Title

Water transfer and losses embodied in the West–East electricity transmission project in China

Permalink

https://escholarship.org/uc/item/2903v2r0

Authors

Zhu, Yongnan
Ke, Jing
Wang, Jianhua
et al.

Publication Date

2020-10-01

DOI

10.1016/j.apenergy.2020.115152

Applied Energy 275 (2020) 115152

Contents lists available at ScienceDirect

Applied Energy

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

Water transfer and losses embodied in the West–East electricity transmission project in China

Yongnan Zhu[a], Jing Ke[b], Jianhua Wang[a,*], He Liu[c,*], Shan Jiang[a], Helcio Blum[b], Yong Zhao[a], Guohua He[a], Yuan Meng[a], Jian Su[c]

[a] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[b] Energy Analysis & Environmental Impacts Division, Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States
[c] Research Institute of Petroleum Exploration & Development, Beijing 100083, China

HIGHLIGHTS

- We analyzed virtual water transfers of the WEET project in China.
- We propose the *virtual water transfer loss* and *water substitution ratio* metrics.
- A total of 2.4 km^3 of virtual water was transmitted eastward in China in 2017.
- The water footprint of the WEET project may double by 2030.
- Water resources sustainability is affected by energy developments in western China.

ARTICLE INFO

Keywords:
West–East Electricity Transmission project
Water–energy nexus
Virtual water
Water footprint
China

ABSTRACT

Electricity is an important output of the global energy system. Large amounts of water can be consumed in the process of producing electricity. This article focuses on how that water is virtually transferred from power-generating regions to electricity-consuming areas. We propose two metrics, i.e., *water substitution ratio* and *virtual water transfer loss*, to assess the efficiency of water use for power generation and virtual transmission of water through the power transmission system, respectively. These metrics are used to estimate the effects of the West–East Electricity Transmission project in China on the water resources used in power-generating regions. Results show that the electricity delivered by the project increased from 228 TWh in 2008 to 683 TWh in 2017. With the construction of wind and solar energy projects, the growth rate of virtual water was slightly slower than that of the electricity transmitted. In 2017, 2.4 km^3 of virtual water was transmitted eastward. The corresponding virtual water transfer loss throughout the transmission system was approximately 100 million m^3. We estimate that the virtual water footprint of the project will exceed 4.4 km^3 by 2030, which may affect the sustainability of water resources and the ecological environment in western regions of China.

1. Introduction

Energy and water have a close relationship and are highly codependent. Water is directly or indirectly required for most types of energy exploitation and conversion [1], whereas energy is essential for water extraction, processing and utilization. These interactions have gradually attracted worldwide research attention and are termed the *water–energy nexus* [2]. Intensive human activity has been exerting increased pressure on the natural water system, as water is increasingly flowing into the social water cycle [3]. Electricity is an important component of the global energy system, accounting for approximately 40% of the global primary energy consumption [4]. Economic development, population growth and innovations that lead to increased electrification indicate a rapid and sustained growth of global electricity demand [5]. With the rapid increase in electricity demand, demand for water will also significantly increase in some regions and challenge their progress toward sustainable development [6].

China's energy production and consumption have been growing rapidly owing to the country's extensive economic growth and urbanization. In 2017, China's energy consumption increased by more than 3%, a growth rate much higher than the global average [7]. In 2019, the International Energy Agency projected that developing economies,

---

* Corresponding authors.
E-mail addresses: wjh@iwhr.com (J. Wang), liuhe@petrochina.com.cn (H. Liu).

https://doi.org/10.1016/j.apenergy.2020.115152
Received 28 February 2020; Received in revised form 1 May 2020; Accepted 5 May 2020

especially China, will account for the largest share of global electricity demand growth in the future [8]. In China, the distribution of energy resources is uneven and does not match the spatial distribution of energy demand [9]. While coal reserves are primarily distributed in the western and northern regions, with 69% of coal resources concentrated in three northwestern provinces—Shanxi, Shaanxi, and Inner Mongolia—and 70% of hydropower resources located in the southwest owing to abundant rainfall there [7], the majority of energy demand is concentrated in the economically developed eastern coastal areas, where few natural energy resources are available. Therefore, large amounts of coal have been transported to eastern areas to generate power, aggravating environmental problems in areas already afflicted by haze pollution [10].

In 2001, China officially launched the West–East Electricity Transmission (WEET) project to reduce demand for coal and alleviate negative environmental impacts in the eastern coastal areas [11]. The project aimed to utilize China's coal and water resources in the Northeast, Northwest, and Southwest regions to generate electricity and transmit it to the eastern coastal areas. Existing research has evaluated the energy [12], economic [13], societal [14] and environmental effects [15] of this project. However, considering the water required by the energy industry, the question of whether China will have sufficient water resources to sustain its energy development has gradually become a priority for researchers and policymakers [16].

A significant volume of water is required to produce power. In addition, the extraction of fossil energy sources, such as coal [17] and oil [18], consumes large amounts of water and generates large volumes of contaminated wastewater [19], causing damage to water systems [20]. Accordingly, many studies devoted to water constraints in energy production have been conducted [21]. According to Spang et al. [22], about 52 km^3 of fresh water is consumed annually for global energy production. From a lifecycle perspective, water is required at all stages of the generation process, including the manufacture of electricity-generating equipment, the construction and operation of energy facilities, and the fuel supply chain [23]. As a generally accepted indicator of water use, *water footprint* provides a basis for quantifying the impact of human activities on water resources associated with a given product [24]. Mekonnen et al. [25] estimated that the global annual consumptive water footprint of electricity and heat is 378 km^3. Some scholars have focused on regional or national electricity water footprints, especially in the United States [26] and China [27]. Fulton and Cooley [28], for instance, found that the water required for energy production in California increased by 260% between 1990 and 2012. China's water demand for energy production is also increasing [29]. *Virtual water* is another relevant indicator related to the effects on water resources associated with a product and expresses the water embodied in a product that is transferred across regions as the product circulates or is traded [30].Based on their analysis of virtual water transfers associated with the U.S. power grid, Chini et al. [31] found that in 2016, 11.2 km^3 of water was transferred through electricity transmission. Gao et al. [32] found that a large volume of virtual water embodied in energy products was transferred from the water-scarce northern and western areas to the relatively water-rich, southeastern areas of China. Liao et al. [33] found that nearly half of the power sector's water use was virtually transferred across provinces in this manner. Because of physical water scarcity and increased water transfer, water-dependent sectors may experience economic losses as their water scarcity risk increases [34]. The risk of water shortage faced by energy-exporting areas has attracted the attention of researchers. Wang et al. [16] quantified the water scarcity risk arising from China's interregional electricity transmission and the population affected by it. Meanwhile, Zhang et al. [35] investigated the evolution of virtual water embodied in electricity transmission from western to eastern regions. These studies focused mainly on the water footprint of thermal power generation, neglecting the fact that hydropower plants, owing to evaporation in reservoirs, may have a larger water footprint than thermal plants [36]. A deeper understanding of the water footprint of hydropower plants and its transfer along with the footprint of other power generation sources and their transfer throughout the power grid is therefore necessary. This is particularly important in the case of China owing to existing and planned large-scale transregional power transmission projects. In addition, while water footprint has mainly been used as a tool for quantifying water use associated with a product or service, there are few studies on the efficiency of virtual water transfer. Note that making water footprint and virtual water transfer useful in water resource management is still an open problem worthy of consideration [37].

This paper focuses on elucidating the manner and efficiency of the transfer of the water footprint of the power sector across regions as the power generated in one region is transmitted to other regions. Herein, we introduce a method for assessing virtual water transfer and efficiency within power transmission networks. The method builds on in-depth studies of various theoretical approaches proposed to estimate water footprint and virtual water. The goal is to assess the virtual water transfer and efficiency of the WEET project in China. The remainder of this paper is structured as follows: Section 2 presents the concepts on which this study relies, particularly the *virtual water transfer loss* and the *water substitution ratio* (and *difference*), which are introduced in this paper; Section 3 describes the data used and their sources; Section 4 presents our results on the water footprint, virtual water transfer loss, and water substitution ratio of the WEET project in 2008 and 2017, as well as a projection of the virtual water transfer of the project in 2030; Section 5 discusses the findings; finally, Section 6 summarizes the findings and suggests possible areas of future research.

2. Methods

2.1. Water footprint

Almost all goods and services (directly or indirectly) use water, and the corresponding water footprint quantifies the amount of water used to produce and use them [24]. Industrial production, especially some types of electric power generation, requires significant amounts of water. Virtual water is embodied in the electricity supplied throughout the entire electricity supply chain, from power generation to transmission, distribution, and the final consumption of the electricity produced. Estimating the water footprint of power generation is therefore necessary for assessing the virtual water transferred and lost in a power transmission network.

According to the Water Footprint Network (WFN) [24], water footprint can be classified into green, blue, and grey. Green refers to the consumption of rainwater and is associated specifically with water used in agriculture; blue refers to the consumption of surface and groundwater; and grey refers to the water required to assimilate pollutant load according to water quality standards. Water is not only used directly in a production process but is also associated with the production and supply of the raw materials used therein [38]. To evaluate the total consumption and virtual transmission of freshwater resources by the WEET project, this study relies on estimates of both direct and indirect blue water footprints of electricity production.

2.2. Dualistic natural–social water cycle and the water substitution ratio

Water not only supports the ecological and environmental systems but also the socioeconomic development of human society. The intensification of human activity has caused profound changes in the natural water cycle [39]. This includes the interference that water intake has on surface and groundwater flow, the interconnected water network formed by artificial excavation, and the discharge of sewage into natural water systems [40]. In particular, the increasing demand for food and energy and the intensification of some industrial processes has increased demand for water [41]. Wang et al. [3] developed the *dualistic natural–social water cycle* theory to describe and study the

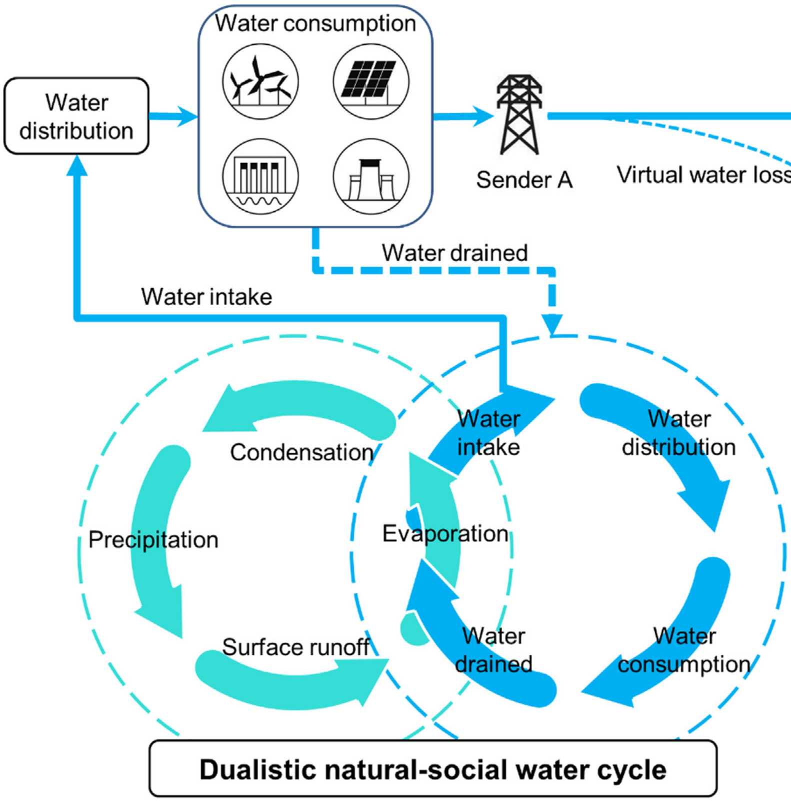

Fig. 1. Water transfer and losses embodied in electricity transmission.

complex interactions between the natural and social water cycles. According to their theory, the water footprint and virtual water transfers through physical products or processes (e.g., electricity transmission) can be considered a part of the social water cycle, as shown in Fig. 1.

By importing products instead of making them locally, the import area reduces local water consumption and virtually moves the pressure on water resources to the export areas. Because of technological and geographical differences, the water intensity of a certain production process may significantly vary across regions. Using the concept of water footprint and virtual water transfer, we can evaluate the impacts of cross-regional trade from the perspective of water-resource utilization efficiency. Inspired by the dualistic natural–social water cycle theory, we define two metrics to express the efficiency with which one type of product (herein, electricity) is produced by a producer in one location (referred to as the *sender*) to substitute the same type of product made and consumed locally in another location (referred to as the *receiver*).

Let c_R be the amount of product P used by receiver R that can be substituted by an amount $c_S \geq c_R$ of the same product P produced by sender S and transferred from S to R:

$$c_R = c_S\cdot\eta_{S,R} = c_S\cdot(1-\phi_{S,R}) \tag{1}$$

where $\phi_{S,R}$ $(0 \leqslant \phi_{S,R} \leqslant 1)$ is the transfer loss rate of product P from sender S to receiver R, and $\eta_{S,R} = (1-\phi_{S,R})$ $(0 \leqslant \eta_{S,R} \leqslant 1)$ is the efficiency of transferring product P from sender S to receiver R. We define the *water substitution ratio* ($\mu_P^{(w)}$) and *water substitution difference* ($d_P^{(w)}$), both related to sender S making product P to substitute its production by receiver R, as follows:

$$\mu_P^{(w)} = \frac{w_S}{w_R} = \frac{q_S\cdot c_S}{q_R\cdot c_R} = \frac{q_S}{q_R\cdot\eta_{S,R}} = \frac{q_S}{q_R\cdot(1-\phi_{S,R})} \tag{2}$$

$$\begin{aligned} d_P^{(w)} &= w_S - w_R = q_S\cdot c_S - q_R\cdot c_R = c_S(q_S - q_R\cdot\eta_{R,S}) \\ &= c_S\,[q_S - q_R\cdot(1-\phi_{S,R})] \end{aligned} \tag{3}$$

where w_S is the water footprint from the production of an amount c_S of P by sender S and q_S is the water footprint per unit of P produced by sender S; w_R is the theoretical water footprint from a hypothetical production of an amount c_R of P by receiver R and q_R is the theoretical water footprint per unit of P hypothetically produced by receiver R, if R needs to make P locally instead of importing it from S. Note that owing to the technological and geographical differences in the production of P, q_S can be smaller, equal to, or greater than q_R, which indicates that the water intensity of product P produced by sender S is lower, equal to, or higher than that of product P hypothetically produced by receiver R, respectively.

The water substitution difference $d_P^{(w)}$ represents the difference between the water footprint from the production of an amount c_S of P by S and the theoretical water footprint from a hypothetical local production of an amount c_R of P by R. Note that the water substitution ratio $\mu_P^{(w)}$ and water substitution difference $d_P^{(w)}$ satisfy the following relationships:

$$\begin{aligned} &\mu_P^{(w)} < 1 \ \text{ if } d_P^{(w)} < 0, \\ &\mu_P^{(w)} = 1 \ \text{ if } d_P^{(w)} = 0, \\ &\mu_P^{(w)} > 1 \ \text{ if } d_P^{(w)} > 0. \end{aligned} \tag{4}$$

The relationships in (4) indicate that the water footprint embodied in P produced by S and transferred to be consumed in R can be respectively smaller, equal to, or larger than the theoretical water footprint of P hypothetically produced by R. In each of these cases, the sign of the water substitution difference and, correspondingly, whether the water substitution ratio is lower or greater than 1, will depend on two effects that are embedded in equation (2). The first effect is the relative per-unit water footprint of P when it is produced in S and in R (q_S/q_R); the second is the relative amount of P that needs to be produced if it is produced in S or in R (c_S/c_R). When the water substitution difference is lower than zero, it is more attractive, from the perspective of water consumption, to produce P in S and transfer it to R rather than produce

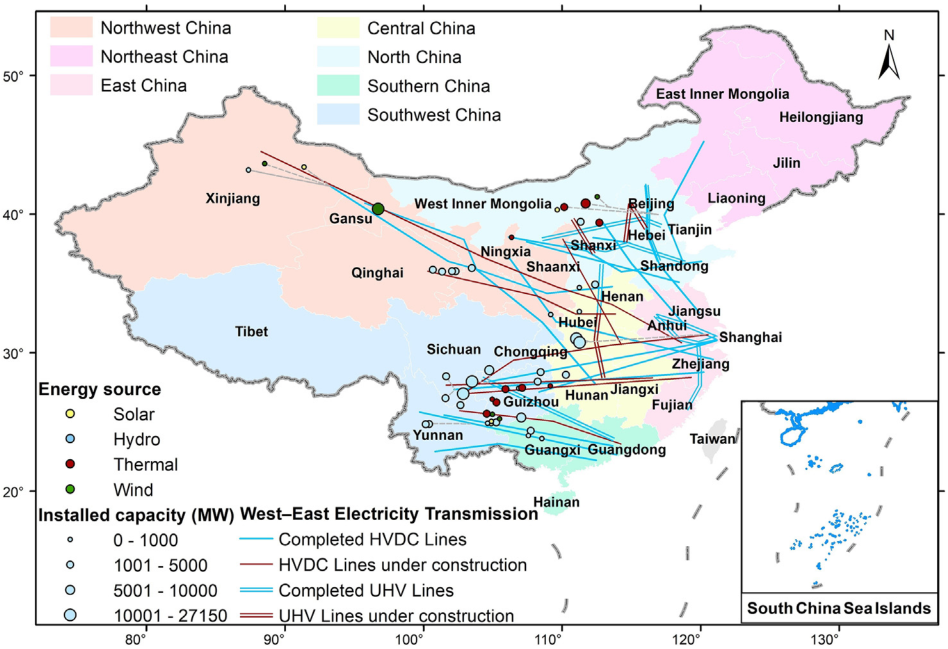

Fig. 2. China's regional power grids, major power plants, and the transmission lines of the WEET project.

it in R. This will happen when the per-unit water footprint of P produced in S is lower than in R ($q_S < q_R$) and the loss rate of the transfer process from S to R is not large enough to outweigh the gains from the difference between the two per-unit water footprints. When the water substitution difference is zero, it is indifferent, from the perspective of water consumption, to produce P in either S or R. This may happen when the per-unit water footprints are the same in S and R ($q_S = q_R$) and there are no losses when P is transferred from S to R ($c_S = c_R$, $\phi_{S,R} = 0$), or when the gains from having a lower per-unit water footprint in S compared to R is outweighed by the loss rate of the transfer process. Finally, when the water substitution difference is greater than zero, it is less attractive to produce P in S than in R, again, from the perspective of water consumption. This will happen when the per-unit water footprint of P produced in S is greater than in R ($q_S > q_R$), or when the gains from having the per-unit water footprint of P produced in S lower than or equal to the per-unit water footprint of P produced in R ($q_S \leqslant q_R$) are outweighed by a large loss rate in the process of transferring P from S to R.

2.3. Virtual water transfer and loss over electricity transmission

In addition to the metrics introduced above, we introduce the following formal descriptions of virtual water transfer and loss across the electricity transmission process.

Assume that there are m senders and n receivers in the electricity transmission network. The water footprint of the electricity generated by sender i ($i = 1,2,\ldots,m$) is expressed as follows:

$$w_i = \sum_j q_{i,j} \times c_{i,j} \tag{5}$$

where w_i is the water footprint (m^3) of the electricity generated by sender i; $c_{i,j}$ is the amount of electricity generated by sender i (kWh) from power plant j, which can be a thermal, hydro, wind, or solar power plant; and $q_{i,j}$ is the water footprint per unit of electricity (m^3/kWh) generated by sender i from power plant j.

Let $\mathbf{W} = [w_1, w_2, \cdots, w_m]^T$ be a vector of water footprints, where w_i, the water footprint of the electricity generated by sender i, is as defined above. In addition, let $\mathbf{R} = [r_1, r_2, \cdots, r_n]^T$ be a vector of the virtual water received by the n receivers, and $\mathbf{L} = [l_1, l_2, \cdots, l_n]^T$ be a vector of losses of virtual water during the transfer process to the n receivers. The following constraint should be observed:

$$\sum \mathbf{W} = \sum \mathbf{R} + \sum \mathbf{L} \tag{6}$$

where $\sum \mathbf{W} = \sum_{i=1}^{m} w_i$, $\sum \mathbf{R} = \sum_{j=1}^{n} r_j$, and $\sum \mathbf{L} = \sum_{j=1}^{n} l_j$.

Let us further define:

$$\mathbf{R} = \mathbf{A}_R^T \mathbf{W} \tag{7}$$

and

$$\mathbf{L} = \mathbf{A}_L^T \mathbf{W} \tag{8}$$

where

$$\mathbf{A}_R = [a_{ij}]_{m\times n} \circ (\mathbf{J}_{m\times n} - [\phi_{ij}]_{m\times n}) \tag{9}$$

is the virtual water delivery matrix,

$$\mathbf{A}_L = [a_{ij}]_{m\times n} \circ [\phi_{ij}]_{m\times n} \tag{10}$$

is the virtual water transfer loss matrix, and

$$\phi_{ij} = f(p_{ij}, h_{ij}) \tag{11}$$

In equations (9)–(11) above, a_{ij} is a non-negative coefficient representing transfer from sender i to receiver j, with $\sum_j a_{ij} = 1$; $\mathbf{J}_{m\times n}$ is an all-ones matrix; ϕ_{ij} ($0 \leqslant \phi_{ij} \leqslant 1$) is the loss rate of electricity transmission from i to j that can be estimated as a function of p_{ij} and h_{ij}, where $p_{ij} \geqslant 0$ is the transmission power (GW) from i to j and $h_{ij} \geqslant 0$ is the transmission distance (km) from i to j.

3. Data

Three groups of data were utilized herein: power generation by power plant and electricity trade between provinces; water consumption for power generation by power plant; and interregional power exchange and transmission data. Electricity production and trade data are derived from the China Energy Statistical Yearbook, published by the National Bureau of Statistics of China [7]. Interprovincial electricity transmission data were obtained from a compilation of statistical data from the China Electricity Council [42].

Table 1
Water footprint per unit of electricity generation by energy source.

Energy source	Water footprint per unit of electricity generation (m^3/MWh)	Reference
Thermal power	1.81–4.97	Zhang et al. [45], Zhu et al. [9]
Hydropower	0.04–15257	Liu et al. [36]
Solar (Photovoltaics)	0.18	Mekonnen et al. [25]
Wind	7.2×10^{-4}	Mekonnen et al. [25]

Note: (1) In addition to per plant data, the unit water footprint of thermal power also refers to the average water footprint of different cooling technologies for thermoelectric power plants in China; (2) the unit water footprint of hydropower plants refers to the per plant water footprint of 209 hydropower plants in 10 major river basins in China.

3.1. The WEET project

The WEET project includes the construction of dams and hydroelectric power plants, thermal power plants, and electricity transfer routes. There are three major transfer routes, mainly structured according to the power supply and receiving areas of China's regional power grids (Fig. 2), i.e., the North (N), Northeast (NE), East (E), Central (C), Northwest (NW), Southwest (SW), and Southern (S) grids. The administrative areas included in each regional power grid are shown in Fig. 2. Among them are the Liaoning, Jilin, and Heilongjiang provinces, as well as the power grid in Eastern Inner Mongolia, all of which are part of the Northeast China grid. Although the power grid in Western Inner Mongolia is owned by the Inner Mongolia Autonomous Region, herein, it is considered part of the North China grid.

The north route of the WEET project includes thermal, solar, and wind power from the Northwest, as well as thermal power from Shanxi and Inner Mongolia. The power from this route is transmitted to the North China grid and then mainly sent to the Beijing, Tianjin, Hebei, and Shandong provinces. The middle route includes electricity generated in Northwest and Central China for the Central and East China grids, including the hydropower generated from the Three Gorges Dam and the tributaries of the Yangtze River. The south route includes thermal power and hydropower from Yunnan and Guizhou, which are transmitted to the southern regions of China, including Guangdong, Guangxi, the Hong Kong Special Administration Region (SAR), and Macao SAR.

In 2017, the WEET project's transmission capacity reached 229.1 GW with the north, middle, and south routes contributing 79.7, 106.6, and 42.8 GW, respectively. The cumulative power transmitted by the WEET project was approximately 6.6 PWh. Nineteen transmission lines, with a total transmission capacity of 133.6 GW, use high-voltage, direct current transmission and ultra-high voltage (UHV) transmission technology. In 2018, the National Energy Administration of China indicated that several major projects for power transmission will be launched in the early 2020s [43]. It is estimated that by 2030, West-to-East electricity transfer will reach 540 GW [44]. This study uses the years 2008 and 2017 as references to analyze the impact of the WEET project on water resources over the past decade.

Part of the WEET project is point-to-point direct power transfer. For these transfers, we collected power generation and water consumption data of the main power projects, including 50 hydro, thermal, wind, and solar power plants (see Fig. 2 for the main power plants). In total, the installed capacity of these power plants is 170 GW. The other part of electricity transfer refers to conventional grid-connected suppliers, with a variety of power sources and consumers. For the latter part of the electricity transferred by the WEET project, we relied on provincial power structure data from the China Energy Statistical Yearbook.

3.2. Water footprint of power generation

The water footprint of thermal power generation varies greatly across power plants owing to technical differences. In addition to the per plant data previously mentioned, the unit water footprint of thermal power considered herein refers to the average water footprint of different cooling technologies from Zhang et al.'s water consumption inventory of thermoelectric power plants in China [45]. For the grid-connected part of power transmission, we rely on the provincial average water footprints from our previous research on the lifecycle water footprint of coal-fired power generation [9].

Hydropower plant dams retain water in large areas and lead to increased evaporation and loss of water resources. Hydropower footprint is not only affected by geographical climate and reservoir surface area but also the installed capacity of hydropower plants [36]. Large variations of water footprint have been reported by different hydropower plants [46]. The unit water footprint of hydropower plants herein refers to the per plant water footprint of 209 power plants in 10 major river basins in China estimated by Liu et al.[36]. While wind and solar power require no direct use of water to generate power, according to Mekonnen et al. [25], the global average lifecycle (including indirect uses of water) water footprint for solar and wind energy production are 0.18 and 7.2×10^{-4} m^3/MWh, respectively. Table 1 summarizes the water footprint per unit of energy for different energy sources of electricity production.

3.3. Future electricity transmission scenarios

In addition to historical power generation and transmission data, we defined scenarios of future electricity transmission based on the power sector development pattern projected by Zhou et al. [44] and on the structure projected by Yao et al. [47] for future renewable energy development. Based on Zhou et al.'s projections [44], in 2030, about 40% of the electricity generated in China's western regions will be delivered to the eastern regions, with the transmission capacity from West to East reaching 441 GW and the annual power transmission reaching 1889 TWh. Concerning renewable sources, we rely on the China clean energy development policy [48] to define three clean-energy growth scenarios (Table 2): low-growth (Low Clean); moderate-growth (Moderate Clean); and high-growth (High Clean). The shares of wind and solar power in the total power generated in the Low, Moderate and High Clean scenarios are 12%, 24%, and 36%, respectively. Total annual power transmission was assumed to be the same in the three clean-energy growth scenarios.

The water footprints per unit of energy in 2030 are projected to be the same as those presented in Table 1. Considering advances in water-saving technologies, we used the lower value for thermal power plants in Table 1 as the water footprint per unit of energy of newly constructed thermal power plants.

3.4. China's power generation and interregional power exchange

In 2017, the total national power generation was 6.5 PWh, an increase of 88% over the total power generated in 2008. The development of thermal power generation in China has slowed down since 2013, in contrast to the boom in renewable energy development. Nevertheless, thermal power generation remains the main electricity source in China

Table 2
Energy structure scenarios for the WEET project in 2030.

Scenario	Thermal power	Hydropower	Wind power	Solar power
Low Clean	60%	28%	7%	5%
Moderate Clean	48%	28%	14%	10%
High Clean	36%	28%	21%	15%

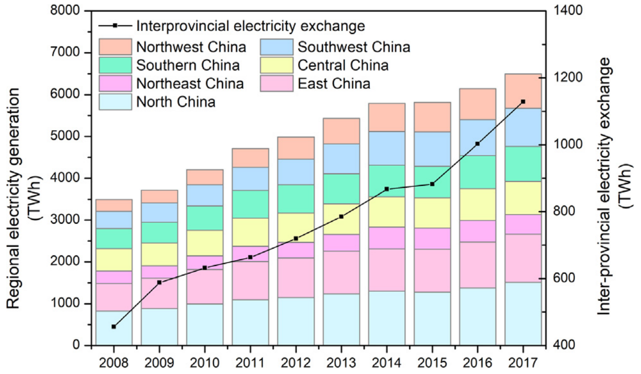

Fig. 3. China's regional electricity generation and interprovincial power exchange in recent years.

and accounted for 71% of the total electricity generated in 2017. Compared with 2008, thermal power generation has increased by 66%. Meanwhile, the development of cleaner energy sources, such as hydropower and nuclear power plants, has increased by 1.1 and 2.6 times, respectively. Compared with other energy sources, wind power has developed the most rapidly. China's wind power generation reached 295 TWh in 2017, an increase of 21.6 times over the wind power generated in 2008.

China's power generation capacity and electricity demand have grown unevenly. The growth of power generation exhibits strong regionality and is defined by regional power demand and the availability of power generation resources (Fig. 3). Energy-rich regions have witnessed the fastest growth in power generation. Over the past decade, power generation in the energy-resource-rich Southwest and Northwest regions has increased by 120% and 190%, respectively. In Northeast and Central China, which are regions with less energy resources, the increase in power generation was smaller, at only 57% and 49%, respectively, in a decade. With the continuous development of the WEET project, the volume of interprovincial power exchange is expected to continue to grow. In 2017, China's interprovincial power transmission almost tripled over the previous decade, reaching 1130 TWh.

4. Results

4.1. Water footprint and virtual water transfer losses of the WEET project

In 2008, the power transmission capacity from West to East reached 63.2 GW and 228.1 TWh of electricity was transmitted from the western regions to the eastern. The north, middle, and south routes transported 86.3, 50.4, and 91.4 TWh of electricity, respectively.

The electricity over the north route was mainly transported from Shanxi, Inner Mongolia, Liaoning to Hebei Province, and then forwarded to Beijing and Tianjin. Electricity sent by Shanxi and Inner Mongolia accounted for 71% and 22% of the north route, respectively. As shown in Fig. 4(a), the electricity transported along this route was mainly thermally generated, and the total water footprint was 172.6 million m^3.

In 2008, electricity from hydropower transported from Hubei to Shanghai, Jiangsu, and Jiangxi accounted for 85% of the power transmitted by the middle route. The water footprint of the electricity transferred by the middle route to central China was approximately 317.8 million m^3. The south route mainly includes the transmission lines from Guizhou, Yunnan, and Hubei to Guangxi and Guangdong. The power generated in this part of the WEET project was from a mix of hydropower and thermal power, with an annual water footprint of about 413.4 million m^3. In 2008, a total water footprint of 903.8 million m^3 was transferred from West to East. The average transmission-line loss of the WEET project in 2008 was about 2.6%. Because of the power loss over transmission, the annual virtual water transfer loss was 29.2 million m^3.

With the implementation of several UHV projects, the power transmission capacity from the western to eastern regions tripled in a decade. As shown in Fig. 4(c), the project expanded westward. By 2017, more provinces had joined the project, including Sichuan, Gansu, and Xinjiang. The power transmission distance also increased significantly. The national power transmission capacity from western to eastern regions reached 221.1 GW by the end of 2017, and a total of 682.5 TWh of electricity was transmitted to the eastern regions during that year.

The north route transported 240.9 TWh of electricity to North China, an increase of 2.8 times over that of 2008. Inner Mongolia was still the main exporter, accounting for 38% of the electricity transmission along the north route. Meanwhile, the electricity exports from Shanxi, Liaoning, Ningxia, and Shaanxi also significantly increased. Notably, Shanxi's electricity transmission reached 67.5 TWh in 2017, an increase of 260% compared with that in 2008. The rapid development of wind and solar energy in the Northwest has changed the mix of the power transported in terms of energy sources, whereas the proportion of clean power carried by the north route increased significantly. The annual water footprint of the electricity transported along the north route was 276.1 million m^3 in 2017.

In 2017, more hydropower was transported from Sichuan and Hubei to the central and eastern regions. The two provinces exported 110.1 and 39.3 TWh of electricity, respectively, accounting for 47% and 17% of the total power transmission of the middle route. In addition, Xinjiang, Ningxia, and Shaanxi in the Northwest also began to transmit thermal power and clean energy to Southwest and Central China. A total of 7.8 million kWh of electricity was delivered from the Northwest, accounting for 34% of the electricity received from the middle route. The total water footprint of the middle route was 1.05 km^3, of which, 91% was the hydropower water footprint.

Guangdong is the main importer along the south route. In 2017, a total of 206.5 TWh of electricity was transmitted to Guangdong from the Yunnan, Guizhou, Hubei, and Guangxi provinces. As a relay station, Guangdong sent 17.1 TWh of electricity to Hong Kong SAR and Macau SAR. The total water footprint of the south route was 1.07 km^3, of which 97% was the hydropower water footprint. Yunnan is one of the major exporters of electricity on the south route. In recent years, Yunnan's clean energy, especially hydropower, has developed rapidly and the construction of power transmission lines in the province was the fastest in China. By the end of 2017, the maximum power transmission capacity from Yunnan to the eastern regions reached 28.7 GW. Moreover, the annual electricity transmission to the East was 125 TWh, corresponding to 60% of the electricity transmitted by the south route and was seven times the power transmitted in 2008.

The annual virtual water transferred by the WEET project totaled 2.4 km^3 in 2017, an increase of 2.7 times over 2008. Note that the water footprint growth was slower than power transmission during this period. This was mainly due to changes in the mix of energy sources, especially the rapid increase in wind and solar power with a much smaller water footprint per unit of electricity than thermal and hydropower. In addition, with upgraded technology, the water footprint per unit of electricity of thermal power has also reduced.

In 2017, the average transmission-line loss of the WEET project was about 3.7% and the annual virtual water transfer loss was 98.3 million m^3. The virtual water loss per unit of electricity increased from 128 m^3/GWh in 2008 to 144 m^3/GWh in 2017. The transmission lines from Sichuan to Shanghai had the largest virtual water loss, amounting to 425 m^3/GWh. In addition, the unit water loss from Hubei and Sichuan to Shanghai, Jiangsu, and Zhejiang exceeded 350 m^3/GWh. Consequently, the middle route had the largest virtual water transfer loss among the three transmission routes, which we estimated to be 58.6 million m^3 in 2017.

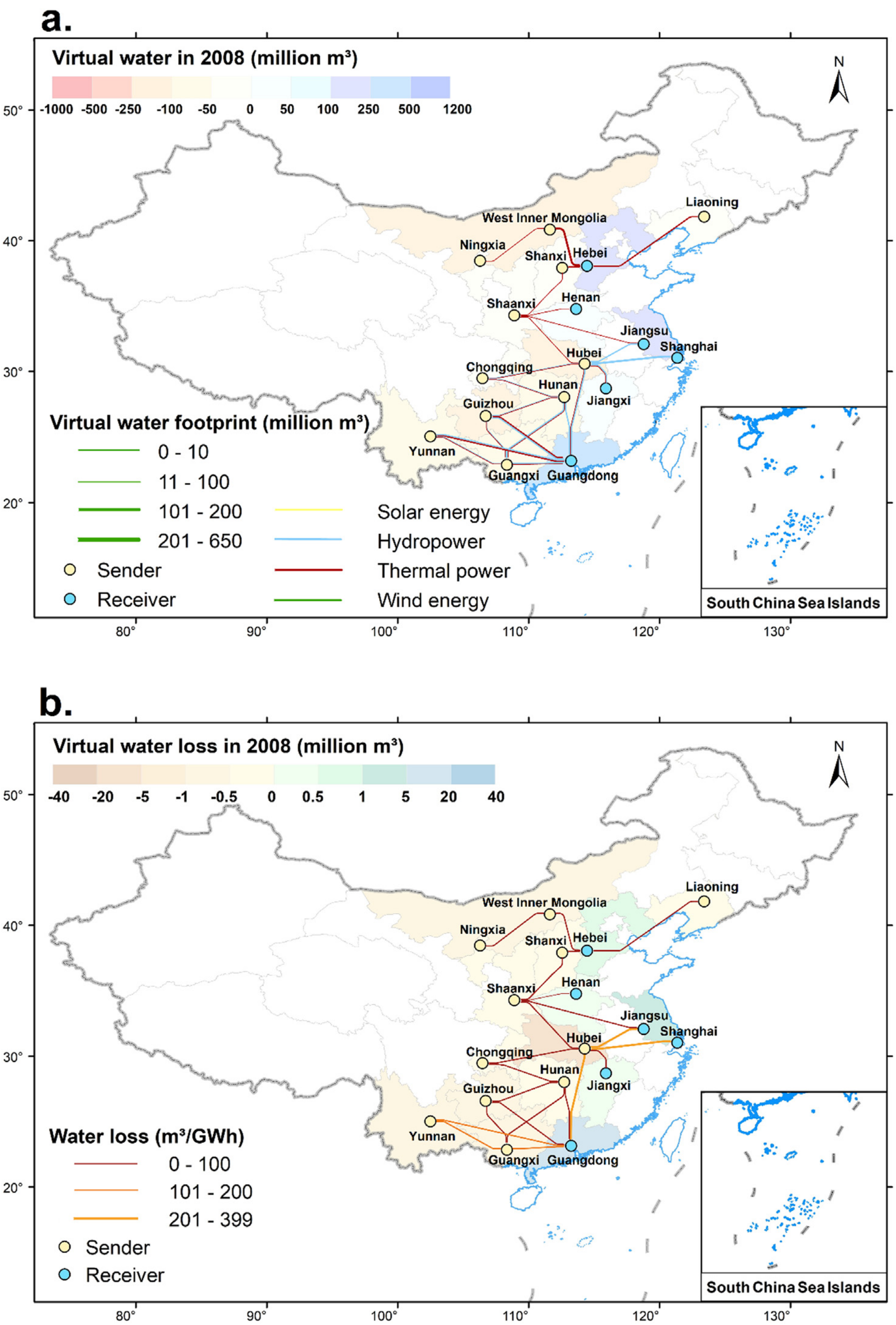

Fig. 4. Virtual water transfer and loss in the WEET project for 2008 and 2017.

4.2. Water substitution ratio

With electricity transmission by the WEET project, water resources and consumption in the electricity-exporting and importing regions have been virtually redistributed. We analyzed the water substitution difference and water substitution ratio of each transmission line of the WEET project.

With the increased transmission of electricity across regions, the self-produced power in electricity-importing areas is reduced and the water resources of the importer are conserved. At the same time, water consumption in the electricity-exporting areas increases. We analyzed the water footprint of power generation in each region with and without the WEET project. The regional water substitution differences and water substitution ratios of different transmission lines are shown in Fig. 5. As defined previously, water substitution difference represents the difference between the water footprints of a power exporter and importer, with the water footprint per unit of power generated being influenced by both power plant type and water intensity. As shown in Fig. 5, the transmission of electricity from Northwest to North, Northwest to Central, North to North, and Southwest to Central exhibits negative water substitution differences. From the perspective of water consumption, these negative water substitution differences suggest that generating the power at the sender region may be more attractive than at the receiver. However, the water substitution differences for the transmission route from the Southwest and Central regions, where electricity generation is dominated by hydropower, are positive. These

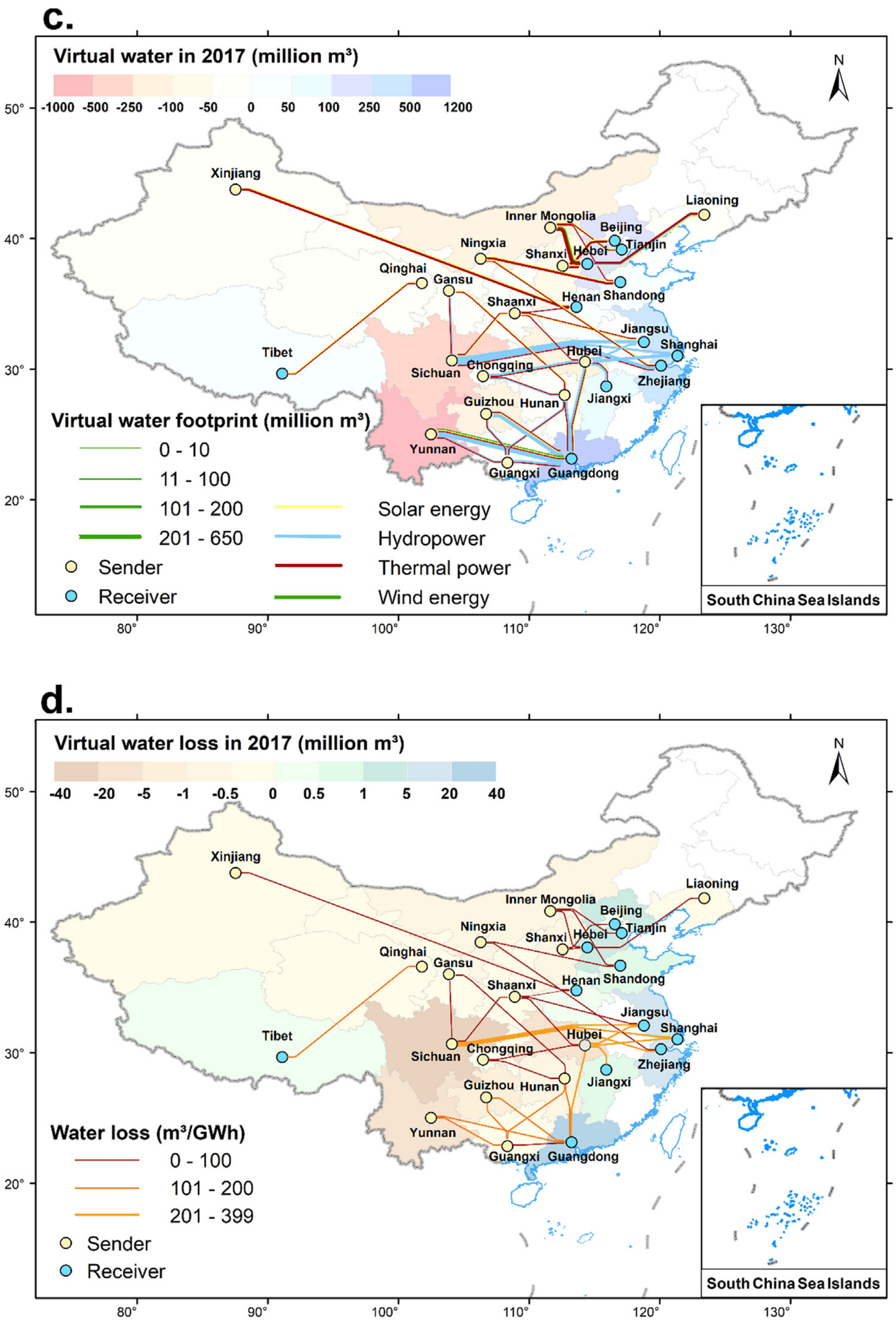

Fig. 4. (*continued*)

positive water substitution differences indicate that generating electricity at the sender region and transferring the electricity to the receiver consume more water than generating electricity at the receiver region.

In 2008, transmission lines from the Northwest to the Central had the lowest water substitution ratio, which we estimated as 0.62. This is due to the lower water footprint per unit of thermal power in the Northwest. With the construction of generation facilities based on clean energy technologies, such as wind power and solar photovoltaic, the water substitution ratio of these regions has further improved to 0.39, and the water substitution difference from the Northwest to the Central was negative 64 million m^3 in 2017. In that same year, the water substitution ratio of transmission lines from the north route (NW-N, N-N, NE-N) was less than 0.65. Because of the difference between the water footprints of hydropower in the Southwest and thermal power in the Northwest, the water substitution ratio from the Northwest to the Southwest was 0.16.

4.3. Projection of virtual water transfer through the WEET project in 2030

China’s economic development heavily relies on energy. The increase in living standards also heralds an increase in electricity demand. At the end of 2018, China's National Energy Administration announced that it was starting to plan nine electricity transmission projects with a total transmission capacity of 57 GW. It is estimated that by 2030, power transmission from West to East will reach 441 GW, which is

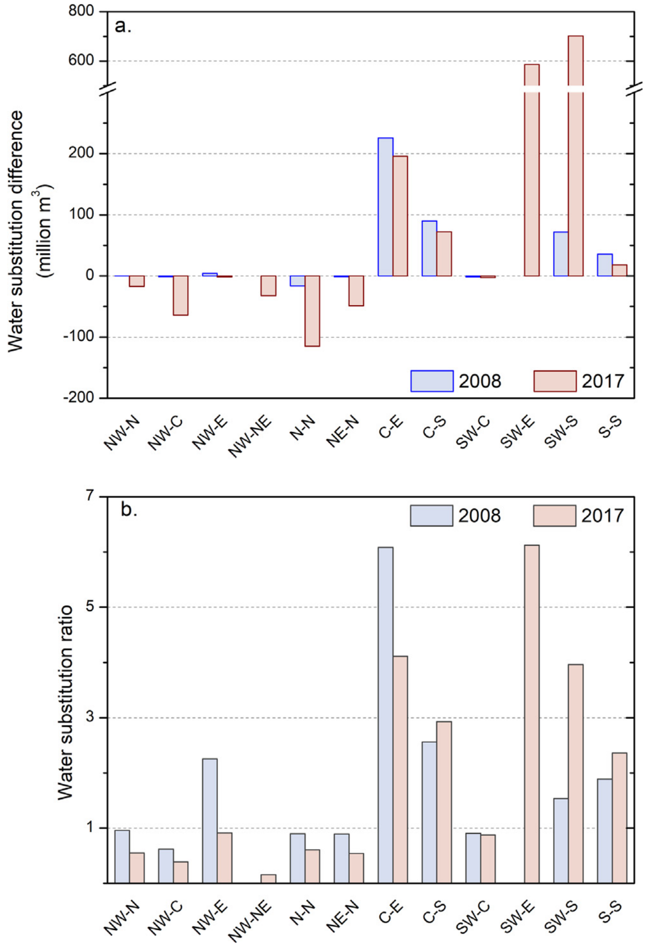

Fig. 5. Water substitution difference (a) and water substitution ratio (b) of the WEET project in 2008 and 2017. The horizontal axis denotes electricity export–import regions: NW stands for Northwest; N for North; C for Central; E for East; S for South; NE for Northeast; and SW for Southwest.

nearly double the transmission capacity in 2017.

The Southwest is rich in hydropower resources, and most ongoing hydropower projects are located there. Because of the long design and construction time of hydropower plants, the transmission capacity to transfer the electricity to be generated by new hydropower plants was set at the same value in our three clean-energy growth scenarios (28% of the total power export). The projected output of hydropower plants is about 557 TWh, with an estimated water footprint of 3.5 km^3, which is 1.8 times the water footprint of hydropower plants in 2017.

For the Low Clean scenario, thermal power is the main energy source of electricity, accounting for 60% of the total power transmission. China's fossil energy is concentrated in the Northwest, where much of the future thermal power generation capacity is expected to be installed. Under the Low Clean scenario, the water footprint of thermal power exported from the Northwest will reach 1.1 km^3, which is 2.9 times higher than in 2017. For the Moderate- and High Clean scenarios, where the shares of thermal power are equivalent to 80% and 60% of the share in the Low Clean scenario, respectively, we estimated annual water footprints of 1.0 and 0.8 km^3, respectively, in 2030.

All the three scenarios assume the same amount of hydropower transmission. Therefore, the difference in total water footprint mainly emerges from the transmission of thermal power. As shown in Fig. 6, the Low Clean scenario, dominated by thermal power, presents the largest total water footprint among the three scenarios. More specifically, the annual water footprint of the Low Clean scenario is estimated to reach 4.7 km^3 in 2030, which is double the water footprint in 2017.

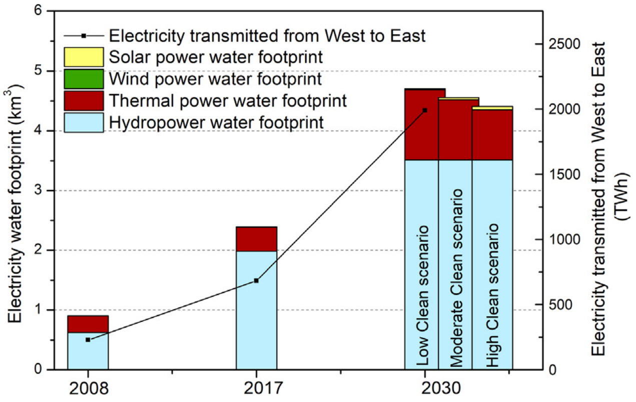

Fig. 6. Power transmission and water footprint from West to East in 2008, 2017, and 2030.

Compared to thermal power and hydropower, the unit water footprint of wind power and solar energy is relatively small. Therefore, the total water footprint decreases as wind and solar power increase. Under the High Clean scenario, the total water footprint is estimated to reach 4.4 km^3 in 2030, which is about 6% less than in the Low Clean scenario.

Based on the transmission line loss rate in 2017, we estimate that the virtual water loss over the power transmission process in 2030 to be between 181 (High Clean scenario) and 192 (Low Clean scenario) million m^3, which is nearly double that of the current virtual water loss.

5. Discussion

5.1. Impact of power delivery on the water resources and ecosystem in the western regions

After decades of development, the WEET project has become an indispensable power supplier for the eastern regions of China. In 2017, the electricity delivered by the western regions of China accounted for 38.2% of the total electricity consumed in Beijing-Tianjin and Hebei area, 34.6% in Guangdong, and 14.5% in Jiangsu-Zhejiang and Shanghai area. The electricity transmitted from the western regions accounts for 21.8% of their total power generation. It has contributed significantly to the economic development of the western regions of China.

However, the water resources in the western regions of China are unevenly distributed. The Northwest is rich in fossil energy resources, but short in water resources. The annual precipitation in most areas is less than 200 mm, resulting in severe ecological vulnerability across China. Large amounts of water are needed for energy exploitation and power generation. We estimate that the current amount of virtual water from the Northwest, embodied in the WEET project, is around 300 million m^3 per year. Energy development in the region is seriously restricted by the lack of abundant water resources, which will further affect the ecological and environmental security of the region. The Northwest is also rich in wind and solar energy resources. The unit water footprint of wind and solar power is much smaller than that of thermal power, and thus the transmission project can considerably reduce the total water consumption by transmitting more electricity generated using wind and solar energy. The development of clean energy in the region may be an effective and better way to manage and conserve water resources while retaining the region's ability to export energy.

As a renewable energy source, hydropower, which is abundant in the Southwest, is generally more environmentally friendly than fossil energy. However, the water footprint associated with evaporation from reservoirs is larger than that of thermal power, a resource consumption that cannot be ignored in the process of hydropower development. With the continuous development of the WEET project, more electricity will be delivered to the eastern regions of China. In 2030, the water footprint of hydropower in the Southwest will probably double. Hydropower not only leads to the transfer of large amounts of virtual water but also changes the natural river flow, water depth, and flow pattern, which have a cumulative impact on biodiversity and the ecological environment [49]. More research is needed to balance hydropower development and ecological protection.

5.2. Water loss during power transmission

Energy loss in the form of heat is inevitable in transmission networks and is a burden in many developing countries [50]. Energy losses can be estimated from complex nonlinear functions [51], and they exist not only in transmission lines but also in transformer modulators and substations. This study quantifies the water losses associated with power transmission in the WEET project. As energy is lost during power transmission, so (indirectly) is the water used to generate the lost power. In 2017, the average water loss per unit of transmitted power for the WEET project was 144 m^3/GWh. In the increasingly complex power grid, losses in transmission lines should be managed not only with electric and economic goals but also to save water.

Transmission line losses are related to the operational and technical characteristics of the electricity network [13]. We associated observed losses in the main transmission lines of the WEET project with electric current flows and the length of lines. Note that the same transmission distance, losses may vary significantly owing to the operational and technical characteristics of the lines. Taking the transmission line from Sichuan to Shanghai as an example, when the annual average transmission power increased from 1.7 to 3.7 GW, the transmission line losses increased from 4.7% to 6.5%. Minimizing losses in transmission lines and thus reducing the corresponding water losses could be a new research focus for power transmission networks.

5.3. Data uncertainties and limitations

There are three main sources of data uncertainty embodied herein. The first refers to the data used to express the water footprint per unit of power generated. Although data on the water footprint per unit of thermal power and hydropower generated are based on results from research conducted on power plants in China, the corresponding data for wind power and solar energy, owing to the lack of information specific to power plants in China, are from research conducted at the global level. However, as the water footprint per unit of solar power is around 10 times smaller than that of thermal power, and wind presents an even smaller water footprint, typically around 250 times smaller than that of solar power, we believe that relying on global values for those two water footprints has little impacts on our results.

The other sources of uncertainty are the complex parameters that affect transmission line losses during power transmission. In fact, transmission line losses vary according to the operating conditions of the power network (e.g., load and node voltage) [52]. By relying on the annual averages of transmission line losses, our results neglect the potential variability of those losses. Further research exploring the effects of that variability on water losses should be conducted to provide seasonally or temporally adjusted water losses associated with power transmission in the WEET project.

Finally, there are uncertainties in our assumptions of socioeconomic development, future technologies, and policies, which were not fully explored herein. While we simulated three scenarios with different levels of penetration of clean energy, further research is needed to explore other sources of uncertainty that could affect our results, such as alternative projections of economic development and their spatial distribution, reduced water footprint of thermal power plants, and increased transmission efficiency in the WEET project.

6. Conclusion

During the last decade, China has experienced rapid changes in its regional economy and electricity demand. The implementation of the WEET project not only addresses electricity demand in the eastern coastal areas of the country but also promotes the development of the western regions. Compared with 2008, the electricity transmitted in 2017 from western to eastern regions has tripled, and along with the increase in electricity transmission, a significant amount of water was transferred to the eastern regions in the form of virtual water.

This paper presents estimates of the water footprint embodied in the electricity transmitted by the WEET project. We introduce the concepts of virtual water transfer loss and water substitution ratio (and difference) to express the productivity of the transmission process of the project concerning water (direct and indirect) use. We found that in 2017, the virtual water transfer loss over the electricity transmission process of the WEET project was approximately 100 million m^3, about four times that in 2008. With the socioeconomic development of the eastern regions of China, the energy demand in these regions will continue to increase. We estimate that in 2030, the water footprint of the WEET project will exceed 4.4 km^3, with a virtual water transfer loss of nearly 200 million m^3.

Our results also show that hydropower plants contribute a higher water footprint per unit of power generated than thermal power, an aspect usually neglected in similar studies. Wind and solar power have smaller water footprints than hydro- and thermal power and increasing their penetration in electricity-exporting regions can significantly reduce the total water footprint of the project in the future. The results also show that with the projected increase in transmission distance and power, the virtual water transfer losses through the transmission process of the project also tend to increase. We note that improving the efficiency of the transmission system is particularly important, not only from electrical and economic perspectives but also as a means to conserve water resources in the electricity-exporting regions. Overall, the study calls attention to the impacts that the WEET project has on water resource sustainability and ecosystem stability in the western regions of China. In addition, we suggest that the metrics introduced in this paper should be considered when planning for new transmission lines in a transregional electricity transmission project. Further research that relies on these metrics can be developed to estimate virtual water transfers and losses in other electricity transmission systems around the world, leading to a better understanding of the water–energy interdependencies in power transmission systems.

CRediT authorship contribution statement

Yongnan Zhu: Methodology, Writing - original draft, Writing - review & editing. **Jing Ke:** Methodology, Writing - review & editing. **Jianhua Wang:** Conceptualization, Funding acquisition. **He Liu:** Conceptualization, Funding acquisition. **Shan Jiang:** Data curation. **Helcio Blum:** Validation, Funding acquisition. **Yong Zhao:** Validation. **Guohua He:** Data curation. **Yuan Meng:** Visualization. **Jian Su:** Visualization.

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.

Acknowledgements

This work was jointly supported by the U.S./China Clean Energy Research Center for Water-Energy Technologies (CERC-WET) through the National Key Research and Development Program of China (Grant

No. 2018YFE0196000) and the Energy Systems Analysis and Integration Division of the U.S. Department of Energy's Office of Policy (Contract No. DE-AC02-05CH11231). J. Wang, Y. Zhu, S. Jiang, Y. Zhao, G. He, and Y. Meng were also supported by the National Science Foundation of China for Distinguished Young Scholars (Grant No. 51625904), the Key Consulting Project of Chinese Academy of Engineering (Grant No. 2019-XZ-33), and the China Institute of Water Resources and Hydropower Research (IWHR) Research & Development Support Program (Grant No. WR0145B622017).

References:

[1] Gleick P. Water and energy. Annu Rev Energ Env 1994;19:267–99.
[2] WWAP. The United Nations World Water Development Report: Water and Energy. Paris: UNESCO; 2014. p. 2014.
[3] Wang H, Jia Y, Yang G, Zhou Z, Qiu Y, Niu C, et al. Integrated simulation of the dualistic water cycle and its associated processes in the Haihe River Basin. Chinese Sci Bull 2013;58:3297–311.
[4] BP. BP Statistical Review of World Energy 2018. London: BP; 2018.
[5] Shaffer B. Global energy trends: Demands for scientific innovation. MRS Energy Sustain 2019;6.
[6] Fricko O, Parkinson S, Johnson N, Strubegger M, van Vliet MT, Riahi K. Energy sector water use implications of a 2 °C climate policy. Environ Res Lett 2016;11:34011.
[7] National Bureau of Statistics of China. China Energy Statistics Yearbook 2018. Beijing: China Statistics Publishing House; 2018.
[8] IEA. World Energy Outlook 2019. Paris: International Energy Agency; 2019.
[9] Zhu Y, Jiang S, Zhao Y, Li H, He G, Li L. Life-cycle-based water footprint assessment of coal-fired power generation in China. J Clean Prod 2020::120098.
[10] Wang Y, Yao L, Wang L, Liu Z, Ji D, Tang G, et al. Mechanism for the formation of the January 2013 heavy haze pollution episode over central and eastern China. Sci China Earth Sci 2014;57:14–25.
[11] The State Council of China. The Tenth Five-Year Plan for National Economic and Social Development. 2001.
[12] Zeng M, Li H, Ma M, Li N, Xue S, Wang L, et al. Review on transaction status and relevant policies of southern route in China's West to East Power Transmission. Renew Energ 2013;60:454–61.
[13] Zeng M, Peng L, Fan Q, Zhang Y. Trans-regional electricity transmission in China: Status, issues and strategies. Renew Sust Energy Rev 2016;66:572–83.
[14] Chen W, Li H, Wu Z. Western China energy development and west to east energy transfer: Application of the Western China Sustainable Energy Development Model. Energ Policy 2010;38:7106–20.
[15] Xue Z, Hao J, Chai F, Duan N, Chen Y, Li J, et al. Air quality impact of the coal-fired power plants in the northern passageway of the China west-east power transmission project. J Air Waste Manage 2005;55:1816–26.
[16] Wang C, Wang R, Hertwich E, Liu Y, Tong F. Water scarcity risks mitigated or aggravated by the inter-regional electricity transmission across China. Appl Energ 2019;238:413–22.
[17] Ma X, Yang D, Shen X, Zhai Y, Zhang R, Hong J. How much water is required for coal power generation: An analysis of gray and blue water footprints. Sci Total Environ 2018;636:547–57.
[18] Hickenbottom K, Hancock N, Hutchings N, Appleton E, Beaudry E, Xu P, et al. Forward osmosis treatment of drilling mud and fracturing wastewater from oil and gas operations. Desalination 2013;312:60–6.
[19] Tiwary R. Environmental impact of coal mining on water regime and its management. Water Air Soil Poll 2001;132:185–99.
[20] Wang J, Lu C, Sun Q, Xiao W, Cao G, Li H, et al. Simulating the hydrologic cycle in coal mining subsidence areas with a distributed hydrologic model. Sci Rep-UK 2017;7:39983.
[21] Cormos C, Vatopoulos K, Tzimas E. Assessment of the consumption of water and construction materials in state-of-the-art fossil fuel power generation technologies involving CO_2 capture. Energy 2013;51:37–49.
[22] Spang E, Moomaw W, Gallagher K, Kirshen P, Marks D. The water consumption of energy production: an international comparison. Environ Res Lett 2014;9:105002.
[23] Meldrum J, Nettlesanderson S, Heath G, Macknick J. Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environ Res Lett 2013;8:015031.
[24] Hoekstra A, Chapagain A, Aldaya M, Mekonnen M. The water footprint assessment manual. London: Earthscan; 2011.
[25] Mekonnen M, Gerbens-Leenes P, Hoekstra A. The consumptive water footprint of electricity and heat: a global assessment. Environ Sci-Water Res 2015;1:285–97.
[26] Ackerman F, Fisher J. Is there a water–energy nexus in electricity generation? Long-term scenarios for the western United States. Energ Policy 2013;59:235–41.
[27] Zhu Y, Jiang S, Han X, Gao X, He G, Zhao Y, et al. A Bibliometrics review of water footprint research in China: 2003–2018. Sustain-Basel 2019:5082.
[28] Fulton J, Cooley H. The water footprint of California's energy system, 1990–2012. Environ Sci Technol 2015;49:3314.
[29] Shang Y, Hei P, Lu S, Shang L, Li X, Wei Y, et al. China's energy-water nexus: Assessing water conservation synergies of the total coal consumption cap strategy until 2050. Appl Energ 2018;210:643–60.
[30] Chapagain A, Hoekstra A. The global component of freshwater demand and supply: an assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. Water Int 2008;33:19–32.
[31] Chini C, Djehdian L, Lubega W, Stillwell A. Virtual water transfers of the US electric grid. Nat Energy 2018;3:1115–23.
[32] Gao X, Zhao Y, Lu S, Chen Q, An T, Han X, et al. Impact of coal power production on sustainable water resources management in the coal-fired power energy bases of Northern China. Appl Energ 2019;250:821–33.
[33] Liao X, Xu Z, Hall J, Guan D. Categorising virtual water transfers through China's electric power sector. Appl Energ 2018;226:252–60.
[34] Qu S, Liang S, Konar M, Zhu Z, Chiu ASF, Jia X, et al. Virtual water scarcity risk to the global trade system. Environ Sci Technol 2018:673–83.
[35] Zhang C, He G, Zhang Q, Liang S, Zipper SC, Guo R, et al. The evolution of virtual water flows in China's electricity transmission network and its driving forces. J Clean Prod 2020;242:118336.
[36] Liu J, Zhao D, Gerbens-Leenes PW, Guan D. China's rising hydropower demand challenges water sector. Sci Rep-UK 2015;5:11446.
[37] Chenoweth J, Hadjikakou M, Zoumides C. Review article: Quantifying the human impact on water resources: a critical review of the water footprint concept. Hydrol Earth Syst Sci 2014;10:2325–42.
[38] Chai L, Liao X, Yang L, Yan X. Assessing life cycle water use and pollution of coal-fired power generation in China using input-output analysis. Appl Energ 2018;231:951–8.
[39] Liu J, Zhou Z, Yan Z, Gong J, Jia Y, Xu C, et al. A new approach to separating the impacts of climate change and multiple human activities on water cycle processes based on a distributed hydrological model. J Hydrol 2019:124096.
[40] Qin D, Lu C, Liu J, Wang H, Wang J, Li H, et al. Theoretical framework of dualistic nature–social water cycle. Chinese Sci Bull 2014;59:810–20.
[41] Montanari A, Young G, Savenije HHG, Hughes D, Wagener T, Ren LL, et al. "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022. Hydrolog Sci J 2013;58:1256–75.
[42] China Electricity Council. Power Industry Statistics Compilation in 2017; 2018.
[43] National Energy Administration of China. Notice on accelerating the planning and construction of key projects for power transmission and transformation; 2018.
[44] Zhou X, Lu Z, Liu Y, Development Chen S. models and key technologies of future grid in China. Proc CSEE 2014;34:4999–5008.
[45] Zhang C, Zhong L, Wang J. Decoupling between water use and thermoelectric power generation growth in China. Nat Energy 2018;3:792–9.
[46] Scherer L, Pfister S. Global water footprint assessment of hydropower. Renew Energ 2016;99:711–20.
[47] Yao W, Ding J, Nan J, Yang C, Yan C, Wen J, et al. Construction and selection of transmission modes for renewable energy of Western China in the Future. In: 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), IEEE; 2019, pp. 417–422.
[48] Lu Z, Li W, Xie B, Shang L. Study on China's wind power development path—Based on the target for 2030. Renew Sust Energ Rev 2015;51:197–208.
[49] Winemiller K, McIntyre P, Castello L, Fluet-Chouinard E, Giarrizzo T, Nam S, et al. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science 2016;351:128–9.
[50] Min B, Golden M. Electoral cycles in electricity losses in India. Energ Policy 2014;65:619–25.
[51] Conejo A, Arroyo J, Alguacil N, Guijarro A. Transmission loss allocation: a comparison of different practical algorithms. IEEE Trans Power Syst 2002.
[52] Chen B, Xiang K, Yang L, Su Q, Huang D, Huang T. Theoretical line loss calculation of distribution network based on the integrated electricity and line loss management system. 2018 China International Conference on Electricity Distribution (CICED). IEEE; 2018. p. 2531–5.