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Categorising virtual water transfers through China's electric power sector

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HIGHLIGHTS

- China's thermoelectric power consumed 3.8 billion m^3 of water in 2010.
- China's hydropower consumed 14.6 billion m^3 of water in 2010.
- 60.2% of the power sector's water use was driven by industries' power demands.
- 47.5% of the power sector's water use was virtually transferred across provinces.
- Water-scarce inland provinces are exporting virtual water via their power sector.

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ABSTRACT

Water consumption in thermoelectric and hydropower plants in China increased from 1.6 and 6.1 billion m^3, respectively, to 3.8 and 14.6 billion m^3 from 2002 to 2010. Using the concept of virtual water, we attribute to different electricity users the total water consumption by the electric power sector. From 2002 to 2010, virtual water embodied in the final consumption of electricity (hereinafter referred to as VWEF) increased from 1.90 to 7.35 billion m^3, whilst virtual water in electricity used by industries (hereinafter referred to as VWEI) increased from 5.82 to 11.13 billion m^3. The inter-provincial virtual water trades as a result of spatial mismatch of electricity production and consumption are quantified. Nearly half (47.5% in 2010) of the physical water inputs into the power sector were virtually transferred across provincial boundaries in the form of virtual water embodied in the electricity produced, mainly from provinces in northeast, central and south China to those in east and north China. Until 2030, VWEF and VWEI are likely to increase from 5.27 and 14.89 billion m^3 to 7.19 and 20.33 billion m^3, respectively. Climate change mitigation and water conservation measures in the power sector may help to relieve the regional pressures on water resources imposed by the power sector.

1. Introduction

While electric power is crucial to modern human society's development and prosperity, production of electricity uses another essential commodity, i.e. water [1–3]. Water-related issues have curtailed power production around the globe [4]. With water being recognized as the top global risk facing humanity over the next decade [5], water challenges for the energy sector are set to intensify [6].

Although water is required throughout the life cycle of electricity production, the operational phase plays a dominant role [3,7,8]. Apart from some forms of renewable electricity production, e.g. solar PV and wind, which require negligible amounts of on-site water inputs, many studies have shed light on the water uses for thermoelectric power production, primarily for cooling purposes, on global, national and regional scales [9–13]. However, little work has been done to reveal how the physical water inputs to the electric power sector in one region turn into virtual water embodied in the power produced traversing geographical boundaries and then being used by different sectors, e.g. households, industries, in another region.

Virtual water refers to water used for the production of goods and services, which can then be transferred among economic sectors and regions through trade [14,15]. Studies of virtual water provide insights into how production, trade and consumption in other regions and sectors can exacerbate or alleviate over-exploitation of water resources [16,17]. However, existing studies quantifying sub-national virtual water fluxes within China's electric power system have adopted a

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production-based bottom-up approach [18–21]. Their work failed to address the inter-sectoral contributions among the final electricity users. Incorporating insights from a consumption-based perspective analyzing virtual water embodiments in the electric power consumed by different sectors can help to provide a more complete picture of the water footprint of different sectors and of the geographical fluxes of virtual water. Furthermore, although Liu et al. [22] have shed light on the water consumption in China's hydroelectric power plants and pointed out that they have a higher water consumption factor, measured as water consumption per unit of electricity produced, than other types of electricity production, hydropower production's water consumption has not been examined on a provincial scale.

We propose a framework that maps out the water flows related to the power sector, from physical water inputs to virtual water embodiments:

1. To produce electricity, physical water is directly consumed in (i) thermoelectric power plants for cooling and other purposes; (ii) hydroelectric power plants through evaporation from dammed water.
2. After power production, abovementioned physical water inputs are transformed into virtual water embodiments in (i) electricity consumption by final demand, including urban and rural household consumption, the public sector and so forth (VWEF) and (ii) electricity as intermediate inputs into other industrial sectors (VWEI).

This framework can be illustrated by the Sankey diagram (Fig. 1) demonstrating the corresponding water fluxes from physical water consumption to virtual water embodiments in China's power sector in 2010 (see data section for data sources):

A Water Embodied in Trade model (WET) based on the data from Multi-Regional Input-Output (MRIO) tables (see Data section) is used to quantify the two categories of virtual water flows among China's thirty province in 2002, 2007, 2010 and 2030. We focus on water consumption by the power sector in this study, which is defined as water withdrawn from the environment but not discharged back to any water bodies [23].

In summary, this study distinguishes itself from existing literature with four significant contributions: (i) including water consumption by both thermoelectric and hydropower productions at a provincial level; (ii) quantifying virtual water embodiments in the electricity consumed by the final demand as well as intermediate input to industries; (iii) quantifying the inter-provincial virtual water transfers based on this improved categorisation; (iv) investigating the future possibilities of water consumption by China's power sector and consequential virtual water transfers under various future scenarios of different provincial generation mixes and technology configurations in the electric power sector.

2. Method and data

2.1. Quantifying water consumption for power production

Water consumption for both thermoelectric power production and hydroelectric power production are quantified in this study. Regarding thermoelectric power production, coal-fired power production is used as a proxy for two reasons: (i) electric power generated from natural gas occupied only 3.1% of thermoelectric power production in China in 2014; (ii) provincial energy statistics do not differentiate gas-fired and coal-fired power generations.

This study focuses on the operational phase of coal-fired power production, which needs water for cleaning, cooling, boiler make up and other on-site water-requiring processes, e.g. flue gas desulfurization (FGD), coal transport and domestic uses. Coal-fired power plants' water consumption factors differ significantly depending on the cooling technology used [2]. Three commonly used cooling technologies in China are: open-loop cooling, closed-loop cooling and air cooling. Closed-loop cooling systems consume the largest amount of water because of the evaporative loss of recirculated water in cooling towers, whereas open-loop cooling systems use running water and thus have much lower water consumption. Air cooling systems require the least amount of water as they do not need water for cooling purposes. According to Liao et al. [24], in a typical coal-fired power plant equipped with closed-loop cooling systems, evaporative water loss accounts for around 80% of its total operational water consumption. Thermoelectric power plants' water consumption can be calculated by Eq. (1):

$$W_{it} = WF_{it} \cdot P_{it} \tag{1}$$

where WF_{it} indicates water consumption factor for thermoelectric power production in province i; P_{it} is province i's thermoelectric power production and W_{it} is the water consumption for province i's thermoelectric power generation.

According to Liao et al., coal-fired power plants equipped with closed-loop, open-loop and air-cooled systems occupy 56.6%, 30.8% and 12.6%, respectively, in China. Further provincial distributions can be obtained from their study [12]. Regarding water consumption factors of coal-fired power plants equipped with different cooling technologies, only a small number of coal-fired power plants reported their water consumption factors in China [25,26]. For plants with closed-loop and open-loop cooling systems, we use the median values (1.87 and 0.39 m^3/MWh, respectively) in the US as reviewed by Macknick et al. They are on par with the reported values from Chinese power plants [12]. Regarding coal-fired power plants with air cooling systems, as they are not included in Macknick et al., we use the median water consumption factor (0.32 m^3/MWh) reported by Chinese power plants [25,26]. It is worth noting that although cooling tower's water evaporation will be affected by ambient temperature and relative humidity change, those effects are not considered in this study. China's provincial thermoelectric power sector's water consumption factors can then be

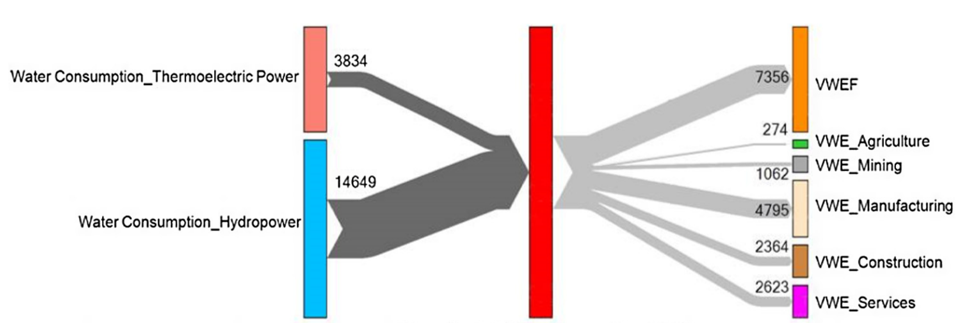

Fig. 1. Water fluxes from physical water consumption to virtual water embodiments in China's power sector (million m^3) (Dark Grey – Physical Water; Light Grey – Virtual Water; the width of the fluxes are proportionate to the amount of water).