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Assessing life cycle water use and pollution of coal-fired power generation in China using input-output analysis

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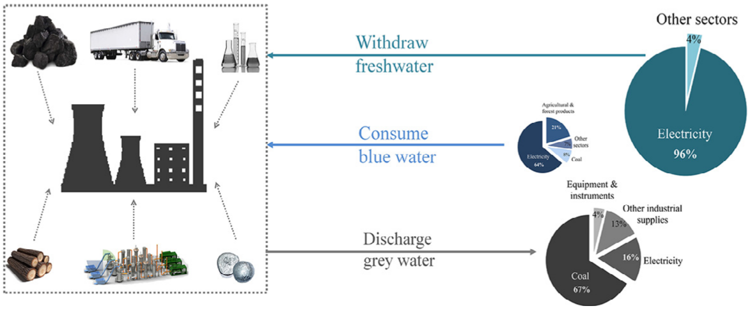
HIGHLIGHTS

- Both water depletion and pollution by coal-fired power generation are quantified.
- Petroleum pollutant determines the life cycle grey water footprint.
- Water pollution mostly occurs in the fuel supply sector.
- The grey water footprint was reduced by 49% from 2002 to 2012.

GRAPHICAL ABSTRACT



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ABSTRACT

In the present study, both water depletion and degradation in the life cycle of power generation at coal-fired power plants in China are quantified using a mixed-unit input-output model. National life cycle Withdrawal, Blue and Grey water footprint (WF) of thermal power production in China are estimated to be 35.46, 2.14 and 17.67 m^3 per MWh of electricity produced, respectively. Those three types of life cycle WFs experienced significant reductions from 2002 to 2012 due to improved technologies such as water saving and wastewater treatment. Although Chemical Oxygen Demand (COD) pollutant had the largest discharge amount in the life cycle process of electricity generation, petroleum pollutant that was mostly discharged from coal production determined the Grey WF because of its lower permissible concentration. The spatial distribution of scarce WFs, incorporating regional water stresses, is also studied at the provincial level to identify the impacts of thermal power generation on regional water scarcities. Scarce water consumption was concentrated in northern China while scarce water was predominantly withdrawn in eastern China.

1. Introduction

Water security is identified as a severe global challenge in the next decade in terms of its potential impacts [1]. Thermal power industry, as a water-intensive sector, aggravates regional and global water shortages. Globally, around 19 billion m^3 of freshwater, which equals to the basic demands of over 1 billion people, is consumed annually by coal-fired power plants (CPPs) [2]. In China, three quarters of water consumed by coal-fired power plants is from water-deficient regions [3,4]. Water withdrawal and consumption are projected to increase over 4.3 and 3.2 times respectively from 2014 to 2050 if the current policies continue to affect [5]. Incorporating effective water resource management into the power sector's development can mitigate the potential water crisis [6]. For instance, U.S. has improved water-saving

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efforts in the power generation sector and significantly reduced the impact of power generation on water depletion [7].

A large amount of water is withdrawn and consumed by cooling systems at CPPs in order to remove the residual heat from steam turbines. Water consumption refers to water being evaporated or lost in the production processes after being withdrawn [8]. The magnitudes of water withdrawal and consumption are largely determined by cooling technologies at power plants [9,10]. Feeley et al. claimed that there exists a great potential for water use reduction by upgrading and popularizing recirculation cooling technologies in the U.S [11]. DeNooyer et al. demonstrated that substituting open-loop cooling systems for closed-loop cooling ones in the U.S. can reduce national freshwater withdrawal by 96% but consumes 58% more water [12]. Lee et al. suggested the water stressed regions use less water-intensive cooling technologies such as closed-loop cooling [13]. Besides cooling types, spatial distribution of power plants is another important factor that needs to be considered in order to mitigate regional water scarcities [14]. Zhang et al. estimated the national water consumption by coal-fired power plants in China and concluded that it was largely from the water deficient regions [3].

Quantifying water use of electricity per unit energy is essential to the aforementioned studies. Water footprint (WF), as a multi-dimensional indicator proposed by Hoekstra, is widely used to measure water use in a product [15]. Water footprint is comprised of three components: (1) green water that refers to the evaporation of rainwater stored in soils [16]; (2) blue water that refers to the consumption of freshwater resources, including surface water and groundwater; (3) grey water which refers to freshwater requirement to dilute pollutants to the safe concentration set by related standards [17]. Previous research has been conducted to estimate Green and Blue WFs of electricity production from different resources including biomass [16], fossil fuels [18], wind [19], hydropower [20], etc. Besides being withdrawn and consumed directly at power plants, water is also used as being embodied in the fuel supply, construction, maintaining, etc. Thus it is necessary to estimate the life cycle WF of electricity production in order to evaluate its aggregated impacts on national and global water resources [21]. Process-based modeling from a bottom-up perspective has been widely employed in previous studies to investigate the direct water use in each process (i.e. fuel supply, construction, electricity generation, etc.) [22] and assess the aggregated impacts [23]. The results estimated by bottom-up approach are depended on the system boundary setting, and there exist cut-off errors. Input-output method is a kind of top-down approach that can avoid cut-off errors [24], but also has the errors when using monetary flows to estimate physical flows. A Mixed-Unit Input-Output model, as proposed by Hawkins [25], can avoid the disadvantages of both process-based approach and monetary input-output model, and has been successfully employed to assess the life cycle water use of energy production [26].

Many previous studies have evaluated the water depletion by electricity production in many countries, such as China [5,27], U.S. [7], UK [28], Italy [29], Thailand [30], etc., and claimed that the large amount of cooling water used by power stations has a great impact of the regional water resources [19]. However, the life cycle water pollution remains unknown. There are various water pollutants, including chemical oxygen demand (COD), volatile phenols, petroleum, heavy metals, etc., discharged in the life cycle process of power generation, such as coal mining and washing [31]. Previous studies have demonstrated the high content of water pollutants in the coal mining drainage [32], the high contamination of diffuse mine-water sources [33], and the water pollution from coal washing plants [34]. Therefore the life cycle impacts of thermal power sector on water pollution are needed to be examined in a comprehensive water-energy assessment.

In order to better understand the impacts of coal-fired power generation (CPG) on both water quantity and quality, we assess the life cycle water pollution and incorporated the Grey water into the WF assessment. Furthermore, this study examines the decadal change of the life cycle WF per unit thermoelectric power in China from 2002 to 2012, and determines the contributions of different sectors to the life cycle water depletion and pollution of CPG. For the first time, the major contributors to water pollution are examined in the life cycle of CPG, which is of significance to the water quality management in water-energy system. These improvements over previous studies provide a more comprehensive insight to the assessment of CPG' impacts on water resources.

2. Methodology

2.1. Assessing the water footprint in the life cycle process

Electricity price varies greatly in different regions, consumers and the time; for instance, the electricity price for residents is lower than that for commercial sectors, and the price in the night is lower than that in the day. In order to avoid the price effect, we employ the Mixed-Unit Input-Output (MUIO) model in this study to perform the water assessment for CPG. The MUIO model has been widely employed to assess the water [26], exergy [35] and carbon emissions [36] embodied in energy products, and also to trace the inter-regional flow of virtual water [37], carbon emissions [38] and embodied energy [39]. The Water Footprint (WF), including indirect component (as contained in the upstream supplies) and direct component (which occurs directly at production sites), can be estimated as Eq. (1) below:

$$\sum_{j=1}^{n} \mathrm{WF_j} = \sum_{j=1}^{n}\sum_{i=1}^{n} \mathrm{WF_i a_{ij}} + \sum_{j=1}^{n} \mathrm{DW_j} \tag{1}$$

where $\mathrm{WF_j}$ indicates the WF of sector j; $\mathrm{a_{ij}}$ indicates the demand of sector i by sector j; $\mathrm{DW_j}$ indicates the direct water use coefficient, referring to the direct Withdrawal WF, the direct Blue WF, and the direct water pollutants discharge in sector j. The WF and DW are measured in units of $\mathrm{m^3}$ per kWh (electricity) and $\mathrm{m^3}$ per Yuan (other goods and services).

WF can be calculated by the MUIO model as Eq. (2):

$$\mathbf{WF} = \mathbf{DW}*(\mathbf{I}-\mathbf{A})^{-1} \tag{2}$$

where WF is a vector, comprised of WFs of all sectors; DW is a direct water use coefficient vector; A is a matrix of technical coefficients of intermediate inputs; I is an identity matrix.

There are three types of WFs estimated in this study, including Withdrawal, Blue (also denoted as consumptive) and Grey WF. Grey WF, as an indicator to quantify the impacts of pollutants on water resources, is the volume of freshwater required to dilute the polluted water to a safe concentration set by regulations [17,40]. The specific Grey WF for each pollutant was calculated as Eq. (3):

$$\mathrm{DW_{grey,p}} = \frac{\mathrm{L_p}}{\mathrm{C_{max,p}}-\mathrm{C_{nat,p}}} \tag{3}$$

where $\mathrm{DW_{grey,p}}$ ($\mathrm{m^3}$) is the direct Grey WF of pollutant p and; $\mathrm{L_p}$ is the discharge amount of pollutant p to environment and is measure in a physical unit of grams; $\mathrm{C_{max,p}}$ is the maximum permissible concentration (gram per liter) for pollutant p in the water body set by China's quality standard for surface water [41]; $\mathrm{C_{nat,p}}$ (gram per liter) is the concentration of pollutant p in the natural water body, which is usually assumed to be zero.

The Grey WF ($\mathrm{m^3}$ per kWh) is determined by the maximum specific Grey WF among pollutants as Eq. (4):

$$\mathrm{WF_{grey}} = \max\{\mathrm{WF_{grey,1}}, \mathrm{WF_{grey,2}}, \cdots, \mathrm{WF_{grey,p}}\} \tag{4}$$

In order to better understand the impact of CPG on regional water resources, regional water scarcity that varies considerably among different regions needs to be considered. Scarce WF for each province was assessed by multiplying a water stress index (WSI) (proposed by Pfister et al. [42]). WSI has been adopted by researchers to study the virtual