New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors

*Yuli Shan[1], Jianghua Liu[2,i], Zhu Liu[3], Xinwanghao Xu[4], Shuai Shao[2], Peng Wang[5], Dabo Guan[1, 6,]**

[1] Tyndall centre for Climate Change Research, School of International Development, University of East Anglia, Norwich NR4 7TJ, UK

[2] Institute of Finance and Economics Research, School of Urban and Regional Science, Shanghai University of Finance and Economics, Shanghai 200433, China

[3] Applied Physics and Materials Science, California Institute of Technology Resnick Sustainability Institute, Pasadena CA 91125, USA

[4] State Key Laboratory of Urban and Regional Ecology, Research Centre for Eco-Environmental Sciences, Chinese Academy of Sciences, 100085 Beijing, China

[5] Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou, 510640, China

[6] Ministry of Education Key Laboratory for Earth System Modelling, Centre for Earth System Science, Tsinghua University, Beijing 100084, China

[i] Corresponding authors. Email address: liu.jianghua@shufe.edu.cn (Jianghua Liu) and dabo.guan@uea.ac.uk (Dabo Guan).

Abstract

This study employs "apparent energy consumption" approach and updated emissions factors to re-calculate Chinese provincial CO_2 emissions during 2000 to 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 3,160 million tonnes in 2000 to 8,583 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.

Keywords: CO_2 emissions accounting; emissions socioeconomics; energy flows; Chinese provinces

Highlights:

- We calculate the provincial CO_2 emissions in China from 2000 to 2012 based on the "apparent energy consumption" and updated measured emission factors for the first time.

- During 2000 to 2012, 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%)
- Provinces located in the northwest and north had higher per capita CO_2 emissions and emission intensities than the central and southeast coastal regions.

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 1,470 million metric tonnes coal equivalent (tce) in 2000 to 4,260 million metric tce in 2014. The huge amount of energy consumption has led to rapid increase CO_2 emissions recent years (shown in Figure 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 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 Figure 1). In 2011, the lowest estimate was 7,452 million tonnes of CO_2 by the IEA, and the highest estimate was 9,229 million tonnes by the U.S. Energy Information Administration (EIA); the difference between these estimates, 1,777 million tonnes (23.9%), is nearly equal to the total CO_2 emissions of India or Russia [23].

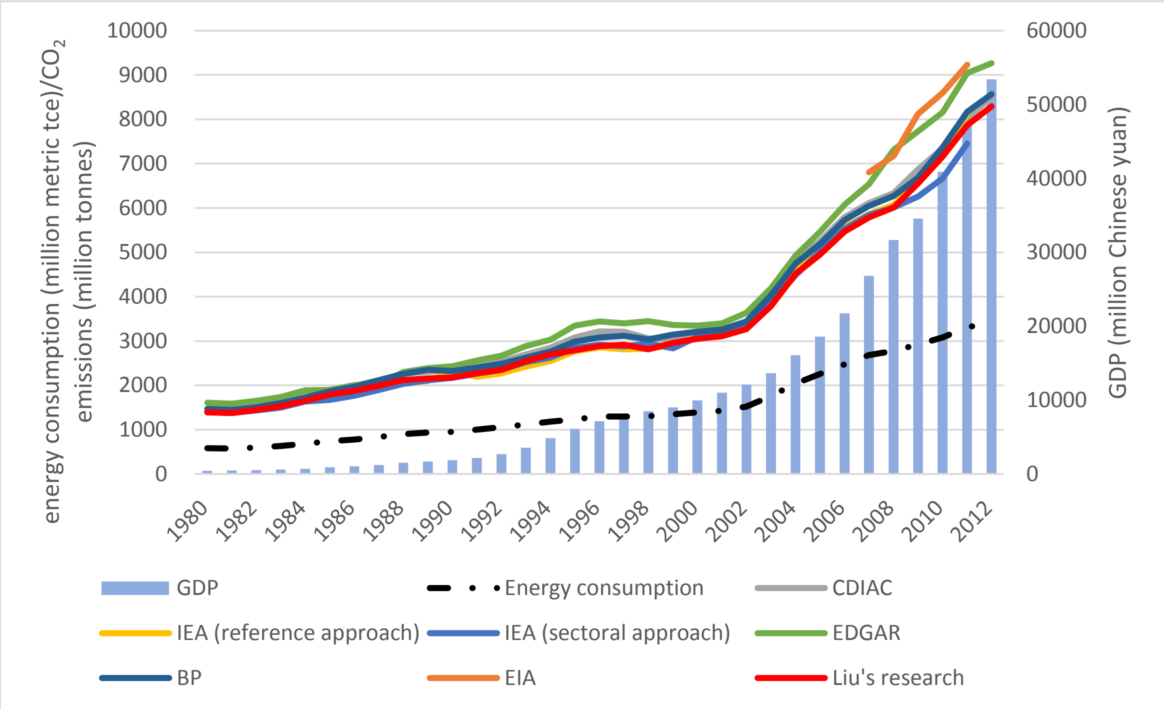

Figure 1. Total energy consumption, GDP and fossil fuel-related CO_2 emissions growth in China, 1980–2012
Data sources: GDP [24], Energy consumption [25], emission estimates by Carbon Dioxide Information Analysis Centre (CDIAC) [26], emission estimates by International Energy Agency (IEA) [27], emission 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].

The uncertainty of China's CO_2 emission estimates mainly come 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, Liu [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 2,368 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 presents a clear emission-socioeconomic features of each provinces. 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 Equation 1,

$$CE_i = AD_i \times EF_i \qquad \text{Equation 1}$$

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 Equation 2.

$$CE = \sum CE_i \qquad \text{Equation 2}$$

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 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 Equation 3.

Apparent 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*

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 (Figure 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.

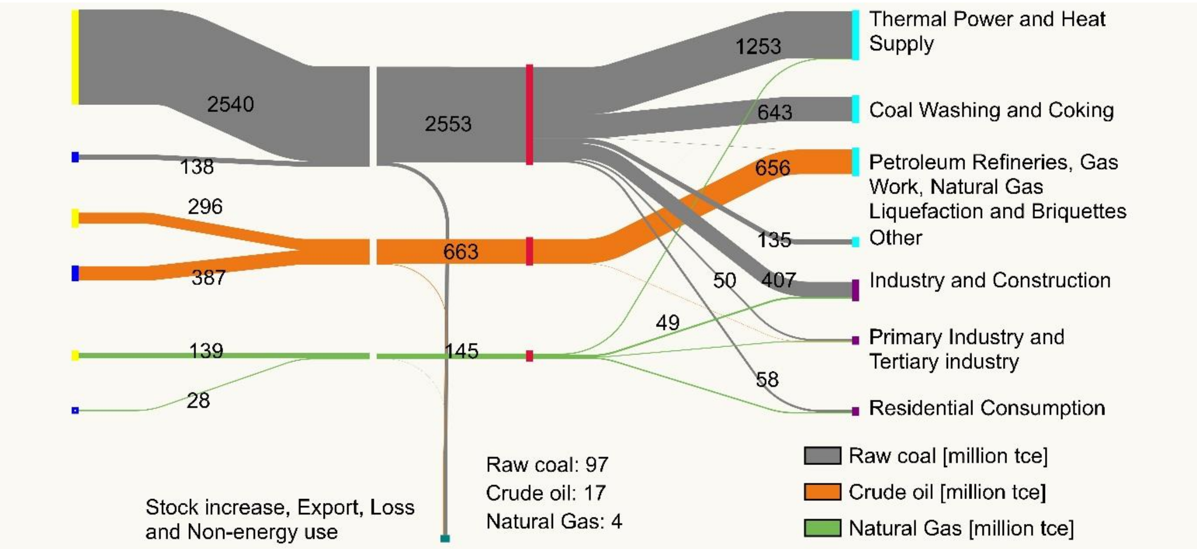

Figure 2. Chinese energy flows, 2012

The red module in Figure 2 is the apparent energy consumption, which totalled 3,361 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 Figure 2, 633 million metric tce). Most primary fossil fuels were transformed into secondary energy types (the aqua module in Figure 2, 2,728 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].

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.

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

3. Results

Figure 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, 7,471 million tonnes (10.35%). The three provinces with the highest cumulative emissions were Liaoning. Hebei and Shanxi, which emitted 4,833 (6.69%), 4,816 (6.67%) and 4,511 (6.25%) million tonnes CO_2, respectively. The data on emissions for all 30 provinces over 2000–2012 are presented in Table 2.

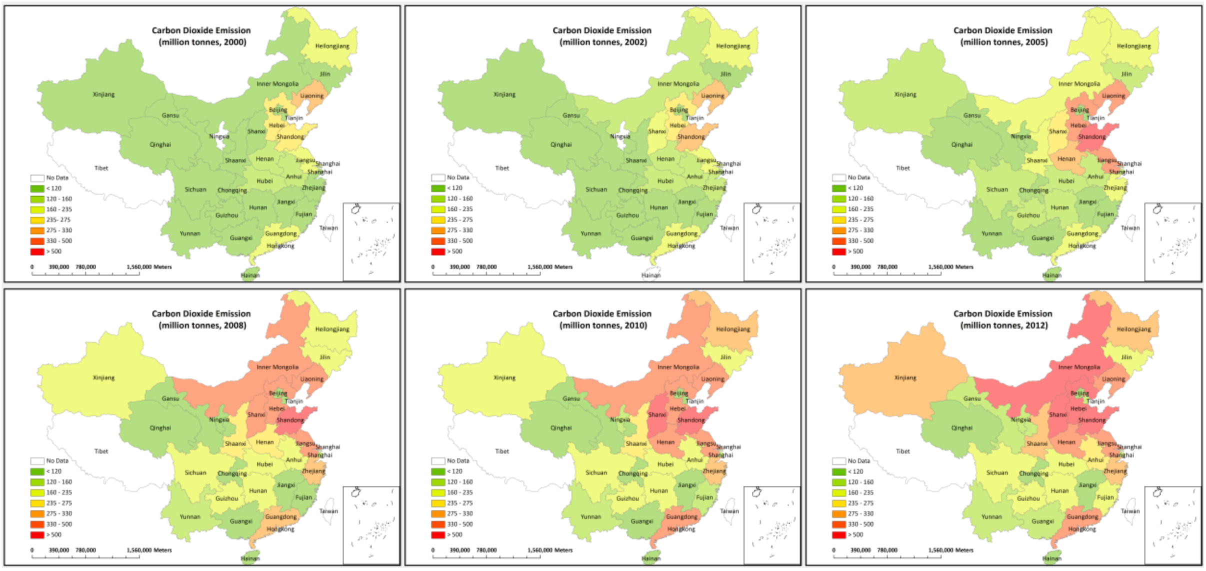

Figure 3. CO_2 emissions from 30 provinces in China

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	3,160.15	3,235.79	3,410.46	3,998.49	4,670.25	5,088.96	5,625.51
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	147.58
Guizhou	147.46	166.28	189.13	192.51	204.88	218.75	153.70
Yunnan	121.39	121.85	130.04	129.85	135.65	140.22	123.65
Shaanxi	208.76	238.30	222.81	248.41	272.63	323.27	173.95
Gansu	110.89	111.21	107.73	119.46	138.05	140.75	102.21
Qinghai	23.19	28.19	29.77	29.30	39.39	45.38	22.64
Ningxia	91.90	94.21	119.06	121.10	151.39	151.99	76.23
Xinjiang	148.17	163.36	190.27	204.53	239.09	276.96	143.29
Province Aggregation	5,968.24	6,203.03	6,791.78	7,333.66	8,135.68	8,582.70	5,625.51

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 Figure 4. Our estimation of provincial aggregate CO_2 emissions (8,583 Mt) are similar to that of CDIAC (8,518) and 7.96 % lower than the highest estimation (EDGAR, 9,266 million tonnes, and are coincident with the national emissions estimated by the same approach (8,342 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.

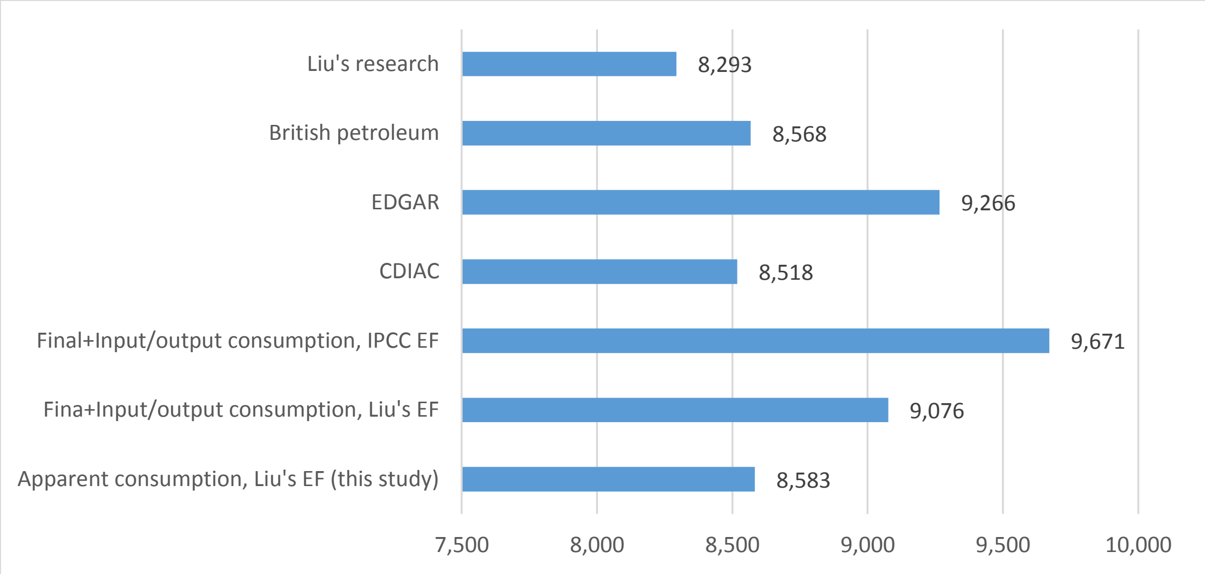

Figure 4. National CO_2 emission comparison of different sources, 2012, million tonnes
Data sources: emission estimates by Liu's research [31], emission estimates by British petroleum [29], emission estimates by EDGAR [28], and emission estimates by CDIAC [26],

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 Figure 4). The gap comes from two parts: 6.94% from the emission factors and 5.75% from activity data with reasons are discussed above.

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

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.

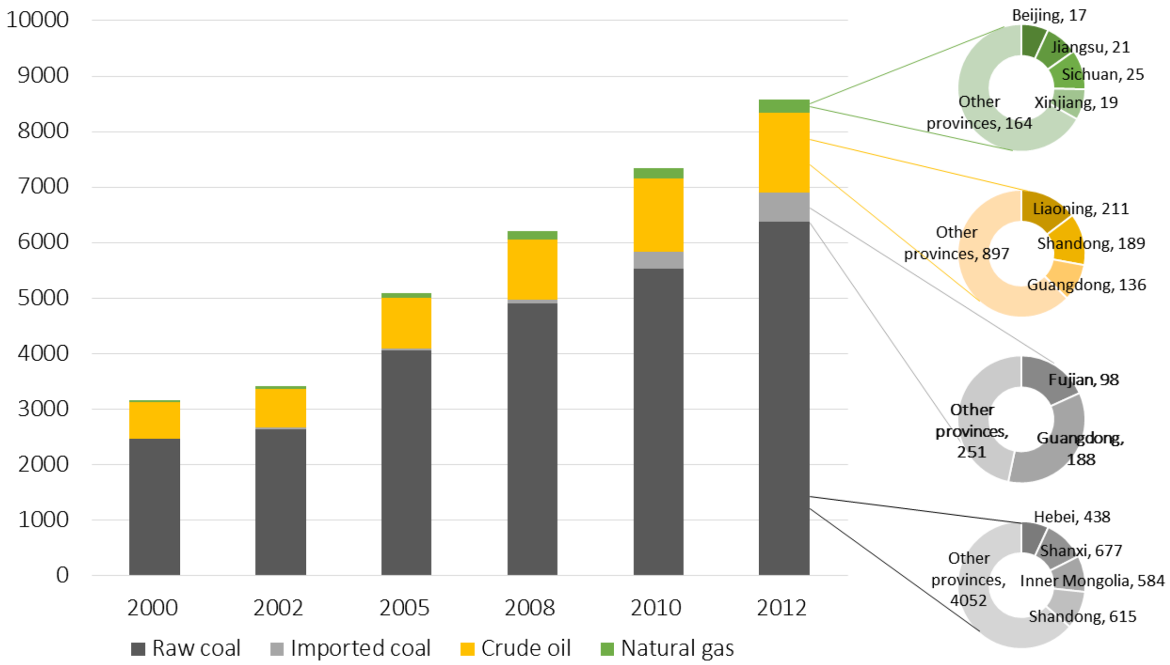

Figure 5. Provincial CO_2 emissions by fossil fuel types, million tonnes

Several provinces that contributed most to emissions of each fossil fuel type in 2012 are presented in Figure 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 Figure 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.

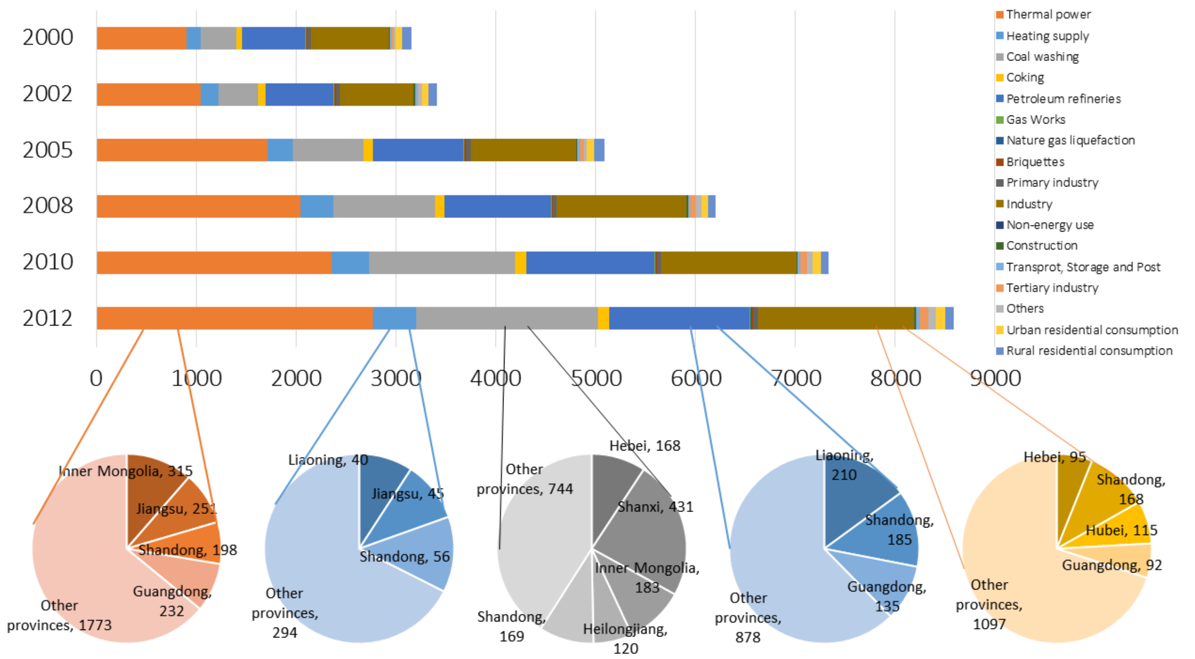

Figure 6. Provincial CO_2 emissions by sectors, million tonnes

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 Figure 7). The calculations and data sources are presented in Table 4.

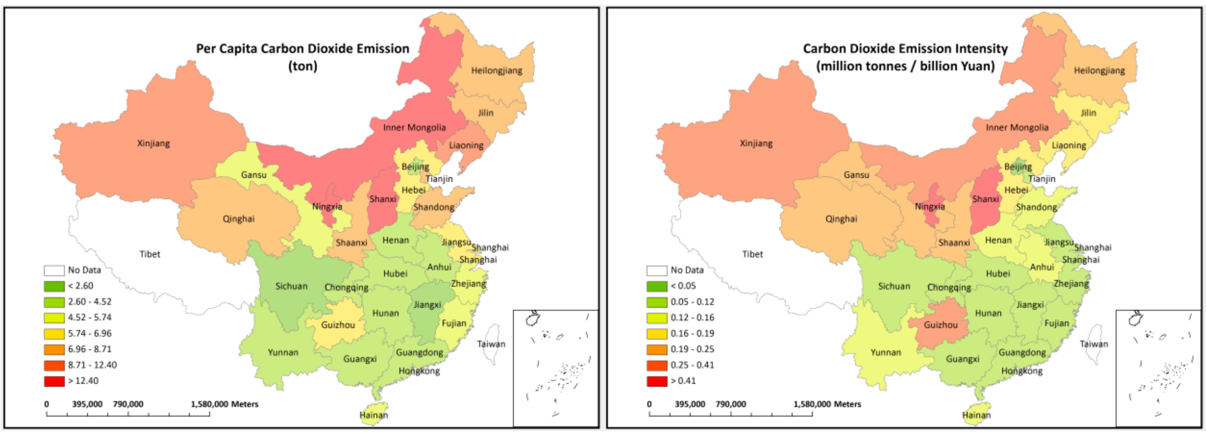

Figure 7. Emission-socioeconomic nexus of China's 30 provinces, 2012

Table 4. Emission socioeconomic indices of 30 provinces, 2012

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	2,069	1.70	4.01	0.46	4.88
Tianjin	123.02	1,289,388	1,413	1.20	8.71	0.95	10.25
Hebei	506.94	2,657,501	7,288	19.00	6.96	1.91	2.67
Shanxi	684.23	1,211,283	3,611	16.00	18.95	5.65	4.28
Inner Mongolia	656.67	1,588,058	2,490	118.00	26.37	4.14	0.56
Liaoning	474.30	2,484,643	4,389	15.00	10.81	1.91	3.16
Jilin	213.63	1,193,924	2,750	19.00	7.77	1.79	1.12
Heilongjiang	326.03	1,369,158	3,834	46.00	8.50	2.38	0.71
Shanghai	154.59	2,018,172	2,380	0.63	6.49	0.77	24.38
Jiangsu	493.63	5,405,822	7,920	10.00	6.23	0.91	4.94
Zhejiang	314.57	3,466,533	5,477	10.00	5.74	0.91	3.15
Anhui	266.08	1,721,205	5,988	14.00	4.44	1.55	1.90
Fujian	203.03	1,970,178	3,748	12.00	5.42	1.03	1.69
Jiangxi	114.79	1,294,888	4,504	17.00	2.55	0.89	0.68
Shandong	816.13	5,001,324	9,685	16.00	8.43	1.63	5.10
Henan	414.84	2,959,931	9,406	17.00	4.41	1.40	2.44
Hubei	234.02	2,225,045	5,779	19.00	4.05	1.05	1.23
Hunan	207.34	2,215,423	6,639	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	4,682	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	2,945	8.20	3.70	0.96	1.33
Sichuan	208.94	2,387,280	8,076	49.00	2.59	0.88	0.43
Guizhou	218.75	685,220	3,484	18.00	6.28	3.19	1.22
Yunnan	140.22	1,030,947	4,659	39.00	3.01	1.36	0.36
Shaanxi	323.27	1,445,368	3,753	21.00	8.61	2.24	1.54
Gansu	140.75	565,020	2,578	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	2,233	166.00	12.40	3.69	0.17
Aggregation/Average	8,582.70	57,585,081	134,481	841.73	6.38	1.49	1.02

Source: China Statistical Yearbook, 2013 [24].

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 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 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 Figure 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.

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 2ºC 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 3,160 million tonnes in 2000 to 8,583 million tonnes in 2012. Our estimates for 2012 are similar to that of CDIAC (8,518) and 7.96 % lower than the highest estimation (EDGAR, 9,266 million tonnes). Of the 30 provinces, Shandong contributed the most to national accumulative CO_2 emissions of the last 13 years (7,471 million tonnes), with an average of 10.35% over 13 years. The following three provinces were Liaoning, Hebei and Shanxi, with cumulative emissions of 4,833 (6.69%), 4,816 (6.67%) and 4,511 (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. While 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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