Science of the Total Environment 636 (2018) 547–557

Contents lists available at ScienceDirect

Science of the Total Environment

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

How much water is required for coal power generation: An analysis of gray and blue water footprints

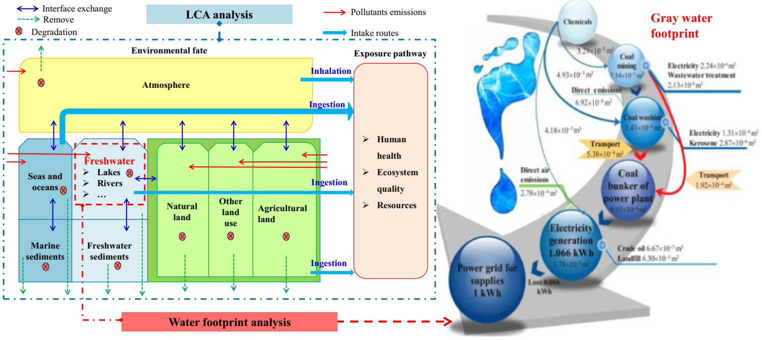
Xiaotian Ma, Donglu Yang, Xiaoxu Shen, Yijie Zhai, Ruirui Zhang, Jinglan Hong *

Shandong Provincial Key Laboratory of Water Pollution Control and Resource Reuse, School of Environmental Science and Engineering, Shandong University, Qingdao 266237, China

HIGHLIGHTS

- A water footprint analysis of coal power generation in China is conducted.
- The water footprint of coal power generation is 3.2×10^{-3} m^3/kWh in 2015.
- National gray water footprint in China exceeded blue water footprint since 2013.
- Transport, freshwater consumption, and direct air emission are key processes.
- Control of phosphorus and heavy metals should be strengthened.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 March 2018
Received in revised form 23 April 2018
Accepted 23 April 2018
Available online xxxx

Editor: Frederic Coulon

Keywords:
Water footprint
Life cycle assessment
Coal-based electricity
Time course
Transportation

ABSTRACT

Although water resource shortage is closely connected with coal-based electricity generation, relevant water footprint analyses remain limited. This study aims to address this limitation by conducting a water footprint analysis of coal-based electricity generation in China for the first time to inform decision-makers about how freshwater consumption and wastewater discharge can be reduced. In China, 1 kWh of electricity supply obtained 1.78×10^{-3} m^3 of gray water footprint in 2015, and the value is 1.3 times the blue water footprint score of 1.35×10^{-3} m^3/kWh. Although water footprint of 1 kWh of electricity supply decreased, the national total gray water footprint increased significantly from 2006 to 2015 with increase in power generating capacity. An opposite trend was observed for blue water footprint. Indirect processes dominated the influence of gray water footprint, whereas direct freshwater consumption contributed 63.6% to blue water footprint. Ameliorating key processes, including transportation, direct freshwater consumption, direct air emissions, and coal washing could thus bring substantial environmental benefits. Moreover, phosphorus, mercury, hexavalent chromium, arsenic, COD, and BOD_5 were key substances of gray water footprint. Results indicated that the combination of railway and water transportation should be prioritized. The targeted transition toward high coal washing rate and pithead power plant development provides a possibility to relieve environmental burdens, but constraints on water resources in coal production sites have to be considered.

1. Introduction

Electricity is essential for human activities and production processes. Given the surge in global economy and population, global electricity production has increased considerably in the past

---

* Corresponding author at: School of Environmental Science and Engineering, Shandong University, Qingdao 266237, China.
E-mail address: hongjing@sdu.edu.cn (J. Hong).

https://doi.org/10.1016/j.scitotenv.2018.04.309
0048-9697/© 2018 Elsevier B.V. All rights reserved.

40 years (from 6.3×10^{12} kWh to 2.4×10^{13} kWh), with an average annual growth rate of 3.4% (IEA, 2017). Approximately 40% of the current global electricity is generated by coal-fired plants (IEA, 2017), and this value reaches 65.2% in China, where electricity production capacity ranks first in the world (NBSC, 2017). Coal-based electricity generation demonstrates high water sensitivity because water is indispensable in all stages of electricity generation (IEA, 2016). Over 6% of the total industrial freshwater consumption and 7% of wastewater discharge has been observed throughout the life cycle of electricity generation in China (NBSC, 2016a; NBSC, 2016b). In addition to exacerbating water scarcity, high wastewater discharge exerts significant impacts on water environments, such as freshwater eutrophication and ecotoxicity (Cui et al., 2012). In particular, the operation stage of power plants is responsible for 4.7% of China's total industrial freshwater consumption and 1.6% of the country's wastewater discharge, and the proportions for coal mining and washing stages are 1.3% and 5.5%, respectively (NBSC, 2016a; NBSC, 2016b). Furthermore, the water demand and emissions that are synchronously induced in other indirect stages (e.g., building construction and waste disposal) should be considered in water management of electricity generation (Fthenakis and Kim, 2010). Therefore, the systematic analyses of the water consumed and discharged during the entire life cycle of China's coal-based electricity generation are necessary.

Water footprint (WF) functions as a comprehensive indicator of assessing water resource consumption (i.e., blue and green WFs) and pollution status (i.e., gray WF) caused by anthropogenic activities in geographical and temporal dimensions; it considers all direct and indirect processes (Hoekstra et al., 2011). WF was first proposed by Hoekstra (Hoekstra et al., 2011). Although studies on WF applications have been conducted, they have focused on agricultural fields (Cao et al., 2018; Lovarelli et al., 2016) and regional levels (Hoekstra and Mekonnen, 2012; Pellicer-Martínez and Martínez-Paz, 2018). By contrast, systematic and detailed studies on industrial activities, particularly those at the enterprise level, remain limited. Furthermore, traditional methods not only fail to analyze the complex industrial processes during its all life cycle stages (Berger et al., 2012) but also fail to consider air and soil emissions that influence water quality (ISO, 2014). These methods also do not allow the comparison of different products (Ridoutt and Pfister, 2013). The International Organization for Standardization proposed the life cycle assessment (LCA) method as an international standard for WF analysis (ISO, 2014). This method includes an inventory analysis that is similar to that in traditional methods (e.g., virtual water) and comprehensively considers the environmental impact of the entire life cycle of certain products, processes, or activities. Among the researchers who have studied WF methodology, Bayart et al. (2010) proposed a generic framework that integrates freshwater use into LCA. Meanwhile, a series of methodologies related to water scarcity was presented successively (Boulay et al., 2011; Hoekstra, 2016). Berger et al. (2014) further developed the WF methodology by considering atmospheric evaporation recycling. In aforementioned studies, environmental influences were derived mainly from water resource shortage, which further affects agricultural irrigation, food production, and ecosystem diversity. Most current case studies on LCA-based WF analysis have combined only LCA results and blue WF (Jefferies et al., 2012). However, gray WF exerts greater environmental impact than blue WF (Gu et al., 2015). Thus, gray WF should be quantitatively studied to assess its impact on water resources. To date, the quantification of gray WF is mainly based on pollutant concentration. Most studies have disregarded the environmental fate of pollutants in water, soil, and atmosphere media; exposure pathway; and toxic effects on humans and the environment. One exception is the study of Ridoutt and Pfister (2013), who examined toxic effects via the ReCiPe method. However, the ReCiPe method is well-known for assessing toxicity effects by adopting multi-media fate and multi-pathway intake (Fig.1; Goedkoop et al., 2013). WF is an indicator for assessing the water resources consumed and polluted by human activities (Hoekstra et al., 2011); thus, toxicity analysis in gray WF evaluation should only consider the impact generated from water media based on multi-pathway intake (e.g., fish and water intake; Bulle et al., 2013). Fig. 1 distinguishes the boundary between LCA and WF analyses. As that pollutants emitted to multi-media (e.g., soil, plant, air, and sediment) can enter water media, the steady-state concentration of pollutants in water media should be used to obtain the intake factor for WF analysis. The toxicity impacts generated from the steady-state concentration of pollutants in other media via multi-pathway intake should be excluded because of the system boundary of WF (Fig. 1; ISO, 2014; Bulle et al., 2013). Accordingly, the toxicity effect reported by Ridoutt and Pfister (2013) overestimated WF (Fig.S1). Moreover, variations in regional water resource quantity and quality have been rarely considered in gray WF evaluation, while both of them can affect the ability of water media to tolerate pollutants.

At present, research on WF analysis in electricity generation remains limited except for little attention about hydropower (Mekonnen and Hoekstra, 2012; Herath et al., 2011), bioenergy (Gerbens-Leenes et al., 2009), and water use during electricity generation (Shaikh et al., 2017). With regard to the LCA-based WF analysis of electricity, the only available studies focus on blue WF, such as the investigations reported by Fthenakis and Kim (2010), Mekonnen et al. (2015), and Ou et al. (2016). Gray WF has rarely been examined. Furthermore, to the best of our knowledge, no WF analysis of coal-based electricity has been conducted using the LCA model. Thus, the current study aims to (1) quantify the WF, including the gray and blue WF scores, of China's coal-based electricity generation via LCA method at the macro level; (2) analyze the time course of WF from 2006 to 2015; (3) identify the key direct and indirect influencing factors during whole electricity generation stages; (4) provide useful suggestions for improving water management in China's coal-based electricity generation.

2. Methodology

2.1. Goal and scope definition

In this study, the functional unit was defined as 1 kWh of electricity supply to provide a comparative benchmark for all analysis results and inventories. Fig. 2 shows the system boundary. Coal mining and washing, transportation (i.e., coal, construction materials, chemicals, and solid waste), and three power generation technologies (i.e., subcritical, supercritical, and ultra-critical) were considered. Each process involves waste disposal, direct waste emissions, infrastructure of power plants (i.e., equipment and buildings), and land occupation. Moreover, direct WF includes water consumed in operation stages and on-site waste generation (i.e., wastewater, waste gas, and solid waste), while indirect WF represents water consumed and waste generated from raw material production, transportation, and other relevant indirect processes in the supply chain.

2.2. WF method

Gray and blue WFs were involved in this study, whereas green WF was excluded because rainwater is generally considered in agriculture. Five categories including carcinogens, non-carcinogens, freshwater ecotoxicity, aquatic eutrophication, and water scarcity were considered at the midpoint level. The updated characterization factors (Eq. (1)) in three former categories from the USEtox™ model (Huijbregts et al., 2010) were adopted in this study. This model traces the emissions, environmental fate, exposure pathway, intake routes, risk, and damage in China based on the investigations of Li et al. (2016) and Zhang et al. (2016). Notably, only pollutants that enter freshwater through direct emissions and migration were considered in this study (Fig. 1). The characterization factors for aquatic