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Water footprints of energy sources in China: Exploring options to improve water efficiency

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A B S T R A C T

Knowledge of water resource consumption and pollution during the life cycle of energy production and developing energy industry in regions with abundant water resources are two ways to improve water efficiency. In this study, a water footprint model for energy sources was developed, and water footprint inventories of the primary fossil fuels (e.g., coal, crude oil, natural gas) and power sources (e.g., thermal, nuclear, wind, solar photovoltaic, and hydropower) in China were compiled. The water footprints calculated for coal, crude oil, and natural gas were 0.14 m^3/GJ, 0.29 m^3/GJ, and 0.11 m^3/GJ, respectively. The water footprints of power sources increased as follows: wind (0.14 m^3/GJ), nuclear (0.19 m^3/GJ), thermal (1.19 m^3/GJ), solar (5.3 m^3/GJ), and hydropower (6.75 m^3/GJ). From a life cycle perspective, the water footprints of the three primary energy sources mainly originated from the extraction stages. The water footprint from upstream stages accounted for the highest proportion of the total water footprint of nuclear, wind, and solar power. Regional analyses revealed that provinces such as Sichuan, Yunnan, Hunan etc. have appropriate water resources and capacity for future development of energy system. A water footprint inventory of primary energy could provide basic data for water footprint analyses of secondary energy, materials, and products downstream across multiple sectors and could support water management in the energy industry.

1. Introduction

Water and energy are crucial and closely linked resources (Lubega and Farid, 2014). The energy industry is one of the largest consumers of water resources. Water is necessary across the entire life cycle of energy production (e.g., mining or extraction, processing, and conversion). The increasing demand for energy will require increasing volumes of water resources. Furthermore, declining water availability is beginning to limit energy choices (Davies et al., 2013). If the quality, quantity, and accessibility of water declines, the diverse supply of reliable, affordable, and sustainable energy is also at stake (Carrillo and Frei, 2009).

Nearly half the world's population is projected to live in areas that will experience severe water shortages (Hoekstra, 2014). For one, China is at risk of a severe water shortage. In 2013, the water resources available per capita in China were 2060 m^3—less than a quarter of the global average. As a water-intensive sector, the Chinese energy industry should take responsibility for minimizing water consumption over the life cycle of energy production. Insights into the water-demand profile of energy production systems will be helpful in this regard.

The energy sector can improve water efficiency in two ways. First, water consumption during the life cycle of energy production can be reduced. Life cycle management is essential to protect the environment, as highlighted by government plans and actions in China (SC, 2016). However, knowledge of water resource consumption and pollution during the life cycle of energy production is necessary to reduce water consumption. Second, the energy industry should be developed according to water endowment, meaning that energy should be developed and adjusted in regions with abundant water resources.

China's Energy Development Strategy Plan (2014–2020) and 13th Five-Year Plan for Economic and Social Development (2016–2020) for the power sector proposed two significant strategies for energy development according to regional water resources: they aim to build a large coal base according to the

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distribution and capacity of water resources and to optimize the distribution of power. However, additional information regarding the ideal location and implementation methodology require further investigation.

The water footprint (WF) concept was developed to calculate the amount of water needed to manufacture consumer products. Hoekstra (Hoekstra 2003) introduced and defined WF as the total annual volume of freshwater used to produce goods and services related to a certain consumption pattern. Hoekstra and Chapagain (Hoekstra and Chapagain, 2007, Hoekstra and Chapagain, 2008) further developed the method. The WF is an indicator of freshwater use that looks not only at direct water use but also at indirect water use. It is a volumetric measure of water consumption and pollution. The WF thus offers a better and wider perspective on how a consumer or producer relates to the use of freshwater system and water pollution (Hoekstra et al. 2011).

Hoekstra's WF includes three subtypes: the green WF, the blue WF, and the grey WF (Hoekstra et al., 2011). The green WF refers to precipitation over land that does not run off or infiltrate ground water; instead, it is stored in the soil or stays on top of the soil or vegetation. Eventually, this precipitation evaporates, or plants transpire it. The blue WF is an indicator of the consumptive use of surface water or ground water. The grey WF is defined as the amount of water needed to dilute the pollutants released into natural waterways during production processes to the extent that the quality of ambient water remains above acceptable water quality standards.

WFs can be applied as a tool to identify the critical and effective stages for reducing the impact of water use during the life cycle of products. Initially, the WF method was applied to evaluate the water consumption of agricultural products such as crops and grains (Mekonnen and Hoekstra, 2011; Cao et al., 2014; Vanham and Bidoglio, 2014). Later, the WF of bio-energy production was also analyzed (Chiu et al., 2015; Su et al., 2015; Gerbens-Leenes et al., 2009). Gradually, this concept extended to evaluate the water performance of industrial materials and products (Pena and Huijbregts, 2014; Gu et al., 2015) and particular industrial sectors (Ayres, 2014; Wang et al., 2014). WFs have also been used to assess water requirements at the regional and national levels (Ene et al., 2012; Ercin and Hoekstra, 2014; Dong et al., 2013).

Some researchers have assessed the water requirements for energy production within the context of life cycle assessment (LCA) (Harto et al., 2010; Arent et al., 2014). Carrillo and Frei, (2009) analyzed the water needs of energy production in Spain for specific energy-related sectors (electrical power generation, transportation, or domestic use) and process types (the extraction and refining of raw materials or thermal plant use) and calculated the water withdrawal needed for each type. Vasilis and Hyung calculated the life cycle uses of water for electricity generation in the U.S., including the stages of fuel acquisition, preparation, and device/plant construction (Fthenakis and Kim, 2010b).

The life cycle studies above just focused on water requirements instead of WF, and did not consider water pollution. However, the environment impacts caused by water will be underestimated if water pollution is not considered. It is proved that the grey WF is five times greater than the water consumption in Beijing (Zeng and Liu, 2013).

Some studies have focused on regional water consumption. Fulton and Cooley studied regional water consumption in California (Fulton and Cooley, 2015) and indicated that shifting from more water-intensive oil production to less water-intensive oil production reduced the energy WF between 1990 and 2012. Using the LCA method, some researchers used China's provincial Input-Output table to trace the inter-regional and inter-sectoral demands on water resources and related environment impacts (Zhang and Anadon, 2013). Regional studies have indicated that strategies must be developed to address the challenges posed by the geographic mismatch between water resources and energy production. However, further details are needed to identify regions for potential development and to assess water depletion levels following the energy production in these regions.

In addition to that, the national average WF database are also needed for unified standard. To establishing one set of unified standard, certification and labeling systems (USCLS) of green product is key step for sustainable development in China. Green products means consuming less resources and energy, emitting less pollution during its life cycle. The government has released related policy for promoting the USCLS for green products (SC, 2016). Nowadays, some research agencies and organizations have started carrying out the carbon footprint program for USCLS. They found that the unified database is the foundation for USCLS (CQC, 2016). The national database is the first pilot step for unified system. Water resource is an important aspect of green product., therefore our study can provide basic method and data for the USCLS in perspective of WF.

Using a bottom-up approach, this study applied the WF method to the life cycle of energy production. WF distribution and water deprivation (WD) maps were drawn for China to identify regions suitable for energy development based on their water resources. This study aimed (1) to develop a WF model of energy, (2) to calculate the WF of energy production in China, providing basis for national database for water footprint and interface for WF standard, certification and labeling system (3) to suggest measures to mitigate water resource stresses during the life cycle of the energy industry, and (4) to provide basic information about regions that can potentially develop energy production based on their water resources.

2. Methodology and data

2.1. Scope definition

A WF study must define the energy types and life cycle stages that it will cover. Fig. 1-1 and 1-2 shows the system boundary applied to analyze the WF during the life cycles of three types of fossil fuels (coal, crude oil, and natural gas) and five power sources (thermal power, hydropower, nuclear power, wind power, and solar photovoltaic power (solar power)) during various stages, including the mining, processing, conversion, and generation of energy. The functional unit used was m^3 of water per GJ of energy production.

2.2. Modeling the water footprint of energy production

The WF model of energy shown in Fig. 1-1 and 1-2 includes both direct and indirect WFs. Direct water consumption refers to the water used during the production of energy, whereas indirect water consumption refers to the water use associated with inputs such as materials, energy, and other resources.

The total WF of energy production includes only the blue and grey WFs, and excludes the green WF. The green WF refers to the volume of rainwater consumed during production processes, and it is particularly relevant to agricultural and forestry products. The WF of primary energy can be expressed using Eq. (1):

$$W_E = W_{direct} + W_{indirect} = W_{b,d} + W_{g,d} + W_{b,in} + W_{b,in} \quad (1)$$

where

W_E is the WF of energy production.

W_{direct} is the direct WF of energy production, including the blue and grey WFs,