economy in 2014 was almost 4 times of the size of in 2000. According to the latest energy consumption revision by Chinese Statistics Bureau, China's total energy consumption also increased quickly, from 1470 million metric tonnes coal equivalent (tce) in 2000 to 4260 million metric tce in 2014. The huge amount of energy consumption has led to rapid increase CO_2 emissions recent years (shown in Fig. 1).

As the World's largest CO_2 emitter, China plays an important role in global climate change mitigation. The global emissions decreased slightly by 2015 for the first time, one of the important reasons behind it is Chinese coal consumption decreasing [1]. Contributing to the global climate change mitigation, China has recently pledged to peak its greenhouse gas emissions ahead of

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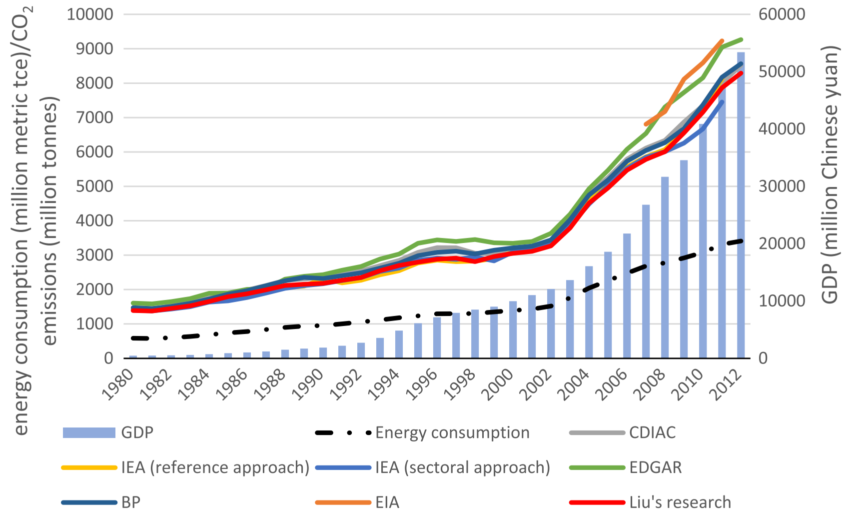

Fig. 1. Total energy consumption, GDP and fossil fuel-related CO_2 emissions growth in China, 1980–2012. *Data sources:* GDP [24], Energy consumption [25], emission estimates by Carbon Dioxide Information Analysis Centre (CDIAC) [26], emission estimates by International Energy Agency (IEA) [27], emission estimates by Emission Database for Global Atmospheric Research (EDGAR) [28], emission estimates by British Petroleum (BP) [29], emission estimates by EIA [30] and emission estimates by Liu's research [31].

2030 [2]. China's national mitigation targets are expected to be allocated to the sub-administrative region [3,4]. Therefore, it is of great importance to develop accurate and most up to date regional CO_2 emission inventories for China.

However, emissions estimated by previous researches [5–18] are generally estimated rather than measured directly. In many circumstances, emissions estimates are relatively uncertain [19,20]. This uncertainty may originate from the accounting scopes, basic energy statistics, the carbon content of fuel, and other potential sources [21,22]. These uncertainties have led to a wide range of CO_2 emission estimations by different world energy research institutions (see Fig. 1). In 2011, the lowest estimate was 7452 million tonnes of CO_2 by the IEA, and the highest estimate was 9229 million tonnes by the U.S. Energy Information Administration (EIA); the difference between these estimates, 1777 million tonnes (23.9%), is nearly equal to the total CO_2 emissions of India or Russia [23].

The uncertainty of China's CO_2 emission estimates mainly comes from two sources. The first is the uncertainty of energy statistics. Previous research on China's CO_2 emissions accounting collected energy consumption data from China's national statistics bureau [32–41]. However, there was a 20% gap between the aggregated energy consumption from 30 provinces and national consumption. Guan et al. [42] reported a gap of 1.4 gigatonnes between CO_2 emissions calculated on the basis of two publicly available official energy datasets for 2010. The gap may be caused by the application of different statistical standards [43] and misuse of units [25] for different provinces and the whole nation. The second source of uncertainty is the difference of estimated emission factors. We reviewed 2368 research articles about China's carbon emissions on the Web of Science published during 2004–2014, We found that most of the previous researches have collected emission factors from the IPCC or China's National Development and Reform Commission (NDRC), whereas fewer than ten studies (less than 1% of total studies) have adopted emission factors based on experiments and field measurements [44–49]. The study show that emission factors from different sources can differ by as much as 40% [31].

In this study we adopt the "apparent energy consumption" and updated emission factors [31] to re-calculate the China's provincial CO_2 emissions from 2000 to 2012 in this study. The new provincial CO_2 emission inventories will help reduce the uncertainty of China's provincial CO_2 emissions and present a clear emission-socioeconomic features of each province. Figuring out the emissions and emission-socioeconomic characteristics of Chinese provinces provide a foundation for both China and global carbon emissions control and industry transfer policy support.

The remaining sections of this paper are structured as follows: Section 2 describes the method and underlying database used in this study. Section 3 presents the results of provincial CO_2 estimation and analyses provincial emission-socioeconomic characteristics. Policy implications and conclusions are given in Section 4.

2. Method and data source

In this study, we calculate Chinese provincial CO_2 emissions based on "apparent energy consumption" and updated emission factors. The inventory includes all the fossil fuel related CO_2 emissions induced within the regional boundary.

2.1. CO_2 emissions calculation

In this study, we estimate fossil fuel-related CO_2 emissions by energy types based on the mass balance of carbon [50]. See Eq. (1),

$$CE_i = AD_i \times EF_i \tag{1}$$

where CE_i are CO_2 emissions from different energy types, AD_i (activity data) are the fossil fuels combusted within the province boundary measured in physical units (metric tonnes of fuel expressed as t fuel), and EF_i are the emission factors for the relevant fossil fuels.

By summarizing the emissions from different energy types together, we obtain the total CO_2 emissions for one province in Eq. (2).

$$CE = \sum CE_i \tag{2}$$

2.2. Data collection

2.2.1. Energy flows and apparent consumption calculations

In general, the energy consumption of one region can be directly calculated as the final consumption plus input usage of transformation, named "final and input/output consumption". Otherwise, it can also be estimated based on the mass balance of

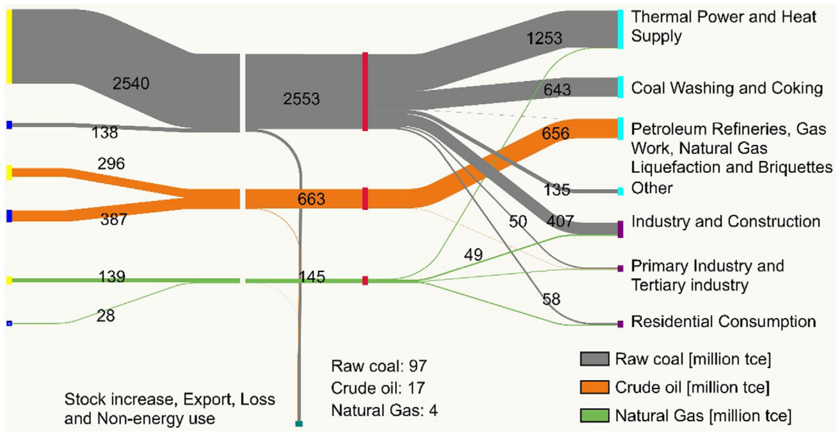

Fig. 2. Chinese energy flows, 2012.

energy, the so-called "apparent energy consumption" estimation [22,31,51]. The apparent energy consumption is the mass balance of fuels produced domestically for energy production, trade, international fuelling and change in stock, see Eq. (3).

$$\begin{aligned}&\text{Apparent fossil fuel consumption}\\&\quad=\text{indigenous production}+\text{imports}-\text{exports}\\&\qquad+\text{moving in from other provinces}\\&\qquad-\text{sending out to other provinces}\pm\text{stock change}\\&\qquad-\text{non-energy use}-\text{loss}\end{aligned}\tag{3}$$

Technically, we will get the equal number of energy consumption via "final and input/output consumption" and "apparent energy consumption" approaches. However, due to statistic error and poor quality in China's energy statistic, there are around 5% difference between the two consumption [52]. Energy consumption calculated from production-side (apparent energy consumption) is approved to be more accurate than the one calculated from consumption-side (final and input/output consumption) [31]. There are two reasons. First of all, the apparent energy consumption is calculated based on production and trade statistics. The statistics of fuel production and trade are more reliable and consistent than data of final energy consumption. Especially, coal production and trade data is consistently released earlier than coal consumption data. In addition, the apparent consumption approach considers only three primary fuel types (raw coal, crude oil and natural gas) in order to avoid accounting errors due to energy transformation between primary and second energy types (e.g., coal washing, coking, and power generation).

Taking the national energy utilization in 2012 as an example (Fig. 2). Raw coal, crude oil and natural gas are presented as grey, orange and green lines, respectively. In general, there are two primary energy sources: indigenous production (shown as the yellow module) and imports (shown as the blue module). Excluding exports, stock decreases, losses and non-energy use, we obtain the apparent fossil fuel consumption.

The red[1] module in Fig. 2 is the apparent energy consumption, which totalled 3361 million metric tonnes coal equivalent (tce) in 2012. Raw coal was the largest primary energy type used in China (75.9%), followed by crude oil (19.7%) and natural gas (4.3%). Only a small amount of primary fossil fuels was used by the final consumption sectors (the purple module in Fig. 2, 633 million metric tce). Most primary fossil fuels were transformed into secondary energy types (the aqua module in Fig. 2, 2728 million metric tce), such as electricity, heat, cleaned coal, coke and gasoline. Therefore, the apparent primary fossil fuel consumption includes all energy types consumed within one regional boundary.

Here, we adopt the "apparent energy consumption" to account Chinese provincial CO_2 emissions. The raw data were collected from each province's energy balance table [53].

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

Table 1
Comparison of different emission factors.

Energy type	IPCC default value [50]	NDRC default value [54]	Liu's study [31]
Raw coal	0.713	0.518	0.499
Imported raw coal	0.713	0.518	0.508
Crude oil	0.838	0.839	0.838
Natural gas	0.521	0.591	0.590

2.2.2. Updated emission factors

Both the IPCC and NDRC (for year 1994 and 2005) provide default emission factors for the three primary fossil fuels [50,54]. However, based on measurements of 602 coal samples from the 100 largest coal-mining areas in China [31], the emission factors recommended by the IPCC and NDRC are frequently higher than the real emissions factors in 2012 (see Table 1). In this study, we adopted the updated emission factors, which we assume to be more accurate than the IPCC and NDRC default values.

3. Results

Fig. 3 presents the CO_2 emissions of 30 provinces. Total national emissions increased by 171.6% over the period, from 3160 to 8583 million tonnes. Among the 30 provinces, Shandong emitted the most CO_2 cumulatively, 7471 million tonnes (10.35%). The three provinces with the highest cumulative emissions were Liaoning. Hebei and Shanxi, which emitted 4833 (6.69%), 4816 (6.67%) and 4511 (6.25%) million tonnes CO_2, respectively. The data on emissions for all 30 provinces over 2000–2012 are presented in Table 2.

Our estimation by apparent energy consumption and updated emission factors could be more accurate and coincident with the national emissions compared with the traditional calculation approach. Taking the year 2012 as an example, we compare the CO_2 emissions estimated by different approaches and emission factors in Table 3 and Fig. 4. Our estimation of provincial aggregate CO_2 emissions (8583 Mt) are similar to that of CDIAC (8518) and

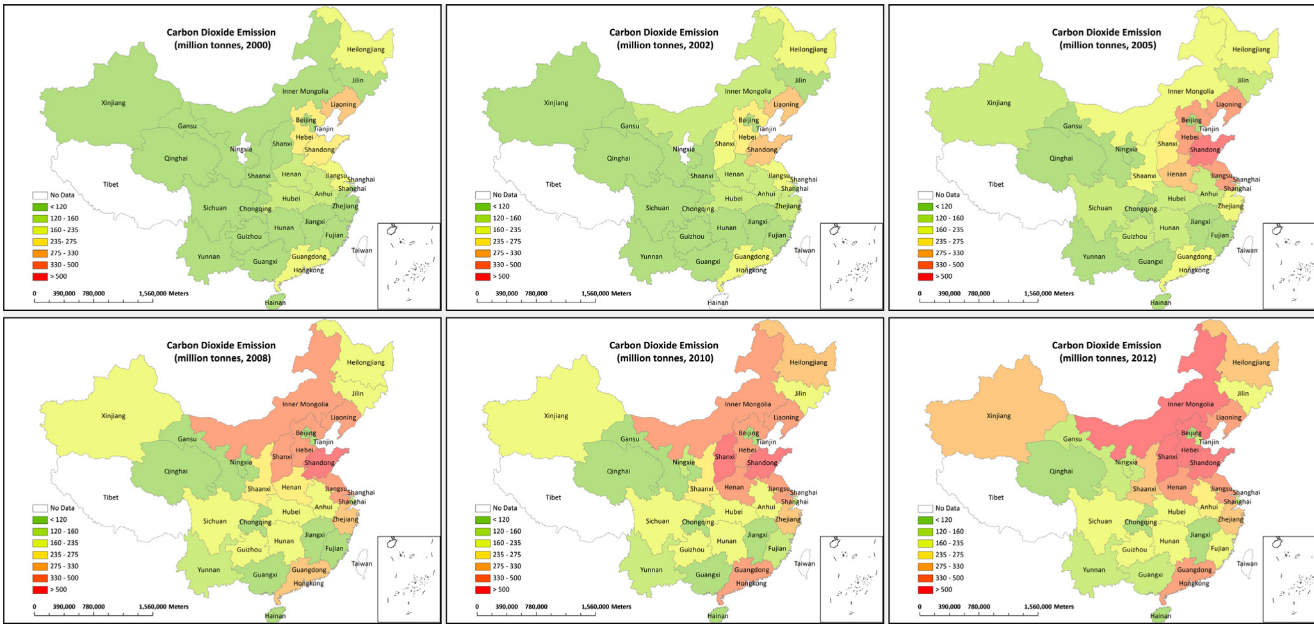

Fig. 3. CO_2 emissions from 30 provinces in China.

7.96% lower than the highest estimation (EDGAR, 9266 million tonnes), and are coincident with the national emissions estimated by the same approach (8342 Mt [31]). The newly calculated CO_2 emissions in this study reduced the 20% gap between national and provincial aggregate CO_2 emissions [55], and improved the accuracy in Chinese CO_2 emission accounts.

Our estimation of provincial aggregate emissions are 12.69% smaller than the one estimated by "Final and input/output consumption" approach and IPCC emission factors (see Table 3 and Fig. 4). The gap comes from two parts: 6.94% from the emission factors and 5.75% from activity data with reasons are discussed above.

In order to have a deep understanding of Chinese provinces' emission and emission-socioeconomic characteristics, we discuss emissions by different fossil fuel types and sectors, and calculate the per capita emissions and emission intensity in the following parts.

3.1. Emissions by fossil fuel types and sectors

The energy utilization structure in China has been very stable over the past 13 years. Based on natural resource endowments, raw coal contributed the most to the total fossil fuel CO_2 emissions in China, representing an average of 79.6% over the period. Due to increasing imports, the emissions share from imported coal as a portion of total raw coal increased from 0.1% in 2000 to 7.8% in 2012. Crude oil's contribution to total fossil fuel CO_2 emissions decreased from 20.7% to 16.7%, whereas the share of emissions from natural gas increased from 1.7% to 3.9% between 2000 and 2012.

Several provinces that contributed most to emissions of each fossil fuel type in 2012 are presented in Fig. 5. Shanxi, Shandong, Inner Mongolia and Hebei contributed the most to raw coal-related CO_2 emissions. These provinces are either coal bases or manufacturing provinces. Most of the imported coal was consumed in Guangdong and Fujian, which are located on the southeast coast, where it is cheaper to import coal from abroad rather than transport it from coal sources in the interior. Coastal Guangdong, Shandong and Liaoning also have more developed shipping industries for similar reasons. Most of the raw coal are consumed in fire power plant to generate electricity [56]. More crude oil was consumed in these provinces, resulting in increased CO_2 emissions. Sichuan, Jiangsu, Xinjiang and Beijing consumed high levels of natural gas in 2012; Sichuan and Xinjiang are the locations of the main natural gas fields in China. Jiangsu and Beijing are the most developed provinces in China and are exploring cleaner energy utilization pathways. As natural gas is a cleaner fossil fuel than raw coal and crude oil, increased the proportion of natural gas consumption would help control CO_2 emissions.

Similar to energy utilization, fossil fuel CO_2 emissions can be divided into 16 sectors (see Fig. 6). The first eight sectors belong to "input & output of transformation" sectors, and the last eight sectors are "final consumption" sectors. Most CO_2 emissions are produced by thermal power, industry final consumption, petroleum refineries and coal washing.

3.2. Provincial emission-socioeconomic characteristics in 2012

To analyse the emission characteristics of different provinces, we calculated the per capita CO_2 emissions and CO_2 emissions intensity for 2012 (see Fig. 7). The calculations and data sources are presented in Table 4.

3.2.1. Per capita CO_2 emissions

The national average CO_2 emissions per capita in 2012 were 6.38 metric tonnes. The emissions per capita varied among provinces due to differences in development stage and development pathways. Only 13 of 30 provinces had emissions per capita above the national level.

The top three provinces were Inner Mongolia, Ningxia and Shanxi. All three provinces are primary coal producers, with many large coal mines, and the coal usage per capita is much higher here as compared with the national average level. Mongolia and Ningxia host the China Shenhua Energy Company Limited (the nation's largest energy company), and Shanxi is the base of the China National Coal Group Corporation (the second largest energy company). The two enterprises are the only two energy enterprises in China among the 112 central enterprises (i.e., firms under government control) updated in 2015 [57]. Central enterprises are normally pillars of economic growth, with high output and added value. In addition, coal is a high-emission fossil fuel compared with crude

Table 2
Provincial CO_2 emissions, million tonnes, 2000–2012.

Province	2000	2001	2002	2003	2004	2005	2006
Beijing	64.08	61.96	62.29	65.98	49.91	91.67	75.73
Tianjin	69.79	68.47	67.60	69.78	79.12	82.33	85.53
Hebei	262.70	266.75	271.78	296.39	341.33	354.87	364.31
Shanxi	90.80	93.53	196.51	293.68	310.72	264.53	288.97
Inner Mongolia	117.49	122.11	126.91	120.30	203.00	221.36	256.89
Liaoning	296.56	275.76	297.28	315.34	358.70	364.86	393.45
Jilin	98.94	104.11	101.09	110.96	119.82	130.87	151.07
Heilongjiang	180.09	168.45	161.87	167.97	193.13	209.78	218.95
Shanghai	104.94	109.63	109.44	122.51	136.17	130.77	130.86
Jiangsu	214.86	211.15	211.48	241.05	291.88	331.58	369.78
Zhejiang	91.79	139.67	144.87	161.27	211.83	223.14	260.99
Anhui	124.85	128.14	122.81	137.51	154.15	148.36	166.04
Fujian	52.38	50.59	55.91	66.46	79.93	83.96	97.33
Jiangxi	50.07	50.22	49.65	59.15	74.55	73.22	84.35
Shandong	258.06	297.32	318.94	386.49	483.76	570.80	663.51
Henan	138.59	149.83	147.46	212.64	221.81	297.93	313.44
Hubei	128.20	124.32	124.07	137.26	157.72	142.72	175.62
Hunan	73.49	78.00	85.78	93.52	105.49	143.88	163.22
Guangdong	173.40	175.17	183.00	203.74	235.68	231.80	270.30
Guangxi	44.02	40.69	33.91	40.75	59.83	56.32	66.40
Hainan	6.06	6.22	0.00	8.87	7.99	5.88	12.53
Chongqing	60.16	54.03	51.83	47.53	57.38	61.81	72.99
Sichuan	96.39	95.28	103.12	134.66	157.36	136.33	147.58
Guizhou	64.19	55.56	64.22	104.70	117.83	128.17	153.70
Yunnan	54.13	57.81	57.42	74.78	53.48	106.18	123.65
Shaanxi	69.15	68.60	80.21	87.17	112.64	194.71	173.95
Gansu	71.49	73.01	75.63	85.86	97.80	93.46	102.21
Qinghai	12.99	15.67	15.68	17.47	18.59	19.02	22.64
Ningxia	0.00	0.00	0.00	35.72	59.06	66.42	76.23
Xinjiang	90.48	93.72	89.73	98.95	119.60	122.26	143.29
Province Aggregation	3160.15	3235.79	3410.46	3998.49	4670.25	5088.96	5625.51

Province	2007	2008	2009	2010	2011	2012
Beijing	76.21	84.58	85.46	83.48	81.56	82.94
Tianjin	86.33	83.18	86.32	115.56	126.87	123.02
Hebei	409.05	404.04	419.43	441.14	477.14	506.94
Shanxi	219.91	412.36	506.95	540.20	608.96	684.23
Inner Mongolia	307.60	373.11	402.34	459.35	596.51	656.67
Liaoning	392.08	387.86	403.74	430.36	443.05	474.30
Jilin	150.80	163.37	168.20	181.53	209.87	213.63
Heilongjiang	212.93	212.01	239.40	290.08	309.62	326.03
Shanghai	126.55	131.85	128.71	141.68	148.68	154.59
Jiangsu	389.40	380.09	393.98	428.55	478.61	493.63
Zhejiang	286.58	276.40	285.83	297.85	314.99	314.57
Anhui	174.44	196.95	219.15	213.88	234.55	266.08
Fujian	111.44	106.54	128.99	153.78	178.07	203.03
Jiangxi	89.25	89.02	87.12	96.86	102.71	114.79
Shandong	696.59	707.56	741.96	749.92	779.74	816.13
Henan	352.68	266.81	380.50	444.09	500.29	414.84
Hubei	187.24	173.23	186.64	211.94	242.51	234.02
Hunan	179.19	160.43	165.91	171.90	200.40	207.34
Guangdong	294.67	284.80	333.66	387.32	435.57	478.47
Guangxi	77.09	60.78	80.32	104.50	134.14	158.55
Hainan	32.56	31.63	33.39	37.86	41.47	43.66
Chongqing	79.78	98.59	109.25	102.22	110.87	109.00
Sichuan	184.12	194.45	215.73	204.45	198.41	208.94
Guizhou	147.46	166.28	189.13	192.51	204.88	218.75
Yunnan	121.39	121.85	130.04	129.85	135.65	140.22
Shaanxi	208.76	238.30	222.81	248.41	272.63	323.27
Gansu	110.89	111.21	107.73	119.46	138.05	140.75
Qinghai	23.19	28.19	29.77	29.30	39.39	45.38
Ningxia	91.90	94.21	119.06	121.10	151.39	151.99
Xinjiang	148.17	163.36	190.27	204.53	239.09	276.96
Province Aggregation	5968.24	6203.03	6791.78	7333.66	8135.68	8582.70

oil and natural gas because it emits more CO_2 to produce the same unit of heat compared with other energy types [43]. Thus, these three provinces have the highest CO_2 emissions per capita.

The second group includes eight provinces: Xinjiang, Liaoning, Tianjin, Shaanxi, Heilongjiang, Shandong, Qinghai and Jilin. These are either primary energy suppliers (such as Xinjiang, Shaanxi, Heilongjiang and Qinghai) or bases for heavy industry (such as Liaoning, Tianjin, Shandong and Jilin). The third group includes six provinces: Hebei, Shanghai, Guizhou, Jiangsu, Zhejiang and Gansu. The CO_2 emissions per capita of these provinces were near the national average. The remaining 13 provinces belong to the last group. Some of these provinces are located in the central and southwest parts of China, with primary industry as their pillar economy; others are among the most developed provinces with

Table 3
Comparison of provincial emissions, million tonnes.

Province	Final + input/output consumption, IPCC EF		Final + input/output consumption, Liu's EF		Apparent energy consumption, Liu's EF	
	Total emissions	# Raw coal	Total emissions	# Raw coal	Total emissions	# Raw coal
Beijing	89.21	39.08	86.29	36.16	82.94	33.74
Tianjin	136.00	83.11	129.78	76.89	123.02	70.75
Hebei	582.80	528.17	543.29	488.66	506.94	452.80
Shanxi	811.81	803.73	751.68	743.61	684.23	677.39
Inner Mongolia	740.25	727.87	685.80	673.42	656.67	645.79
Liaoning	511.17	290.52	489.44	268.79	474.30	253.16
Jilin	246.96	212.83	231.04	196.91	213.63	180.18
Heilongjiang	366.19	299.47	343.78	277.06	326.03	256.60
Shanghai	160.61	81.67	154.50	75.56	154.59	76.25
Jiangsu	553.68	441.91	520.62	408.85	493.63	384.38
Zhejiang	339.60	247.34	321.10	228.83	314.57	223.73
Anhui	312.72	294.70	290.67	272.66	266.08	248.88
Fujian	180.79	139.51	170.35	129.08	203.03	162.94
Jiangxi	120.45	103.34	112.72	95.61	114.79	97.90
Shandong	932.04	729.33	877.48	674.77	816.13	615.28
Henan	590.34	544.10	549.64	503.40	414.84	372.44
Hubei	269.77	234.99	252.19	217.41	234.02	200.16
Hunan	236.01	204.33	220.73	189.04	207.34	176.20
Guangdong	438.32	286.42	416.89	265.00	478.47	328.76
Guangxi	158.41	113.53	149.92	105.04	158.55	113.69
Hainan	48.15	16.50	46.92	15.26	43.66	15.66
Chongqing	128.79	113.66	120.29	105.16	109.00	96.07
Sichuan	240.32	202.38	225.18	187.24	208.94	173.50
Guizhou	250.11	249.59	231.44	230.92	218.75	218.31
Yunnan	165.87	165.65	153.48	153.26	140.22	140.03
Shaanxi	363.89	281.43	342.84	260.38	323.27	246.41
Gansu	157.53	108.55	149.41	100.43	140.75	92.09
Qinghai	52.51	42.21	49.36	39.05	45.38	35.84
Ningxia	177.76	161.56	165.68	149.47	151.99	136.30
Xinjiang	309.33	213.00	293.39	197.06	276.96	179.67
Aggregation	9671.39	7960.48	9075.89	7364.98	8582.70	6904.90

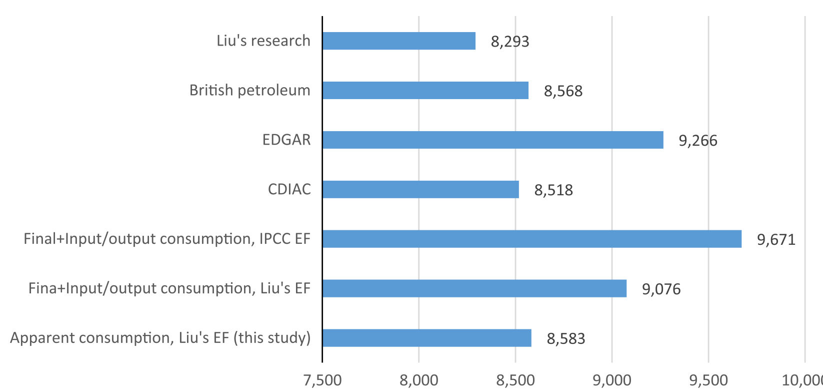

Fig. 4. National CO_2 emission comparison of different sources, 2012, million tonnes. *Data sources:* emission estimates by Liu's research [31], emission estimates by British petroleum [29], emission estimates by EDGAR [28], and emission estimates by CDIAC [26].

highly developed service industries (such as Beijing and Guangdong). Jiangxi and Sichuan had the lowest CO_2 emissions per capita, 2.55 and 2.59 metric tonnes, respectively.

3.2.2. CO_2 emissions intensity

The national average CO_2 emission intensity in 2012 was 0.15 million tonnes/billion yuan. One half (15) of the provinces had an emission intensity above the national level. As shown in Fig. 7, the distribution of CO_2 emission intensity is similar to that of CO_2 emissions per capita. The provinces in the north and northwest had higher emission intensities, whereas the provinces in the central and southeast areas had lower intensities. The differences in emission intensities among these provinces reflect differences in their natural resource endowments. As mentioned above, the provinces in north and northwest have more coal mines (such as Shanxi and Inner Mongolia) and oil fields (such as Xinjiang). Therefore, the industries of energy production and transformation are the pillar industries of the local economy, including coal mining and dressing, coking and petroleum processing. These industries are all high energy intensity, and huge amounts of primary fossil fuels are consumed in these provinces for energy transformation and final consumption. As CO_2 emissions were calculated here using the apparent scope energy consumption approach, all of the primary energy transformed into the second energy was included in the energy consumption of the province. Hence, the CO_2 emission intensity of the energy-producing provinces is much higher.

By contrast, the more developed provinces have lower CO_2 emission intensities, such as Beijing (0.05), Shanghai (0.08) and Guangdong (0.08). These more developed provinces have greater service industry, which is less energy dependent.

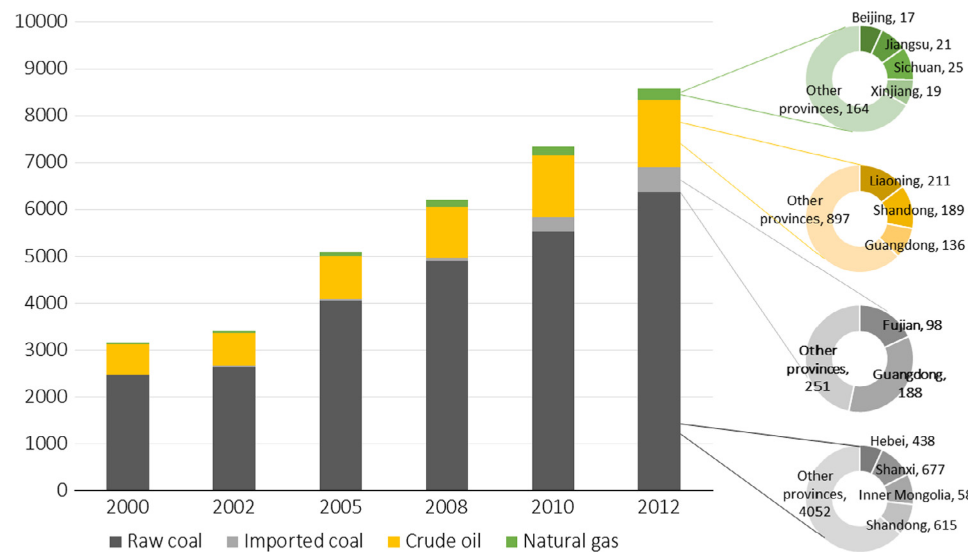

Fig. 5. Provincial CO_2 emissions by fossil fuel types, million tonnes.

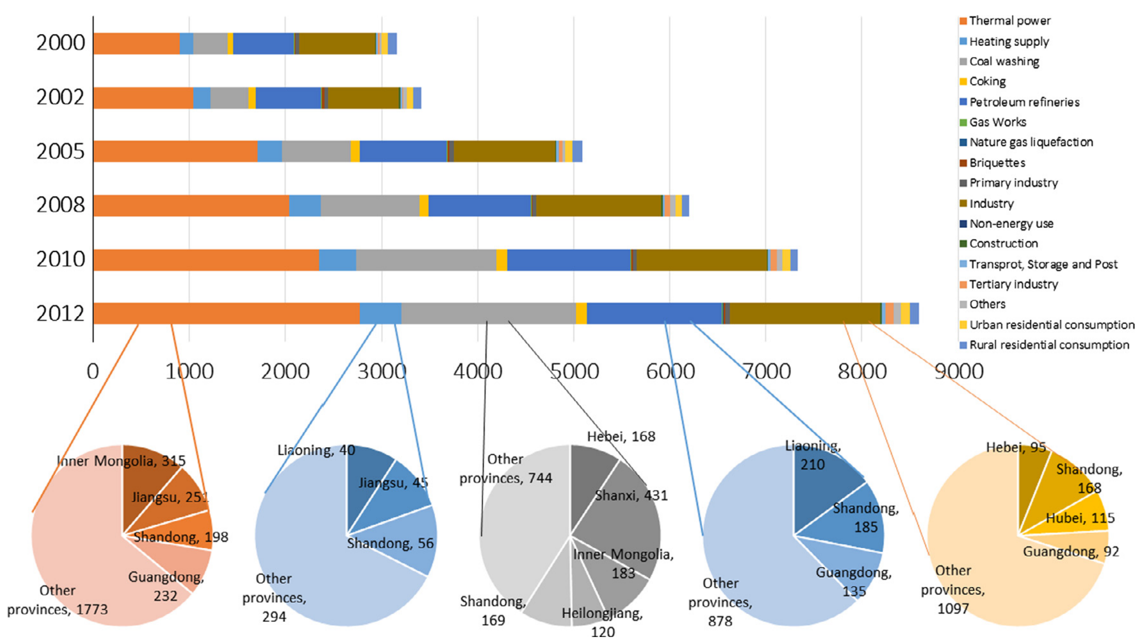

Fig. 6. Provincial CO_2 emissions by sectors, million tonnes.

4. Policy implications and conclusions

Climate policy discussions have made great process in the 2015 at the United Nations Climate Change Conference held in Paris, where the participated 195 counties agreed to reduce their carbon output as soon as possible and to do their best to keep global warming to well below 2 °C compared with the pre-industrial level. China is the most important participant as the biggest CO_2 emitter and should also take the responsibility.

First of all, it is of great significance to account China's CO_2 emissions as accurate as possible both at national level and provincial level. We re-estimated the CO_2 emission inventories of 30 Chinese provinces over the last 13 years. We included emissions from three primary fossil fuels in eight input & output transformation sectors and eight final consumption sectors. The CO_2 emissions were calculated based on "apparent energy consumption" approach along with updated emission factors. The new accounting method can be applied to further research on multi-scale carbon emission accounts, such as city-level and industrial process. Our results of accurate national and provincial CO_2 emissions could help policy makers develop strategies and policies for emission reductions and track the process of those policies.

The results indicate that Chinese provincial aggregated CO_2 emissions calculated by the apparent energy consumption and updated emissions factors are coincident with the national emissions estimated by the same approach, which are 12.69% smaller than the one calculated by the traditional approach. Chinese provincial aggregate CO_2 emissions increased from 3160 million tonnes in 2000 to 8583 million tonnes in 2012. Our estimates for 2012 are similar to that of CDIAC (8518) and 7.96% lower than the highest estimation (EDGAR, 9266 million tonnes). Of the 30 provinces, Shandong contributed the most to national accumulative CO_2 emissions of the last 13 years (7471 million tonnes), with an average of 10.35% over 13 years. The following three provinces

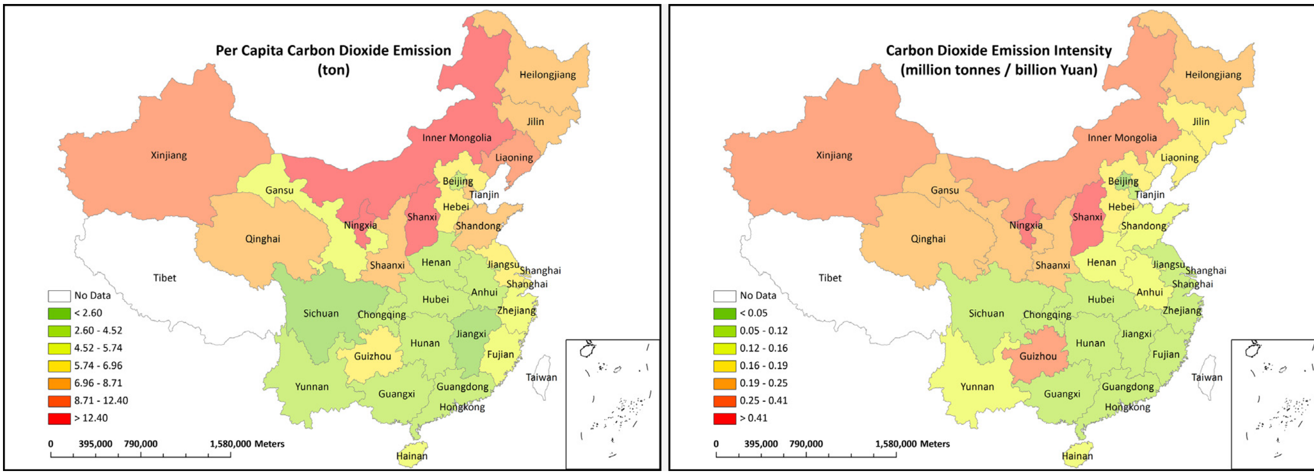

Fig. 7. Emission-socioeconomic nexus of China's 30 provinces, 2012.

Table 4
Emission socioeconomic indices of 30 provinces, 2012. *Source:* China Statistical Yearbook, 2013 [24].

Province	CO_2 emissions (million tonnes)	GDP (million yuan)	Population (10^4)	Land area (10^4 km^2)	Emissions per capita (tonnes)	Emissions intensity (million tonnes/10^4 yuan)	Emissions per area (10^3 tonnes/km^2)
Beijing	82.94	1,787,940	2069	1.70	4.01	0.46	4.88
Tianjin	123.02	1,289,388	1413	1.20	8.71	0.95	10.25
Hebei	506.94	2,657,501	7288	19.00	6.96	1.91	2.67
Shanxi	684.23	1,211,283	3611	16.00	18.95	5.65	4.28
Inner Mongolia	656.67	1,588,058	2490	118.00	26.37	4.14	0.56
Liaoning	474.30	2,484,643	4389	15.00	10.81	1.91	3.16
Jilin	213.63	1,193,924	2750	19.00	7.77	1.79	1.12
Heilongjiang	326.03	1,369,158	3834	46.00	8.50	2.38	0.71
Shanghai	154.59	2,018,172	2380	0.63	6.49	0.77	24.38
Jiangsu	493.63	5,405,822	7920	10.00	6.23	0.91	4.94
Zhejiang	314.57	3,466,533	5477	10.00	5.74	0.91	3.15
Anhui	266.08	1,721,205	5988	14.00	4.44	1.55	1.90
Fujian	203.03	1,970,178	3748	12.00	5.42	1.03	1.69
Jiangxi	114.79	1,294,888	4504	17.00	2.55	0.89	0.68
Shandong	816.13	5,001,324	9685	16.00	8.43	1.63	5.10
Henan	414.84	2,959,931	9406	17.00	4.41	1.40	2.44
Hubei	234.02	2,225,045	5779	19.00	4.05	1.05	1.23
Hunan	207.34	2,215,423	6639	21.00	3.12	0.94	0.99
Guangdong	478.47	5,706,792	10,594	19.00	4.52	0.84	2.52
Guangxi	158.55	1,303,510	4682	24.00	3.39	1.22	0.66
Hainan	43.66	285,554	887	3.40	4.93	1.53	1.28
Chongqing	109.00	1,140,960	2945	8.20	3.70	0.96	1.33
Sichuan	208.94	2,387,280	8076	49.00	2.59	0.88	0.43
Guizhou	218.75	685,220	3484	18.00	6.28	3.19	1.22
Yunnan	140.22	1,030,947	4659	39.00	3.01	1.36	0.36
Shaanxi	323.27	1,445,368	3753	21.00	8.61	2.24	1.54
Gansu	140.75	565,020	2578	43.00	5.46	2.49	0.33
Qinghai	45.38	189,354	573	72.00	7.92	2.40	0.06
Ningxia	151.99	234,129	647	6.60	23.48	6.49	2.30
Xinjiang	276.96	750,531	2233	166.00	12.40	3.69	0.17
Aggregation/Average	8582.70	57,585,081	134,481	841.73	6.38	1.49	1.02

were Liaoning, Hebei and Shanxi, with cumulative emissions of 4833 (6.69%), 4816 (6.67%) and 4511 (6.25%) million tonnes CO_2, respectively.

From the perspective of fossil fuel types, the paper confirms that raw coal combustion contributes most to provincial CO_2 emissions, especially for Shanxi, Shandong and Inner Mongolia provinces. Whilst for Guangdong and Fujian province, the main source of CO_2 emissions is imported coal. Differentiated policies should be made corresponding to different emitting sources. For Shanxi, Shandong and Inner Mongolia, policies such as increasing coal mining efficiency, obtaining higher percentage of coal recovery could be used. For Guangdong and Fujian, polices regarding replacing coal with oil and natural gas could be encouraged. Several policy instruments could be used to support gas replacement like feed-in tariff (FIT) policies, capacity payment, price-setting policies, quantity setting policies, renewable portfolio standard, etc.

If we divide the total CO_2 emissions into final consumption and energy transformation sectors, we can see that the thermal power sector emits the most CO_2, followed by the industrial final consumption, petroleum refinery and coal washing sector. Therefore, it is of great significance to increase the efficiency of thermal power generator through promotion of the most advanced technologies, such as supercritical generator, combined heat and power and IGCC (Integrated Gasification Combined Cycle) technology.

In additional, policy makers should also take the different socioeconomic characteristics of each province into account when making climate policies [58]. The study shows that provinces located in the northwest and north had higher per capita CO_2 emissions and emission intensities than the central and southeast coastal regions. Understanding emissions and the associated socioeconomic characteristics of different provinces provides a basis for carbon emission control policy and goal in China.

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Data Descriptor: China CO_2 emission accounts 1997–2015

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China is the world's top energy consumer and CO_2 emitter, accounting for 30% of global emissions. Compiling an accurate accounting of China's CO_2 emissions is the first step in implementing reduction policies. However, no annual, officially published emissions data exist for China. The current emissions estimated by academic institutes and scholars exhibit great discrepancies. The gap between the different emissions estimates is approximately equal to the total emissions of the Russian Federation (the 4th highest emitter globally) in 2011. In this study, we constructed the time-series of CO_2 emission inventories for China and its 30 provinces. We followed the Intergovernmental Panel on Climate Change (IPCC) emissions accounting method with a territorial administrative scope. The inventories include energy-related emissions (17 fossil fuels in 47 sectors) and process-related emissions (cement production). The first version of our dataset presents emission inventories from 1997 to 2015. We will update the dataset annually. The uniformly formatted emission inventories provide data support for further emission-related research as well as emissions reduction policy-making in China.

Design Type(s)	time series design • data integration objective
Measurement Type(s)	carbon dioxide emission process
Technology Type(s)	computational modeling technique
Factor Type(s)	fuel • carbon dioxide emission
Sample Characteristic(s)	China • coal • hydrocarbon gas • oil • petroleum • paraffin • fuel oil • liquefied natural gas • natural gas • manufacturing process

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Background & Summary

With lifestyle changes and rapid economic growth in China, the CO_2 emissions in China have increased rapidly. The CO_2 emissions from fossil fuel combustion (energy-related emissions) and cement production (process-related emissions) in China rose steadily and slowly in the pre-WTO era (1980–2002). These emissions increased from 1,467 to 3,694 million tonnes during this period[1], a rate of 8% per year. After China joined the WTO in 2002, manufacturing in China quickly started to expand. Thus, China's emissions also spiked. The annually averaged emissions rate increase from 2002 to 2007 reached 13%. This expansion led China to become the world's top energy consumer and CO_2 emitter[2]. Now, the human-induced CO_2 emissions in China account for approximately 30% of global emissions[3]. Consequently, China is playing an important role in global emissions reduction and climate change mitigation. The Chinese government has promised that its CO_2 emissions will peak by 2030[4] and that it will achieve a 60%-65% reduction in its emission intensity (per GDP CO_2 emissions) by 2030 compared with its 2005 level[5].

An accurate accounting of China's CO_2 emissions is the first step in achieving emissions reductions. However, the CO_2 emissions accounts for China have not been well documented. There is no annual, officially published emission report in China. The Chinese government has only published national CO_2 emission inventories for 1994[6], 2005[7], and 2012[8]. Scholars and research institutes have previously assumed the responsibility for calculating China's CO_2 emissions. The discrepancy between their estimations exceeded 1,770 million tonnes (20%) in 2011, which is approximately equal to the Russian Federation's total emissions in 2011[9]. Considering that the Russian Federation was the 4th highest emitter in the world at that time[3], the uncertainties in China's emission accounts should not be underestimated. Compared with the three official CO_2 emissions in China for 1994, 2005, and 2012, the estimates by international academic institutes have been relatively high. For example, in 2012, the Emission Database for Global Atmospheric Research (EDGAR) and Carbon Dioxide Information Analysis Centre (CDIAC) estimates were 10,057 and 10,020 million tonnes, respectively, which are 8% higher than the official estimate of China's emissions (9,323 million tonnes). The primary reason is that nearly all the research institutes and scholars use the default emission factors recommended by IPCC, which are higher than China's survey value[10]. The energy data quality is another reason for the limited veracity of China's emission accounts[11]. Furthermore, all the existing datasets only present the national total CO_2 emissions. There are scarcely any emission inventories constructed according to fossil fuel types and industrial sectors for China and its 30 provinces.

Considering the large uncertainties/data gaps in China and its provincial CO_2 emission accounts, our first version of the dataset presents the CO_2 emission inventories of China and its 30 provinces from 1997 to 2015. We also provide the national and provincial energy data used in the calculation for transparency and verifiability. We will update and publish the dataset annually. Our emissions are calculated based on the updated emission factors[10] and most up to date energy consumption data[12]. The inventories are constructed in a uniform format, which includes emissions from 17 fossil fuels burned in 47 socioeconomic sectors (energy-related emissions) and those from the cement production industry (process-related emissions). The uniformly formatted time-series emission inventories can be utilized widely. These inventories can provide robust data support for further analysis of China's environmental issues[13–17] and emissions reduction policy-making[13]. The data can be downloaded freely from China Emission Accounts and Datasets (CEADs, www.ceads.net) and Figshre.

Methods

The CO_2 emissions in this dataset were estimated in terms of the IPCC administrative territorial-based accounting scope. The administrative territorial emissions refer to emissions '*taking place within national (including administered) territories and offshore areas over which the country has jurisdiction (page overview.5)*'[18]. The territorial-based emissions do not include emissions from international aviation or shipping[19]. The administrative territorial emissions can be used to evaluate the human-induced emissions by domestic production and resident activities directly within one region's boundaries[20,21]. Our CO_2 emission inventories were constructed in two parts: energy- and process-related (cement) CO_2 emissions. The energy-related emissions can be calculated using two approaches: the sectoral and reference approaches. Figure 1 presents a diagram of the entire construction of our emission inventories.

Energy-related sectoral approach emissions

The energy-related emissions refer to the CO_2 emitted during fossil fuel combustion. According to the IPCC guidelines[22], the sectoral approach emissions are calculated based on the fossil fuels' sectoral combustion; see equation (1) below.

$$CE_{ij} = AD_{ij} \times NCV_i \times CC_i \times O_{ij} \tag{1}$$

where CE_{ij} refers to the CO_2 emissions from fossil fuel i burned in sector j; AD_{ij} represents the fossil fuel consumption by the corresponding fossil fuel types and sectors; NCV_i refers to the net caloric value, which is the heat value produced per physical unit of fossil fuel combustion; CC_i (carbon content) is the CO_2 emissions per net caloric value produced by fossil fuel i; and O_{ij} is the oxygenation efficiency, which refers to the oxidation ratio during fossil fuel combustion.

The subscripts i (fossil fuel) and j (sector) correspond to those used in Table 1 and Table 2. There are 26 fossil fuels in China's energy statistics systems, listed in the most recent energy balance table in the

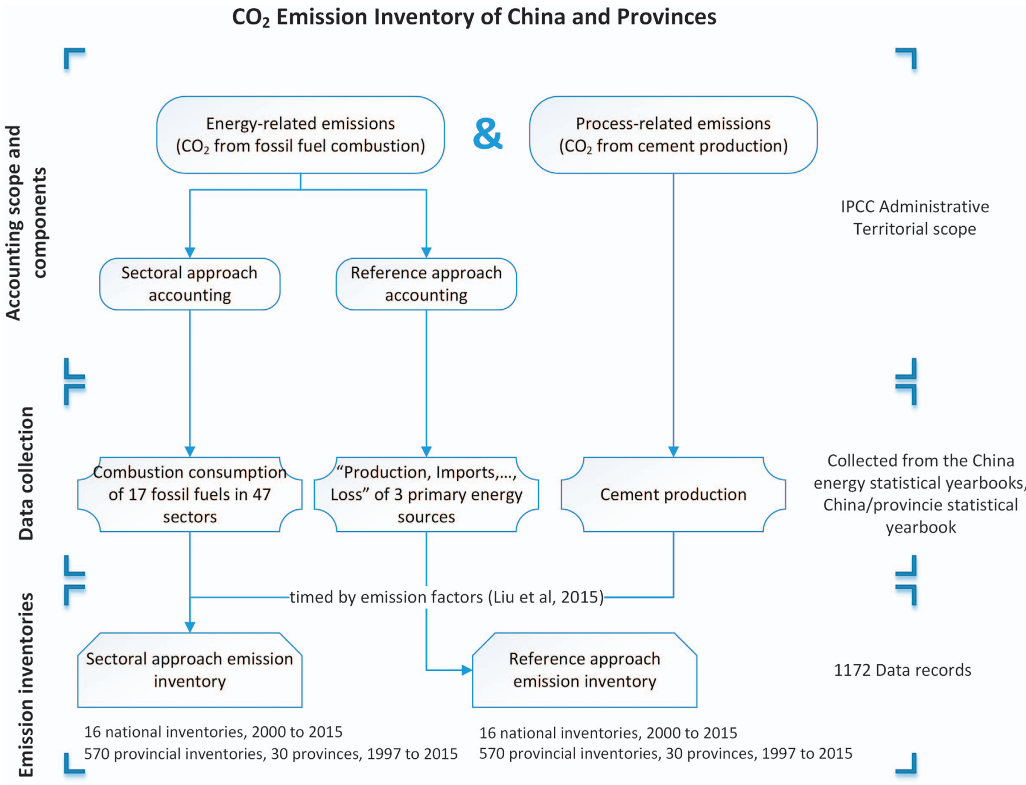

Figure 1. Diagram of CO_2 emission inventory construction.

China energy statistical yearbook. We merged these fuels into 17 types due to the small consumption and similar quality of certain fuels to that of others, as shown in Table 1. Among the 17 fossil fuels, raw coal, crude oil, and natural gas are primary energy sources. The remaining 14 fuels are classified as secondary energy sources, which are extracted or processed from primary sources. The 47 sectors used in the energy statistical system are also consistent with those used in China's national economic accounting[23] (see Table 2). Due to all the administrative boundaries (at both the national and provincial scales) that span both urban and rural geographies in China, urban and rural households are listed separately in the multi-scale CO_2 emission inventories.

Fossil fuels used as chemical raw materials ('non-energy use' in the Energy Balance Table), as well as the energy loss during transportation, were removed from the total fossil fuel consumption to avoid double counting. The non-burning fossil fuels input during energy conversion processes was also excluded as the processes involve little CO_2 emissions. Taking the process of coal washing as an example, the carbon elements in raw coal are converted into cleaned coal and other washed coal during the process. The real CO_2 emissions concentrated in the combustion of cleaned coal and other washed coal. Other similar processes include 'coking', 'petroleum refineries', 'gas works', 'briquettes'. Only fossil fuels burnt during the transformation processes were taken into account for emission calculation, i.e., 'thermal power' and 'heating supply'.

Emissions from electricity/heat generated within city boundaries were counted based on the energy input for power/heat generation ('thermal power' and 'heating supply') and were allocated to the electricity generation sector[24]. Our administrative territorial emission inventories excluded emissions from imported electricity and heat consumption from outside the nation/one province boundaries. We only focused on fossil fuels consumed within the nation/one province boundary.

The national sectoral fossil fuel consumption (AD_{ij}) was collected from the Energy Statistical Yearbooks published officially by the National Bureau of Statistics of China[25]. China has officially revised its national energy statistics four times since 2000 (in 2004, 2005, 2009, and 2014's China energy statistical yearbooks). Each revision has modified the energy balance sheets and sectoral energy consumption. For example, the total energy consumption of 2011 are modified from 3,480 to 3,870million tonnes of standard coal equivalent (in coal equivalent calculation) in 2014's revision, enlarged by 11.2%. Our emission inventories were calculated based on the most up to date energy data published after 2014[25].

For the provincial scale, the China Energy Statistical Yearbooks only publish each province's energy balance table every year. We collected the total consumption of the 17 fossil fuels from the balance table and then used the provinces' sectoral fossil fuel consumption to divide the total consumption. Most of the provinces' sectoral fossil fuel consumption was collected from the provinces' corresponding statistical

No. (i) Unit	Fuels in China's Energy Statistics	Fuels in this study	NCV_i	CC_i
			$PJ/10^4$ *tonnes*, $10^8 m^3$	*tonneC/TJ*
1	Raw coal	Raw coal	0.21	26.32
2	Cleaned coal	Cleaned coal	0.26	26.32
3	Other washed coal	Other washed coal	0.15	26.32
4	Briquettes	Briquette	0.18	26.32
	Gangue			
5	Coke	Coke	0.28	31.38
6	Coke oven gas	Coke over gas	1.61	21.49
7	Blast furnace gas	Other gas	0.83	21.49
	Converter gas			
	Other gas			
8	Other coking products	Other coking products	0.28	27.45
9	Crude Oil	Crude oil	0.43	20.08
10	Gasoline	Gasoline	0.44	18.90
11	Kerosene	Kerosene	0.44	19.60
12	Diesel oil	Diesel oil	0.43	20.20
13	Fuel oil	Fuel oil	0.43	21.10
14	Naphtha	Other petroleum products	0.51	17.2
	Lubricants			
	Paraffin			
	White spirit			
	Bitumen asphalt			
	Petroleum coke			
	Other petroleum products			
15	Liquefied petroleum gas (LPG)	LPG	0.47	20.00
16	Refinery gas	Refinery gas	0.43	20.20
17	Nature gas	Nature gas	3.89	15.32

Table 1. Fossil fuels and emission factors (NCV_i, CC_i).

yearbooks. For certain provinces (Hebei, Jiangsu, Zhejiang, Shandong, Guangxi, Hainan, Sichuan, and Guizhou) that do not have the data in their yearbooks, we used the national economic census data from 2008[26], which assumes the industry structure was stable during the intervening years.

Both the IPCC and National Development and Reform Commission of China (NDRC) have published default factors (NCV_i, CC_i) for China. Most of the current research uses the IPCC default value. According to our previous survey on China's fossil fuel quality and cement process[10], the IPCC default emission factors are approximately 40% higher than China's survey value. In our datasets, we used the updated emission factors, see Table 1. As our previous study only reported the emission factors of three primary fossil fuels (i.e., raw coal, crude oil, and natural gas), we estimated the emissions factors of other 14 secondary fossil fuels by scaling them down according to the ratio of the updated primary fossil fuels' emission factors to those of NDRC. We used the ratio of raw coal, crude oil to update emission factors of coal-related, oil-related fuels, respectively. For O_{ij}, our datasets adopted different oxygenation efficiencies for the fossil fuels used in different sectors[27], which represents the different combustion technology levels of the sectors (shown in Table 3 (available online only)).

We used MATLAB R2014a to construct the emission inventories with sectoral fossil fuel consumption and emission factors. We provided the code in the Supplementary Information. We also provided the formatted energy data of China and its provinces (energy inventories) in our datasets for additional data transparency and verifiability (see Data Citation 1, File 'China national energy inventory, 2000–2015' and File 'China provincial energy inventory, 1997–2015'). Researchers will be able to use the MATLAB code and energy inventories to recalculate the CO_2 emissions for China by adopting different emission factors.

Energy-related reference approach emissions

Apart from the sectoral approach, the energy-related emissions of one region can also be estimated using the reference approach. '*The Reference Approach is a top-down approach, using a country's energy supply data to calculate the emissions of CO_2 from combustion of mainly fossil fuels. The Reference Approach is a straightforward method that can be applied on the basis of relatively easily available energy supply statistics (Volume 2, Chapter 6, Page 5)*'[22]. The IPCC suggests '*to apply both a sectoral approach and the reference approach to estimate a country's CO_2 emissions from fuel combustion and to compare the results of these*

No. (j)	Socioeconomic sectors	Category	
1	Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy	The primary industry	
2	Coal Mining and Dressing	Energy production	Manufacturing industries
3	Petroleum and Natural Gas Extraction	Energy production	
4	Ferrous Metals Mining and Dressing	Energy production	
5	Nonferrous Metals Mining and Dressing	Energy production	
6	Non-metal Minerals Mining and Dressing	Energy production	
7	Other Minerals Mining and Dressing	Energy production	
8	Logging and Transport of Wood and Bamboo	Light manufacturing	
9	Food Processing	Light manufacturing	
10	Food Production	Light manufacturing	
11	Beverage Production	Light manufacturing	
12	Tobacco Processing	Light manufacturing	
13	Textile Industry	Light manufacturing	
14	Garments and Other Fibre Products	Light manufacturing	
15	Leather, Furs, Down and Related Products	Light manufacturing	
16	Timber Processing, Bamboo, Cane, Palm Fibre & Straw Products	Light manufacturing	
17	Furniture Manufacturing	Light manufacturing	
18	Papermaking and Paper Products	Light manufacturing	
19	Printing and Record Medium Reproduction	Light manufacturing	
20	Cultural, Educational and Sports Articles	Light manufacturing	
21	Petroleum Processing and Coking	Energy production	
22	Raw Chemical Materials and Chemical Products	Heavy manufacturing	
23	Medical and Pharmaceutical Products	Light manufacturing	
24	Chemical Fibre	Heavy manufacturing	
25	Rubber Products	Heavy manufacturing	
26	Plastic Products	Heavy manufacturing	
27	Non-metal Mineral Products	Heavy manufacturing	
28	Smelting and Pressing of Ferrous Metals	Heavy manufacturing	
29	Smelting and Pressing of Nonferrous Metals	Heavy manufacturing	
30	Metal Products	Heavy manufacturing	
31	Ordinary Machinery	Heavy manufacturing	
32	Equipment for Special Purposes	Heavy manufacturing	
33	Transportation Equipment manufacturing	Heavy manufacturing	
34	Electric Equipment and Machinery	High-tech industry	
35	Electronic and Telecommunications Equipment	High-tech industry	
36	Instruments, Meters, Cultural and Office Machinery	High-tech industry	
37	Other Manufacturing Industry	High-tech industry	
38	Scrap and waste	High-tech industry	
39	Production and Supply of Electric Power, Steam and Hot Water	Energy production	
40	Production and Supply of Gas	Energy production	
41	Production and Supply of Tap Water	Heavy manufacturing	
42	Construction	Construction	
43	Transportation, Storage, Post and Telecommunication Services	Services sectors	
44	Wholesale, Retail Trade and Catering Services		
45	Other Service Sectors		
46	Urban Resident Energy Usage	Household	
47	Rural Resident Energy Usage		

Table 2. Economic sectors.

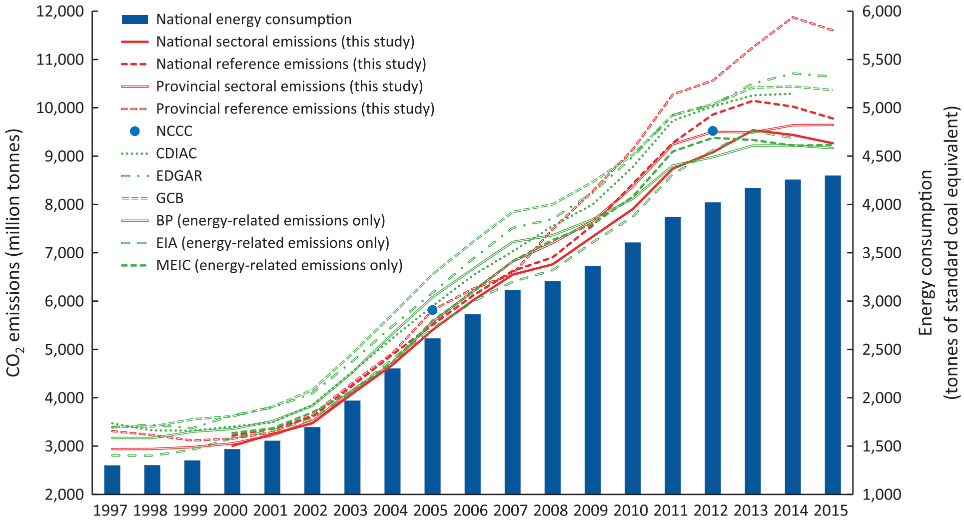

Figure 2. Comparisons of the two-approach emissions and other existing emission inventories. Data source: National energy consumption[12]; National Communication on Climate Change (NC) 2005[7]; NC2012[8]; Carbon Dioxide Information Analysis Centre (CDIAC)[42]; Emissions Database for Global Atmospheric Research (EDGAR)[43]; Global Carbon Budget (GCB)[44]; British Petroleum (BP)[45]; U.S. Energy Information Administration (EIA)[46]. Multi-resolution emission inventory for China (MEIC)[47–49]. Note that emissions by NC2005 include CO_2 emissions from lime and glass production as well, emissions by MEIC, BP and EIA include the energy-related emissions only.

two independent estimates (Volume 2, Chapter6, Page 5)'[22]. The reference emissions can be used to verify and support the sectoral emissions.

As the reference emissions were calculated from the fossil fuels' production base, we only considered three primary fossil fuels (raw coal, crude oil, and natural gas). With the assumption of carbon balance, the carbon in the supply of the 3 primary fossil fuels should be equal to the carbon contained in the total consumption of the 17 fossil fuels[9]. We calculated the reference approach emissions as in equation (2):

$$CE_{ref-i} = AD_{ref-i} \times EF_i \tag{2}$$

where CE_{ref-i} refers to the reference CO_2 emissions from fossil fuel i, EF_i and AD_{ref-i} are the emission factors and apparent consumption of the corresponding fossil fuel, respectively. The emission factors for the 3 primary fossil fuels are the same as those used in the sectoral approach emissions calculation[10]. Values of AD_{ref-i} were calculated as in equation (3). For the same reason, we removed the non-energy use and loss parts from the fuel's apparent consumption. The items in bracket were only used to calculate the apparent consumption of provinces and were skipped when calculating the national consumption.

$$\begin{aligned} AD_{ref-i} &= Indigenous\ Production + Imports - Exports \\ &+ (Moving\ in\ from\ Other\ Provinces - Sending\ Out\ to\ Other\ Provinces) \\ &\pm Stock\ Change - Non\text{-}Energy\ Use - Loss \end{aligned} \tag{3}$$

All the items in equation (3) (at both the national and provincial scales) were collected from the most up to date energy balance tables published officially in the *China Energy Statistical Yearbooks*[25].

Process-related (cement) CO_2 emissions

The process-related emissions refer to CO_2 emitted as a result of physical-chemical reactions in the production process and not the energy combusted by the industry[28]. '*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 (page 240)*'[29]. In this study, we only investigated cement production, which accounts for approximately 75% of China's total process-related CO_2 emissions[7]. We calculated the cement-related CO_2 emissions as in equation (4):

$$CE_t = AD_t \times EF_t \tag{4}$$

where CE_t refers to the process-related CO_2 emissions from cement production and AD_t is the activity data for cement-related emissions accounting, which refer to cement production. We collected data for the cement productions of China and its provinces from the official dataset of the National Bureau of Statistics[30], which are consistent with the *China Statistical Yearbooks*[31]. The expression EF_t refers to the emission factor for cement production, which is 0.2906, also collected from Liu, *et al.*[10]. The cement-

Items		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Raw Coal	Indigenous production	2532.6	2692.4	2836.7	3357.3	3883.7	4327.4	4701.8	5049.7	5312.3	5700.1	6272.9	6887.7	7218.3	7271.7	7088.0	6854.9
	Import	4.1	5.0	21.0	20.7	34.7	48.8	71.2	96.1	81.3	245.6	340.9	414.0	537.1	609.0	542.4	380.0
	Export(−)	−100.8	−164.9	−153.5	−172.0	−158.6	−131.2	−115.8	−97.3	−83.4	−41.0	−34.8	−26.6	−16.7	−13.5	−10.3	−9.5
	Stock decrease	−23.8	3.9	14.9	49.8	−0.3	65.2	127.9	129.6	76.1	−19.0	−63.7	−53.0	−52.6	−48.1	−60.9	33.6
	Loss	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Non-energy use	58.4	61.5	64.0	76.0	94.3	107.4	115.4	114.6	119.6	124.3	129.6	127.8	139.7	151.1	141.3	152.9
	Raw coal total	2353.7	2474.8	2655.1	3179.7	3665.2	4202.8	4669.6	5063.5	5266.6	5761.5	6385.7	7094.3	7546.4	7668.1	7418.0	7106.2
Crude Oil	Indigenous production	500.8	503.8	513.1	521.1	540.4	557.2	567.7	572.6	585.2	582.2	623.8	623.4	637.5	645.0	649.7	659.3
	Import	215.9	185.2	213.3	279.7	377.1	389.7	446.1	501.3	549.7	625.8	730.3	779.8	832.8	865.7	947.5	1030.8
	Export(−)	−31.7	−23.2	−23.6	−25.0	−16.9	−24.8	−19.5	−11.9	−13.0	−15.6	−9.3	−7.7	−7.5	−5.0	−1.8	−8.8
	Stock decrease	−28.1	−4.0	−3.2	−1.9	−9.2	2.4	−3.4	−16.1	−31.0	−20.8	−27.3	−44.7	−28.4	−10.3	−11.5	−19.2
	Loss	5.9	5.8	5.8	4.9	4.6	4.7	6.1	6.1	6.2	5.7	5.9	5.4	5.5	6.5	3.3	2.7
	Non-energy use	2.5	2.6	2.7	3.2	3.5	3.5	6.0	5.3	4.4	5.0	4.8	2.5	1.1	2.7	11.2	4.2
	Crude oil total	648.7	653.4	691.1	765.7	883.4	916.3	978.8	1034.5	1080.2	1160.9	1306.8	1342.9	1427.9	1486.2	1569.3	1655.3
Natural Gas	Indigenous production	58.8	65.6	70.7	75.7	89.7	106.7	126.7	149.8	173.7	184.5	207.2	227.9	239.3	261.5	281.6	291.2
	Import	0.0	0.0	0.0	0.0	0.0	0.0	2.1	8.7	10.0	16.5	7.7	31.0	47.2	59.9	68.7	73.7
	Export(−)	−6.8	−6.6	−6.9	−4.1	−5.3	−6.4	−6.3	−5.6	−7.0	−6.9	−8.7	−6.9	−6.3	−5.9	−5.6	−7.0
	Stock decrease	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Loss	1.4	1.3	1.4	1.4	1.7	2.2	2.1	2.4	3.0	4.7	3.7	3.2	3.6	2.6	4.4	4.4
	Non-energy use	12.4	13.6	14.3	16.5	17.6	19.0	17.1	20.0	22.5	21.8	16.9	21.4	26.5	24.7	26.3	21.0
	Natural gas total	38.2	44.1	48.1	53.8	65.1	79.1	103.2	130.4	151.1	167.6	185.6	227.4	250.0	288.1	314.0	332.5
Process	Cement	173.5	192.1	210.7	250.5	281.0	310.6	359.4	395.6	406.8	477.7	546.9	610.0	634.7	702.1	724.2	685.6
Total reference CO_2 emissions		3214.1	3364.4	3605.0	4249.7	4894.7	5508.8	6111.1	6624.1	6904.7	7567.6	8425.0	9274.6	9859.0	10144.6	10025.5	9779.5
Total Sectoral CO_2 emissions		3003.4	3250.1	3472.1	4085.6	4680.4	5401.1	6008.7	6546.3	6761.0	7333.7	7904.5	8741.6	9080.5	9534.2	9438.4	9265.1

Table 5. Sectoral and reference approach CO_2 emission inventory of China, 2000–2015 (in million tonnes)

related CO_2 emissions were allocated to the sector 'Non-metal Mineral Products' in the final emission inventories.

Comparison of the sectoral- and reference-approach emission inventories

The difference between the sectoral- and reference-approach emission inventories laid in the way we calculated the fossil fuel consumptions when estimated the energy-related emissions. The process-related emissions from the two approaches were exactly the same. The sectoral emissions were calculated from the energy consumption aspect while the reference emissions were calculated via the energy production and trade data. The reference approach assumed that all the carbon elements from the primary energy sources (excluding the transport loss and non-energy usage part) were converted into CO_2 emissions. IPCC suggest calculating the reference emissions for one country as a validation of the sectoral emissions. Therefore, we calculated both the sectoral and reference emission for China and its provinces in our datasets. The red lines in Fig. 2 compared the sectoral and reference emissions.

Our reference emissions were 1 to 7% higher than the sectoral emissions. The differences between the two approaches can be explained from three aspects. First, the energy loss during energy transformation process was not excluded from the reference energy consumption. Second, only transport loss and non-energy usage of primary energy sources were excluded from the total consumption in the reference approach. Those of secondary energy sources were not removed. Third, there was roughly 1.2% statistical difference between the energy production and consumption data in China's energy balance table[12].

As discussed in the energy-related reference approach emissions section above, the reference emissions were calculated with the data of primary fossil fuels only, while the emissions embodied in the secondary fossil fuels cannot be reflected. Due to the frequent energy trade among Chinese provinces, especially the secondary energy types, the provincial reference emissions cannot reflect the real CO_2 emissions within one provincial boundary. Considering the data completeness and transparency, we provided the provincial reference emission inventories in our datasets as well for reference.

Data Records

A total of 1,172 data records (emission and energy inventories) are contained in the datasets. Of these,

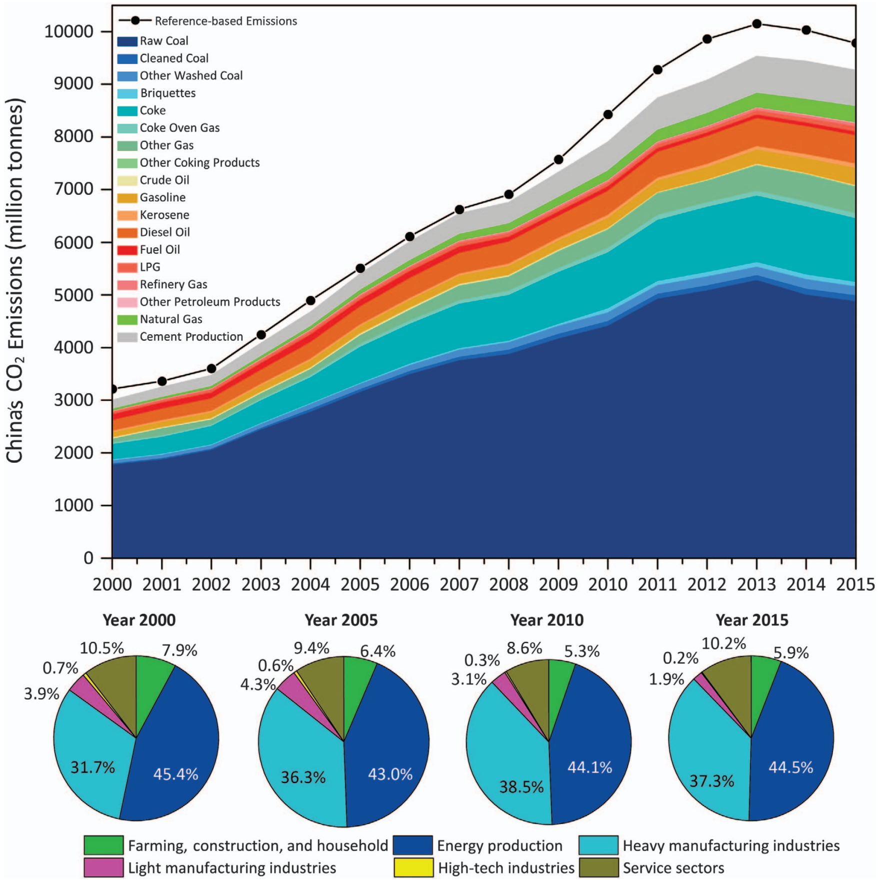

Figure 3. China's CO_2 emissions 2000 to 2015, in million tones. The stack area chart above represents CO_2 emissions from 17 fossil fuels, and the black line represents the reference emissions. The chart shows that China's total CO_2 emissions peaked in 2013 (9,524.24 million tonnes, sectoral-based emissions; 10,145, reference-based emissions). Raw coal was the primary source of CO_2 emissions, accounting for 52.58% of the total emissions in 2015. The four pie charts below illustrate the sectoral structure in CO_2 emissions in 2000, 2005, 2010, and 2015. The energy production and heavy manufacturing industries were the primary contributors.

- 16 are national energy inventories (from 2000 to 2015) [Data Citation 1, File 'China national energy inventory, 2000–2015'];
- 570 are provincial energy inventories (30 provinces, from 1997 to 2015) [Data Citation 1, File 'China provincial energy inventory, 2000–2015'];
- 16 are national sectoral approach inventories (from 2000 to 2015) [Data Citation 1, File 'China national CO_2 emission inventory (sectoral approach), 2000–2015'];
- 16 are national reference approach inventories (from 2000 to 2015) [Data Citation 1, File 'China national CO_2 emission inventory (reference approach), 2000–2015'];
- 570 are provincial sectoral approach inventories (30 provinces, from 1997 to 2015) [Data Citation 1, File 'China provincial CO_2 emission inventory (sectoral approach), 1997–2015'];
- 570 are provincial reference approach inventories (30 provinces, from 1997 to 2015) [Data Citation 1, File 'China provincial CO_2 emission inventory (reference approach), 1997–2015'];

Our CO_2 emission inventories were constructed in a uniform format. The sectoral approach emission inventories are matrices with 19 columns and 47 rows, as shown in Table 4 (available online only) (an example of the China CO_2 emission inventory, 2015). The 19 columns are 17 fossil fuel-related emissions, cement-related emissions and total emissions. The 47 rows represent the 47 socioeconomic sectors. Each element of the matrices represents the CO_2 emissions from fossil fuel combustion/cement production in the corresponding sector. The sectoral and reference approach inventories include emissions from every individual item (e.g., production and import) of the three primary energy sources and the cement process. As an example, Table 5 presents the sectoral and reference approach emission inventories for China from 2000 to 2015.

Provinces	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Beijing	61.9	63.3	66.6	68.2	77.4	77.9	82.0	88.1	92.1	96.7	102.9	99.2	100.4	103.0	94.4	97.2	93.4	92.5	95.2
Tianjin	51.4	51.8	53.0	58.2	60.4	65.1	66.2	78.3	89.0	95.5	103.4	110.2	122.3	136.6	152.0	158.0	157.0	155.4	151.9
Hebei	212.1	211.3	222.8	237.3	251.5	284.4	328.6	374.2	459.1	486.7	529.0	554.4	577.8	647.0	724.6	714.5	768.9	751.9	734.1
Shanxi	148.7	147.5	145.6	148.0	184.2	221.4	251.7	267.9	290.0	320.1	344.9	370.9	375.4	406.5	438.8	466.0	488.2	475.7	440.2
InnerMongolia	97.0	92.4	97.3	105.5	115.8	127.1	149.3	207.3	240.5	290.7	340.0	411.4	445.3	477.4	598.2	621.6	576.2	582.2	584.7
Liaoning	200.7	190.6	184.5	213.0	205.5	220.7	236.7	250.2	279.6	317.9	362.2	371.4	406.9	446.3	455.1	461.0	482.0	484.5	472.1
Jilin	98.6	83.3	84.0	83.0	89.1	92.2	134.3	112.3	143.4	158.9	170.5	179.4	185.7	202.1	233.9	229.5	222.3	222.6	207.6
Heilongjiang	129.1	124.2	122.1	125.3	121.1	117.9	129.6	140.2	158.1	179.0	187.4	197.3	203.2	218.3	247.4	269.2	256.8	269.1	265.5
Shanghai	103.2	104.4	115.6	118.0	122.5	128.4	137.0	148.7	158.9	165.2	174.8	178.2	179.1	187.1	200.2	194.8	201.2	187.7	188.6
Jiangsu	183.9	186.6	194.0	199.4	191.6	220.1	250.8	311.6	396.1	440.9	468.7	496.6	515.6	580.3	633.3	656.2	694.3	704.5	759.5
Zhejiang	115.4	114.9	121.1	131.4	142.9	156.5	178.4	218.0	255.8	290.3	325.3	330.2	338.5	358.6	379.4	377.2	379.0	375.3	375.4
Anhui	109.5	105.8	113.2	118.7	127.0	112.8	168.0	153.8	156.7	175.8	197.7	225.0	251.5	261.9	291.3	318.2	343.1	350.4	351.3
Fujian	44.2	46.6	60.2	56.4	56.4	67.3	82.8	100.2	123.9	135.4	161.3	165.7	187.8	199.4	236.9	232.2	229.4	243.4	230.4
Jiangxi	51.8	50.7	51.4	53.3	58.0	63.3	75.9	89.2	96.4	108.8	127.2	130.3	142.2	148.4	164.0	164.0	197.4	202.3	210.4
Shandong	199.3	212.7	213.5	194.8	232.7	258.8	325.0	397.7	556.5	605.5	663.0	697.7	717.9	766.6	800.8	842.2	761.6	790.4	824.4
Henan	154.3	155.8	157.2	162.1	181.3	194.3	215.7	277.6	336.2	379.0	426.2	435.6	450.7	504.7	548.5	520.7	483.9	535.4	517.8
Hubei	133.9	132.6	135.0	136.8	135.2	154.2	165.2	182.2	189.3	225.2	249.8	254.0	275.2	324.3	373.6	367.6	309.2	310.2	308.2
Hunan	98.0	99.2	80.6	77.3	85.4	92.1	104.9	125.3	178.5	203.2	223.3	226.5	239.0	254.9	285.5	281.7	271.2	269.9	289.2
Guangdong	165.1	172.8	185.2	199.6	210.0	231.5	261.7	296.9	341.8	376.2	410.1	416.9	437.6	471.5	520.6	504.7	496.8	503.8	444.1
Guangxi	50.8	51.8	52.4	56.2	56.1	56.5	66.7	86.6	98.9	112.8	128.2	133.0	151.8	171.8	192.3	204.9	210.0	207.8	269.7
Hainan	7.2	10.4	8.1	8.7	9.2	N/A	15.6	17.2	16.5	19.2	21.7	24.8	27.0	28.9	34.9	37.3	39.5	40.7	42.3
Chongqing	55.4	63.7	69.1	71.3	65.2	70.0	68.4	68.3	81.6	90.0	99.2	126.3	133.1	141.5	160.3	164.8	140.3	156.2	179.3
Sichuan	123.1	123.0	109.3	105.0	108.8	124.0	157.2	175.0	170.1	189.8	208.5	230.1	263.1	303.8	303.4	330.7	343.1	341.3	322.8
Guizhou	72.2	78.3	77.2	81.2	82.9	86.3	110.1	128.6	145.6	169.6	172.0	163.4	184.7	191.5	211.0	230.1	233.2	231.0	233.6
Yunnan	58.0	56.8	54.9	53.0	61.4	72.3	88.8	58.7	133.1	150.2	161.2	163.8	187.2	194.2	205.4	211.7	206.2	194.6	175.9
Shaanxi	68.9	65.7	59.3	58.9	68.4	76.3	86.3	107.7	122.3	128.7	148.1	165.4	186.0	218.6	243.8	261.9	265.6	277.2	276.9
Gansu	50.3	50.9	51.5	54.3	56.1	59.0	67.0	77.9	84.2	89.4	97.8	103.3	100.8	126.5	138.9	152.7	159.6	163.5	158.5
Qinghai	11.5	11.6	13.7	12.1	14.7	15.7	17.6	19.0	19.9	24.4	26.0	31.6	33.5	31.8	36.6	44.6	47.9	48.5	51.1
Ningxia	17.1	17.6	17.4	N/A	N/A	N/A	55.3	65.8	51.7	58.8	66.5	75.4	80.0	95.3	137.3	135.0	142.9	142.6	140.8
Xinjiang	63.2	63.5	62.3	65.4	53.5	69.7	77.2	90.2	101.1	113.9	125.3	137.2	156.7	167.6	203.0	251.5	292.7	329.2	342.5

Table 6. Sectoral approach CO_2 emission inventory of China's provinces, 1997–2015 (in million tonnes

Figure 3 represents China's CO_2 emissions by fossil fuel types since 2000 and the sector structure of 2000, 2005, 2010, and 2015. Table 6 and 7 show the sectoral and reference approach emissions of China's 30 provinces (excluding the Tibet, Hong Kong, Macro and Taiwan due to data lacking).

Technical Validation

Uncertainty analysis

Uncertainty analyses are an important tool for improving emission inventories with uncertainty, which are an essential element of a greenhouse gas emissions inventory. Considering the small amounts and low uncertainties of the process-related emissions in cement production[10,32], we only calculated the uncertainties from energy-related emissions in this study. The uncertainties of inventory are caused by many reasons, as the energy-related CO_2 emissions were calculated as fossil fuel consumption (activity data) multiplied by the emission factors, the uncertainties should be '*derived for the component parts such as emission factors, activity data and other estimation parameters (Volume 1, Chapter 3, Page 6)*'[22]. We quantified both the uncertainties of emission factors and fossil fuel consumption data for our datasets.

As introduced above in the Methods section, this study adopted the emission factors from Liu, *et al.*[10]. However, the emission factors of China's fossil fuel combustions may have large variations as discussed in subsequent studies (such as Olivier, *et al.*[33]; Le Quéré, *et al.*[34]; Korsbakken, *et al.*[35]; Jackson, *et al.*[36]). To quantitatively characterize the range of emission factor, we summarised the emission factors (NCV_i, CC_i, and O_i) from seven other sources: IPCC, National Bureau of Statistics (NBS), NDRC, Initial National Communication on Climate Change (NC1994), Second National Communication on Climate Change (NC2005), Multi-resolution emission inventory for China (MEIC), UN-China, and UN-average (shown

Provinces	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Beijing	60.5	60.3	60.7	63.4	61.7	64.3	69.3	53.9	95.3	81.2	80.5	92.1	107.8	96.7	94.7	96.0	86.8	89.0	83.3
Tianjin	56.7	55.6	57.0	67.1	66.8	68.9	71.4	78.9	89.5	90.3	89.9	92.7	156.4	134.2	148.9	143.1	150.9	150.0	82.4
Hebei	248.9	247.1	251.8	257.7	266.6	290.2	320.8	365.4	409.0	409.3	454.1	482.0	563.4	569.4	623.3	642.4	657.7	624.7	639.4
Shanxi	231.0	232.5	142.0	87.9	93.3	207.7	308.4	322.9	296.5	313.9	238.1	593.7	589.8	654.1	766.2	854.8	1499.0	1553.8	1474.5
Inner mongolia	107.3	100.5	103.4	110.9	117.6	132.1	126.2	209.9	246.4	278.0	328.7	437.7	477.1	562.5	740.5	788.8	783.7	903.2	858.8
Liaoning	243.8	237.1	248.6	290.5	272.4	294.1	319.5	355.8	398.0	417.2	410.7	436.4	457.0	494.7	524.7	543.3	529.9	521.0	502.4
Jilin	108.6	94.4	95.3	95.9	102.5	105.1	116.4	123.6	146.9	164.0	162.0	190.7	202.0	226.1	264.6	265.2	237.4	234.9	218.7
Heilongjiang	184.5	171.0	165.3	172.1	163.2	164.1	171.8	193.3	228.1	231.5	222.6	239.3	274.4	351.7	381.2	393.1	363.4	350.4	347.7
Shanghai	86.6	87.0	92.6	100.8	106.0	109.1	124.0	134.1	142.4	138.4	131.8	144.3	142.4	161.3	170.5	168.4	181.6	156.7	161.8
Jiangsu	202.8	202.5	207.9	216.4	217.0	232.3	268.0	314.1	386.8	419.5	436.3	462.2	485.9	546.2	613.1	620.1	638.4	621.1	634.2
Zhejiang	116.6	108.8	120.7	100.2	147.8	163.0	184.0	231.8	267.4	302.1	326.2	338.6	351.8	375.9	398.5	383.6	387.7	380.9	381.6
Anhui	115.6	112.6	114.8	122.4	129.0	133.2	150.4	165.4	171.6	188.7	197.5	240.4	273.3	283.0	315.4	355.9	387.2	401.7	392.8
Fujian	41.8	43.2	49.3	53.9	53.6	61.9	75.0	86.7	99.4	112.6	128.7	137.0	161.9	179.6	210.2	208.5	203.5	229.2	234.4
Jiangxi	56.9	51.5	47.8	51.6	52.7	56.3	67.8	83.4	90.3	101.0	107.3	115.5	117.3	134.4	144.7	146.4	162.2	165.5	170.4
Shandong	264.7	261.3	260.6	261.5	303.3	345.9	424.2	518.3	661.9	745.4	765.6	831.3	880.1	929.1	976.5	1007.7	944.4	998.0	1052.2
Henan	176.6	133.5	139.6	140.3	156.5	162.7	231.9	239.3	343.4	352.5	394.8	330.9	472.0	573.4	654.1	545.8	594.4	557.8	537.2
Hubei	121.8	110.6	123.4	127.8	126.9	135.1	150.5	169.0	167.7	199.7	210.5	212.1	232.8	279.6	321.9	311.4	252.9	251.8	252.7
Hunan	74.7	101.2	79.0	75.9	82.0	94.5	104.2	114.4	167.3	184.9	202.4	198.3	212.0	231.7	269.7	275.3	266.4	255.9	250.5
Guangdong	155.5	146.7	157.8	182.1	185.5	198.7	225.6	251.4	272.4	310.4	327.6	357.1	394.8	445.0	501.2	486.6	493.0	541.6	506.7
Guangxi	44.8	44.0	44.8	47.4	44.9	41.7	49.6	67.2	70.5	80.9	89.6	95.8	109.6	134.2	173.3	192.8	189.6	183.4	173.2
Hainan	3.0	9.4	3.2	4.8	4.9	N/A	8.3	5.8	8.1	14.8	34.5	35.7	38.3	44.9	53.0	54.3	52.1	58.9	65.3
Chongqing	57.0	54.9	60.3	60.6	56.5	58.0	54.5	64.5	73.4	83.9	91.5	119.9	136.4	138.3	150.7	149.4	134.1	144.8	146.6
Sichuan	119.8	117.8	99.9	104.1	105.8	113.7	148.7	169.8	159.3	167.7	207.7	234.0	271.1	283.8	280.5	289.6	284.8	360.0	307.8
Guizhou	100.2	105.1	62.4	61.4	55.6	68.6	111.8	123.4	144.1	167.5	159.6	195.3	227.2	246.9	268.7	287.2	314.3	319.5	327.6
Yunnan	64.1	61.1	57.9	53.6	58.6	63.3	82.0	59.7	124.5	140.7	137.4	150.4	165.5	176.3	187.8	195.4	195.8	187.7	178.7
Shaanxi	78.3	77.8	73.8	68.7	70.4	84.9	93.5	116.3	217.5	187.3	234.2	274.8	262.3	308.3	344.5	405.1	482.9	639.0	665.8
Gansu	65.1	66.7	66.6	70.7	73.1	79.1	90.2	99.5	104.4	110.3	118.0	126.5	124.4	145.1	169.7	173.8	181.5	180.4	176.6
Qinghai	12.2	12.3	14.5	12.5	15.4	16.5	18.3	19.7	21.2	24.3	25.1	32.2	35.4	37.2	50.2	58.6	70.7	74.5	51.3
Ningxia	24.7	29.4	28.2	N/A	N/A	N/A	38.0	61.4	74.0	82.4	98.3	109.5	140.1	151.5	191.0	188.6	187.8	195.2	193.4
Xinjiang	85.1	89.3	86.7	89.4	93.6	92.1	103.0	121.0	132.4	148.5	152.4	179.0	214.4	240.9	286.2	333.4	336.4	542.3	535.0
Total	3309.2	3225.2	3115.9	3152.4	3284.1	3639.2	4307.3	4919.9	5809.7	6248.9	6563.6	7485.4	8276.9	9136.0	10275.5	10564.6	11250.5	11872.9	11603.0

Table 7. Reference approach CO_2 emission inventory of China's provinces, 1997–2015 (in million tonnes)

in Table 8 (available online only)). It is found that the fuels' net caloric values varied a larger range than those of carbon content and oxygenation efficiency. Taking raw coal as an example, the Coefficient of Variation (CV, the standard deviation divided by the mean) of raw coal's net caloric value is 15%, while the CVs of carbon content and oxygenation efficiency are 2 and 4% respectively. The CV of raw coal's comprehensive emission factor ($NCV_i \times CC_i \times O_i$) is 18%. The emission factor of coal-related fuels varied in a wider range than those of oil-related fuels and the natural gas. The average CV of coal-related fuels is 18%, while that for the oil-related fuels and natural gas is 4 and 5% respectively. Among the emission factors from eight sources, the IPCC and UN-average have the highest values, while Liu *et al.*'s study (used in this study), MEIC and NC1994 have the lowest values.

Due to the poor quality of China's fossil fuel data, the fossil fuel consumption data also have large uncertainties. According to the previous literature, the fossil fuel consumed in electricity generation sector had a CV of 5%[37,38], while the fossil fuel consumed in other industry and construction sector had a CV of 10%[22,39]. The CV of fossil fuel consumed in the transportation sector was 16%[40], while residential and primary industry fossil fuel usage even had higher CVs of 20%[22] and 30%[41] respectively. The uncertainties in China's fossil fuel data has been addressed and discussed by Guan, *et al.*[11] previously. Possible reasons include the opaqueness in China's statistical systems, especially on the '*statistical approach on data collection, reporting and validation (Page 673)*'[11]; and the dependence of China's statistics departments with other government departments. As a result, China's national fossil fuel consumption is smaller than the provincial aggregated data. Despite that China enlarged its 2000–2013

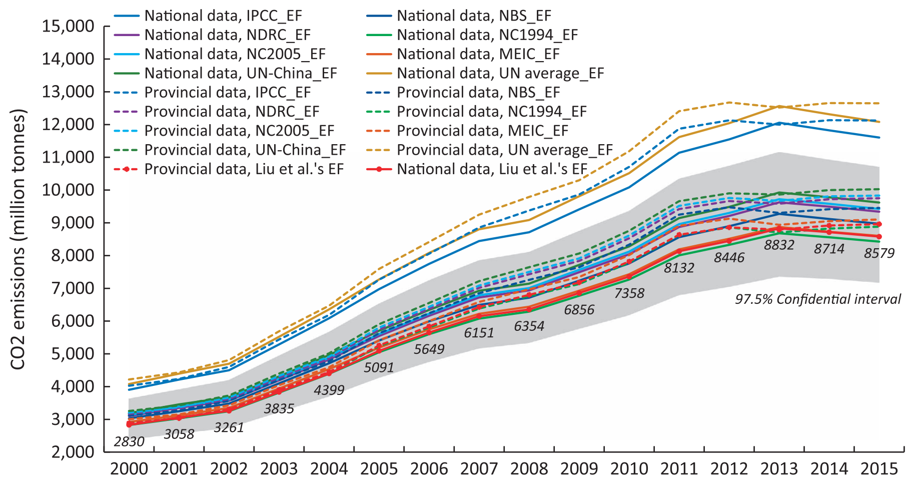

Figure 4. Uncertainties of the emissions. The grey area in the figure shows the 97.5% confidential interval of China's CO_2 emission estimations. The lines present China's CO_2 emission calculated based on the national/provincial aggregated energy data and different emission factors. The figure shows that emissions calculated based on the NBS, NDRC, NC1994, NC2005, MEIC, UN-China's emission factors fall in the 97.5% confidential interval.

national energy data in 2014, there was still roughly 5% gap between the latest national and provincial aggregated energy data.

We employed the Monte Carlo simulations to propagate the uncertainties induced by both fossil fuel consumption and emission factors to provide the uncertainty estimates for entire emission inventories[22]. According to the Monte Carlo technique, we first assumed normal distributions (probability density functions) for both activity data (fossil fuel consumption) and emission factors with CVs discussed above[10,32]. Random sampling on both the activity data and emission factors were then conducted for 100,000 times and generated 100,000 estimations on the CO_2 emissions. The uncertainty range, therefore, was 97.5% confidential intervals of the estimations. The above simulation was conducted in MATLAB R2014a.

We found that the uncertainties of the entire CO_2 emissions inventories were roughly (−15%, 25%) at a 97.5% confidential level. Table 9 (available online only) and Fig. 4 show the uncertainties in the national emission inventories from 2000 to 2015. The above ranges, e.g., (−15%, 25%), reflected the uncertainties from both emission factor and activity data. In particular, concerning the continuous debate on the emission factor of fossil fuel combustion in China[33–36], we incorporated 8 emission factors from independent sources to represent the uncertainty of emission factors. In order to separate the uncertainty induced by emission factor and activity data, we then conducted the Monte Carlo simulations by assuming the CV of one of them was 0. The results showed that uncertainties from the emission factors in 2015 were (−15.8%, 23.7%), while the uncertainties from the activity data were (−1.4%, 9.2%). This implied the emission factors of fossil fuels induced higher uncertainty to the final estimation.

In Fig. 4, the grey area in the figure indicates the 97.5% confidential interval of China's CO_2 emission estimations of this study. The solid lines present China's CO_2 emission calculated based on the national energy data and 8 different emission factors, while the dash lines present the emissions based on the provincial aggregated energy data. The figure shows that emissions calculated based on emission factors from Liu *et al.*'s nature, NBS, NDRC, NC1994, NC2005, MEIC, and UN-China's fall in the 97.5% confidential interval. Emissions calculated based on the IPCC and UN-average emissions factors are 10% larger than the upper bound of the 97.5% confidential interval due to their high emission factor value, while the emissions calculated based on the emission factors from Liu *et al.*'s nature, NC1994, and MEIC have relatively low values. In addition, the emissions calculated based the provincial aggregated energy data are about 5% higher than that based on national data due to the difference in the national and provincial data.

In addition to the uncertainties of emission factors and fossil fuel data considered in the Monte Carlo techniques above, there were some other uncertainties that should be taken into consideration when using the datasets, such as 'lack of completeness', 'lack of data', 'measurement error'. These uncertainties were very small and difficult to quantify; however, they were also essential parts of the inventories' uncertainties. 1) Lack of completeness: We only considered the energy-related emissions and cement-related emissions in our datasets. Emissions from other sources were not taken into account, such as 'agriculture', 'land-use change and forestry', 'waste', and other industrial processes. 2) Lake of data: As discussed above, the sectoral fossil fuel consumption of 8 provinces were lacking. We used the sectoral fossil fuel consumption structure in 2008 to estimate that of the intervening years. Such a replacement had no much effect on the total emissions, but increased the uncertainties in provincial sectoral emissions. Also, the emission factors for secondary fossil fuels were estimated based on the primary fossil fuel emission factors' ratio. 3) Measurement error: the '*measurement error is random or systematic, results from errors in measuring, recording and transmitting information; inexact values of constants and other parameters obtained from external sources (Volume 1, Chapter 3, Page 11)*'[22]. The measurement errors might be generated in the energy statistics and emission factors' calculation.

Comparison with existing emission estimates

We compared our emissions with estimates from other research institutes, shown in Fig. 2. We found that our national sectoral emissions were the lowest among the estimates. The Global Carbon Budget (GCB) had the highest value until EDGAR passed it since 2012. Our national sectoral emissions were 9 to 18% lower than the highest value. This was mainly because that we used the updated emission factors, which were lower than the IPCC default value. Our results were 1–3% higher than BP and MEIC's since 2013. Even considering the emissions from BP and MEIC not including the cement-related emissions, they had closer results with our datasets compared with other emission estimations. Our estimates were highly consistent with the newly published official emission inventory. The Chinese government published the 'First Biennial Update Report on Climate Change[8]' by the end of 2016. In the report, the energy-related CO_2 emissions in 2012 were 8,688 million tonnes (the blue points in Fig. 2), only 2.79% higher than our estimates (national sectoral emissions, 8,446 million tonnes). This tiny difference falls into the uncertainty range of the both inventories.

From the aspect of format, the existing emission estimates only present the total energy-related emissions of the whole country, or emissions from three fossil fuel categories at most (solid, liquid, and gas). Our datasets provided the energy-related CO_2 emissions from 47 socioeconomic sectors and 17 fossil fuels to give detailed demonstrations of China's emission statue as well as its provinces. Thus, our datasets can be a more detailed supplement to the existing emission estimates and the official emission inventories.

Limitations

Our datasets have the following limitations: 1) We used the national average emission factors of fossil fuels and cement production when calculating the provincial CO_2 emissions in the current version. The emission factors should be different in different regions considering the discrepancy in energy quality and cement production technology. In the future research, we will specify the emission factor of each province to achieve more accurate emission inventories for provinces; 2) In the current version, we used the sectoral fossil fuel consumption structure in 2008 to estimate that of the intervening years for 8 certain provinces. In the future, we will investigate the 8 provinces for more accurate data. 3) We only considered emissions from cement production in the current process-related emissions accounts. The latest official emission inventory in 2012 include other 9 processes such as glass, lime, steel production. In the future research, we will extend the scope of our datasets to include more industrial processes.

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Data Citations

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Author Contributions

Y.S. led the project, collected and assembled the data, and prepared the manuscript. D.G. designed the research. H.Z. collected the raw data. J.O., Y.L., J.M., Z.M., Z.L., and Q.Z. revised the manuscript and participated in the construction of the database.

Additional Information

Tables 3, 4, 8 and 9 are only available in the online version of this paper.

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CO_2 emissions from China's lime industry

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HIGHLIGHTS

- We calculated CO_2 emissions from China's lime production from 2001 to 2012.
- The lime production process emissions was 141.72 Mt CO_2 in 2012, while the scope 1 emissions from fossil fuel combustion were 56.55 Mt, and the scope 2 indirect emission were 4.42 Mt.
- Lime production is a significant emission source and should be considered by the future emission inventory.

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ABSTRACT

China is now the world's leading energy consumer and CO_2 emitter; therefore, precise quantification of the CO_2 emissions that occur in China is of serious concern. Although most studies focus on CO_2 emissions from fossil fuel combustion and cement production, the emissions from lime production is not well researched. Lime production is the second largest source of carbon emissions from industrial processes after cement production. This is the first study to present an analysis of CO_2 emissions from China's lime production from 2001 to 2012, and we have estimated the process emissions (scope 1 direct emissions caused by the process), fossil fuel combustion emissions (scope 1 direct emissions caused by fossil fuel combustion), and scope 2 indirect emissions (CO_2 emissions caused by electricity consumption) from China's lime industry. The estimations show that the process emissions increased rapidly from 88.79 million tonnes to 141.72 million tonnes from 2001 to 2012. In 2012, the scope 1 emissions from fossil fuel combustion were 56.55 million tonnes, whereas the scope 2 indirect emissions were 4.42 million tonnes. Additionally, we analysed the uncertainty of our estimations, and our analysis shows that the relative uncertainty of the emission factors and activities data falls between 2.83% and 3.34%.

1. Introduction

With rapid economic development, changed lifestyle and consumption patterns [1], China is now the world's top consumer of primary energy and emitter of greenhouse gases [2]. Among economic sectors, the industrial sector has accounted for more than 50% of China's total energy consumption over the past 30 years, a value that is much higher than what is found in approximately 30% of Organisation for Economic Co-operation and Development (OECD) countries [3]. Additionally, according to the National Development and Reform Commission (NDRC) [4], the total greenhouse gas emissions by China in 1994 were 2665.99 million tonnes CO_2-eq, with the emissions contributed by industry at 1501.00 million tonnes, which accounted for 56.30% of the total national greenhouse gas emissions The emissions from industry include process emissions and direct emissions from fossil fuel combustion (see Table A1). In 2010, the emissions from industry increased to 5154 million tonnes rapidly and accounted for 64.7% of the total national emissions [5]. As a result, the industrial sector is the major contributor of greenhouse gas emissions and considered as the main area for developing low carbon technologies in China [6].

According to the emissions distribution figures (see Table A1), lime production is the second largest industrial process emission source in China after cement production. Based on estimates in Second National Communication on Climate Change [7], greenhouse gas emissions from the lime production process amount to 85.62 Mt CO_2-eq (15.06%).

More importantly, China has produced the majority of total emissions from global lime production in recent years (see Fig. A1). The percentage increased from 29.45% in 1970 to 64.86% in 2009. In 2009, greenhouse gas emissions from China's lime production process (142.50 Mt CO_2-eq) were greater than the total

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national emissions from certain developed countries, such as Finland (128.97 Mt CO_2-eq) or Greece (117.16 Mt CO_2-eq) [8].

The greenhouse gases emitted from China's lime production are considerably higher and account for a large percentage of both global lime emissions and China's industrial emissions [8]. However, the emissions from China's lime production are poorly understood, and comprehensive studies on the emissions from the lime industry in China are rarely conducted. In a search of 297 international peer-reviewed publications from SCI indexed dataset in most recent 10 years (2004–2014) using the keywords "carbon emissions", "industry process" and "China", we only found 73 articles relevant to industrial production, and none of them were related to lime production. When using the keywords "CO_2 emissions industry China," 82 journal articles on industrial production were found, but none were related to lime production in China (see Table A2). This literature review shows that most of the previous studies have focused on greenhouse gases emitted from fossil fuel combustion and cement production [9–17], whereas limited studies have addressed emissions from lime production in China. From the global view, only few studies have addressed emissions from lime industry However, these studies mostly focused on the industry process and technique, such as the environmental impact of lime production process [18] and emissions from different lime kilns [19]. There is still no research related to CO_2 emissions accounting for lime production. Thus, understanding and quantification of CO_2 emissions from lime production is the current research gap, and associated studies are urgent needed.

In this study, we estimated CO_2 emissions based on three system boundaries: process emissions (scope 1 direct CO_2 emissions caused by the process), fossil fuel combustion emissions (scope 1 direct emissions caused by fossil fuel combustion) and scope 2 indirect emissions (CO_2 emissions caused by electricity consumption). After performing calculations, scenarios from the two dimensionalities technological improvement and production growth are defined and the implied emissions reduction potential in the near future is analysed. This is the first analysis that quantify CO_2 emissions from lime production in terms of production process emissions and energy related emissions. This research will contribute to filling current research gap and provide a practical implication for the global low carbon development.

2. Concepts and methodologies

2.1. Scope of emissions accounting

Life-cycle assessments (LCAs) are generally employed to evaluate CO_2 emissions in industrial production processes and have been widely applied in carbon accounting [20–22]. A LCA was conducted to assess environmental impacts of the lime industry in Cuba [18]. Lime is usually processed in five basic steps (see Fig. 1) and are described as follows: limestone is first quarried; the quarried rocks are then transferred to the crushing and screening unit to size the stones for the calcination stage; correct-size stones are fed to the kiln and heated, where $CaCO_3$ dissociates into CaO and CO_2; quicklime is then milled, hydrated with water, and classified to increase the product quality; and the product is finally packed and stored.

At the calcination stage, calcium oxide (CaO or quicklime) is formed by heating limestone to dissociate the carbonate [23]. This step is usually performed in a shaft or rotary kiln at high temperature, and the process releases CO_2. Because this is the primary stage where greenhouse gases, such as CO_2, are emitted during the production, this study will focus on CO_2 emissions at the calcination stage.

Different metrics for expressing the total greenhouse gas emissions attributable to industry sectors can be developed according to definitions of spatial boundaries and life-cycle perspectives. Table 1 presents different measurement terms defined by the World Resources Institute/World Business Council for Sustainable Development [24]. These terms were originally defined to express emissions in relation to the spatial boundaries of cities. In this study, they are adapted to describe emissions boundaries of industry sectors.

Greenhouse gas emissions for one industry are usually defined using these two scopes [26–30]. Scope 1 only includes emissions that are produced within the boundaries of the industry sectors. The emissions include in-boundary components from fossil fuel combustion, waste, industrial processes and product use, which are determined using guidelines from the Intergovernmental Panel on Climate Change (IPCC) [23,31]. Scope 2 includes out-of-boundary emissions related to the electricity used in industry sectors [31].

In this study, CO_2 emissions from the thermal decomposition of limestone were classified as process emissions, the CO_2 emitted during the burning of fuel in lime kilns should be counted as scope 1 direct emissions. Because all of the electricity consumed by the industry is purchased from power plants, the emitted CO_2 from electricity consumption should be counted as scope 2 indirect emissions [32]. Therefore, this study focuses on both scope 1 and 2 CO_2 emissions from China's lime industry.

2.2. Estimation method and data sources

2.2.1. Process emissions

When estimating CO_2 emissions from industrial processes, methodologies recommended by the IPCC are widely used [33–38]. In the Guidelines for National Greenhouse Gas Inventories 2006 [23], three basic methodologies are proposed to estimate process emissions from the lime industry: an output-based approach that uses default values (Method 1); an output-based approach that estimates emissions from CaO production and employs country-specific information for correction factors (Method 2); and an input-based carbonate approach (Method 3). Considering the data feasibility and Chinese circumstances, Method 1 will be used in this research.

In Method 1, a default emission factor is applied to the national level lime industry data. Although country-specific information on lime production by type (e.g., high calcium lime, dolomitic lime, or hydraulic lime) is not necessary, it is important to identify specific types of lime produced in the country if data is available. Thus, Eq. (1) may be used in Method 1 [23]:

$$CE_{pro} = AD_{lime} \times EF_{lime} \tag{1}$$

where CE_{pro} represents process CO_2 emissions; AD_{lime} represents the total production of the lime industry; and EF_{lime} represents the emission factor for the lime production process.

The production of lime from 2001 to 2012 is archived in the Almanac of the Chinese Building Materials Industry as shown in

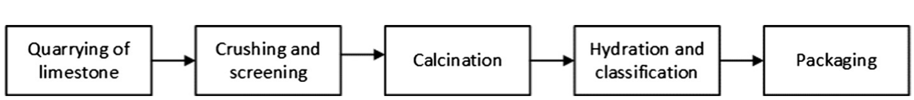

Fig. 1. General process flow diagram of the lime industry [18].

Table 1
Comparison of measurement terms for greenhouse gas estimations [25].

Term	Spatial boundaries	Components
Scope 1	In-boundary emissions	• In-boundary fossil fuel combustion • In-boundary waste (landfill) emissions • In-boundary industrial process and product use
Scope 2	In-boundary electricity use	• Out-of-boundary electricity emissions at power plants

Table 2
Emission factors and weights of different power grids, tonnes CO_2/mW h [42,43].

Gird	Emission factor	Weight (%)
North China grid	1.0302	24.67
North-east China grid	1.1120	6.78
East China grid	0.8100	24.34
Centre China grid	0.9779	18.17
Northwest China grid	0.9720	9.24
South China grid	0.9223	16.81

Table 3
Economic and environmental indexes of lime kilns.

Lime kilns	Unit coal consumption	Unit electricity consumption	Emission intensity	Lime production
Unit	kg/ton	kW h/ton	tonnes/ton	million tonnes
Rotary kiln	153.00	42.97	323.45	33.20
Maerz lime kiln	122.00	54.57	277.01	6.23
Shaft kiln	127.00	44.73	277.01	6.23
Finikas lime kiln	135.00	52.68	299.28	12.45
Air shaft kiln	163.00	41.04	340.14	4.15
Mechanical shaft kiln	149.73	17.63	293.58	16.60
Sinopec shaft kiln	151.00	6.97	285.90	33.20
Others	147.54	13.65	285.78	95.45
Total	–	–	–	207.50

Table 4. Data of lime production is compiled by the Chinese Lime Association, the only institution that records the production, and their figures are based on the demand of downstream consumer sectors [39].

According to the IPCC guidelines [23], in the absence of country-specific data, the default emission factor for the processing of lime is 0.75 ton CO_2/ton lime produced. The NDRC also provides default emission factors for lime processing in their Guidelines for Provincial Greenhouse Gas Inventories [40]. The emission factor recommended by the NDRC is 0.683 ton CO_2/ton lime produced, which is 8.93% smaller than the emission factor recommended by the IPCC. In this study, we adopted the emission factor recommended by the NDRC because it is more relevant to Chinese practical circumstances/experience.

2.2.2. Emissions from fossil fuel combustion

This study estimates emissions from fossil fuel combustion based on the IPCC national greenhouse gas inventory guidelines [23]. According to the Almanac of the Chinese Building Materials Industry [39], coal is used as a fuel during the lime production process: the emissions are calculated according to Eq. (2):

$$CE_{coal} = AD_{coal} \times EF_{coal} \tag{2}$$

where CE_{coal} represents fossil fuel combustion CO_2 emissions; AD_{coal} represents coal combusted in lime kilns; and EF_{coal} represents the emission factor for coal. In this case, we assume that all coal can be fully combusted in the lime kilns.

Table 4
Process CO_2 emissions from China's lime production.

Year	Lime production (AD_{lime})	Emission factor for lime (EF_{lime})	CO_2 emissions from process (CE_{pro})
Unit	million tonnes	ton CO_2/ton lime	million tonnes
2001	130.00	0.683	88.79
2002	132.00	0.683	90.16
2003	135.73	0.683	92.70
2004	143.28	0.683	97.86
2005	154.30	0.683	105.39
2006	162.60	0.683	111.06
2007	171.10	0.683	116.86
2008	178.10	0.683	121.64
2009	187.00	0.683	127.72
2010	170.00	0.683	116.11
2011	205.50	0.683	140.36
2012	207.50	0.683	141.72

The coal combusted in the lime kilns could be calculated based on the economic and technical indexes of different lime kilns (see Table 5). We adopt 1.85 tonnes CO_2/ton as the emission factor for coal, which is based on our previous research [41].

2.2.3. Scope 2 indirect emissions

We have estimated the indirect CO_2 emissions of China's lime industry through the amount of purchased electricity. The total scope 2 indirect CO_2 emissions are calculated according to Eq. (3):

$$CE_{ele} = AD_{ele} \times EF_{ele} \tag{3}$$

where CE_{ele} represents the scope 2 indirect CO_2 emissions; AD_{ele} represents the total electricity consumption in China's lime industry; and EF_{ele} represents the emissions factor of the power grid.

The electricity consumed during the industrial process could be calculated based on the economic and technical indexes of different lime kilns (see Table 6). As for the emission factor (AD_{ele}), we have adopted the weighted average of the emissions factors from regional power grids, including the North China Grid, Northeast China Grid, East China Grid, Centre China Grid, Northwest China Grid, and South China Grid. The emission factors of different power grids are archived by the NDRC [42]. The weights are calculated based on the electricity consumption of different grids in 2012, which are archived in the China Electric Power Yearbook 2013 [43]. Table 2 shows the emission factors and weights of different power grids.

The emission factor of the national power grid is 0.9402 ton CO_2/mW h electricity consumed.

2.3. Current production technologies in China's lime industry

According to the Almanac of the Chinese Building Materials Industry 2002–2013 [39], there are seven types of lime kilns widely used in China's lime industry: rotary kiln, Maerz lime kiln, shaft kiln, Finikas lime kiln, air shaft kiln, mechanical shaft kiln, and Sinopec shaft kiln. Different lime kilns have different energy intensities in producing one unit of lime. Table 3 shows the economic and technical indexes of different lime kilns.

Using the emission factors for coal and electricity, we calculated the CO_2 emission intensity (tonnes CO_2 emission when producing one ton lime) from each type of lime kiln (see Table 3). The CO_2 emission intensity ranged widely from 277.01 to 340.14 tonnes CO_2-eq/ton lime produced.

When producing one ton of lime, if the fossil fuel combustion and scope 2 indirect CO_2 emissions from a lime kiln are less than 290 tonnes, we defined the lime kiln as an environmentally advanced kiln in this study. From Fig. 3, we can see that the environmentally advanced kilns include the Maerz lime kiln, shaft kiln,

Table 5
Emissions from fossil fuel combustion in China's lime production (2012).

Lime kiln Unit	Lime production million tonnes	Coal-consumption (AD_{coal}) million tonnes	Emission factor for coal (EF_{coal}) tonnes CO_2/ton	Fossil fuel combustion emissions (CE_{coal}) million tonnes
Rotary kiln	33.20	5.08	1.85	9.40
Maerz lime kiln	6.23	0.76	1.85	1.40
Shaft kiln	6.23	0.79	1.85	1.46
Finikas lime kiln	12.45	1.68	1.85	3.11
Air shaft kiln	4.15	0.68	1.85	1.25
Mechanical shaft kiln	16.60	2.49	1.85	4.60
Sinopec shaft kiln	33.20	5.01	1.85	9.27
Others	95.45	14.08	1.85	26.05
Total	207.50	30.57	1.85	56.55

Table 6
Indirect CO_2 emissions from electricity consumption for China's lime production (2012).

Lime kilns Unit	Lime production million tonnes	Electricity consumption (AD_{ele}) mW h	Emission factor for electricity (EF_{ele}) ton CO_2/ton	Scope 2 indirect emissions (CE_{ele}) million tonnes
Rotary kiln	33.20	1426604.00	0.9402	1.34
Maerz lime kiln	6.23	339698.25	0.9402	0.32
Shaft kiln	6.23	278444.25	0.9402	0.26
Finikas lime kiln	12.45	655866.00	0.9402	0.62
Air shaft kiln	4.15	170316.00	0.9402	0.16
Mechanical shaft kiln	16.60	292658.00	0.9402	0.28
Sinopec shaft kiln	33.20	231404.00	0.9402	0.22
Others	95.45	1302892.50	0.9402	1.22
Total	207.50	4697883.00	0.9402	4.42

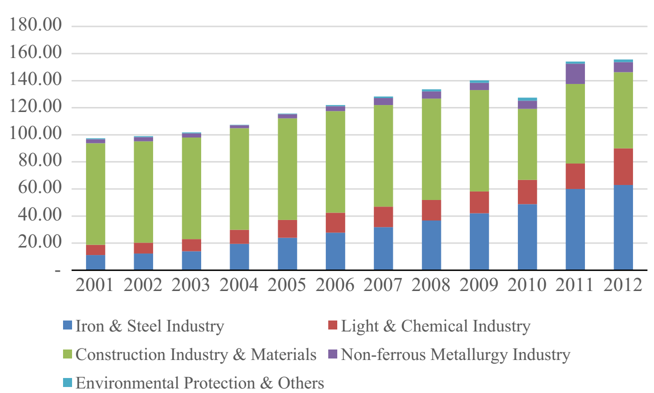

Fig. 2. Process CO_2 emissions caused by downstream sectors' lime consumption (million tonnes).

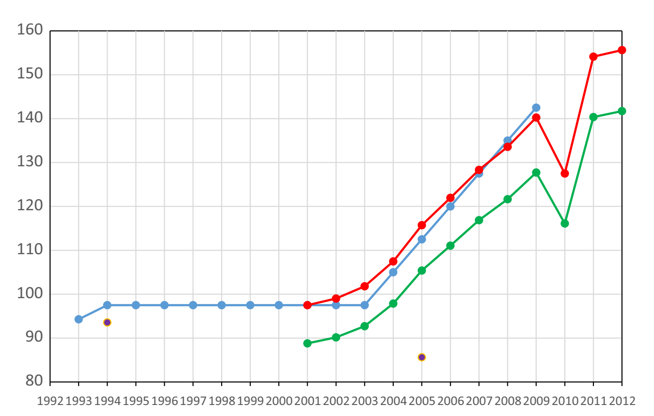

Fig. 3. Comparison of different estimates of process CO_2 emissions (million tonnes).

and Sinopec shaft kiln because these kilns are more efficient and environmentally friendly when producing lime, and they are currently the most advanced technology.

3. Results

3.1. Processing emissions

We have estimated process CO_2 emissions from China's lime production from 2001 to 2012 as shown in Table 4.

3.1.1. Changing features

Beginning in 2004, rapid growth of process CO_2 emissions occurred in China's lime industry because of increased lime production. The average annual growth rate from 2004 to 2009 was 5.49%. Subsequently, the CO_2 emissions dropped by 9.09%. The emissions in 2009 were 127.72 million tonnes and dropped to 116.11 million tonnes in 2010, which was remarkable compared with the previous 5.45% growth. A similar phenomenon also occurred for the emissions from the cement industry, and to explore the causes, we divided the total emissions into five downstream consumer sectors.

3.1.2. Downstream consumer sector distribution

There are several downstream consumer sectors of the lime industry [39], including the following five consumer sectors: iron and steel industry, light and chemical industry, construction industry and materials, non-ferrous metallurgy industry and environmental protection and others. Based on the lime consumed in different sectors, this research divides the total process CO_2 emissions into these five consumer sectors (see Fig. 2).

As shown in Fig. 2, the "Construction Industry and Materials" sector should account for the majority of CO_2 emissions because of the long-term high demand for lime. The "Iron and Steel Industry" sector quickly increased from 11.54% to 40.48% over the past 12 years and surpassed the "Construction Industry and Materials" sector to become the largest lime consuming sector beginning in 2011.

The emissions decreased in 2010, this phenomenon may have been caused by the global financial crisis in 2008 [39]. The financial crisis caused global international exports to rapidly decrease. As a result, China was exposed to a deep-rooted structural imbalance in domestic industry, in particular during the global economy slowing down in the second half of 2008. The downstream industries of the lime industry, especially construction (Fig. 2 shows that most of the decrease occurred in the "Construction Industry and Materials" sector), experienced serious problems, such as excess capacity, industry decentralisation, low-quality products, and lack of core competitiveness [44,45]. Such problems caused a decrease in production in downstream industries, and lime industry is directly related to its downstream industries. Therefore, there appeared a decrease in lime production in 2010, which lead a quick drop in CO_2 emit from lime industry.

3.2. Fossil fuel combustion emissions in 2012

We here use the year 2012 as an example to estimate the CO_2 emissions from fossil fuel combustion in China's lime production.

First, we distributed the total production (207.50 million tonnes in 2012) into seven types of lime kilns based on the production percentages. Then, we calculated the coal consumed by each type of kiln. Finally, using the emission factors discussed above, we estimated the CO_2 emissions from fossil fuel combustion from China's lime production as shown in Table 5.

In 2012, CO_2 emissions from fossil fuel combustion in China's lime production accounted for 56.55 million tonnes. Among the total emissions, the amount contributed by the Maerz lime kiln, shaft kiln, and Sinopec shaft kiln, denoted as the environmentally advanced lime kilns, was 12.13 million tonnes or 21.45%.

3.3. Scope 2 indirect emissions in 2012

Using the activity data from the Almanac of the Chinese Building Materials Industry 2013 [39] and power grid emission factors recommended by the NDRC [40], we estimated the scope 2 indirect emissions from China's lime production, which are listed in Table 6.

The scope 2 indirect CO_2 emissions from China's lime production were 4.42 million tonnes in 2012. Similar to the CO_2 emissions from fossil fuel combustion, the indirect emissions contributed by environmentally advanced lime kilns accounted for 0.8 million tonnes or 18.10% of the total scope 2 indirect CO_2 emissions.

Above all, the scope 1 and 2 CO_2 emissions from China's lime production in 2012 were 202.69 million tonnes, with 69.92% contributed by the industrial process, namely process emissions. Scope 2 indirect emissions from electricity consumption only accounted for 2.18% of the total.

3.4. Discrepancies and uncertainty analysis of process emissions

Process emissions from China's lime production are estimated by a number of different organisations. A comparison of different estimates that were used to determine the discrepancies and perform the uncertainty analyses is shown in Fig. 3.

3.5. Discrepancies

In Fig. 3, our estimates are shown by the red and green lines. The red line was calculated using the IPCC emission factor, whereas the green line was calculated using the NDRC emission factor. There is an 8.93% difference between the two lines. The estimate from the Emissions Database for Global Atmospheric Research (EDGAR) (blue line) [8] is nearly identical to our estimate using the IPCC emission factor, with only a small difference of 1.20%.

The two purple dots in 1994 and 2005 are recorded by the Initial and Second National Communication on Climate Change [4,7], where detailed emission inventories were constructed at national level. In the national communications, the process CO_2 emissions in 1994 are similar to the estimate from EDGAR (93.56 million tonnes). In 2005, however, there is a gap between the national communication and our estimate using the NDRC emission factor by 19.77 million tonnes. This gap is attributable to the difference in activity data because the two estimates use the same emission factor.

According to the national communications for the period from 1994 to 2005, the process CO_2 emissions from China's lime production decreased slightly. During the same period, however, process CO_2 emissions from all industries doubled because of economic and production growth (see Table A1). Therefore, we believe that the measurement standard for lime production used in the national communications should be different from that of other estimates. In the study of uncertainty, we regard the estimates from the national communications as statistically abnormal values and will exclude them in the analysis of uncertainty in the following section.

3.6. Uncertainty

Analysing uncertainty is an important tool for improving emission inventories that contain uncertainty for various reasons [46,47]. Different methods are used to analyse the uncertainty of emissions, such as Monte Carlo simulations [48] and Joint Committee for Guides in Metrology (JCGM) guide for measurement data [49,50]. Jonas et al. [51] describe four relevant uncertainty terms and six techniques that can be used to analyse uncertain emission changes.

In this study, we adopt methodologies and recommendations from the guide to the expression of uncertainty in measurement [49] to evaluate the uncertainty of the estimates. First, different estimates are not obtained from repeated observations, and the Type B standard uncertainty is evaluated by "scientific judgment using the relevant information available" [49]; Second, a uniform or rectangular distribution is assumed for different estimates of process CO_2 emissions from China's lime production because of the absence of specific information on the probability distribution; Third, the upper and lower limits are assumed to be the maximum and minimum estimates of process CO_2 emissions from lime production; specifically, if the maximum and minimum estimates of process CO_2 emissions from lime production by different organisations are denoted as a_+ and a_- , then the probability that the actual process CO_2 emissions from lime production lie within the interval $[a_-, a_+]$ is assumed to be equal to one (the probability that the actual CO_2 emissions from lime production lie outside this interval is essentially zero) [49]; Forth, the process CO_2 emissions from China's lime production are assumed to be uncorrelated; Finally, according to this analysis, our estimate using the NDRC emission factor can be used as the expected value for the actual process CO_2 emissions from China's lime production and is denoted as x'.

According to JCGM [49], the upper and lower bounds a_+ and a_- for the quantity X_i may not be symmetric with respect to the best estimate x'; specifically, if the lower bound is written as $a_- = x' - b_-$ and the upper bound is written as $a_+ = x' + b_+$, then $b_- \neq b_+$ because in this case, x' (assumed to be the best estimate of X_i) is not at the centre of the interval $[a_-, a_+]$; therefore, the probability distribution of X_i cannot be uniform throughout the interval. However, there may not be enough information available to

Table 7
Uncertainties of process CO_2 emissions from China's lime production, million tonnes.

Year	EDGAR	EF-IPCC	EF-NDRC (x')	u	u^{rel} (%)
2001	97.50	97.50	88.79	2.51	2.83
2002	97.50	99.00	90.16	2.55	2.83
2003	97.50	101.80	92.70	2.63	2.83
2004	105.00	107.46	97.86	2.77	2.83
2005	112.50	115.73	105.39	2.98	2.83
2006	120.00	121.95	111.06	3.14	2.83
2007	127.50	128.33	116.86	3.31	2.83
2008	135.00	133.58	121.64	3.86	3.17
2009	142.50	140.25	127.72	4.27	3.34
2010		127.50	116.11	3.29	2.83
2011		154.13	140.36	3.97	2.83
2012		155.63	141.72	4.01	2.83

choose an appropriate distribution, and different models will produce different expressions for the variance. In the absence of such information, the simplest approximation is as follows:

$$u^2(x_i) = (b_+ + b_-)^2/12 = (a_+ + a_-)^2/12 \quad (4)$$

Based on the above assumptions and methodology from JCGM, we have adopted Eq. (4) to measure the variances associated with the best estimates of process CO_2 emissions for China's lime production.

The Type B standard uncertainty can be calculated by Eq. (5) [49]:

$$u(x_i) = \sqrt{(b_+ + b_-)^2/12} = \sqrt{(a_+ + a_-)^2/12} \quad (5)$$

The relative uncertainty of the best estimate x' is defined by Eq. (6):

$$u^{rel} = u/x' \times 100\% \quad (6)$$

The standard and relative uncertainty of the best estimate of process CO_2 emissions of China's lime industry are shown in Table 7.

3.7. Uncertainty factors

As Table 7 shows, the relative uncertainty of our estimate using the NDRC emission factor is between 2.83% and 3.34%, and the analysis on discrepancies indicates that this uncertainty is a product of variations in the emission factors and activities data.

Firstly, the largest component of the uncertainty lies in emission factor. As explained in session 2.2 above, the emission factor for lime process ranges from 0.683 to 0.75 ton CO_2/ton lime produced [23,40]. This uncertainty embodied in our two estimates using different emission factors, the green line and red line.

In additional, lime production data is another challenge of accounting the lime emissions in China. Comparing to other industries (e.g. cement, steel) [52,53], a large portion of lime are produced in small lime mills in China, and their lime productions are usually not recorded in the published statistics. Different organises use data from different sources. This is the primary reason for the discrepancies of estimate from EDGAR and our calculation using IPCC emission factor, since both the two estimates use emission factor from IPCC. The similar uncertainty also embodied in China's coal-related CO_2 emissions [54].

4. Conclusions

China is now the world's leading energy consumer and CO_2 emitter, and the ability to precisely quantify CO_2 emissions in China is vital [55]. The CO_2 emissions from China's lime industry are considerably high and account for a large percentage of both global lime emissions and China's industrial emissions. However, most studies have only focused on the CO_2 emissions from fossil fuel combustion and cement production, and only limited number of studies have analysed the impact of emissions from lime production. This study fills the gap in the literature by presenting for the first time an analysis of CO_2 emissions from China's lime production from 2001 to 2012.

This study estimates the process emissions, fossil fuel combustion emissions, and scope 2 indirect emissions from China's lime industry. The estimations showed that the process emissions increased rapidly from 88.79 million tonnes to 141.72 million tonnes from 2001 to 2012, and fossil fuel combustion emissions in 2012 accounted for 56.55 million tonnes, of which 21.45% were contributed by environmentally advanced lime kilns. The scope 2 emissions amounted to 4.42 million tonnes, among which 18.10% were contributed by environmentally advanced lime kilns. In 2012, the total CO_2 emissions from China's lime production were 202.69 million tonnes, with 69.92% contributed by the industrial process or process emissions. Scope 2 indirect emissions from electricity consumption were only 2.18%.

This study analysed the discrepancies and uncertainties of different estimates. The results showed that our estimates using the NDRC emission factor are the closest to the actual process CO_2 emissions from China's lime production, and the uncertainty in our estimates, which was produced by differences in the emission factors and activities data, is between 2.83% and 3.34%.

Our results have global impacts. With the total emission of 142 million tonnes CO_2, emission from lime production is equivalent to the total emission from some developed countries. However, little attention has been paid to the mitigation of CO_2 emission from lime industry. Cleaner production, efficiency improvement as well as energy saving in lime production need to be addressed with the same priority as the mitigation strategy in energy sectors, so that the low carbon development can be achieved at the national and global level.

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Appendix A

See Fig. A1, Tables A1 and A2.

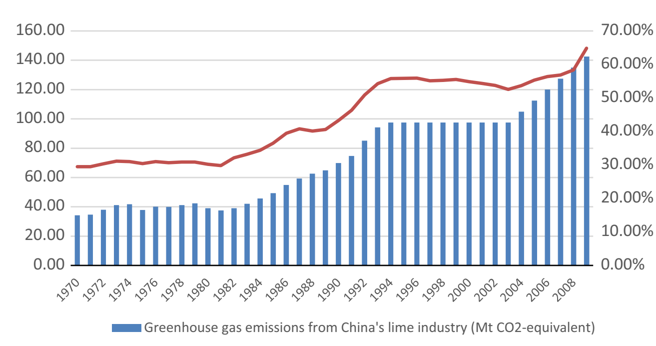

Fig. A1. Greenhouse gas emissions from China's lime industry and global percentage [8].

Table A1
Greenhouse gas (GHG) emissions in China, million tonnes CO_2-eq [4,7].

Items	1994		2005	
	GHG emissions	Percentage (%)	GHG emissions	Percentage (%)
National total emissions	2665.99	100.00	5975.57	100.00
Industrial energy use	1223.02	45.87	2114.03	35.38
Industrial process	277.98	10.43	568.60	9.52
Other	1164.99	43.70	3292.94	55.11
Industry process emissions	277.98	100.00	568.60	100.00
Cement process	157.78	56.76	411.67	72.40
Lime process	93.56	33.66	85.62	15.06
Steel process	22.68	8.16	46.95	8.26
Calcium carbide process	3.97	1.43	10.32	1.81
Other	0.00	0.00	14.04	2.47

Table A2
Number of relevant peer-reviewed journal articles in the Science Citation Index databases in the most recent 10 years.

Sectors	Carbon emissions industry China		CO_2 emissions industry China	
Cement	14	19.18%	17	20.73%
Power	10	13.70%	13	15.85%
Iron and steel	9	12.33%	11	13.41%
Transportation	8	10.96%	8	9.76%
Construction	7	9.59%	4	4.88%
Chemical	3	4.11%	3	3.66%
Dyeing and textile	2	2.74%	1	1.22%
Mining	2	2.74%	0	0.00%
Metal	1	1.37%	1	1.22%
Manufacture	1	1.37%	0	0.00%
Non-ferrous metal	1	1.37%	4	4.88%
Plate glass	1	1.37%	1	1.22%
Other	14	19.18%	20	24.39%
Total relevant articles	73	100.00%	82	100.00%

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Energy consumption and CO_2 emissions in Tibet and its cities in 2014

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Key Points:
- This study discussed the CO2 emissions from Tibet cities
- 5.52 million tons of CO2 were emitted in Tibet in 2014, Lhasa contributes over half of them
- Tibet has a lower per capita emission and a higher emission intensity compared the whole China

Supporting Information:
- Supporting Information S1

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Abstract Because of its low level of energy consumption and the small scale of its industrial development, the Tibet Autonomous Region has historically been excluded from China's reported energy statistics, including those regarding CO_2 emissions. In this paper, we estimate Tibet's energy consumption using limited online documents, and we calculate the 2014 energy-related and process-related CO_2 emissions of Tibet and its seven prefecture-level administrative divisions for the first time. Our results show that 5.52 million tons of CO_2 were emitted in Tibet in 2014; 33% of these emissions are associated with cement production. Tibet's emissions per capita amounted to 1.74 tons in 2014, which is substantially lower than the national average, although Tibet's emission intensity is relatively high at 0.60 tons per thousand yuan in 2014. Among Tibet's seven prefecture-level administrative divisions, Lhasa City and Shannan Region are the two largest CO_2 contributors and have the highest per capita emissions and emission intensities. The Nagqu and Nyingchi regions emit little CO_2 due to their farming/pasturing-dominated economies. This quantitative measure of Tibet's regional CO_2 emissions provides solid data support for Tibet's actions on climate change and emission reductions.

1. Introduction

The Tibet Autonomous Region is one of China's 34 provincial-level divisions. It is located in the most south-westerly part of China and is China's second largest province. Tibet is a vast territory with a sparse population. Its administrative area is 1.2 million km^2 and accounts for one-eighth of the country's geographic expanse; however, its 2014 population constitutes only 0.23% of China's population (3.18 million). Tibet is a typical agriculture-based autonomous region, and its primary industry contributed over 45% to the economy in the early 1990s. After years of development, Tibet now has a tertiary industry as a foundational economic driver, and this tertiary industry contributed 53.5% to total gross domestic product (GDP) in 2014. Even so, the primary industry remains the largest sector in Tibet, and 43.7% of the working population work in the primary industry. The secondary industry, which includes industry and construction, is the smallest segment of Tibet's national economy; it employs only 14.7% of Tibet's working population. The secondary industry's GDP in 2014 was 33.68 billion yuan, which is quite small compared with China's national GDP of 27,176.45 billion (0.12%) [*National Bureau of Statistics of China*, 2015].

Due to its small scale of energy-intensive industries, Tibet consumes very little energy every year and its consumption of conventional fossil fuels is particularly low. Moreover, because it is covered primarily by forests, lakes, and other natural ecological reserves, Tibet has large carbon sink capacities. For example, Tibet's forests covered 14%+ of its total area in 2015, and its forest stock is 2.09 billion m^3, ranking at the top of Chinese provinces [*The State Council Information Office of China*, 2015]. The forests' ecosystem will absorb 50.65 million tons of carbon every year [*National Energy Administration*, 2014]. Tibet's carbon sink function is larger than its human-induced carbon emissions. Even so, both Chinese central and local governments have taken actions on Tibet's emission reduction and climate change mitigation. In the "Tibet action on climate change and emission reduction during 2014-2015" issued by *Tibet Autonomous Region Government* [2014], the energy consumption intensity (energy consumption per GDP) in 2015 is required to decrease by 2.09% compared with that in 2014, while the CO_2 emissions are required to keep stable with 2010. In the assessment of each province's emission intensity (CO_2 emissions per GDP) reduction by the *National Development and Reform Commission of China* [2015], Tibet had the worst performance among China's 31 provinces.

Given the targets of emission reduction in Tibet autonomous region, a quantitative measure of Tibet's regional CO_2 emissions is urgently needed. However, due to lack of data, this research field is still vacant. Generally speaking, CO_2 emissions of one administrative region could be calculated in three ways: territorial-based, production-based, and consumption-based approach [*Barrett et al.,* 2013], among which, territorial-based emissions are used to account emissions *"taking place within national (including administered) territories and offshore areas over which the country has jurisdiction (page overview.5)"* [*Intergovernmental Panel on Climate Change [IPCC]*, 1996]. We therefore adopt the territorial-based emission scope in this study, as it could describe the emission characteristics as well as emission sources of one region. According to the IPCC, CO_2 emissions can be calculated as activity data (energy consumption/industry products' production) timed by emission factors [*IPCC*, 2006]. Scholars use energy balance tables industrial sectoral energy consumption to calculate the emission inventories of China and its provinces [*Peters et al.,* 2006; *Shao et al.,* 2011, 2016a, 2016b; *Guan et al.,* 2012; *Liu et al.,* 2016]. However, this method can only be used in provinces with consistent energy data, such as Beijing, Shanghai, and Hebei. Tibet is not included in China's energy statistical system. China's National Bureau of Statistics releases national and provincial energy data in its annual "China Energy Statistical Yearbook". The yearbook is the only official energy report in China [*National Bureau of Statistics of China*, 2016a]. There is no Tibet's energy data in the yearbook.

Due to the data missing, previous studies on China's national/provincial inventory excludes Tibet [*Liu et al.,* 2015; *Shan et al.,* 2016; *Wu et al.,* 2017], as well as analysis on China's energy consumption and greenhouse gas emissions [*Fan et al.,* 2015, 2016; *Wang et al.,* 2016; *Wang and Feng*, 2017]. Few studies have focused on Tibet's energy consumption. Only three English-language papers could be found covering Tibet's energy consumption on the Web of Science [*Liu et al.,* 2008; *Ping et al.,* 2011; *Zhang et al.,* 2015], and 11 Chinese documents [*Wang*, 1985; *Cai and Zhang,* 2006a, 2006b; *Wang,* 2006a, 2006b; *Pei and Liu*, 2007; *Wang et al.,* 2007; *Yao*, 2013; *Tang and Chen*, 2015; *Yang and Zheng*, 2015; *Zhao et al.,* 2016] were found on China's National Knowledge Infrastructure datasets. Most of these papers discussed Tibet's sustainable energy development and its carbon sink function, as well as emissions from biomass fuels [*Xiao et al.,* 2015]. *Zhao et al.* [2016] is the only study that has discussed Tibet's human-induced CO_2 emissions so far. These authors estimate the fossil fuel consumption in Tibetan industries and calculate the related CO_2 emissions for the year 2012.

Cities (prefecture-level administrative divisions) are the core targets of climate change mitigation and greenhouse gas emissions reduction. Previous studies have focused almost exclusively on mega-cities and affluent cities in China [*Kennedy et al.,* 2009, 2015; *Hillman and Ramaswami*, 2010; *Chen and Chen*, 2016; *Lu and Chen*, 2016; *Mi et al.,* 2016; *Meng et al.,* 2017]. Although emission inventory construction methods have been developed for cities with limited energy data [*Kennedy et al.,* 2010; *Shan et al.,* 2017], there is yet no research examining CO_2 emissions from Tibet's cities. There are seven cities (prefecture-level administrative divisions) in the Tibet Autonomous Region: Lhasa City, Qamdo City, Xigaze City, Shannan Region, Nagqu Region, Ngari Region, and Nyingchi Region (specific location seen in Figure 3). In this study, we fill this research gap by estimating Tibet's CO_2 emissions and its cities for the first time, by sectoral approach. Our quantitative measure of Tibet's regional CO_2 emissions will provide solid data support for Tibet's actions on climate change and emission reductions.

2. Method and Data Collection

2.1. CO_2 Emission Calculation

In this study, we use IPCC territory administrative CO_2 emissions from Tibet and its seven cities. Our CO_2 emissions include two parts: emissions from fossil fuel combustion (energy-related emissions) and emissions from industrial processes (process-related emissions). The process-related emissions involve CO_2 emissions produced during chemical reactions in industrial processes. As Tibet has only a cement production industrial process, the process-related emissions in this study include only those emissions from cement production. The emissions related to fossil fuel burning to power cement production are counted as energy-related emissions, rather than process-related emissions.

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According to IPCC guidelines, energy-related CO_2 emissions (CE_{energy}) are calculated as fossil fuel combustion multiplied by factors; see equation 1.

$$CE_{energy} = \sum_i \sum_j CE_{ij} = AD_{ij} \times NCV_i \times EF_i \times O_i \quad (1)$$

where CE_{ij} refers to CO_2 emissions from fossil fuel i combust in sector j, and AD_{ij} (activity data) is the burning consumption of fossil fuel i by sector j. Tibet has a relatively simple energy structure in which only six types of fossil fuel are used (see Table S1, Supporting Information). NCV_i, EF_i, and O_i are net caloric value, the emission factor, and the oxygenation efficiency of fossil fuel i, respectively. In this study, we collect these parameters from our previous survey of China's fossil fuel quality [*Liu et al.,* 2015], which are thought to be more accurate regarding China's energy consumption.

CO_2 emissions from the cement process could be estimated in equation 2.

$$CE_{process} = AD_t \times EF_t \quad (2)$$

where AD_t is production of the product, which refers to cement production in this study. The emission factor for cement production (EF_t) is 0.2906 tons of CO_2 per ton of cement production, which is collected from *Liu et al.* [2015] as well.

2.2. Cement Production

Data regarding cement production in Tibet for 2014 was collected from the Tibet statistical yearbook 2015 [*Tibet Bureau of Statistics*, 2015]. In 2014, Tibet produced a total of 3422.48 thousand tons of cement. According to the "Tibet 12th Five-year Plan for Building Materials Industry" [*Tibet Autonomous Region Government*, 2011], there are only seven cement manufacturing companies in Tibet; see Table S2. We use Tibet's 2014 cement production to scale each plant's production and total up by regions. Then, we obtain the cement production for each city, as shown in Table S3.

2.3. Energy Consumption

Unlike provinces with consistent energy statistics, the energy consumption data can be collected from the energy balance tables in China energy statistical yearbooks, only limited information about Tibet's fossil fuel consumption can be found online. Thus, we estimate fossil fuel consumption for Tibet and its seven cities in a bottom-up approach. We collect the consumption of specific energy types of Tibet from multiple sources, such as government reports, news reports, and literature.

As the abundant hydro power in Tibet, electricity from hydro power station plays the dominant part in Tibet industrial and residential energy consumption, which also suppress the fossil fuel usage in Tibet. Most emissions from fossil fuel come from the industrial production and transportation.

2.3.1. Coal

2.3.1.1. Industrial Coal Consumption

There are no official reports on Tibet's coal consumption statistics. Approximately 85% of Tibet's coal consumption is associated with cement plants to provide power; the remaining 15% is used for restaurants and residences [*Zhao et al.,* 2016]. Therefore, we use Tibet's cement production to estimate coal consumption in equation 3.

$$CC_{total} = \frac{CC_{cement}}{85\%} = \frac{CP_{clinker} \times uCC_{clinker}}{85\%} \quad (3)$$

where CC_{total} indicates total coal consumption in Tibet; CC_{cement} presents the coal consumption for cement production in Tibet; CP_{cinker} means cement-clinker production in Tibet; $uCC_{clinker}$ is the coal consumption for the unit cement clinker output. As there is no cement-clinker production in Tibet's statistical yearbook, we use the national cement-clinker production ratio to estimate Tibet's cement production. According to "The 12th Five-year Plan for Building Materials Industry" [*Ministry of Industry and Information Technology of China*, 2011], the national new dry cement-clinker production in 2010 was 1260.00 million tons, taking 81% of overall cement clinker. Thus, total cement-clinker production in 2010 is estimated as 1555.56 (=1260/81%) million tons. At the same time, the national total cement production is 1880.00 million tons, which means that the average cement-clinker production ratio is approximately 82.74% (=1555.56Mt/1880.00Mt)

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in China. We use the national average ratio to estimate Tibet's cement-clinker production as 2831.85 (=3422.48 × 82.74%) thousand tons in 2014. According to the same report, average coal consumption of cement-clinker production is 160 kg per ton clinker production in China. We adopt the national average value and calculate the entirety of Tibet's coal consumption as 533.05 (=2831.85 × 160/85%/1000) thousand tons of coal.

2.3.1.2. Residential Coal Consumption

Among the total coal consumption, 453.10 thousand tons are consumed in cement plants and the remaining 79.95 thousand tons are consumed for residential usage. We allocate the residential consumption of coal to each city based on its population in 2014. The populations of each administrative division are collected from the sixth national population census [*National Bureau of Statistics of China*, 2012].

2.3.2. Oil

2.3.2.1. Diesel Consumption in Thermal Power Plants

The total thermal power generation of Tibet was 149 million kWh in 2014 [*National Bureau of Statistics of China*, 2016a]. The State Grid Tibet Electricity Power Company Limited has two thermal power plants in Tibet: the Ngari thermal plant and the Dongga (Lhasa) thermal plant. The Ngari thermal plant has four 2500 kW diesel generating sets [*State Grid Tibet Electricity Power Company Limited*, 2015], and the total installed capacity of the Ngari thermal plant is 10 thousand kW. The Dongga (Lhasa) thermal plant has six 11,500 kW diesel generating sets before 2010, China's Huaneng Group invested in another nine 11,500 kW sets in 2010, bringing the total installed capacity of the Dongga (Lhasa) thermal plant to 172.5 thousand kW. Therefore, we assume that the electricity generated by the Ngari thermal plant was 8.16 million kWh in 2014, whereas the electricity generated by the Dongga thermal plants in Lhasa was 140.84 million kWh.

The fuel consumption of the diesel generating set is approximately 190–250 g/kWh [Weifang Chengfeng Power Equipment CO. Ltd; *Xiao*, 2001; *Bao and Tian*, 2014], which means that in producing 1 kWh electricity, the generating set will combust 190–250 g of diesel oil. Considering the low combustion efficiency in the plateau, we adopt a high threshold value of 250 g/kWh in this study. In this manner, we calculate that the Dongga (Lhasa) thermal plant burned 35.21 (=140.84mkWh × 250 g/kWh/1000) thousand tons of diesel oil in 2014, whereas the Ngari thermal plant burned 2.04 (=8.16mkWh × 250 g/kWh/1000) thousand tons.

2.3.2.2. Other Refined Oil Consumption in Transportation Sector

Tibet consumed approximately 745 thousand tons of refined oil in 2012, which consists mainly of diesel oil in road transportation and thermal power plants (410 thousand tons), gasoline in road transportation (310 thousand tons), diesel oil in railway transportation (10 thousand tons), and kerosene in air transportation (15 thousand tons). Among the 745 thousand tons of consumption, 600 thousand tons were sold by China's National Petroleum Corporation (CNPC) [*Zhao et al.*, 2016]. In 2014, CNPC sold 786.30 thousand tons of petroleum products in Tibet [*National Development and Reform Commision of China*, 2016]. We estimated total petroleum product consumption at 976.32 (= 786.30/600 × 745) thousand tons in 2014, including diesel oil burned in thermal power plants, which were identified previously as the 37.25 thousand tons calculated above. The consumption levels of diesel oil for road transportation, diesel oil for railway transportation, gasoline for road transportation, and kerosene for air transportation are estimated as 500.06, 13.11, 406.26, and 19.66 thousand tons, respectively.

We allocate diesel oil and gasoline consumption in road transportation to each city according to cities' tertiary industry GDP (including transport, storage and post as dominating contributors). The diesel oil consumed for railway transportation and kerosene for air transportation are calculated in Lhasa due to Lhasa's dominant volume of freight traffic and passengers in Tibet (see Table S4).

2.3.3. Residential Gas Usage

2.3.3.1. Natural Gas and Liquefied Petroleum Gas Consumption in the Lhasa Urban Area

The "Gas Tibet" project was launched by Qinghai Oilfield, CNPC in 2010 to bring natural gas to Lhasa for the first time. Natural gas consumption increased 10 times in the last 3 years [*Ren and Yang*, 2014]. The total natural gas supplied to Lhasa reached 160 thousand m^3 in 2014. In addition, Tibet also consumed a small amount of liquefied petroleum gas (LPG) in its urban area, approximately 62.48 thousand tons in

Table 1. Conventional Energy Consumption and Cement Production of Tibet and Its Cities, 2014

Division	Cement	Coal	Diesel	Gasoline	Kerosene	LPG	Natural gas
Unit	10^3 tons						10^3 m^3
Lhasa	1789.80	251.85	260.32	172.23	19.66	62.48	160.00
Qamdo	179.62	41.29	49.96	40.59	—	—	—
Shannan	1162.22	162.63	44.85	36.44	—	—	—
Xigaze	221.79	48.09	71.89	58.40	—	—	—
Nagqu	-	12.31	51.32	41.69	—	—	—
Ngari	69.04	11.68	20.06	14.64	—	—	—
Nyingchi	-	5.20	52.03	42.27	—	—	—
Total	3422.48	533.05	550.42	406.26	19.66	62.48	160.00

2014 [*National Bureau of Statistics of China*, 2016a], which are all assumed to be consumed in Lhasa's urban households.

In summary, the levels of conventional energy consumption and cement production in Tibet and its cities in 2014 are shown in Table 1. We use these activity data for CO_2 emissions estimation in the following section.

3. Results

3.1. Tibet's Total CO_2 Emissions in 2014

In 2014, Tibet emitted a total of 5.52 million tons of CO_2 related to fossil fuel combustion and cement production. These emissions were relatively small both in their absolute amounts and in terms of the proportion of national emissions (9438.45 million tons), which stands at 0.06% of China's total emissions [*CEADS*, 2016]. The small emissions amount results from Tibet's limited industry but also from its renewable-dominant energy structure. Tibet is rich in renewable energy, such as hydro energy, wind power, and solar energy [*Tang and Chen*, 2015]. In fact, 3.24 billion kWh of the electricity generated in Tibet was from renewable energies in 2014, accounting for 89.94% of total electricity generation. Hydro energy contributed 80.64% of this amount (2.90 billion kWh). Only 10.06% (0.36 billion kWh) of electricity was generated in fire-powered plants. Tibet's renewable energy proportion in the energy mix was much higher than the national average level of 11.30% in 2014.

Apart from non-fossil fuel energies, diesel and gasoline consumption are Tibet's main sources of energy-related emissions (see Figure 1a). These two energy types contributed 31.42% (1.73 million tons) and 21.94% (1.21) to total CO_2 emissions, respectively, in 2014. In addition, coal is responsible for only 975.48 thousand tons of CO_2, accounting for 17.68% of total emissions primarily because of Tibet's simple energy structure. This is significantly different from China's overall emission structure and from the structures in other provinces: coal and its related products dominate energy consumption (65.60%) and CO_2 emissions (77.21%) and is burned mainly in coal-based fire-powered plants for power. In Tibet, as discussed above, coal is consumed exclusively in cement plants and for residential usage, the only two fire-powered plants are diesel-based power plants. This is a result of Tibet's limited coal sources and low coal production. Almost all the coal used in Tibet are imported from its nearby provinces. In 2014, 625.5 thousand tons of coal are imported to Tibet according to "China Coal Industry Yearbook 2014" [*China Coal Information Institute*, 2014]. Considering the factor of stock changing and statistical error, our estimation of 533.05 thousand tons' coal consumption is relatively accurately.

The cement process is another large contributor to Tibet's CO_2 emissions, accounting for 18.02% (994.57 thousand tons) in 2014. This percentage is much higher than the national average level of 7.67% in 2014.

From the sectorial perspective, we find that transportation and cement production are two primary contributors to CO_2 emissions (Figure 1b). Indeed, 50.48% (2.79 million tons) of total emissions are associated with road transportation, which is mainly induced by gasoline usage in private cars and passenger coaches and by diesel used in cargo trucks. Cement production contributed 33.05% (1.82 million tons) to total emissions. The cement production emissions include two parts: emissions from the cement process (994.57 thousand tons), which is the same as the cement process in Figure 1a; and emissions from coal combustion in cement

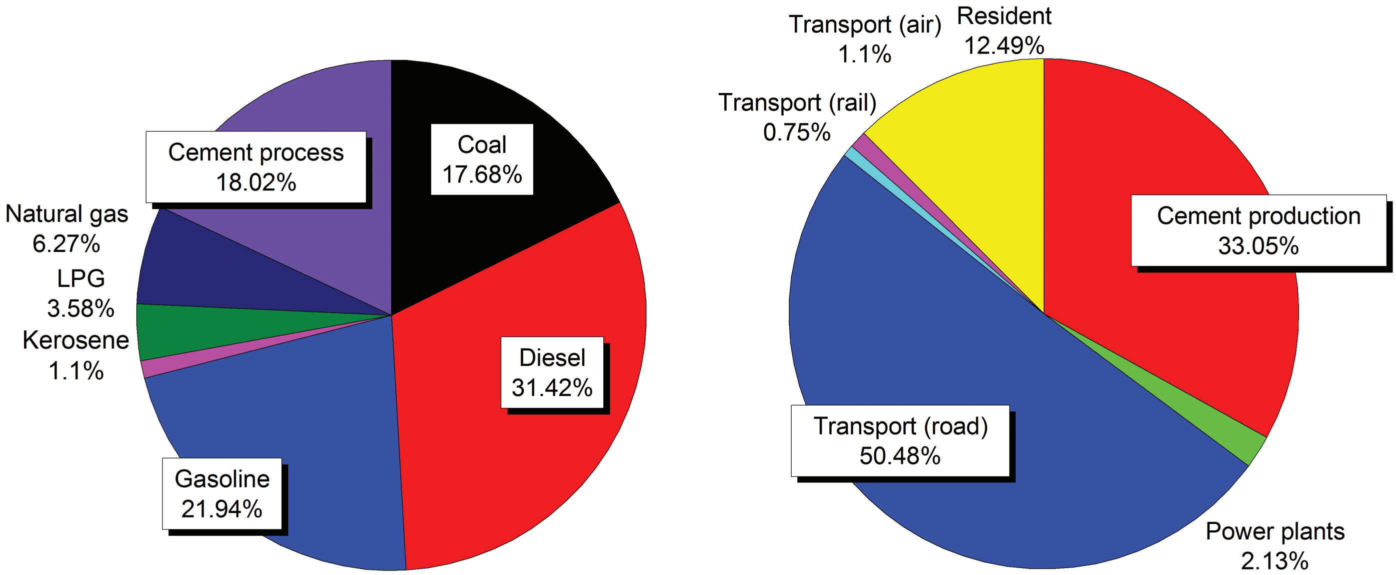

Figure 1. CO_2 emissions from fossil fuel types and sectors in Tibet, 2014.

plants for power (829.17 thousand tons). The remaining 16.47% of CO_2 emissions are associated with air transportation, rail transportation, power plants, and residential consumption.

Figure 2 provides a detailed illustration of energy structures in different sectors' CO_2 emissions. This figure shows that in road transportation, 56.54% emissions are from diesel consumption (mainly used in cargo trucks). The remaining 55.54% is induced by gasoline combustion in private cars and passenger coaches. Apart from electricity, residents in Tibet consumed a substantial amount of LPG, which contributes 28.64% of the total residential emissions. LPG and natural gas (50.13%) are consumed only in Lhasa City, having benefited from the "Gas Tibet" project since 2010 [*Ren and Yang*, 2014]. Households in rural and less-developed areas (particularly Nagqu, Ngari, and Nyingchi) use coal as their main energy source for heating and cooking due to the lack of electricity and gas. This segment of coal consumption emitted 146.31 thousand tons of CO_2 in 2014.

We calculate Tibet's per capita CO_2 emissions at 1.74 tons and its emission intensity at 0.60 ton per thousand yuan in 2014. Per capita CO_2 emissions in Tibet are remarkably lower than the national level of 6.90 tons [*CEADS*, 2016]. Tibet is one of the least developed provinces in China, as most of its residents continue to maintain a farming-based lifestyle, which consumes less energy than urban lifestyles. However, Tibet's emission intensity is much higher than the national level of 0.15 ton per thousand yuan because of the low combustion heat value in the plateau, backward production technologies in industrial system and Tibet's simple industrial structure. Heavy industries account for the lion's share of the 58.86% in Tibet's overall industrial output. Cement production is the primary contributor, accounting for 34.05% of heavy industrial output. Tibet's emission intensity is close to Ningxia's (0.52 ton per thousand yuan) due to the nearby geographical location and similar simple industry structure.

3.2. Tibet's Historical CO_2 Emissions Growth

Based on the CO_2 emissions in 2014, this study estimates Tibet's time-series emissions from 2003 to 2013 with its energy consumption/cement production increasing rate. The cement process-, LPG-, and natural gas-related emissions are calculated with their own historical emissions [*National Bureau of Statistics of China*, 2016a]. The emissions from coal consumption are calculated based on the cement production increasing rate [*National Bureau of Statistics of China*, 2016b]. The refined oil consumption in Tibet increased 13% per year steadily [*Tibet Autonomous Region Government*, 2007], we use the ratio to estimate Tibet's CO_2 emissions from diesel, gasoline, and kerosene.

Our results find that Tibet's CO_2 emissions in 2003 are about 1300 thousand tons, and then increased smoothly at a speed of 14+% per year, see Table S5. With the growth rate of 15%, we estimate Tibet's CO_2

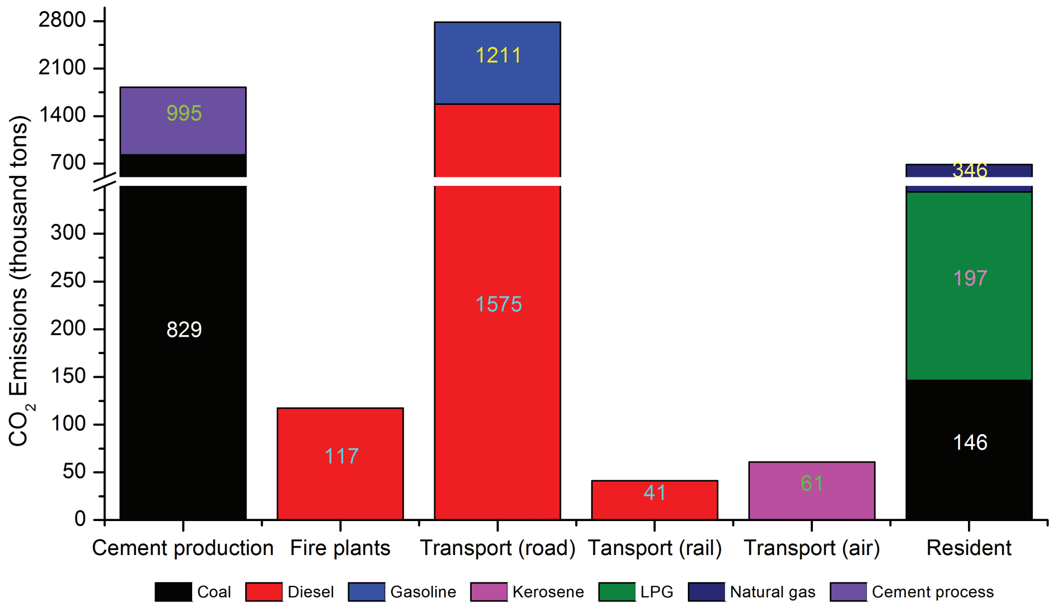

Figure 2. Tibet CO_2 emissions in 2014 by different sectors and by energy types. Diesel and coal are main fossil fuel used in Tibet, and cement production and road transport contribute the most to the CO_2 emissions.

emissions in 2015 as 6346 thousand tons. However, benefited from the "Gas Tibet" project, the natural gas consumption in Tibet increased sharply in 2015, reached 13,460 thousand m^3 [*China Energy Web*, 2016; *National Bureau of Statistics of China*, 2016a]. Considering this, we reckon Tibet's total CO_2 emission would surpass 35,000 thousand tons in 2015.

3.3. The CO_2 Emissions of Tibet's Cities

We calculate the CO_2 emissions of seven of Tibet's cities in 2014, as shown in Figure 3. The pie chart in the top right corner presents the emission proportion of each administrative division (in thousand tons). The detailed emissions from energy sources and sectors are shown in Table S6.

This figure shows that over half of Tibet's CO_2 emissions come from Lhasa City. Lhasa is the capital and the largest and most developed city in Tibet, contributing 37.73% to Tibet's economic growth in 2014. Therefore, Lhasa has the most complex emission structure of all the cities, as shown in Figure 4. Like Tibet's emission structure, approximately 83% of Lhasa's emissions are from cement production (38.28% or 953.73 thousand tons) and road transportation (44.54% or 1.11 million tons). Lhasa is the largest cement production base in Tibet, with four cement plants, and produces 52.30% of Tibet's total cement production. Lhasa is also the entrepot of Tibet, with high volumes of passenger and freight traffic. As discussed above, LPG and natural gas are used in Lhasa's urban households, and these two energy types account for 95.22% of Lhasa's CO_2 residential emissions. This percentage is substantially higher than China's average level of 37.90% in 2014 [*National Bureau of Statistics of China*, 2016a].

The Shannan region is another large CO_2 emitting region in Tibet, accounting for 16% of emissions. Most of its CO_2 emissions are also related to cement production (69.96%, 619.32 thousand tons) and road transportation (28.23%, 249.87 thousand tons). Lhasa and Shannan have the highest per capita emissions and emission intensities among Tibet's cities. The per capita emissions of the two divisions are 4.93 and 2.54 tons, respectively. The value is close to that of Sichuan province (4.19 tons) and Yunnan province (4.14 tons), areas that are contiguous to Tibet. The emission intensity of Lhasa and Shannan is 0.84 and 0.88 tons per thousand yuan, respectively. The high emission intensity is caused by a large amount of cement production in these administrative divisions.

Nagqu and Nyingchi regions are the only two divisions with no cement production in Tibet. These two cities' emission intensities are therefore the lowest (0.37 and 0.32, respectively). Nagqu is a pure pasturing zone: 73.99% of its area (333.33 thousand km^2) is meadow. Nyingchi is a typical mountainous region in Tibet: the

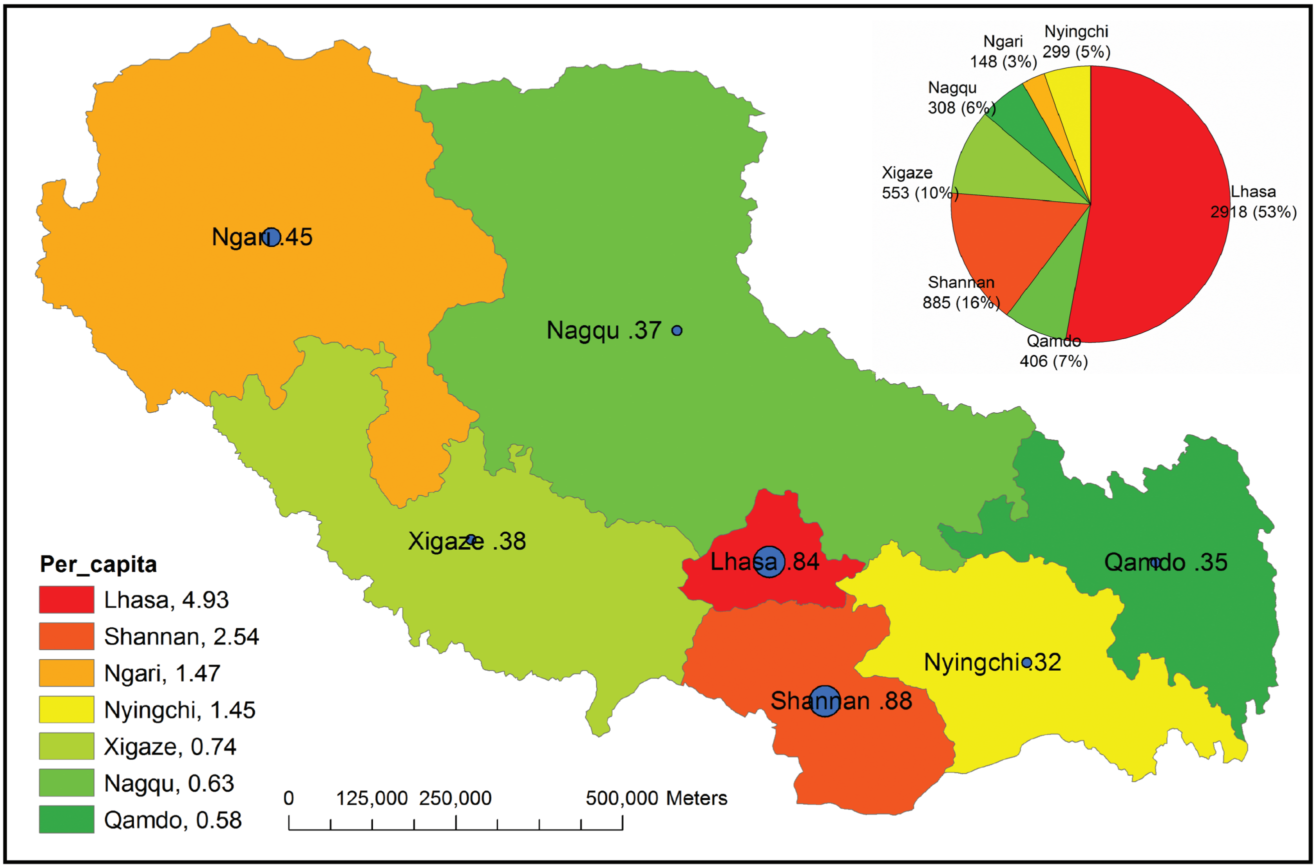

Figure 3. CO_2 emissions from seven cities in Tibet, 2014. The colors of the map show the per capita emissions (CO_2 emissions/population, in ton) of each city. Greener city has a lower per capita emission while redder city have a higher one. The Blue circles represent emissions intensity (CO_2 emissions/total GDP) for each city, bigger circle refers to a higher emission intensity. The numbers on the map shows the emission intensity of each city (in ton per thousand yuan), for example, the emission intensity of Lhasa is 0.84 ton per thousand yuan.

Himalayas and the Nyenchen Tanglha Mountains run through it. Nyingchi's forest coverage rate is 46.0%, and 80% of Tibet's forest is in Nyingchi. There is very little industry in Nagqu and Nyingchi regions.

4. Discussion and Conclusion

Tibet's autonomous region has always been absent in energy statistics and CO_2 emissions accounting. Previous studies on China's national and provincial emissions accounting typically ignore Tibet. In this paper, we estimate its energy consumption according to limited online documents and calculate Tibet's energy- and process-related CO_2 emissions of Tibet and its seven cities in 2014 for the first time. This study has achieved the following give main findings.

1. Tibet emitted 5.52 million tons of CO_2 in 2014; 18% of these emissions are associated with the cement production's process emissions, and the remaining 82% from fossil fuel combustion.
2. Diesel and gasoline are two dominating energy types in Tibet's emission structure. Approximately 90% of Tibet's CO_2 emissions in 2014 are associated with cement production and road transportation.
3. The per capita emission of Tibet in 2014 was 1.74 tons, which is remarkable lower than the national average level, whereas the emission intensity of Tibet is relatively high, at 0.60 ton per thousand yuan in 2014.
4. Lhasa City and the Shannan region are two large CO_2 contributors among the seven cities in Tibet. They also have the highest per capita emissions and emission intensities. The Nagqu and Nyingchi regions emit little CO_2 every year as a result of their farming/pasturing-dominated economies.

The detailed analysis of Tibet's emission characteristics implies that possible measures regarding Tibet's CO_2 emissions reduction could be taken as follows.

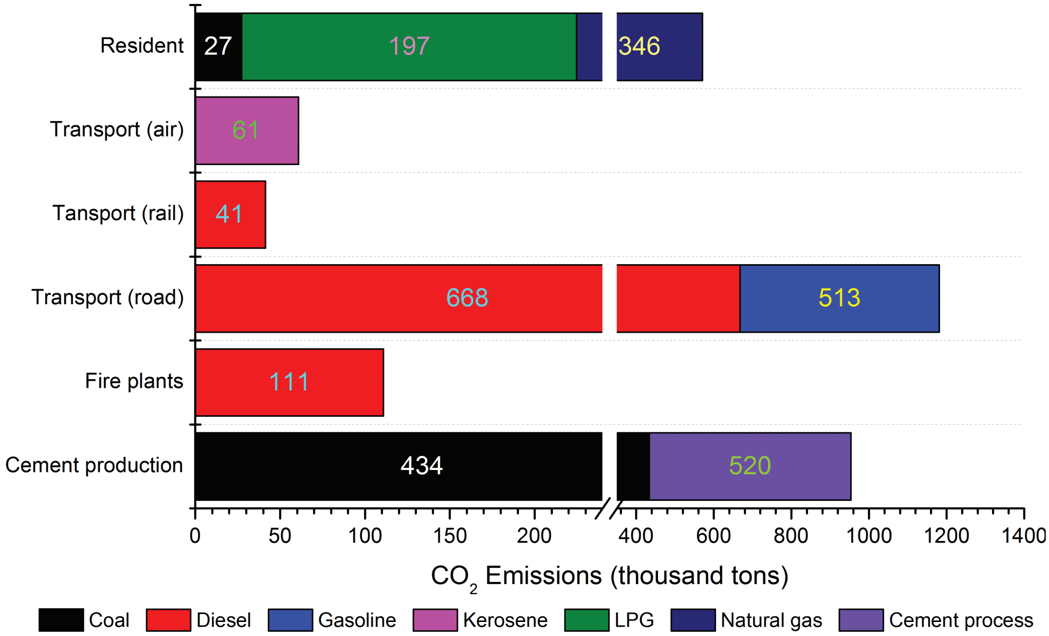

Figure 4. Lhasa CO_2 emissions in 2014. As the capital and largest city of Tibet, Lhasa has the most complex emission structure of all the cities. Transportation and cement production are the primary contributor to Lhasa's CO_2 emissions. LPG and natural gas used in households also emit lot of CO_2.

1. Despite Tibet's per capita emissions is much lower than the national average level, there is a certain amount of scattered coal combusted by households in Tibet's rural regions. Tibet should replace residential coal usage in rural and less-developed regions by natural gas. The "Gas Tibet" project has met with huge success in Lhasa city during the past 3 years and increased its natural gas consumption by 10 times. We suggest that the project should be continued and expanded to other administrative divisions in Tibet. Coal is more carbon-intensive energy type than natural gas, and replacing coal by natural gas in residential usage could thus reduce Tibet's CO_2 emissions effectively.
2. Considering the emission intensity in Tibet is relatively high, Tibet should improve its industry production process. As the only energy-intensive industrial process in Tibet, cement production contributes substantially to emissions each year, although Tibet's cement production is relatively limited compared with other regions in China. Measures such as improving the energy combustion efficiency/combustion heat value, reducing the unit energy consumption in cement production could lower Tibet's emission intensity.
3. Tibet could weed out the behindhand generator set in the fire-power plant. We suggest replacing the four 2500 kW diesel generating sets in the Ngari thermal plant by 11,500 kW or more advanced sets. The advanced sets have lower unit energy consumption.
4. Tibet could maintain the development of renewable energies. Notably, Tibet has abundant water resources and thereby great potential to develop its renewable energy, particularly via hydropower. As Tibet has developed its hydropower capability, Tibet's green electricity generation increased rapidly from 1.72 in 2010 to 3.24 billion kWh in 2014. The percentage in total electricity generation also increased from 81.81% to 89.94% during the same period. Although energy consumption and CO_2 emissions in Tibet are much lower than in other provinces, Tibet's role in national climate change mitigation should not be underestimated. Because of its high potential capacity of hydropower, Tibet is more likely to act as the electricity exporter and to ease electricity shortage and decrease energy consumption in other regions. Tibet should continue this increasing trend and develop its renewable energies in the future. Despite all these, conventional fossil fuels would still play an important role in Tibet's energy structure. Booming infrastructure development in Tibet, particularly in road construction, would directly bring about a rise in diesel and gasoline consumption, thereby increasing emissions. Tibet's energy and emission structure would be more likely to change in the future.

Due to the data availability, this research only considers several energy types (coal, diesel, gasoline, kerosene, LPG, and natural gas), as well as several sectors (transportation, cement production, residential usage) in the emission accounts. In the future work, we would detail the Tibet's CO_2 emissions if more detailed energy data could be collected. Also, we would like to conduct the time series CO_2 emissions research for Tibet and try to categorize emissions changes patterns.

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