

17 **Abstract**

18 This study employs “apparent energy consumption” approach and updated emissions factors to re-
19 calculate Chinese provincial CO₂ emissions during 2000 to 2012 to reduce the uncertainty in
20 Chinese CO₂ emission estimates for the first time. The study presents the changing emission-
21 socioeconomic features of each provinces as well. The results indicate that Chinese provincial
22 aggregated CO₂ emissions calculated by the apparent energy consumption and updated emissions
23 factors are coincident with the national emissions estimated by the same approach, which are
24 12.69% smaller than the one calculated by the traditional approach and IPCC default emission
25 factors. The provincial aggregated CO₂ emissions increased from 3,160 million tonnes in 2000 to
26 8,583 million tonnes in 2012. During the period, Shandong province contributed most to national
27 emissions accumulatively (with an average percentage of 10.35%), followed by Liaoning (6.69%),
28 Hebei (6.69%) and Shanxi provinces (6.25%). Most of the CO₂ emissions were from raw coal, which
29 is primarily burned in the thermal power sector. The analyses of per capita emissions and emission
30 intensity in 2012 indicates that provinces located in the northwest and north had higher per capita
31 CO₂ emissions and emission intensities than the central and southeast coastal regions. Understanding
32 the emissions and emission-socioeconomic characteristics of different provinces is critical for
33 developing mitigation strategies.

34

35 **Keywords:** CO₂ emissions accounting; emissions socioeconomics; energy flows; Chinese provinces

36

37 **Highlights:**

38 ➤ We calculate the provincial CO₂ emissions in China from 2000 to 2012 based on the “apparent
39 energy consumption” and updated measured emission factors for the first time.

- 40 ➤ During 2000 to 2012, Shandong province contributed most to national emissions
41 accumulatively (with an average percentage of 10.35%), followed by Liaoning (6.69%), Hebei
42 (6.69%) and Shanxi provinces (6.25%)
- 43 ➤ Provinces located in the northwest and north had higher per capita CO₂ emissions and emission
44 intensities than the central and southeast coastal regions.

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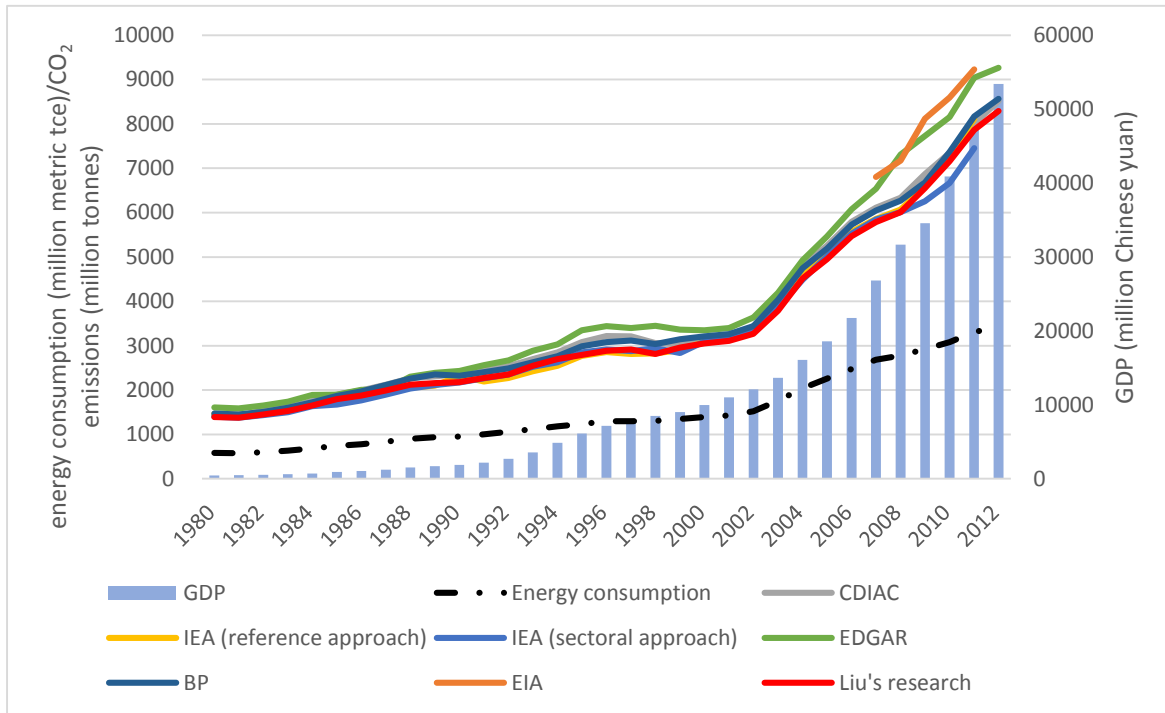
46 **1. Introduction**

47 China's economy has developed rapidly since joining the WTO in 2001. The nation's economy in
48 2014 was almost 4 times of the size of in 2000. According to the latest energy consumption revision
49 by Chinese Statistics Bureau, China's total energy consumption also increased quickly, from 1,470
50 million metric tonnes coal equivalent (tce) in 2000 to 4,260 million metric tce in 2014. The huge
51 amount of energy consumption has led to rapid increase CO₂ emissions recent years (shown in Figure
52 1).

53 As the World's largest CO₂ emitter, China plays an important role in global climate change mitigation.
54 The global emissions decreased slightly by 2015 for the first time, one of the important reasons
55 behind it is Chinese coal consumption decreasing [1]. Contributing to the global climate change
56 mitigation, China has recently pledged to peak its greenhouse gas emissions ahead of 2030 [2].
57 China's national mitigation targets are expected to be allocated to the sub-administrative region[3, 4].
58 Therefore, it is of great importance to develop accurate and most up to date regional CO₂ emission
59 inventories for China.

60 However, emissions estimated by previous researches [5-18] are generally estimated rather than
61 measured directly. In many circumstances, emissions estimates are relatively uncertain [19, 20]. This
62 uncertainty may originate from the accounting scopes, basic energy statistics, the carbon content of
63 fuel, and other potential sources [21, 22]. These uncertainties have led to a wide range of CO₂
64 emission estimations by different world energy research institutions (see Figure 1). In 2011, the
65 lowest estimate was 7,452 million tonnes of CO₂ by the IEA, and the highest estimate was 9,229

66 million tonnes by the U.S. Energy Information Administration (EIA); the difference between these
 67 estimates, 1,777 million tonnes (23.9%), is nearly equal to the total CO₂ emissions of India or Russia
 68 [23].



69
 70 **Figure 1.** Total energy consumption, GDP and fossil fuel-related CO₂ emissions growth in China, 1980–2012
 71 Data sources: GDP [24], Energy consumption [25], emission estimates by Carbon Dioxide Information Analysis
 72 Centre (CDIAC) [26], emission estimates by International Energy Agency (IEA) [27], emission estimates by
 73 Emission Database for Global Atmospheric Research (EDGAR) [28], emission estimates by British Petroleum
 74 (BP) [29], emission estimates by EIA [30] and emission estimates by Liu’s research [31].
 75
 76

77 The uncertainty of China’s CO₂ emission estimates mainly come from two sources. The first is the
 78 uncertainty of energy statistics. Previous research on China’s CO₂ emissions accounting collected
 79 energy consumption data from China’s national statistics bureau [32-41]. However, there was a 20%
 80 gap between the aggregated energy consumption from 30 provinces and national consumption. Guan,
 81 Liu [42] reported a gap of 1.4 gigatonnes between CO₂ emissions calculated on the basis of two
 82 publicly available official energy datasets for 2010. The gap may be caused by the application of
 83 different statistical standards [43] and misuse of units [25] for different provinces and the whole
 84 nation. The second source of uncertainty is the difference of estimated emission factors. We reviewed
 85 2,368 research articles about China’s carbon emissions on the Web of Science published during 2004-

86 2014, We found that most of the previous researches have collected emission factors from the IPCC
87 or China's National Development and Reform Commission (NDRC), whereas fewer than ten studies
88 (less than 1% of total studies) have adopted emission factors based on experiments and field
89 measurements [44-49]. The study show that emission factors from different sources can differ by as
90 much as 40% [31].

91 In this study we adopt the "apparent energy consumption" and updated emission factors [31] to re-
92 calculate the China's provincial CO₂ emissions from 2000 to 2012 in this study. The new provincial
93 CO₂ emission inventories will help reduce the uncertainty of China's provincial CO₂ emissions and
94 presents a clear emission-socioeconomic features of each provinces. Figuring out the emissions and
95 emission-socioeconomic characteristics of Chinese provinces provide a foundation for both China and
96 global carbon emissions control and industry transfer policy support.

97 The remaining sections of this paper are structured as follows: Section 2 describes the method and
98 underlying database used in this study. Section 3 presents the results of provincial CO₂ estimation and
99 analyses provincial emission-socioeconomic characteristics. Policy implications and conclusions are
100 given in Section 4.

101 **2. Method and data source**

102 In this study, we calculate Chinese provincial CO₂ emissions based on "apparent energy consumption"
103 and updated emission factors. The inventory includes all the fossil fuel related CO₂ emissions induced
104 within the regional boundary.

105 **2.1. CO₂ emissions calculation**

106 In this study, we estimate fossil fuel-related CO₂ emissions by energy types based on the mass balance
107 of carbon [50]. See Equation 1,

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

108 where CE_i are CO₂ emissions from different energy types, AD_i (activity data) are the fossil fuels
109 combusted within the province boundary measured in physical units (metric tonnes of fuel expressed
110 as t fuel), and EF_i are the emission factors for the relevant fossil fuels.

111 By summarizing the emissions from different energy types together, we obtain the total CO₂
112 emissions for one province in Equation 2.

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

113 2.2. Data collection

114 2.2.1. Energy flows and apparent consumption calculations

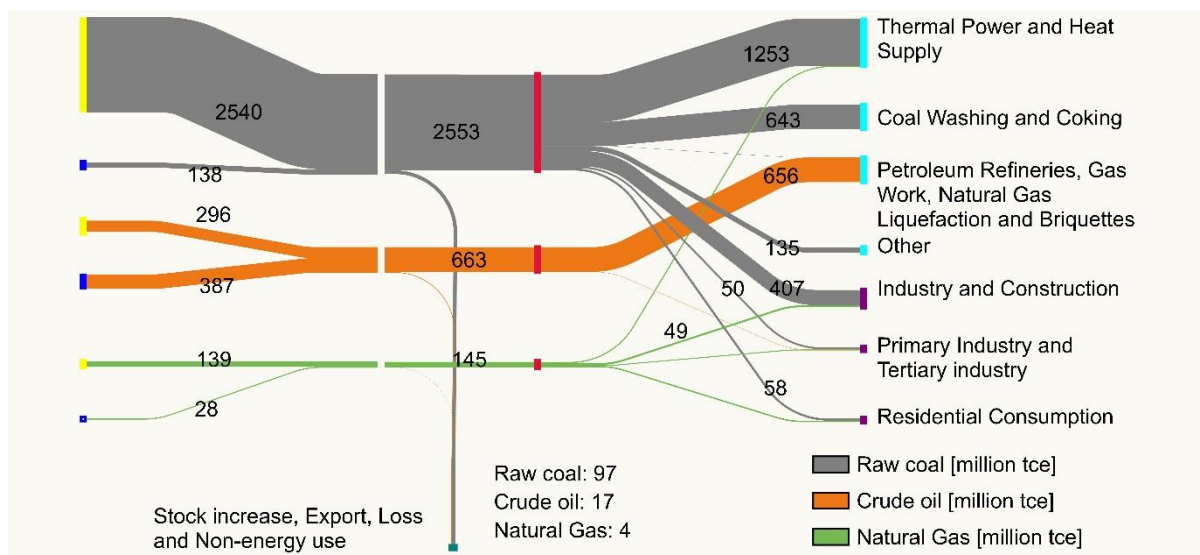
115 In general, the energy consumption of one region can be directly calculated as the final consumption
116 plus input usage of transformation, named “final and input/output consumption”. Otherwise, it can
117 also be estimated based on the mass balance of energy, the so-called “apparent energy consumption”
118 estimation [22, 31, 51]. The apparent energy consumption is the mass balance of fuels produced
119 domestically for energy production, trade, international fuelling and change in stock, see Equation 3.

$$\begin{aligned} \text{Apparent fossil fuel consumption} = & \text{indigenous production} + \text{imports} - \text{exports} + \\ & \text{moving in from other provinces} - \text{sending out to other provinces} \pm \text{stock change} - \\ & \text{non-energy use} - \text{loss} \end{aligned} \quad \text{Equation 3}$$

120 Technically, we will get the equal number of energy consumption via “final and input/output
121 consumption” and “apparent energy consumption” approaches. However, due to statistic error and
122 poor quality in China’s energy statistic, there are around 5% difference between the two consumption
123 [52]. Energy consumption calculated from production-side (apparent energy consumption) is
124 approved to be more accurate than the one calculated from consumption-side (final and input/output
125 consumption) [31]. There are two reasons. First of all, the apparent energy consumption is calculated
126 based on production and trade statistics. The statistics of fuel production and trade are more reliable
127 and consistent than data of final energy consumption. Especially, coal production and trade data is

128 consistently released earlier than coal consumption data. In addition, the apparent consumption
 129 approach considers only three primary fuel types (raw coal, crude oil and natural gas) in order to
 130 avoid accounting errors due to energy transformation between primary and second energy types (e.g.,
 131 coal washing, coking, and power generation).

132 Taking the national energy utilization in 2012 as an example (Figure 2). Raw coal, crude oil and
 133 natural gas are presented as grey, orange and green lines, respectively. In general, there are two
 134 primary energy sources: indigenous production (shown as the yellow module) and imports (shown as
 135 the blue module). Excluding exports, stock decreases, losses and non-energy use, we obtain the
 136 apparent fossil fuel consumption.



137
 138 **Figure 2.** Chinese energy flows, 2012
 139

140 The red module in Figure 2 is the apparent energy consumption, which totalled 3,361 million metric
 141 tonnes coal equivalent (tce) in 2012. Raw coal was the largest primary energy type used in China
 142 (75.9%), followed by crude oil (19.7%) and natural gas (4.3%). Only a small amount of primary fossil
 143 fuels was used by the final consumption sectors (the purple module in Figure 2, 633 million metric
 144 tce). Most primary fossil fuels were transformed into secondary energy types (the aqua module in
 145 Figure 2, 2,728 million metric tce), such as electricity, heat, cleaned coal, coke and gasoline.
 146 Therefore, the apparent primary fossil fuel consumption includes all energy types consumed within
 147 one regional boundary.

148 Here, we adopt the “apparent energy consumption” to account Chinese provincial CO₂ emissions. The
 149 raw data were collected from each province’s energy balance table [53].

150 *2.2.2. Updated emission factors*

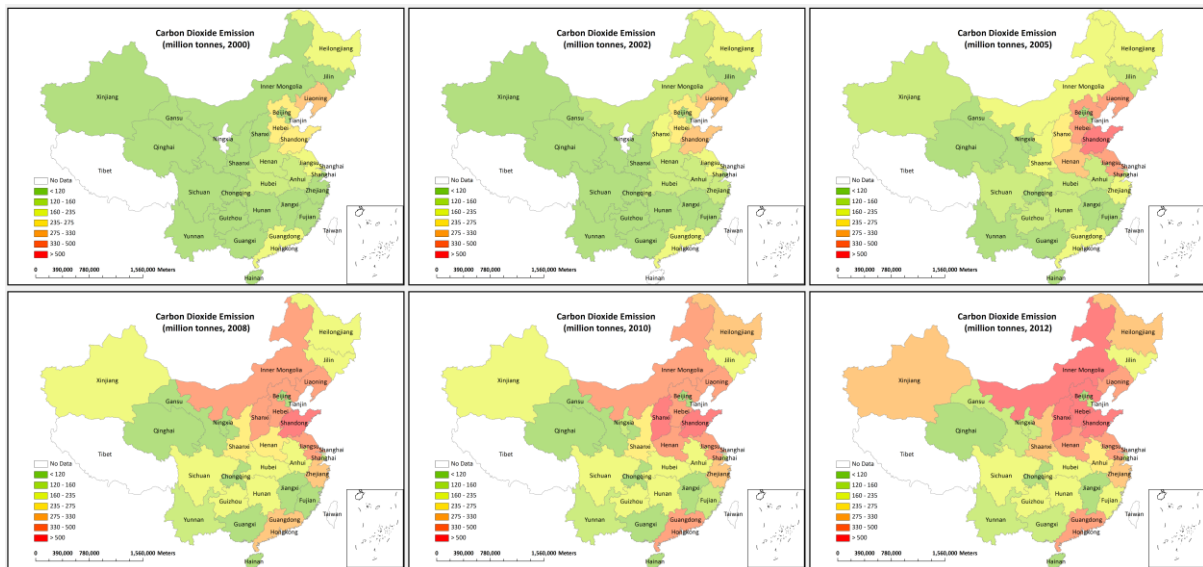
151 Both the IPCC and NDRC (for year 1994 and 2005) provide default emission factors for the three
 152 primary fossil fuels [50, 54]. However, based on measurements of 602 coal samples from the 100
 153 largest coal-mining areas in China [31], the emission factors recommended by the IPCC and NDRC
 154 are frequently higher than the real emissions factors in 2012 (see Table 1). In this study, we adopted
 155 the updated emission factors, which we assume to be more accurate than the IPCC and NDRC default
 156 values.

157 **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 |

158 **3. Results**

159 Figure 3 presents the CO₂ emissions of 30 provinces. Total national emissions increased by 171.6%
 160 over the period, from 3160 to 8583 million tonnes. Among the 30 provinces, Shandong emitted the
 161 most CO₂ cumulatively, 7,471 million tonnes (10.35%). The three provinces with the highest
 162 cumulative emissions were Liaoning, Hebei and Shanxi, which emitted 4,833 (6.69%), 4,816 (6.67%)
 163 and 4,511 (6.25%) million tonnes CO₂, respectively. The data on emissions for all 30 provinces over
 164 2000–2012 are presented in Table 2.



165
166 **Figure 3.** CO₂ emissions from 30 provinces in China
167

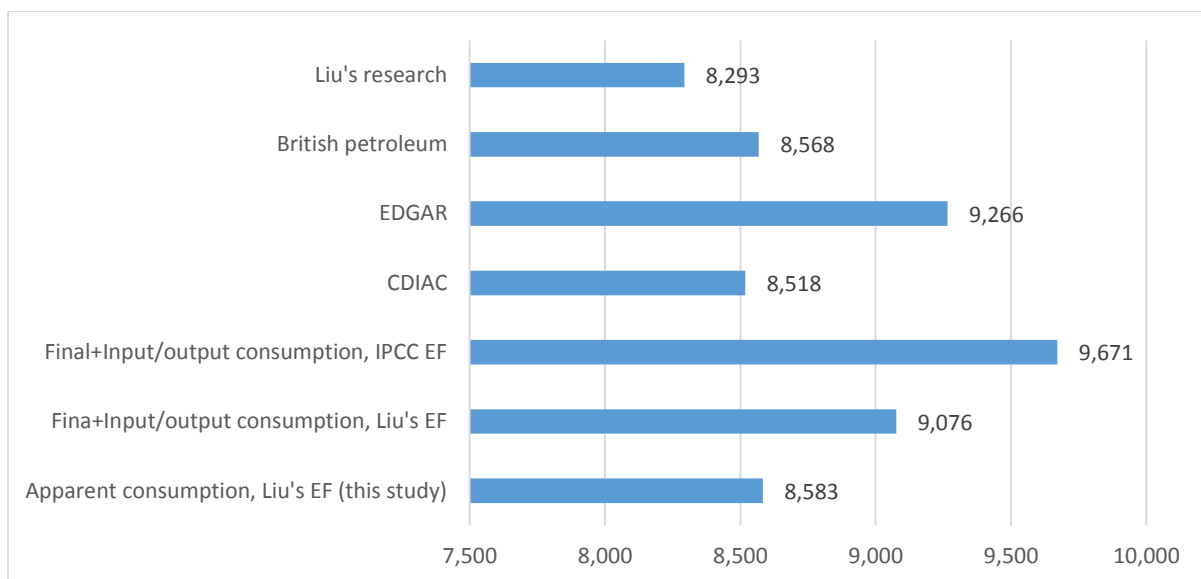
168 **Table 2.** Provincial CO₂ emissions, million tonnes, 2000–2012

| 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 |

169

170 Our estimation by apparent energy consumption and updated emission factors could be more accurate
171 and coincident with the national emissions compared with the traditional calculation approach. Taking
172 the year 2012 as an example, we compare the CO₂ emissions estimated by different approaches and
173 emission factors in Table 3 and Figure 4. Our estimation of provincial aggregate CO₂ emissions
174 (8,583 Mt) are similar to that of CDIAC (8,518) and 7.96 % lower than the highest estimation
175 (EDGAR, 9,266 million tonnes, and are coincident with the national emissions estimated by the same
176 approach (8,342 Mt [31]). The newly calculated CO₂ emissions in this study reduced the 20% gap
177 between national and provincial aggregate CO₂ emissions [55], and improved the accuracy in Chinese
178 CO₂ emission accounts.



179

180 **Figure 4.** National CO₂ emission comparison of different sources, 2012, million tonnes

181 Data sources: emission estimates by Liu's research [31], emission estimates by British petroleum [29], emission
 182 estimates by EDGAR [28], and emission estimates by CDIAC [26],

183

184 Our estimation of provincial aggregate emissions are 12.69% smaller than the one estimated by "Final

185 and input/output consumption" approach and IPCC emission factors (see Table 3 and Figure 4). The

186 gap comes from two parts: 6.94% from the emission factors and 5.75% from activity data with

187 reasons are discussed above.

188 **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 |

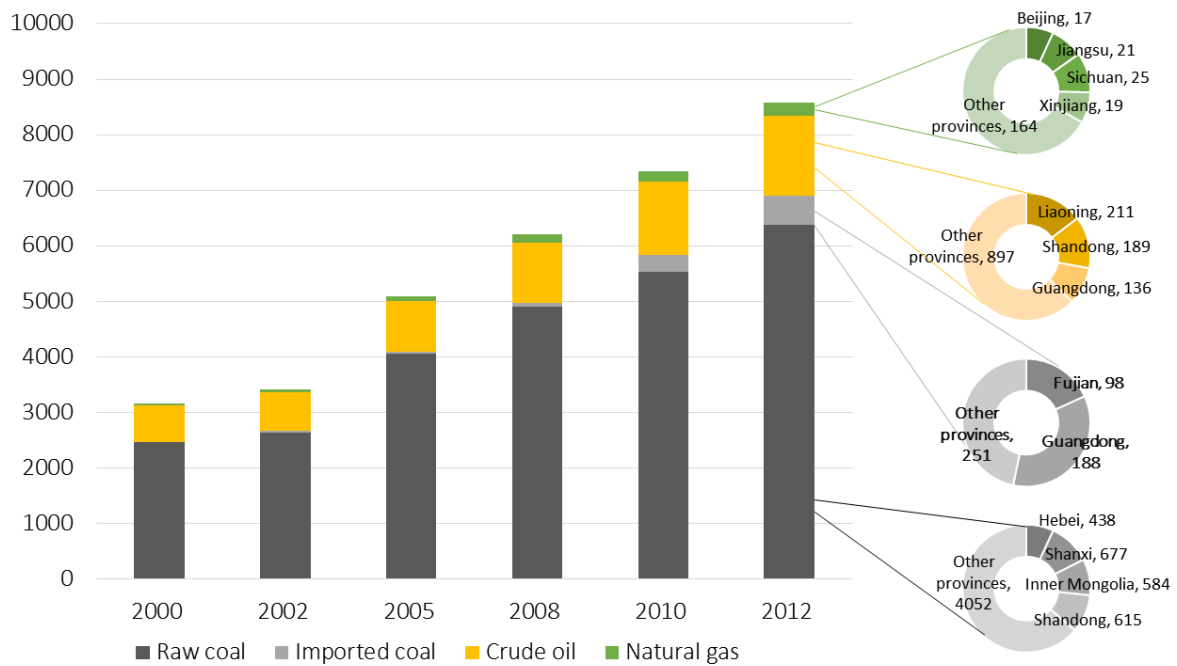
| | | | | | | |
|-------------|---------|---------|---------|---------|---------|---------|
| Guangxi | 158.41 | 113.53 | 149.92 | 105.04 | 158.55 | 113.69 |
| Hainan | 48.15 | 16.50 | 46.92 | 15.26 | 43.66 | 15.66 |
| Chongqing | 128.79 | 113.66 | 120.29 | 105.16 | 109.00 | 96.07 |
| Sichuan | 240.32 | 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 |

189

190 In order to have a deep understanding of Chinese provinces' emission and emission-socioeconomic
191 characteristics, we discuss emissions by different fossil fuel types and sectors, and calculate the per
192 capita emissions and emission intensity in the following parts.

193 **3.1. Emissions by fossil fuel types and sectors**

194 The energy utilization structure in China has been very stable over the past 13 years. Based on natural
195 resource endowments, raw coal contributed the most to the total fossil fuel CO₂ emissions in China,
196 representing an average of 79.6% over the period. Due to increasing imports, the emissions share
197 from imported coal as a portion of total raw coal increased from 0.1% in 2000 to 7.8% in 2012. Crude
198 oil's contribution to total fossil fuel CO₂ emissions decreased from 20.7% to 16.7%, whereas the
199 share of emissions from natural gas increased from 1.7% to 3.9% between 2000 and 2012.



200

201 **Figure 5.** Provincial CO₂ emissions by fossil fuel types, million tonnes

202

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

204 Figure 5. Shanxi, Shandong, Inner Mongolia and Hebei contributed the most to raw coal-related CO₂

205 emissions. These provinces are either coal bases or manufacturing provinces. Most of the imported

206 coal was consumed in Guangdong and Fujian, which are located on the southeast coast, where it is

207 cheaper to import coal from abroad rather than transport it from coal sources in the interior. Coastal

208 Guangdong, Shandong and Liaoning also have more developed shipping industries for similar reasons.

209 Most of the raw coal are consumed in fire power plant to generate electricity [56]. More crude oil was

210 consumed in these provinces, resulting in increased CO₂ emissions. Sichuan, Jiangsu, Xinjiang and

211 Beijing consumed high levels of natural gas in 2012; Sichuan and Xinjiang are the locations of the

212 main natural gas fields in China. Jiangsu and Beijing are the most developed provinces in China and

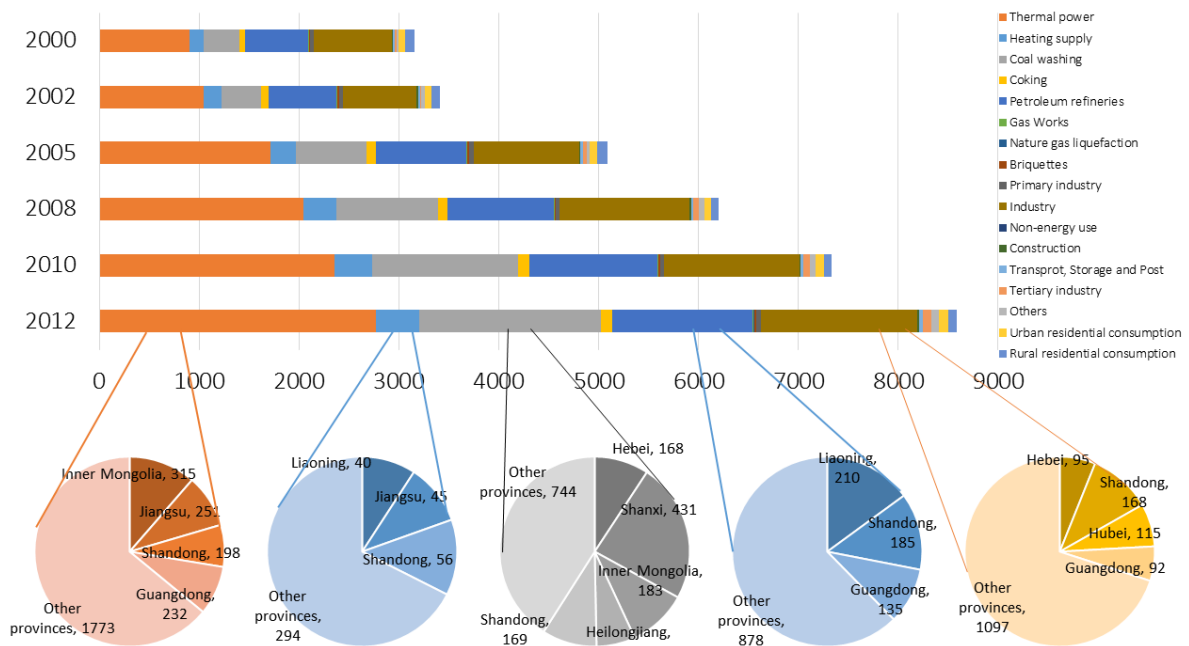
213 are exploring cleaner energy utilization pathways. As natural gas is a cleaner fossil fuel than raw coal

214 and crude oil, increased the proportion of natural gas consumption would help control CO₂ emissions.

215 Similar to energy utilization, fossil fuel CO₂ emissions can be divided into 16 sectors (see Figure 6).

216 The first eight sectors belong to “input & output of transformation” sectors, and the last eight sectors

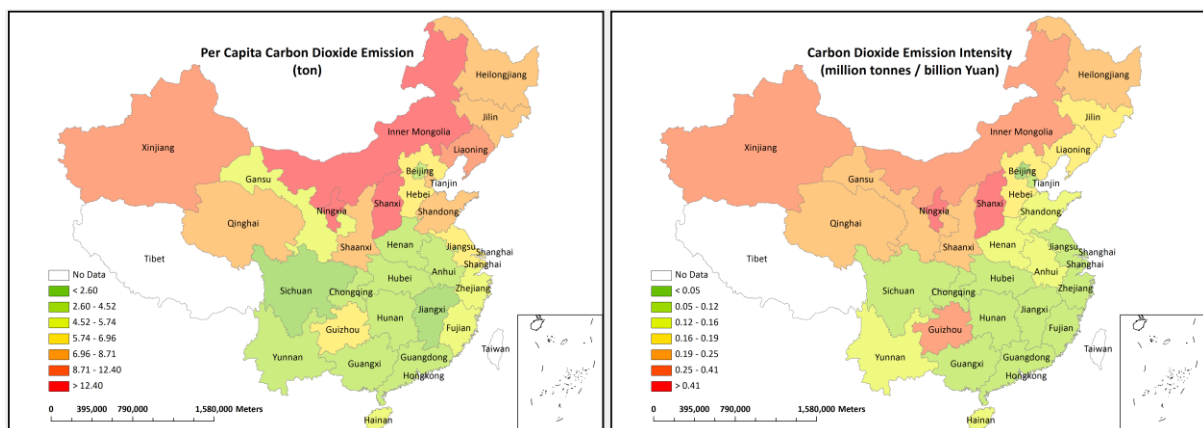
217 are “final consumption” sectors. Most CO₂ emissions are produced by thermal power, industry final
 218 consumption, petroleum refineries and coal washing.



219
 220 **Figure 6.** Provincial CO₂ emissions by sectors, million tonnes

221 **3.2. Provincial emission-socioeconomic characteristics in 2012**

222 To analyse the emission characteristics of different provinces, we calculated the per capita CO₂
 223 emissions and CO₂ emissions intensity for 2012 (see Figure 7). The calculations and data sources are
 224 presented in Table 4.



225
 226 **Figure 7.** Emission-socioeconomic nexus of China's 30 provinces, 2012

227

228 **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 |

229 Source: China Statistical Yearbook, 2013 [24].
230

231 *3.2.1. Per capita CO₂ emissions*

232 The national average CO₂ emissions per capita in 2012 were 6.38 metric tonnes. The emissions per
233 capita varied among provinces due to differences in development stage and development pathways.

234 Only 13 of 30 provinces had emissions per capita above the national level.

235 The top three provinces were Inner Mongolia, Ningxia and Shanxi. All three provinces are primary
236 coal producers, with many large coal mines, and the coal usage per capita is much higher here as
237 compared with the national average level. Mongolia and Ningxia host the China Shenhua Energy
238 Company Limited (the nation's largest energy company), and Shanxi is the base of the China National

239 Coal Group Corporation (the second largest energy company). The two enterprises are the only two
240 energy enterprises in China among the 112 central enterprises (i.e., firms under government control)
241 updated in 2015 [57]. Central enterprises are normally pillars of economic growth, with high output
242 and added value. In addition, coal is a high-emission fossil fuel compared with crude oil and natural
243 gas because it emits more CO₂ to produce the same unit of heat compared with other energy types
244 [43]. Thus, these three provinces have the highest CO₂ emissions per capita.

245 The second group includes eight provinces: Xinjiang, Liaoning, Tianjin, Shaanxi, Heilongjiang,
246 Shandong, Qinghai and Jilin. These are either primary energy suppliers (such as Xinjiang, Shaanxi,
247 Heilongjiang and Qinghai) or bases for heavy industry (such as Liaoning, Tianjin, Shandong and
248 Jilin). The third group includes six provinces: Hebei, Shanghai, Guizhou, Jiangsu, Zhejiang and
249 Gansu. The CO₂ emissions per capita of these provinces were near the national average. The
250 remaining 13 provinces belong to the last group. Some of these provinces are located in the central
251 and southwest parts of China, with primary industry as their pillar economy; others are among the
252 most developed provinces with highly developed service industries (such as Beijing and Guangdong).
253 Jiangxi and Sichuan had the lowest CO₂ emissions per capita, 2.55 and 2.59 metric tonnes,
254 respectively.

255 *3.2.2. CO₂ emissions intensity*

256 The national average CO₂ emission intensity in 2012 was 0.15 million tonnes/ billion yuan. One half
257 (15) of the provinces had an emission intensity above the national level. As shown in Figure 7 , the
258 distribution of CO₂ emission intensity is similar to that of CO₂ emissions per capita. The provinces in
259 the north and northwest had higher emission intensities, whereas the provinces in the central and
260 southeast areas had lower intensities. The differences in emission intensities among these provinces
261 reflect differences in their natural resource endowments. As mentioned above, the provinces in north
262 and northwest have more coal mines (such as Shanxi and Inner Mongolia) and oil fields (such as
263 Xinjiang). Therefore, the industries of energy production and transformation are the pillar industries
264 of the local economy, including coal mining and dressing, coking and petroleum processing. These

265 industries are all high energy intensity, and huge amounts of primary fossil fuels are consumed in
266 these provinces for energy transformation and final consumption. As CO₂ emissions were calculated
267 here using the apparent scope energy consumption approach, all of the primary energy transformed
268 into the second energy was included in the energy consumption of the province. Hence, the CO₂
269 emission intensity of the energy-producing provinces is much higher.

270 By contrast, the more developed provinces have lower CO₂ emission intensities, such as Beijing
271 (0.05), Shanghai (0.08) and Guangdong (0.08). These more developed provinces have greater service
272 industry, which is less energy dependent.

273 **4. Policy implications and conclusions**

274 Climate policy discussions have made great process in the 2015 at the United Nations Climate Change
275 Conference held in Paris, where the participated 195 counties agreed to reduce their carbon output as
276 soon as possible and to do their best to keep global warming to well below 2°C compared with the
277 pre-industrial level. China is the most important participant as the biggest CO₂ emitter and should also
278 take the responsibility.

279 First of all, it is of great significance to account China's CO₂ emissions as accurate as possible both at
280 national level and provincial level. We re-estimated the CO₂ emission inventories of 30 Chinese
281 provinces over the last 13 years. We included emissions from three primary fossil fuels in eight input
282 & output transformation sectors and eight final consumption sectors. The CO₂ emissions were
283 calculated based on "apparent energy consumption" approach along with updated emission factors.
284 The new accounting method can be applied to further research on multi-scale carbon emission
285 accounts, such as city-level and industrial process. Our results of accurate national and provincial CO₂
286 emissions could help policy makers develop strategies and policies for emission reductions and track
287 the process of those policies.

288 The results indicate that Chinese provincial aggregated CO₂ emissions calculated by the apparent
289 energy consumption and updated emissions factors are coincident with the national emissions
290 estimated by the same approach, which are 12.69% smaller than the one calculated by the traditional

291 approach. Chinese provincial aggregate CO₂ emissions increased from 3,160 million tonnes in 2000 to
292 8,583 million tonnes in 2012. Our estimates for 2012 are similar to that of CDIAC (8,518) and 7.96 %
293 lower than the highest estimation (EDGAR, 9,266 million tonnes). Of the 30 provinces, Shandong
294 contributed the most to national accumulative CO₂ emissions of the last 13 years (7,471 million
295 tonnes), with an average of 10.35% over 13 years. The following three provinces were Liaoning,
296 Hebei and Shanxi, with cumulative emissions of 4,833 (6.69%), 4,816 (6.67%) and 4,511 (6.25%)
297 million tonnes CO₂, respectively.

298 From the perspective of fossil fuel types, the paper confirms that raw coal combustion contributes
299 most to provincial CO₂ emissions, especially for Shanxi, Shandong and Inner Mongolia provinces.
300 While for Guangdong and Fujian province, the main source of CO₂ emissions is imported coal.
301 Differentiated policies should be made corresponding to different emitting sources. For Shanxi,
302 Shandong and Inner Mongolia, policies such as increasing coal mining efficiency, obtaining higher
303 percentage of coal recovery could be used. For Guangdong and Fujian, policies regarding replacing
304 coal with oil and natural gas could be encouraged. Several policy instruments could be used to support
305 gas replacement like feed-in tariff (FIT) policies, capacity payment, price-setting policies, quantity
306 setting policies, renewable portfolio standard, etc.

307 If we divide the total CO₂ emissions into final consumption and energy transformation sectors, we can
308 see that the thermal power sector emits the most CO₂, followed by the industrial final consumption,
309 petroleum refinery and coal washing sector. Therefore, it is of great significance to increase the
310 efficiency of thermal power generator through promotion of the most advanced technologies, such as
311 supercritical generator, combined heat and power and IGCC (Integrated Gasification Combined Cycle)
312 technology.

313 In addition, policy makers should also take the different socioeconomic characteristics of each
314 province into account when making climate policies [58]. The study shows that provinces located in
315 the northwest and north had higher per capita CO₂ emissions and emission intensities than the central
316 and southeast coastal regions. Understanding emissions and the associated socioeconomic

317 characteristics of different provinces provides a basis for carbon emission control policy and goal in
318 China.

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