# Categorising virtual water transfers through China's electric power sector

**Xiawei Liao[1], Xu Zhao[2*], Jim W. Hall[1], Dabo Guan[3]**

[1] Environmental Change Institute, University of Oxford, OX1 3QY, Oxford, UK

[2] Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Ministry of Education, College of Environment, Hohai University, Nanjing 210098, China

[3] Water Security Research Centre, School of International Development, University of East Anglia, Norwich NR4 7TJ, United Kingdom

*Corresponding author: Xu Zhao (Email Address: xuzhao@hhu.edu.cn; xu.zhao.water@hotmail.com)

# Abstract

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

# Key words:

Electric Power; Water-Energy Nexus; Virtual Water; Multi-regional Input-output Analysis

# 1. Introduction

While electric power is crucial to modern human society's development and prosperity, production of electricity uses another essential commodity, i.e. water [1, 2, 3]. Water-related issues have curtailed power production around the globe [4]. With water being recognized as the top global risk facing humanity over the next decade [5], water challenges for the energy sector are set to intensify [6].

Although water is required throughout the life cycle of electricity production, the operational phase plays a dominant role [3, 7, 8]. Apart from some forms of renewable electricity production, e.g. solar PV and wind, which require negligible amounts of on-site water inputs, many studies have shed light on the water uses for thermoelectric power production, primarily for cooling purposes, on global, national and regional scales [9, 10, 11, 12, 13]. However, little work has been done to reveal how the physical water inputs to the electric power sector in one region turn into virtual water embodied in the power produced traversing geographical boundaries and then being used by different sectors, e.g. households, industries, in another region.

Virtual water refers to water used for the production of goods and services, which can then be transferred among economic sectors and regions through trade [14, 15]. Studies of virtual water provide insights into how production, trade and consumption in other regions and sectors can exacerbate or alleviate over-exploitation of water resources [16, 17]. However, existing studies quantifying sub-national virtual water fluxes within China's electric power system have adopted a production-based bottom-up approach [18, 19, 20, 21]. Their work failed to address the inter-sectoral contributions among the final electricity users. Incorporating insights from a consumption-based perspective analyzing virtual water embodiments in the electric power consumed by different sectors can help to provide a more complete picture of the water footprint of different sectors and of the geographical fluxes of virtual water. Furthermore, although Liu *et al.* (2015) [22] have shed light on the water consumption in China’s hydroelectric power plants and pointed out that they have a higher water consumption factor, measured as water consumption per unit of electricity produced, than other types of electricity production, hydropower production’s water consumption has not been examined on a provincial scale.

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

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

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

[Insert Figure 1]

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

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

## 2. Method and data

### 2.1. Quantifying water consumption for power production

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

This study focuses on the operational phase of coal-fired power production, which needs water for cleaning, cooling, boiler make up and other on-site water-requiring processes, e.g. flue gas desulfurization (FGD), coal transport and domestic uses. Coal-fired power plants' water consumption factors differ significantly depending on the cooling technology used [2]. Three commonly used cooling technologies in China are: open-loop cooling, closed-loop cooling and air cooling. Closed-loop cooling systems consume the largest amount of water because of the evaporative loss of recirculated water in cooling towers, whereas open-loop cooling systems use running water and thus have much lower water consumption. Air cooling systems require the least amount of water as they do not need water for cooling purposes. According to Liao et al. (2017) [24], in a typical coal-fired power plant equipped with closed-loop cooling systems, evaporative water loss accounts for around 80% of its total operational water consumption. Thermoelectric power plants' water consumption can be calculated by equation (1):

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

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

According to Liao et al. (2016), coal-fired power plants equipped with closed-loop, open-loop and air-cooled systems occupy 56.6%, 30.8% and 12.6%, respectively, in China. Further provincial distributions can be obtained from their study [12]. Regarding water consumption factors of coal-fired power plants equipped with different cooling technologies, only a small number of coal-fired power plants reported their water consumption factors in China [25, 26]. For plants with closed-loop and open-loop cooling systems, we use the median values (1.87 and 0.39 $m^3$ /MWh, respectively) in the US as reviewed by Macknick et al. (2012). They are on par with the reported values from Chinese power plants [12]. Regarding coal-fired power plants with air cooling systems, as they are not included in Macknick et al. (2012), we use the median water consumption factor (0.32 $m^3$ /MWh) reported by Chinese power plants [25, 26]. It is worth noting that although cooling tower's water evaporation will be affected by ambient temperature and relative humidity change, those effects are not considered in this study. China's provincial thermoelectric power sector's water consumption factors can then be estimated assuming that all power plants in the same province have the same running hours. This assumption is valid because of China's unique generator dispatch mechanism trying to assure all contracted power generators comparable running hours [27]. Furthermore, provincial seawater uses by the thermoelectric power sector are calculated in Liao et al. (2016) and since we are only concerned with freshwater consumption, seawater use is not included in this study.

In terms of hydropower, its provincial water consumption can be calculated by equation (2) below:

$$W_{ih} = WF_{ih} \bullet P_{ih} \qquad (2)$$

where $WF_{ih}$ denotes water consumption factor for hydropower in province $i$, which is the water evaporated per unit of hydropower produced; $P_{ih}$ is province $i$'s hydropower output and $W_{ih}$ is the water consumption for province $i$'s hydropower production.

Liu *et al.* (2015) [22] compiled the water consumption factors for 209 major hydropower plants in China based on their reservoir area, measured annual evaporation and primary use. We extrapolate $WF_{ih}$ based on the average value of water consumption factors of all hydropower plants within province $i$. Run-of-river hydro electricity is not included in this study due to lack of data availability.

Provincial thermoelectric and hydroelectric power productions for 2002, 2007 and 2010 are obtained from China's national statistics bureau (2014) [28]. More detailed description of the methods and corresponding limitations are presented in Appendix of Supporting Information.

## 2.2. Quantifying virtual water embodied in all sectors using Water Embodied in Trade model

When local water was physically abstracted and consumed in the production process of a sector, this water is then turned into virtual water embodied in that sector, and redistributed through the supply chain consumed by final demand of this sector and other sectors. Hence, the physical water consumption of a sector does not equal to the virtual water consumption of final demand in that sector, but the sum of the total physical water consumption of all sectors equals to the sum of the virtual water consumption of all sectors, which is shown as followed.

$$\sum PW_j = \sum VW_j \tag{3}$$

The virtual water redistribution among sectors can be quantified using an input-output analysis. We applied the 'Water Embodied in Trade' (WET) model to study the virtual water embodied in final consumption of different regions for all sectors [15, 29]. The assumption in a WET framework is that bilateral trade between regions is all directed towards final consumption [30]. This means the international purchase of intermediate consumption is assigned to the international purchase of final consumption. For region *r*, the local total output was assigned to intermediate demand, domestic final demand and export to other regions.

$$\mathbf{x}^r = \mathbf{A}^{rr}\mathbf{x}^r + \mathbf{y}^{rr} + \sum\nolimits_{s\neq r}\mathbf{e}^{rs} \tag{4}$$

where $\mathbf{x}^r$ is the total output in region *r*, $\mathbf{A}^{rr}$ the technical coefficient, representing the intermediate inputs of each sector per unit of their output, $\mathbf{y}^{rr}$ is the domestic purchase of final demand in region *r*, and $\sum\nolimits_{s\neq r}\mathbf{e}^{rs}$ is the international purchase of final demand from regions. Noting that in a WET framework, the local output in region *r* does not contain imports from other regions, because the assumption in WET that intermediate demand is all from local production.

Equation (4) can be solved as follows:

$$\mathbf{x}^r = (\mathbf{I}-\mathbf{A}^{rr})^{-1}(\mathbf{y}^{rr} + \sum\nolimits_{s\neq r}\mathbf{e}^{rs}) \tag{5}$$

where $\mathbf{L}=(\mathbf{I}-\mathbf{A}^{rr})^{-1}$ is the Leontief inverse matrix which measuring both direct and indirect input in each sector to satisfy one unit of final consumption.

Combining equation (3) and (5), the virtual water embodiment in final demand can be expressed as followed.

$$\mathbf{VW}^r = \frac{\mathbf{pw}^r}{\mathbf{x}^r}(\mathbf{I}\text{-}\mathbf{A}^{rr})^{-1}(\mathbf{y}^{rr} + \sum\nolimits_{s \neq r} \mathbf{e}^{rs}) \qquad (6)$$

where $\mathbf{VW}^r$ is the matrix form of virtual water embodiment. $\mathbf{d}^r = \mathbf{pw}^r / \mathbf{x}^r$ is the vector of direct physical water use intensity of region *r* that represents the direct physical water use per unit of output in each sector. $\mathbf{pw}^r$ is the vector of direct physical water consumption in each sector of region *r*. $\mathbf{m}^r = \mathbf{d}^r(\mathbf{I}\text{-}\mathbf{A}^{rr})^{-1}$ represents the vector of total direct and indirect water input from region *r* to produce one unit of final consumption.

The virtual water related to region *r* can be classified into two groups. First, region *r* consumes physical water to produce the goods and services within the region, this physical water all turns into virtual water embodied the goods and services, and will be further distributed through the supply chain for local final consumption $\mathbf{y}^{rr}$ ($\mathbf{vw}^{rr} = \mathbf{m}^r \times \mathbf{y}^{rr}$) and for export $\mathbf{e}^{rs}$ ($\mathbf{vw}^{rs} = \mathbf{m}^r \times \sum\nolimits_{s \neq r} \mathbf{e}^{rs}$).

## 2.3. Quantifying virtual water consumption embodied in the power demands

For region *r* with *n* sectors, the virtual water embodied in power sector *k* ($vwe^r$) can be divided into electricity consumption by final demand ($vwef^r$) and electricity as intermediate inputs into other industrial sectors ($vwei^r$).

$$vwe_k^r = vwef_k^r + vwei_k^r \qquad (7)$$

The elements in equation (7) can be calculated as followed

$$vwe_k^r = \sum_{p=1}^{\mathrm{n}} \mathrm{VW}_{kp}^{rr} + \sum_{s\neq r} \sum_{p=1}^{n} \mathrm{VW}_{kp}^{rs} \tag{8}$$

$$vwef_k^r = \mathrm{VW}_{kk}^{rr} + \sum_{s\neq r} \mathrm{VW}_{kk}^{rs} \tag{9}$$

$$vwei_k^r = \sum_{p=1}^{n} \mathrm{VW}_{kp}^{rr} + \sum_{s\neq r} \sum_{p=1}^{n} \mathrm{VW}_{kp}^{rs} \quad (k \neq p) \tag{10}$$

## 2.4. Data sources, availability and treatment

Two sets of data are needed in this study, i.e. time series MRIO tables and corresponding sectoral specific water consumption data. China's MRIO tables for years 2002, 2007, and 2010 are available from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences [31, 32, 33]. China's MRIO table of 2030 is obtained from Zhao *et al.* (2015) [34]. In Zhao *et al.* (2015), final demands of each sector, e.g. the electric power sector, include five components: rural household consumption, urban household consumption, government consumption, gross fixed capital formation, and stock changes. First, sectoral rural and urban household consumption are estimated using income elasticity and revenue growth following the projections from Guan *et al.* (2008) [35]. Then the other three components of sectoral final demands as well as sectoral total outputs are estimated assuming they have the same change rate as sectoral rural and urban household consumption.

Apart from the power sector's water consumption that is calculated above, two following steps are undertaken to match water use statistic data with sectors in MRIO tables: (1) regarding primary and tertiary industries, water withdrawal data can be obtained from the Water Resource Bulletin in different Provinces (2007) [36]. It should be noted that, water withdrawal in tertiary industry (service sectors) and for domestic water use are aggregated in the Water Resource Bulletins. As about 50% of national urban domestic water use was for water use in service sectors, we assume the total water withdrawal of all service sectors in each province is 50% of its urban domestic water use. Then the distribution of different service sectors' water withdrawal is the same as in Zhao *et al.* (2015); (2) Water withdrawal data of all industrial sectors (secondary industry), except the power sector, in different provinces are taken from the China Economic Census Yearbook (2008) [37], whose 39 industrial sectors are aggregated to 22 industrial sectors as in MRIO tables (detailed sector aggregation is shown in Supporting Information). Water withdrawal data are then converted to water consumption by multiplying the corresponding sectoral water consumption coefficient from provincial Water Resource Bulletins (2007).

The power sector in IO tables includes Thermoelectric Power, Hydropower, Renewable and Heat production. According to Zhang and Anadon (2013), water use for heat production is negligible compared to that of power production. Therefore, we do not disaggregate Power and Heat Production. Combined Heat and Power (CHP) production is also not considered in this study because: (i) there is no statistical data for CHP capacity and heat generation for 2002 and 2007; (ii) although cogeneration can reduce coal-fired power plants' water consumption and neglecting it could result in overestimation of thermoelectric power sector's water usage. However, as China's current CHP units are mostly of small capacities and lower efficiencies and only provide heat during the winter, on an annual base, their total water consumption factors are on par with that of large non-heat generating coal-fired units [25, 26]. The latter is adopted for estimations in this study. (Self-reported total water consumption factors of over 700 coal-fired power generation units in China, which include both CHP units and non-heat-generating units, are discussed in Supporting Information). Renewable energy sources, e.g. solar PV and wind, which contribute to rather small amount of China's electricity (less than 5%) and use a negligible amount of water during the operation phase, are also not included [3]. Last but not least, we only include freshwater consumption in this study.

# 3. Results

## 3.1. Physical water consumption by electricity production

Hydropower makes up about 20% of China's power production [28], yet little attention has been paid to its water loss. Water is consumed in hydropower primarily as evaporative loss from reservoirs. Hydropower's water consumption grew substantially from 6.1 to 14.6 billion m³ between 2002 and 2010, which represented some 80% of the power sector's total water consumption. Hydropower's water consumption in a certain region is decided by the region's hydropower production and its water consumption factor. According to Liu *et al.* (2015), hydropower has higher water consumption factor than other energy sources, especially in provinces in the north and northwest, where water scarcity is particularly pronounced, because of the local climatic and land surface conditions, e.g. high wind and little vegetation

[22]. Despite the upward trend at a national scale, hydropower production has gone down in the north from 2007 to 2010. When hydropower production of multipurpose reservoirs reduces, a greater proportion of their water use will be attributed to other purposes, including agriculture and flood control, hence the amount of water use attributed to hydropower decreases.

Regarding the water consumption for thermoelectric power production, this study recaps on methods and results from the authors' previous analysis of the water use in China's thermoelectric power plants [12]. By multiplying provincial water consumption factors of thermoelectric power and power outputs, we calculate that, from 2002 to 2010, China's thermoelectric power production's consumptive water use has increased markedly from 1.6 to 3.8 billion $m^3$.

[Insert Figure 2]

As shown in Fig. 2, nationally, water consumed to generate electricity in China has more than doubled from 7.72 billion $m^3$ in 2002 to 18.48 billion $m^3$ in 2010. Unlike other regions, there is a downward trend in the north from 2007 to 2010. This could possibly be attributed to either decrease in local electricity consumption or increase in virtual water imports, which will be further discussed in the following sections.

## 3.2. Virtual water embodiments in electricity consumption

The largest proportion of electric power supplied was consumed by final demand, accounting for 39.8% in 2010. The remainder of electricity was used by industries, in the following proportions: Manufacturing (25.5%), Services (14.2%), Construction (12.8%), Mining (5.7%) and Agriculture (1.5%). Consumption of virtual water in electricity (VWE) follows these proportions, with some minor regional variations (see Appendix of Supporting Information). Nationally, VWEF has increased from 1.91 billion $m^3$ in 2002 to 7.36 billion $m^3$ in 2010; meanwhile VWEI also grew from 5.82 to 11.13 billion $m^3$. The share VWEI occupied has steadily decreased from 75.4% in 2002 to 61.2% and 60.2% in 2007 and 2010, respectively. This reflects growing final electricity demand, such as by households and government, associated with rapid urbanization and economic development, alongside increasing electricity efficiency in industry and a gradual shift in economic activity from manufacturing, mining and agriculture to service industries.

[Insert Figure 3]

Due to either relocation of industries or improvement in their energy efficiency, it can be seen from Fig. 3 that despite a slight increase in VWEF, the north has had a significant decrease in its VWEI from 2007 to 2010, which partially explains the decreasing water consumption of its power production illustrated in Fig. 2.

### 3.3. Virtual water trade via the electric power sector

When goods and services in different sectors are traded among different provinces, they carry a certain amount of virtual water embodiments that can be traced back from the physical water input into its production. Consequently, the physical water consumption in power sector is virtually redistributed across administrative boundaries. The differences in regional pattern of virtual water embodied in different electricity uses, either by final demand or other industries (Fig. 3), compared to electricity production (Fig. 2) illustrates how power demands in some regions are driving water consumption in some other regions. For example, in 2010, 4.58 billion $m^3$ of water was consumed for power production in the north, while all power demands in the north required 5.22 billion $m^3$ of water inputs in total, which means power demands in the north, which is relatively water scarce, also induced water consumption in other regions.

[Insert Figure 4]

Inter-provincial virtual water transfer via the power sector has increased from 2.81 billion $m^3$ in 2002 to 8.77 billion $m^3$ in 2010. The percentage in the power sector's total water consumption has gone up from 36.4% to 47.5%. This is to say, nearly half of the power sector's physical water inputs were finally used for inter-provincial trading purposes in 2010. According to Fig. 4 (a), it can be seen that virtual water was predominantly transferred eastward to coastal provinces, where there is more dense population and more developed economy, from their nearby inland provinces.

The amount of inter-regional virtual water transfers through the power sector has increased steadily from 1.48 billion $m^3$ in 2002 to 4.92 billion $m^3$ in 2010. Fig. 4 (b) shows water has been primarily transferred from the northeast and the central, whose net virtual water export was 0.64 and 0.49 billion $m^3$, respectively, while the north and the east were the main net virtual water importers, whose respective net water import was 0.64 and 0.74 billion m³ in 2010.

## 3.4. Outlook to 2030

To look at the future possibilities of China's power sector's virtual water embodiments as well as the associated sub-national water transfers, four scenarios of different provincial power generation mixes and technology configurations are investigated: no new policies are implemented besides the existing ones in the Baseline scenario (Scenario 1: BS); Energy demands are met with renewable or low-carbon energy sources, respectively, in High Renewable (Scenario 2: HR) and Low Carbon (Scenario 3: LC) scenarios; Thermoelectric power plants' cooling technologies are altered in Technology Change (Scenario 4: TC) scenario, i.e. all closed-loop cooling systems in the north (north, northeast and northwest) and open-loop cooling systems in the south (south, east and central) are replaced by air cooling and closed-loop ones respectively. According to Fig. 5, in addition to thermoelectric power generation, we project hydropower is likely to use 17.04 to 18.65 billion m³ of freshwater resources, mostly in central, south and northwest China, depending on its different levels of development (Further method see Appendix of Supporting Information). In total, 20.79 to 26.87 billion m³ of freshwater resources is projected to be consumed in China's power sector.

[Insert Figure 5]

Among all the water consumption for power production, the total amount of inter-regional virtual water transfers via the power sector will increase to 10.46 to

13.14 billion $m^3$. Compared with the Baseline Scenario, the High Renewable and Low Carbon Scenarios will increase virtual water exports from northwest and south China as, especially, hydropower is favourably developed in these regions. Under the Technology Change scenario, water consumption is increased in east and central China as open-loop cooling systems are replaced by closed-loop ones, while in northern China (north, northeast and northwest), employing air cooling systems reduces water consumption. Consequently, virtual water export from central China increases and virtual water import by east China decreases.

With these scenario studies, we demonstrate that climate change mitigation and water conservation measures may impose different water pressures on different regions. These inter-regional contingencies need close examination when future policies are formulated and implemented. It should be noted that improving energy efficiency may also contribute to both climate change mitigation and water conservation throughout the whole country. However, these improvements are not incorporated in the input-output table for 2030 that we used, so we have not been able to evaluate the co-benefits of further enhancing energy efficiency.

# 4. Discussion

## Consumption-based inter-sectoral analysis

For the first time, we have considered water embodied in the power production for intermediate inputs to other economic sectors from a consumption-based perspective. More than half, 60.2% in 2010, of the water consumed for power production was driven by power demands from industries, i.e. VWEI, particularly manufacturing, construction and services. The inter-sectoral analysis on virtual water flows demonstrates the importance of joint accountability throughout all sectors and regions for sustainable use of water resources. Potential risks for water shortages for the power sector can be reduced by either improved water efficiency in the power sector or reductions in the economy's electricity use, which can bring other co-benefits of carbon emissions reduction from the power sector and savings for energy users.

### Hydropower's water consumption

From 2002 to 2010, hydropower production in China almost tripled from 283.7 TWh to 722.2 TWh [28]. To mitigate climate change while securing power provision, hydropower is often considered as the most favourable alternative to fossil fuels [22]. In 2012, China planned to increase its hydropower capacity by 70% by 2020 to 420 GW [38]. However, its impact on water resources is seldom talked about in the energy community. Our results show that hydropower's water consumption made up the largest part of the power sector's water demands, which underscores the importance of incorporating hydropower's water loss into future life-cycle energy development, from energy planning to power plants operation.

### Virtual water transfers through the power sector

Virtual water trades driven by the spatial mismatch between power demands and production can be revealed by virtual water analysis. According to our quantification, nearly half of water consumption for power production (8.77 billion $m^3$ in 2010) was used for inter-provincial trading purposes in China, i.e. driven by power demands from other provinces. The top-five inter-provincial virtual water flows highlight China's West-to-East Power Transmission Project (WEPT), Guangxi to Guangdong in the south corridor and Shanxi to Hebei/Shandong and Inner Mongolia to Jilin/Shandong in the north corridor. The WEPT was initiated in China's Tenth Five-year Plan (2000-2005) [39] and designed to bring economic development to the lagging west while alleviate the resources pressure in the east, where dense population, heavy industrialization and rapid urbanization require substantial power supplies and thus put enormous pressure on local resources. However, the associated environment pressures in the inland west, especially the water-stressed northwest, brought by this spatial shift of power provision need to be evaluated. Moreover, similar to China's south-to-north water diversion project, water transfer, either virtually or physically, raises the question of spatial inequalities of development and opportunities [40], especially when virtual water is transferred outward from water-scarce regions.

## Electricity transmissions and regional water scarcities

As shown in Fig. 6, most coastal provinces in the east, namely Beijing, Tianjin, Hebei, Shandong, Jiangsu and Shanghai, are facing different levels of water scarcities as a result of large water demands by extensive populations and advanced development. Importing virtual water through their power sector contributes to the alleviation of their physical water scarcities. On the contrary, water scarcities in inland provinces in the north and northwest are aggravated by their power sector's virtual water exports.

[Insert Figure 6]

Although provinces in north and northwest China are suffering from different levels of water scarcities, as they are also home to China's major coal bases, coal-fired electricity exports from those regions through the WEPT Northern corridor to Jin-Jin-Ji (Beijing-Tianjin-Hebei) megalopolis are still encouraged in China's 13th Five-Year Electricity Planning [41]. In 2016, the National Energy Administration of China issued a 'Notice on Establishing a Coal-fired Power Planning and Construction Risk Warning Mechanism (hereinafter referred to as 'the mechanism')' [42]. The mechanism grades each province for its suitability to further expand its coal-fired power capacity from Red (discouraged development), Orange (cautious development) to Green (normal development) based on three sets of index: bankability, generation capacity adequacy and resource constraints. Although the mechanism explicitly listed water availability as one of the resource constraints, several water-scarce provinces, e.g. Ningxia, Shanxi, Inner Mongolia, are nonetheless not discouraged to develop their coal-fired capacities due to any resource constraints.

## Future virtual water transfers through the power sector in China

We expect that the water demands by China's power sector will continue to grow until 2030. Northwest China will become one of the main net water exporters due to the expansion of WETP and development of both hydropower and thermoelectric power in the region [43]. The virtual water outflow from the Yellow River basin is likely to grow remarkably in the future. Such planning that lacks comprehensive cross-sector considerations may lead to overexploitation of scarce water resources or energy infrastructure, e.g. coal-fired power plants, being stranded in the electricity-exporting regions. Power provision in the electricity-importing regions, often with dense population and high levels of urbanization and industrialization, may be exposed to risks brought by water scarcities beyond their administrative boundaries.

## Limitations and future research needs

This study has certain limitations due to the nature of the method (top-down) and paucity of data. First, the future scenario analysis was built using input-output data from Zhao *et al.* (2015), which does not account for changes of the upstream supplies and the consequent water uses brought by the power sector’s energy structure transformations under different scenarios. Data of higher spatial and sectoral resolution could contribute significantly in this regard. Secondly, it should be noted that Liu *et al.* (2016) calculated hydropower’s water consumption with gross instead of net evaporation (subtracting evaporation from the original rivers before the reservoir is constructed) and, as Bakken *et al.* (2017) [44] have pointed out, it may exaggerate reservoirs’ impacts on local water resources (Several limitations of our calculation of China’s hydropower’s water consumption are discussed in Appendix of Supporting Information). Lastly, as cooling water consumption makes up about 80% of coal-fired power plants’ total water consumption [24], utilizing the residual heat by retrofitting large electricity generation units for heat cogeneration could reduce the electric power sector’s water uses.

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## Figure Captions

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

**Figure 2.** Water consumption for power production in 2010 in China's six grids: North, Northeast, Northwest, East, Central and South [13]

**Figure 3.** Virtual water embodiment in electric power use in China's six grids in 2010

**Figure 4.** (a) Inter-provincial virtual water trade and the top-10 flows through the power sector in 2010 (billion $m^3$); (b) Inter-regional net import of virtual water embodied in the power sector in China's six grids

**Figure 5.** Virtual water transfers via the power sector in China's six grids in 2030 (BS – Baseline Scenario; HR-High Renewable Scenario; LC-Low Carbon Scenario; TC-Technology Change Scenario)

**Figure 6.** Provincial water scarcities and their net virtual water transfers through the power sector

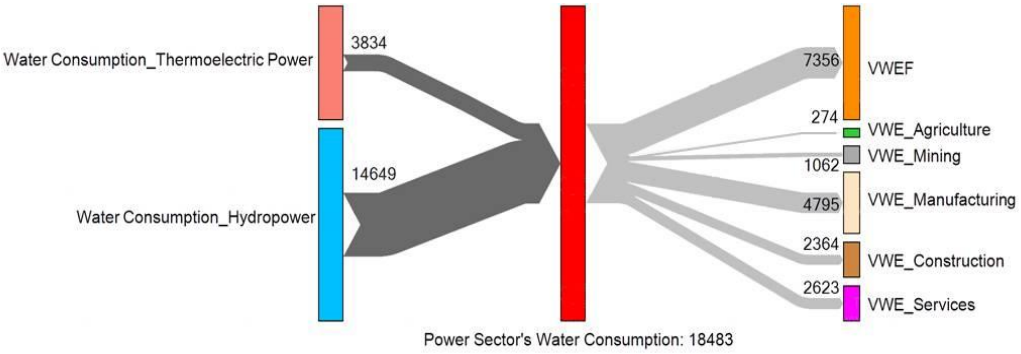

**Fig. 1.** Water fluxes from physical water consumption to virtual water embodiments in China's power sector (million m³) (Dark Grey – Physical Water; Light Grey – Virtual Water; the width of the fluxes are proportionate to the amount of water)

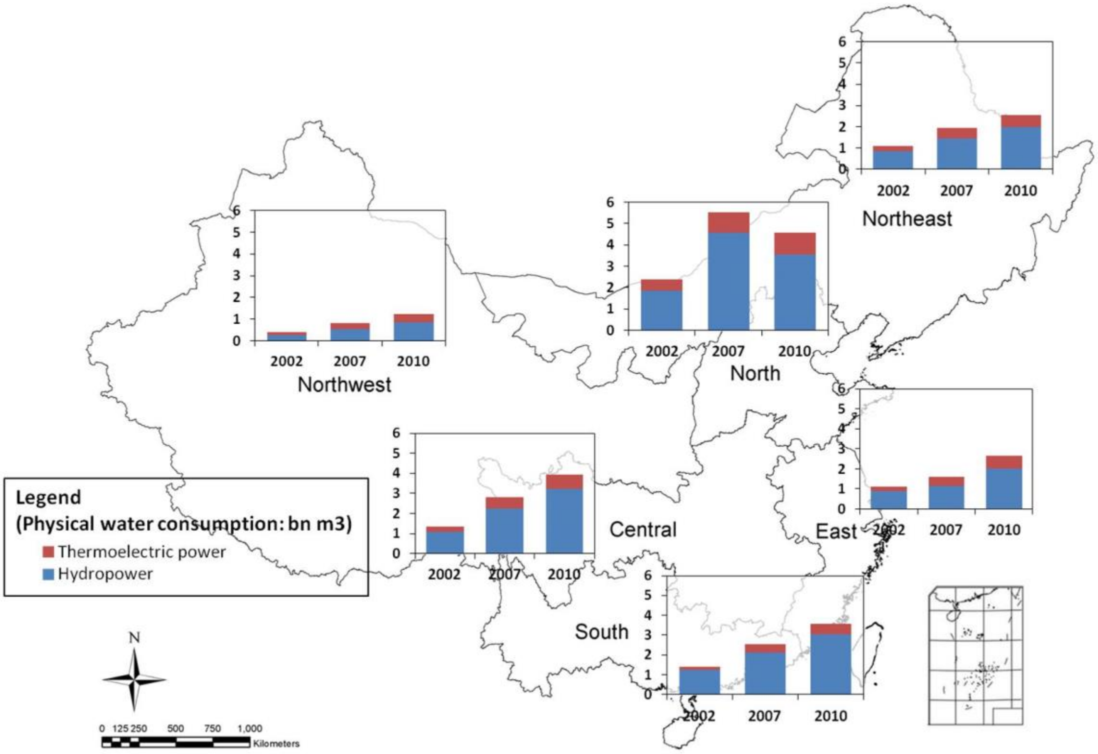

**Fig. 2.** Water consumption for power production in 2010 in China’s six grids: North, Northeast, Northwest, East, Central and South [13]

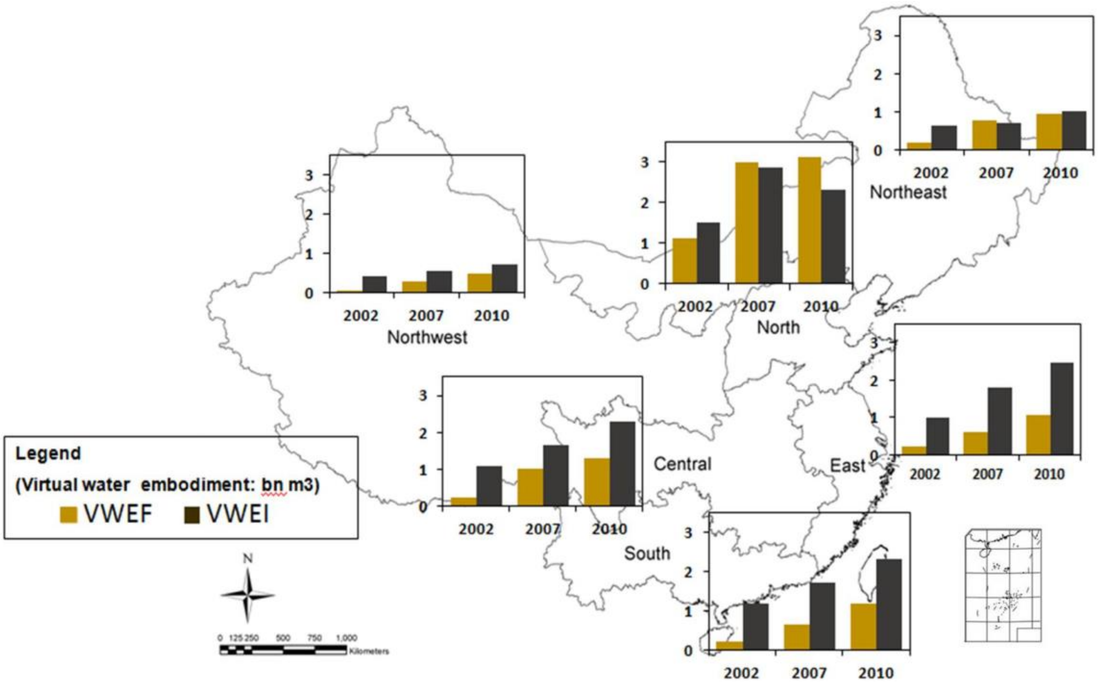

**Fig. 3.** Virtual water embodiment in electric power use in China's six grids in 2010

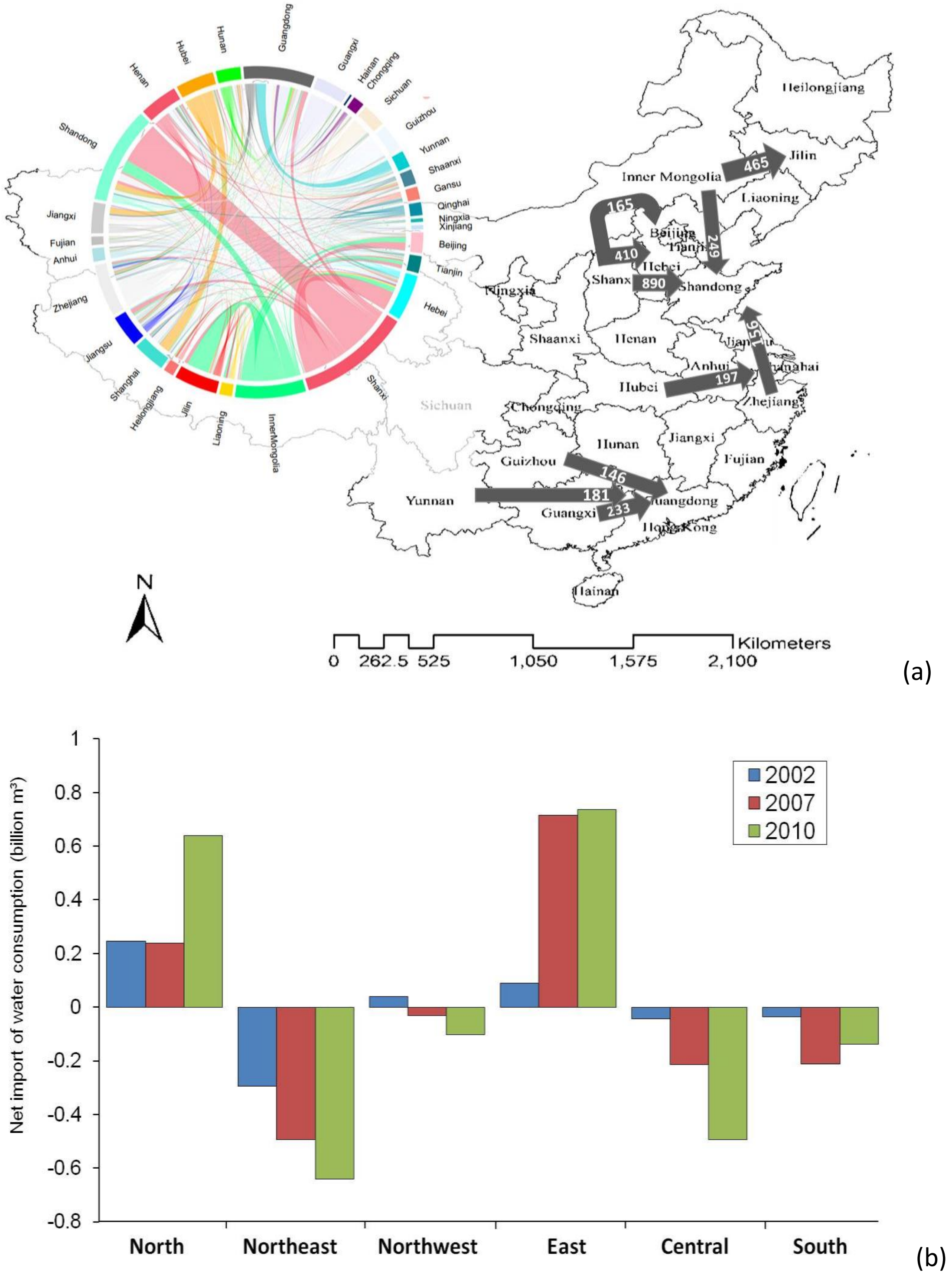

**Fig. 4.** (a) Inter-provincial virtual water trade and the top-10 flows through the power sector in 2010 (million m³); (b) Inter-regional net import of virtual water embodied in the power sector in China's six grids

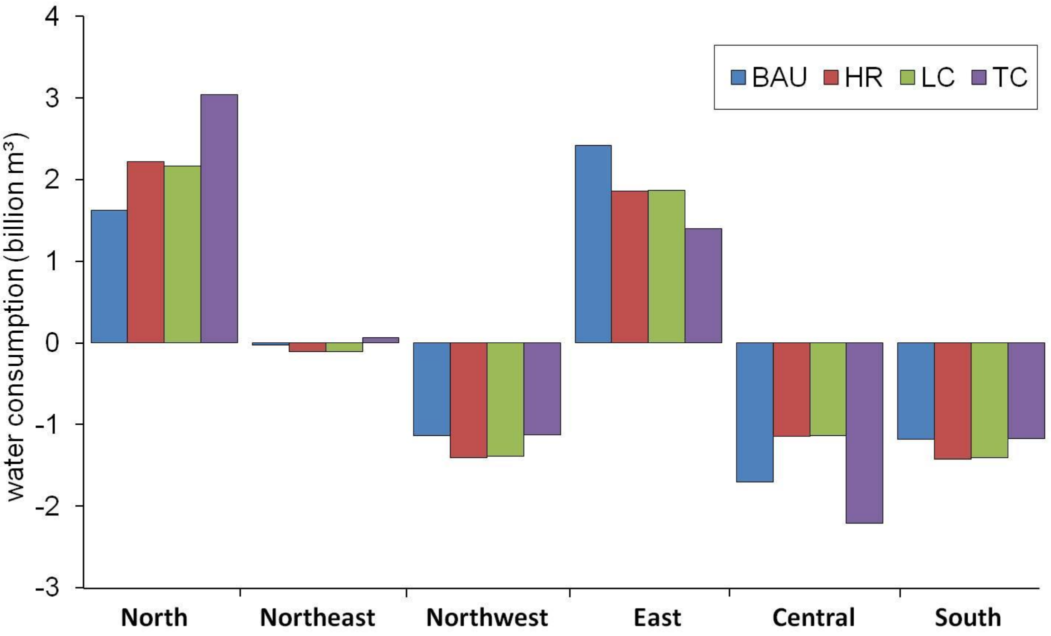

**Fig. 5.** Virtual water transfers via the power sector in China's six grids in 2030 (BS – Baseline Scenario; HR-High Renewable Scenario; LC-Low Carbon Scenario; TC-Technology Change Scenario)

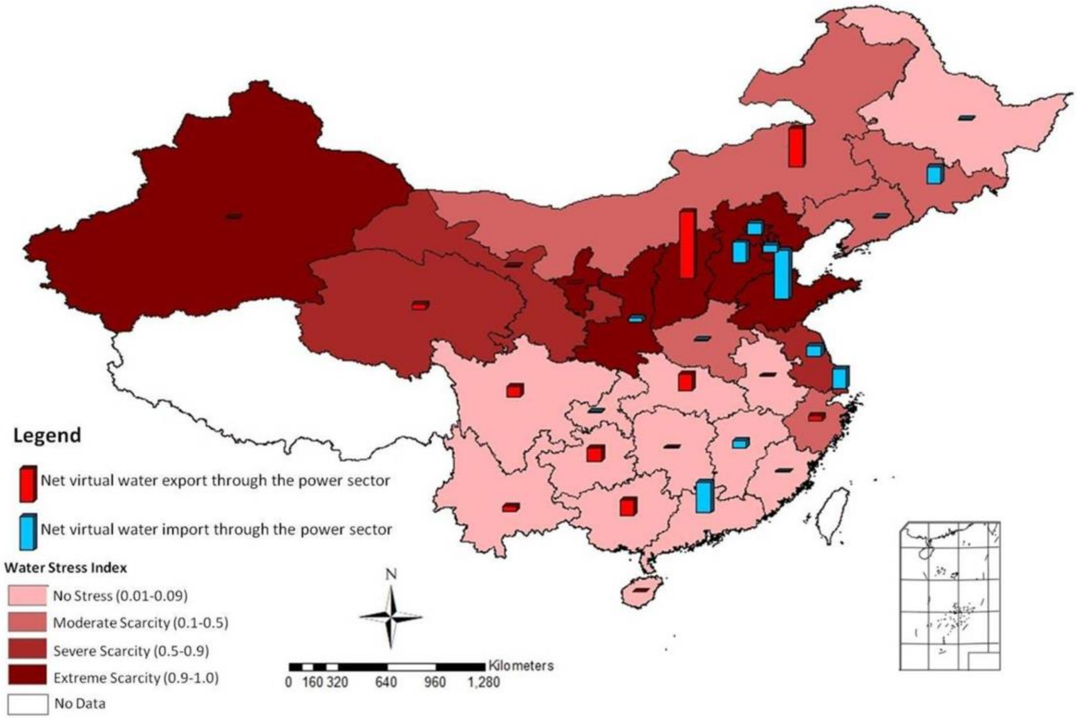

**Fig. 6.** Provincial water scarcities and their net virtual water transfers through the power sector

# Appendix: Supporting Information

## 1. Physical water consumption by thermoelectric power sector in China

To calculate the physical water consumption of China's thermoelectric power sector, this study builds on methods and data from our previous study (Liao *et al.*, 2016). Thermoelectric power's water consumption factor, measured as water consumption per unit of power produced, varies by energy type, boiler technology and, predominantly, cooling technology. As China's coal-fired power production occupies more than 95% of China's thermoelectric power production, we focus on coal-fired power plants in our study for the current status and include other energy sources, i.e. natural gas, inland nuclear, to assess future scenarios. Therefore, China's thermoelectric power production's water consumption can be calculated by the equation below:

$W_{it} = WF_{it} * P_{it}$

Where $WF_{it}$ indicates water consumption factor for thermoelectric power production in province i, which is determined by thermoelectric power plants' cooling technology uptakes, including closed-loop cooling, open-loop cooling and air cooling; $P_{it}$ is province i's thermoelectric power production and Wit is the water consumption for province i's thermoelectric power generation.

Similar to Byers *et al.* (2015), Liao *et al.* (2016) identified the cooling system of China's 1072 coal-fired power plants whose aggregate capacity amounts to 855 GW through Google imagery. For further details, please refer to Liao *et al.* (2016).

Combined Heat and Power is not differentiated in this study because according to self-reported water consumption factor ($m^3$ /MWh) data from over 700 power generation units in 2013 whose total capacity amounts to 342.9 GW, 40% of the national total, coal-fired power generation's total water consumption factor shows greater agreement when organized according to cooling technologies as opposed to turbine types (Table A1). Table A2 shows that CHP units are mainly small units with lower efficiencies, which may result in higher non-cooling water uses.

Table A1: Self-reported water consumption factors by China's coal-fired power plants (CEC 2013a, 2013b)

| Cooling System | Turbine Type | Boiler Type | Average Water Consumption Factor ($m^3$/MWh) | Median values by Macknick *et al.* (2012) ($m^3$/MWh)§ |
|---|---|---|---|---|
| Air cooling | SCT* | Subcritical | 0.79 | 0.32 |
| | CHP | Subcritical | 0.54 | |
| | SCT | Supercritical | 0.45 | |
| | SCT | Ultra-supercritical | 0.43 | |
| Open-loop | SCT | Super High Voltage | 1.19 | 0.39 |
| | CHP | Super High Voltage | 1.57 | |
| | SCT | Subcritical | 1.45 | |
| | CHP | Subcritical | 0.81 | |
| | SCT | Supercritical | 0.62 | |
| | CHP | Supercritical | 0.42 | |
| | SCT | Ultra-supercritical | 0.38 | |
| Closed-loop | CHP | High Voltage | 4.80 | 1.87 |
| | SCT | Super High Voltage | 3.17 | |
| | CHP | Super High Voltage | 3.37 | |
| | SCT | Subcritical | 2.80 | |
| | CHP | Subcritical | 2.48 | |
| | SCT | Supercritical | 2.38 | |
| | CHP | Supercritical | 2.01 | |
| | SCT | Ultra-supercritical | 1.91 | |
| | CHP | Ultra-supercritical | 2.01 | |
| *: SCT: straight condense turbines do not generate heat; CHP: Combined Heat and Power<br>§:Water consumption factors used for estimations in this study | | | | |

Table A2: Boiler type of CHP units and STC (non-heat-generating) units.

| **Boiler type** | **CHP (MW)** | **STC (MW)** | Percentage of CHP units |
|---|---|---|---|
| High Voltage (100-200 MW) | 200 | | 100.0% |
| Super High Voltage (100-200 MW) | 3255 | 4630 | 41.3% |
| Subcritical (300-600 MW) | 41430 | 142600 | 22.5% |
| Supercritical (300-600 MW) | 2700 | 89200 | 2.9% |
| Ultra-supercritical (600 MW -) | 1000 | 57920 | 1.7% |

## 2. Physical water consumption by hydropower production in China

Provincial water consumption of hydropower can be calculated by the equation below:

$W_{ih} = WF_{ih} * P_{ih}$

Where $WF_{ih}$ denotes water consumption factor for hydropower in province i, which is the water evaporated per unit of hydropower produced; $P_{ih}$ is province i's hydropower production and $W_{ih}$ is the water use for province i's hydropower.

Liu *et al.* (2015) calculated the gross evaporation of China's 875 major reservoirs. Among which, 209 have hydropower production and their hydropower production's water consumption factor, $WF_h$, is allocated by economic values of their multiple purposes.

Province i's hydropower production's water consumption factor, $WF_{ih}$, can be extrapolated based on the average $WF_h$ value of all hydropower plants within its territory. For further details, please refer to Liu *et al.* (2016).

As Bakken *et al.* (2017) pointed out, any study on hydropower's water consumption should be used with great caution due to many methodological debates. There are three major limitations should be noted:

1, Liu *et al.* (2016) used gross evaporation instead of net evaporation (subtracting evaporation from the original rivers or lakes before the reservoirs are constructed), it may therefore exaggerate the impacts of constructing the reservoirs on local water resources. This may also explain why our results of China’s hydropower’s water consumption exceeded that of thermoelectric power markedly.

2, Liu *et al.* (2016) allocated multi-purpose reservoirs’ water consumption to hydropower production by economic values. Consequently, many other values, e.g. social values of entertainment, were neglected. Therefore, hydropower may be assigned larger share of water consumption.

3, Neither the increase of blue water during dry seasons by building reservoirs nor the returned water after evaporation due to reservoirs’ microclimate is considered by Liu *et al.* (2016) and both may contribute to the overestimation of reservoirs’ water losses.

4, There is no additional evaporation considered with run-of-river hydropower. However, they are not considered in this study. Using solely hydropower reservoirs’ water consumption to calculate the provincial hydropower water consumption factor may result in overestimation.

**Table A3.** Physical water consumption by hydropower production in China

| Province | Hydropower's Water Consumption Factor [m$^3$/GJ] | 2002 | 2007 | 2010 | 2002 | 2007 | 2010 | 2002 | 2007 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Hydropower production (0.1 billion kWh) | | | Hydropower production (million GJ) | | | Hydropower water use (million m$^3$) | | |
| Anhui | 9.64 | 10.51 | 19.67 | 18.85 | 3.78 | 7.08 | 6.79 | 36.47 | 68.26 | 65.42 |
| Beijing | 21.6 | 4.1 | 4.93 | 4.4 | 1.48 | 1.77 | 1.58 | 31.88 | 38.34 | 34.21 |
| Chongqing | 3.47 | 37.48 | 83.75 | 169.25 | 13.49 | 30.15 | 60.93 | 46.77 | 104.52 | 211.22 |
| Fujian | 2.62 | 224.35 | 311.59 | 453.69 | 80.77 | 112.17 | 163.33 | 211.21 | 293.34 | 427.12 |
| Gansu | 2.09 | 105.74 | 189.08 | 262.32 | 38.07 | 68.07 | 94.44 | 79.61 | 142.35 | 197.48 |
| Guangdong | 4.24 | 108.62 | 241.03 | 348.86 | 39.1 | 86.77 | 125.59 | 165.78 | 367.88 | 532.46 |
| Guangxi | 8.31 | 184.12 | 323.52 | 475.26 | 66.28 | 116.47 | 171.09 | 550.56 | 967.39 | 1421.12 |
| Guizhou | 4.04 | 221.53 | 340.62 | 416.58 | 79.75 | 122.62 | 149.97 | 322.1 | 495.26 | 605.71 |
| Hainan | 17 | 13.74 | 13.09 | 13.34 | 4.95 | 4.71 | 4.8 | 84.09 | 80.11 | 81.64 |
| Hebei | 20.41 | 3.64 | 5.68 | 5.55 | 1.31 | 2.04 | 2 | 26.74 | 41.73 | 40.78 |
| Henan | 4.43 | 15.52 | 88.53 | 91.67 | 5.59 | 31.87 | 33 | 24.77 | 141.29 | 146.3 |
| Hubei | 2.14 | 272.58 | 937.7 | 1263.83 | 98.13 | 337.57 | 454.98 | 209.57 | 720.93 | 971.66 |
| Hunan | 3.72 | 227.93 | 312.56 | 502.53 | 82.05 | 112.52 | 180.91 | 305.33 | 418.7 | 673.19 |
| Inner Mongolia | 260.9 | 6.69 | 11.86 | 16.29 | 2.41 | 4.27 | 5.86 | 628.35 | 1113.94 | 1530.02 |
| Jiangxi | 10.17 | 61.51 | 85.06 | 117.85 | 22.14 | 30.62 | 42.43 | 225.1 | 311.29 | 431.29 |
| Jilin | 6.35 | 44.57 | 61.83 | 105.5 | 16.05 | 22.26 | 37.98 | 101.89 | 141.34 | 241.17 |
| Liaoning | 9.98 | 14.46 | 43.81 | 43.98 | 5.21 | 15.77 | 15.83 | 51.94 | 157.36 | 157.97 |
| Ningxia | 0.1 | 7.78 | 17.47 | 18.02 | 2.8 | 6.29 | 6.49 | 0.28 | 0.63 | 0.65 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Qinghai | 3.05 | 88.97 | 207.76 | 371.11 | 32.03 | 74.79 | 133.6 | 97.72 | 228.19 | 407.59 |
| Shaanxi | 2.44 | 25.92 | 55.45 | 87.24 | 9.33 | 19.96 | 31.41 | 22.74 | 48.65 | 76.54 |
| Shandong | 2.16 | 0.01 | 0.77 | 2.14 | 0 | 0.28 | 0.77 | 0.01 | 0.6 | 1.67 |
| Shanxi | 263.5 | 18.83 | 47.32 | 36.63 | 6.78 | 17.04 | 13.19 | 1786.21 | 4488.77 | 3474.72 |
| Sichuan | 1.81 | 409.85 | 814.13 | 1213.42 | 147.55 | 293.09 | 436.83 | 267.75 | 531.86 | 792.7 |
| Xinjiang | 4.97 | 29.21 | 58.84 | 97.08 | 10.52 | 21.18 | 34.95 | 52.31 | 105.36 | 173.84 |
| Yunnan | 1.36 | 209.24 | 430.95 | 814.12 | 75.33 | 155.14 | 293.08 | 102.75 | 211.62 | 399.77 |
| Zhejiang | 18.06 | 95.29 | 118.15 | 230.85 | 34.3 | 42.53 | 83.11 | 619.69 | 768.35 | 1501.27 |
| Jiangsu | 18.06 | 2.98 | 2.95 | 1.03 | 1.07 | 1.06 | 0.37 | 19.38 | 19.18 | 6.7 |
| Heilongjiang | 8.16 | 22.53 | 10.41 | 15.09 | 8.11 | 3.75 | 5.43 | 66.21 | 30.59 | 44.35 |

## 3. Provincial and regional water consumption for power production (million m³)

**Table A4.** Provincial and regional water consumption for power production (million m³)

| million m³ | 2002 | | 2007 | | 2010 | | | 2002 | | | 2007 | | | 2010 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Thermo | Hydro | Thermo | Hydro | Thermo | Hydro | | Thermo | Hydro | Total | Thermo | Hydro | Total | Thermo | Hydro | Total |
| Beijing | 25.47 | 31.88 | 41.73 | 38.34 | 48.96 | 34.21 | N | 531.06 | 1844.84 | 2375.90 | 949.91 | 4569.44 | 5519.35 | 1031.89 | 3551.38 | 4583.27 |
| Tianjin | 45.61 | 0.00 | 65.26 | 0.00 | 82.90 | 0.00 | | | | | | | | | | |
| Hebei | 155.32 | 26.74 | 223.01 | 41.73 | 251.51 | 40.78 | | | | | | | | | | |
| Shanxi | 94.40 | 1786.21 | 169.71 | 4488.77 | 159.89 | 3474.72 | | | | | | | | | | |
| Shandong | 210.27 | 0.01 | 450.20 | 0.60 | 488.64 | 1.67 | | | | | | | | | | |
| Inner Mongolia | 60.47 | 628.35 | 216.98 | 1113.94 | 245.51 | 1530.02 | NE | 247.47 | 848.39 | 1095.86 | 515.89 | 1443.23 | 1959.12 | 579.09 | 1973.50 | 2552.60 |
| Liaoning | 79.43 | 51.94 | 126.80 | 157.36 | 147.94 | 157.97 | | | | | | | | | | |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jilin | 38.10 | 101.89 | 64.20 | 141.34 | 69.84 | 241.17 | | | | | | | | | | |
| Heilongjiang | 69.47 | 66.21 | 107.91 | 30.59 | 115.80 | 44.35 | | | | | | | | | | |
| Shanghai | 40.12 | 0.00 | 43.57 | 0.00 | 44.16 | 0.00 | E | 219.68 | 886.75 | 1106.43 | 463.16 | 1149.14 | 1612.30 | 635.81 | 2000.50 | 2636.30 |
| Jiangsu | 76.16 | 19.38 | 196.03 | 19.18 | 242.45 | 6.70 | | | | | | | | | | |
| Zhejiang | 29.28 | 619.69 | 81.36 | 768.35 | 122.92 | 1501.27 | | | | | | | | | | |
| Anhui | 62.08 | 36.47 | 109.21 | 68.26 | 180.38 | 65.42 | | | | | | | | | | |
| Fujian | 12.03 | 211.21 | 32.98 | 293.34 | 45.90 | 427.12 | | | | | | | | | | |
| Jiangxi | 18.26 | 225.10 | 49.05 | 311.29 | 69.50 | 431.29 | C | 258.52 | 1079.29 | 1337.82 | 569.41 | 2228.58 | 2798.00 | 699.16 | 3226.36 | 3925.52 |
| Henan | 146.97 | 24.77 | 317.76 | 141.29 | 371.70 | 146.30 | | | | | | | | | | |
| Hubei | 24.06 | 209.57 | 56.66 | 720.93 | 71.92 | 971.66 | | | | | | | | | | |
| Hunan | 7.71 | 305.33 | 29.72 | 418.70 | 41.19 | 673.19 | | | | | | | | | | |
| Chongqing | 8.11 | 46.77 | 32.34 | 104.52 | 38.23 | 211.22 | | | | | | | | | | |
| Sichuan | 53.42 | 267.75 | 83.89 | 531.86 | 106.63 | 792.70 | | | | | | | | | | |
| Guangdong | 76.56 | 165.78 | 157.77 | 367.88 | 187.58 | 532.46 | S | 174.34 | 1225.28 | 1399.62 | 431.90 | 2122.26 | 2554.16 | 515.82 | 3040.70 | 3556.52 |
| Guangxi | 4.82 | 550.56 | 27.20 | 967.39 | 39.51 | 1421.12 | | | | | | | | | | |
| Hainan | 1.42 | 84.09 | 3.96 | 80.11 | 5.36 | 81.64 | | | | | | | | | | |
| Guizhou | 60.89 | 322.10 | 154.41 | 495.26 | 181.21 | 605.71 | | | | | | | | | | |
| Yunnan | 30.65 | 102.75 | 88.55 | 211.62 | 102.15 | 399.77 | | | | | | | | | | |
| Shaanxi | 41.19 | 22.74 | 73.85 | 48.65 | 114.42 | 76.54 | NW | 154.10 | 252.65 | 406.75 | 294.01 | 525.18 | 819.19 | 372.69 | 856.11 | 1228.80 |
| Gansu | 43.81 | 79.61 | 71.39 | 142.35 | 71.10 | 197.48 | | | | | | | | | | |
| Qinghai | 9.45 | 97.72 | 18.68 | 228.19 | 18.17 | 407.59 | | | | | | | | | | |
| Ningxia | 30.53 | 0.28 | 68.38 | 0.63 | 73.43 | 0.65 | | | | | | | | | | |
| Xinjiang | 29.13 | 52.31 | 61.72 | 105.36 | 95.57 | 173.84 | | | | | | | | | | |

(Note: N – North; NE – Northeast; E – East; C – Central; S – South; NW – Northwest)

## 4. Categorization of sectors and provinces

The sectors of this input-output analysis are categorized as below:

**Table A5.** Categorization of sectors and provinces

| Tier 1 Classification | Tier 2 Classification | Tier 1 Classification | Tier 2 Classification |
|---|---|---|---|
| Agriculture | Agriculture, Forestry, Husbandry and Fishery | Construction | Construction |
| Mining | Coal Mining and Dressing | Power Provision | Power and Heat Production and Provision |
| | Oil and Natural Gas Mining | Services | Gas and Water Production and Provision |
| | Metal Mining and Dressing | | Transport and Storage |
| | Non-Metal and Other Mining and Dressing | | Wholesale and Retail |
| Manufacturing | Food and Tobacco | | Accomodation and Catering |
| | Textile | | Rental and Commercial Service |
| | Cloth, Footwear and Leather Products | | Research and Experimental Development |
| | Timber and Furniture | | Other Services |
| | Paper, Cultural, Educational and Sports Products | | |
| | Petroleum processing, coking and nuclear fuel processing | | |
| | Chemical Industry | | |
| | Non-metalic Mineral Products | | |
| | Smelting and Pressing of Metals | | |

| | |
|---|---|
| | Metalic Mineral Products |
| | General and Special Equipment Manufacturing |
| | Transport Equipment |
| | Electric Machinery and Equipment |
| | Communication, Computer and Other Electronic Equipment |
| | Instruments, Meters and other cultural, office equipment |
| | Other Manufacturing |

**Table A6.** Sector aggregation between water use statistic data and MRIO tables

| **Industry** | **Sectors in China Economic Year Book 2008** | **Sectors in MRIO tables** |
|---|---|---|
| Primary | Agriculture | Agriculture |
| Secondary | Coal Mining and Dressing | Coal Mining and Dressing |
| | Petroleum and Natural Gas Extraction | Petroleum and Natural Gas Extraction |
| | Ferrous Metals Mining and Dressing | Metals Mining and Dressing |
| | Nonferrous Metals Mining and Dressing | |
| | Non-metal Minerals Mining and Dressing | Non-metal Minerals Mining and Dressing |
| | Other Minerals Mining and Dressing | |
| | Food Processing | Food and Tobacco Processing |
| | Food Production | |
| | Beverage Production | |
| | Tobacco Processing | |
| | Textile Industry | Textile Industry |
| | Garments and Other Fibre Products | Garments, Leather, Furs, Down and Related Products |

| | | |
|---|---|---|
| | Leather, Furs, Down and Related Products | |
| | Timber Processing, Bamboo, Cane, Palm & Straw Products | Timber Processing and Furniture Manufacturing |
| | Furniture Manufacturing | |
| | Papermaking and Paper Products | Papermaking, Cultural, Educational and Sports Articles |
| | Printing and Record Medium Reproduction | |
| | Cultural, Educational and Sports Articles | |
| | Petroleum Processing and Coking | Petroleum Processing and Coking |
| | Raw Chemical Materials and Chemical Products | Chemicals |
| | Medical and Pharmaceutical Products | |
| | Chemical Fibre | |
| | Rubber Products | |
| | Plastic Products | |
| | Non-metal Mineral Products | Non-metal Mineral Products |
| | Smelting and Pressing of Ferrous Metals | Smelting and Pressing of Metals |
| | Smelting and Pressing of Nonferrous Metals | |
| | Metal Products | Metal Products |
| | Ordinary Machinery | General and Specialized Machinery |
| | Equipment for Special Purpose | |
| | Transportation Equipment | Transportation Equipment |
| | Electric Equipment and Machinery | Electric Equipment and Machinery |
| | Electronic and Telecommunications Equipment | Electronic and Telecommunications Equipment |
| | Instruments, Meters Cultural and Office Machinery | Instruments, Meters Cultural and Office Machinery |
| | Other Manufacturing Industry | Other Manufacturing Products |
| | Scrap and waste | |
| | Electric Power, Steam and Hot Water Production and Supply | Electricity and Heating Power Production and Supply |

| | | |
|---|---|---|
| | Gas Production and Supply | Gas and Water Production and Supply |
| | Tap Water Production and Supply | |
| Tertiary | Construction | Construction |
| | Freight Transport and Warehousing | Freight Transport and Warehousing |
| | Wholesale and Retail Trade | Wholesale and Retail Trade |
| | Hotels, Food and Beverage Places | Hotels, Food and Beverage Places |
| | Real Estate and Social Services | Real Estate and Social Services |
| | Scientific Research | Scientific Research |
| | Other Services | Other Services |

## 5. Provincial distribution of sectoral power demands (%)

Nationally speaking, final sectors consume the largest proportion of electric power supplied: 39.9%, in 2010. The remainder of electricity was used by industries, in the following proportions: Services (27.8%), Manufacturing (25.5%), Mining (5.5%) and Agriculture (1.3%). Consumption of virtual water in electricity (VWE) follows these proportions. It should be noted there are significant regional variations in terms of the distribution of sectoral power demands and associated virtual water consumption. In provinces (cities) like Beijing, the final sectors, e.g. households, constitute the dominant power consumer, occupying over 60% of the total power demand, while in provinces like Liaoning, manufacturing makes up almost 70% of the power demands.

**Table A7.** Provincial distribution of sectoral power demands (%)

|  | 2002 |  |  |  |  |  | 2007 |  |  |  |  |  | 2010 |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Agriculture | Mining | Manufacture | Construction | Final Sector | Service | Agriculture | Mining | Manufacture | Construction | Final Sector | Service | Agriculture | Mining | Manufacture | Construction | Final Sector | Service |
| Beijing | 1.98 | 2.55 | 15.91 | 2.79 | 59.74 | 17.04 | 1.39 | 0.6 | 19.75 | 2.16 | 67.83 | 8.27 | 1.01 | 1.89 | 20.65 | 2.22 | 62.25 | 11.98 |
| Tianjin | 0.87 | 2.48 | 16.38 | 1.01 | 65.27 | 13.99 | 1.9 | 4.73 | 30.51 | 2.56 | 50.81 | 9.48 | 1.31 | 9.95 | 27.75 | 5.78 | 41.21 | 13.99 |
| Hebei | 1.29 | 10.93 | 20.55 | 2.99 | 50.23 | 14.01 | 0.88 | 23.22 | 20.81 | 2.2 | 45.91 | 6.98 | 0.82 | 30.24 | 17.65 | 3.8 | 39.79 | 7.69 |
| Shanxi | 1.63 | 2.88 | 18.12 | 23.56 | 20.01 | 33.8 | 1.36 | 2.05 | 23.78 | 28.18 | 17.61 | 27.01 | 1.72 | 1.52 | 9.16 | 16.9 | 37.24 | 33.45 |
| Inner Mongolia | 4.53 | 5.91 | 17.75 | 20.87 | 28.35 | 22.6 | 1.82 | 2.15 | 24.56 | 20.49 | 23.41 | 27.58 | 1.87 | 1.4 | 17.33 | 27.74 | 33.21 | 18.46 |
| Liaoning | 4.61 | 4.21 | 27.5 | 8.4 | 25.18 | 30.1 | 1.6 | 6.39 | 43.73 | 8.19 | 12.27 | 27.82 | 0.97 | 9.29 | 45.71 | 12.3 | 15.8 | 15.92 |
| Jilin | 1.55 | 5.9 | 47.73 | 8.18 | 7.78 | 28.85 | 0.78 | 0.81 | 10.2 | 1.96 | 80.56 | 5.7 | 0.36 | 1.01 | 12.44 | 5.58 | 74.09 | 6.52 |
| Heilongjiang | 0.98 | 8.65 | 53.17 | 4.4 | 13.92 | 18.87 | 1.75 | 3.91 | 34.3 | 5 | 33.51 | 21.53 | 1.56 | 3.93 | 33.81 | 6 | 31.03 | 23.67 |
| Shanghai | 2.35 | 1.71 | 53.65 | 2.05 | 14.26 | 25.98 | 2.49 | 6.43 | 35.7 | 1.13 | 46.78 | 7.47 | 1.33 | 8.91 | 29.52 | 0.59 | 51.96 | 7.69 |
| Jiangsu | 21.2 | 0.77 | 29.18 | 9.64 | 21.89 | 17.32 | 1.7 | 13.71 | 57.55 | 4.42 | 15.19 | 7.43 | 1.39 | 19.43 | 51.94 | 3.36 | 15.03 | 8.85 |
| Zhejiang | 1.86 | 0.65 | 47.48 | 14.4 | 13.6 | 22.02 | 1.24 | 2.79 | 57.42 | 10.6 | 17.97 | 9.98 | 0.79 | 3.5 | 47.66 | 15.48 | 18.96 | 13.6 |
| Anhui | 3.24 | 1.65 | 49.42 | 9.86 | 17.68 | 18.15 | 3.61 | 4.62 | 41.64 | 9.06 | 11.78 | 29.29 | 1.97 | 6.02 | 43.31 | 14.08 | 15.22 | 19.39 |
| Fujian | 2.05 | 3.08 | 51.78 | 7.61 | 25.66 | 9.82 | 1.71 | 1.49 | 43.26 | 8.27 | 18.53 | 26.75 | 0.99 | 1.54 | 32.55 | 11.31 | 37.54 | 16.08 |
| Jiangxi | 4.24 | 1.36 | 34.38 | 17.26 | 12.66 | 30.1 | 1.5 | 1.99 | 16.26 | 15.84 | 53.55 | 10.86 | 0.58 | 0.9 | 16.5 | 15.32 | 59.28 | 7.41 |
| Shandong | 16.63 | 0.77 | 33.73 | 11.07 | 20.3 | 17.5 | 0.75 | 0.34 | 11.64 | 2.49 | 81.31 | 3.47 | 0.74 | 0.36 | 13.68 | 3.84 | 78.89 | 2.49 |
| Heinan | 6.7 | 3.08 | 35.12 | 11.16 | 18.95 | 24.99 | 1.92 | 5.4 | 31.31 | 7.7 | 42.45 | 11.21 | 1.73 | 5.6 | 31.98 | 9.03 | 40.53 | 11.12 |
| Hubei | 2.52 | 4.63 | 33.21 | 16.5 | 19.3 | 23.85 | 3.91 | 4.54 | 41.2 | 16.61 | 15.11 | 18.63 | 2.23 | 5.58 | 32.23 | 19.99 | 19.56 | 20.42 |
| Hunan | 3.24 | 2.4 | 36.19 | 25.44 | 10.52 | 22.21 | 2.72 | 5.32 | 26.52 | 12.65 | 31.29 | 21.51 | 2.58 | 3.57 | 27.63 | 18.11 | 26.01 | 22.11 |
| Guangdong | 4.9 | 1.16 | 39.41 | 8.26 | 15.64 | 30.63 | 1.44 | 8.6 | 44.71 | 7.56 | 30 | 7.69 | 0.83 | 10.24 | 41.89 | 9.29 | 32.13 | 5.62 |
| Guangxi | 2.33 | 1.62 | 39.03 | 19.59 | 14.54 | 22.89 | 2.65 | 5.05 | 16.58 | 19.58 | 21.71 | 34.43 | 1.44 | 1.6 | 17.97 | 24.95 | 36.86 | 17.18 |
| Hainan | 12.28 | 1.31 | 47.41 | 8.97 | 2.86 | 27.16 | 2.44 | 2.39 | 14.69 | 46.73 | 10.89 | 22.86 | 1.29 | 3.62 | 15.06 | 46.69 | 9.47 | 23.87 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chongqing | 2.7 | 1.12 | 38.86 | 13.94 | 12.85 | 30.52 | 1.84 | 4.83 | 28.33 | 12.64 | 37.02 | 15.35 | 2.18 | 5.73 | 25.05 | 28.25 | 29.61 | 9.18 |
| Sichuan | 4.29 | 1.45 | 22.97 | 25.64 | 17.78 | 27.87 | 3.09 | 1.96 | 25.92 | 15.7 | 33.12 | 20.22 | 3.9 | 2.44 | 32.31 | 19.04 | 20.3 | 22.01 |
| Guizhou | 7.18 | 3.09 | 35.9 | 29.52 | 12.07 | 12.24 | 2.77 | 3.12 | 20.17 | 15.39 | 24.82 | 33.73 | 2.33 | 1.17 | 13.8 | 22.35 | 23.07 | 37.28 |
| Yunnan | 7.7 | 1.03 | 35.23 | 18.24 | 13.37 | 24.42 | 4.75 | 3.52 | 29.24 | 17.85 | 22.21 | 22.42 | 3.4 | 2.54 | 24.43 | 22.59 | 34.59 | 12.45 |
| Shaanxi | 4.25 | 4.41 | 59.19 | 6.51 | 4.9 | 20.74 | 2.2 | 1.84 | 39.77 | 4.79 | 35.14 | 16.25 | 1.82 | 2.47 | 32.97 | 7.91 | 40.13 | 14.7 |
| Gansu | 6.14 | 4.31 | 45.71 | 8.97 | 12.27 | 22.59 | 2.84 | 14.87 | 14.18 | 16.43 | 24.24 | 27.44 | 3.71 | 28.79 | 12.31 | 20.56 | 18.99 | 15.63 |
| Qinghai | 4.26 | 3.65 | 35.29 | 37.3 | 8.44 | 11.07 | 1.36 | 6.76 | 19.36 | 12.78 | 45.3 | 14.44 | 3.53 | 2.14 | 8.8 | 21.14 | 43.27 | 21.13 |
| Ningxia | 2.35 | 6.16 | 48.9 | 18.65 | 6.84 | 17.1 | 1.62 | 4.28 | 29.53 | 16.05 | 26.9 | 21.61 | 0.94 | 8.23 | 22.91 | 26.91 | 27.16 | 13.85 |
| Xinjiang | 1.89 | 0.09 | 27.71 | 19.01 | 18.13 | 33.18 | 3.63 | 1.01 | 28.77 | 10.22 | 15.87 | 40.51 | 4.27 | 0.7 | 22.36 | 11.62 | 40.83 | 20.22 |

## 6. Provincial and regional virtual water embodiments in power demands (million $m^3$)

**Table A8.** Provincial and regional virtual water embodiments in power demands (million $m^3$)

| Million $m^3$ | 2002 | | 2007 | | 2010 | | | 2002 | | | 2007 | | | 2010 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | VWEI | VWEF | VWEI | VWEF | VWEI | VWEF | | VWEI | VWEF | Total | VWEI | VWEF | Total | VWEI | VWEF | Total |
| Beijing | 91.84 | 368.85 | 144.90 | 305.51 | 165.42 | 272.77 | N | 1520.04 | 1101.59 | 2621.63 | 2880.64 | 2876.59 | 5757.23 | 2317.19 | 2905.17 | 5222.36 |
| Tianjin | 85.28 | 160.25 | 152.82 | 157.88 | 191.67 | 134.34 | | | | | | | | | | |
| Hebei | 310.34 | 313.23 | 529.41 | 449.33 | 547.85 | 362.01 | | | | | | | | | | |
| Shanxi | 838.85 | 209.89 | 1684.77 | 360.12 | 999.44 | 593.11 | | | | | | | | | | |
| Shandong | 193.73 | 49.36 | 368.74 | 1603.75 | 412.82 | 1542.94 | | | | | | | | | | |
| Inner Mongolia | 250.14 | 98.97 | 244.05 | 74.60 | 395.66 | 196.71 | NE | 627.74 | 172.88 | 800.63 | 719.34 | 744.77 | 1464.11 | 1016.25 | 894.61 | 1910.86 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Liaoning | 116.47 | 39.21 | 230.98 | 32.32 | 279.21 | 52.41 | | | | | | | | | | |
| Jilin | 97.32 | 8.21 | 141.38 | 585.97 | 204.11 | 583.72 | | | | | | | | | | |
| Heilongjiang | 163.82 | 26.49 | 102.93 | 51.88 | 137.27 | 61.77 | | | | | | | | | | |
| Shanghai | 115.12 | 19.15 | 223.55 | 196.52 | 297.96 | 322.30 | E | 988.09 | 206.67 | 1194.76 | 1810.92 | 516.77 | 2327.69 | 2471.72 | 902.02 | 3373.75 |
| Jiangsu | 125.06 | 35.05 | 406.68 | 72.85 | 502.52 | 88.92 | | | | | | | | | | |
| Zhejiang | 495.19 | 77.93 | 753.92 | 165.11 | 1154.26 | 270.13 | | | | | | | | | | |
| Anhui | 97.19 | 20.87 | 157.34 | 21.01 | 213.56 | 38.34 | | | | | | | | | | |
| Fujian | 155.52 | 53.67 | 269.44 | 61.28 | 303.43 | 182.33 | | | | | | | | | | |
| Jiangxi | 205.58 | 29.79 | 267.24 | 308.03 | 283.24 | 412.27 | C | 1097.53 | 197.55 | 1295.08 | 1649.68 | 934.22 | 2583.90 | 2282.47 | 1148.94 | 3431.41 |
| Henan | 176.67 | 41.30 | 264.18 | 194.90 | 353.98 | 241.26 | | | | | | | | | | |
| Hubei | 153.82 | 36.79 | 384.48 | 68.45 | 456.87 | 111.13 | | | | | | | | | | |
| Hunan | 275.71 | 32.41 | 303.05 | 137.99 | 507.28 | 178.30 | | | | | | | | | | |
| Chongqing | 65.92 | 9.72 | 125.22 | 73.59 | 195.53 | 82.26 | | | | | | | | | | |
| Sichuan | 219.83 | 47.53 | 305.51 | 151.27 | 485.57 | 123.71 | | | | | | | | | | |
| Guangdong | 314.98 | 58.42 | 838.35 | 359.33 | 1121.27 | 530.84 | S | 1181.69 | 182.65 | 1364.34 | 1732.09 | 610.05 | 2342.14 | 2313.44 | 1104.31 | 3417.76 |
| Guangxi | 402.16 | 68.44 | 488.09 | 135.34 | 621.38 | 362.76 | | | | | | | | | | |
| Hainan | 94.03 | 2.77 | 59.70 | 7.30 | 62.86 | 6.58 | | | | | | | | | | |
| Guizhou | 244.21 | 33.52 | 208.77 | 68.92 | 281.41 | 84.37 | | | | | | | | | | |
| Yunnan | 126.31 | 19.50 | 137.18 | 39.17 | 226.52 | 119.77 | | | | | | | | | | |
| Shaanxi | 113.15 | 5.83 | 135.78 | 73.58 | 179.15 | 120.06 | NW | 400.21 | 45.73 | 445.94 | 545.44 | 241.61 | 787.05 | 726.09 | 400.78 | 1126.87 |
| Gansu | 113.39 | 15.86 | 127.34 | 40.74 | 197.44 | 46.28 | | | | | | | | | | |
| Qinghai | 75.37 | 6.95 | 104.25 | 86.34 | 144.00 | 109.84 | | | | | | | | | | |
| Ningxia | 31.58 | 2.32 | 41.05 | 15.11 | 54.17 | 20.19 | | | | | | | | | | |
| Xinjiang | 66.71 | 14.77 | 137.02 | 25.84 | 151.33 | 104.41 | | | | | | | | | | |

## 7. Future scenarios

### Future input-output tables

We use China's multi-regional input-output table of 2030 from Zhao *et al.* (2016). There are a few methods to develop input-output tables for a future year and Zhao *et al.* (2016) applied a branch of the RAS method named GRAS, which was first proposed by Gunluk-Senesen and Bates (1988). For detailed information please refer to Zhao *et al.* (2016).

An input-output table constitutes inter-industry table, primary inputs and final sectors. An Environmental Extended Input-output table includes natural resources as primary inputs.

To incorporate scenarios of the power sector's water use, we only consider the changes of the primary water inputs to the power sector according to different scenarios on the energy sector's energy and water efficiencies and energy portfolios as in Liao *et al.* (2016). Due to data paucity, changes in the whole economy's structure and upstream supplies to the power sector, e.g. biofuel, cannot be accounted.

### Future physical water consumption in the power sector

This section recaps method in section 1 and 2. Thermoelectric power and hydropower's water consumption is estimated by multiplying power production and water consumption factors. Future thermoelectric, hydropower productions and corresponding water consumption factors in 2030 under different scenarios are from Liao *et al.* (2016).

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