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RESEARCH ARTICLE

Development of a stationary carbon emission inventory for Shanghai using pollution source census data

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Abstract This study utilizes 521,631 activity data points from the 2007 Shanghai Pollution Source Census to compile a stationary carbon emission inventory for Shanghai. The inventory generated from our dataset shows that a large portion of Shanghai's total energy use consists of coal-oriented energy consumption. The electricity and heat production industries, iron and steel mills, and the petroleum refining industry are the main carbon emitters. In addition, most of these industries are located in Baoshan District, which is Shanghai's largest contributor of carbon emissions. Policy makers can use the enterprise-level carbon emission inventory and the method designed in this study to construct sound carbon emission reduction policies. The carbon trading scheme to be established in Shanghai based on the developed carbon inventory is also introduced in this paper with the aim of promoting the monitoring, reporting and verification of carbon trading. Moreover, we believe that it might be useful to consider the participation of industries, such as those for food processing, beverage, and tobacco, in Shanghai's carbon trading scheme. Based on the results contained herein, we recommend establishing a comprehensive carbon emission inventory by inputting data from the pollution source census used in this study.

Keywords carbon emission inventory, greenhouse gas (GHG), statistical yearbook, pollution source census, Shanghai

1 Introduction

Increasing greenhouse gas (GHG) emissions, particularly those emitted from human activity, are the primary source of current climate change. According to the IPCC Fifth Assessment Report (AR5) of Working Group I, the first decade of the 21st century was the warmest period in the instrumental record. The report also indicated that the global mean surface temperature increased by 0.72°C over the 1951–2012 period (Stocker et al., 2013). It is widely acknowledged that current climate change is mainly caused by human activities — particularly the consumption of fossil fuels over the past few centuries — and that extreme climate events, such as storms, floods, and droughts, are occurring more frequently (Xu et al., 2013).

Most human social and economic activities occur in cities, and urban areas are the most concentrated areas of anthropogenic carbon emissions. More than half of the world's population is now living in cities, and this percentage will reach 66% by 2050 (World Urbanization Prospects, 2014). Therefore, more attention must be given to the level of urban GHG emissions, and a comprehensive understanding of city-level carbon emission inventories in terms of climate change mitigation and adaptation is becoming increasingly important.

The earliest city-level carbon emission inventories were developed in the 1990s (Harvey, 1993; Baldasano et al., 1999). Many studies have been conducted on city-level GHG emission inventories; some of which analyzed and compared carbon emissions from different cities (Dhakal, 2009; Kennedy et al., 2010; Sovacool and Brown, 2010; Liu et al., 2012; Sugar et al., 2012), while others created a single-city emission inventory and made recommendations for carbon reduction (Shimada et al., 2007; Li et al., 2009; Liu et al., 2009; Bi et al., 2011; Xi et al., 2011).

China is the largest GHG emitter in the world and produces approximately 25% of global GHG emissions (International Energy Outlook, 2010). Some Chinese researchers have conducted studies at different scales on the carbon emission inventories of various Chinese cities. Dong et al. (2013) chose the tiered hybrid LCA method to evaluate the carbon footprint of the Shenyang Economic and Technological Development Zone. Liu et al. (2014)

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established a comprehensive GHG emissions inventory for the Beijing Economic Technological Development Area that included energy consumption, industrial processes and product use, and waste. Xie et al. (2010) utilized low-carbon indicators in their environmental impact assessment of an industrial park. Bi et al. (2011) and Xi et al. (2011) developed a bottom-up method to assess GHG emissions and generated inventories for Nanjing and Shenyang (Bi et al., 2011; Xi et al., 2011). Yu et al. (2015) calculated energy consumption and CO_2 emissions in Beijing over the 2005–2011 period and then forecasted energy consumption and CO_2 emissions under two different scenarios for the 2012–2030 period. Liu et al. (2012) generated a top-down GHG inventory for Beijing, Tianjin, Shanghai, and Chongqing by adopting data from the Chinese Energy Statistics Year Book and analyzed the features, trajectories and driving forces of energy-related GHG emissions in those four cities (Liu et al., 2012). Cai and Zhang (2014) studied CO_2 emissions with respect to four types of urban boundaries found in Tianjin and made sound policy implications regarding urban energy management and carbon emission reduction.

Shanghai is one of four municipalities (Beijing, Tianjin, Shanghai, and Chongqing) directly under central government control. As the largest economic center, it is also one of the largest contributors to GHG emissions in China. With an area of 6,340 km^2 and a population of 24.14 million in 2013[1)], Shanghai's 2014 GDP was 2,356 billion CNY (USD $330 billion). Its primary, secondary, and tertiary industry percentages of its GDP were 0.5%, 34.7%, and 64.8% in 2014, respectively[2)]. As a hub of the Yangtze River Delta economic region, Shanghai's annual economic growth has increased over 10% in the last three decades[3)]. Such rapid growth inevitably results in high energy consumption and also produces significant carbon emissions due to the enormous agglomeration (Bi et al., 2011). In recent years, efforts have been made to improve the industrial structure and energy efficiency in Shanghai, although energy use and GHG emissions are likely to continue increasing through the foreseeable future due to expectations for continued increases in economic development.

Creating a GHG emission inventory for a city such as Shanghai, with its wide variance in material and energy flows, is a highly complex task (Ramaswami et al., 2011). Methods for accounting for GHG emissions at the city level are already being utilized by some organizations (UNEP, 2010; ICLEI, 2013). The majority of Chinese researchers who have compiled carbon emission inventories have used data from statistical yearbooks for their studies. For instance, Wu et al. (1997), among many other scholars, assessed Shanghai's carbon emissions using a top-down approach to create a carbon emission inventory in the context of carbon emission reduction strategies (Wu et al., 1997). Li et al. (2009) analyzed the status of carbon sources and deposits in Shanghai during the 1985–2007 period based on energy consumption and industrial structure data. Li et al. (2010) adopted the Shanghai statistical yearbooks and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories to create a CO_2 emission inventory for Shanghai from 1995 to 2006. Zhao et al. (2010) also used the Shanghai statistical yearbooks and IPCC guidelines to create a bottom-up industrial carbon emission inventory that covered 33 industrial sectors from 1996 to 2007. These researchers found that industrial growth was the main cause for the increase in carbon emissions. Shao et al. (2011) calculated energy-related industrial CO_2 emissions from 32 sub-sectors in Shanghai between 1994 and 2009. Wang et al. (2013) created a relatively complete carbon emission inventory using a bottom-up model for Shanghai in 2000–2008, which covered six sectors (stationary combustion, transportation, industrial processes, waste disposal and treatment, agricultural activities, and forestry sink). These studies selected the data from statistical yearbooks to assess carbon emissions. However, other researchers have created a useful method for utilizing data related to air pollution at the individual enterprise level to create an inventory. Unfortunately, the data in the Chinese statistical system regarding industrial energy consumption are limited to energy consumption information for only those industrial enterprises with annual production values of more than 20 million CNY, which makes these data both insufficient and uncomprehensive (Yang, 2010). However, the pollution source census data for Shanghai (the case study for this paper) contain all data related to energy use for all industrial enterprises in Shanghai and is thus a good primary data source for building the carbon emission inventory.

This study compiles a stationary carbon emission inventory for Shanghai, with input from pollution source data from the Shanghai Pollution Source Census (SPSC) of 2007. Section 2 presents a detailed introduction of the SPSC. The advantages of using the data from the SPSC compared with the data from the statistical yearbooks are discussed in Section 4. Based on the outcomes of the study, recommendations are provided to correct the existing weaknesses in current methods and to produce more reliable carbon inventories for Chinese cities. Finally, policy suggestions for promoting carbon trading in Shanghai are also introduced based on the inventory developed herein.

1) Shanghai Statistical Website. Available online: http://www.stats-sh.gov.cn/frontshgl/18665.html.
2) Shanghai Statistical Website. Available online: http://www.stats-sh.gov.cn/sjfb/201501/276531.html.
3) Shanghai Statistical Yearbook (2003–2014). Available online: http://www.stats-sh.gov.cn/data/release.xhtml.

2 Methodology

2.1 Research scope

According to the classification method of the International Council for Local Environmental Initiatives (ICLEI), the boundary for accounting for GHG emissions at the city level can be classified into three scopes (ICLEI, 2009):

•Scope 1 includes all direct GHG emissions within the city's geographical boundaries.

•Scope 2 contains the embodied emissions from electricity and heat generation, even when the actual emissions occur outside the city boundaries.

•Scope 3 covers the emissions from a life-cycle perspective, which means that the energy, materials, and products are used within the city boundary, even though the embodied emissions occur outside of city boundaries.

Ideally, an integrated method to account for the GHG emissions of cities would include Scopes 1, 2, and 3; however, few cities can track an emission inventory, including all three scopes, due to the lack of available data.

In Shanghai, approximately 27% of the electricity consumed was purchased from sources beyond city boundaries, whereas only a small amount of locally generated electricity was exported in 2005 (WWF Shanghai Low Carbon Development Roadmap Research Team, 2011). The proportion of purchased electricity compared to total consumption in Shanghai continues to increase, i.e., from 27% in 2005 to 35% in 2012[1)]. The carbon emission factors for electricity and heat generation in China vary among different regions due to regional differences in the energy production structures of these industries (Lindner et al., 2013). Purchased electricity and heat are not considered in this study because we cannot ensure where such electricity and heat originate or what the associated emission factors are. Considering this limitation, we focus only on ICLEI Scope 1 emissions in Shanghai. Three major GHGs (CO_2, CH_4, and N_2O) are included in the carbon emission inventory in this study. GHG emissions are expressed as their carbon dioxide equivalent (CO_2e) by multiplying the parameters of the Global Warming Potential (GWP), which are 1, 25, and 298 for CO_2, CH_4, and N_2O, respectively (IPCC, 2007a, b).

2.2 Data sources

China's government issues official specific pollution data based on the Chinese Pollution Source Census (CPSC), created by the State Council of the People's Republic of China, the Ministry of Environmental Protection of the People's Republic of China, and local environmental protection departments (CPSC, 2008). The first national pollution source census was taken between 2006 and 2009, providing an important basis for understanding the environmental situation in China. Furthermore, it provided basic data for scientific research on environmental protection, including four types of pollution sources: industrial, agricultural, domestic, and those from pollution treatment facilities, with the number identified for each in the CPSC as 1.75 million, 2.9 million, 1.45 million, and 4,790, respectively. China's local governments officially include pollution sources under their respective administrative jurisdictions.

The data in this study were collected from the Shanghai Pollution Source Census (SPSC), taken in 2007 as part of the CPSC. The SPSC includes pollution data from the same four pollution sources identified above for the CPSC. The domestic sources include those from residential services, accommodation and catering services, hospitals, independent burning, residential areas, and automobiles. In this study, the carbon emissions from automobiles, agricultural sources, and centralized pollution treatment facilities are not estimated because the required activity data (i.e., types of vehicles, crops, and waste), are missing. Data for the remaining sources from the SPSC are included. Therefore, this paper focuses on energy-related emissions from the energy and industrial sectors.

Pollution sources assessed in this study include: industrial, residential service, accommodation and catering services, hospital, independent burning, and residential sources. The information for and descriptions of the sources used for generating this inventory is given in Table 1. There are 48,753 industrial sources, 1,724 residential service sources, 1,313 accommodation and catering service sources, 243 hospital sources, 548 independent burning sources, and 50 residential sources, respectively.

Each emission category from each industrial source has a specific industrial code under the CPSC. All codes are classified by the Chinese Standard Industrial Classification of All Economic Activities (CSIC). To ensure that the results of this study can be compared with results from similar studies made by other researchers, we converted all data from the CSIC into standard IPCC classified data through the International Standard Industrial Classification of All Economic Activities (ISIC) (Appendix A). Thus, all sources are classified into two sectors: energy and industrial processes. The energy sector (i.e., all energy-related emission sources) is classified into three divisions: energy industries, manufacturing industries, and other sub-sectors (Table 2) (ISIC, 1990; CSIC, 2002; IPCC, 2006; ISIC, 2008). According to the CPSC, the "other sub-sectors" in the energy sector here include commercial and residential sources. Commercial sources include residential services, accommodation and catering services, hospitals, and independent burning sources. We classify the industrial processes sector into three divisions (i.e.,

1) Shanghai Statistical Yearbook (2006–2013). Available online: http://www.stats-sh.gov.cn/data/release.xhtml.

Table 1 Information/description of the sources adopted in the study

Source	Item	Content
Industrial sources	Basic information	Name of organization, industrial code
	Raw material and production	Name of raw material, raw material amount, name of production, output of production, name of craft processes
	Energy consumption	Type of energy, consumption of energy
Residential service sources, accommodation and catering service sources, hospital sources, independent burning sources	Basic information	Name of organization, industrial code
	Fuel consumption	Type of fuel, consumption of fuel
Residential sources	Basic information	Name of district or county
	Fuel consumption	Type of fuel, consumption of fuel

mineral, chemical, and metal industries) and 11 categories (Table 2) for two reasons. First, the mineral, chemical, and metal industries are the main industrial process carbon emitters in Shanghai (Sugar et al., 2012; Wang et al., 2013). Second, several industrial processes, such as in the electronics industry, do not emit CO_2, CH_4, and/or N_2O under IPCC guidelines and are thus not considered in this inventory.

In the energy sector, the activity data are generated by the consumption of each fuel. Types of fuels include raw coal, washed coal, other washed coals, briquette, coke, coke oven gas, blast furnace gas, natural gas, natural gas liquids, liquefied petroleum gases, refinery gas, crude oil, gasoline kerosene, diesel oil, fuel oil, and other fuels.

In the industrial processes sector, the activity data are from production volumes, which are classified into 3 divisions and 11 categories, as presented in Table 2.

2.3 Analysis method

The analytical method utilized in this study is a bottom-up approach, which is also called the sectoral approach and is a way of calculating the local emissions inventory by using the data on fuel consumption from various industries and the corresponding emission factors of each fuel.

The assessment approach chosen for the energy sector is under Tier 2 of the IPCC guidelines (IPCC, 2006). The local CO_2 emission factor ($EF_{i,j-CO_2}$), CH_4 emission factor ($EF_{i,j-CH_4}$), and N_2O emission factor ($EF_{i,j-N_2O}$) for fuel i and industry j in the energy sector can be calculated by Eqs. (1), (2), and (3):

$$EF_{i,j-CO_2} = NCV_i C_{i,j} O_i \frac{44}{12}, \quad (1)$$

$$EF_{i,j-CH_4} = NCV_i CH_{4i,j}, \quad (2)$$

$$EF_{i,j-N_2O} = NCV_i N_2O_{i,j}, \quad (3)$$

where NCV_i is the net calorific value of fuel i, $C_{i,j}$ is the carbon content per unit heat of fuel i in industry j, O_i is the carbon oxidation rate of fuel i, $CH_{4i,j}$ is the amount of CH_4 emission per unit heat of fuel i in industry j, and $N_2O_{i,j}$ is the amount of N_2O emission per unit heat of fuel i in industry j.

The emission factors are selected from various research papers and documents (IPCC, 2006; NGGI, 2007; GPCC, 2008; Cai et al., 2009; PGGGI, 2011). Table 3 shows the average net calorific value and the carbon oxidation rates of various fuels in China.

Carbon emission is estimated by production volume in the industrial sector. The descriptions of source types, calculations, and emission factors are shown in Table 4 (IPCC, 2006; Wang, 2006; Cui and Liu, 2008; PGGGI, 2011).

3 Results

By using the method with input data from the SPSC (as discussed in Section 2.3), the results show that total stationary carbon emissions amounted to approximately 140 $MtCO_2e$ in Shanghai in 2007 (Fig. 1). The energy sector (i.e., energy and manufacturing industries, and other sub-sectors) produced 88% of the total carbon emissions, whereas the remaining 12% were from industrial processes (i.e., metal, chemical, and mineral industries). A total of 125.07 $MtCO_2e$ emissions were from the energy sector, with the energy industries, manufacturing industries, and other sub-sectors (domestic sources) responsible for 55.2%, 38.8%, and 6%, respectively. The emissions from industrial processes were approximately 17 $MtCO_2e$, with the mineral, chemical, and metal industries responsible for 2.2%, 11.8%, and 86.0%, respectively. The detailed share of carbon emissions for each category is given in Tables 5 and 6. In the energy sector, over 95% of the total emissions resulted from 9 categories out of a total of 16 (Table 5). The

Table 2 Divisions and categories of sectors of energy and industrial processes

Sector	Division	Category	Data source
Energy sector	Energy industries	Electricity and heat production industries (EHP)	Energy consumption is from power plant or industrial organizations
		Petroleum refining (PR)	
		Manufacturer of solid fuels and other Energy industries (SFOEI)	
	Manufacturing industries	Iron and steel (IS)	
		Non-ferrous metals (NFM)	
		Chemicals	
		Pulp, paper, and print (PPP)	
		Food processing, beverages, and tobacco (FPBT)	
		Non-metallic minerals (NMM)	
		Transport equipment (TE)	
		Machinery	
		Wood and wood products (WWP)	
		Textile and leather (TL)	
		Non-specified industry (NSI)	
	Other sub-sectors	Commercial	Energy consumption is from domestic sources
		Residential	
Industrial processes	Mineral industry	Cement production	The volume of production is from industrial organizations
		Lime production	
		Glass production	
	Chemical industry	Ammonia production	
		Nitric acid production	
		Adipic acid production	
		Glyoxylic acid production	
		Petrochemical and carbon black production	
	Metal industry	Iron and steel production	
		Ferroalloys production	
		Aluminum production	

top three categories (i.e., the electricity and heat production industries, iron and steel industries, and petroleum refining industries) were responsible for 79.31% of the total carbon emissions from the energy sector. In the industrial processes sector, iron and steel production, petrochemicals, and carbon black were responsible for over 95% of total carbon emissions (Table 6).

3.1 The energy sector

The primary carbon emission sources in the energy sector include those from industrial (i.e., industrial enterprises) and domestic use (IPCC, 2006).

3.1.1 Industrial sources

Industrial enterprises were found to be the primary contributors in the carbon emission inventory for Shanghai. Energy-related emissions were 53%, 27%, 4%, and 4% of total emissions associated with the consumption of raw coal, washed coal, fuel oil, and coke, respectively (Fig. 2). Over half of the total emissions were produced by coal-consuming industry enterprises. These statistics demonstrate that coal is the dominant energy source for industries in Shanghai. In Fig. 2, 'others' represents the energies of liquefied petroleum gases, coke oven gas, briquette, crude oil, kerosene, other washed coal, and natural gas liquids.

Carbon emissions from different industrial organizations and enterprises in Shanghai in 2007 are presented in Fig. 3. The top four emitters are the electricity and heat production industries, the iron and steel industries, the petroleum refining industries, the manufacturers of solid fuels, and other energy industries. These four industry categories were responsible for nearly 90% of total emissions. Figure 3 also shows that over 90% of emissions produced by the electricity and heat production industries were from raw coal consumption. The emissions produced by iron and steel enterprises through consuming washed coal exceeded

Table 3 Average net calorific value, carbon oxidation rate of fuels in China.

Fuel type	Net calorific value/($GJ \cdot ton^{-1}$) [b)]	Carbon oxidation rate/%
Raw coal	20.91	89.00 [c)]
Washed coal	26.34	89.00 [c)]
Other washed coal	8.36	89.00 [c)]
Briquette	26.38	90.00 [e)]
Coke	28.44	92.80 [e)]
Coke oven gas [a)]	17.35	99.50 [d)]
Blast furnace gas [a)]	3.76	99.50 [d)]
Natural gas [a)]	38.93 [e)]	99.00 [e)]
Natural gas liquids	4.18×10^{-6} [e)]	99.00 [e)]
Liquefied petroleum gases	50.18	98.90 [e)]
Refinery gas	46.06	98.90 [e)]
Crude oil	41.82	97.90 [e)]
Gasoline	43.07	98.00 [e)]
Kerosene	43.07	98.00 [e)]
Diesel oil	42.65	98.20 [e)]
Fuel oil	41.82	98.50 [e)]
Other	29.31 [f)]	95.95 [f)]

a) The fuel is gas state, and the unit is $GJ/(10^4\ m^3)$. b) Source: GPCC, 2008. c) Source: Cai et al., 2009. d) Source: IPCC, 2006. e) Source: NGGI, 2007. f) The value is the average of all fuels.

Table 4 Description of the source types, calculations, and emission factors in the industrial processes sector

Source category	Calculation	Sources of emission factor
Cement production	The CO_2 emissions = Cl × EF, where Cl presents the mass of clinker produced, tons; EF is the emission factor from raw materials during clinker production process, tons CO_2/ tons clinker	(IPCC, 2006; Wang, 2006; Cui and Liu, 2008) According to the investigations, $EF_{clinker}$ uses the value of 0.55
Lime production	The CO_2 emissions = Lp× EF, where Lp means the mass of lime produced, tons; EF is the mission factor of lime production process, tons CO_2/ tons lime	(PGGGI, 2011)
Glass production, ammonia production, nitric acid production, adipic acid production, glyoxylic acid production, petrochemical and carbon black production, iron and steel production, ferroalloys production, aluminum production	Tier 1 approach, Volume 3, IPCC (2006) The emissions = Pro × EF, where Pro is the mass of production, EF is the emission factor of specific production	(IPCC, 2006)

70% of their total emissions. The top four emission fuels in the petroleum refining industries were raw coal, refinery gas, other fuel, and fuel oil, which together contributed over 95% of the industries' total carbon emissions. In the manufacturing of solid fuels and other energy industries, washed coal and raw coal were the two main carbon emission contributors, responsible for over 80% of total carbon emissions.

Carbon emission intensities for energy use and per-monetary-unit production are the two main indicators for weighing the low carbon development level of an industry. Energy consumption data for the energy sector (Table 7) is measured using standard coal equivalent (tce) units (GPCC, 2008). In Table 7, the carbon emission intensity for the energy use of 14 categories in the energy sector ranges from 1.78 to 2.58 tCO_2e/tce. The three categories with the lowest efficiencies of energy use are the electricity and heat production industries, iron and steel industries, and manufacturers of solid fuels, and other energy industries, with energy intensities of (2.58, 2.50, and

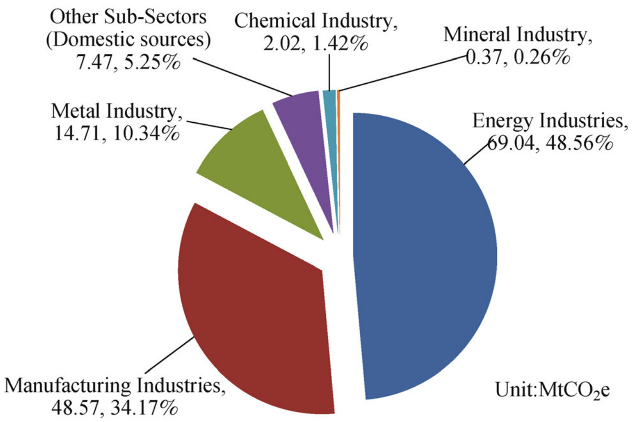


Fig. 1 Carbon emissions inventory in Shanghai 2007.

Table 5 Carbon emissions share in each category in the energy sector

Category	Carbon emissions	
	kt CO_2e	% of total
Main activity electricity and heat production	52,282.08	41.80
Iron and steel industries	36,035.33	28.81
Petroleum refining	10,881.78	8.70
Manufacture of solid fuels and other energy industries	5,871.16	4.69
Residential *	5,194.64	4.15
Machinery	2,523.92	2.02
Non-metallic minerals	2,425.28	1.94
Chemicals	2,352.62	1.88
Commercial *	2,270.54	1.82
Textile and leather	1,631.14	1.30
Non-specified industry	887.97	0.71
Pulp, paper and print	813.52	0.65
Food processing, beverages and tobacco	786.46	0.63
Transport equipment	623.84	0.50
Non-ferrous metals	331.89	0.27
Wood and wood products	161.34	0.13
Total	125,073.51	100

* Sources are from domestic sources.

2.40) tCO_2e/tce, respectively. The three categories with the highest efficiencies of energy use include manufacturers of wood and wood products, petroleum refineries, and transport equipment, with energy intensities of (1.78, 1.88, and 1.98) tCO_2e/tce, respectively. The carbon intensity for per-monetary-unit production varies considerably between industries within the energy sector, ranging from 0.02 to 12.57 $tCO_2e/(10^4$ CNY) (Table 7). The three industry categories with the highest carbon intensity per monetary unit production are the electricity and heat

Table 6 Carbon emissions share in each category in industrial processes

Category	Carbon emissions	
	kt CO_2e	% of total
Iron and steel production	14,699.07	86.00
Petrochemical and carbon black production	1,888.29	11.05
Cement production	223.67	1.31
Lime production	121.40	0.71
Nitric acid production	64.18	0.38
Ammonia production	33.39	0.20
Glyoxylic acid production	32.78	0.19
Glass production	21.98	0.13
Aluminium production	6.43	0.04
Ferroalloys production	1.30	0.01
Total	17,092.48	100

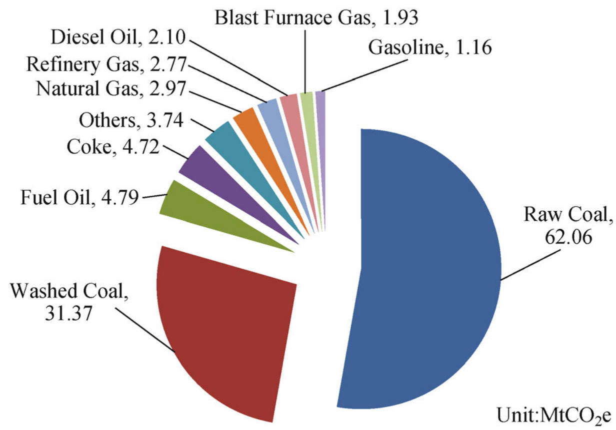
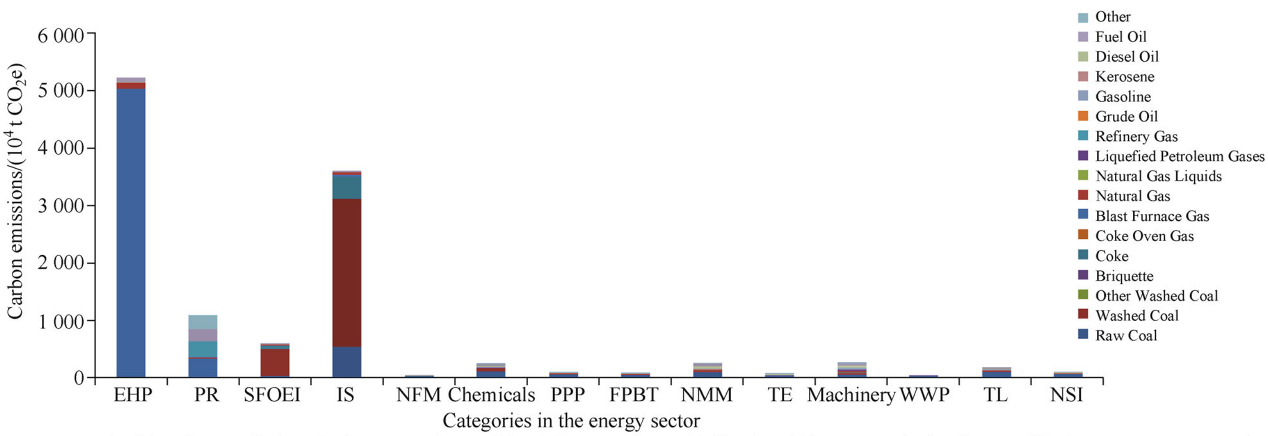


Fig. 2 Carbon emissions from different industrial sources in Shanghai in 2007.

production industries, manufacturers of solid fuels, other energy industries, and iron and steel industries, measuring (12.57, 6.32, and 2.21) $tCO_2e/(10^4$ CNY), respectively. The three industries with the lowest carbon emission intensity, calculated on a per-monetary-unit of production basis, are transport equipment, machinery, and non-specified industry, measuring (0.02, 0.02, and 0.06) $tCO_2e/(10^4$ CNY), respectively. Thus, the transport equipment and machinery industries are more energy efficient with the lowest carbon emission intensity, calculated on a per-monetary-unit basis, likely due to the fact that they are technology-intensive industries. The output value of transport equipment and machinery is the highest among all industries, but their energy consumption is lower than other industries (Table 7). The electricity and heat production industries, iron and steel industries, manufacturers of solid fuels, and other energy industries are energy-intensive. Energy consumption in these industries is thus



EHP—Electricity and Heat Production Industries; PR—Petroleum Refining; SFOEI—Manufacture of Solid Fuels and Other Energy Industries; IS—Iron and Steel; NFM—Non-Ferrous Metal; PPP—Pulp,Paper and Print; FPBT—Food Processing,Beverages and Tobacco; NMM—Non-Metallic Minerals; TE—Transport Equipment; WWP—Wood and Wood Products; TL—Textile and Leather; NSI—Non-specified Industry

Fig. 3 Industrial carbon emissions from different categories of the energy sector in Shanghai in 2007.

Table 7 Carbon emission intensities in different industries in the energy sector

Categories	Carbon emission intensity			
	Energy consumption/tce	Carbon emission intensity for energy use/($tCO_2e \cdot tce^{-1}$)	Gross output value of industry /(10^4 CNY)	Carbon emission intensity for per monetary unit production /($tCO_2e \cdot (10^4\ CNY)^{-1}$)
EHP	20,254,129.74	2.58	4,160,458.87	12.57
PR	33,986,805.50	1.88	11,309,064.10	0.96
SFOEI	3,276,515.22	2.40	929,160.81	6.32
IS	14,396,973.88	2.50	16,270,246.78	2.21
NFM	144,128.48	2.30	3,722,604.11	0.09
Chemicals	1,931,688.06	2.18	17,482,446.63	0.13
PPP	373,485.35	2.18	4,098,920.71	0.20
FPBT	339,663.56	2.32	8,826,304.91	0.09
NMM	1,108,496.33	2.19	5,628,021.20	0.43
TE	314,561.72	1.98	25,568,229.33	0.02
Machinery	1,177,940.39	2.14	104,504,285.98	0.02
WWP	90,684.59	1.78	1,215,820.29	0.13
TL	707,114.02	2.31	9,679,227.47	0.17
NSI	431,174.41	2.06	15,001,159.32	0.06
Average	——	2.20	——	1.67

higher; and moreover, they are lowest in energy efficiency and are the highest carbon emitters per monetary unit of production.

3.1.2 Domestic sources

Domestic energy sources include those from commercial and residential use. We classified fuels into the three types of domestic use: coal (e.g., raw, washed, coke), gas (e.g., natural gas), and oil (e.g., crude, gasoline, and kerosene).

There were 2.27 $MtCO_2e$ and 5.19 $MtCO_2e$ emissions from commercial and residential sources in Shanghai in 2007, which comprised 30.42% and 69.58% of total emissions, respectively (Fig. 4). The consumption structure by domestic sources is presented in Fig. 5, demonstrating that oil contributed to approximately 72.7% of all carbon emissions from commercial sources. For residential sources, the major emission contributor was gas consumption, accounting for 93.7% of all emissions.

3.2 Industrial processes

Total carbon emissions from the industrial processes sector were 17.09 $MtCO_2e$, which comprised only 12.7% of the

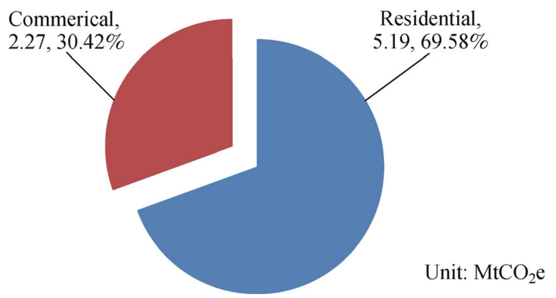


Fig. 4 Carbon emissions from domestic sources in Shanghai in 2007.

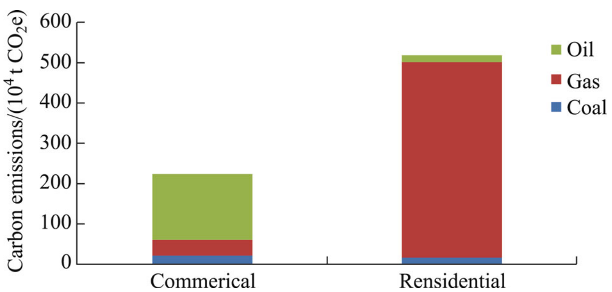


Fig. 5 Carbon emissions from fuels in domestic sources in Shanghai in 2007.

total industrial emissions in Shanghai in 2007. Iron and steel production was responsible for 86% of all carbon emissions in the industrial processes sector (Fig. 6). The petrochemical and carbon black industry and the cement production industry were responsible for 11.05% and 1.31% of all carbon emissions, respectively. In Fig. 6, 'others' represents the production of nitric acid, ammonia, glyoxylic acid, glass, aluminum, and ferroalloy.

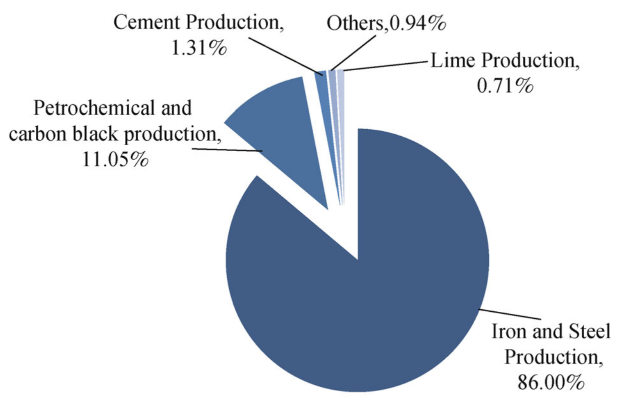


Fig. 6 Carbon emissions in industrial processes in Shanghai, 2007.

3.3 Emission attribution to districts and counties in Shanghai

Figure 7 shows that Baoshan District was the largest emitter of the 19 districts and counties, contributing approximately 50% of Shanghai's total carbon emissions, and dominated by industrial sources (Fig. 8). Carbon emissions were highest in the Shanghai districts with the greatest concentrations of energy-intensity industries (such as Baoshan District and Jinshan District). Baoshan District had the largest concentration of iron and steel industries, whereas the petrochemical industry was predominant in the Jinshan District.

Figures 7 and 8 show that the highest proportion of carbon emissions and greater stationary emission points were mainly generated by industrial enterprises, mainly located in the suburban area of Shanghai. Emissions from central areas of Shanghai (i.e., Yangpu, Hongkou, Zhabei, Putuo, Changning, Jing'an, Huangpu, Luwan, Xuhui Districts) were much lower than those from suburban areas. Residential and commercial sources were the main producers of carbon emissions in Shanghai's central areas. The proportion of carbon emissions from commercial sources was greater in the Luwan, Jing'an, and Changning Districts (Fig. 8) than in the other districts. Thus, the total stationary carbon emissions were lowest in the three named districts (Fig. 7).

In summary, the results contributed through the bottom-up approach input data from the SPSC demonstrate that the emission contribution from the energy sector was far greater than that from the industrial processes sector in Shanghai in 2007. In the energy sector, more carbon emissions originated from industrial energy-related sources than from domestic sources. The top four carbon-emitting categories in the energy sector were the electricity and heat production industries, the iron and steel industries, the petroleum refining industries, manufacturers of solid fuels, and other energy industries. Iron and steel production was the main emitter in the industrial processes sector. Coal was the dominant fuel and was the major carbon emitter in the energy sector. Thus, Baoshan District was the largest contributor of carbon emissions in Shanghai.

3.4 Analysis of different results made by inventories

At this juncture, we will compare our results with the results from other published papers. Table 8 presents the results of four inventories using different methods and data sources, how they are associated, and how selected methods are determined by data sources. The top-down method adopts energy supply data from national statistical yearbooks and has no detailed information regarding individual fuel consumption for each sector. Conversely, the bottom-up approach provides detailed data for the various fuels used in all sectors, which is a variable related to methods and data sources and is also addressed by the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). For instance, the missing information regarding fuel stock changes for final consumers may

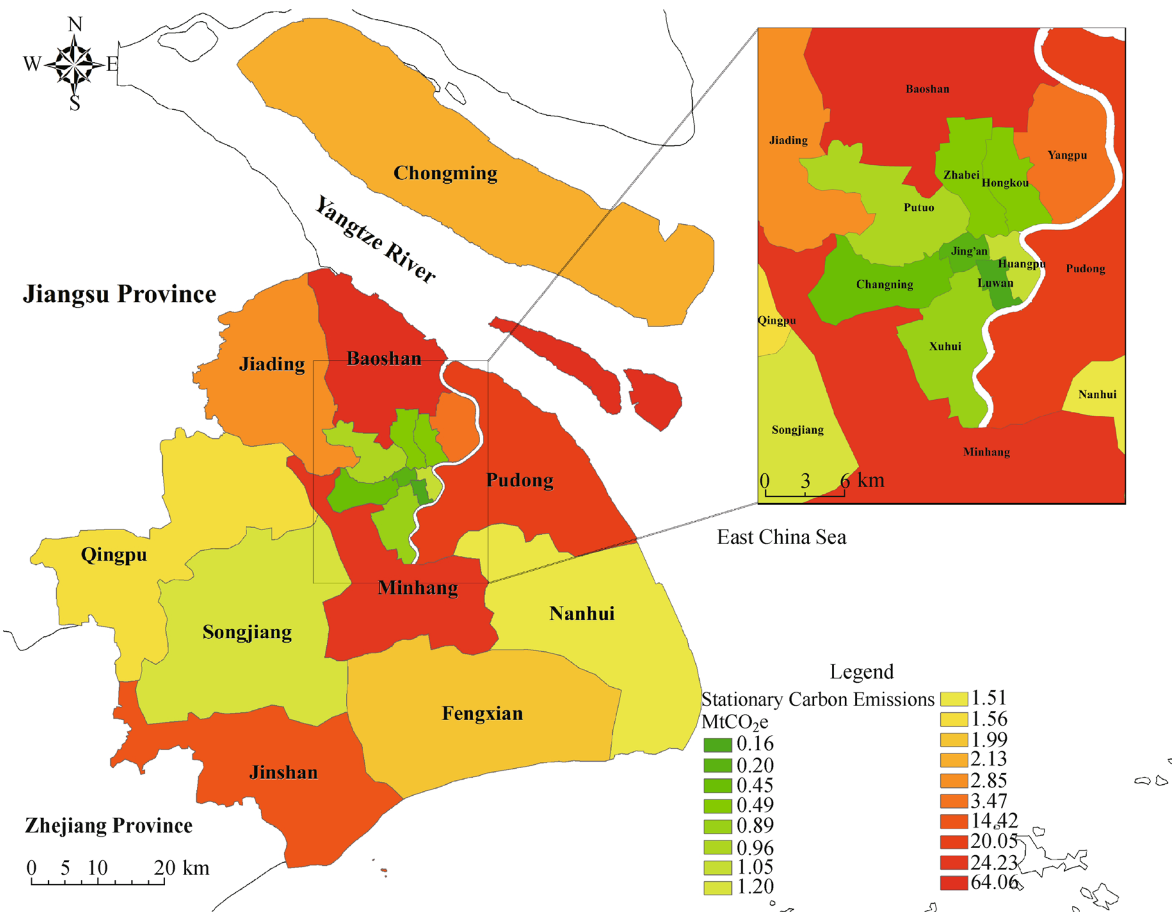


Fig. 7 Stationary carbon emissions in districts and counties of Shanghai in 2007.

lead to different estimations under different approaches and methods.

Thus, one of the main reasons for obtaining different results regarding the carbon emission inventories presented in Table 8 involves the data source chosen. For example, as discussed above, industrial energy consumption in the Shanghai statistical yearbooks contains only the energy consumption from those industrial enterprises with an individual annual production value of more than 20 million CNY (Yang, 2010). However, SPSC contains data related to the energy use of all industrial enterprises in Shanghai. Section 4.1 below provides further discussion regarding the different results for inventories calculated with traditional statistical data and the pollution source census.

4 Discussion

4.1 Advantages of using the Pollution Source Census

In the relevant Chinese studies, most researchers prefer to source data from the Chinese statistical system (Dhakal, 2009; Li et al., 2009; Liu et al., 2012). However, using statistical data published by Chinese statistic departments at the national and/or local levels involves constraints in terms of generating carbon inventories for several reasons (Bi et al., 2011; Guan et al., 2012; Wang et al., 2013).

First, the existing statistical system has limitations. An analysis of national and provincial statistical yearbooks reveals that the method of data collection and analysis adopted in the statistic indicator system changes frequently, which causes data sources from the statistical yearbooks to be unstable and invalid. For instance, information concerning energy consumption is absent in the 2007–2010 Shanghai statistical yearbook. The National Bureau of Statistics has developed a basic framework for statistical yearbooks, but this framework is not sufficiently precise to be implemented effectively for many purposes. Therefore, there are differences in the results in the statistical yearbooks at the national and local levels in China because of the unsound framework. These differences might result in difficulties with assessing and comparing the carbon emissions of different provinces and cities.

Second, using statistical yearbooks to compile carbon emission inventories might lead to several problems in calculating results because of inaccurate data sources. For example, Wang et al. (2013) noted that the assessment

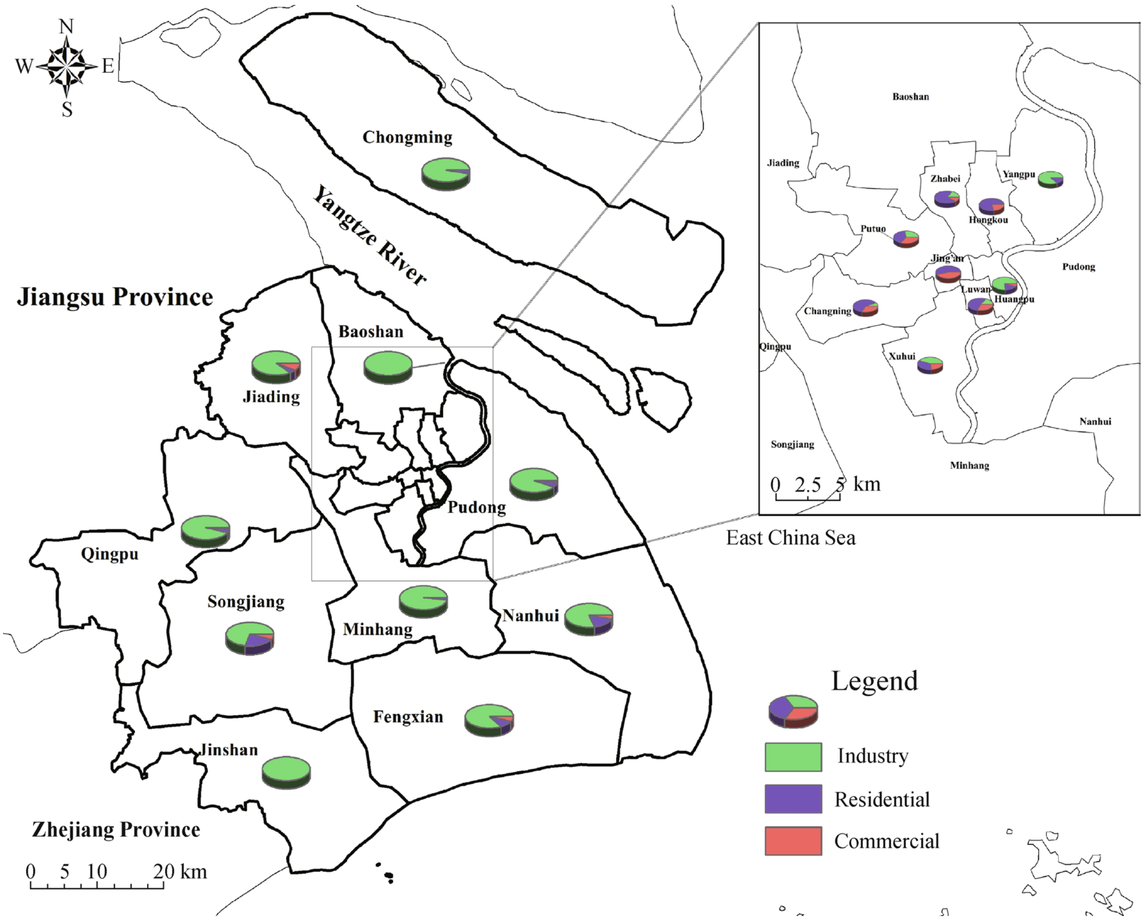


Fig. 8 Structure of carbon emissions in districts and counties for Shanghai in 2007.

Table 8 Results of carbon emission inventories in different studies

Literature	Data source	Method	Stationary energy-related carbon emission
Liu et al. (2012)	Chinese Energy Statistics Year Book	Top-down	175 $MtCO_2e$ (2007)
Wang et al. (2013)	Shanghai Statistical Yearbook, China Industry Economy Statistical Yearbook	Bottom-up	160 $MtCO_2e$ (2007)
This study	SPSC	Bottom-up	125 $MtCO_2e$ (2007)
Li et al. (2010)[a)]	Shanghai Statistical Yearbook	Bottom-up	68 $MtCO_2$ (2007)

a) This inventory only consider CO_2.

method and classification system for fuel data in China's statistical yearbooks are different from the method and system that were issued by the IPCC. The fuel types in China's statistical yearbooks are raw coal, cleaned coal, other cleaned coal, briquette, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, coke oven gas, refinery gas, and natural gas. The fuel types in the IPCC are anthracite, coking coal, lignite, bituminous coal, brown coal, crude oil, motor gasoline, aviation gasoline, aviation kerosene, diesel oil, heavy oil, bitumen, coal gas, coke oven gas, blast furnace gas, and natural gas (Wang et al., 2013). Furthermore, under China's current statistical systems, key data used in carbon emission inventories are often absent or incomplete (Bi et al., 2011; Wang et al., 2013). Guan et al. (2012) found that the issued data on coal consumption varied between the national and provincial statistics under the current Chinese government energy statistic systems. For example, in 2010, the amount of total raw coal consumption from the national energy balance sheet was 3,163 Mt, whereas the aggregated figure in the provincial sheets was 3,910 Mt (Guan et al., 2012).

All the problems and constraints listed above are likely to increase the unreliability and invalidity of carbon emission inventories generated using input data from China's statistical yearbooks.

Based on a data analysis for calculating the carbon emission inventory, the data collected from the SPSC have the following features that distinguish them from the data from the statistical yearbooks:

• The data from the CPSC have a uniform statistical caliber. Compared with the weaknesses described above in the process of statistical data collection and analysis, the process of obtaining and handling pollution data is more accurate and stable in the CPSC than in the statistical yearbooks. The carbon emission inventory generated using CPSC allows for a sound comparison of carbon emissions between different provinces and cities.

• The records of pollution source census data are integrated and complete. For example, detailed data are available for the pollution sources in the industry category, which includes raw materials, energy types, energy consumption, and products. All data have been recorded and reported regularly by industrial enterprises under the policy. Compared with the statistical yearbooks, the more detailed data from the industrial pollution sources might allow for the development of a sophisticated method for estimating carbon emissions.

• Since every enterprise has detailed records of energy-related pollution data, it is possible to clearly identify the fuels and raw materials. For example, end-use energy consumption contains two categories, "fuel consumption" and "raw materials consumption," which are identified by the pollution source census, but are not clearly separated in the statistical yearbooks.

Due to the standardized and accurate method of data collection and analysis in the pollution source census, use of census data for the carbon emission inventory would likely provide more reliable and valid results than those inventories produced based on data from the statistical yearbooks. The inventories compiled with pollution source census can also be used to compare carbon emissions between regions.

Although the data from the pollution source census have some advantages over the statistical yearbooks, some potential constraints in the data collection and analysis methods of the pollution source census might influence the process of generating a carbon emission inventory. For instance, in the industrial processes sector, we use the amount of production for activity data in our method, but production names are not standardized in the pollution source census. One type of production might have different names, which makes it difficult to estimate carbon emissions from the industrial processes sector. Therefore, the only way to overcome the potential disadvantages of using data from the pollution source census is to standardize data collection and analysis in future pollution source censuses.

Due to the unresolved constraints of adopting data from the pollution source census, the data from the statistical yearbooks might still be a good supplement for calculating integrated carbon emission inventories in Chinese cities. For instance, energy-related carbon emissions might be assessed by activity data from the pollution source census, and the carbon emissions from the industrial processes, agricultural, and transportation sectors might be assessed by activity data from the statistical yearbooks.

4.2 Policy recommendations

In 2007, the proportion of Shanghai industry added value and tertiary industry added value was 43.5% and 52.6%, respectively. Notably, Shanghai is focusing on the development of tertiary industries, which is conducive to reducing total carbon emissions.

However, industrial sources are the primary emission contributors in Shanghai (Fig. 1), and the reduction of industrial carbon emission remains an important task for the Shanghai government. By utilizing the findings of this study, we can make several policy recommendations that aim to reduce industrial carbon emissions.

4.2.1 Optimize the industrial structure

The Shanghai government is focused on the development of six priority industries: electronics and information products manufacturing, automotive manufacturing, petrochemical manufacturing, steel, equipment manufacturing, and bio-medical. These six priority industries correspond to the following carbon emissions-producing industries in this inventory: petroleum refining, chemicals, iron and steel, transport equipment, and machinery. The machinery and transport equipment industries are the main contributors to Shanghai's industrial GDP (at 57%), and the carbon intensities per monetary unit production for both are 0.02 $tCO_2e/10^4$ CNY. Moreover, these industries have the lowest carbon emission per unit of production because they are technology-intensive (Table 8). The iron and steel industries and the petroleum refining industry contribute 12% of Shanghai's industrial GDP (Table 8) and produce 38% of the energy-related carbon emissions in the energy sector (Table 5). Compared with other industries, the iron and steel and the petroleum refining industries have higher carbon emission intensities — as calculated on a per-monetary-unit of production basis — due to their energy-intensity industries (Table 8). To reduce carbon emissions, Shanghai's policy makers should promote the development of industries with low carbon intensity, calculated on a per-monetary-unit of production basis (i.e., machine industry), and phase out energy-intensive industries (i.e., iron and steel and petroleum refineries).

4.2.2 Optimize the energy structure

In the iron and steel industry, carbon emissions are dominated by the consumption of raw and washed coal (Fig. 3), and the carbon emission intensity for energy use is 2.50 tCO_2e/tce (Table 8). In the petroleum refining industry, carbon emissions are dominated by the consumption of raw coal, refinery gas, and fuel oil (Fig. 3), and the carbon emission intensity for energy use is 1.88 tCO_2e/tce (Table 8). Compared with the iron and steel industry's coal-dominated energy structure, the petroleum refining industry's energy structure is diversified. Therefore, the petroleum refining industry has lower carbon emission intensity for energy use than the iron and steel industry. For energy-intensive industries, the energy structure should be optimized to reduce carbon emissions, which indicates that the coal-dominated energy structure should be gradually transformed into an oil-dominated or gas-dominated energy structure.

4.2.3 Improve energy efficiency

Policy makers might also encourage technological innovation for energy-intensive industries to reduce their carbon emission intensity, calculated on a per-monetary-unit production basis, and then increase their adjustment of the energy structure to reduce carbon emissions per unit of standard coal. Carbon trading, which began in 2013 in Shanghai, is an important way to encourage enterprises to effectively improve their energy efficiency and carbon reduction technologies. The current scheme contains 197 enterprises, covering the iron and steel, chemical, electricity, non-ferrous metal, building material, textile, paper, rubber, and chemical fiber industries. These enterprises all operate in energy-intensive industries. According to the results of this study, the carbon emission intensity for the energy use level of the food processing, beverage, and tobacco (FPBT) industries is higher than average. Thus, the FPBT industry should be contained in Shanghai carbon trading to encourage the Shanghai FPBT industry to become more energy efficient and/or to restructure its energy use to reduce carbon emissions (Table 8).

This study also contributes to the monitoring, reporting, and verification (MRV) of the carbon trading system. Compared with those inventories compiled using data from the statistical yearbooks, adopting inventories generated from data derived from the SPSC in the carbon emission trading system has two additional advantages:

1) The information/data of key pollution sources in the SPSC is updated annually. Thus, it is possible to use the inventory compiled with this data to monitor the carbon emissions of key enterprises over time.

2) It is easier to make carbon emission assessments and reports for the carbon trading system by utilizing enterprise-level SPSC data to develop a carbon emission inventory.

In conclusion, using an inventory compiled by the enterprise-level pollution source census is conducive to carbon trading. It is also important for policy makers to use an enterprise-level carbon emission inventory to make sound energy-conservation and carbon-reduction policies. For instance, policy makers might design a new carbon trading scheme or other economic incentive policy to support and encourage industries to adopt low carbon technologies and to improve emissions management.

5 Conclusions

This study used a total of 521,631 data points on pollution sources from the SPSC of 2007 to create a carbon emission inventory. We converted all industry data from the pollution source census into qualified data under the standard classification given by the IPCC according to the CSIC and ISIC. The inventory generated in the study includes 2 sectors, 6 divisions, and 27 categories. According to the inventory, the total carbon emissions in Shanghai were approximately 140 $MtCO_2e$ in 2007, and the energy sector emitted far more GHGs than the industrial processes sector. In the energy sector, the top four categories were the industries for electricity and heat production, iron and steel, petroleum refineries, manufacturers of solid fuels, and other energy industries. Furthermore, emissions from iron and steel production have a significant impact on the entire industrial processes sector. The inventory also indicates that Shanghai's energy consumption is dominated by coal use. According to the results of this carbon emission inventory, the machinery and transport equipment industries' carbon intensities per monetary unit production are both 0.02 $tCO_2e/(10^4$ CNY), which is the lowest level for all industries. The energy-intensive industries have the lowest efficiency of energy use and the highest carbon emissions per monetary unit of production.

Based on the results of this study, we recommend that the Shanghai government develop industries with low carbon emission intensity per monetary unit of production, promote technological innovation, and adjust the energy structure to reduce industrial energy-related carbon emissions. As an important way of reducing carbon emissions, we recommend carbon trading — along with developing carbon emission inventories with pollution source census data — to enhance the carbon trading MRV system. Those industries that are closely connected to consumers, such as FPBT, should be included in the Shanghai carbon trading scheme in the future.

We also compare the advantages and disadvantages between statistical system data and pollution source census data in the study. The data from the current statistical systems have no uniform and/or standardized statistical caliber or data structure between the national and local statistical yearbooks, but do have a good definition of production code for the industrial process sector. By contrast, the pollution source census data have a uniform and standardized statistical caliber and data structure, but lack a good production coding convention in the industrial processes sector. These problems might be avoided by adopting decent and standardized pollution data sources.

Furthermore, the data from the statistical system might be a good supplement for calculating the carbon emissions inventories in Chinese cities, given the current data situation. To develop a sound carbon emission inventory, we may need to adopt mixed data sources by comprehensively considering the statistical data and the pollution source census data in the future.

An integrated inventory should contain emission data from agricultural activities, transport, waste treatment, and carbon sink sectors, which could be collected from the more accurate statistical data or from other sources, such as remote sensing data. This study will be improved by considering these possibilities and opportunities in the future.

China is a developing country with vastly different levels of development in its eastern and western zones. For instance, in comparison with carbon emissions from urbanization, those from agricultural activities accounted for only 11% of total emissions in 2005, according to the Second National Communication on Climate Change of the People's Republic of China. Thus, this paper focuses on carbon emissions in urban areas. As the city with the highest level of urbanization and economic development in China, Shanghai is a good subject for presenting the trajectory of carbon emissions during China's urban development (Wang et al., 2013). According to the results of this study, the main carbon emission contributor is from the industrial sector, as evidenced from the coal-dominated energy structure in Shanghai's industrial sector. All these characteristics in Shanghai's carbon emission inventory are similar to other Chinese cities. For other mega cities in China (i.e., Beijing, Chongqing, Shenzhen, Hangzhou), carbon emission inventories can be compiled using the pollution source census with the aim of optimizing the industrial and energy structures, and improving energy efficiency by reducing carbon emissions and promoting low carbon sustainability.

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Appendix A ISIC and CSIC conversion

Categories		ISIC Rev.3.1	ISIC Rev.4	CSIC 2002
Code	Name	Code	Code	Code
1	Energy			
1A	Fuel combustion activities			
1A1	Energy industries			
1A1a	Electricity and heat production industries			44
1A1b	Petroleum refining			251
1A1c	Manufacture of solid fuels and other energy industries			45, 252, 253
1A2	Manufacturing industries and construction			
1A2a	Iron and steel	Group 271 and Class 2731	241, 2431	32
1A2b	Non-ferrous metals	Group 272 and Class 2732	242, 2432	33
1A2c	Chemicals	Division 24	20, 21	26, 27, 28
1A2d	Pulp, paper and print	Division 21 and 22	17, 18	22, 23
1A2e	Food processing, beverages and tobacco	Divisions 15 and 16	10, 11, 12	13, 14, 15, 16
1A2f	Non-metallic minerals	Includes products such as glass, ceramic, cement, etc., Division 26	23	31
1A2g	Transport equipment	Division 34 and 35	29, 30	37
1A2h	Machinery	Divisions 28, 29, 30, 31, 32	25, 261 – 264, 27, 28	34, 35, 36, 39, 40, 41
1A2i	Mining (excluding fuels) and quarrying	Division 13 and 14		——
1A2j	Wood and wood products	Division 20	16	20
1A2k	Construction	Division 45	F	——
1A2l	Textile and leather	Division 17, 18, 19	13, 14, 15	17, 18, 19
1A2m	Non-specified industry	Division 25, 33, 36,37	22, 265 – 268, 31, 32, 33	21, 24, 29, 30, 42, 43, 46
1A4	Other sectors			
1A4a	Commercial/institutional	Divisions 41,50,51,52,55,63 – 67,70 – 75,80,85,90 – 93 and 99	36, 45, 46, 47, 52, 53, I(55,56), 60, 61, 62, 63, 77, 79, K, L, M, O, P, Q, R, S, U	N, H, 3726, 57 – 59, I, G, L, J, K, M, S, P, Q, R, O, T
1A4b	Residential	All emissions from fuel combustion in households		
2	Industrial processes and product use			
2A	Mineral industry			25, 31
2B	Chemical industry			26
2C	Metal industry			32, 33