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The energy-water nexus of China's interprovincial and seasonal electric power transmission

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HIGHLIGHTS

- 16% of China's power water consumption was transferred via transmission.
- Power transmission reduces water withdrawal but increases consumption in China.
- The virtual water transfer varies greatly through the year and peaks in August.
- Water stress is shifted to the west, with Shanghai as one of the beneficiaries.

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ABSTRACT

Modern energy systems use large amounts of water for electric power production. This has important impacts on future water management and energy system planning decisions. In this study, we quantify the physical water use of power production and virtual water transfer via power transmission between Chinese provinces using the information on 5408 electricity-generating units and interprovincial power transmission. We show that China's power production withdrew 62.7 billion m^3 of freshwater in 2017, of which 13 billion m^3 was consumed (i.e. not returned to the original water basin but lost via evaporation, etc.). A large volume of freshwater was virtually traded through the transmission system. Overall, 6.2 billion m^3 of freshwater withdrawal and 2.1 billion m^3 of water consumption was traded. Nationally, power transmission reduced freshwater withdrawal but increased consumption in China because, compared to the east, the west generally has a larger water consumption factor but a lower withdrawal factor. Water stress was more equally distributed across provinces through power transmission. We find large seasonal variations in inter-regional virtual water consumption transfer, with an August peak. While the Yangtze River basin and downstream of the Yellow River basin have abundant water relative to other basins, the many power plants located along the two rivers aggravate local water stress. These dynamics will become increasingly important for policymakers and energy planners as China undergoes climatic changes and a rapid energy transition.

1. Introduction

Global electricity demand grew 4% in 2018 and is already a major driver for water stress worldwide [1,2]. Meanwhile, climate change and water shortages have increased the sensitivity of power systems to water availability [3], raising both research and policy concerns [4]. In 2017, 26% of global electric power was produced by China [2], with thermal and hydropower the main contributors. Both technologies depend on water resources and satisfying this requirement is a key component of energy security [5,6]. Specifically, China accounts for 29% and 28% of the world's thermal power and hydropower production, respectively [7]. An assessment of the water use of the two energy technologies in China is important for understanding the global energy-water nexus. Across China's border regions, especially in the South and Southwest, power production may have impacts on transboundary water resources, for instance across the Lancang Mekong river basin [8], depending on what choices are made for electricity generation and cooling as these regions develop further. The operations of hydropower dams in the

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mainstem on the Lancang Mekong Basin have effects on the downstream water flows, generally reducing the flow during the wet season and increasing it during the dry season [9]. Another example of transboundary water resources originating in China is the Brahmaputra River, which directly flows through three countries: China, India, and Bangladesh, and is an important water source for the domestic and agricultural practices in these countries [10,11]. Since the river flows through some highly disputed areas, the potential for riparian conflicts of interest over water resources development is significant [12]. In China's recently released (November 2020) China's national development plan, more water resources of the Brahmaputra River will be used for hydropower generation [13]. The type of hydropower plant (i.e. run-of-river or running with reservoirs [5]) will determine the impacts of power generation on the water availability of downstream users inside and outside of China. As the world's largest carbon dioxide (CO_2) emitter [14], China promises to make efforts to be carbon neutral before 2060 [15]. This is likely to entail the large-scale use of carbon capture and storage (CCS) which requires additional water resources [16]. This may be used both in the power sector (which comprises 50% of China's emissions) and in the development of negative emission technologies [17,18]. For the regions that lack sufficient water resources to meet the additional water demands of CCS, the adoption of CCS can exacerbate the vulnerability of power plants to water scarcity. A spatially explicit mapping of power plants' water use is essential to the trade-offs between CO_2 emissions reduction and water scarcity mitigation for China and the world.

Water use is typically split into two forms: withdrawal and consumption [19]. The former reflects the volume of water diverted from a water source for use, all or part of which may be returned (but generally at a lower quality), while the latter refers to the volume of water not returned to the water body due to evaporation, transpiration or incorporation into products, i.e. water consumed always reduces the remaining water quantity [20,21]. The cooling requirement of thermal power production needs a significant amount of water [5,22,23]. There are three common cooling types: 1) once-through cooling, requiring large amounts of water withdrawal and directly returning most of that water to its source; 2) closed-loop (wet tower) cooling in which some of the water is consumed through evaporation (it withdraws less but consumes more than once-through cooling); and 3) air cooling using air-cooled condensers for steam cooling, which avoids evaporative water losses [24]. Power plants with closed-loop cooling technology are large water consumers, while plants with once-through cooling technology are leading water withdrawers [25–29]. Previous studies showed that 57.6 billion m^3 of freshwater was withdrawn for thermal power production in China in 2015 [30], approximately 9.4% of the national total water withdrawal in that year [31]. Estimates for the annual freshwater consumption of thermal power production in China range from 3.8 to 5.7 billion m^3 [30,32,33], largely depending on the assumed water consumption factors. Hydropower was not considered in these studies but consumes large amounts of water through reservoir evaporation [5]. Hydropower can be water-intensive depending on the reservoir area and local evaporation rate [6,34]. Previous research indicates a wide range for hydropower water use, from negative values (due to reservoir water storage increasing availability downstream) to more than 115000 m^3 MWh^{-1} [35]. In China specifically, Liu et al. showed hydropower water use ranges of 13 to 15244 m^3 MWh^{-1} [36]. Zhu et al. [37] and Liao et al. [32] estimated that 11.5 to 14.6 billion m^3 of freshwater was consumed for hydropower production in China in 2010. However, they used water consumption factors at subnational or provincial levels, neglecting differences in evaporation across individual reservoirs.

A further complication to understanding power-related water dependence is that different power plants may use different types of water resources. Four types of water can be discerned: surface water, groundwater, reclaimed water, and seawater. Depending on the technology installed, thermal power plants have the potential to use all four water resources, whereas hydropower uses surface water only. Without distinguishing these water uses, studies omit important factors for estimating freshwater security. For instance, in contrast to Zhu et al. [37] where the freshwater consumption of thermal power was not reported separately (and which found 10.2 billion m^3 of water consumed in China in 2010), Liao et al. [32] focused on freshwater and found that around 3.8 billion m^3 was consumed in that year.

Water is used for power production and then transmitted, virtually, across the power transmission network. Chini et al. studied the virtual water flows of the US electric grid, finding freshwater transfer of 11.2 billion m^3 in 2016 [38]. In China, around 13.7% of total national electricity was transported inter-provincially via transmission in 2011 [39], growing to 16% in 2017 [40]. This implies an increasing amount of water withdrawal and consumption which is serving other provinces as where withdrawal or consumption takes place. The volume of virtual water transfer via transmission has already raised concerns in China [41,42]. He et al. assessed China's virtual water transfer at the subnational level, finding that virtual water transfer accounted for 9% of the total water consumption for electricity generation in 2016 [43]. Zhang et al. showed that the volume of virtual water transfer increased by a factor of 1.5 between 2006 and 2016 (however, hydropower was not considered) [44]. Zhang et al. used national average water intensities and showed that virtual water in electricity transmission increased five-fold between 2005 and 2014 [45]. Zhu et al. [46] analyzed virtual water transfers of the West-East Electricity Transmission project in China and found that 2.4 billion m^3 of virtual water was transmitted eastward in 2017. Previous studies have shown 1.4 billion m^3 of water consumption transfer through electricity transmission among China's six subnational regions in 2012 [47], and 6.3 billion m^3 of withdrawal transfer between China's provinces in 2014 [41]. Wang et al. [42] looked at the impacts of electricity transmissions on water scarcity at the river basin level rather than provinces, and calculated changes in the water-stressed population. Our work differs from these previous studies as follows. We explicitly differentiate between withdrawal and consumption, and types of cooling water used (in which particularly the differentiation between fresh and seawater is essential). Further, previous studies did not examine the seasonal variations in water transfer.

Virtual water transfer via power exports could reduce overall water withdrawal and consumption for power generation in China if the exporting region has higher water productivity or availability than the importing region [41]. Conversely, in the opposite situation power transmission may have negative impacts on water use. These dynamics are rarely quantified. An identical amount of water consumption may result in different impacts on exporting or importing regions with different levels of water stress [48]. Zhang et al. [49] tried to link power-related water transfer and regional water stress for China, but this study had limitations that it was based on water use factors from studies on the US and did not differentiate between types of water resources. Zhang et al. [50] quantified the impact of the spatial distribution of power generation on water consumption at a provincial level in China, indicating that transferring part of power generation tasks away from water-deficient areas could have significant impacts on the mitigation of water scarcity. However, more detailed technical causes of water use and transfer could not be deeply analyzed since it was not conducted at the plant level.

We compiled a state-of-the-art database of over 5,000 power-generating units and a model of the Chinese power transmission network. We investigated the water use of power plants and virtual water transfer by power transmission. Water consumption and water withdrawal are differentiated for a better understanding of water use. Water types (surface water, groundwater, reclaimed water, and seawater) are also distinguished in the assessment. The extensive inventory of plant information allows for a detailed analysis of the drivers of spatio-temporal variations in water use and transfer. Besides, we presented the impact of power production and transmission on provincial water stress using a metric of 'power-related water use to availability' (UTA_p), which is the ratio of power-related water use to regional water availability. Meanwhile, a counterfactual scenario was set to assess the counterfactual UTA_p that would be at stake if the province would fully generate its own power, and make a comparison to the actual UTA_p related to power consumption in a province. The difference between actual and counterfactual UTA_p represents the contribution of power transmission in terms of increasing or ameliorating water stress [51]. This work represents a significant improvement to the understanding of the energy-water nexus across China at multiple spatial scales and water resource levels. This work also provides a template for similar analyses in other nations.

2. Materials and methods

2.1. Materials

Power: we include coal, gas, biomass, geothermal, nuclear and hydropower. Thermal plant information included: plant name, installed capacity, the beginning year of operation, unit type, location, operation status, cooling system, and monthly electricity generation. Hydropower information included: plant name, installed capacity, year of operation start, location, operation status, reservoir area, and electricity generation. Data were sourced from the Global Coal Plant Tracker [7], World Electric Power Plants Database [52], GRanD v1.3 [53] and Liu et al. [36]. For the cooling system of thermal power plants, we used Google satellite imagery cross-checked with information from the China Electricity Council [54]. We collected the installed capacity of each plant and used the monthly provincial capacity factor to estimate the electricity generation of each plant. The provincial capacity factor was calculated by dividing the provincial power production by provincial installed capacity. Both provincial power production and installed capacity are provincially available data, obtained from the Chinese National Bureau of Statistics [55] and China electric power yearbook [56] respectively. The compiled database covered 96%, 75%, 50% and 23% of the national installed capacity for coal, nuclear, hydropower and gas power plants, respectively. In total, 5408 power production units were included. The information of these units was used to assess the provincial power-related water use factors and total water use.

Transmission: The power transmission data in 2017 were obtained from the China Electricity Council [40]. These data are mostly reported in the form of province-to-province transmission. A small amount of transmission data are from provinces to the subnational grid. We disaggregate them into the province-to-province transmissions based on actual electricity transmission lines [39,57]. Monthly provincial power transfers were obtained from the Professional Knowledge Service System for Energy [58]. The provinces are shown in **Fig. A.1a**.

Water consumption and withdrawal: We use China-specific water withdrawal and consumption factors for power plants. Specifically, water use factors of most coal power units were obtained from the National Energy Efficiency Benchmarking Competition [54]. We also obtained data for other power units from the inventory compiled in our previous study [5]. Finally, some once-through cooling water withdrawals were obtained from Zhang et al. [30], who used the monitoring data of withdrawals for some plants with once-through cooling systems in the Yangtze River basin (The nine river basins are shown in **Fig. A.1b**). A once-through cooling system is a technically simple system, which requires large amounts of water withdrawal and directly returns most of that water to its source. In a closed-loop (wet tower) cooling system, water goes through a cooling tower where some of the water is consumed through evaporation. Closed-loop cooling generally withdraws less but consume more water than once-through cooling. An air cooling system uses air-cooled condensers for steam cooling and can avoid evaporative water losses [24]. The water type was obtained from the China Electricity Council [54] and the Power Industry Statistical Information System [59]. For hydropower, water use was determined by the evaporation factor and reservoir area. The reservoir evaporation factor for each month was extracted from the Noah Land Surface Model [60]. Water consumption and withdrawal within basins were obtained from the World Resources Institute Aqueduct database [61] and adjusted for the year 2017 using China's water use data from the National Bureau of Statistics [31]. The provincial available water, comprising both surface water and groundwater supply, was obtained from the Water Resources Bulletin [62]. Appendix A discusses in more detail how we build our database with these data sources above and presents more specific information on each power plant. Two assumptions were made for water use assessment: that the water use factors of thermal power plants and the reservoir area of hydropower plants were assumed to be constant throughout the year.

2.2. Methods

The modeling schematic is shown in Fig. 1. We outline each step in detail below but provide a brief overview here. First, we use individual plant data to estimate regional water use factors. We then combine this with data on regional power production and regional power transmission, and we can assess regional water use and virtual water transfers. Finally, we examine the impacts of the electric power system on water stress.

2.2.1. Calculating the water use of power production

A bottom-up approach was used, discerning six power production technologies: coal, gas, biomass, geothermal, nuclear and hydropower. Wind and photovoltaic power technology were not included because they consume negligible water. Four types of water resources were considered: surface water, groundwater, reclaimed water and seawater. Water use was specified as water consumption and water withdrawal. The water use of power production can be estimated in several steps.

The first step is to estimate water use at the plant level, beginning with thermal power:

$$WU_i = F_i \cdot PP_i \tag{1}$$

In which, WU_i denotes the water use of power plant i (m^3); F_i denotes the water use factor of power plant i (m^3/MWh); PP_i denotes the power production of power plant i (MWh). The water use of hydropower plants is calculated as follows:

$$WU_i = E_i \cdot A_i \cdot \eta_i \cdot 1000 \tag{2}$$

In which, E_i denotes the evaporation factor at the site of hydropower plant i (mm/month); A_i denotes the reservoir area of hydropower plant i (km^2); η_i is a dimensionless parameter to allocate the water use of a reservoir to hydropower plant i, determined by the economic values of the different purposes of the reservoir [36]. The water withdrawal of hydropower is assumed to be equal to water consumption, i.e. the surface water evaporated from the reservoir.

The power production for each plant is calculated as:

$$PP_i = \frac{RPP_{m,r,e}}{CP_{r,e}} \cdot CP_{r,e,i} \tag{3}$$

Where $RPP_{m,r,e}$ denotes the provincial power production using technology e in region r in month m (MWh); $CP_{r,e}$ denotes the provincial installed capacity using technology e in region r (MW); $CP_{r,e,i}$ denotes the installed capacity of plant i with technology e in region r (MW). Equation (3) implies an assumption that in each province the power production for each plant is proportional to the installed capacity of this plant. This assumption is made based on the small differences in the capacity factor across plants according to the information (described in **Table A.1**) on the capacity factor of 1111 electricity-generating units in 28 provinces.

The third step is to calculate water use at the regional level:

$$WU_{m,r,e,s,u} = \sum_i WU_{m,r,e,s,u,i} \tag{4}$$

Where $WU_{m,r,e,s,u}$ denotes the regional water use of power production from the power plants in the database we complied (m^3) in month m,

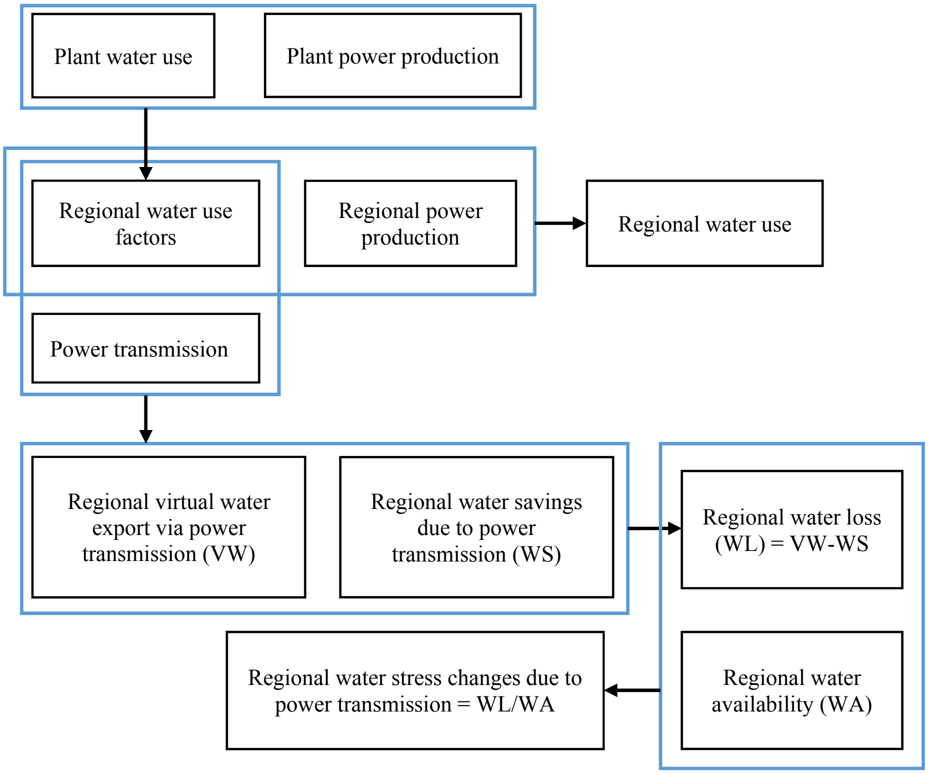

Fig. 1. Flow chart of the calculation process.

region r, for power production technology e; water resource type s; water use type, i.e. water consumption vs. water withdrawal is given by u. The power production of plants in the database is aggregated to the regional level using:

$$PP_{m,r,e} = \sum_i PP_{m,r,e,i} \tag{5}$$

In which, $PP_{m,r,e}$ denotes the power production using technology e in region r in month m from the power plants in the database we complied (MWh); e is categorized into three types: hydropower, nuclear, and other thermal power (not six types due to data limitations on the availability of power production).

Then, the regional water use factor of each power-generating technology (*WUF*) can be obtained by dividing the total water use of plants by their total power production in the region.

$$WUF_{m,r,e,s,u} = \frac{WU_{m,r,e,s,u}}{PP_{m,r,e}} \tag{6}$$

Where, $WUF_{m,r,e,s,u}$ denotes the quantity of water of type s consumed/withdrawn per unit of power production from technology e in region r in month m (m^3/MWh). The regional water use (*RWU*) of power production can now be obtained:

$$RWU_{y,r,s,u} = \sum_m RWU_{m,r,s,u} = \sum_e WUF_{m,r,e,s,u} \cdot RPP_{m,r,e} \tag{7}$$

Where, $RWU_{y,r,s,u}$ gives the quantity of water of type s consumed/withdrawn for power production in region r in the year 2017 (m^3); $RWU_{m,r,s,u}$ gives the quantity of water of type s consumed/withdrawn for power production in region r in month m (m^3). The regional water use factor of power production can be obtained for assessing the virtual water transfer via power transmission:

$$RWUF_{m,r,s,u} = \sum_e WUF_{m,r,e,s,u} \cdot \frac{RPP_{m,r,e}}{RPP_{m,r}} \tag{8}$$

Here, $RWUF_{m,r,s,u}$ denotes the quantity of water of type s consumed/withdrawn per unit of power production in region r in month m (m^3/MWh); $RPP_{m,r}$ denotes the total power production in region r in month m (MWh).

$$RWUF_{y,r,s,u} = \sum_m WUF_{m,r,e,s,u} \cdot \frac{RPP_{m,r}}{RPP_{y,r}} \tag{9}$$

Where $RWUF_{y,r,s,u}$ denotes the quantity of water of type s consumed/withdrawn per unit of power production in region r in the year 2017 (m^3); $RPP_{y,r}$ denotes the total power production in region r in the year 2017 (MWh).

2.2.2. Calculating virtual water transfer via power transmission

The virtual water transfer across regions can be estimated by:

$$VW_{i,j,s,u} = RWUF_{y,i,s,u} \cdot PT_{i,j} \tag{10}$$

Where $VW_{i,j,s,u}$ denotes the virtual water exported from region i to j through power transmission (m^3); $RWUF_{y,i,s,u}$ denotes the quantity of water of type s consumed/withdrawn per unit of power production in region i in the year 2017 (m^3/MWh); $PT_{i,j}$ denotes the yearly power transmission from region i to j (MWh). Power importing regions save water, which can be estimated by using a counterfactual where a region does not import power but satisfies the local demand by producing power itself using the expression:

$$WS_{j,s,u} = RWUF_{y,j,s,u} \cdot \sum_i PT_{i,j} \tag{11}$$

Where $WS_{j,s,u}$ denotes the water-saving in region j by importing power (m^3). The impact of power transmission on regional water use can now be estimated:

$$WL_{j,s,u} = \sum_i VW_{j,i,s,u} - WS_{j,s,u} \tag{12}$$

In which $WL_{j,s,u}$ denotes the water loss in region j due to power transmission (m^3). A negative value of $WL_{j,s,u}$ indicates that in region j the water-saving achieved by importing power is larger than the water export by exporting power, thus region j saves water through power transmission; a positive value of $WL_{j,s,u}$ indicates that there is water loss in region j.

2.2.3. Assessing the impact of the power system on water stress

Power production is a large water user, but its impact on water use differs across regions due to the differences in power-generating technologies. Also, regional water use already differs across the country. The proportion of the power-related water use to the total water use is estimated at the basin level using:

$$WP_{b,u} = \frac{\sum_i WU_{b,u,i}}{WU_{b,u}} \tag{13}$$

Where $WP_{b,u}$ denotes the proportion of the power-related water use to the total water use in basin b; $WU_{b,u,i}$ denotes the water use of power plant i within basin b (m^3); $WU_{b,u}$ denotes the total water use of basin b (m^3). To assess the changes in water stress caused by power transmission, we use the above counterfactual method. The indicator use-to-availability (UTA_p), which is the ratio of power-related water use to regionally available water resources [33], was used to assess the impact of power transmission on regional water resources. Specifically, both water consumption and water withdrawal were considered, i.e. we calculated both CTA_p (consumption-to-availability) and WTA_p (withdrawal-to-availability) using:

$$PCTA_p = \frac{RWU}{WA} \tag{14}$$

$$CCTA_p = \frac{RWU - WL}{WA} \tag{15}$$

$$DCTA_p = CCTA_p - PCTA_p \tag{16}$$

Where $PCTA_p$ denotes the CTA_p driven by the present power system; $CCTA_p$ denotes the counterfactual CTA_p without power transmission; $DCTA_p$ denotes the CTA_p decrease induced by power transmission, a positive value means provincial CTA_p is reduced via power transmission; RWU denotes the provincial water consumption for power production; WL denotes the water consumption increased by power transmission (eq.12); WA denotes the provincial water availability. WTA_p is calculated analogously.

3. Results

3.1. Water use characteristics at the plant and national level

In 2017, 14.6 billion m^3 of water resources were consumed for power production in China, comprising of 12.8 billion m^3 surface water, 0.23 billion m^3 groundwater, 0.27 billion m^3 reclaimed water and 1.25 billion m^3 seawater. Hydropower was responsible for 68% of the surface

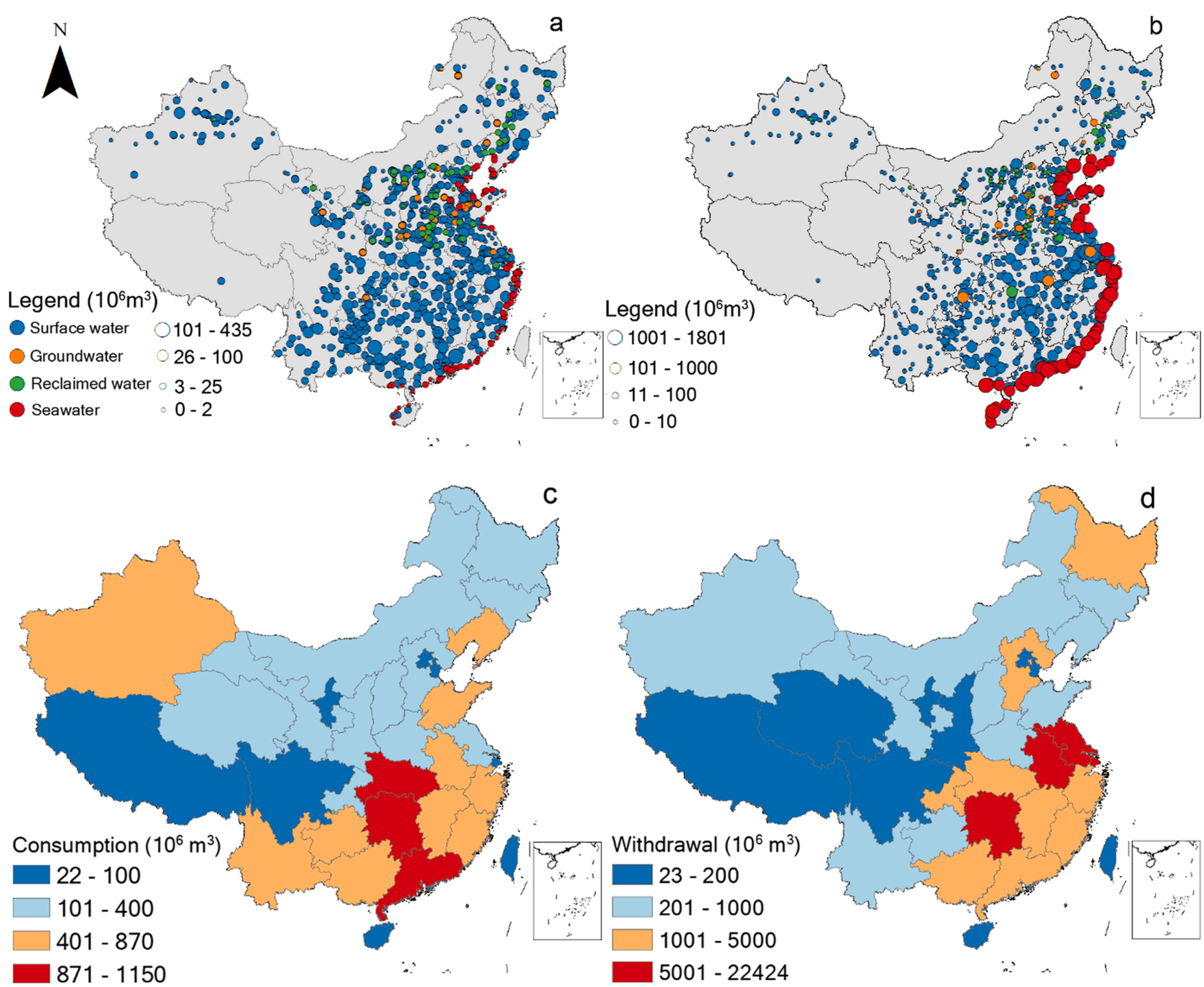

Fig. 2. Water consumption (a, c) and water withdrawal (b, d) of power at the plant and province level in China in 2017. For more details of plants' location, water use and power output, see Appendix B.

water consumed by power generation. Power plants using groundwater and reclaimed water are generally situated in northern China (Fig. 2**a**). In northwestern China, both direct and indirect air-cooling systems are commonly used to save water. There are many power plants with closed-loop cooling systems located downstream of the Yellow River basin, which increases local water consumption. All nuclear power plants in China are located along the coastline and use seawater for cooling. Coal power plants comprise 4 billion m^3 of freshwater consumption in 2017.

With respect to total water withdrawals (as opposed to consumption), power production in China withdrew 62.7 billion m^3 of freshwater, which amounts to approximately 10% of the national total for all sectors in 2017. In this study, we define freshwater as surface water and groundwater [62]. Compared to other regions, water withdrawal in southeastern China is much larger due to the preponderance of once-through cooling systems at generation units, cooling systems that require larger water withdrawals. Many of these once-through plants are in the Yangtze river basin (Fig. 2**b**) and aggravate local water competition (**Fig. A.2**). There are heterogeneities in freshwater use of power production across plants. 80% of power production withdrew just 10% of the total water for power in China whereas the remaining 20% withdrew 90%. Large water withdrawers are hydropower with large reservoirs and thermal power plants with once-through cooling systems.

Power-related water use differs widely across provinces (Fig. 2**c-d**). The top three freshwater consumers are Hunan (1.2 billion m^3), Hubei (0.9 billion m^3), and Guangdong (0.9 billion m^3). Hunan province is the largest freshwater consumer due to the high water consumption factor of hydropower. The top three freshwater withdrawers are Jiangsu (22.4 billion m^3), Shanghai (5.8 billion m^3), and Anhui (5.4 billion m^3). Jiangsu sees the largest freshwater withdrawal due to its large-scale power production and wide use of once-through cooling systems. In terms of monthly figures, July sees the largest consumption and withdrawal in Hunan (147 million m^3) and Jiangsu (2261 million m^3), respectively. Groundwater is mainly consumed in water-scarce regions: Hebei (65 million m^3), Shandong (62 million m^3), and Inner Mongolia (25 million m^3). Reclaimed water is mainly used in the northern regions: Liaoning (65 million m^3), Hebei (36 million m^3), and Beijing (35 million m^3). Seawater is used in coastal provinces such as Jiangsu, Guangdong, and Zhejiang. From the perspective of power type, hydropower dominates surface water consumption (9 billion m^3), while thermal power dominates surface water withdrawal (52 billion m^3). The descriptive statistics of electricity-generating units by region are shown in **Table A.2.**

3.2. Power transmission transfers freshwater across provinces

Provinces export virtual water by exporting power and import virtual

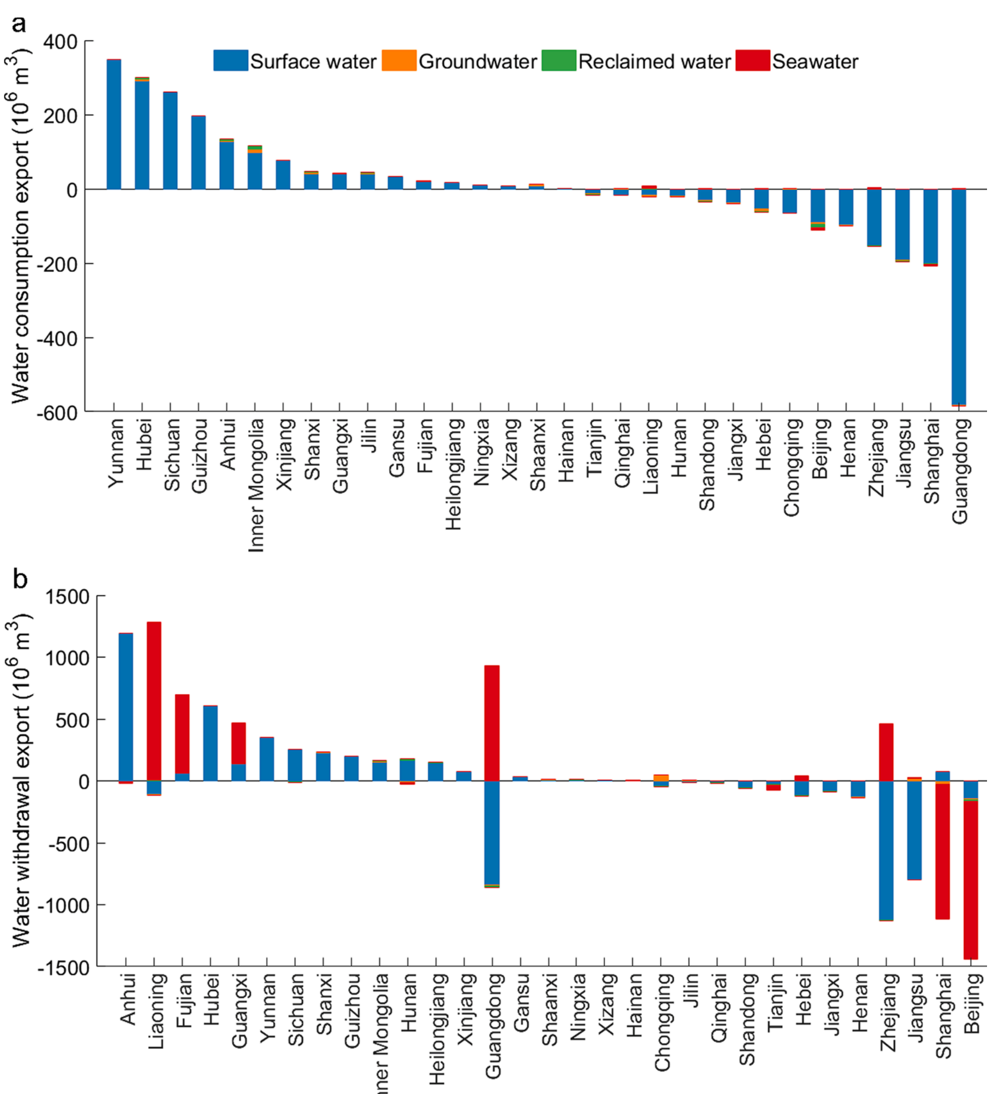

Fig. 3. Net exports of water consumption (a) and water withdrawal (b) across provinces in China in 2017. The positive values designate net water export, while the negative values designate net water import.

water by importing power (Fig. 3). As the largest electricity importer, Guangdong sees a virtual inflow of 0.58 billion m^3 in water consumption, mainly by importing hydropower from Yunnan. Large volumes of water withdrawals are exported from Anhui, where once-through cooling systems are used for thermal power, to Jiangsu (0.55 billion m^3) and Zhejiang (0.7 billion m^3) provinces. Liaoning and Guangdong export large amounts of virtual seawater used for nuclear power plants. Focusing on freshwater, power transmission accounts for total virtual water withdrawal and consumption of 6.2 and 2.1 billion m^3, respectively. Compared with the counterfactual scenario with no interprovincial power transmission, power transmission reduced national freshwater withdrawal by 10.1 billion m^3 but increased consumption by 0.21 billion m^3 in 2017 (**Table A.3**). These counterintuitive results are caused by the differences in electricity technologies and cooling systems between western and eastern regions. As shown in Fig. 4**a-b**, in Ningxia, Sichuan and Yunnan provinces, power production is much larger than local power demand and more than 35% of power-related water use is exported to other provinces via power export. The proportion is less than 5% for 11 provinces, most of which are in the developed Southeastern and Northern regions with high power demand.

Large seasonal variations exist in inter-regional water transfer (Fig. 4**)**. Specifically, both consumption and withdrawal transfer peaked in August. There are two causes: first, large amounts of electricity were transferred from southwest to south and east in summer due to the high power demand of cooling, especially in economically developed regions, such as Guangdong, Shanghai, Jiangsu, Zhejiang, and Beijing. In the peak month of August, 19% of the national electric power is transferred across provinces, 5% larger than in February. Second, higher temperatures during the summer cause higher evaporation, leading to higher water exports from hydropower plants in the southwest and central provinces. Specifically, the median provincial water consumption factor of hydropower varies significantly throughout the year, with 3,355 and 21,133 m^3/GWh in February and August respectively. In the peak month, the largest exporter and importer of water consumption are Yunnan (43 million m^3) and Guangdong (76 million m^3), while the largest exporter and importer of water withdrawal are Anhui (126 million m^3) and Jiangsu (147 million m^3). The water export of the central region, which does not exhibit the typical peak in August, is determined by Hubei province. There is a trough in the water export of the central region in August because of the decrease in power export in Hubei province from 10.7 TWh in July to 8.4 TWh in August.

Nationally, seasonal virtual water consumption transfer is dominated by hydropower, while withdrawal transfer is dominated by thermal power (**Fig. A.3**). Yunnan, Sichuan and Hubei are large virtual water exporters via hydropower, exporting between 264 and 329 million m^3 each. The top 3 transmission corridors of hydropower-related virtual water consumption transfer are Yunnan to Guangdong (277 million m^3), Guizhou to Guangdong (99 million m^3), and Sichuan to Zhejiang (79 million m^3) (**Fig. A.4**). Inner Mongolia, Anhui and Guizhou are large virtual water exporters via thermal power, exporting between 71 and 94 million m^3 each. The top 3 transmission corridors for thermal power-related virtual water consumption transfer are Guizhou to Guangdong (55 million m^3), Anhui to Zhejiang (43 million m^3), and Anhui to Jiangsu (34 million m^3) (**Fig. A.5**). There are considerable flows of virtual water withdrawal among Anhui, Jiangsu, Shanghai, and Zhejiang provinces, mainly due to the use of once-through cooling systems for thermal power. Since these provinces are within the eastern region, their withdrawal transfers do not involve the other six regions. The east and south are net water importers throughout the year.

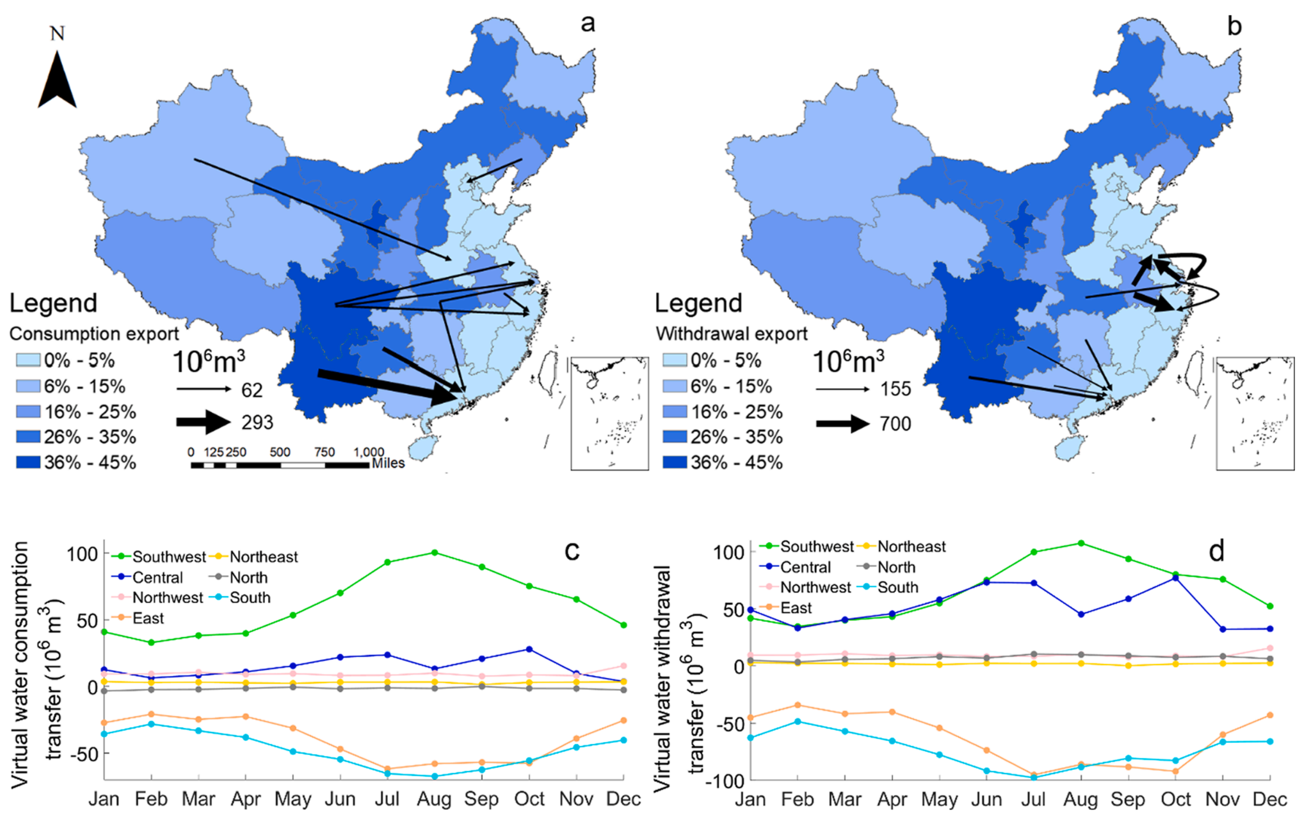

Fig. 4. Interprovincial transfer of freshwater consumption (a) and freshwater withdrawal (b). The colours show the proportions of provincial water consumption and withdrawal of power production that are exported respectively. Monthly net transfer of freshwater consumption (c) and freshwater withdrawal (d) via power transmission in China in 2017. A positive value means virtual water export in a region is larger than import. Provinces are classified into seven regions as in Cai et al. [63]. The transfers of all water types are provided in Appendix B.

3.3. The impacts of the power system on water stress

Power-related virtual water transfer through transmission networks changes provincial water stress for both freshwater consumption (Fig. 5**a**) and withdrawal (Fig. 5**b**). We define the water stress in terms of the consumption-to-availability (CTA) ratio and the withdrawal-to-availability ratio (WTA). Power transmission exacerbates issues when the CTA or WTA is larger than in the counterfactual scenario. Overall, water stress was more equally distributed through power transmission. The relative standard deviations of provincial CTA (from 130% to 127%) and WTA (from 186% to 136%) decreased through power transmission. Yunnan province sees the largest increase in CTA with 2.2%, mainly due to hydropower exports. In terms of WTA, power transmission appears to be an effective way to help reduce pressures in regions such as Shanghai, Jiangsu, and Chongqing, where WTA reduces 46%, 7%, and 5% respectively. If Shanghai were to satisfy its power demand itself, the freshwater demand for power production would exceed the total current water supply, unless it were to shift to cooling systems with a lower water intensity or that use more seawater. Anhui province contributed to the water stress alleviation in the above regions, with a WTA increase of 4.2%.

The environmental impact of power production depends on both provincial water consumption and water scarcity. Provinces are classified into four categories according to provincial water consumption and water stress index (WSI) (**Fig. A.6**). The provincial WSI is assessed in this study according to Scherer et al. [64] using annual withdrawal data, and a WSI of 0.5 defines the threshold between medium and high water scarcity [65,66]. For water consumption, the median value (373 million m^3) is used as the line between medium and high water consumption. There is large heterogeneity in water scarcity across provinces. Shandong, Xinjiang, Liaoning supply large amounts of freshwater for power production even though they face severe water scarcity. Hunan and Hubei have low water stress despite large amounts of power-related freshwater consumption.

4. Discussion

4.1. Trends in water use and transfers of virtual water through the power system

Several recent trends are particularly important for the electric power system and its water use in China. First, the volume of freshwater withdrawal for thermoelectric cooling has decreased since 2011 due to increasing numbers of air-cooled and seawater cooled units [30,67]. As once-through cooling systems are being phased out and replaced with more efficient systems in terms of water withdrawal [68], the total withdrawal for power production is expected to continually decrease. Meanwhile, since air cooling systems are increasingly used for new plants and there is no significant increase of closed-loop cooling plants, thermal power plants will very likely also reduce water consumption per

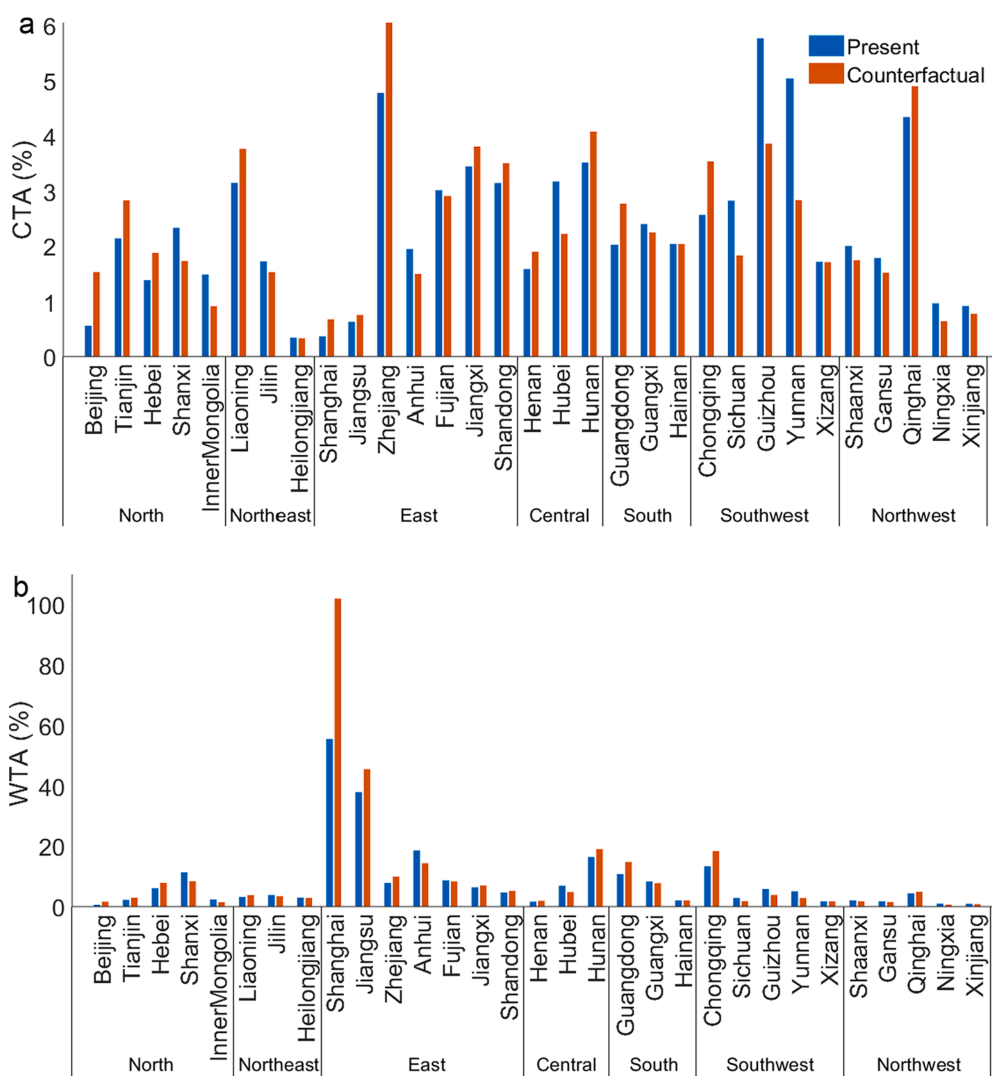

Fig. 5. The changes in provincial CTA (a) and WTA (b) caused by interprovincial power transmission in 2017.

unit of electricity production in the future. In any case, water consumption is mainly driven by hydropower plants and is hard to reduce given that annual reservoir areas do not change greatly. While this study focuses on annual water scarcity, there may be large seasonal variations, and the impact of hydropower on water scarcity is often alleviated by storing water in the wet season and releasing it in the dry season [6]. Second, although thermal power and hydropower still dominate power production, renewables and their low water-intensity are expanding quickly, especially wind power and photovoltaic (PV), with increases in capacity of 12.4% and 34% in 2018, respectively [69]. Due to reduced costs and decreased power curtailments, the expansion of wind and PV in western and northern China is expected to reduce local water export and alleviate local water stress [70]. Nuclear power is also growing, but will not put pressure on freshwater resources as only seawater is used.

Third, despite the rapid expansion of low water-intensity technologies, there are still large uncertainties in total water use in the future due to the growth of China's power demand. Coal power and hydropower generation increased by 5.3% and 3.2% in 2018 respectively [69,71]. Also, increasing hydropower production is crowding out thermal power in many provinces, especially Yunnan, Zhejiang, Fujian, Hunan, and Guangdong [72], which would increase water consumption. Fourth, as part of air pollution mitigation, China began the construction of twelve long-distance power transmission lines in 2014 [73]. These lines transmit inland electricity eastwards to coastal areas [74]. Ten lines carry mainly hydropower and coal electricity, with the other two carrying both coal and wind power [41]. Among the twelve lines, there are eight ultra-high voltage, all completed at the end of 2017 [56]. Nationally, these lines are contributing to an increase in interprovincial water transfer. The power transmission of the transmission corridor from Yunnan to Guangdong has increased rapidly (**Fig. A.7**) and virtual water transfer is expected to continue increasing. The transmission corridor between Guizhou and Guangdong is the largest for both hydropower- and thermal power-related virtual water transfer because of its large amount of power production and transmission of both energy types.

Last, in recent years China has been paying more attention to groundwater resources and has banned its use in new power plants and units in the northern water-deficient areas since 2004 [68,75]. Combining our results with Liao et al. [76], we see that although groundwater is still consumed for power production in the Huang-Huai-Hai area of northern China, the volume consumed is significantly decreasing. In the coming years reclaimed and surface water will substitute groundwater in many areas of northern China due to stricter regulations on water use and the completion of the 'South-to-North Water Diversion' project. Currently, the freshwater requirement is high in some coastal regions such as Jiangsu, Shanghai, and Guangdong. However, seawater use is expected to increase in these regions with the development of seawater treatment projects encouraged by the government [77,78]. Although hydropower is the largest water consumer among all energy technologies previous studies and government reports usually neglect the technology.

4.2. Comparison with previous studies

Our estimates show that in 2017 the freshwater consumption for the cooling of thermal power was 4.3 billion m^3, falling within the range of published values [30,32,33]. This study also examines the detailed technical causes of water use. 54% of the coal-power units are equipped with closed-loop cooling systems, resulting in a high level of water consumption. As for freshwater withdrawal, Zhang et al. [30,33] found 68 billion m^3 in 2010 and 57 billion m^3 in 2015 for thermal power. Our estimates suggest that this was further reduced to 52 billion m^3 by 2017. The capacity factor is a key variable in water use assessment but has been seldom indicated in previous studies. We show that both the median and average capacity factor of coal power units are 70% in China in 2017. Zhu et al. [37] and Liao et al. [32] estimated the water consumption of China's hydropower production, indicating water consumption between 11.5 and 14.6 billion m^3 in 2010. Both studies were conducted at the regional level using national or provincial averaged water consumption factors for assessments but did not consider the differences in the reservoir area and evaporation rate across regions. This study is based on plant-specific data, including evaporation factors. The results show the large differences in the water consumption factors of hydropower across provinces, demonstrating the importance of the high spatial detail.

Liao et al. [41] indicated that power transmission could save 20.1 billion m^3 of water withdrawals nationally in 2014 due to differences in water productivity in exporting and importing provinces, but water resources were not specified. Our study distinguishes water types and we show that power transmission saved 33 billion m^3 of water withdrawal in 2017, but 69% is seawater, which would not reduce regional freshwater stress. The technical details show that in the western power-exporting provinces, such as Guizhou, Sichuan and Yunnan, hydropower and the thermal power plants with closed-loop cooling systems are commonly adopted, whereas the eastern power-importing provinces, such as Shanghai, Jiangsu and Anhui, have more plants with once-through cooling systems. Compared to the east, the west generally has a larger water consumption factor but a lower withdrawal factor. Power generation that consumes large amounts of water is often transmitted from west to east [42], consequently reducing water withdrawal but increasing water consumption nationally. Zhang et al. [39] estimated virtual water transfers through interprovincial power transmission, finding 0.6 billion m^3 of water consumption was transferred in 2011. However, water consumption of hydropower was not included, which is crucial in some province-relationships, e.g. from Yunnan province to Guangdong province. Interprovincial power transmission was 1.6 times higher in 2017 than in 2011 [39,40], which is also a contributor to the increase of water transfer. Besides, previous studies were on a yearly resolution, while our results show the variations in monthly water transfer.

Thermal power production accounts for 45% of total water withdrawal in the US [79] and 43% of total freshwater withdrawal in Europe [80]. This is explained by the wide use of once-through cooling systems using freshwater across the US and Europe [81]. In contrast, China's total power production is responsible for only 10% of national freshwater withdrawals. Though power plants with once-through cooling systems in China account for 21% of all plants, only 48% of them use freshwater. Furthermore, the relatively high water withdrawal in the US and Europe may be a result of strict temperature regulations since power plants have to withdraw more water for heat discharge in order to keep the cooling water temperature under limits [82,83], whereas China has only vague guidelines on water temperature [84]. It is important to note that low withdrawal does not mean low consumption. China withdraws much less freshwater for annual thermal power production (54 billion m^3) than the US (230 billion m^3) but sees higher consumption (4.3 billion m^3 compared to 4 billion m^3 in the US) [79]. Previous research showed that seasonal variation has a significant influence on power demand for many countries (e.g. India, Algeria, and Germany) [85–87]. This influence can result in variations in power-related water use and virtual water transfer. Moreover, the seasonal variations in virtual water transfer differ across regions. Electricity and virtual water transfer peak in the winter (due to heating demands) in Europe [88], whereas they peak in the summer in China (due to cooling demands). For countries like China and Brazil, wind and solar power are concentrated in some subnational regions [89,90]. Improving the interconnection of electricity transmission across these regions not only reduces energy curtailment but can also conserve water resources.

4.3. Limitations and implications

Although we examined a large database, we were unable to include all power plants. Since 50% of hydropower plants were covered and the average water use factor of them was applied for other unknown plants, there would be uncertainty in the total water use estimate for hydropower. However, since we separately calculated the water use of thermal power and hydropower, the results did not have a bias in the water use of hydropower in the power mix. In China, coal, hydropower and nuclear power dominate power production, while gas power plants account for less than 5% of the total in 2017 (and oil power accounts for only 0.05% so it is not included due to data limitation) [56]. For future global research, efforts are needed to compile a more complete database of power plants. We estimated the power production of individual plants based on installed capacity per plant and the monthly provincial power production data. Precise information on the actual power production at the plant level would allow for more detailed insights. The water use factor of thermal plants was assumed to be constant throughout the year yet plants often have higher water requirements in summer than in winter due to lower thermodynamic efficiencies [5,82]. The reservoir area of hydropower plants was also assumed to be constant throughout the year. Both assumptions would lead to an underestimation of the seasonal variations in power-related water use. Our database covers 80% of the total installed capacity of thermal, nuclear, and hydropower in China. Considering the water demand for power and the current coverage of capacity, efforts are needed to include more gas and hydropower plants in the future. For a better understanding of power-related water use, we suggest power data at a higher spatio-temporal resolution should be provided by power suppliers, such as capacity factor and monthly power production at the plant level, and more detailed province-to-province power transmissions.

The electric power system poses threats to water stress in some regions. There are several ways to reduce the dependence of power system on freshwater: first, we can reduce the water demand of power by developing photovoltaics and wind power, using air cooling systems, replacing coal with gas, and improving the capacity factor of hydropower; second, more seawater and reclaimed water should be used for cooling. Third, we can improve power transmission from low water-scarce to high water-scarce regions. By improving the interconnectivity of electricity grids, capacity in high water-scarce regions can be downsized and less affected by freshwater scarcity. A quantitative analysis is out of scope for this paper. Our study provides an international perspective in terms of the application of methods and results. First, the methods can be applied to other nations if sufficient data on power production and water use are available. Specifically, in this study, the electric power system is examined from two perspectives: power production and power transmission. The method of assessing water use for power production we present here can be applied to other nations if plant data are available, particularly the cooling type of thermal power plants and the reservoir area of hydropower plants. For nations where plants' water use is not available, the methods of studying the power transmission on water stress can still be applied by using national water use factors, though it would entail increased uncertainties. Second, our results for China, as one of the major energy users worldwide, can be used as an important part of a database of global energy-related water use and thus support further analyses of global water use and transfer. Third, the general implications of our study also apply to other countries, e.g. related to the risk to increase water stress through power transmission, the trade-offs between water withdrawal and consumption changes, and the differences between technologies.

5. Conclusions

This study assessed the water use of power production in China for numerous renewable and non-renewable power-generating units, from the perspective of both water consumption and withdrawal. Water sources (surface water, groundwater, reclaimed water, and seawater) are distinguished in the assessment. Based on the results, we also examined the seasonal shift in water stress caused by power transmission. The following conclusions are drawn:

China's power production withdrew 62.7 billion m^3 of freshwater in 2017, of which 13 billion m^3 was consumed. There are large heterogeneities in the water use of power production across plants. Hydropower plants with large reservoirs are large freshwater consumers whereas thermal power plants with once-through cooling systems are large freshwater withdrawers.

Water stress was more equally distributed across provinces through power transmission. Nationally, power transmission reduced freshwater withdrawal but increased consumption in China because, compared to the east, the west generally has a larger water consumption factor but a lower withdrawal factor. Power-related water transfer varied greatly throughout the year, with an August peak due to the high cooling demands in the east and high reservoir evaporation in the southwest.

CRediT authorship contribution statement

Yi Jin: Conceptualization, Methodology, Formal analysis, Data curation, Visualization, Writing - original draft. **Paul Behrens:** Conceptualization, Writing - review & editing, Supervision. **Arnold Tukker:** Writing - review & editing. **Laura Scherer:** Conceptualization, Data curation, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.116493.

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