Energy Policy 115 (2018) 374–384

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

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

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ARTICLE INFO

Keywords:
Coal-fired power generation
Life cycle assessment
Environmental impact
Resource consumption cost
External environmental cost

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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https://doi.org/10.1016/j.enpol.2018.01.040
Received 28 June 2017; Received in revised form 31 December 2017; Accepted 18 January 2018
0301-4215/

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