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CO_2 and SO_2 emission characteristics of the whole process industry chain of coal processing and utilization in China

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Abstract The total coal consumption in China is on the rise. The characteristics of CO_2 and SO_2 emissions in the whole process of coal processing and utilization in China are worthy of study. Based on the five links of the whole process of coal production and utilization, including coal production, raw coal processing, logistics and transportation, conversion and utilization and resource utilization, this paper summarized and analyzed the energy consumption and pollutant emission sources of these five links, combined with the US Environmental Protection Agency's AP-42 method and IPCC method, to calculate total pollutant discharge and emission factors, where the emission factors were corrected by conversion efficiency. At the same time, uncertainty analysis is performed about CO_2 and SO_2 emissions. The results showed that CO_2 emissions were 3.657 billion tons, and emission reductions were 61 million tons, and SO_2 emissions were 4,844,500 tons, and emission reductions were 10.3595 million tons in 2015.

Keywords Coal · Industrial chain · CO_2 · SO_2 · Emission characteristics

1 Introduction

China is the largest producer and consumer of coal in the world (Bi et al. 2017; Yin et al. 2014). The total coal resources forecasted has reached 5.9 trillion tons. The discovered coal resource reserves are 2.02 trillion tons, and the predicted resources are 3.88 trillion tons (Ministry of Land and Resources of China 2015).

As shown in Fig. 1 (2017 annual report on the development of the coal industry 2018), China's total coal production increased from 2.57 million tons in 2006 to 3.52 million tons in 2017. From 2006 to 2013, coal production maintained a growth trend. Due to the impact of overcapacity and the new normal of the economy, coal production began to decline from 2014 to 2017, but began to recover in 2017.

As shown in Fig. 2 (Statistical yearbook 2018), The total energy consumption increased from 2.86 billion tons in 2006 to 4.49 billion tons in 2014, an increase of 60% in 12 years. Coal accounts for about 70% of China's total energy consumption but the ratio has been on a downward trend since 2010. In 2017, coal consumption dropped to 60.4%, but it is still the main energy source in China.

Coal development and utilization processes may generate a large amount of atmospheric pollutants, causing a negative impact on the atmospheric environment (Xu et al. 2000; You et al. 2010; Jin et al. 2013; Chen et al. 2014).

1.1 Pollution of the atmosphere by coal development

The pollution caused by underground coal mining to the atmospheric environment mainly comes from the coal seam gas discharged from the mine and the spontaneous combustion of the coal mine waste rock, which generates harmful gases to the atmosphere (Lei et al. 2009). During the open pit mining process, a series of dust pollution is emitted into the air (Ghose et al. 2001; Du et al. 2013). The

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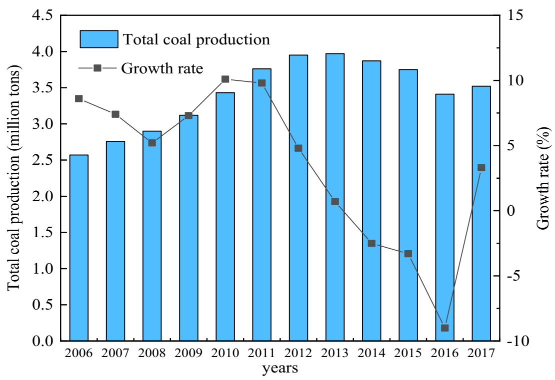

Fig. 1 Total coal production and growth rate in China during 2006–2017

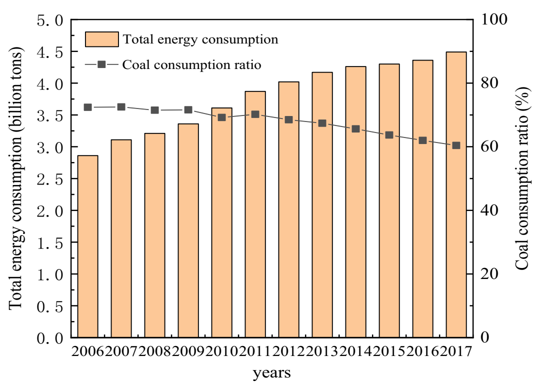

Fig. 2 Total energy consumption and coal consumption ratio in China over the years

greenhouse effect of methane gas is 21 times of carbon dioxide (Rodhe et al. 1990; Zhu et al. 2017). China's emissions of methane gas in 2010 exceeded 20 billion cubic meters. With the increase of underground mining depth, the methane gas emissions will further increase. If we do not increase the intensity of extraction and utilization, it will have a negative impact on climate change.

1.2 Synergistic effects of washing and processing

The air pollutants caused by coal combustion and utilization are smoke and slag. The flue gas produced after coal combustion will increase with the increase of coal utilization. The main reason for the decline in atmospheric environmental quality is caused by the emission of atmospheric pollutants (SO_2, NO_x, particulate matter, etc.) during the utilization of coal. In 2013, China's atmospheric SO_2 and NO_x emissions were 20.439, 22.273 million tons, respectively. of which 85% SO_2, 67% NO_x, and 70% soot were derived from coal-based fossil energy combustion. Among them, insufficient coal washing and processing is an important factor causing air pollution (Tong et al. 2018).

1.3 Positive effects of resource utilization on the atmospheric environment

Coal gangue spontaneous combustion releases a large amount of SO_2 to form acid rain, which makes the soil acidified and salinized, and also causes corrosion of surrounding buildings (Su et al. 2011). As a kind of energy resource, coal mine methane is also a greenhouse gas with a high global warming potential (GWP) (Furukawa et al. 2009; Miller et al. 2019). One ton of methane is equivalent to 21 tons of carbon dioxide equivalent. Therefore, control of coal mine gas can effectively reduce carbon dioxide emissions. Mine water has been used as the water source of the heat pump in foreign countries (Banks et al. 2003). After the mine water source heat pump system is used in the coal mine, the waste heat is recovered, which greatly improves the utilization rate of the mine water. It not only protects the environment, but also achieves great economic benefits and can effectively reduce carbon dioxide and sulfur dioxide emissions (Jablokov et al. 2013).

International agencies, especially major international energy agencies, have always concerned about China's energy and related carbon dioxide emissions, and have made annual estimates based on their own data systems. It shows that China's energy related carbon dioxide emissions show a large increase in the overall trend, but the estimates of various institutions vary (Zhu 2013). Fridley used EIA method of estimating greenhouse gases in the United States, and estimated that China's energy carbon dioxide emissions in 2008 were 6.682 billion tons, of which coal related carbon dioxide emissions were 5.489 billion tons (Fridley et al. 2011). Cui et al. established the 2013 air pollutant emission list of key coal-consuming industries in the Beijing–Tianjin–Hebei region using the method of bottom up. The research showed that the coal power and steel coking industries in the Beijing–Tianjin–Hebei region released 723,500 tons of SO_2, 1,319,900 tons of NOx and 303,600 tons of PM10 in 2013 (Cui et al. 2018). Based on the actual situation of China's coal statistics, Huang (2011) estimated that China's coal-related carbon dioxide emissions in 2005 were 4.458 billion tons according to the IPCC recommended method, and the Monte Carlo model analysis showed that it has a uncertainty of − 3.9% to 23% at the confidence interval of 95% (Huang 2011).

This paper built the emissions and emission factors according to the energy conversion efficiency of the coal conversion and utilization link, which was of positive significance to understand the real emission of air pollutants in China.

2 Analysis of coal industry chain and its affecting factors

The coal development and utilization system consist of various industrial link lines (numbers i, $i = 1, 2, \ldots m$). With coal flow as the main line, each industrial chain is connected in series, as shown in Fig. 3 (Chen 2007).

This study uses statistical methods, combined with the US Environmental Protection Agency (EPA) method (AP-42) to study the participation of China's coal in the emission base. When calculating carbon emissions, the standard coal dioxide emission coefficient recommended by the National Development and Reform Commission Energy Research Institute is 0.67. The Japan Energy Economic Research Institute recommended 0.68, and the US Department of Energy's Energy Information Administration recommended 0.69. The average value of this study is 0.68, which means 0.68 tons of carbon emissions per ton of standard coal, equivalent to 2.493 tons of carbon dioxide emissions. In calculating the sulfur dioxide emissions, the coal-fired sulfur dioxide emission performance of 2015 was calculated to be 0.47 g/kW h. The power supply folding coefficient is 0.315 kgce/kW h in 2015, and the power generation folding coefficient is 0.297 kgce/kW h in 2015. Then, according to the energy consumption and energy conversion efficiency of the five stages of the whole process of coal development and utilization, the pollutants' emissions and emission factor are calculated (where the conversion factor of the conversion utilization section is corrected by the conversion efficiency) as shown in Table 1. Combined with the characteristics of China's coal energy statistics, the following formula is used:

$$A = \sum_{i=1}^{n} B_i \times C_i \tag{1}$$

where A is the emission, 10^4t; B_i is the consumption of energy i, 10^4t according to standard coal; C_i is the emission coefficient of energy i; i is the energy type.

3 Total pollutant emissions from coal

Coal full-process CO_2 emission accounting model, in which coal production, raw coal processing, logistics and transportation, conversion and utilization have a large amount of CO_2 gas discharge, coal gangue power generation in resource utilization, coal gangue building materials also increase carbon dioxide emissions Quantity, but the comprehensive utilization of coal mine gas and mine water has an emission reduction effect on carbon dioxide, and we established CO_2 emission accounting model:

$$E_{tCO_2} = \sum_{i=1}^{5} E_{iCO_2} - \sum_{i=1}^{2} M_{iCO_2} \tag{2}$$

Among them, E_{tCO2} represents the total CO_2 emissions of coal development and utilization; E_{iCO2} represents the CO_2 emissions of coal development and utilization; M_{iCO2} represents the CO_2 emission reduction of resource utilization.

Coal full-process SO_2 emission accounting model, in which coal production, raw coal processing, logistics and transportation, conversion and utilization have a large amount of SO_2 gas discharge. In the process of resource utilization, the comprehensive utilization of coal gangue and mine water has certain certainty for SO_2. The SO_2 emissions accounting model is as follows:

$$E_{tSO_2} = \sum_{i=1}^{5} E_{iSO_2} - \sum_{i=1}^{2} M_{iSO_2} \tag{3}$$

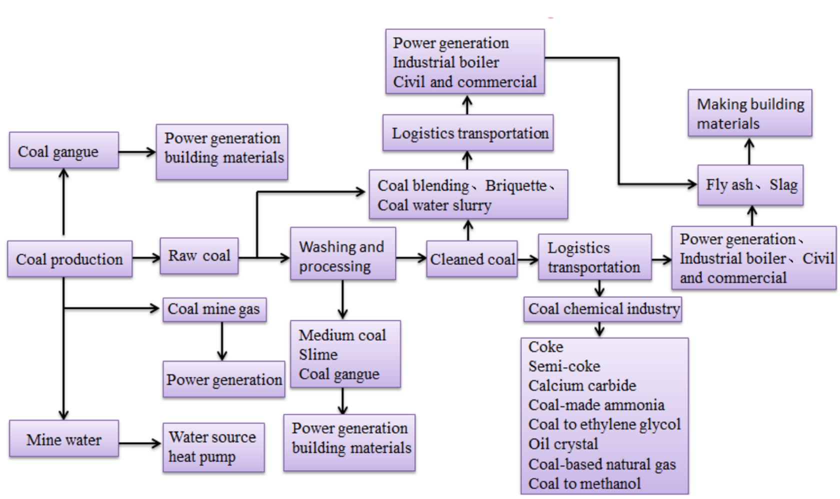

Fig. 3 Analysis of the whole process of coal development and utilization

Table 1 Analysis of factors affecting emissions in the whole process

Link	Element		Influence parameter
Exploit	Overall energy consumption		Raw coal production(billion t)
			Comprehensive energy consumption of raw coal production(kgce/t)
Processing	Washing		Selected amount(billion t)
			Amount of meteorite(billion t)
			Washing energy(ten thousand tce)
			Washing loss(ten thousand tce)
	Coal blending		Total coal energy consumption(ten thousand tce)
	Briquette		Total energy consumption of briquette(ten thousand tce)
	Coal water slurry		Total energy consumption of coal water slurry(ten thousand tce)
Logistics	Railway		Average transport distance of railway(km)
			Unit transportation workload comprehensive energy consumption(tce/million conversion t km)
			Coal railway traffic(billion t)
	Waterway		Average distance of waterway transportation(km)
			Unit transportation workload comprehensive energy consumption(tce/million conversion t km)
			Coal waterway traffic(billion t)
	Highway		Average transport distance of road transport(km)
			Unit transportation workload comprehensive energy consumption(tce/million conversion t km)
			Coal road traffic(billion t)
Utilization	Coal-fired power generation		Thermal power production (Million kilowatt hours)
			Coal-fired power generation(billion kW h)
			The proportion of thermal coal(%)
			Power consumption rate of power plants(%)
	Industrial boiler		Energy conversion efficiency(%)
			The proportion of raw coal consumed by industrial boilers(%)
	Coal chemical industry	Coke	Raw coal(ten thousand t)
		Semi-coke	Raw coal(ten thousand t)
		Calcium carbide	Raw coal(ten thousand t)
		Coal-made ammonia	Raw coal(ten thousand t)
		Coal to ethylene glycol	Raw coal(ten thousand t)
		Coal indirect liquefaction	Raw coal(ten thousand t)
		Coal-based natural gas (billion m^3)	Raw coal(ten thousand t)
		Coal to methanol	Raw coal(ten thousand t)
		–Methanol–Dimethyl ether	Raw coal(ten thousand t)
		–Methanol–Olefins	Raw coal(ten thousand t)
		–Methanol–acetic acid	Raw coal(ten thousand t)
		Direct coal liquefaction	Raw coal(ten thousand t)
	Civil and commercial		Energy conversion efficiency(%)
			The proportion of consumption of raw coal(%)
Recovery	Coal gangue	Power generation	Raw coal production(billion t)
			Coal gangue production(billion t)
			Coal gangue utilization(billion t)
			Power generation using coal gangue(billion t)
			Coal gangue power generation saves energy(ten thousand tce)
		Building materials	Building materials consume coal gangue, including excavation meteorites(billion t)
			Standard coal saved by building materials(ten thousand tce)
	Gas		Gas control and utilization(billion m^3)
			Gas power generation energy savings(ten thousand tce)
	Mine water		Mine water utilization(billion t)
			Water source heat pump saves energy(ten thousand tce)

Among them, E_{tSO2} represents the SO_2 emissions of the whole process of coal development and utilization; E_{iSO2} represents the SO_2 emissions of the five stages of coal development and utilization; M_{iSO2} represents the emission reduction of SO_2 by the resource utilization link. In Table 2, there are the estimations of pollutant emissions and emission reductions of coal processing and utilization in recent years.

4 Uncertainty analysis

The calculation of emissions of atmospheric pollutants in the source list is usually derived from emission factors and activity level data. In the process of inventory preparation, uncertainty exists objectively (Liu et al. 2008). Uncertainty analysis plays an important role in improving the quality and the accuracy of emissions inventories. The study selected Monte Carlo's numerical analysis method to convey the uncertainty of the basic emission unit activity level information and emission factors and obtained the uncertainty of the SO_2 emission inventory in the whole process of coal processing and utilization in 2015.

4.1 CO_2 emission inventory uncertainty analysis results

The simulation results are shown in Fig. 4. The number of repeated calculations of the model is 10,000. Because the input data is assumed to be log-normally distributed, the simulation results of CO_2 emissions in the whole process of coal processing and utilization in 2015 are also log-normal distribution, with an average of 3571.053 million tons, and the median emission level is 3110.2589 million tons, and the 95% confidence interval uncertainty is [− 61%, + 134%]. It can be considered that the list of uncertainty is low and in the acceptable limits.

4.2 SO_2 emission inventory uncertainty analysis results

The simulation results are shown in Fig. 5. The number of repeated calculations of the model is 10,000. Because the input data is assumed to be log-normally distributed, the simulation results of SO_2 emissions in the whole process of coal processing and utilization in 2015 are also log-normal distribution, with an average of 4.476 million tons, and the median emission level is 3.7556 million tons, and the 95% confidence interval uncertainty is [− 62%, + 160%]. It can be considered that the list of uncertainty is low and in the acceptable limits.

5 Conclusions

Based on coal production, raw coal processing, logistics and transportation, conversion and utilization and resource utilization, the national coal situation in the five links, based on the analysis of the five links of energy consumption and pollutant emission sources, combined with the US Environmental Protection Agency's AP-42 The method and the IPCC method were used to calculate pollutant emissions and emission factors (and the emission factors were corrected by conversion efficiency). Through research and calculation, the following main conclusions were obtained:

(1) In 2012, CO_2 emissions were 4.013 billion tons, emission reductions were 48 million tons, SO_2 emissions were 11.306 million tons, and emission reductions were 7,714,500 tons; in 2015, CO_2 emissions were 3.657 billion tons, and emission reductions were 61 million tons, SO_2 The emission is 44845 tons and the emission reduction is 10.3595 million tons.

(2) In 2015, the total pollutant emissions of coal were: 469.272 million tons of CO_2 emissions and 34.42 million tons of SO_2 emissions. The CO_2 emissions from the raw coal processing process were 10.76 million tons and the SO_2 emissions were 0.644 million tons. During the logistics and transportation process, CO_2 emissions were 45.78 million tons and SO_2 emissions were 27.36 million tons. In the process of conversion and utilization, the CO_2 emission during the coal-fired power generation process is 170,266,000 tons, the SO_2 emission is 1,779,200 tons; the CO_2 emission during the

Table 2 Estimation of pollutant emissions and emission reductions of coal processing and utilization in recent years

Year	CO_2 Emissions (billion tons)	CO_2 Emission reduction (billion tons)	SO_2 Emissions (million tons)	SO_2 Emission reduction (million tons)
2010	3.836	0.031	12.262	4.5716
2012	4.013	0.048	1.1306	7.7145
2015	3.657	0.061	4.4845	10.3595

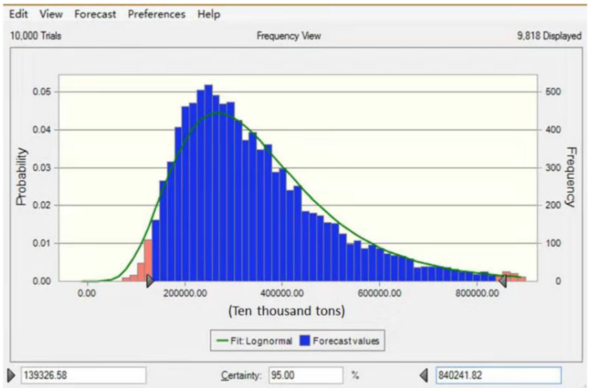

Fig. 4 Simulation results of CO_2 emissions in the whole process of coal processing and utilization in 2015

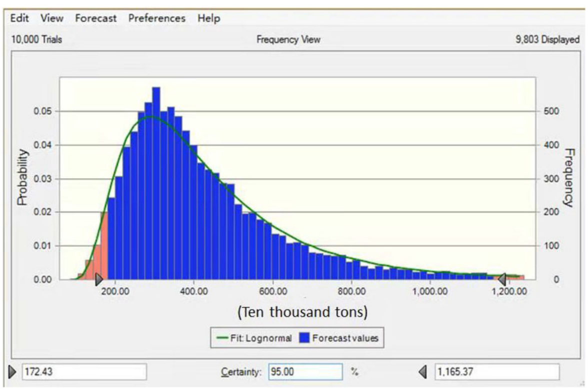

Fig. 5 Simulation results of uncertainty in SO_2 emissions during the whole process of coal processing and utilization in 2015

industrial boiler process is 8,476,700 tons, the SO_2 emission is 767,400 tons; the CO_2 emission during the coal chemical process is 371,962,300 tons, SO_2 emissions are 224,900 tons; in the civil and commercial processes, CO_2 emissions are 12,695,700 tons, and SO_2 emissions are 1,629,600 tons. In the utilization of resources, the comprehensive utilization of coal gangue COD emissions is 87.105 million tons, reducing SO_2 emissions by 10.3593 million tons; the comprehensive utilization of gas reduces CO_2 emissions by 60.677 million tons; the comprehensive utilization of mine water reduces CO_2 emissions by 353,700 tons and reduces SO_2 emissions by 0.012 million. Ton. Among them, the uncertainty of 95% confidence interval of CO_2 emissions is [− 61%, + 134%]; the uncertainty of 95% confidence interval of SO_2 emissions is [− 62%, + 160%].

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