Global Environmental Change 41 (2016) 142–152

Contents lists available at ScienceDirect

Global Environmental Change

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

Water use in China's thermoelectric power sector

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ARTICLE INFO

Article history:
Received 2 March 2016
Received in revised form 12 September 2016
Accepted 27 September 2016
Available online xxx

Keywords:
Water
Energy
Nexus
Policy
China

ABSTRACT

We quantify the current water use of China's thermoelectric power sector with plant-level data. We also quantify the future implications for cooling water use of different energy supply scenarios at both a regional and national levels. Within China, water withdrawal and consumption are projected to exceed 280 and 15 billion m^3 respectively by 2050 if China does not implement any new policies, up from current levels of 65.2 and 4.64 billion m^3. Improving energy efficiency or transforming the energy infrastructure to renewable, or low-carbon, sources provides the opportunity to reduce water use by over 50%. At a regional level, central and eastern China account for the majority of the power sector's water withdrawals, but water consumption is projected to increase in many regions under most scenarios. In high-renewable and low-carbon scenarios, concentrated solar power and inland nuclear power, respectively, constitute the primary fresh water users. Changing cooling technology, from open-loop to closed-loop in the south and from closed-loop to air cooling in the north, curtails the power sector's water withdrawal considerably while increasing water consumption, particularly in eastern and central China. The power sector's water use is predicted to exceed the regional industrial water quota under the '3 Red Line' policy in the east under all scenarios, unless cooling technology change is facilitated. The industrial water quota is also likely to be violated in the central and the northern regions under a baseline scenario. Moreover, in line with electricity production, the power sector's water use peaks in the winter when water availability is lowest. Water-for-energy is a highly contextual issue – a better understanding of its spatio-temporal characteristics is therefore critical for development of policies for sustainable cooling water use in the power sector.

1. Introduction

1.1. Water for thermoelectric power production

Water is an indispensable factor of production throughout the thermoelectric power sector, from upstream fuel extraction and power production to downstream infrastructure dismantling (World Energy Council, 2010). Of these various processes, the operation of power plants contributes the most to total water use (Mekonnen et al., 2015) and cooling to dissipate the residual heat from steam turbines in thermoelectric power production uses the most water (Fthenakis and Kim, 2010; Meldrum et al., 2013).

Water withdrawal refers to water abstracted from the natural environment while water consumption is defined as the water withdrawn but not discharged back to water bodies (AQUASTAT, 1998). Collectively, they are referred to as water use. Since Vassolo and Doll (2005) made the first attempt at estimating the global thermoelectric power sector's water use and presented a global-gridded estimate of the water uses of 63,590 thermal power stations for the year 1995, there has been a proliferation of studies looking at the water use for power generation over the last decade. It is estimated that thermoelectric cooling is responsible for around 43% and 50% of total fresh water withdrawals in the EU and US, respectively (UN, 2014). Globally, around 53 billion m^3 of fresh water is consumed every year by energy production (Spang et al., 2014). Both water shortage and water temperature increase could lead to reductions of electricity generation, which is manifested by the curtailments of power production or plant shutdowns in Europe, as seen in 2003 in France, and in south eastern US where there was insufficient cooling water availabilities (Van Vliet et al., 2012).

Potential conflicts between water availability and demand by the power sector arising from climate change are anticipated in several studies forecasts. Projections based on climate change modelling indicate reductions in usable capacity for over 60% of the global hydropower and over 80% of the thermoelectric power from

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http://dx.doi.org/10.1016/j.gloenvcha.2016.09.007
0959-3780/

2040 to 2069 (Van Vliet et al., 2016). Moreover, some climate change mitigation technologies, e.g. carbon capture and storage (CCS), may have the unintended impact of increasing the power sector's water consumptions (Byers et al., 2014). However, Kyle et al. (2013) argued that increasing water consumption could be offset by water-saving technologies, e.g. open-loop cooling. All the studies highlight the importance of considering future scenarios to avoid unsustainable infrastructure and technological investments.

Amongst various factors impacting the power sector's water intensities, measured as water consumed or withdrawn per unit of electricity produced, the type of thermoelectric plant and the cooling technology they use are the most significant (Macknick et al., 2012). There are primarily three types of cooling technologies: open-loop cooling, which dissipates heat by running water; closed-loop cooling, which dissipates heat by recirculating water in towers or ponds; and air cooling, which removes heat by air circulation. The consumptive water use in an open-loop system is 70–80 percent lower compared with a closed-loop cooling system, but the water withdrawal is 30–60 times higher (WRI, 2015).

Climate change may alter the availability of water by increasing temperatures (and hence the evapotranspiration of surface water) and increasing the variability of precipitation, e.g. increase of drought periods and expansion of drought-affected areas (Gerten et al., 2013; Hanasaki et al., 2013; Wada et al., 2011; Doell and Schmied, 2012). The OECD's baseline scenario projects that 3.9 billion people will be subject to severe water stress by 2050 (OECD, 2012). Water-related risks for power industry are estimated to worsen with the changing climate (IPCC, 2013).

1.2. Significance of the study area

Cooling water is a particular issue in China because of the prevalence of thermoelectric power plants on inland waterways that are potentially at risk of water shortages. Over the last decade, electricity consumption in China has almost quadrupled from 1347 TWh in 2000 to 4976 TWh in 2012 (National Bureau of Statistics of China, 2014), with this trend projected to continue. More than 80% of the power demand was met by thermoelectric power generation (Zhang, 2012).

Yet, China is not abundant in water. Although the country's total amount of surface water ranks sixth in the world at about 2800 bn m^3, its water resource per capita, 2632 m^3 in 2012, only amounts to one fourth of the world average (Ye and Zhang, 2013). In 2011, the Chinese government issued its strictest water management policy called the '3 Red Line' policy. This policy set targets for total water use, industrial and agricultural water use efficiencies and water quality improvements on a national as well as on a regional scale for 2015, 2020 and 2030. Regarding the total water use, the first 'Red Line' sets a national water withdrawal cap at 635, 670 and 700 bn m^3 for 2015, 2020 and 2030, respectively, against the level of 609.5 bn m^3 in 2014 (China Water Resource Bulletin, 2015), which will be enforced through a water permit system. However, without technological changes, the industrial targets for water withdrawals are likely to be exceeded in the energy sector by 2035 (Qin et al., 2015). Accordingly, Yu et al. (2011) conclude that technological innovation is critical in terms of water conservation in China's coal-fired power sector.

China's water resources are unevenly distributed. The precipitation is highest in the southeast and lowest in the northwest. The total average annual internal renewable surface water resources in northern areas are estimated to be 535.5 km^3, which is only 20 percent of the country's total (AQUASTAT, 2014). Moreover, the precipitation's inter-annual variations are greater in the north than in the south (Ye and Zhang, 2013). On the other hand, Zhang and Anadon (2013) conclude that the most important feature of China's thermoelectric power sector's water use is its uneven spatial distribution. The power sector's water withdrawal mostly occurs in the east and south, while water consumption by the power sector was higher in the arid northern regions in 2007 (Zhang and Anadon, 2013). Several river basins in the north and northwest, as well as a number of coastal city clusters in the east and south, have significant water stress (Zhang et al., 2016). Without effective water-saving measures, China's coal industry's water demands could exceed its water availabilities, especially in the north and west (Pan et al., 2012).

China's coal reserves are mostly located in water-scarce areas and, to save cost, a large proportion of power generation capacity is located close to these reserves. Furthermore, over half of China's proposed coal-fired power plants are located in areas with high water stresses (WRI, 2014). According to the assessment by Sadoff et al. (2015), northern China stands out as having the highest water security risks in the world for power generation. Given the significant uneven spatial distributions of China's water resources and power productions along with their geographical mismatches, China's thermoelectric power sector's water use needs to be studied on a regional scale.

The power system in China is operated on six regional grids: the northern, northeastern, northwestern, central, eastern and southern grids. Interregional power transmissions are small (Guo et al., 2016) and therefore not considered in this study. It is therefore useful to look into the power sector's water demands against their water quotas by regional grid.

In terms of future projections on a regional scale, Cai et al. (2014) has examined China's energy production's water withdrawal, from coal mining to power production, under IEA's future energy scenarios. However, water withdrawal and consumption factors were not differentiated in their calculation. Consequently, Cai et al. (2014) underestimated China's energy sector's water withdrawal with results much lower than that from Qin et al. (2015). Moreover, water consumption was not discussed. Water consumption is important especially during dry seasons when upstream power plants' water consumption, instead of water withdrawal, poses the biggest threat to downstream water users.

While power production and its corresponding water demand vary within the year, inter-annual temporal characteristics of China's water for energy are under-studied. Moreover, the spatial patterns of water availability and use are not well understood. This lack of understanding could lead to conflicts between regional energy developments and related water policies. This paper therefore sets to achieve four goals: (1) to better present the current water use by China's power sector with plant-level data that considers different cooling types and water sources; (2) to examine China's future water for energy on a national and regional scales; (3) to examine the regional coherence of China's energy plans and related water policies, i.e. the '3 Red Line' policy; and, (4) to reveal the temporal characteristics of China's power sector's water use.

2. Methodology and data

2.1. Methodology

A bottom-up approach, as in Vassolo and Doll (2005), Yuan et al. (2014) and Byers et al. (2014), is employed in this study to estimate the water uses in China's thermoelectric power sector:

$$A = E^{*}a \quad (1)$$

$$C = E^{*}c \quad (2)$$