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Life cycle assessment and environmental cost accounting of coal-fired power generation in China

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ABSTRACT

It is necessary to analyze the environmental impact of the entire process of coal-fired power generation to take effective measures for controlling energy consumption and reducing pollutant emission. However, very few studies have examined the coal mining, washing and transportation stages in the life cycle of coal-fired power generation and it's environmental cost. In this study, the life cycle assessment (LCA) method was adopted to analyze the environmental impact of coal-fired power generation in China. Further, the relevant cost theory was used to calculate the resource consumption cost and external environmental cost of coal-fired power generation. The key environmental impact category was smoke and dust, and the main emissions were CO_2, CO, SO_2, TSP, COD, and boiler ash. The emissions with high environmental cost were coal, SO_2, COD, and boiler ash. The environmental cost at the power generation stage was the highest, with a value of $50.24. The resource consumption cost and external environmental cost per unit of MWh power in the life cycle was $46.01 and $22.90, respectively. Upgrading the facilities for emission reduction, improving emission standards of pollutants, and strengthening process management of coal-fired power generation are effective ways to reduce the burden on the environment.

1. Introduction

China is one of the few countries in the world using coal as the primary source of energy, with 30% of coal production being used to generate power for domestic use. Moreover, the amount of coal-fired power generated in 2014 reached 5 trillion kWh in China, accounting for about 75% of the total power generated, which was higher than the international average of 28% (Dai, 2014). In recent years, China has committed to reducing the proportion of coal-fired power generation, but it continues to the main source of power generation due to the difficulty in developing nuclear power, hydropower, wind power, and solar power (Hou, 2015). Coal-fired power generation leads to serious environmental pollution, such as air pollution, water pollution, and noise pollution (Andrae and Edler, 2015; Cristobal et al., 2012; Rigotto, 2009; Song and Li, 2015; Zhou et al., 2013). Conducting environmental remediation to mitigate pollution requires huge costs. In addition, these environmental problems are associated with the entire process of coal-fired power generation. Therefore, the environmental impact over the entire life cycle should be synthetically and scientifically analyzed to take specific measures for optimizing resources, controlling energy consumption, and reducing pollutant discharge, and eventually improving the economic, social, and environmental benefits derived from the coal-fired power generation industries (Buke and Kone, 2011; Li and Gibson, 2014; Marshall, 2005).

As LCA is the most effective tool in environmental management, it can be used to comprehensively and scientifically analyze environmental impact from cradle to grave to determine the opportunities for mitigating environmental impact (Finkbeiner et al., 2006; Itsubo and Inaba, 2010; Itsubo et al., 2015). The purpose of an LCA of the coal-fired power generation is to analyze the environmental impacts and advance relevant strategies to promote the sustainable development of coal-fired power generation (Lelek et al., 2016; Spath et al., 1999).

Abbreviations: BOD, Biochemical Oxygen Demand; CCS, Carbon Capture and Sequestration; CCY, China Communication Yearbook; CESY, China Energy Statistical Yearbook; CEY, China Environment Yearbook; CFB, Circulating Fluidized Bed; CH_4, Methane; C_2H_4, Ethylene; CHP, Combined Heat and Power; CO, Carbon Monoxide; CO_2, Carbon Dioxide; COD, Chemical Oxygen Demand; CSY, China Statistical Yearbook; EIA, Environmental Impact Assessment; EU, European Union; Fe, iron; GHG, Greenhouse Gas; IGCC, Integrated Gasification Combined Cycle; KWh, Kilowatt Hour; LCA, Life Cycle Assessment; Mcal/kg, Million Calories Per Kilogram; MWh, Million Watt Hour; N, Nitrogen; NO^{3-}, nitrate ion; N_2O, Nitrous Oxide; NO_x, Ox Nitride; P, Phosphorus; PM_{10}, Particulate Matter; SEA, Strategic Environmental Assessment; SO_2, Sulfur Dioxide; SS, Suspended Substance; TSP, Total Suspended Particulate; UK, the United Kingdom; USA, the United States of America

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Some attempts have been made to analyze the environmental impacts of coal-fired power generation using LCA and other methods. For example, Say et al. (2007) assessed the environmental impact of a coal-fired power plant in Turkey using the environmental assessment software C-EDINFO. Steinmann et al. (2014) presented a novel method of Monte Carlo simulation for differentiating uncertainty from variability in LCAs of coal-fueled power generation in the United States, with a specific focus on greenhouse gas emissions. In addition, some software has been applied to the LCA of coal-fired power technology. For example, database software has been used to conduct the LCA of a coal-fired power plant in Florida, quantitatively and qualitatively comparing the contributions of different pollution, including air pollution, water pollution, solid waste pollution, and heavy metal pollution (Babbitt and Lindner, 2005). The inventory database (ecoinvent) has been used to calculate updated unit process data for Chinese coal power at both the national and the provincial level (Henriksson et al., 2015).

Some attempts have also been made to evaluate the environmental impact of coal-fired power generation with a focus on greenhouse gas (GHG) or carbon capture and sequestration (CCS) using LCA. For example, Koornneef et al. (2008) analyzed the CCS of the flue gas project in a coal-fired power plant in the Netherlands using environmental impact assessment (EIA) and strategic environmental assessment (SEA). Odeh and Cockerill (2008) evaluated the environmental impact of pollution gas emissions from pulverized coal-fired power plants in the UK. Whitaker et al. (2012) focused on reducing variability and clarifying the central tendencies of the estimates of the life cycle of GHG emissions of utility-scale coal-fired electricity generation systems. Modahl et al. (2012) discussed the weighting of environmental trade-offs in CCS of a fossil gas power plant. Corsten et al. (2013) performed an assessment of the existing LCA literature to obtain insights into potential environmental impacts over the complete life cycle of fossil fuel fired power plants with CCS. Liang et al. (2013) presented a complete life cycle model and a comparative assessment of current clean coal-fired power generation technologies in China, revealing that the CCS technologies can reduce the total life cycle of CO_2 emissions from coal-fired power plants.

In addition, LCA has been used to calculate external environmental costs (Bauer et al., 2008; Eliasson and Lee, 2003). Epstein et al. (2011) have estimated the total economically quantifiable costs of coal-fired power generation in Appalachia of the United States, with a focus on the multiple hazards of pollution that affect our health and the environment. A brief life cycle inventory analysis of the external environmental cost of coal-fired power generation has been conducted in Indonesia, with the external environmental costs of PM_{10}, SO_2, NO_X and CO_2 calculated using the loss cost (Wijaya and Limmeechokchai, 2010). There are five main methods of assessing the external environmental costs of power generation: (i) the cost of damage caused by pollutants; (ii) the cost of removal and compensation of pollution damage; (iii) the cost of preventing the occurrence of pollution; (iv) the cost of making people willing to pay to avoid pollution; and (v) the cost of marginal emission control (Itsubo et al., 2015; Kitou and Horvath, 2008; Klöpffer, 2011). From the beginning of the 1990s, damage costs were mainly used for the measurement of the external environmental cost of power generation in the United States and European countries (Alnatheer, 2006). Methods of estimating the external environmental cost of coal-fired power generation include the Exmod method of New York and the ExternE method of the European Union (EU) (El-Kordy et al., 2002). Exmod was applied to analyze the external environmental costs of a New York power plant in 1995 (Bernow et al., 1997). The ExternE method is currently being widely used as a standard method to calculate the environmental costs of power generation (Dones and Heck, 2011; Kitou and Horvath, 2008; Krewitt and Nitsch, 2003; Lenzen, 2006). The method based on the “impact path method" is used to quantify the environmental impact using the exposure-response function and the dose-response function and calculate the monetary value using people's willingness-to-pay (Zhang and Duan, 2003). On the basis of this, the EU has developed a computer model, EcoSense, which includes the atmospheric pollutant dispersion model, the dose-response curve, and the monetary quantitative method (Kareda et al., 2007; Schleisner, 2000). End-point Modeling version 2 (LIMEv2) was also used to estimate the eco-environmental cost of using LCA method. LIMEv2 is one of the several end-point methods that express the end-point damages in monetary units (Andrae, 2015).

In summary, some attempts have been made to examine the environmental impact of coal-fired power generation. However, there are still many problems that need to be explored. First, most of the research focus on a certain stage or a certain category of environmental impact of coal-fired power generation and does not analyze the environmental impact of the entire life cycle systematically and comprehensively; for instance, coal mining, washing, and transportation stages were not covered in the entire life cycle of coal-fired power generation. Second, the algorithm of environmental cost was not generic enough due to the strong specificity. Finally, the application of external environmental cost analysis methods on the LCA of coal-fired power generation was rare. Therefore, the objectives of this study were to (i) construct the LCA index system of the coal-fired power generation technology, covering the coal mining, washing, and coal transportation stages, based on the LCA method, (ii) calculate coal-fired power generation life cycle resource consumption and external environmental costs using the related cost theory, and (iii) determine the main source of environmental impact by explaining the LCA results of the coal-fired power generation.

2. Data collection and methodology

2.1. Data collection

The entire process of coal-fired power generation consumes a large amount of resources and discharges large amounts of pollution gas, wastewater, and solid waste. The resource consumption data and pollutant discharge information were collected from the China Statistical Yearbook (CSY, 2014), China Energy Statistical Yearbook (CESY, 2013), China Environment Yearbook (CEY, 2014), China Communications Yearbook (CCY, 2014), and previous research results. The data from each yearbook indicates the national average level.

The data on resource consumption (including coal, diesel, gasoline, water, and electricity) were obtained from the China Energy Statistical Yearbook (CESY, 2013). The standard coal, which gives 0.0293 GJ/kg of energy, was used in this study. The combustion of 1 kg standard coal can emit approximately 2.46 kg CO_2, 0.08 kg SO_2, 0.02 kg NO_x, and 0.68 kg dust (Xia et al., 2010). The consumptions of steel, wood and limestone were calculated according to the average of four coal-fired power generation plants provided in Zhou's report (Zhou, 2011). The emissions of carbon oxides, sulfur dioxide, methane, and other gaseous pollutants generated by the coal combustion process were derived from the China Environmental Yearbook (CEY, 2014) and the software eBalance (Integrated Knowledge for our Environment, China). Railway was considered as the transportation mode in this study, and the average transportation distance was found to be 722 km according to the China Communications Yearbook (CCY, 2014). The emissions of nitrogen oxides, smoke and dust, and other pollutants discharged in the coal transportation stage were derived from the China Communications Yearbook (CCY, 2014) and the software eBalance. The data on the eutrophic wastewater emissions were taken from the China Statistical Yearbook (CSY, 2014) and Li's report (Li, 2014). The amount of solid waste discharged was derived from the China Energy Statistical Yearbook (CESY, 2013).

2.2. Methodology

2.2.1. Life cycle assessment

As an analysis tool, LCA is used to quantify the various emissions, resource consumption, and energy use derived from the processing of raw materials to the final product. As compared to the traditional environmental impact assessment and environmental accounting, the advantage of LCA lies in considering the entire life cycle of the product, rather than the individual production stage only (Corrado et al., 2006; Zah et al., 2007).

In this study, the life cycle of the coal-fired power generation technology was assessed, and resource consumption and pollutant emissions of the life cycle chain were analyzed based on the research framework of LCA defined by GB/T24040. GB/T24040 is a national standard on the principles and framework of LCA released by China based on the 14040/14044 ISO (Chen et al., 2009).

2.2.2. *System boundaries*

LCA was used to analyze resource consumption, energy use, and environmental emission in the entire life cycle coal-fired power generation, and discuss the entire life cycle environmental impact combined with a method of cost accounting. The purpose was to propose measures to improve coal-fired power generation technology and guide power generation technology development in a clean and efficient direction. In this study, except for the power generation stage, the coal mining, washing, and transportation stages were also included in the LCA of coal-fired power generation. The system input includes raw materials and energy, and the system output includes available products, waste water and gases, noise, and solid pollutants (Spath et al., 1999). The description and scope of the system boundary of coal-fired power generation technology is depicted in Fig. 1.

2.2.3. *Functional unit*

In this study, the eBalance software was used to conduct the LCA of coal-fired power generation technology. LCA involves many quantitative calculations. To facilitate calculation and comparison of the assessment results, the functional unit of each subsystem needs to be unified. One ton of coal, which gives 0.0293 GJ/kg of energy, was used as the functional unit of the LCA in the coal mining, washing, and transportation stages. 1 MWh power was used as the functional unit of the LCA in the power generation stage, and the produced power was added to the power plant's own power use and the losses were subtracted. The functional unit in the coal mining, washing, and transportation stages was converted to 1 MWh of power by calculating energy conversion efficiency and using 1 MWh of power as the functional unit of the LCA in all stages.

2.2.4. *Life cycle inventory*

Life cycle inventory analysis of coal-fired power generation involves quantifying the input and output of resources, energy, and emissions for each subsystem in the entire life cycle. It was constructed on the basis of the functional unit for the input and output data on resources and energy, but the effective data need to be standardized. The categories of emissions and resources were confirmed by previous research, a field survey, and expert consulting (Dones et al., 2005; Gagnon et al., 2002; Hondo, 2005; Kannan et al., 2007; Peiu, 2007). The life cycle inventory according to the collected data and the determined major emissions and consumed resources is listed in Table 1.

2.2.5. *Impact assessment*

The LCA of coal-fired power generation was used to sort all categories of mid-point impacts qualitatively or quantitatively based on the consumption data of resources and energy and the output data of emissions from the inventory analysis. Impact assessment was divided into three steps: classification, characterization, and quantification (Finkbeiner et al., 2006; Liu et al., 2009; Mangena and Brent, 2006). In addition, the location and population density were disregarded in this study as the research subject included the entire coal-fired power sector in China.

2.2.5.1. Classification. The classification of the environmental impact assessment refers to the sorting of emissions and resources consumed by different mid-point impact categories. They were divided according to research purpose, research scope, inventory analysis, and the characteristics of coal-fired power generation. The main mid-point impact category and the classification results are shown in Table 2 (Deng and Wang, 2003; Li, 2008; Wang, 2001; Wu, 2006; Yang and Xu, 2002). The sources of equivalent factors in Table 2 were taken from Wu's report (Wu, 2011).

2.2.5.2. Characterization. The equivalent factor method was used for characterization. The environmental impact potential was used to represent the summation of the contributions from the emissions of each mid-point impact category. The calculating formula is as follows:

$$EI(n) = \sum EI(n)_m = \sum [C(n)_m \times EF(n)_m], \tag{1}$$

where m is the m-th emission, n is the n-th kind mid-point impact category, $EI(n)$ is the environmental impact potential of the n-th kind mid-point impact category, $EI(n)_m$ is the m-th emission or resource contribution of the n-th kind mid-point impact category, $C(n)_m$ is the emission or consumption of the m-th emission or resource of the n-th kind mid-point impact category, and $EF(n)_m$ is the equivalent factor of the m-th emission or resource of the n-th kind mid-point impact category.

2.2.5.3. Quantification. Quantification was divided into two calculation processes: standardization and weighting. All social resources per capita consumption and the potential environmental impact per

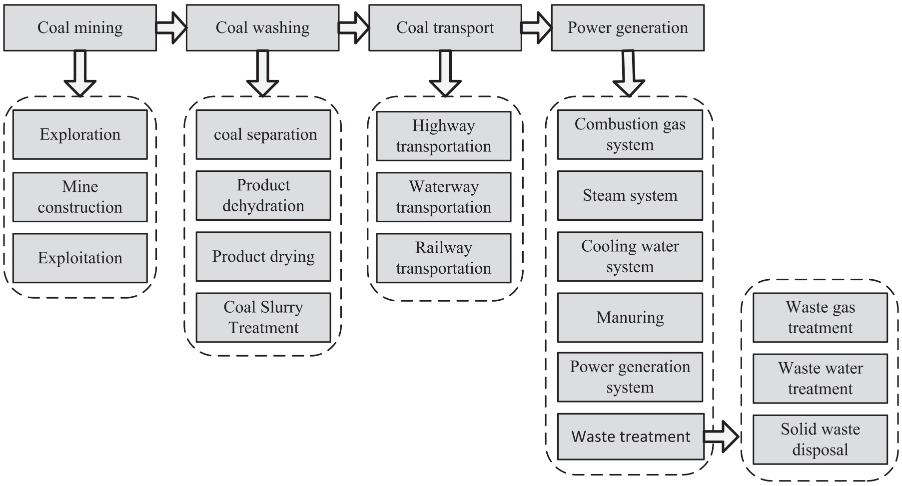

Fig. 1. System boundary of coal-fired power generation technology.

Table 1
Life cycle inventory of coal-fired power generation technology. These figures are valid for 1 MWh of power produced.

Emissions/resources	Unit	Total	Stages			
			Coal mining	Coal washing	Coal transportation	Power generation
Coal	kg	389.62	11.23			378.39
Steel	kg	0.90	0.90			
Wood	kg	1.01	1.01			
Limestone	kg	4.00				4.00
Gasoline	kg	3.71	0.14		3.56	
Diesel	kg	3.06	0.07		2.99	
Water	kg	4624.29	611.30	692.91		3320.08
Electricity	kW h	53.10	8.03	3.49		41.58
CO_2	kg	776.79	9.58		159.19	608.02
CO	kg	12.74	0.32		1.58	10.84
SO_2	kg	21.17	0.65		1.30	19.22
NO_X	kg	2.66	0.07		0.32	2.27
N_2O	kg	1.98	0.14		0.58	1.26
CH_4	kg	2.16	1.69		0.43	0.04
TSP	kg	45.21	0.00	7.81	37.26	0.14
COD	kg	13.00	0.08	0.03		12.89
BOD	kg	0.10	0.08	0.01		0.02
SS	kg	0.19	0.15	0.01		0.02
N	kg	0.09	< 0.01	< 0.01		0.09
P	kg	0.02	0.01	0.00		0.01
Coal gangue	kg	11.66	2.56	9.11		
Boiler ash	kg	78.44	7.31			71.13
Desulfurization gypsum	kg	0.01				0.01
Living garbage	kg	0.06	0.01	0.02		0.03
Peat	kg	0.02		0.02		

Note: TSP – total suspended particulate; COD – chemical oxygen demand; BOD – biochemical oxygen demand; SS – suspended substance.

Table 2
Emissions and resources of coal-fired power generation and their equivalents.

Mid-point impact category	Emissions/ resources	Primary standard	Equivalent coefficient of unit	Equivalent factor
Resource consumption	Steel	Fe	kg Fe/kg Material	3.82
	Wood			0.04
	Coal			0.03
	Limestone			0.82
	Gasoline			1.47
	Diesel			1.46
	Water			0.01
	Electricity			0.10
Global warming	CO_2	CO_2	kg CO_2/kg emission	1
	CO			2
	CH_4			25
	N_2O			320
Photochemical ozone creation	CO	C_2H_4	kg C_2H_4/kg emission	0.03
	CH_4			0.01
Acidification	SO_2	SO_2	kg SO_2/kg emission	1
	NO_X			0.7
Health hazard	CO	CO	kg CO/kg emission	1
	SO_2			100
	NO_X			65
Smoke and dust	TSP	TSP	kg TSP/kg emission	1
Eutrophication	COD	NO_3^-	kg NO_3^-/kg emission	0.23
	BOD			1.79
	SS			0.85
	N			4.43
	P			32
Solid waste	Coal gangue	Peat	kg Peat/kg emission	1
	Boiler ash			1
	Peat			1
	Desulfurization gypsum			1
	Living garbage			1

capita contribution were used as a standardized benchmark to calculate the environmental impact potential of each mid-point impact category in the coal-fired power generation process. The calculating formula is as follows:

$$SI(n) = EI(n) \times \frac{1}{U \times R(n)}, \tag{2}$$

where n is the n-th kind mid-point impact category, $SI(n)$ is the standardized environmental impact potential of the n-th mid-point impact category, U is the life cycle time of the functional unit, $R(n)$ is the standard benchmark of the n-th kind mid-point impact category in the base year, and $EI(n)$ is the environmental impact potential of the n-th kind mid-point impact category.

In this study, the weight of environmental impact in the life cycle of coal-fired power generation was determined by the expert scoring method. The experts gave the weight scores based on a questionnaire. The calculating formula is as follows:

$$WI(n) = W(n) \times SI(n), \tag{3}$$

where n is the n-th kind mid-point impact category, $WI(n)$ is the weighted environmental impact potential of the n-th kind mid-point impact category, $W(n)$ is the weight of the n-th kind mid-point impact category, and $SI(n)$ is the standardized environmental impact potential of the n-th kind mid-point impact category.

The contribution of each emission or resource can be calculated by the amount of emission or consumption multiplied by its equivalent factor. The contribution rate of each emission or resource to its environmental impact category can be obtained according to the ratio between them. The calculation results are presented in Table 3. Through the process of characterization, standardization, and weighting, the contribution rate of each mid-point impact category can be obtained, and the results are presented in Table 4.

2.2.6. Resource consumption cost and external environmental cost accounting

According to the product cost theory and the environmental cost theory of life cycle, the actual costs include resource consumption cost

Table 3
Contributions of different emissions and resources and the contribution rates of the environmental impact categories. These figures are valid for 1 MWh of power produced.

Mid-point impact category	Emissions/ resources	Contributions	Contribution rates
Resource consumption	Steel	3.60	4.7%
	Wood	0.04	0.1%
	Coal	11.88	16.1%
	Limestone	3.24	4.5%
	Gasoline	5.40	7.5%
	Diesel	4.68	6.1%
	Water	39.24	53.9%
	Electricity	5.40	7.1%
Global warming	CO_2	776.86	52.2%
	CO	22.68	1.5%
	CH_4	50.76	3.4%
	N_2O	637.18	42.9%
Photochemical ozone creation	CO	< 0.01	78.5%
	CH_4	< 0.01	21.5%
Acidification	SO_2	17.64	92.6%
	NO_X	1.44	7.4%
Health hazard	CO	1.44	0.4%
	SO_2	356.03	88.9%
	NO_X	43.20	10.7%
Smoke and dust	TSP	45.36	100%
Eutrophication	COD	2.88	67.4%
	BOD	0.18	4.1%
	SS	0.14	3.6%
	N	0.36	10.4%
	P	0.72	14.5%
Solid waste	Coal gangue	11.52	12.9%
	Boiler ash	78.48	87.0%
	Peat	0.02	< 0.1%
	Desulfurization gypsum	0.01	< 0.1%
	Living garbage	0.07	< 0.1%

and external environmental cost. The resource consumption cost of coal-fired power generation was classified as an internal cost from industries, and an external environmental cost resulted from other mid-point impact categories.

2.2.6.1. Resource consumption cost accounting. The resource consumption cost is equal to the actual resource consumption multiplied by the resource price at different stages of coal-fired power generation. The calculating formula is as follows:

$$C'(i) = \sum_{j=1}^{m} Q'(j)_i \times P'(j)_i, \tag{4}$$

$$C'(j) = \sum_{i=1}^{n} Q'(j)_i \times P'(j)_i, \tag{5}$$

$$C' = \sum_{i=1}^{n} C'(i) = \sum_{j=1}^{m} C'(j), \tag{6}$$

where i is the i-th kind resource type, j is the j-th stage of the life cycle of coal-fired power generation; n is the total number of resource types; m is the total number of stages; $Q'(j)_i$ is the i-th kind resource consumption in the j-th stage; $P'(j)_i$ is the i-th kind resource price in the j-th stage; $C'(i)$ is the i-th kind resource consumption cost; $C'(j)$ is the j-th stage of resource consumption cost; and C' is the total resource consumption cost.

2.2.6.2. External environmental cost accounting. The external environmental cost of emissions or resources is equal to the amount of emission or consumption multiplied by the price of emissions or resources. The environmental costs of different kinds of mid-point impact categories, external environmental costs at different stages, and the total external environmental cost can be calculated using the following formulas (Kümmel and Schüssler, 1991; Rey et al., 2004; Wanfo and Yu, 2006):

$$C^{\lambda}(j) = \sum_{i=1}^{n_{\lambda}} Q^{\lambda}(j)_i \times P^{\lambda}(j)_i, \tag{7}$$

$$C(j) = \sum_{\lambda=1}^{\theta} Q^{\lambda}(j), \tag{8}$$

$$C^{\lambda} = \sum_{j=1}^{m} C^{\lambda}(j), \tag{9}$$

$$C' = \sum_{j=1}^{m} C(j) = \sum_{\lambda=1}^{\theta} C^{\lambda}, \tag{10}$$

where λ is the λ-th kind mid-point impact category, i is the i-th emission of the λ-th kind mid-point impact category, j is the j-th stage of the life cycle of coal-fired power generation, n_{λ} is the amount of emissions and resources of the λ-th kind mid-point impact category, m is the total number of stages in the coal-fired power generation, θ is the total number of mid-point impact categories, $Q^{\lambda}(j)_i$ is the emission or consumption of the i-th kind emissions or sources of the λ-th kind mid-point impact category in the j-th stage, $P^{\lambda}(j)_i$ is the cost of the i-th emission of the λ-th kind mid-point impact category in the j-th stage, $C^{\lambda}(j)$ is the external environmental cost of the λ-th kind mid-point impact category in the j-th stage, $C(j)$ is the external environmental cost of the j-th stage, C^{λ} is the external environmental cost of the λ-th kind mid-point impact category, and C' is the total external environmental cost.

Table 4
Contributions and contribution rates of the weighted environmental impact potential.

Mid-point impact category	Environmental impact potential (kg/year)	Standard benchmark (kg/year)	Standardized environmental impact potential	Weight	Weighted environmental impact potential	Contribution rates
Resource consumption	72.90	13,324	0.01	0.38	0.208×10^{-2}	0.97%
Global warming	1486.94	8700	0.17	0.2	0.034	15.98%
Photochemical ozone creation	0.01	0.65	0.01	0.085	0.610×10^{-3}	0.28%
Acidification	19.01	36	0.54	0.036	0.019	8.92%
Health hazard	400.42	9100	0.04	0.085	0.359×10^{-2}	1.74%
Smoke and dust	45.21	18	2.52	0.054	0.136	63.33%
Eutrophication	4.43	62	0.07	0.13	0.969×10^{-2}	4.46%
Solid waste	90.18	251	0.36	0.026	0.933×10^{-2}	4.31%

3. Results and discussion

3.1. Environmental impact classification analysis

3.1.1. Resource consumption

According to Table 3, resource consumed in the life cycle of coal-fired power generation include water, coal, gasoline, electricity, and diesel oil. The proportion of water, coal, and gasoline consumption was 53.9%, 16.1%, and 7.5%, respectively. Most resources, including water, coal, electricity, and limestone, were consumed in the power generation stage.

Water consumption was very high in the coal mining stage, which indicated that plenty of water was consumed in the entire life cycle of coal-fired power generation, from the coal mining to power generation (Pfister et al., 2011; Torcellini et al., 2003). According to the reports of the Ministry of Water Resources of China, water consumption for coal-fired power generation in 2010 in China reached 114 trillion tons, accounting for 20% of the total water consumption. Therefore, the coal-fired power plants must strictly conduct water-saving measures, pay attention to the water balance test, improve the utilization ratio of circulating water, and improve its water-saving efficiency according to water quality requirements for different uses and recycling (Song and Gao, 2006).

The consumption of coal resources in the entire life cycle of coal-fired generation was second to water consumption. Moreover, the proportion of coal consumption for power generation was relatively high in China as compared to in the Europe or United States (Wang et al., 2010). Therefore, the coal consumption needs to be reduced throughout the entire life cycle of coal-fired power generation. The coal was combusted in the boiler, and to achieve a good coal-saving effect, it is necessary to study the process of coal combustion. As boiler equipment quality, the boiler heat transfer effect, boiler sealing performance, and boiler maintenance can improve coal combustion efficiency (Shah and Adhyaru, 2011, the corresponding measures need to be improved.

3.1.2. Global warming

The contribution of the weighted environmental impact potential of global warming was relatively high, with a contribution rate of 15.98%, second only to the contribution rate of smoke and dust. Moreover, CO_2 was the main emission causing global warming, with a contribution rate of 52.2%, followed by N_2O with 42.9%. In addition, plenty of GHG were mainly emitted in the power generation stage due to the combustion of a large amount of coal (Guest et al., 2013; Yu et al., 2010). Liang et al. (2013) reported similar results. The GHG emissions during coal power plant operations account for approximately 90% of the total emissions (Liang et al., 2013). The largest share of GHG emissions comes from the coal combustion process, which releases the fixed carbon in the coal to the atmosphere as CO_2. Therefore, some measures should be used to reduce GHG emissions.

CCS technologies can substantially reduce the total life cycle of CO_2 emission from coal power plants, but higher levels of CO_2 was generated from the extra energy consumption by CCS (Liang et al., 2013). CCS technology is potentially a viable choice to fight global warming. Some other new critical technologies can also be used to reduce carbon emission, including circulating fluidized bed technology (CFB), integrated gasification combined cycle technology (IGCC), and combined heat and power (CHP) technology. These technologies can improve the efficiency of power generation and reduce GHG emissions (Liszka et al., 2013; Suomalainen et al., 2013). and as such, they should be selectively used according to actual conditions. In addition, the Chinese government has a plan to refurbish the existing power plants to increase efficiency and reduce emissions. It proposed that coal-fired power plant must carry out technique upgrading to reduce power consumption and pollution emissions by 2020. The average coal consumption of existing power plants must be less than 310 g per kWh power and the plants that do not meet the standards must be shut down resolutely. Therefore, the plan is also beneficial to reduce GHG emissions.

3.1.3. Photochemical ozone synthesis

CO accounted for the largest contribution to photochemical ozone synthesis in the life cycle of coal-fired electricity generation, with a contribution rate of 78.5% (Table 3), followed by CH_4 with 21.5%. A large amount of CO was emitted during the power generation stage because of the incomplete burning of coal by the power generation equipment. The CH_4 was mainly emitted in the coal mining stage as mine gas emission (Yue et al., 2012). Some previous studies demonstrated that the contribution rate of CO was above 60% in the life cycle of coal-fired power generation, which also indicated that the main emission on photochemical ozone synthesis was CO (Liu et al., 2009). Therefore, to reduce the environmental impact of photochemical ozone synthesis, measures need to be taken to reduce CO emissions in the power generation process, including an increase in the amount of combustion air in the boiler and improvements in coal distribution and ventilation (Wang and Sun, 2001).

3.1.4. Acidification

The contribution rates of SO_2 and NO_X to acidification were 92.6% and 7.4%, respectively (Table 3). The SO_2 and NO_X emissions had a strong acidification effect on the environment in all the stages of the life cycle of coal-fired power generation. It was difficult to control acidic gas emissions in the coal mining stage and coal transportation stage as compared to the power generation stage, despite the proportion of emissions being relatively low in both the stages. Some studies have indicated that the contribution rate of SO_2 to acidification throughout the entire life cycle was more than 80%, which also indicates that the acidification impact of SO_2 in the process of coal combustion is the most significant (Restrepo et al., 2015). Therefore, to reduce the amount of SO_2 emissions generated by coal combustion, coal desulfurization technology must be used to remove sulfur from raw coal in the power generation stage (Kuang and Zhao, 2004; Srivastava and Jozewicz, 2001). Additionally, the SO_2 and NO_X emissions from the coal combustion process can also be reduced by using improved coal combustion technologies, such as liquid coal technology.

3.1.5. Health hazard

The contribution of the weighted environmental impact potential of health hazard was relatively low, with a contribute rate of 1.74%. SO_2 and NO_X were major health hazards in the life cycle of coal-fired power generation (Table 3), and the health hazard impact of SO_2 was greater than that by NO_X. Similar results have been reported for Portugal by Garcia et al. (2014). In addition, the health hazard in the power generation stage was higher than that in any other stage (Liu, 2007). Desulfurization and denitrification technologies should be applied to reduce the emissions of SO_2 and NO_X (Wang, 2014).

3.1.6. Smoke and dust

The contribution of the weighted environmental impact potential of smoke and dust was the highest, with a contribute rate of 63.33%. The actual emissions of total suspended particulates (TSP) can be used to analyze the environmental impact of smoke and dust. In the coal transportation stage, a large amount of TSP was released because of the dust generated during transportation. Therefore, to reduce the TSP emissions in the transportation process, the exhaust gas emission of the vehicle must follow the level V emission standards of China. The level V emission standards are similar to the European level V emission standards, which is currently being implemented. In addition, increasing urban greenery can also effectively reduce TSP emissions (Hu and Dong, 2013).

3.1.7. Eutrophication

Eutrophication was caused in the coal mining, coal transportation, and power generation stages. The effect was largest during the coal mining stage because of the emissions of mine wastewater, coal gangue leaching water, and living wastewater (Kadam, 2002). The contribution rate of COD to eutrophication was 67.4% (Table 3), the highest among the emissions. Related studies have also demonstrated that the contribution rate of COD to eutrophication in the entire life cycle of coal-fired power generation was more than 50%, with the eutrophication impact of COD being the most significant in the process of coal combustion (Kang et al., 2015).

Eutrophication treatment measures included engineering measures, chemical methods, biological measures, aquatic animal treatment, ecological prevention, and comprehensive prevention. Biological measures and aquatic animal treatment were the most popular methods for reducing water eutrophication pollution. In addition, controlling exogenous nutrient inputs can also effectively reduce eutrophication at the source (Sherwood and Qualls, 2001).

3.1.8. Solid waste

The solid waste discharge in increasing order of magnitude was boiler ash, coal gangue, living garbage, peats, and desulfurization gypsum, with the discharge being the highest in the power generation stage (Table 3). A large amount of boiler ash is produced in the coal combustion process in the power generation stage (Yang et al., 2008). Solid waste disposal measures included physical, chemical, and biological measures. These measures were used to transform solid waste into a suitable form for transportation and industrial and agricultural use (Yang et al., 2010).

3.2. Comprehensive analysis on environmental impact

Environmental impact classification analysis can help to explain environmental impact in the life cycle of coal-fired power generation, while comprehensive analysis can investigate the environmental impact at each stage. Each mid-point impact category at each stage can be compared based on the ration of each mid-point impact category to the total mid-point impact categories.

3.2.1. Coal mining stage

Global warming was the most serious mid-point impact category in the coal mining stage, accounting for 44.36% (Fig. 2). The mine gas emissions and spontaneous combustion of coal gangue produce a large amount of greenhouse gases, especially CH_4 and CO_2. Liang et al. (2013) reported that the coal mining stage made the second largest contribution to global warming, mainly in the form of CH_4 leakage at the coal mining stage, which accounted for 98% of the total CH_4 emissions in the entire life cycle of coal-fired power generation. CH_4 is trapped in coal beds and liberated during mining. Several factors determine its volume, the most important being the coal rank (different types of coal contain different volumes of CH_4), coal seam depth, and mining method employed (Branco et al., 2013). The proportion of eutrophication reached 23.15%. The eutrophication was resulted from mine wastewater and living wastewater in the mining area. The proportion of solid waste reached 21.28%, mainly produced by rock and coal gangue. The proportion of resource consumption was 6.09%. Roadway maintenance consumed large amounts of water, and operation of coal mining machinery, boiler use and mine offices also consumed large amounts of electricity. The proportion of photochemical ozone synthesis was 2.32%, which may be mainly produced by exhaust gas of machinery, mine gas, coal spontaneous combustion gas and so on (Kadam, 2002; Pfister et al., 2011).

3.2.2. Coal washing stage

The mid-point impact category that seriously affected the environment during the coal washing stage was smoke and dust, accounting for 94.70% (Fig. 2); the proportion of solid waste was 3.77%, followed by eutrophication with 0.81%. During the coal washing process, a part of the coal was separated. Typically, this amounts to 20% (by weight) of the mined coal that undergoes washing, but it depends on the operation (Branco et al., 2013). Coal washing technology included physical and chemical separation processes, both of which generate dust and solid waste in the process of separation. Discharge of wastewater after washing contained the eutrophication elements (Liu, 2013).

3.2.3. Coal transportation stage

The mid-point impact category that seriously affected during the coal transportation stage the environment was also smoke and dust, accounting for 92.54%. The large amount of dust generated may be caused by long transportation distances, as reported by other related studies (Branco et al., 2013).

3.2.4. Power generation stage

The mid-point impact category that seriously affected the environment during the power generation was global warming, accounting for 37.63% (Fig. 2). This may be due to the large amounts of CO_2 emissions generated during coal combustion (House et al., 2011). The proportion of acidification was 28.98%, which may be due to the large amounts of SO_2 emission, which is the main emission of acidification, generated during coal combustion (Zhao et al., 2009). Liang et al. (2013) reported similar results regarding the impacts of global warming and acidification during this stage. The proportion of eutrophication was 12.94%, which may arise from the discharge of circulating water, desulphurization of wastewater, living wastewater, and so on. The proportion of solid waste was 11.42%, with boiler ash and living waste occupying a

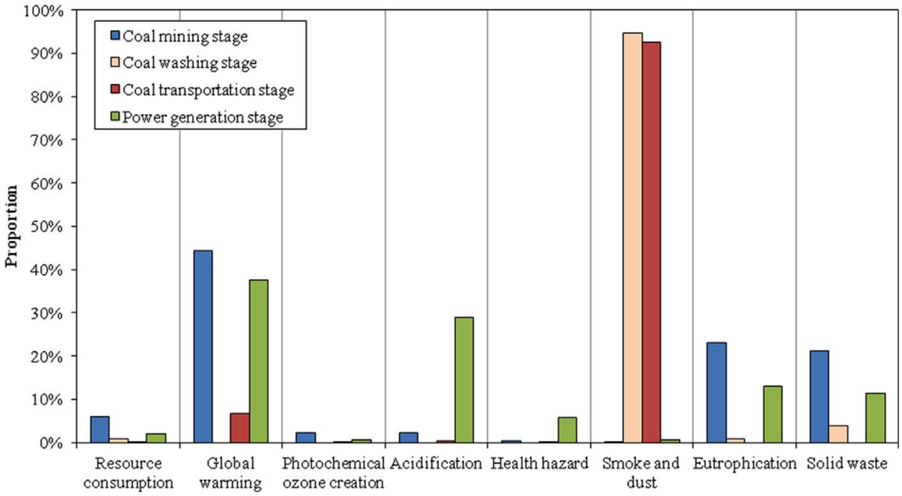

Fig. 2. Proportion of the weighted environmental impact potential per 1 MWh production of power of all the stages.

Table 5
Prices of emissions and resources.

Emissions/ resources	The price ($\$ \cdot kg^{-1}$)	Emissions/resources	The price ($\$ \cdot kg^{-1}$)
Steel	0.86	NO_X	0.33
Wood	0.16	TSP	0.18
Coal	0.095	COD	The cost of water pollution: $0.47 per ton
Limestone	0.023	BOD	
Gasoline	1.04	SS	
Diesel	0.92	N	
Water	0.21×10^{-3}	P	
Electricity	8.73×10^{-5}	Coal gangue	The cost of general industrial solid waste disposal: $3.82 per ton
CO_2	0.19×10^{-2}	Boiler ash	
CO	0.018	Peat	
CH_4	0.049	Desulfurization gypsum	
N_2O	0.91	Living garbage	
SO_2	0.44		

Note: The prices of resource consumption and air pollution were from Wu' results (Wu, 2011), and the prices of water pollution and solid waste pollution were from Ni' reports (Ni, 2015).

Table 6
Cost and proportions of resource consumption and external environmental costs at different stages.

Mid-point impact category	The stage	The cost	The proportion
Resource consumption cost	Coal mining	2.38	5.19%
	Coal washing	0.14	0.32%
	Coal transportation	6.48	14.04%
	Power generation	37.01	80.45%
The cost of air pollution	Coal mining	0.28	1.28%
	Coal washing	1.44	6.45%
	Coal transportation	7.92	35.80%
	Power generation	12.49	56.47%
The cost of water pollution	Coal mining	0.01	2.40%
	Coal washing	< 0.01	0.48%
	Coal transportation	0	0.00%
	Power generation	0.47	97.12%
The cost of solid waste pollution	Coal mining	0.03	8.36%
	Coal washing	0.03	10.43%
	Coal transportation	0	0.00%
	Power generation	0.27	81.21%

Table 7
Costs and proportions of resource consumption and external environmental costs of different emissions and resources.

Mid-point impact category	Emissions/resources consumed	The cost	The proportion
Resource consumption cost	Steel	0.76	1.67%
	Wood	0.17	0.36%
	Coal	37.29	81.09%
	Limestone	0.09	0.2%
	Gasoline	3.89	8.45%
	Diesel	2.84	6.15%
	Water	0.97	2.07%
	Electricity	0.01	0.01%
The cost of air pollution	CO_2	1.48	6.75%
	CO	0.23	1.05%
	CH_4	0.11	0.47%
	N_2O	1.80	8.18%
	SO_2	9.32	42.28%
	NO_X	0.90	4.01%
	TSP	8.24	37.26%
The cost of water pollution	COD	0.47	96.92%
	BOD	< 0.01	0.75%
	SS	< 0.01	1.40%
	N	< 0.01	0.78%
	P	< 0.01	0.15%
The cost of solid waste pollution	Coal gangue	0.03	10.38%
	Boiler ash	0.30	89.51%
	Peat	< 0.01	0.02%
	Desulfurization gypsum	< 0.01	0.01%
	Living garbage	< 0.01	0.08%

large amount of land (Gao and HU, 2002). The proportion of health hazard was 5.69%, with SO_2 and NO_X as the main emissions of health hazards. SO_2 is produced by the combustion of sulfur coal, while NO_X is generated at high temperature from the boiler air.

The proportion of resource consumption also could not be ignored, accounting for 2.10%. In the power generation stage, most of the coal mined at the coal mining stage was consumed; moreover, the generating equipments, plant cleaning and staff living will consume large amounts of water and electricity. The environmental impact produced by photochemical ozone synthesis was mainly from CO and CH_4, accounting for 0.71%.

3.3. Environment cost classification analysis

Environmental costs can be classified as resource consumption costs and external environmental costs. The external environmental costs included the costs of air pollution, water pollution, and solid waste pollution. The actual resource consumption and emissions at each stage are presented in Table 1. The prices of emissions used to determine resource consumption costs and external environmental costs are presented in Table 5. The costs of resource consumption costs and external environmental costs at each stage along with their respective proportions are presented in Table 6. The resource consumption cost and external environmental cost of each form of emission along with their respective proportions are presented in Table 7.

3.3.1. Resource consumption cost

The resource consumption cost in the power generation stage was the highest, accounting for 80.45% of the total costs. The coal consumption cost in the entire life cycle of coal-fired power generation was the highest, accounting for 81.09% of the total costs.

3.3.2. The cost of air pollution

The cost of air pollution was the highest in the power generation stage, followed by the coal transportation stage. The proportion of external environmental cost of SO_2 was 42.28%, followed by TSP with 37.26%. The proportion of air pollution cost of CO_2 resulting in global warming was 6.75%. Bhattacharyya (1997) also reported that SO_2 and TSP contributed the most to the environmental costs of air pollution. In addition, the air pollution cost of CO_2 was most evident at power generation stage as collection and storage of CO_2 were difficult at this stage. Based on the air pollution cost of each emission, the air pollution cost per 1 MWh production of power was $22.08. This air pollution cost was relatively high than that reported by Bhattacharyya (1997) for India, which was $12 in 1994. This may be due to two reasons. The first reason is that Bhattacharyya's study only included the environmental costs of SO_2 and TSP, while the second reason was the effect of the time value of cost.

3.3.3. The cost of water pollution

The cost of water pollution in the life cycle of coal-fired power generation is equal to the pollution water emissions multiplied by the average economic loss. The economic loss caused by water pollution has been evaluated in China and was found to be $0.16 per ton discharge. Considering the change in the price index, the average economic loss caused by the discharge of wastewater was found to be $0.47 per ton for the year 2014 (Ni, 2015).

The proportion of water pollution cost during the power generation stage was 97.12%, followed by the coal mining stage with 2.40%. The proportion of the pollution cost of COD discharged from wastewater was 96.92%. According to this study, the cost of water pollution per 1 MWh production of power was $0.50.

3.3.4. *The cost of solid waste pollution*

The cost of general industrial solid waste disposal was $3.06 per ton of solid waste discharge in 2008, and $3.82 per ton (according to the price index change) in 2014. Considering that coal gangue can be disposed by underground backfill during the coal mining stage, the cost of governance can be neglected. According to Table 1, the solid waste emissions per 1 MWh production of power was 87.62 kg, except for coal gangue emissions during the coal mining stage. The cost of solid waste pollution per 1 MWh production of power was found to be $0.32.

The cost of solid waste pollution was the highest during the power generation stage, followed by the coal washing stage, and their percentages were 81.21% and 10.43%, respectively. At the power generation stage, large amounts of boiler ash and desulfurization gypsum were produced, which occupied a certain land space and resulted in a high environmental cost.

3.4. *Comprehensive analysis on environmental cost*

The resource consumption cost per 1 MWh production of power in the life cycle of coal-fired generation was approximately $46.01. The proportion of the resource consumption cost of the power generation stage was the highest, accounting for 80.45%, followed by the transportation, mining, and washing stages. The external environmental cost per 1 MWh production of power in the life cycle of coal-fired generation was approximately $22.90. Further, the proportions of the costs of air pollution, water pollution and solid waste pollution were 96.42%, 2.12%, and 1.46%, respectively. The proportions of external environmental cost of the power generation, transportation, washing and mining stage were 57.69%, 34.52%, 6.38%, and 1.40%, respectively.

4. Conclusions and policy implications

This study adopted the LCA and cost accounting theory to evaluate China's coal-fired power generation technology. The emissions with the greatest environmental impact were CO_2, CO, SO_2, TSP, COD, and boiler ash. The contribution rates to environmental impact of smoke and dust was the highest, accounting for 63.33%. The environmental impact was different at different stages of the life cycle of coal-fired power generation. The mid-point impact category of global warming had the greatest impact in the coal mining stage and power generation stages, whereas smoke and dust had great impact in the coal washing and transportation stages. The resource consumption cost per 1 MWh production of power in the life cycle of coal-fired generation was approximately $46.01. The emissions generated by coal, gasoline, diesel, water and steel had relatively high resource consumption costs. The external environmental cost per 1 MWh production of power in the life cycle of coal-fired generation was approximately $22.90, while the proportions of costs of air pollution, water pollution and solid waste pollution were 96.42%, 2.12%, and 1.46%, respectively. There were also great differences in the resource consumption cost and external environmental cost at different stages. The resource consumption and external environmental costs were the highest in the power generation stage.

In recent years, rapid increase in energy consumption and its resulting impact on the environment and energy security have become a serious problem in China. The results of this study provide meaningful implications to help alleviate the environmental impact of nationwide coal-fired power generation based on the life cycle perspective. As coal will continue to be the most important energy source for producing electricity, clean coal technology with higher efficiency and lower emissions is the key to fulfill the goal of sustainable development for China. Strengthening the application of new facilities for emission reduction, improving the emission standards of pollutants, and strengthening the process management of coal-fired power generation are effective ways of reducing the environmental burden caused by environmental impact factors. To reduce the environmental impact of coal-fired power generation technology, CO_2, CO, SO_2, TSP and other harmful gas emissions, wastewater, and solid waste discharge should follow national regulated emission standards. Environmental emissions of coal-fired power generation were found to be concentrated in the power generation stage, which indicates that upgrading technologies, especially coal combustion technology, at this stage can help polish environmental coordination. Further, the coal quality should be improved to reduce greenhouse gas emissions during the mining stage, while smoke and dust emissions in the washing and transportation stages must be controlled. Moreover, attention should be paid to the environmental cost of coal-fired power generation. The consumption of coal and water and the emissions of SO_2, COD and boiler ash should be reduced to control the environmental costs of these emissions throughout the entire life cycle of coal-fired generation. Although China's government is already supporting clean coal technology projects with preferential fiscal policies on a case-by-case basis, a comprehensive policy that integrates environmental protection policies, energy policies, and industrial regulation is also needed.

Further research should be focused on the determination of the equivalent coefficient and the weight of the mid-point impact category. In addition, a complete database and a practical software have been established to carry out the LCA of coal-fired power generation and to promote the development of coal-fired power generation LCA in China; however, in the evaluation process, the input and output datum of the material and energy in each stage were very complex and massive, and thus the follow-up data need to be further improved and enriched.

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