



Article

# Re-Examining Embodied SO<sub>2</sub> and CO<sub>2</sub> Emissions in China

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**Abstract:** CO<sub>2</sub> and SO<sub>2</sub>, while having different environmental impacts, are both linked to the burning of fossil fuels. Research on joint patterns of CO<sub>2</sub> emissions and SO<sub>2</sub> emissions may provide useful information for decision-makers to reduce these emissions effectively. This study analyzes both CO<sub>2</sub> emissions and SO<sub>2</sub> emissions embodied in interprovincial trade in 2007 and 2010 using multi-regional input–output analysis. Backward and forward linkage analysis shows that Production and Supply of Electric Power and Steam, Non-metal Mineral Products, and Metal Smelting and Pressing are key sectors for mitigating SO<sub>2</sub> and CO<sub>2</sub> emissions along the national supply chain. The total SO<sub>2</sub> emissions and CO<sub>2</sub> emissions of these sectors accounted for 81% and 76% of the total national SO<sub>2</sub> emissions and CO<sub>2</sub> emissions, respectively.

**Keywords:** multi-regional input–output analysis; CO<sub>2</sub> emissions; SO<sub>2</sub> emissions; interregional trade

## 1. Introduction

The Paris Agreement entered into force on 4 November 2016 signed by 188 countries, accounting for over 90% of global greenhouse emissions [1,2]. China promised to achieve peak CO<sub>2</sub> emissions around 2030 and make its best efforts to achieve this goal earlier (National Development and Reform Commission of China, 2015). One of the persistent problems of controlling carbon emissions is that China's energy structure is still coal-dominated although the economy is being restructured (National Bureau of Statistics of China, 2016).

Closely linked to this structural problem is the serious haze pollution that is afflicting many areas in China. A number of cities and provinces frequently issue red alerts for haze, especially the Beijing–Tianjin–Hebei area. Numerous studies have established the links between air pollution and human health, such as cardiovascular and pulmonary mortality [3–5]. For example, Xu et al. [6] found that short-term exposure to particulate air pollution is related to increased ischemic heart disease mortality. Lu et al. [7] concluded that the risks of mortality and years of life lost (YLL) were closely related to current ambient concentrations of respirable particulate matter (PM<sub>10</sub>) and gaseous pollutants (NO<sub>2</sub>, SO<sub>2</sub>). Yang et al. [8] found a significant linear correlation between YLL from cardiovascular mortality and air pollution in Guangzhou, China, for the years

2004–2007. Haze governance has become a shared concern of the public, media and policy makers. In September 2013, the State Council of China released an “air pollution prevention and control action plan” to combat air pollution in an effort to ease mounting public concern over air quality.

In fact, many air pollutants and greenhouse gases have the same emission sources, such as fossil fuel combustion, which allows government to take integrated measures to achieve a synergistic effect of reducing greenhouse gas emissions, mitigating climate change and controlling air pollution [9–11]. A large number of studies have shown how synergies across policy arenas are more cost-effective than single-issue focused solutions [12–17]. For instance, Chae and Park [18] find that the benefits of integrated environmental strategies are greater than those obtained by air-quality management and greenhouse gas (GHG) reduction measures individually. China should combine air-quality improvement with carbon emission reduction targets, through better coordination between departments and joint emission control measures, since connecting CO<sub>2</sub> emissions mitigation with air-quality management measures is more effective. In order to provide more information for provincial government to formulate and implement environment-friendly measures and climate policies, we investigated both CO<sub>2</sub> emissions and SO<sub>2</sub> emissions embodied in interprovincial trade inside China using multi-region input–output (MRIO) analysis, then backward and forward linkage were used to help identify sectors and regions to prioritize emission-reduction measures.

## 2. Background

At present, there are two methods of calculating carbon emissions embodied in trade: the emissions embodied in bilateral trade (EEBT) framework and multi-regional input–output analysis (MRIO). A key difference between these two methods is that the EEBT method does not separate bilateral trade into intermediate and final consumption while the MRIO model does [19,20]. Peters [19] (2008, p. 17) compared the EEBT and MRIO models, and concluded that “the MRIO model is better suited for the analysis of final consumption, while the EEBT model is better for analysis of trade and climate policy where transparency is important”. Calculations have shown that the differences between these two models can be more than 20% for some countries [19,20]. MRIO can track the impacts of international/interregional production and supply chains, spanning multiple sectors in multiple countries/regions, and covers all indirect impacts along the upstream supply chains [21,22]. Thus, MRIO is widely used to examine embodied emissions and materials in international/interregional trade, such as carbon/CO<sub>2</sub> emissions [23–31], energy flows [32–34], water consumption [35,36], PM<sub>2.5</sub> [37], SO<sub>2</sub> emissions [37–39], NO<sub>x</sub> emissions [37,38], CH<sub>4</sub> emissions [40], non-methane volatile organic compounds (NMVOC) [37].

Carbon emissions embodied in international trade have been widely studied at the national level, which helps to reveal the carbon leakage between developed countries and developing countries to support national climate policy making and international negotiations [25]. Liu and Wang [41] (2017, p. 4) recognized that “since there are fewer barriers in interprovincial trade than in international trade, the interprovincial pollution transfer may be more serious”. There is a growing body of literature focusing on embodied carbon emissions and air pollution inside China (see Table 1 for an overview). For a large country like China, we find a similar phenomenon, that is, rich regions outsource pollution and thus reduce their mitigation cost to poor regions through regional trade [42,43]. A number of scholars have begun to pay attention to regional carbon leakage in China. For example, Feng et al. [43] studied Chinese interprovincial embodied carbon emissions in trade and concluded that the rich eastern coastal areas in China outsource large quantities of carbon emissions to western regions within China. Su and Ang [25] found that China’s central region is the largest contributor to other regions’ CO<sub>2</sub> emissions. The research of Shan et al. [2] indicates that provinces in the north-west and north have higher emission intensity and per capita emissions than the central and south-eastern coastal areas. Zhao et al. [44] quantified exported CO<sub>2</sub> emissions and atmospheric pollutant emissions of the Beijing–Tianjin–Hebei area.

As atmospheric pollution has become a serious environmental problem in China, there have been several studies on the embodied air pollution in interprovincial trade [37,39–41,45]. Liu and Wang [39] reexamined SO<sub>2</sub> emissions embodied in China's exports, and found that more than one fifth of embodied emissions in eastern China's exports are outsourced to the central and western regions. Zhao et al. [37] and Wang et al. [45] found that the more developed regions, such as Beijing–Tianjin, the East coast, and the South coast, consumed large amounts of emission-intensive products or services imported from less-developed regions including the Central, North-west and South-west regions through interprovincial trade due to differences in the economic status and environmental policies.

**Table 1.** Literature on embodied carbon emissions and air pollution in China.

Citation	Methods	Type of Emissions	Regions	Economic Sectors	Study Period
Liu et al. [28]	Multi-region input–output (MRIO) analysis	Carbon emissions	8 regions	17 sectors	1997, 2007
Zhang et al. [46]	MRIO	Energy use	4 municipalities	30 sectors	2007
Zhang et al. [47]	MRIO	Energy use	30 provinces	30 sectors	2007
Zhang et al. [34]	MRIO	Energy transfers	8 regions	17 sectors	2002, 2007
Feng et al. [43]	MRIO	CO <sub>2</sub> emissions	30 provinces	21 sectors	2007
Mi et al. [48]	Single-region input–output (SRIO) model	CO <sub>2</sub> emissions	13 cities	47 sectors	2007
Liu and Wang [39]	MRIO	SO <sub>2</sub> emissions	30 provinces	export	2002, 2007
Liu and Wang [41]	Emissions embodied in bilateral trade (EEBT) and MRIO	SO <sub>2</sub> emissions	30 provinces	27 sectors	2002, 2007
Liu et al. [1]	MRIO	Carbon emissions	8 regions	4 sectors	2002, 2007
Zhang [49]	MRIO	Carbon emissions	30 provinces	30 sectors	2007, 2010
Wang et al. [45]	MRIO	COD,NH <sub>3</sub> -N,SO <sub>2</sub> ,NO <sub>x</sub>	30 provinces/8 regions	30 sectors	2007
Zhao et al. [37]	MRIO	PM <sub>2.5</sub> ,SO <sub>2</sub> ,NO <sub>x</sub> ,NMVOC	30 provinces/8 regions	/	2015
Su and Ang [25]	Hybrid emissions embodied in trade (HEET) approach	CO <sub>2</sub> emissions	8 regions	/	1997
Zhang et al. [40]	MRIO	CH <sub>4</sub>	30 provinces	12 sectors	2010
Zhang et al. [33]	MRIO	Energy use	7 regions	/	2002, 2007

### 3. Method and Data

#### 3.1. Multi-Regional Input-Output Analysis

In this study, MRIO is adopted to analyze the SO<sub>2</sub> emissions and CO<sub>2</sub> emissions embodied in interprovincial trade within China.

The production-based SO<sub>2</sub> emissions (or CO<sub>2</sub> emissions) and consumption-based SO<sub>2</sub> emissions (CO<sub>2</sub> emissions) for region  $r$  are calculated as Equations (1) and (2), respectively. The production-based SO<sub>2</sub> emissions (CO<sub>2</sub> emissions) mean the SO<sub>2</sub> emissions (CO<sub>2</sub> emissions) produced domestically in region  $r$  not only meet the demand of domestic consumption, but also the demand of other regions. The consumption-based SO<sub>2</sub> emissions (CO<sub>2</sub> emissions) mean the SO<sub>2</sub> emissions (CO<sub>2</sub> emissions) produced both domestically and in other regions to meet the demand for region  $r$ . Net emissions are obtained by consumption-based emissions minus production-based emissions. More details could be found in Peters [24].

$$f_r^p = F(I - A)^{-1} p^r \quad (1)$$

$$f_r^c = F(I - A)^{-1} c^r \quad (2)$$

where  $f_r^p$  is the production-based SO<sub>2</sub> emissions (CO<sub>2</sub> emissions),  $f_r^c$  is the consumption-based SO<sub>2</sub> emissions (CO<sub>2</sub> emissions),  $I$  is the identity matrix and  $F$  is the vector of SO<sub>2</sub> emissions (CO<sub>2</sub> emissions)

intensities.  $p^r = \begin{bmatrix} 0 \\ y^{rr} + \sum_s y^{rs} \\ 0 \\ 0 \end{bmatrix}$ ,  $c^r = \begin{bmatrix} y^{1r} \\ y^{2r} \\ \vdots \\ y^{mr} \end{bmatrix}$ .

### 3.2. Backward and Forward Linkage Analysis

Backward linkage  $BL_j$  is defined as follows:

$$BL_j = \frac{1}{n} \sum_{i=1}^n m_{ij} / \frac{1}{n^2} \sum_{j=1}^n \sum_{i=1}^n m_{ij}, j = 1, 2, \dots, n \quad (3)$$

where  $m$  is the elements of matrix  $M$ , defining  $M = F(I - A)^{-1} \cdot \sum_{i=1}^n m_{ij}$  denotes the total CO<sub>2</sub> emissions (SO<sub>2</sub> emissions) increase of the whole economy system when final demand for the product of sector  $j$  increases by one unit.  $\frac{1}{n} \sum_{i=1}^n m_{ij}$  is the average CO<sub>2</sub> emissions (SO<sub>2</sub> emissions) to be supplied by one sector chosen at random when final demand for the product of sector  $j$  increases by one unit. To conduct consistent interdepartmental comparisons, we normalized these averages by the overall average defined as  $\frac{1}{n^2} \sum_{j=1}^n \sum_{i=1}^n m_{ij}$  [50–54]. If  $BL_j$  is larger than 1, a one-unit increase in final demand of sector  $j$  would result in an above-average increase in the CO<sub>2</sub> emissions of all the sectors in the entire economy [55].

The Ghosh inverse matrix  $(I - B)^{-1}$  can be derived from the direct supply coefficient matrix  $B$ . Define  $G = (I - B)^{-1}F$ ,  $g$  is the elements of matrix  $G$ .  $\sum_{j=1}^n g_{ij}$  reflects the total CO<sub>2</sub> emissions (SO<sub>2</sub> emissions) increase of the whole economic system due to the value added of sector  $i$  increases by one unit.  $\frac{1}{n} \sum_{j=1}^n g_{ij}$  is the average CO<sub>2</sub> emissions (SO<sub>2</sub> emissions) increase by one sector chosen at random when the value added of sector  $i$  increases by one unit. Similarly the normalized forward linkage  $FL_i$  is defined as follows [54,56]:

$$FL_i = \frac{1}{n} \sum_{j=1}^n g_{ij} / \frac{1}{n^2} \sum_{i=1}^n \sum_{j=1}^n g_{ij}, i = 1, 2, \dots, n \quad (4)$$

If both  $BL$  and  $FL$  of one sector are greater than 1, then the sector will be considered as polluting sector. If only  $BL$  is greater than 1, then the sector can be seen as a backward-oriented sector. If only  $FL$  is greater than 1, then the sector can be seen as forward-oriented sector. The last category is low-emission generation sectors with both the  $BL$  and  $FL$  less than 1 [54].

### 3.3. Data Sources

The interregional input–output tables in 2007 and 2010 are provided by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences [28,57,58]. The CO<sub>2</sub> emissions of 30 Chinese provinces in 2007 and 2010 are from the China Emission Account and Datasets (CEASs, <http://www.ceads.net/>). The national sub sectoral SO<sub>2</sub> emissions and total SO<sub>2</sub> emissions of each province are from the China Statistical Yearbook (National Bureau of Statistics 2008, 2011). Due to the lack of sub-sectoral SO<sub>2</sub> emissions of each province, we adopt the method in the Supplementary Materials.

Because some industrial sectors in the energy balance tables of the statistical yearbook are more detailed than the sectors in the inter-regional input–output table, we aggregated the sector from the statistical yearbook to match the sectors in the interregional input–output tables, as shown in Table A1 in the Supplementary Materials. On the other hand, if the input–output (IO) tables were more granular than the sectors in the energy balance table, we kept that higher level of detail assuming that the sectors in the same aggregate sector have the same emission coefficients.

There are some uncertainties in the inventories for Chinese fossil fuel CO<sub>2</sub> emissions. Liu et al. [59] concluded that there is a 7.3% uncertainty range of Chinese fossil fuel CO<sub>2</sub> emissions. Guan et al. [60] found that CO<sub>2</sub> emissions based on national statistical data and 30 provincial statistical data differ

by 1.4 gigatonnes for 2010. This may bring about uncertainties of the results in our study and other research using climate models. Guan et al. [60] (2012, p.2–3) explained that “There are two explanations for such a large uncertainty. First, the statistical approach on data collection, reporting and validation is opaque” . . . “Second, the statistics departments in China are not politically independent agencies, but are often pressurized by other government agencies to provide statistical data ‘to fit’ different political purposes”. Sinton [61] concluded that understaffing and underfunding in the National Bureau of Statistics is another reason for the inaccuracy and unreliability of China’s energy statistics. Independent satellite observational data can provide more reliable emission inventories and have been used in many studies [62,63]. However, they cannot be used to verify data at the level of specific economic sectors as required for input–output analysis or any detailed economic analysis. More bottom-up research based on qualified statistical labor forces and their on-site surveys would help to improve the data [60].

## 4. Results and Discussions

### 4.1. China’s Total SO<sub>2</sub> Emissions and CO<sub>2</sub> Emissions

China’s total SO<sub>2</sub> emissions decreased by 16.1%, i.e., from 16.5 million tons (Mt) in 2007 to 13.9 Mt in 2010. Our SO<sub>2</sub> results are lower (by 16.3% and 18.8% in 2007 and 2010, respectively) than those reported by the National Bureau of Statistics. This is due to the inconsistency of statistical data. The national SO<sub>2</sub> emissions from industrial sectors are 22% lower than the total SO<sub>2</sub> emissions by adding each province’s emissions. Guan et al. [60] also found a similar issue with CO<sub>2</sub> data. Thus, the results using the MRIO model has uncertainties based on the underlying data. Our results show that SO<sub>2</sub> emissions in China have been reduced, which is consistent with the findings of Li et al. [64] and Chen et al. [65]. Embodied SO<sub>2</sub> emissions in interprovincial trade contributed 46.2% of the national total emissions in our study, which was close to Wang et al. (45%) [58], the shares were respectively 35% and 54% according to the results of Liu and Wang [41] and Zhao et al. [37]. The differences are caused by different data sources and data processing modes.

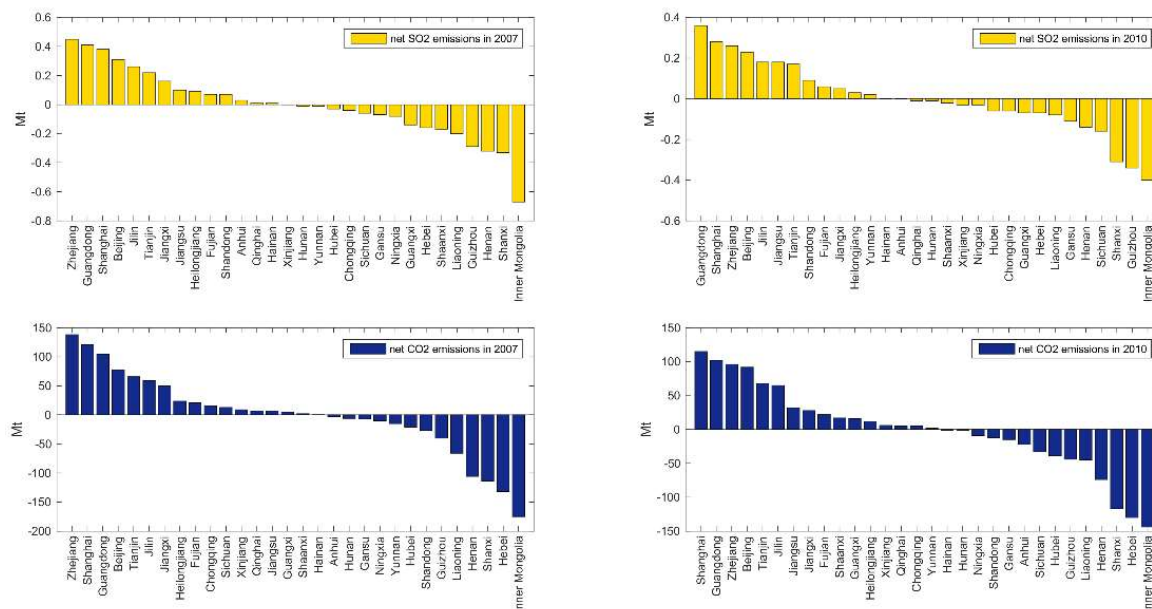
China’s total CO<sub>2</sub> emissions increased by 17.3% from 5.5 gigatonnes (Gt) in 2007 to 6.5 Gt in 2010. The embodied CO<sub>2</sub> emissions in interprovincial trade in this study accounted for 45% and 43.1% of the total national CO<sub>2</sub> emissions in 2007 and 2010, respectively. The results are lower than those of Feng et al. (57% in 2007) [43] and Mi et al. (approximately 50%) [66], but higher than that of Liu et al. (21.1% in 2007) [1]. Liu et al. [1] reported an average annual growth rate of total interregional carbon flows of approximately 23% during 2002–2007 using the multi-regional IO tables from 2002 and 2007 issued by the State Information Center of China [67]. In our study, the annual growth rate of total interregional carbon flows was 3.9% for the 2007–2010 period.

### 4.2. Net SO<sub>2</sub> Emissions and Net CO<sub>2</sub> Emissions of Each Province

Each province’s production-based and consumption-based emissions are shown in Table A2. Most provinces’ SO<sub>2</sub> emissions were decreasing, while CO<sub>2</sub> emissions increased. Net SO<sub>2</sub> emissions and net CO<sub>2</sub> emissions of each province in 2007 and 2010 are shown in Figure 1. The results in this study are similar to other studies’ results, which used the same data sources. For example, the largest net CO<sub>2</sub> importer is Zhejiang for 2007 in both our study and that of Feng et al. [43], and the net CO<sub>2</sub> emissions of Zhejiang were 138 Mt and 136 Mt, respectively. Consumption-based CO<sub>2</sub> emissions for Shanghai are 227 Mt in 2007, which is between Feng et al. [43] (238 Mt) and Mi et al. [48] (199 Mt). Most net CO<sub>2</sub> emissions importers also were net SO<sub>2</sub> emissions importers except Chongqing, Sichuan and Shaanxi in 2007, and Shaanxi, Guangxi, Xinjiang, Qinghai and Chongqing in 2010. The results reflects the fact that these western provinces’ CO<sub>2</sub> emissions were increasing due to the economic growth and national policy adjustment [66].

The largest net importers of SO<sub>2</sub> and CO<sub>2</sub> emissions were located in the more affluent eastern regions, with larger shares of services and light industry, such as Zhejiang, Guangdong,

Shanghai and Beijing, whereas the top net exporters of SO<sub>2</sub> and CO<sub>2</sub> emissions were the resource-intensive provinces, for example, Inner Mongolia and Shanxi [37,43,66]. Hainan and Sichuan changed from net CO<sub>2</sub> importer to net CO<sub>2</sub> exporter, while Yunnan changed from net CO<sub>2</sub> exporter to net CO<sub>2</sub> importer. Qinghai changed from net SO<sub>2</sub> importer to net SO<sub>2</sub> exporter, while Yunnan changed from net SO<sub>2</sub> exporter to net SO<sub>2</sub> importer. These changes are related to changes in industrial structure, technological level, and changes of their contribution to domestic supply chains.



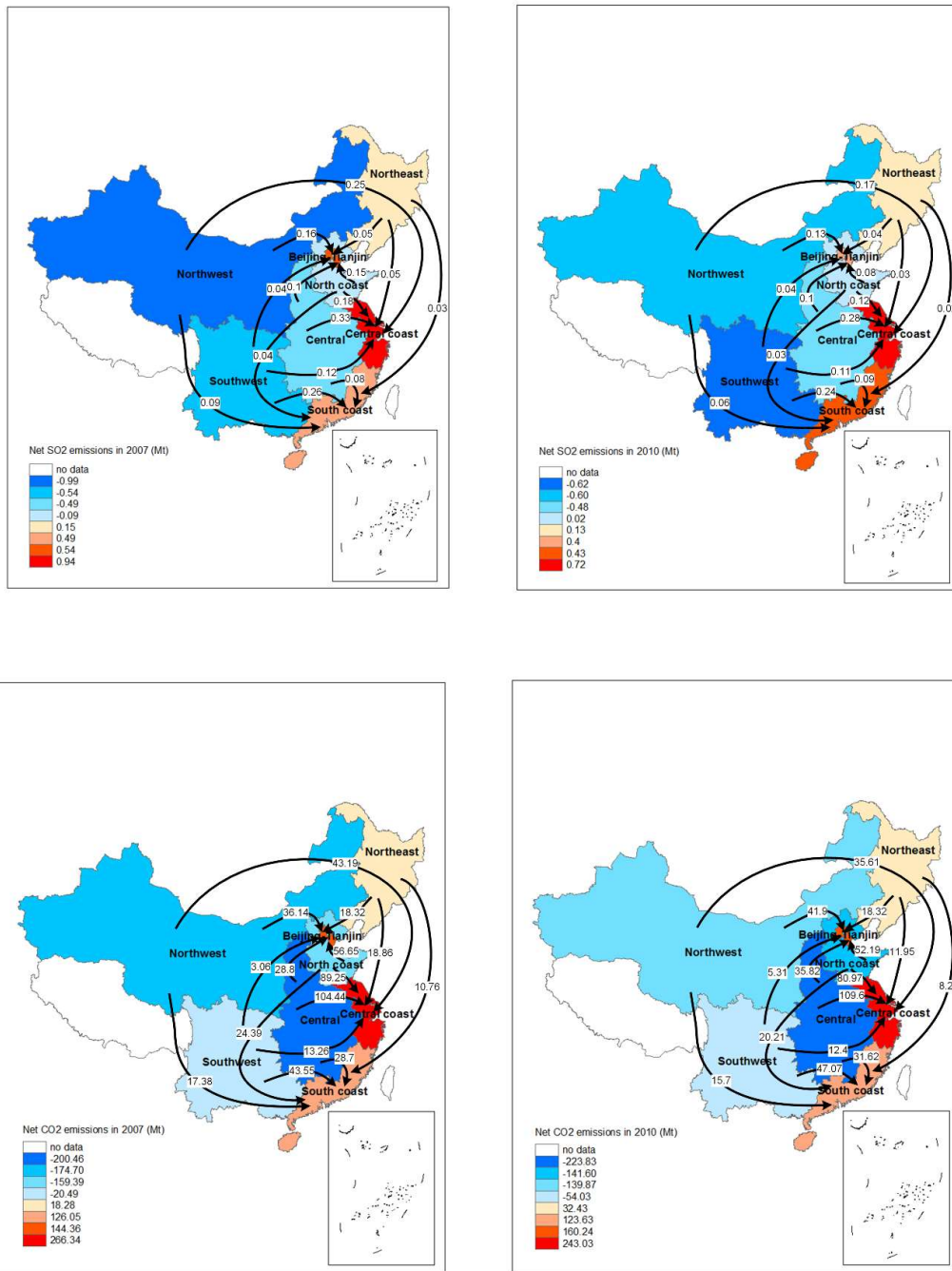
**Figure 1.** Net SO<sub>2</sub> emissions and net CO<sub>2</sub> emissions of each province in 2007 and 2010. Positive values mean net emissions importers. Negative values mean net emissions exporters.

#### 4.3. Interregional SO<sub>2</sub> Emissions and CO<sub>2</sub> Emissions Flows

Thirty Chinese provinces and cities are grouped into eight geographical regions, as shown in Table A3. Tables A4 and A5 show the interregional SO<sub>2</sub> and CO<sub>2</sub> emissions flows in 2007 and 2010, respectively. We find that most interregional SO<sub>2</sub> emissions in interregional trade decreased. By contrast, most interregional CO<sub>2</sub> emissions were increasing from 2007 to 2010. For example, the outsourced SO<sub>2</sub> emissions from Beijing–Tianjin to the North-west decreased by 3.6%, while the outsourced CO<sub>2</sub> emissions increased by 25.6%. As the largest emissions outsourcing region, the central coast’ outsourced SO<sub>2</sub> emissions decreased by 22.9% from 2007 to 2010, while outsourced CO<sub>2</sub> emissions increased by 3.9%.

Figure 2 shows the regional net SO<sub>2</sub> emissions and net CO<sub>2</sub> emissions in 2007 and 2010, respectively. Beijing–Tianjin, the Central coast, South coast and North-east regions were both net SO<sub>2</sub> and net CO<sub>2</sub> importers in 2007 and 2010, respectively. The Central, South-west, and North-west regions were both net SO<sub>2</sub> and net CO<sub>2</sub> exporters in 2007 and 2010, respectively.

From Figure 2 we also can see the interregional net SO<sub>2</sub> emissions flows in 2007 and 2010. SO<sub>2</sub> emissions and CO<sub>2</sub> emissions were transferred to Beijing–Tianjin, the Central coast and South coast regions from the Central, North-west, South-west, and North-east regions through interregional trade. These results are consistent with the findings of Feng et al. [43] and Zhao et al. [37]. For example, in 2010 the Central, South-west, North-west and North-east regions transferred 0.28 Mt, 0.11 Mt, 0.17 Mt, and 0.03 Mt of net SO<sub>2</sub> emissions to the Central coast, respectively. The corresponding net CO<sub>2</sub> inflows in 2010 were 109.6 Mt, 12.4 Mt, 35.61 Mt, and 11.95 Mt, respectively.

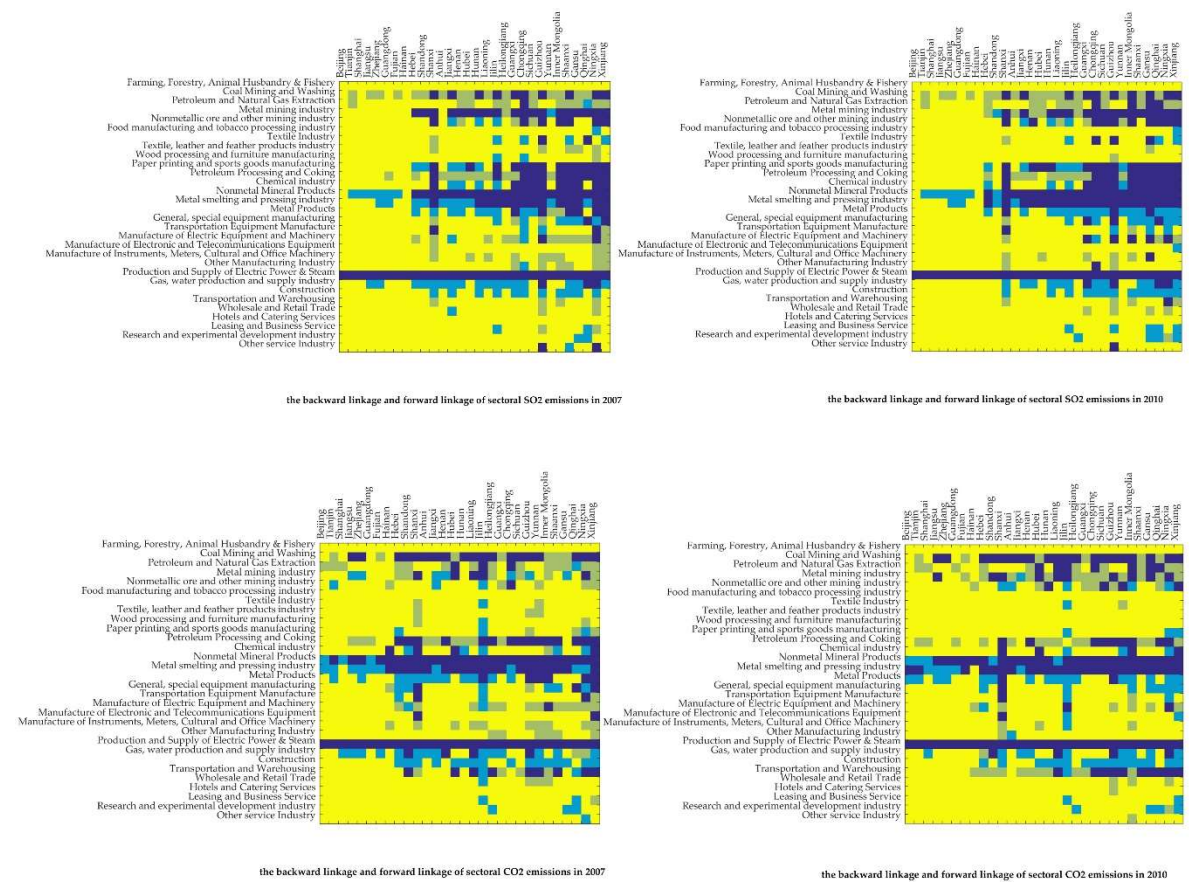


**Figure 2.** Regional net SO<sub>2</sub> emissions and net CO<sub>2</sub> emissions in 2007 and 2010. Arrows in the upper row show the interregional net SO<sub>2</sub> emissions flows in 2007 and 2010. Arrows in the lower row show the interregional net CO<sub>2</sub> emissions flows in 2007 and 2010.

#### 4.4. Backward Linkage and Forward Linkage Analysis

To identify the high-polluting industries and select the key sectors for emissions reduction, based on Equations (3) and (4), we calculated backward linkages (BL) and forward linkages (FL) of SO<sub>2</sub> emissions and CO<sub>2</sub> emissions of each sector for 30 provinces, as shown in Figure 3. The BL and FL of both SO<sub>2</sub> emissions and CO<sub>2</sub> emissions of Production and Supply of Electric Power and Steam for all the provinces are greater than in 2007 and 2010, meaning that the development of Production and Supply of Electric Power and Steam would drive both SO<sub>2</sub> and CO<sub>2</sub> emissions significantly. Non-metal

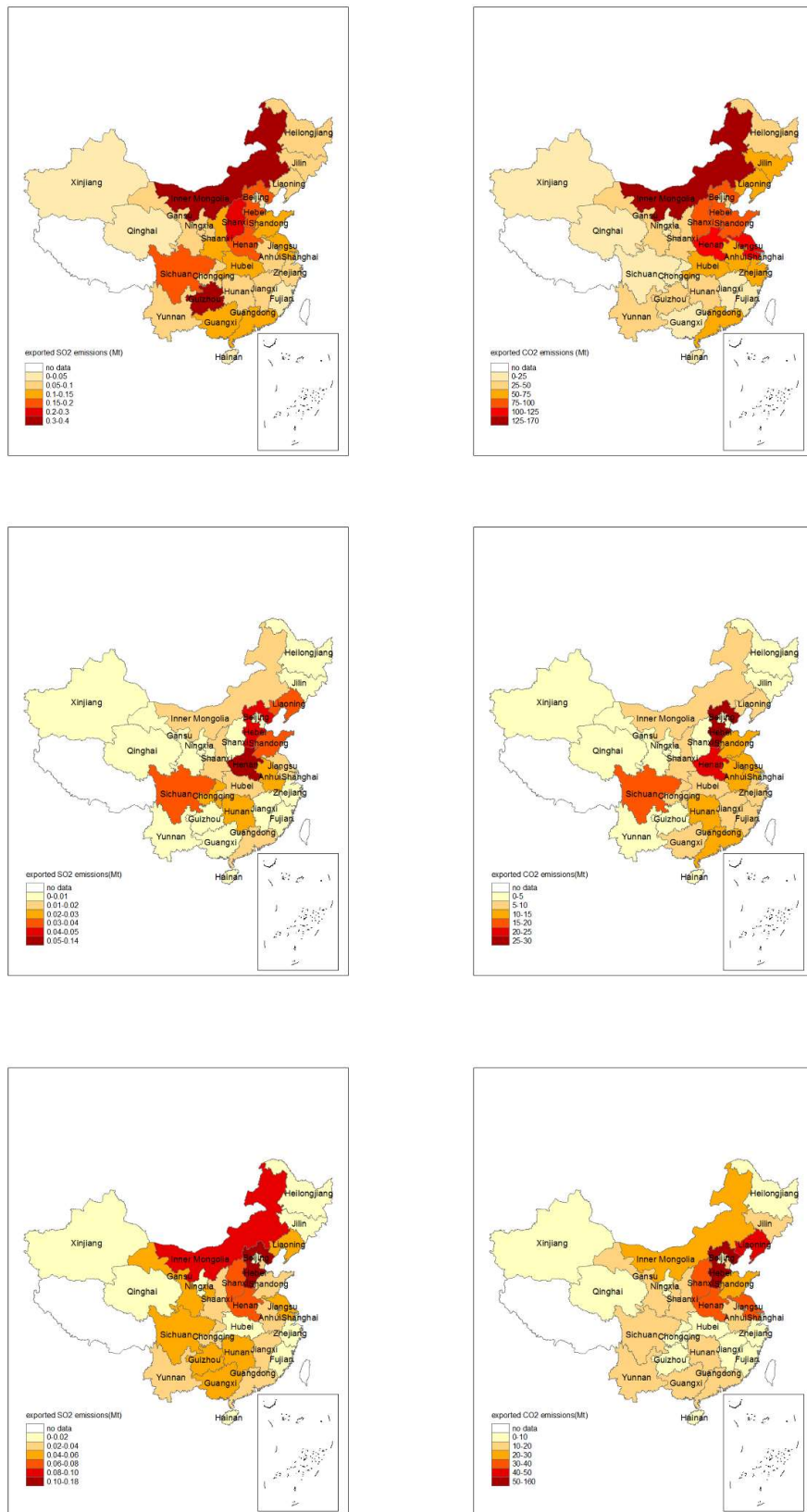
Mineral Products, the Metal Smelting and Pressing industry, Petroleum Processing and Coking, and Coal Mining and Washing were heavily polluting sectors as well.



**Figure 3.** Backward linkages and forward linkages of sectoral SO<sub>2</sub> emissions and CO<sub>2</sub> emissions, plotted by province on the horizontal axis and sector on the vertical. The dark blue square denotes BL > 1 and FL > 1; The light blue square denotes BL > 1 and FL < 1; The green square denotes BL < 1 and FL > 1; The yellow square denotes BL < 1 and FL < 1.

#### 4.5. Export-Related SO<sub>2</sub> Emissions and CO<sub>2</sub> Emissions of the Top Three Polluting Sectors

In 2010, the total SO<sub>2</sub> emissions and CO<sub>2</sub> emissions from the Production and Supply of Electric Power and Steam, Non-metal Mineral Products, and the Metal Smelting and Pressing industry were 11.2 Mt and 4921.5 Mt, which accounted for 81% and 76% of the total national SO<sub>2</sub> emissions and CO<sub>2</sub> emissions, respectively. Thus it is of great significance to analyze the emissions from these sectors to control both SO<sub>2</sub> and CO<sub>2</sub> emissions. Each province’s total SO<sub>2</sub> and CO<sub>2</sub> emissions of these sectors are shown in Table A6. Among these, large amounts of emissions were related to exports to other provinces. Each province’s export-related SO<sub>2</sub> and CO<sub>2</sub> emissions of these sectors are shown in Figure 4. For Production and Supply of Electric Power and Steam, Inner Mongolia had the largest export-related SO<sub>2</sub> emissions and the largest export-related CO<sub>2</sub> emissions in 2010. For Non-metal Mineral Products, Henan had the largest export-related SO<sub>2</sub> emissions, and Hebei had the largest export-related CO<sub>2</sub> emissions. For the Metal Smelting and Pressing industry, Hebei had the largest export-related SO<sub>2</sub> emissions and the largest export-related CO<sub>2</sub> emissions.



**Figure 4.** Export-related SO<sub>2</sub> emissions and CO<sub>2</sub> emissions of the top three polluting sectors. The first row is Production and Supply of Electric Power and Steam, the second row is Non-metal Mineral Products, and the third row is the Metal Smelting and Pressing industry.

## 5. Conclusions

In this study, we calculated embodied SO<sub>2</sub> emissions and CO<sub>2</sub> emissions in interprovincial trade in China in 2007 and 2010, respectively, using MRIO, in order to analyze the characteristics of interprovincial embodied SO<sub>2</sub> emissions and CO<sub>2</sub> emissions and identify their similarities and differences so as to provide a basis for more integrated environmental policies for governmental decision makers. From 2007 to 2010, China's total SO<sub>2</sub> emissions decreased by 16.1%, while total CO<sub>2</sub> emissions increased by 17.3%. Most provinces' SO<sub>2</sub> emissions declined from 2007 to 2010, whereas, CO<sub>2</sub> emissions of most provinces increased.

This may be related to the environment policies of the Chinese government due to the fact that air pollution is local and impacts public health relatively directly and immediately. Another important aspect is that the amount of SO<sub>2</sub> emissions can be determined by industrial production technology. This fact makes it easier to reduce SO<sub>2</sub> through technological fixes, such as the use of desulfurization equipment [68]. However, reducing CO<sub>2</sub> requires a change in energy mix and a reduction of energy consumption, which is closely linked to economic development [69,70].

Most net CO<sub>2</sub> emissions importers were also net SO<sub>2</sub> emissions importers. SO<sub>2</sub> emissions and CO<sub>2</sub> emissions were transferred from Beijing–Tianjin, the Central coast, and South coast to the Central, North-west, South-west, and North-east regions through interregional trade. Eastern provinces have stricter environmental regulations and higher marginal abatement costs [71]. To avoid the high cost of desulphurization technological applications, some polluting industries were transferred to western regions, which have relatively loose environmental policies. The highly pollution-intensive products are then imported to satisfy the needs of eastern provinces through interprovincial trade.

Production and Supply of Electric Power and Steam, Non-metal Mineral Products, and the Metal Smelting and Pressing industry accounted for 81% and 76% of the total national SO<sub>2</sub> emissions and CO<sub>2</sub> emissions in 2010, respectively. These sectors have significantly driven the increase in SO<sub>2</sub> emissions and CO<sub>2</sub> emissions. Thus, it is of great importance to pay more attention to these sectors and their entire supply chains to achieve emission-reduction targets and control air pollution, such as improving energy efficiency and adopting clean energy.

China aims to reach its carbon emissions peak around 2030, and many provinces have set energy conservation and emission-reduction targets in their respective 13th Five-Year Plan. For example, Guangdong proposes to reduce energy intensity by 17% and SO<sub>2</sub> emissions 3% by 2020 based on the levels of 2015. Research has shown that carbon reduction and air pollution control policies should be simultaneously considered since carbon emissions and some air pollution have the same pollution sources. Strict air pollution control policies could provide an effective mechanism for carbon reduction. Therefore, stricter regulation and enforcement of air pollution control should be included in the comprehensive evaluation system of economic and social development in each province.

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## Appendix A

Due to the lack of sub-sectoral SO<sub>2</sub> emissions of each province, provincial sub-sectoral SO<sub>2</sub> emissions were obtained by sectoral output multiplied by the national sectoral SO<sub>2</sub> emissions intensity. By summing up the SO<sub>2</sub> emissions of each province, we obtain the national SO<sub>2</sub> emissions, as follows:

$$NS = \sum_j PS_j = \sum_j \sum_i PX_i \cdot \frac{NSO_{2i}}{NX_i} \quad (A1)$$

$NS$  represents the national  $SO_2$  emissions,  $PS_j$  is total  $SO_2$  emissions of province  $j$ ,  $PX_i$  is provincial sectoral output.  $NSO_{2i}$  and  $NX_i$  denote the national sectoral  $SO_2$  emissions and national sectoral output, respectively.  $i$  and  $j$  denote sector and province, respectively.

By contrasting the results with the national and provincial  $SO_2$  emissions ( $NS'$  and  $PS'$ , respectively) in the China Statistical Yearbook, we found that  $NS$  were close to  $NS'$ , but the  $SO_2$  emissions at provincial level varied a lot. Based on the total  $SO_2$  emissions of the nation and each province, we calculated the ratio of each province's  $SO_2$  emissions. According to the ratio, we recalculated each province's total  $SO_2$  emissions.

$$APS_j = NS \cdot \frac{PS'_j}{NS'} \quad (A2)$$

Then with the ratio of industrial sector'  $SO_2$  emissions of each province and the output data from IO tables, sectoral  $SO_2$  emissions intensity of each province can be obtained, as follows:

$$PSI_{ij} = \frac{APS_{ij}}{PX_{ij}} = \frac{APS_j \cdot \frac{PX_i \cdot \frac{NSO_{2i}}{NX_i}}{PS_j}}{PX_{ij}} \quad (A3)$$

$PSI_{ij}$  represents the  $SO_2$  emissions intensity of sector  $i$  in province  $j$ ,  $PX_{ij}$  is the output of sector  $i$  in province  $j$ .  $APS_{ij}$  is the adjusted  $SO_2$  emissions of sector  $i$  in province  $j$ .

**Table A1.** Sector correspondence.

Sectors in IO Tables	Sectors In Energy Balance Tables
Metal mining industry	Mining and processing of Ferrous Metal Ores Mining and Processing of Non-Ferrous Metal Ores
Non-metallic ore and other mining industry	Mining and Processing of Non-metal Ores Mining of Other Ores
Food manufacturing and tobacco-processing industry	Processing of Food from Agricultural Products Manufacture of Foods Manufacture of Beverages Manufacture of Tobacco
Textile, leather and feather products industry	Manufacture of Textile Wearing Apparel, Footware, and Caps Manufacture of Leather, Fur, Feather and Related Products
Wood processing and furniture manufacturing	Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products Manufacture of Furniture
Paper printing and sports goods manufacturing	Manufacture of Paper and Paper Products Printing, Reproduction of Recording Media Manufacture of Articles For Culture, Education and Sport Activity
Chemical industry	Manufacture of Raw Chemical Materials and Chemical Products Manufacture of Medicines Manufacture of Chemical Fibers Manufacture of Rubber Manufacture of Plastics Manufacture of Raw Chemical Materials and Chemical Products
Metal smelting and pressing industry	Smelting and Pressing of Ferrous Metals Smelting and Pressing of Non-ferrous Metals
General, special equipment manufacturing	Manufacture of General Purpose Machinery Manufacture of Special Purpose Machinery
Gas, water production and supply industry	Production and Supply of Gas Production and Supply of Water
Wholesale, and retail trade industry Lodging and catering industry	Wholesale, Retail Trade and Catering Services
Leasing and business services Research and development industry Other services	Others

**Table A2.** SO<sub>2</sub> emissions and CO<sub>2</sub> emissions from both production-based and consumption-based accounting methods.

Provinces	Production-Based SO <sub>2</sub> Emissions (Mt)		Consumption-Based SO <sub>2</sub> Emissions (Mt)		Production-Based CO <sub>2</sub> Emissions (Mt)		Consumption-Based CO <sub>2</sub> Emissions (Mt)	
	2007	2010	2007	2010	2007	2010	2007	2010
Beijing	0.06	0.07	0.37	0.30	69.20	70.76	147.26	162.95
Tianjin	0.18	0.14	0.39	0.31	86.87	105.17	153.17	173.23
Hebei	1.09	0.80	0.93	0.73	495.48	515.07	363.06	385.55
Shanxi	0.84	0.83	0.51	0.52	273.02	333.96	159.17	217.19
Inner Mongolia	1.06	0.93	0.38	0.53	294.99	390.44	120.15	246.21
Liaoning	0.89	0.66	0.69	0.58	319.73	354.73	254.15	309.46
Jilin	0.37	0.24	0.63	0.42	196.61	169.71	256.03	235.16
Heilongjiang	0.41	0.34	0.50	0.36	187.86	179.31	212.30	191.55
Shanghai	0.22	0.19	0.60	0.47	105.18	128.61	226.55	243.45
Jiangsu	0.72	0.54	0.82	0.72	323.78	390.35	330.66	422.16
Zhejiang	0.49	0.34	0.94	0.59	225.90	235.98	363.99	332.36
Anhui	0.40	0.35	0.43	0.35	164.04	215.24	161.19	193.71
Fujian	0.26	0.23	0.33	0.29	105.87	144.87	127.20	167.02
Jiangxi	0.43	0.34	0.60	0.40	107.46	113.73	157.10	141.90
Shandong	1.09	0.90	1.16	0.99	495.90	559.91	468.93	547.82
Henan	1.10	0.91	0.79	0.77	347.11	418.14	240.87	344.24
Hubei	0.46	0.41	0.43	0.35	200.05	261.03	178.61	222.14
Hunan	0.62	0.54	0.61	0.52	198.48	214.30	192.78	213.38
Guangdong	0.72	0.56	1.13	0.92	254.70	311.53	359.35	413.51
Guangxi	0.77	0.59	0.63	0.52	112.16	142.48	117.09	158.13
Hainan	0.02	0.02	0.02	0.02	17.15	24.28	17.21	23.77
Chongqing	0.57	0.50	0.53	0.44	87.87	122.47	104.15	127.35
Sichuan	0.88	0.79	0.82	0.63	183.73	254.92	196.56	222.06
Guizhou	0.68	0.75	0.39	0.41	135.03	154.29	95.48	110.14
Yunnan	0.32	0.31	0.32	0.33	126.99	151.84	112.01	154.29
Shaanxi	0.75	0.52	0.58	0.49	139.90	176.91	141.84	194.26
Gansu	0.34	0.37	0.27	0.26	76.27	103.16	68.97	88.44
Qinghai	0.10	0.09	0.11	0.08	25.50	24.87	32.63	29.76
Ningxia	0.27	0.20	0.19	0.17	56.22	77.52	45.86	68.54
Xinjiang	0.41	0.39	0.41	0.36	114.26	137.43	123.01	143.26

**Table A3.** China's eight economic regions.

Regions	Provinces/Cities Included
Beijing–Tianjin	Beijing, Tianjin
North coast	Hebei, Shandong
Central coast	Shanghai, Jiangsu, Zhejiang
South coast	Fujian, Guangdong, Hainan
Central	Shanxi, Anhui, Henan, Hubei, Hunan, Jiangxi
South-west	Inner Mongolia, Xinjiang, Shaanxi, Gansu, Qinghai, Ningxia
North-west	Chongqing, Sichuan, Guizhou, Yunnan, Guangxi
North-east	Heilongjiang, Jilin, Liaoning

**Table A4.** Interregional SO<sub>2</sub> emissions flows in 2007 and 2010 (Mt).

Year	Region	Beijing-Tianjin	North Coast	Central Coast	South Coast	Central	South-West	North-West	North-East
2007	Beijing-Tianjin	-	0.01	0.03	0.01	0.02	0.01	0.01	0.02
	North coast	0.16	-	0.26	0.06	0.15	0.08	0.11	0.14
	Central coast	0.04	0.08	-	0.07	0.12	0.05	0.06	0.05
	South coast	0.02	0.02	0.08	-	0.10	0.07	0.02	0.01
	Central	0.12	0.30	0.46	0.18	-	0.15	0.17	0.11
	Southwest	0.06	0.08	0.18	0.33	0.32	-	0.08	0.04
	Northwest	0.18	0.24	0.32	0.12	0.21	0.14	-	0.32
Northeast	0.07	0.13	0.10	0.04	0.08	0.04	0.06	-	
2010	Beijing-Tianjin	-	0.01	0.02	0.01	0.02	0.01	0.01	0.01
	North coast	0.10	-	0.18	0.04	0.13	0.05	0.10	0.10
	Central coast	0.03	0.05	-	0.05	0.10	0.04	0.06	0.04
	South coast	0.01	0.01	0.06	-	0.08	0.05	0.02	0.01
	Central	0.11	0.27	0.39	0.17	-	0.13	0.18	0.09
	South-west	0.05	0.08	0.16	0.29	0.30	-	0.10	0.04
	North-west	0.14	0.19	0.23	0.09	0.18	0.09	-	0.21
North-east	0.05	0.09	0.07	0.03	0.06	0.03	0.05	-	

**Table A5.** Interregional CO<sub>2</sub> emissions flows in 2007 and 2010 (Mt).

Year	Region	Beijing-Tianjin	North Coast	Central Coast	South Coast	Central	South-West	North-West	North-East
2007	Beijing-Tianjin	-	9.10	16.90	6.54	11.42	8.70	8.47	9.99
	North coast	65.75	-	125.17	31.11	67.85	33.07	46.96	64.32
	Central coast	18.78	35.92	-	27.52	53.83	23.67	28.17	21.19
	South coast	6.04	6.73	26.75	-	33.85	22.67	8.81	5.04
	Central	40.22	99.25	158.27	62.55	-	49.09	56.53	34.08
	South-west	11.76	15.05	36.92	66.22	51.68	-	14.48	7.43
	North-west	44.60	58.08	71.36	26.19	46.56	30.01	-	82.66
North-east	28.32	50.71	40.05	15.80	34.35	15.86	21.34	-	
2010	Beijing-Tianjin	-	8.68	17.26	6.79	12.59	9.45	10.64	8.60
	North coast	60.87	-	118.78	28.14	83.50	31.91	60.83	66.32
	Central coast	23.47	37.82	-	30.94	67.41	27.85	40.75	22.70
	South coast	7.28	7.93	29.67	-	41.99	25.16	14.28	6.08
	Central	48.41	114.46	177.00	73.61	-	56.73	80.59	38.71
	South-west	14.77	21.08	40.25	72.23	63.40	-	27.81	10.39
	North-west	52.53	70.67	76.35	29.98	60.49	31.41	-	81.15
North-east	26.93	48.13	34.65	14.33	36.30	13.38	27.82	-	

**Table A6.** Each province's total SO<sub>2</sub> and CO<sub>2</sub> emissions from Production and Supply of Electric Power and Steam, Non-metal Mineral Products, and Metal Smelting and Pressing industry in 2010.

Provinces	Production and Supply of Electric Power and Steam		Nonmetal Mineral Products		Metal Smelting and Pressing Industry	
	SO <sub>2</sub> Emissions (Mt)	CO <sub>2</sub> Emissions (Mt)	SO <sub>2</sub> Emissions (Mt)	CO <sub>2</sub> Emissions (Mt)	SO <sub>2</sub> Emissions (Mt)	CO <sub>2</sub> Emissions (Mt)
Beijing	0.06	30.52	0.00	3.57	0.00	5.36
Tianjin	0.07	53.98	0.01	3.18	0.04	25.92
Hebei	0.38	190.58	0.07	39.64	0.22	208.81
Shanxi	0.52	171.60	0.04	11.74	0.16	63.24
Inner Mongolia	0.59	251.44	0.06	18.09	0.16	42.87
Liaoning	0.28	156.88	0.10	23.45	0.12	92.18
Jilin	0.12	97.16	0.02	14.19	0.03	20.43
Heilongjiang	0.23	104.37	0.01	9.54	0.01	8.72
Shanghai	0.12	59.87	0.01	2.50	0.02	15.38
Jiangsu	0.26	220.35	0.06	48.36	0.11	69.55
Zhejiang	0.19	149.57	0.03	32.18	0.03	10.68
Anhui	0.19	121.30	0.05	31.39	0.04	26.96
Fujian	0.14	80.21	0.03	19.80	0.02	16.84
Jiangxi	0.17	49.74	0.02	20.50	0.08	21.79
Shandong	0.34	279.49	0.15	48.81	0.12	76.30
Henan	0.36	203.37	0.25	45.79	0.13	61.82
Hubei	0.23	97.09	0.05	45.15	0.05	37.44
Hunan	0.25	81.57	0.07	38.10	0.10	32.76
Guangdong	0.37	185.67	0.05	37.46	0.04	18.29
Guangxi	0.36	54.50	0.04	33.74	0.12	28.52
Hainan	0.01	11.31	0.00	4.10	0.00	0.01
Chongqing	0.26	40.18	0.08	22.76	0.08	14.57
Sichuan	0.41	64.31	0.12	58.73	0.11	42.71
Guizhou	0.58	88.58	0.03	13.07	0.07	11.56
Yunnan	0.19	60.76	0.01	20.19	0.06	27.47
Shaanxi	0.32	95.47	0.03	19.03	0.05	14.34
Gansu	0.21	58.76	0.02	9.15	0.07	19.99
Qinghai	0.06	8.77	0.00	2.82	0.02	4.62
Ningxia	0.15	51.79	0.01	5.70	0.02	6.20
Xinjiang	0.22	70.66	0.02	8.73	0.01	14.89

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