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Working Paper 39
http://ceep.bit.edu.cn/english/publications/wp/index.htm

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August 2012

This paper can be cited as: *Yu S, Wei Y-M, Guo H, Ding L. 2012. Carbon emission coefficient measurement of the coal-to-power energy chain in China. CEEP-BIT Working Paper.*

This study is supported by the National Natural Science Foundation of China under Grant Nos.71103016, the New Century Excellent Talents in University NCET-12-0952, and the China university of Geosciences Takeoff Plan. The views expressed herein are those of the authors and do not necessarily reflect the views of the Center for Energy and Environmental Policy Research.

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Carbon emission coefficient measurement of the coal-to-power energy chain in China

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Abstract: Coal-fired electricity generation has become the largest source of carbon emission in China. This study utilizes life-cycle assessment to assess the effect of carbon emissions and to calculate the coefficient of carbon emissions in coal-to-energy chains. Results show that the carbon emission coefficient of the coal-to-energy chain in China is 875 g/kW h^{-1}, which is a relatively low level compared with that of other countries. CO_2 is the main type of greenhouse gas emission and the most abundant type of direct emission. China has to reduce electrical consumption in the coal-mining process to reduce carbon emissions in coal-to-energy chains, as well as to facilitate railway-line construction to improve the proportion of railway transportation to coal transportation.

Keywords: coal-fired power; carbon emission coefficient; life cycle assessment; sensitivity analysis

1. Introduction

As an important source of global anthropogenic CO_2 emissions, power plants contribute more than 40% of global anthropogenic CO_2 emissions and over 24% of total greenhouse gas (GHG) emissions[1]. With

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the acceleration of industrialization and urbanization in China, the total amount of generated power increased from 1.65 trillion kW h^{-1} in 2002 to 4.72 trillion kW h^{-1} in 2011, of which the proportions of thermal power generation were 80% and 82.54%, respectively. According to statistical data, over 99% of the thermal power comes from the coal-fired thermal power group[2]. Coal resources are relatively abundant in China. Electrical production of China has long been based on coal-fired electricity generation. In 2011, the coal-fired electricity generation capacity of China was 3.8975 trillion kW h^{-1}, with supply consumption of 330 gce/kW h^{-1}. The coal-fired electricity generation capacity of China in 2011 decreased by 3 gce/kW h^{-1} compared with 2010, which indicates that coal-fired electricity generation consumes roughly 1.286 billion tonnes of coal equivalent (tce). The amount of CO_2 produced by coal-fired electricity is approximately 3.164 billion tonnes, and the calculated CO_2 emission intensity of coal is 2.46 kg CO_2/kg. The estimated CO_2 emission in China in 2011 was 8.5 billion tonnes [3], and the emissions from coal-fired electricity generation accounted for 37 percent of total CO_2 emissions. Thus, coal-fired electricity generation is the largest emission source in China.

The energy resource endowment of China, that is, “rich coal, less oil, gas shortage,” suggests that coal is and will always be the main energy resource of the country[4]. In the future, with the improvement of residential living standards and with the growth of the population, the consumption demand for electricity will further increase. Therefore, in the context of global warming, the power industry is bound to become the focus of CO_2 reduction.

Coal poses significant environmental risks not only from direct combustion, but also from mining and transport [5]. On one hand, energy consumption in coal mining produces carbon emissions. On the other hand, CH_4 and other GHGs leak from coal seam mining. Therefore, scholars investigate the types and amount of GHG emissions in the total chain of coal-fired electricity plants to reduce carbon emissions and to establish reasonable carbon emission policies. As a valuable tool in providing a comprehensive “cradle-to-grave” view of the environmental burdens of technology, life-cycle assessment (LCA) is often used to estimate the GHG emissions of energy systems [6]. Over the past two decades, energy analyses of electricity generation systems using LCA have been extensively conducted worldwide [7-9]. Different authors have recently conducted extensive studies on carbon emissions of coal-fired electricity generation in different countries using LCA. Odeh and Cockerill calculated the full life cycle of the GHG emissions of a coal-fired power plant in the United Kingdom [10]. The results of their study indicate that the intensity of GHG emissions of the power plant is 990 g CO_2/kW h^{-1}. Hondo provided GHG emission analyses of nine different power-generation technologies from a life-cycle perspective and argued that the CO_2 emission factor of coal-fired power plants is 975 g/kW h^{-1}, but the photovoltaic factor is only 53 g/kW h^{-1} [11]. The emission factor of Canada is 1.2 kg/kW h^{-1} [12], whereas the emission factor of the United States is approximately (0.84 to 0.86) kg/kW h^{-1} [13]. The emission factor of Germany is (0.66 to 0.77) kg/kW h^{-1} [14]. CO_2 capture and geological storage are recognized as the primary options in the portfolio of GHG mitigation technologies being developed worldwide. Scholars recently investigated the effect of CO_2 emission factor on the implementation of carbon capture and storage of coal-fired power plants based on LCA [15-18]. These studies investigated power generation plants with alternative CO_2 capture systems and concluded that CO_2 capture can reduce CO_2 emissions by approximately 80% throughout the life cycle of power generation.

Based on the carbon emissions of coal-fired power plants in China, Wu *et al.* used a U23 multi-component infrared gas analyzer and TH880F dust analyzer to monitor the CO_2 and N_2O emissions of 30 representative thermal power-generating units in China [19]. The results of the previous study showed that CO_2 emissions are mainly affected by the useful life of installed capacity, as well as fuel and crew and maintenance quality. N_2O emission factors of conventional pulverized coal units decrease with increasing installed capacity. However, this result does not measure the overall emission of coa-to-power energy chains. By using LCA, Xia *et al.* estimated that the carbon emission factor of the coal-to-energy chain in China is 0.97524 kg/kW h^{-1}, through which coal mining in electrical consumption is calculated as a source of thermal power [20]. Thus, the emission factor is overestimated. Furthermore, the 2005 data on emission cannot reflect the present stage of CO_2 emissions of the coal-to-power energy chain in China. Ye *et al.* calculated the thermal energy per kilowatt GHG emissions in an east power plant as 1.018 kg based on the GHG intensity model [21]. In the calculation of indirect carbon emissions in coal transportation, rail transport type is assumed to be only a single electric locomotive. However, Chinese diesel locomotives account for 42.5% of total rail transport.

This paper assesses the effect of carbon emissions based on the current energy consumption of the coal mining industry, transportation, energy consumption, and the technological level of power generation in China. In addition, a sensitivity analysis of the main parameters in the econometric model is conducted to estimate the effect of carbon emissions in the coal-to-power energy chain. Suggestions are proposed for the reduction of GHG emissions in the energy chain.

2. LCA boundary of carbon emissions in coal-fired power plants and the measurement model

2.1 LCA boundary of carbon emissions in coal-fired power plants

According to the principles of LCA analysis, the life-cycle stages of coal-fired electricity generation include upstream, fuel cycle, and downstream processes, as shown in Fig. 1. The upstream processes include the following: raw material extraction, material manufacturing, component manufacturing, transportation from the manufacturing facility to the construction site, and on-site construction. The fuel cycle includes processes modulated by the amount of coal combusted, which include mining, preparation (selecting and washing), transportation, and coal combustion. The downstream processes include waste disposal, power plant decommissioning, and coalmine rehabilitation. Fuel-cycle processes are the major source of carbon emissions in coal-fired electricity energy, including CH_4 leakage, coal self-ignition, and energy consumption. The emission of transportation processes is mainly from the energy consumption of different types of transportation, whereas the emissions of coal-fired power generation are mainly from coal combustion and related auxiliary activities. In this study, the evaluated model focuses on fuel-cycle processes. The upstream and downstream processes are not involved in the model for the following reasons: GHG emissions by equipment manufacturers and material production is relatively small; GHG emissions from construction, decommissioning, and waste disposal are negligible; and emissions related to coal mining and coal transport can be significant [22]. Recent studies have shown that with the improvement of production technology and energy efficiency, the GHG emission proportion of the equipment and materials related to coal-fired power plant construction is declining. A coal-fired generation power plant with 30 years operation, the GHG emission from the equipment and materials is only 0.5% in the total emissions [23], whereas Japan dropped to 0.4% [11].To 2008, the emission's proportion just 0.1% in the United Kingdom [10]. And we can basically negligible. Furthermore, GHG from equipment and materials is a highly controversial issue. According to the principle of LCA, the emission of all nodes associated with the study object should be considered. However, the limitation of the factors to be considered remains unclear. Moreover, determining the energy consumption per unit of electricity is difficult because statistical data in the construction aspects of materials and material consumption are lacking.

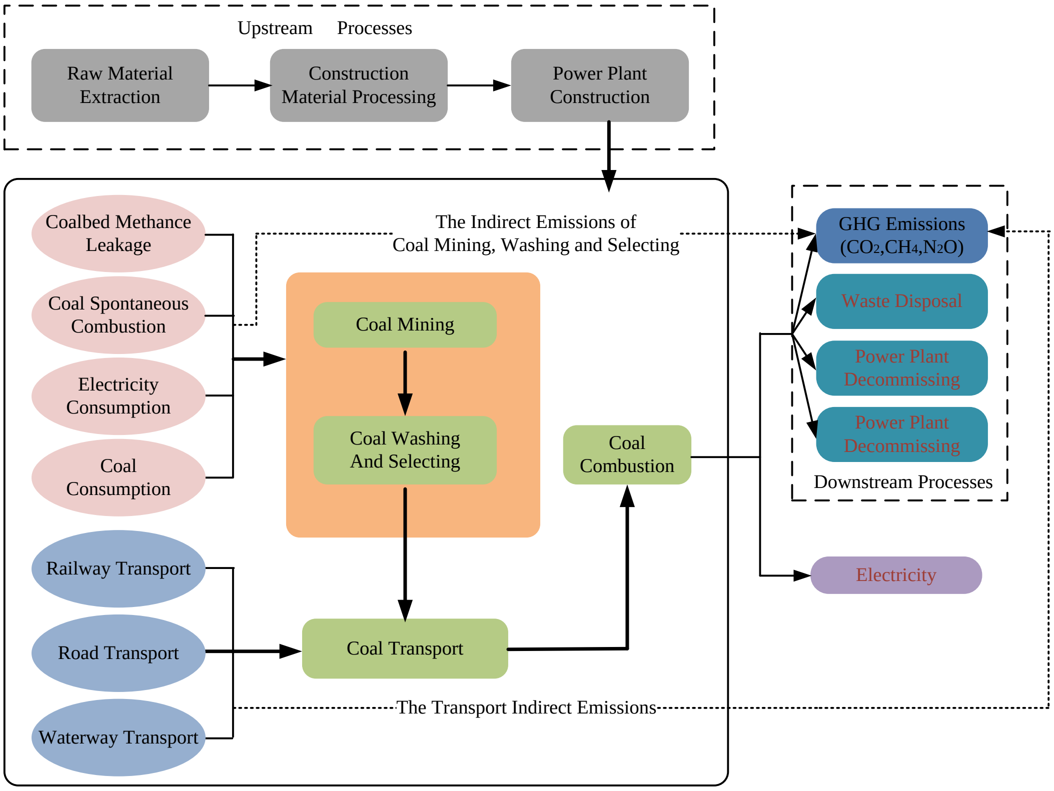

Fig. 1 LCA boundary of carbon emissions of coal-fired power plants

2.2 Measurement model of carbon emissions of coal-fired power plants

Based on the determined boundary in Fig. 1, the GHG of the coal-to-energy chain is mainly produced from the four power generation processes: coal mining, coal washing, coal transportation, and coal combustion. As shown in Eq. (1), this study proposes a model that measures the carbon emission coefficient in the coal-to-power energy chain as a sum of the emission of the four processes.

$$E_{kwh} = M_e + S_e + T_e + G_e, \tag{1}$$

where E_{kwh} is the total GHG emission for a generating unit of coal-fired electricity in the life cycle; M_e is the GHG emission of required coal for a generating unit of coal-fired electricity in the mining process; S_e is the GHG emission of required coal for a generating unit of coal-fired electricity in the selection and coal washing processes; T_e is the GHG emission of required coal for a generating unit of coal-fired electricity in coal transportation; and G_e is the GHG emission of required coal for a generating unit of coal-fired electricity in coal combustion process. The various processes of carbon emission are calculated as follows:

(1) Carbon emissions in the coal-mining process

$$M_e = \sum_{i \in I} ME_i \cdot \delta_i \cdot (1+\lambda) + ME_e \cdot C_v \cdot \rho \cdot GWP_c \, , \quad (2)$$

where ME_i is the i^{th} energy consumed in the generating unit of coal-fired electricity in the mining process; δ_i is the factor of the carbon emissions of the i^{th} energy; λ is the loss rate or spontaneous combustion rate; ME_e is the amount of coaled CH_4 of the coal required in the generating unit of coal-fired electricity in the mining process; C_v is the proportion of CH_4 in the coaled CH_4; ρ is the density of CH_4 under normal temperature and pressure; and GWP_c is the ratio of the greenhouse effect of a unit weight of CH_4 and CO_2 in the atmosphere. Global warming potential (GWP) is used within the Kyoto Protocol of the United Nations Framework Convention on Climate Change as a metric for weighing the climatic effect of the emission of different GHGs.

(2) Carbon emissions in the coal selection and washing process

$$S_e = \sum_{i \in I} SE_i \cdot \delta_i \, , \quad (3)$$

where SE_i is the i^{th} energy required for a unit coal-fired coal consumed in washing, and δ_i is the carbon emission factor for the i^{th} energy.

(3) Carbon emissions in the coal transportation process

$$T_e = \sum_{i=1}^{3} TQ_i \cdot R_i \cdot L_i \, , \quad (4)$$

where TQ_i denotes the GHG emissions of a unit journey required for generating 1 kW h^{-1} coal power in the i -model transport, which is denoted in kg CO_2/t·km; R_i is the proportion of the i -mode of transport for power coal; and L_i is the average transport distance of the power coal in the i -th mode transport.

(4) Carbon emissions in the process of coal-fired power plants

$$G_e = \sum_k Ec \cdot \delta_k \cdot GWP_k \tag{5}$$

where Ec is the coal equivalent consumption for 1 kW h^{-1} coal power, δ_k is the carbon emission factor of the k^{th} GHG, and GWP_k is the global warming potential for the k^{th} GHG.

2.3 Basic principle behind the measurement of the carbon emissions of the coal-to-power chain

To measure the upstream GHG emissions caused by the production of 1 kW h^{-1} coal power in the chain accurately, the amount of raw coal required in the process of coal mining, selection, washing, and transport is calculated. According to the relationship between power generation and coal consumption, the total transportation amount Et required for generating 1 kW h^{-1} coal power can be described as Eq. (6).

$$Et = \frac{Ec \cdot \delta}{1 - \eta} \tag{6}$$

Where Ec is the coal equivalent consumption for power plant (gce/kW h^{-1}), δ is the conversion coefficient between standard coal and raw coal, and η is the total loss rate of power coal transportation. The power coal handling and transport process generally causes spills and dust. However, the value of η is still not official or authoritative in China. According to related research results, the average coal transportation distance by highway is about 1,000 km, and the average loss ratio of China's coal transportation by railway is 1.2%, of which the smallest ratio is 0.8%. The average coal transportation distance by highway is between 100 and 500 km, of which coal transportation loss ratio by automobile is beyond 0.96%[24]. China's steam coal transportation by water way mainly include ocean channel used for shipping coal from north to south China, such as the coal transportation channel of the Yangtze river, the Beijing–Hangzhou Canal, and Xijiang River (coal from regions located in Xijiang upstream such as Baise and Guigang is shipped to Guangdong and Guangxi areas). According to “the goods joint transportation rules of railway and waterway,” the natural reduction standard of coal transported by waterway is fixed at 1.5% [25]. Based on related literature and expert’s suggestions, various transport way distances, ratio, and average loss rates are shown in Table 1. The current average loss rate for transportation in China is calculated to be $\eta = 1.23\%$.

Table 1 Raw coal transport parameters in China*

Mode of transportation	Average transport distance (km)	Percentage (%)	Average loss rate(%)
Railway	1,000	75	1.2
Water Transport	650	17	1.5
Long-distance highway	310	8	0.96
Short-distance highway	50	100	0.96

* 1. Based on references [26] and [27], and expert advice; 2. The sum of all percentages of transport patterns may exceed 100% because of relay phenomenon.

The coal mining, washing, and transportation processes have a significant power demand. However, the electricity consumed in these processes can mainly be attributed to coal-fired power plants. Therefore, carbon emissions from these processes will depend on the amount of carbon emissions by the power generation of coal-fired power plant units. In this study, the emission factor of coal-fired power plants is calculated, and then the carbon emissions of upstream processes such as coal mining, selection, and washing are measured. Finally, various processes of each GHG emission factor are added to derive the total emission factor of the coal-to-energy chain.

3. Data and inventory analysis

3.1 Structure of China’s Coal-fired power generation units

Coal is the primary energy source in China; it provides more than 80% of electricity [28]. Since 1990, China's coal-fired power generation technology has been continuously upgraded. Domestic-made subcritical coal-fired power generation units with a capacity of 300 MW have been used broadly, whereas low-efficiency and high-coal-consumption units with a capacity under 300 MW have been weeded out gradually. Since 2003, domestic-made supercritical (600 MW) and ultra-supercritical (1,000 MW) coal-fired units have been used widely. According to CEC statistics, up to the end of 2010, 6,373 coal-fired power generation units (above 0.6 MW) with a total capacity of 69,349 MW have been used, including 1,169 subcritical, supercritical and ultra-supercritical units with a capacity equal to or greater than 30 MW each [2]. According to sampling statistics of coal-fired generation power units (0.6 MW and above) in China (sample unit capacity is 54,252 MW, taking up 77.1% of the same caliber coal-fired power installed capacity), the shares of various power generation technologies (subcritical, supercritical, ultra-supercritical, and others) are shown in Fig. 2(a). As shown in the figure, subcritical and supercritical power units take up 80.09% of thermal power generation. The proportions of subcritical, supercritical, and ultra-supercritical power units are 40.46%, 20.86%, and 1.86%, respectively [Fig.2(b)]. This result indicates that China's present coal-fired power generation technology is still mainly based on subcritical and supercritical units.

In 2010, supply consumption of subcritical and supercritical generation units are 330 and 317 gce/kW h^{-1}, respectively. According to the different proportions of various power generation units, the average supply consumption of subcritical and supercritical generation units, which share 80.1% of the total coal-fired power generation, is 324 gce/kW h^{-1}.

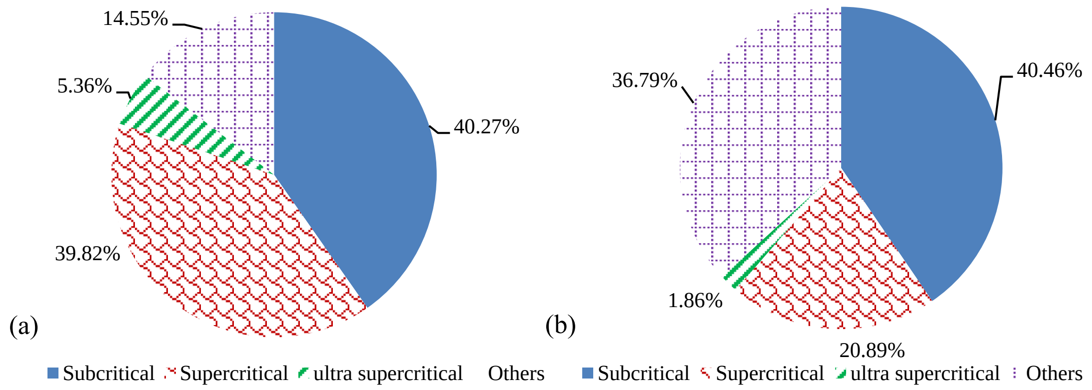

Fig. 2. Proportion of unit number and generating capacity of different coal-fired power generation technologies (2010).

3.2 Data acquisition

The basic data and sources in the calculation process are shown in Table 2.

Table 2 Basic data and their sources

Index		Data	Source
Supply standard coal consumption		324 gce /kW h^{-1} (Converted into raw coal: 459.2395 g/kW h^{-1})	China electric power industry statistics analysis (2011)
CO_2 emission factor per tce		2.4567 t CO_2/tce	National Energy Research Institute
NO_x emission factor per tce		0.0156t NO_x/tce	Energy-saving manual 2006
Conversion factor between raw coal and its coal equivalent		0.7143 tce/t raw coal	2011 China Statistics Yearbook
IPCC GWP of default value of the GHG	CO_2	1	IPCC 4th Assessment Report (2007)
	CH_4	25	
	N_2O	298	

3.3 Inventory analysis[1]

According to Eq. (5) and Table 1, the coal demand (the amount arrived at the plant) required for generating 1 kW h^{-1} coal power is as follows: $Et = 328.0348$ gce; that is, 459.2395 g raw coal.

According to *Chinese Mining Yearbook (2011)*, by the end of 2010, China has 14,357 coal mining enterprises [29]. From the size of coal mining enterprises, the number of small and micro mineral enterprise

[1] The data of the inventory analysis retains four significant digits to accurately measure, but the data of N2O retains six as their small values.

plays a dominant role, accounting for 87.81% [Fig.3(a)]. However, from the coal production, 3.24 billion tons of raw coal is produced, including large and medium coal enterprises that account for 74.90% of the national coal total output (Fig. 3(b)).

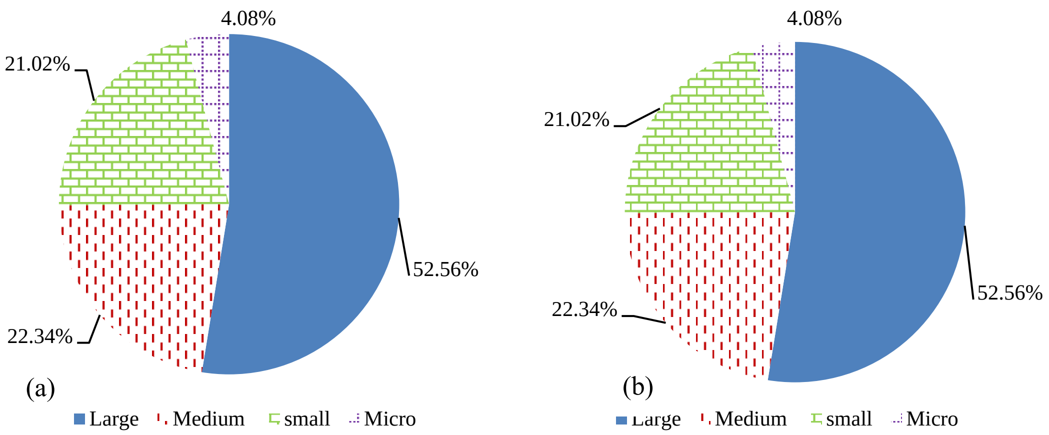

Fig. 3. Number of enterprises and coal production in China (2010).

(1) Inventory analysis of carbon emission in the power generation process

GHGs in coal-fired power plants are mainly composed of CO_2 and a small amount of N_2O. NO_x is generally generated by the conventional combustion mode, in which NO accounts for approximately 90%, whereas N_2O accounts for approximately 1% of the total generated NO_x in coal-fired power plants [30]. Calculation shows that the GHG emissions whn generating 1 kW h^{-1} of coal power using coal combustion are as follows: CO_2 emissions, 328.0348 gce/kW h^{-1} × 2.4567 t/tce = 805.8831 g/kW h^{-1}; and N_2O emissions, 328.0348 gce/kW h^{-1} × 0.0156 t/tce × 0.01 = 0.051173 g/kW h^{-1}. The emission factor of N_2O normalized CO_2 equivalent is 0.051173× 298 = 15.2500 g. Therefore, the CO_2 equivalent emission factor is 821.1328g.

(2) Carbon emission factor calculation in coal mining

① Carbon emission calculation of energy consumption

The coal-mining methods most often used in China are underground and open pit mining. Underground mining accounts for more than 90% of total coal output [20]. Energy consumption in the coal-mining process mainly comes from two sources: power consumption of mining equipment and coal consumption of heating supply boilers in the mine area. According to the Chinese energy consumption indicator and trends of coal output in the mining process provided by the CCRI, the coal consumption of per ton coal output and power consumption in mining in 2000 are 27.7 kg and 33.0 kW h^{-1}, respectively. In 2005, the coal consumption per ton coal output and power consumption in mining are 26.7 kg and 34.3 kW h^{-1}, respectively. China has recently promoted energy saving and emission reduction in coal mining industries vigorously, such that the energy consumption of unit raw coal production began to decrease. In this study, the raw coal consumption of per ton coal production is 25 kg, which is equal to 0.0179 gce, whereas electrical consumption is 34 kW h^{-1}.

CO_2 emissions of 1 kW h^{-1} electricity generation required by raw coal production is 459.2395 g/kW h^{-1} × 0.0179 gce /g × 2.4567g/gce = 20.0950 g/kW h^{-1}, whereas the N_2O emissions are 459.2395 g/kW h^{-1} × 0.0179 gce/g × 0.000156 g/gce = 0.001282 g/kW h^{-1}. The CO_2 equivalent emission coefficient is 0.382149 g in coal mining.

According to the *China Statistical Yearbook*, coal-fired power generation accounted for 80.8% of the total national power generated in 2010. Other forms of power sources are relatively clean energy sources, such as hydropower, nuclear power, and wind power [28] . Accordingly, the electrical consumption per ton raw coal production is 34 kW h^{-1}, of which roughly 27.472 kW h^{-1} came from coal power. Therefore, CO_2 emissions of 1 kW h^{-1} coaled-fire electricity generation, which are caused by electrical consumption in the coal-mining process, are 0.000027 kW h^{-1}/g × 459.2395 g/kW h^{-1} × 805.8831 g/kW h^{-1} = 10.1672 g/kW h^{-1}. The N_2O emission is 0.051173 g /kW h^{-1} × 0.000027 kW h^{-1}/g*459.2395 g/kW h^{-1}=0.000635 g/kW h^{-1}. The normalized CO_2 equivalent emission coefficient is 0.1892 g.

The total GHG emissions of 1 kW h^{-1} coaled-fire electricity generation caused by electrical consumption in coal mining are as follows: CO_2 is 20.0950 g (coal consumption) + 10. 1672 g (power consumption) = 30.2622 g; N_2O is 0.001282 (coal consumption) + 0.000635 g/ kW h^{-1} (electricity consumption) = 0.001917 g; and normalized to CO_2 is 0.5713 g. Thus, the total CO_2 emission is 30.8335 g.

② Calculation of carbon emission in coalbed CH_4 leak in the coal-mining process

Coalbed CH_4 and CO_2 are released in the coal mining, selection, and washing processes, particularly in coal mining. Most of the coalbed CH_4 is directly emitted into the atmosphere because of the large difference between the CH_4 content in the coal bed and the low concentration of CH_4. According to the Ministry of Land and Resources Statistics, coalbed CH_4 extraction volume in China was 8.8 billion m^3 in 2010. However, only 3.6 billion m^3 was utilized, and the remainder was emitted directly into the atmosphere [31]. The CO_2 emission after CH_4 is emitted directly or utilized for power generation is calculated by using Eq. (7).

$$ME_e \cdot C_v \cdot \rho \cdot GWP_c \tag{7}$$

The chemical equation of CH_4 combustion is $CH_4 + 2O_2 = CO_2 + 2H_2O$. Based on the chemical formula of CH_4, one CH_4 molecule is changed into one CO_2 molecule during combustion. The greenhouse effect of the 3.6 billion m^3 CH_4 is lower than that of CO_2 by 1/25 because the GWP_c of CH_4 is 25 times that of CO_2. Therefore, the production of CH_4 in China was 5.344 billion m^3 in 2010. In 2010, the raw coal production in China was 3.24 billion tonnes (*NSB*, 2011), whereas the CH_4 production per raw ton was 1.6494 m^3. CH_4 concentrations in the coalbed differ according to the type and depth of coal fields. CH_4 generally ranges from 20% to 60% in coalbed gases, with 35% to 50% of CH_4 contributing to the total production [32]. Therefore, in this study, the concentration of CH_4 is taken to be 35%; and the density is $\rho = 0.7$ kg/m^3 under normal temperature and pressure, that is, 1.6494 m^3/t × 35% ×0.7 kg/m^3 = 0.404103 kg. The CH_4 emission per ton of raw coal production is 0.000404 g.

The CH_4 emission of 1 kW h^{-1} coaled-fire electricity generation caused by electrical consumption in the coal-mining process is 459.2395 g/kW h^{-1} × 0.000404 g = 0.185533 g /kW h^{-1}. The normalized CO_2 equivalent emission factor is 4.6383 g.

③ Carbon emission calculation of coal spontaneous combustion in the coal-mining process

Raw coal losses exist occur in the mining process, the most important of which is the loss of spontaneous coal combustion. Obtaining the loss rate in China accurately is difficult. Xiao *et al.* estimated that the spontaneous loss rate is approximately 1% in coal mining, that is, 1 t of raw coal mining will be accompanied by a loss of 0.01 t of raw coal spontaneous combustion [33]. The calculation shows that to generate 1 kW h^{-1} coal power, the raw coal amount of spontaneous loss is 4.5924 g raw coal (3.2803 gce), the CO_2 emissions are 8.0588 g, the N_2O emissions are 0.000512 g, and the normalized CO_2 equivalent emission factor is 8.2113 g.

④ Total carbon emissions in the process of coal mining

According to the emission factors of energy consumption as well as the coalbed CH_4 leak and coal spontaneous combustion, the GHG emission of generating 1 kW h^{-1} coal power in the process of mining are as follows: CO_2 emission is 30.3622 g (energy consumption of mining) + 8.0588 g (spontaneous combustion) = 34.4211 g; N_2O emissions is 0.001928 g (energy consumption of mining) + 0.000512 g (spontaneous combustion) = 0.002440 g; and CH_4 emission is 0.185533. Therefore, the total normalized CO_2 equivalent emission is 43.7864 g CO_2.

(2) Calculation of carbon emission factor in coal selecting and washing

GHG emissions are also caused by energy consumption during raw coal selection and washing. Electricity is utilized by equipment in the selection and washing processes. CCRI estimated that, at the present stage of China, the energy consumption per ton of raw coal for the selection and washing processes is approximately 3 kW h^{-1}. The GHG emission of 1 kW h^{-1} coaled-fire electricity generation is as follows: CO_2 = (0.000003 kW h^{-1}/g × 80.8%) × 459.2395 g/kW h^{-1} × 8805，8831 g/kW h^{-1} = 0.8971 g/kW h^{-1}; N_2O = (0.000003kW h^{-1}/g × 80.8%) × 459.2395 g/kW h^{-1} × 0.051173 g/kW h^{-1} = 0.000053 g/kW h^{-1}; and normalized CO_2 equivalent emission is 0.0170 g. However, not all steam coal have been washing and selecting procedures. In 2020, China’s steam coal production is 2.3 billion tonnes, which is the mainly fuel type of coal-fired power generation plants. However, only 0.8 billion tonnes steam coal have been selected, namely the selective rate is only 35% [34]. And then, the total CO_2 emission in the selection and washing processes 0.9141*35%=0.3199 g.

(3) Calculation of carbon emission factor in coal transportation

Coal resources and production in China are mainly concentrated on the “three west” regions of Shanxi, Shaanxi, and western Inner Mongolia. The coal reserves of the regions accounted for 64.1% of coal reserves in China. However, the coal consumption regions are mainly in the east and south coastal areas. The industrial layout forms the basic pattern of coal transportation, which transports from west to east, north to south, and railway and sea combined. The modes of coal transportation in China are railways, highways, and waterways. Railways are mainly used for coal transportat. According to the table of “Transportation of Goods Categories Transport Turnover” in the statistical yearbook, the proportion of railway transportation has remained at nearly 50% in the late 1990s, even approaching 60% in 2001. Statistical data on coal transportation proportion of highway and water in China are missing. Thus, data from the literature and expert advice have been referenced. The distances and proportions of the various modes of transportation are shown in Table 1.

Respirable particulate matter and NO_x emissions of heavy vehicles have become major pollution sources. In some countries and regions, the contribution of diesel engine and other pollutants from heavy vehicles to CO_2 emissions has reached 70% [35]. The emissions from diesel engines are mainly respirable particulate matter and NO_x. NO_x, which is the generic term for various nitrogen oxides in diesel combustion, includes NO, NO_2, N_2O_3, N_2O_4, N_2O_5, and N_2O, among others. Among these oxides, NO content is the highes [36]. N_2O has a small proportion in the traffic exhaust NO_x and can thus be neglected. The specific proportion cannot be determined, and N_2O emissions in the transport sector have not been investigated in previous studies. For these reasons, N_2O emission from coal transportation is no longer considered.

The GHG emissions from the different coal transportation models can be calculated by using the following factors:

① Carbon emission of energy consumption from coal railway transportation

In railways, the transportation task of passenger and freight is undertaken by diesel and electric locomotives. Steam locomotives are only utilized for scheduling in a few regions with undeveloped economies and technologies. The proportion of steam locomotive transportation in China was less than 0.5% in 2010 [37]. Chinese data on the proportion of different locomotives, energy consumption, and average transport mileage of railways have been collected in this study. Data show that the proportions of diesel and electric locomotives were 53.4% and 46.1% in 2010, respectively [38]. Existing published data in 2008 are utilized because of insufficient data on the recent average transport mileage of railways. The energy consumption of diesel locomotive per ton km is 24.9 kg/($10^{\times 4}$ t·km). The millions ton–km power consumption of the electric locomotive is 110.9 kW h^{-1}/ ($10^{\times 4}$ t·km) [39]. In addition, according to the annual report of the *Intergovernmental Panel on Climate Change* (IPCC, 2007), the CO_2 emission factor of diesel is 3.0968 g/kg.

As shown in Eq. (4), the diesel consumption of diesel locomotive for transporting coal, which is required to generate 1 kW h^{-1} power in the plant, is 24.9kg/($10^{\times 4}$ t·km) × 459.2395 g/kW h^{-1} × 1000 km = 1.1435 g.

The electrical consumption of electric locomotives is 111.8 kW h^{-1}/($10^{\times 4}$ t·km) × 459.2395 g/kW h^{-1} × 1000 km = 0.0051 kW h^{-1}.

According to the proportion of diesel locomotives in railway transportation, CO_2 emission from the generation of 1 kW h^{-1} power is 3.5412 g × 53.4% = 1.8910 g. The CO_2 emission from electric locomotives is 0.0053 kW h^{-1}/kW h^{-1} ×805.8831 g/kW h^{-1} × 80.8% × 46.1% = 1.5412 g/kW h^{-1}; N_2O emission is 0.0053 kW h^{-1}/kW h^{-1} × 0.05117 g/kW h^{-1} × 80.8% × 46.1% = 0.000098 g/kW h^{-1}; and the normalized CO_2 equivalent emission is 0.0292 g CO_2. Therefore, the CO_2 emission of railway transportation is 1.8910 g (diesel locomotive) + 1.5412 g (electric locomotive) = 3.4322 g. Thus, the N_2O emission is 0.000098 g, and the total emission is 3.4614 g.

② Carbon emissions of energy consumption from coal highway transportation

The data of energy consumption of highway or waterway coal transportation have not contained in authoritative Statistical Yearbook or other Chinese industry and special statistical yearbooks. Therefore, the energy intensity of highway or waterway transportation has been estimated by referring to related reports and analysis. The average energy consumption of trucks is between 500 and 700 kg oil/$10^{\times 4}$ km [40]. This paper selects the median value of 600 kg/($10^{\times 4}$ t·km).

From Eq. (4), the energy consumption of highway long-distance transportation for coal, which is required to generate 1 kW h^{-1} power in the plant, is 600 kg/($10^{\times 4}$ t·km) × 459.2395 g/kW h^{-1} × 310 km = 8.5419 g diesel per- kW h^{-1}, and the CO_2 emission is 26.4524 g. The diesel consumpution of highway short-distance transportation for coal is 600 kg/($10^{\times 4}$ t·km) × 459.2395 g/kW h^{-1} × 50 km =1.3777g, and the

CO_2 emission is 4.2665 g.

③ Carbon emissions of energy consumption from coal water transportation

As regards water transportation in China, the energy consumption per ton·km of a cargo ship with 300 t load is approximately 50 kg, and the value is approximately 70 kg/10$^{\times 4}$ t·km for 800 t load cargo ships [41]. This study selects the median value 60 kg/(10$^{\times 4}$ t·km). Thus, the diesel consumption of cargo ships for coal transportation, which is required to generate 1 kW h^{-1} power in the plant, is 60 kg/(10$^{\times 4}$ t·km) × 459.2395 g/kW h^{-1} × 650 km = 1.7910 g/kW h^{-1}, and the CO_2 emission is 5.5465 g.

④ Total carbon emissions in coal transportation

According to the transportation proportion of the railway, waterway, long-distance highway, and short-distance highway in electrical coal transportation, the GHG emissions for generation of 1 kW h^{-1} coal-fired electricity is as follows: CO_2, 3.4322 g × 75% (railway) + 26.4524 g × 8% (long-distance highway) + 5.5465g × 17% (waterway) + 4.2665 g (short-distance highway) = 9.8998 g; N_2O, 0.000098 g × 75% (railway) = 0.000074 g; the normalized CO_2 equivalent emission is 0.0219 g. Thus, the total CO_2 emission in the process of coal transportation is 9.9217 g.

3.4 Summary of carbon emission factor in the coal-energy chain

According to the measurement model of carbon emissions in the coal-energy chain, the main GHG emissions of the different processes can be calculated by using the normalized CO_2 equivalent, thereby obtaining the total carbon factor (Table 3). The results retain two decimal places. The CO_2 emission of unit of coal power generation in China is 875.1608 g.

Table 3 GHG emission factor of coal-energy chain (g/kW h^{-1})

Process	Type of emissions	Emission Value	CO_2 equivalent	Subtotal of various process	Total
Mining	CO_2	38,4211	38.4211	43.7864	875.1608
	CH_4	0.185533	4.6383		
	N_2O	0.002440	0.7270		
Selecting and washing	CO_2	0.3140	0.3140	0.3199	
	CH_4	-	-		
	N_2O	0.000020	0.0059		
Transportation	CO_2	9.8998	9.8998	9.9217	
	CH_4	-	-		
	N_2O	0.000074	0.0219		
Electricity generation	CO_2	805.8831	805.8831	821.1328	
	CH_4	-	-		
	N_2O	0.051173	15.2497		

4. Result analysis and discussion

4.1 Result analysis

(1) In the coal-to-energy chain, 1 kW power of coal-fired power plant generates nearly 0.9 kg of CO_2 equivalent emissions, and electricity production is the largest source of emission in the chain. According to the LCA, the current CO_2 emission factor of the coal-energy chain is 0.876 kg. The proportion of GHG

emission of various processes is shown in Fig. 4, which also shows various aspects of the coal-energy chain. The emissions of the power generation process (821.1328 g/kW h^{-1}) account for 93.8% of the total emission in the whole chain, thus being the largest contributor. Carbon emission from coal production is in second place, followed by that from transportation. Carbon emission from the selection and washing processes is the least, accounting for only 0.1% of the total. In 2010, the coal-fired power generating capacity of China was 3.4166 trillion kW h^{-1}, and the estimated total CO_2 emission from the coal-to-energy chain was roughly 29. 90 billion tonnes. The CO_2 emission of coal mining was 149.60 million tonnes. The CO_2 emission from coal transportation was 33.90 million tonnes, whereas that from coal combustion in plants was only 2.81 billion tonnes.

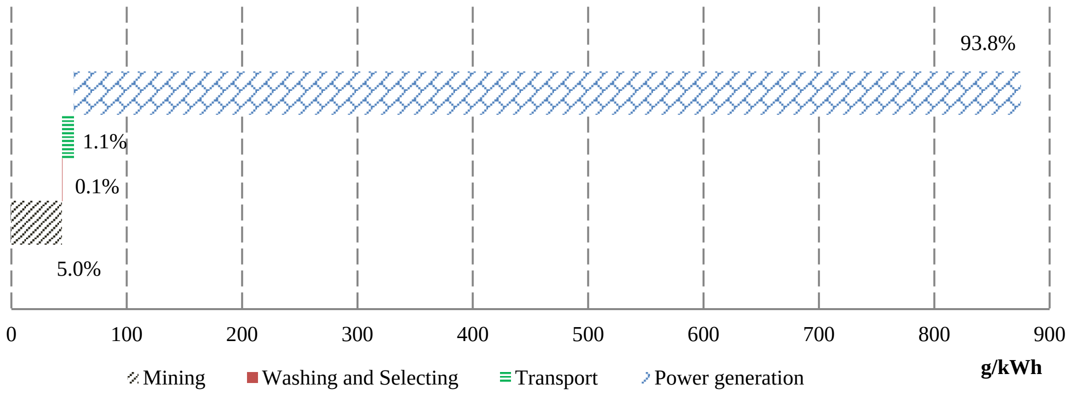

Fig. 4. Proportion of GHG emission of various processes in the coal-energy chain.

(2) In the total coal-to-energy chain, CO_2 is the main type and the most direct GHG emission. As shown in Fig. 5., CO_2 accounts for 97.6% of all types of GHG gases, followed by N_2O. Although CO_2 content is less than CH_4, CO_2 content will be higher than that of CH_4 if the greenhouse effect converts gases into CO_2. The absolute and relative quantities of N_2O and CH_4 are minimal and are thus not the main type of GHG emissions in the chain. CH_4 emission is mainly from the leakage of the coal-mining process, whereas the N_2O emission results from all the processes of the chain, although N_2O emission is minimal. Direct GHG emission mainly results from coal combustion, which accounts for 93.8% of total GHG emission. However,

indirect emissions caused by energy consumption in the processes of mining, transportation, and washing only account for 6.2% of total GHG emissions, as shown in Fig. 6.

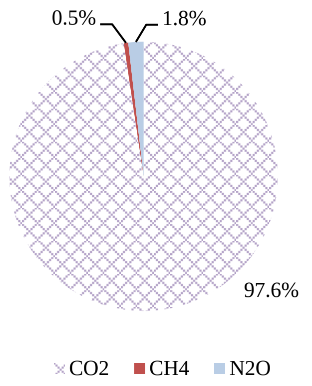

Fig. 5. Proportion of the various GHG emissions

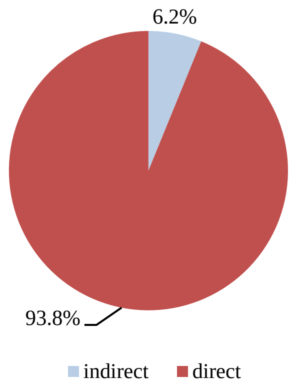

Fig. 6. Proportion of direct and indirect emissions

(3) The total CO_2 emissions per 1 kW h^{-1} of total coal-fired electricity in China are lower than that of other countries. However, China has higher coal mining emissions. A comparison of CO_2 emissions in the coal-to-energy chain of China with that of other countries in existing literature is shown in Table 4. The total emission of China is lower than those of the United States, Japan, and the United Kingdom. This phenomenon may be caused by the recent "encourage large but push down small" strategy of China, which forces small coal-fired power plants to shut down and reduce their coal consumption in power supply. According to statistics, by the end of 2010, China has shut down small thermal power of 72.1 million kW h^{-1}; the coal consumption of 1 kW h^{-1} power supply is 6000 kW h^{-1}; and the above-average power plants dropped to 333 g/kW h^{-1} [42], which is an advanced level in the world. However, the emission of coal mining is significantly higher than that of other countries. The emission in coal mining is mainly caused by the energy consumption in the mining process. Therefore, the energy consumption for mining raw coal in China, which is required to generate 1 kW h^{-1} coal power, is higher than those of the United States, Japan, and the United Kingdom. Thus, changing the current extensive coal mining methods of China, as well as vigorously promoting energy conservation to reduce energy consumption of per ton coal mining, is

necessary.

Table 4 Comparison results on LCEs from coal-fired power plants.

Country of studies	Unit States	Japan	United Kingdom	Unit States	Canada	China
Date	1999[23]	2005 [11]	2008 [10]	2009 [13]	2010 [12]	2010
Assumptions	360 MW, 32% efficiency	1000 MW, 40% efficiency	-	3920 MW 35% efficiency	550MW, 41%	600 MW, 35% efficiency
GHGs	CO_2,N_2O, CH_4	CO_2,CH_4	CO_2,N_2O, CH_4	CO_2,N_2O, CH_4	CO_2,N_2O, CH_4	CO_2,N_2O, CH_4
Coal mining and processing						
CO_2	8.3	9.7	19.0	9.3	2.8	38.5
N_2O				7.3	0.013	0.7
CH_4	19.8	52.9	72.5	0.2	68.7	4.6
Coal Transport						
CO_2	17.7	15.6	1.0	38.7	4.7	10.0
N_2O				1.7	0.0039	0.02
Power generation						
CO_2	967.0	886.8	855.3	939	863.8	805,9
N_2O			9.9	0.6	0.0094	15.3
Total CO_2	933.0	912.1	875.0	987	871.0	854.5
Total GHG	1012.8	965.0	957.4	996.8	940.0	875.2

4.2 Sensitivity analysis

(1) Most sensitive factor

Fig. 2 shows that carbon emissions of coal combustion in plants have the highest emission in the total coal-energy chain and is the most sensitive factor. If the supply coal consumption of unit power generation decreases by 5%, that is, decreases from 324 g/kw to 307.8 g/kw, then CO_2 emission will decrease from 821.1328 g/kW h^{-1} to 780.8825 g/kW h^{-1} per unit power generation. The total CO_2 emission of the unit coal-to-energy chain will fall by 5.1%, thus becoming 830.8396 g. Taking the capacity of coal-fired electricity generation (3.4166 trillion kW h^{-1}) as an example, CO_2 emission will decrease to 173.03 million tonnes.

(2) Sensitivity of energy consumption in the process of coal mining

In all processes of the coal-to-energy chain, the CO_2 emission of mining is the second largest emission source, with coal combustion in plants being the number one emission source. However, the Chinese CO_2 emission factor of coal mining (38.5 g/kW h^{-1}) is higher than that of Japan (8.3 g/kW h^{-1}), the United States (9.3 g/kW h^{-1}), and the United Kingdom (19.0 g/kW h^{-1}). If the unit energy consumption of coal mining drops by 5%, namely the coal consumption of per ton coal production drop from 0.0179 gce to 0.0170 gce, whereas electrical consumption drop to 32.3 kW h^{-1}, then the CO_2 emission of mining will decrease by 3.3%, thereby resulting in a decrease of 0.2% of the total emissions in the chain.

(3) Sensitivity of the mode of coal transportation

According to the calculation of the GHG emissions of coal transportation, CO_2 emissions from the diesel locomotive of railways and electric locomotives used to transport coal for 1 kW h^{-1} coal power generation are 3.5412 g and 3.3432 g, respectively. However, for an average 310 km highway transport, the emission reaches up to 26.4524 g, which is roughly 7.5 times that of rail transport. If the proportion of coal railway transport increases from 75% to 80% and the proportion of highway transport decreases from 8% to 3%, then CO_2 emission from transporting the raw coal required per unit power generation is reduced to 1.1496 g. Thus, the carbon emission of the total coal-to-energy chain will decrease by 0.1%. The 3.4166 trillion kW h^{-1} coal-fired electricity generation of China in 2010 will be reduced to approximately 4.34 million tonnes of CO_2 emission. Therefore, China needs to strengthen its railway line construction for coal transportation to lessen carbon emission.

5. Conclusions

In this study, the carbon emission factor of the coal-to-energy chain is calculated based on LCA. According to the calculated results and the sensitivity analysis, the following results can be concluded:

(1) The carbon emission factor of the coal-to-energy chain in China is 875.2 g/kW h^{-1}, which is a relatively low level compared with other countries. The “encourage large capacity generation units but push down small units” strategy of China has forced small coal-fired power plants to shut down, thereby resulting in the reduction of coal consumption of power plants from 367 gce/kW h^{-1} in 2006 to 333 gce/kW h^{-1} in 2010, with an annual average decrease rate of 2.4%. Therefore, further improving the coal-to-energy conversion efficiency remains the most effective methods to reduce GHG emissions in the coal-to-electricity energy chain.

(2) CO_2 is the main type and the most direct GHG emission. GHG emission mainly results from coal combustion, which accounts for 93.8% of the total GHG emissions. Indirect emissions from the energy consumption in the mining, transportation, and washing processes account for only 6.2% of total GHG emissions.

(3) A significant decline in potential energy use exists in the coal-mining process compared with other countries. In coal-to-power energy chain, China’s CO_2 emissions of coal mining are four times that of the US, twice that of the UK, four times that of Japan, and 10 times that of Canada. High energy consumption and high rates of methane emission are the main reasons that the emissions are high in China. Therefore, to reduce the total emission of the chain, coal-mining companies should enhance their energy conservation and emission reduction measures. In particular, coal mining companies should reduce their electrical

consumption. Conversely, methane utilization should be strengthened, which had direct emissions rates of up to 59.1% in 2010, to reduce greenhouse effect caused by methane emission.

(4) Increasing the proportion of railway transportation in coal transportation is also an important step to reduce carbon emissions of coal-fired power production. Given China's endowment of energy resources, coal transportation has always traversed form northern regions (coal-rich regions) to southern areas and from western to eastern areas because coal and electric power plants are far from each other. Coal transport distance is long (average transport distance of up to 1,000 km in 2010). Thus, strengthening mine power plant construction in coal mining area to shorten the distance of coal transportation is an important measure for reducing carbon emissions of the chain. Moreover, emissions caused by highway transportation are 7.5 times those of railway transportation. However, the capacity of coal railway transportation is limited. Constructing a coal railway transport line between coal mines and coal-fired power plants as well as increasing the proportion of coal railway transportation are other measures to reduce emissions from power coal transportation.

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