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Liao, X, Zhao, X, Liu, W et al. (4 more authors) (2020) Comparing water footprint and water scarcity footprint of energy demand in China’s six megacities. Applied Energy, 269. 115137. ISSN 0306-2619

https://doi.org/10.1016/j.apenergy.2020.115137

Comparing Water Footprint and Water Scarcity Footprint of Energy Demand in China's Six Megacities[1]

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ABSTRACT

Water is required throughout the life-cycle processes of energy production to meet the growing energy demands in China's megacities. However, the spatially explicit impact on water scarcity both inside and outside the megacity boundaries from megacities' energy demands remains unknown. We quantified and compared the water footprint and water scarcity footprint for final energy demand (WFE and WSFE) in China's megacities from a consumption perspective. Six acknowledged megacities, i.e. Beijing, Tianjin, Shanghai, Chongqing, Shenzhen and Guangzhou, were evaluated with an extended multi-region input-output model. The results showed that these megacities were endowed with only 2.60% of the national available water resources, but their WFE (WSFE) made up nearly 14.00% (13.50%) of the national total. The megacities located in Northern China generated a larger WSFE in their WFE than the cities in Southern China. Energy demands in these megacities were heavily dependent on scarce water sourced from beyond their administrative boundaries, together importing 84.10% of WSFE from elsewhere. Electricity demand dominated the volumetric water consumption, representing 52.00% of the WFE. The distribution was different for scarce water consumption, with coal demand generating 34.00% of total WSFE, followed by electricity (31.00%) and petroleum (26.00%). Although Northern China is faced with dire water scarcity, its scarce water is still being predominantly outsourced to support energy demands in both Northern and Southern megacities, mainly due to their coal and petroleum reserves. Location-specific pathways and foci should be applied for different megacities to decouple their energy demands and their scarce water consumption.

Keywords: Input-output analysis; Virtual water; Virtual scarce water; Water-energy nexus

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[1] The short version of the paper with **paper ID 184** was presented by Xiawei Liao at CUE2019, Oct 16-18, Xiamen, China. This paper is a substantial extension of the short version of the conference paper.

1. Introduction

Rapid urbanization, especially in global south, has created many large urban areas with populations in excess of 10 million inhabitants, i.e. megacities. A research on 27 of world's megacities showed that energy supply is a major limiting factor in the development of megacities [1]. To meet growing energy demands in megacities, a critical issue is the amount of water required throughout the life-cycle processes of energy production. This could be the water used for coal mining and dressing, or for condensing steam in thermoelectric power plants [2-5]. Moreover, most of this water is sourced outside the city boundary [6]. Such reliance on external water resources may introduce risk to future urban energy supply when water resources are overexploited in water stressed regions [7]. Freshwater resource is already identified as the main risk facing humanity during the next decades [8], and megacities usually act as the recipient of large amounts of internal water resources [9], as well as external water resources embodied in traded goods [10-11]. Increasing water consumption as a result of rising energy demand may be compromised by potential water scarcities throughout the life-cycle supply chain, especially under climate change scenarios. These potential conflicts are particularly pronounced in rapidly developing economies such as China, where population growth in megacities and bourgeoning lifestyles are exerting increasing environmental pressures both within and beyond city boundaries [12]. More importantly, megacities in emerging economies are typically at varying states of economic development, have different economic structures and water endowments, hence it is difficult to identify a unified pathway to decoupling energy demand and water resource impact.

There has been increasing interest in use of the water footprint concept to analyze the impact of energy demand on water resources [13-14]. The water footprint can be defined as the amount of freshwater consumed to produce certain goods or services for final demand [15]. Water footprint not only measures water consumed inside a geographical boundary to produce products for final demand, i.e. internal water footprint, but also water consumed beyond the geographical boundary to produce products which are then imported and consumed within the geographical boundary, i.e. external water footprint [16]. The water footprint of energy demand (WFE) can thus be defined as the freshwater consumption throughout the life cycle supply chain to meet final energy demands, including electricity generation and fuel production. The WFE has been quantified using a bottom-up approach associated with life-cycle analysis [13], a top-down approach using input-output analysis [17], or a hybrid approach combining input-output data with process analysis [14]. For a comparison between bottom-up and top-down approaches, the reader is referred to the excellent paper by Feng et al. [18]. As far as megacities are concerned, Zhang et al. [19] used a single-region input-output approach to calculate the WFE for the megacity of Shanghai. Applying a consumption perspective, they found around 79% of Shanghai's water use for energy supply occurred beyond Shanghai's city boundary. These previous studies have demonstrated the importance of considering upstream water use and external scarcity risk. However, they only focus on a single region, and no insights are provided for multiple regions at different stages of economic development. Moreover, the volumetric water footprint has the limitation of showing the impact on water scarcity from the contributions of energy demand.

An identical amount of water consumption in exporting regions with different levels of water scarcity may result in different impacts on local water resources [20-21], and can also expose water footprint of final energy demand in importing regions to different levels of vulnerability [22-23]. The water scarcity footprint is therefore a useful indicator that incorporates direct and indirect water scarcity into volumetric water footprint accounting throughout life cycle processes [24-25]. It may be defined as the consumption of "scarce water", i.e. freshwater consumption weighted by water stress index, throughout the life-cycle production processes of certain goods or services [20]. The most important feature of the water scarcity footprint approach is that it enables meaningful comparisons to be made between regions in which water footprint contributes to different internal and external water scarcity [20].

Existing studies calculating the water scarcity footprint of energy demand (WSFE) are rare. We found only two peer-reviewed studies quantifying the WSFE with the bottom-up approach. Djehdian et al. [6] evaluated the water scarcity footprint of electricity generation and fuel production for 69 U.S. cities. Xie et al. [26] quantified the water scarcity footprint of electricity generation for China's provinces. Using bilateral commodity flow data, the bottom-up approach studies only calculated direct scarce water transfers embodied in energy supply, and didn't consider water consumption during the upstream processes of energy production. Focusing on direct water use ignores some important processes contributing to the overall water footprint, for example water used in the production of coal mine props in the agricultural sector [5]. It also incurs double accounting truncation errors [15], for example electricity is used as an intermediate input to fuel production.

To quantify the WSFE throughout life-cycle processes, one of the solutions is to apply an input-output analysis from a consumption perspective [27]. An input-output analysis is a top-down approach applying sectoral monetary transactions to account for industrial interdependencies [28], thus enabling the allocation of all upstream processes to final demand. Ridoutt et al. [25] first coupled the water scarcity footprint with a multi-region input-output (MRIO) model to show how agricultural demand in Australia has an impact on water scarcity around the world. They indicated that development of a water scarcity footprint accounting framework based on a MRIO model can reflect the full supply chain effects of final demand on water scarcity of different regions.

Research by Chai et al. [5] is the only paper we've found quantifying the WSFE using an input-output model. However, this study focused on electricity generation at China's provincial level, and didn't differentiate between internal and external WSFE. As far as we know, no study has applied a MRIO to quantify and compare megacity WSFE through life cycle processes. Comparing the results of different megacities is particularly important for China given the diversity of social-economic-natural characteristics of these massive urban areas. These comparisons will then be able to provide insights into the differing impacts of urbanization on energy demand, internal, and external water scarcity footprint. This in turn will help megacities identify their priorities for water saving actions under complex supply chains.

In this study, we evaluated and compared the WFE and WSFE from a consumption perspective using a refined Chinese MRIO table. Six of China's recognized megacities, namely Beijing, Tianjin, Shanghai, Chongqing, Shenzhen and Guangzhou were included in the case study. Much research work has already been done to investigate the water footprint of energy demand (WFE) for China at national, regional or provincial levels using a MRIO approach [3, 17, 27]. Previous analyses of China's megacities have mainly focused on Beijing, Shanghai, Tianjin and Chongqing as China's four provincial-level municipalities whose input-output data are included in readily available tables [10-11]. In order to present a more comprehensive picture of China's megacities, we developed a more refined MRIO table that includes six of China's recognized megacities. According to the latest statistics, these six megacities are the most populated and economically developed (measured by GDP) megacities in China [29]. They occupy only 1.3% of national geographic area, but are home to over 7.80% of the Chinese population and produce over 17% of its GDP. To support the rapid development of those megacities, China has constructed massive infrastructure systems to improve inter-regional connectivity and utilize natural resources which are abundant in its interior. The three electricity transmission routes supplying electricity from the Northwestern, Central and Southwestern regions to these megacities manifest such development plans [30]. However, before advancing more energy transmission infrastructure projects resulting in virtual water export from these inland regions, it is important to evaluate their induced local water stress. Two useful indicators to enable this are the water scarce footprint for energy demand (WSFE), and virtual scarce water transfers that incorporate local water scarcity into virtual water transfer [10, 21, 31]. These indicators can thus be used to evaluate the impact of megacity energy demand on regional water risk of providing goods and services for energy production.

2. Method and data

2.1 Method

The "Water Embodied in Trade" (WET) approach was applied to calculate the water footprint of China's megacities [18, 32]. The WET approach, derived from the emissions embodied in bilateral trade (EEBT), is a transparent approach allocating all bilateral trade to final consumption [33].

To calculate the water footprint of all sectors, direct water use intensity is introduced as follows:

$$\mathbf{d}^r = \mathbf{w}^r \cdot (\mathbf{x}^r)^{-1} \tag{1}$$

Where $\mathbf{d}^r$ is the direct water use intensity of city r, $\mathbf{w}^r$ is the water consumption of each sector, and $\mathbf{x}^r$ is the total output.

The matrix form of WET can be shown as follows:

$$\begin{bmatrix} \mathbf{W}^{11} & \cdots & \mathbf{W}^{1r} & \cdots & \mathbf{W}^{1u} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbf{W}^{r1} & \cdots & \mathbf{W}^{rr} & \cdots & \mathbf{W}^{ru} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbf{W}^{u1} & \cdots & \mathbf{W}^{ur} & \cdots & \mathbf{W}^{uu} \end{bmatrix} \tag{2}$$

$$= \begin{bmatrix} \hat{\mathbf{d}}^{1} & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & \hat{\mathbf{d}}^{r} & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & \hat{\mathbf{d}}^{u} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{L}^{11} & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{L}^{rr} & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & \mathbf{L}^{uu} \end{bmatrix} \cdot \begin{bmatrix} \hat{\mathbf{y}}^{11} & \cdots & \hat{\mathbf{y}}^{1r} & \cdots & \hat{\mathbf{y}}^{1u} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \hat{\mathbf{y}}^{r1} & \cdots & \hat{\mathbf{y}}^{rr} & \cdots & \hat{\mathbf{y}}^{ru} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \hat{\mathbf{y}}^{u1} & \cdots & \hat{\mathbf{y}}^{ur} & \cdots & \hat{\mathbf{y}}^{uu} \end{bmatrix}$$

Where $\hat{\mathbf{d}}^{r}$ is the diagonal form of $\mathbf{d}^{r}$. $\mathbf{L}^{rr}=(\mathbf{I}-\mathbf{A}^{rr})^{-1}$ is the Leontief inverse matrix of city *r*, $\mathbf{I}$ is the unit matrix, and $\mathbf{A}^{rr}$ represents the technical coefficient of city *r*, showing the requirements of domestically produced products to produce the unit output. $\hat{\mathbf{y}}^{rr}$ is the diagonal form of final demand of city r from the local production of city *r*. $\hat{\mathbf{y}}^{r\mathbf{s}}$ ($s \neq r$, *s from 1 to u*) in diagonal form is the exports of city r to support the final demand of region *s*, while $\hat{\mathbf{y}}^{\mathbf{sr}}$ in diagonal form is the import of city r from region s to support the final demand of city r.

Based on equation (2), we can calculate both the internal and external water footprint of city r, which are expressed as follows:

$$\mathbf{iwf}^{r}=\mathbf{d}^{r}\mathbf{L}^{rr}\mathbf{y}^{rr} \tag{3}$$

$$\mathbf{ewf}^{r}=\sum_{s\neq r}\mathbf{d}^{s}\mathbf{L}^{ss}\mathbf{y}^{sr} \tag{4}$$

Where $\mathbf{iwf}^{r}$ and $\mathbf{ewf}^{r}$ are, respectively, the internal and external water footprint of city *r* for all sectors. $\mathbf{d}^{s}$ is the direct water use intensity of region *s*, and $\mathbf{L}^{ss}$ is the Leontief inverse matrix of region s.

To calculate the water scarcity footprint, we first derive a direct water scarcity use intensity, which is the multiplication of the direct water use intensity with its regional Water Stress Index (*wsi*), i.e. $\mathbf{s} = wsi \cdot \mathbf{w} \cdot (\mathbf{x})^{-1}$. Hence the internal and external water scarcity footprints may be expressed as follows:

$$\mathbf{iwsf}^{r}=\mathbf{s}^{r}\mathbf{L}^{rr}\mathbf{y}^{rr} \tag{5}$$

$$\mathbf{ewsf}^{r}=\sum_{s\neq r}\mathbf{s}^{s}\mathbf{L}^{ss}\mathbf{y}^{sr} \tag{6}$$

Where $\mathbf{iwsf}^p$ and $\mathbf{ewsf}^p$ are, respectively, the internal and external water footprints of city *p* for all sectors, and $\mathbf{s}^p$ and $\mathbf{s}^q$ are the direct water scarcity use intensities of city *p* and region *q*.

The Water Stress Index was calculated according to Pfister et al. [34], which was adapted from the water withdrawal-to-availability indicator by applying a logistic function to acquire continuous values between 0.01 and 1. The equation may be shown as follows:

$$WSI = \frac{1}{1 + e^{-6.4 \cdot WTA^*}\left(\frac{1}{0.01} - 1\right)} \tag{7}$$

Where *WSI* is the water stress index. The *WTA* indicator is the well-known water-to-availability indicator, and *WTA** is a modified *WTA* indicator considering the difference for watersheds with and without strongly regulated flows.

The global grid level of the *WSI* was acquired through Pfister et al. [34]. The WSI values for the provincial and megacity levels in China were then aggregated using an arithmetic average of grid WSI for the province or megacity [21]. Four levels of water stress were classified in the WSI, i.e. Minor (0.01-0.09); Moderate (0.09-0.5); Severe (0.5-0.91); and Extreme (0.91-1).

Amongst the 30 economic sectors included in the MRIO tables (Table A1), five sectors relating to the production of energy products for final energy demand are 'Coal Mining and Dressing', 'Petroleum and Natural Gas Extraction', 'Petroleum Processing and Coking', 'Electricity and Heating Power Production' and 'Gas and Water Production and Supply' [3]. The water footprint for energy demand (WFE) is therefore the sum of the water footprints of these five economic sectors.

2.2 Data

The existing Chinese MRIO table was extended to include six megacities, i.e. Beijing, Tianjin, Shanghai, Chongqing, Shenzhen and Guangzhou. We used the 2010 Chinese MRIO table from Liu et al [35], which was the most up-to-date table available during our extension work. Thirty sectors for thirty provincial-level administrative regions are included in the MRIO table. Guangdong Province was divided into the following sub-regions: Guangzhou, Shenzhen, and Rest of Guangdong (ROG) (Detailed sectors and administrative regions are listed in Table A1 and A2). A gravity model, first developed by Leontief and Strout [36], was applied to estimate the inter-regional trade of the three sub-regions. Three variables are necessary to estimate the interregional trade of the three sub-regions using the gravity model [37]. These are the supply of sector *i* in the exporting sub-region, the demand of sector *i* in the importing sub-region, and the total production of sector *i* for all sub-regions. We acquired these data through the single-regional input-output tables of Guangzhou, Shenzhen, and Guangdong Province. The interregional trade between the three sub-regions and other Provinces in China was estimated using same trade ratio between Guangzhou Province and other Provinces in China.

Water footprint in a product is comprised of three components: 1) green water, referring to rainwater stored in soils; 2) blue water, referring to freshwater resources including surface water and groundwater; and 3) grey water, which refers to freshwater requirement to dilute pollutants to safe concentrations set by related water quality standards [38]. Green water is mainly used to support plant growth in the agricultural sector [39], and is also a contributor to the energy sectors' life cycle water use [3], and grey water is required to dilute the pollution generated throughout the life cycle of energy products [40]. Both green water and grey water consumption aggravates water scarcity by reducing available water resources to other uses. However, we only consider blue water consumption in this study and will include green and grey water in future works. The sectoral water use data for all provinces were taken from Zhao et al. [21]. The sectoral water withdrawal data were multiplied by the water consumption coefficient for that sector to acquire sectoral water consumption data. The water consumption coefficient is taken from the Water Resource Bulletin in different Chinese provinces. We set the system boundary within China, i.e. focusing on the impact of megacities' energy demand on water scarcity to other provinces within China. The embodied water flows in megacities' international trade are not considered.

3. Results

3.1 Water footprint vs water scarcity footprint of energy demand in China's six megacities

The total WFE of the six Chinese megacities was 867.93 million m^3. It can be seen from Fig. 1 that the WFE differed significantly across the six megacities. In Shanghai, the WFE amounted to 292.64 million m^3, whereas Shenzhen's WFE was only 73.01 million m^3. In decreasing order, the other four cities, Guangzhou, Tianjin, Chongqing and Beijing, each had a WFE of 177.25, 120.87, 113.02 and 91.14 million m^3 respectively. In per capita terms, although inhabitants in Beijing and Chongqing required similar amounts of WFE compared to the national average (4.65 m^3/capita), this number doubled in Tianjin (9.30 m^3/capita) and Shenzhen (7.05 m^3/capita), and tripled in Shanghai (12.71 m^3/capita) and Guangzhou (13.96 m^3/capita). It is therefore evident that megacities generally amplify anthropogenic impacts on natural resources.

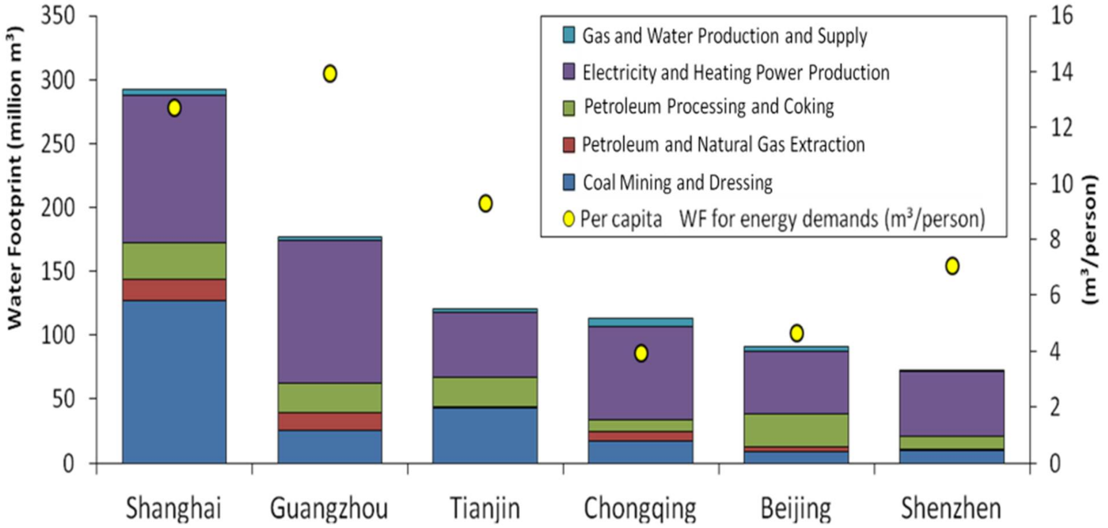

Fig. 1. Water footprint of energy demand (WPE) in China's six megacities.

We evaluated the WSFE for the six megacities considering the water stress differences within China. The total WSFE of the six megacities was 342.19 million m^3, including 54.47

million m^3 internal WSFE and 287.73 million m^3 external WSFE. Shanghai's WSFE was the largest amongst all the megacities (143.75 million m³). The other five cities, Tianjin, Beijing, Guangzhou, Shenzhen and Chongqing, consumed 80.13, 57.44, 36.06, 13.36 and 11.47 million m³ of scarce water respectively, through the life cycle for their final energy demands. Looking at per capita values, Shanghai and Tianjin required the largest amounts of scarce water for their energy consumption, at 6.24 and 6.17 m^3 /capita, whilst Chongqing required the least (0.40 m^3 /person). The other three megacities, Beijing, Guangzhou and Shenzhen, required 2.93, 2.84 and 1.29 m^3 /capita respectively.

The WSFE differed with WFE across the Chinese megacities (Fig. 2). The megacities located in Northern China, i.e. Tianjin and Beijing, had a WSFE equal to 66.29% and 63.02% of their respective WFE. In contrast, for the megacities located in Southern China i.e. Guangzhou, Shenzhen and Chongqing, only 20.34%, 18.29%, and 10.14%, respectively, of their WFE was consumed as scarce water. Shanghai, located on the border between Northern and Southern China, had 49.12% of its WFE categorized as WSFE. Some Southern China megacities, namely Guangzhou and Chongqing, had relatively larger WFE than Northern cities. For example, the WFE of Guangzhou was much larger than that of Beijing and Tianjin, and the WFE of Chongqing was larger than that of Beijing. However, the WSFE to WFE ratios for Beijing and Tianjin was significantly lower, mainly because they are located in a more water-stressed region, i.e. Northern China.

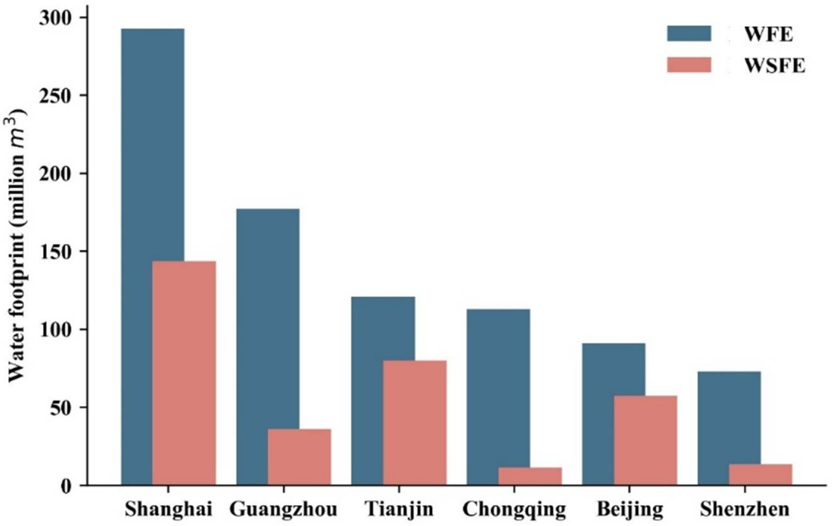

Fig. 2. Water footprint versus water scarcity footprint for final energy demand (WFE VS WSFE) of six Chinese megacities

3.2 Comparing sectoral water footprint and water scarcity footprint of energy demand

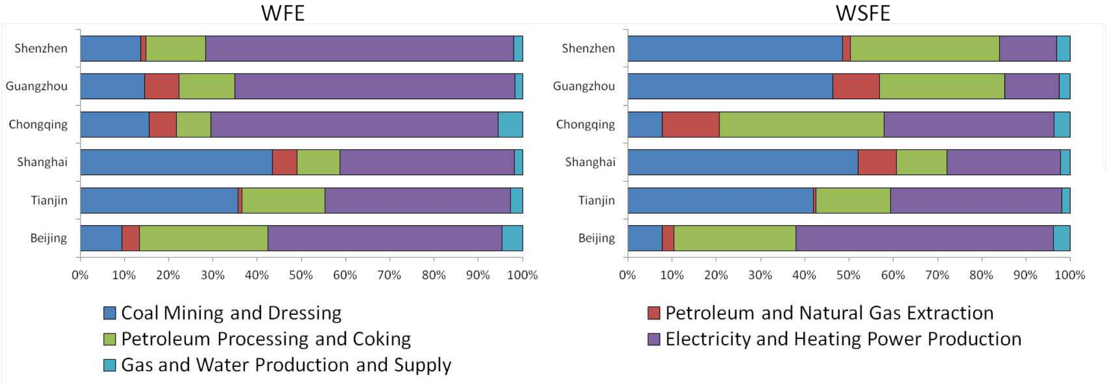

Fig. 3. Distribution of water footprint of energy demand (WFE) and water scarcity footprint of energy demand (WSFE) in the five energy related economic sectors

The WFE of the six Chinese megacities are dominated by two economic sectors, i.e. ‘Electricity and Heating Power Production’ and ‘Coal Mining and Dressing’. These two sectors contributed 51.91% and 26.78% of the total WFE for the six megacities, respectively. As shown in Fig. 3, demands on ‘Electricity and Heating Power Production’ occupied the highest proportion in Shenzhen, at 69.61%, and ‘Coal Mining and Dressing’ demand occupied the highest proportion in Shanghai at 43.40%. The ‘Petroleum Processing and Coking’ sector that provides fuel for conventional vehicles made up 13.70% WFE, ranking third on average overall.

The distribution of the total WSFE across the five energy related economic sectors was quite different to the WFE. The energy sectors with the largest WSFE were ’Coal Mining and Dressing’, accounting for 39.99% of total WSFE, followed by ’Electricity and Heating Power Production’(32.73%), and ’Petroleum Processing and Coking’(18.94%). It can also be seen from Fig. 3 that the final demand in ’Electricity and Heating Power Production’ occupied more than 50% (58.08%) of WSFE in Beijing, whilst in Shanghai final demand in the ’Coal Mining and Dressing’ sector made up 52.01% of its WSFE. It is worth noting that although final demand of ’Electricity and Heating Power Production’ occupied a significant share of Shenzhen’s WFE (69.61%), it made up only a small proportion in terms of it’s WSFE (12.95%). This indicates the WSFE in Shenzhen’s ’Electricity and Heating Power Production’ sector was largely sourced from water-abundant regions. ’Coal Mining and Processing’ occupied 46.25% and 48.55% of the WSFE in Guangzhou and Shenzhen respectively, subtantially increased from 14.63% and 13.67% for the same sectors WFE, while ’Electricity and Heat Power Production’ occupied a much lower proportion of their WSFE (12.33% in Guangzhou and 12.95% in Shenzhen) than their WFE (63.29% in Guangzhou and 69.61% in Shenzhen).

3.3 Allocation of external water footprint and water scarcity footprint of energy demand

Urban economies inevitably draw on resources from beyond their territories to support their populations. When goods and services are transferred from different geographical areas into cities, water embodied in these goods and services is virtually imported and constitutes the external WFE of cities. For example, Shanghai and Guangzhou have the largest WFE, and more than 90.00% of their WFE was induced beyond their administrative boundaries. In fact, all six Chinese megacities imported the majority (more than 50.00%) of their WFE from elsewhere, with Chongqing importing the least (57.02%) and Shenzhen importing the most (97.79%). Looking at the provincial detail, all six megacities imported the largest amounts of

WFE from their respective neighboring provinces. To be specific, the largest WFE exporters to Beijing and Tianjin were Inner Mongolia (19.54 million m^3) and Shanxi (27.10 million m^3), respectively. The largest amount of WFE import for both Guangzhou (61.07 million m^3) and Shenzhen (32.68 million m^3) was from Yunnan in Southern China. Hubei exported 53.42 million m^3 WFE to Shanghai, and Sichuan exported 25.23 million m^3 WFE to Chongqing.

Fig. 4 and 5 illustrate the detailed external WFE of the six Chinese megacities divided into different economic regions. The Central region exported the largest amount of virtual water embodied in energy demand to the six megacities (211.36 million m^3), with the largest outflow (121.43 million m^3) to Shanghai. Following the Central region, the Southwest exported the second largest virtual water to support energy demands in other regions, providing huge amounts of virtual water to Guangzhou (79.16 million m3), Chongqing (43.51 million m^3), and Shenzhen (40.81 million m3). The Northwestern region was the third largest exporter, exporting 29.52, 30.99 and 57.96 million m^3 of WFE to Beijing, Tianjin and Shanghai respectively, to meet their final energy demands.

Each megacity imported at least 70% of its WSFE from external sources. In decreasing order, the proportion of external WSFE to total WSFE was 99.04% (Shenzhen), 98.10% (Guangzhou), 91.13% (Chongqing), 84.59% (Shanghai), 82.42% (Tianjin), and 71.45% (Beijing). This implies that energy demand in these megacities is vulnerable to water shortage risks, such as drought, in places beyond their own territories. Chongqing, Guangzhou and Shenzhen imported larger proportions of WSFE than WFE from external sources, whilst Beijing, Tianjin and Shanghai imported less. This may be explained by Beijing, Tianjin and Shanghai experiencing severe water stress within their own territories. Looking at the spatial distribution of external WSFE of the megacities, although Northern China is already faced with dire water scarcity issues, its scarce water resources are still being exploited and transformed into the form of virtual scarce water to support energy demands in other regions (Fig. 5). According to our quantification, the three northern regions have exported 68.93 (North), 76.36 (Northwest) and 10.55 (Northeast) million m^3 of scarce water to support energy demands in the six megacities, compared to 3.96 and 5.23 million m^3 from the Southern Coast and Southwest respectively. The largest amount of water scarcity footprint was induced in the Central region, 99.16 million m^3, and the largest virtual scarce water flows were all towards Shanghai, from the North (42.38 million m^3), Central (32.72 million m^3) and Northwest (30.38 million m^3) regions.

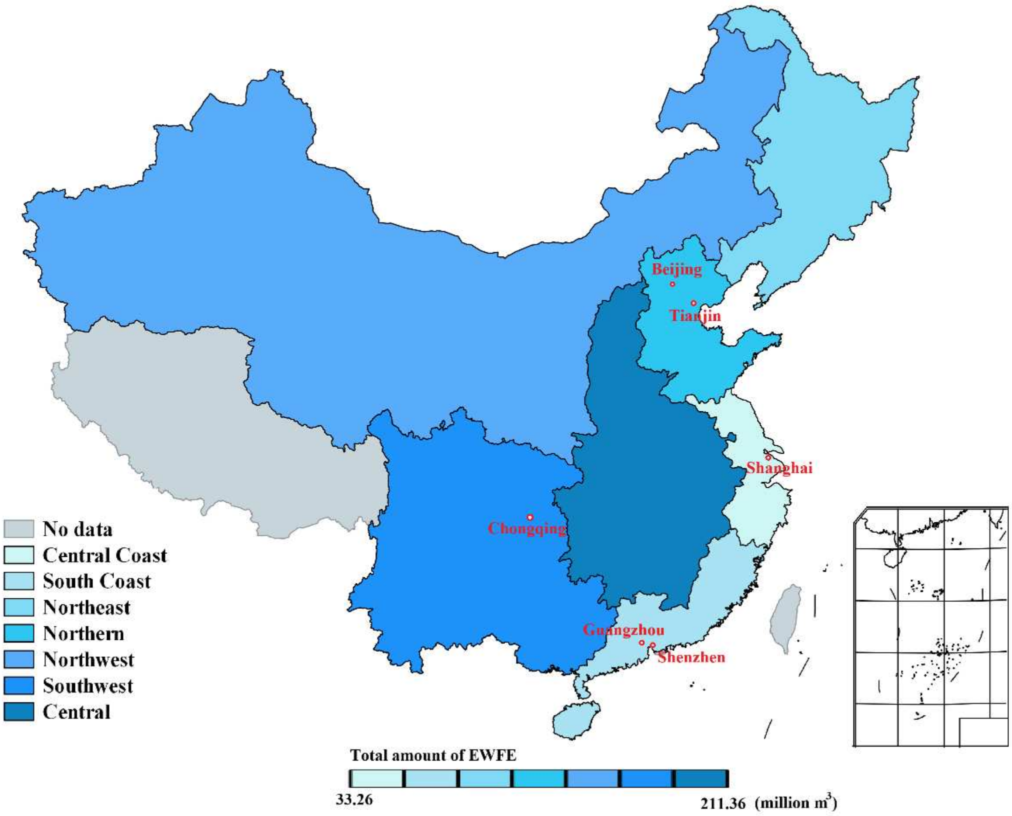

Fig. 4. Allocation of megacities' external water footprint of energy demand (EWFE) to different economic regions.

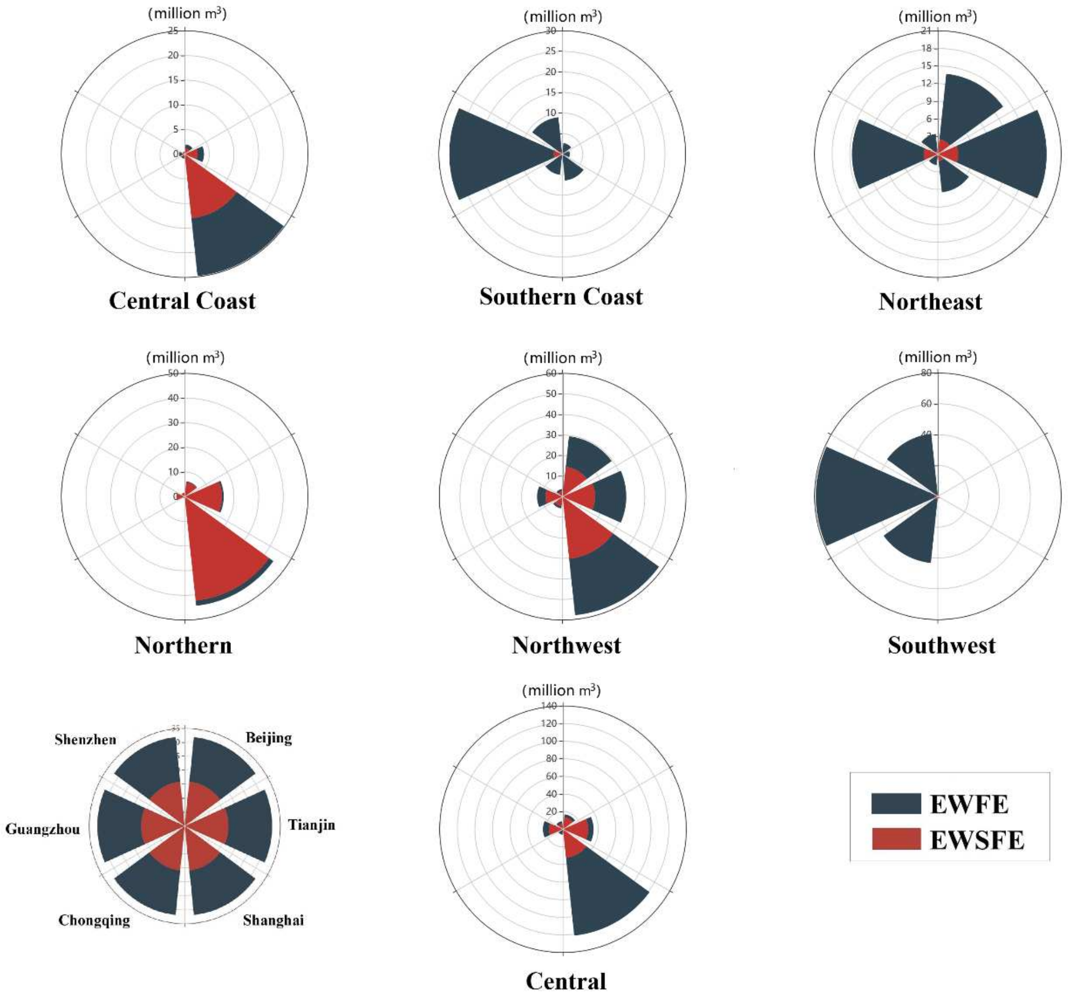

Fig. 5. Distribution of external water footprint of energy demand (EWFE in blue) and external water scarcity footprint of energy demand (EWSFE in red) in different economic regions for different megacities.

3.4 Sectoral origins of water footprint and water scarcity footprint of energy demand

To meet final demand in the energy related economic sectors, water is used along their life-cycle supply chain at almost every stage. Overall, the 'Electricity and Heating Power Production', 'Agriculture', and 'Coal Mining and Dressing' sectors made the largest contributions to WFE in the studied megacities accounting for 40.49%, 26.98%, and 12.45% in total (Fig. 6). The WFE in the 'Electricity and Heating Power production' sector was mostly induced within its own sector, accounting for 71.27% of the WFE of this sector. For 'Petroleum Processing and Coking', concerted effort is required to reduce its WFE from the 'Agriculture', 'Petroleum and Natural Gas Extraction' and the sector itself, which contributed 30.44%, 16.51% and 35.99% of the WFE of this sector respectively. The 'Agriculture' sector topped the list amongst the non-energy economic sectors, contributing the most to the final demand in 'Coal Mining and Dressing' and 'Gas and Water Production and Supply', occupying 44.47% and 33.71% respectively. Such results are consistent with national findings from previous studies [2, 4, 41]. The dominance of the 'Agriculture' sector may be explained by its large water intensities. The main input product from the ‘Agriculture’ sector to the energy related sectors are coal mine props [5]. Coal-fired power plants, a major water user, are often located close to coal production sites [2]. As a result, water is largely consumed through the operation of coal-fired power plants in the Central, Northwestern and Southwestern regions to support energy demand in these megacities. Regarding the sector origins for WSFE, it can be seen from Fig. 6 that the proportion occupied by ’Electricity and Heating Power Production and Supply’ reduced substantially from 40.00% to 26.00%, with the proportions of the other four energy related sectors having all increased accordingly. This reflects the relatively large amount of WFE throughout the life cycle processes to meet electricity consumption is sourced from water-abundant regions.

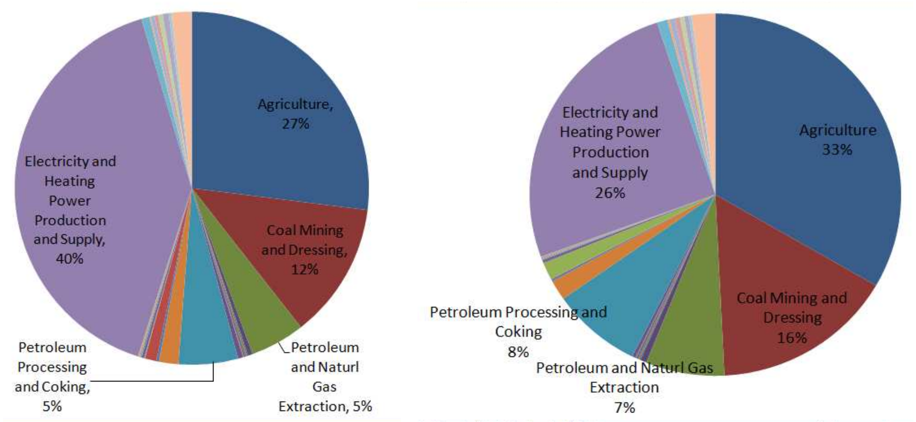

Fig. 6. Sectoral origins of water footprint of energy demand (left) and wate scarcity footprint of energy demand (right) in China’s six megacities. Only sectors with a share of larger than 5% are identified.

4. Discussion and conclusions

4.1 Addressing ‘water for energy’ in megacities considering water scarcity impact

The world is undergoing urbanization at an unprecedented speed and scale [42]. The intensified water-energy interactions (or nexus) associated with urbanization have been met with worldwide concerns [43]. From the ‘water for energy’ perspective, megacities’ final energy demands are found to be highly water intensive [19, 44]. Cities thus resort to water resources beyond their boundaries due to limited domestic resources [45]. Zhang et al. [19] found that in the year 2007, 78.5% of water withdrawal for energy supply in the megacity of Shanghai was from external water resources. Our observations are in line with these literature findings, underscoring megacities’ amplified impacts on both internal and external water resources. The six Chinese megacities are home to only 7.8% of the national population and are endowed with only 2.6% of the national available water resource, but their WFEs and WSFEs together make up nearly 14% and 13%, respectively, of the national total. Most of the WFEs and WSFEs for these megacities were sourced from external water resources, accounting for 86.49% and 84.01% of the total WFEs and WSFEs.

More importantly, our work highlights the necessity of involving water scarcity in megacity WFE accounting from a consumption perspective. Djehdian et al. [6] evaluated the internal and external urban water scarcity of energy demand using a water scarcity metric with a bottom-up approach. Their results illustrated the hotspots of urban external water scarcity. Our work has enriched this research field by using the indicator of water scarcity footprint with an MRIO approach. The results help to identify both internal and external water scarcity risk faced by megacities from a consumption perspective. Generally, we found final energy demand from megacities in water abundant south China were less vulnerable to both internal and external water scarcity, which was shown through the WSFE indicator. In contrast, such a conclusion is difficult to draw through the WFE. For example Guangzhou, was ranked second for its WFE and external WFE, and Chongqing, was ranked first for its internal WFE, amongst the six megacities (Table A3). Such results might give rise to the false impression that these two cities' final energy demands had large internal or external water impact, suggesting water saving actions are required for these two megacities. However, both Guangzhou and Chongqing are located in the water abundant south and, although water consumption might be relatively large, the impact to potential water shortages could be limited. Considering the water scarcity footprint, the rank for the previous indicators for these two megacities drops to fourth amongst the six studies megacities, showing their reduced contribution to internal or external water scarcity. The WSFE thus makes more intuitive sense in understanding the water scarcity situation from final energy demand, enabling urban managers around the world to better safeguard water and energy security.

4.2 Implications from comparing the water scarcity footprint of different megacities

There are substantial differences in the six megacities' WSFEs, which were caused by final demand on different energy related economic sectors, spatial locations, water endowments etc. Comparing these differences amongst the megacities provides insights for urban managers around the world to identify the specific water risks from energy demand for their own cities.

We found that megacities with larger internal WSFE also had a larger external WSFE. The three Northern megacities, i.e. Beijing, Tianjin, and Shanghai had much larger internal WSFE than the three megacities located in the south (Table A3). This may be explained by the fact that Northern China is more water stressed than Southern China [46]. These three megacities also imported large amounts of embodied water for energy from their nearby provinces, also located in Northern China, such as Shanxi, Inner Mongolia, and Hebei. This explains why megacities located in the north also had larger external WSFE. Such findings are in line with Djehdian et al. [6] who used a bottom-up approach to establish that cities usually import products from nearby regions with similar water resource endowments. Shan et al. [47] also indicated that Chinese urban agglomerations are mostly supported by nearby centers of energy production. These findings reveal that megacities located in water scarce areas have more water scarcity risk than previously thought. Urban managers in water scarce megacities are thus recommended to pay special attention to their external water risks.

Important differences were found in the WSFE of the energy related sectors in the six megacities. Such differences highlight potential key sectors for water saving direction for different megacities. First, although both are located in the water scarce north, the per capita WSFE of Beijing is only half that of Tianjin, which is mainly because Beijing has a much lower WSFE in the 'Coal Mining and Dressing' sector compared to Tianjin (Table A4). This difference suggests that the long effort of Beijing in controlling its coal consumption has had an effect

[48], also achieving the co-benefit of reducing its water risk. Since the WSFE of 'Coal Mining and Dressing' in Tianjin took the largest share amongst the five energy related economic sectors, it is suggested that Tianjin should limit its own coal consumption as a priority. Second, Guangzhou and Shenzhen in Southern China have a much lower WSFE for the 'Electricity and Heating Power Production and Supply' sector than the three northern megacities (Table A5), showing less need for them to save water for electricity production. However, comparing the smaller water scarcity impact from electricity consumption, the southern megacities had relatively larger WSFE of 'Coal Mining and Dressing' and 'Petroleum Processing and Coking' (Table A5). This is because a significant mismatch exist between the two Southern megacities and the distributions of coal and petroleum reserves. Whilst development has been concentrated in these two megacities, coal and petroleum reserves and outputs are the highest mainly in Northern China, including Inner Mongolia, Shanxi, Shaanxi, Xinjiang, and Liaoning. Hence, coal and petroleum consumption in Guangzhou and Shenzhen are exposed to water scarcity in Northern China, which indicates the necessity for these two cities to further control their coal and petroleum consumption. In summary, place-specific as well as sector-specific, as opposed to 'one-size-fits-all' policies are recommended to be formulated and applied for different megacities around the world.

4.3 Limitations and future outlook

There are certain limitations in quantifying energy demand water footprint using a top-down methodology. First, we were not able to disaggregate Gas Supply from the 'Gas and Water Supply' sector due to data limitations, which could result in overestimation of the WFE. Second, whilst the 'Agriculture' sector inputs to coal mining are mainly mine props, homogenous water intensity is applied to all different products of the sector, which might overestimate the water footprint of wood mine props. Second, although Shenzhen and Guangzhou are China's two largest southern megacities, we disaggregated these two cities from Guangdong province in China's MRIO tables for only one year. It will be useful to construct time series MRIO tables in future studies to investigate their respective historical WFE evolutions and the corresponding pathway drivers. Third, we only considered the water-energy nexus from 'water for energy' perspective, and the energy used for water supply to support the energy production was not considered. Last but not least, we adopted consumptive water use (water consumption) in our calculations, not water withdrawal/use. Water consumption may be defined as the difference between water withdrawal and water discharge back into the environment. Water that is consumed is considered lost and unavailable to be used for other purposes, and therefore aggravates pressures on water resources especially in water-scarce regions. In this way, water consumption better indicates anthropogenic impacts on water resources. However, water consumption accounting may underestimate the water shortage risks as water withdrawal can be substantially higher than water consumption, especially for thermoelectric power cooling in China's water-abundant south [4]. Large amounts of water withdrawal requirements can expose final energy demands in those megacities to higher levels of water shortage risks either within or outside their administrative boundaries than indicated by the results from this study [49].

Acknowledgements

This work was supported by the National Key R&D Program of China (No.2017YFA0603704; 2017YFC04043012), and the National Natural Science Foundation of China (No. 41830757).

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Appendices

Table A1 Sector list of multi-region input-output table

Number	Sector
1	Agriculture
2	Coal Mining and Dressing
3	Petroleum and Naturl Gas Extraction
4	Metals Minging and Dressing
5	Nonmetal Minerals Mining and Dressing
6	Food and Tobacco Processing
7	Textile Industry
8	Garments, Leather, Furs, Down and Related Products
9	Timber Processing and Furniture Manufacturing
10	Papermaking, Cultural, Educational and Sports Articles
11	Petroleum Processing and Coking
12	Chemicals
13	Nonmetal Mineral Products
14	Smelting and Pressing of Metals
15	Metal Products
16	General and Specialized Machinery
17	Transportation Equipment
18	Electric Equipment and Machinery
19	Electronic and Telecommunications Equipment
20	Instruments, Meters Cultural and Office Machinery
21	Other Manufacturing Products
22	Electricity and Heating Power Production and Supply
23	Gas and Water Production and Supply
24	Construction
25	Freight Transport and Warehousing
26	Wholesale and Retail Trade
27	Hotels, Food and Beverage Places
28	Real Estate and Social Services
29	Scientific Research
30	Other Services

Table A2 Provinces and city list of multi-region input-output table

Numbers	**Province/City**
1	Beijing
2	Tianjin
3	Hebei
4	Shanxi
5	Inner Mongolia

6	Liaoning
7	Jilin
8	Heilongjiang
9	Shanghai
10	Jiangsu
11	Zhejiang
12	Anhui
13	Fujian
14	Jiangxi
15	Shandong
16	Henan
17	Hubei
18	Hunan
19	Guangzhou
20	Shenzhen
21	Guangdong Other
22	Guangxi
23	Hainan
24	Chongqing
25	Sichuan
26	Guizhou
27	Yunnan
28	Shaanxi
29	Gansu
30	Qinghai
31	Ningxia
32	Xinjiang

Table A3 Internal and external water footprint and water scarcity footprint of energy demand, unit: million m^3

	Beijing	Tianjin	Shanghai	Chongqing	Guangzhou	Shenzhen
Internal WFE	16.40	14.09	27.87	48.57	8.73	1.62
External WFE	74.75	106.78	264.77	64.45	168.52	71.40
WFE	91.14	120.87	292.64	113.02	177.25	73.01
Internal WSFE	16.40	14.09	22.16	1.02	0.69	0.13
External WSFE	41.04	66.04	121.59	10.45	35.37	13.23
WSFE	57.44	80.13	143.75	11.47	36.06	13.36

Table A4 Water footprint vs water scarcity footprint of energy demand

	WSFE (million m^3)	WFE (million m^3)	population (million)	Per capita WFE (m^3/person)	Per capita WSFE (m^3/person)

Shanghai	143.75	292.64	23.03	12.71	6.24
Guangzhou	36.06	177.25	12.70	13.96	2.84
Tianjin	80.13	120.87	12.99	9.30	6.17
Chongqing	11.47	113.02	28.85	3.92	0.40
Beijing	57.44	91.14	19.62	4.65	2.93
Shenzhen	13.36	73.01	10.36	7.05	1.29

Table A5 Water scarcity footprint of different final energy demand, unit: million m^3

Cities	**Categories**	S2	S3	S11	S22	S23
Beijing	Internal	0.79	0.39	0.81	12.99	1.41
	External	3.66	1.14	15.05	20.37	0.83
	Sum	4.45	1.52	15.87	33.36	2.24
Tianjin	Internal	0.43	0.32	2.56	10.08	0.70
	External	33.15	0.12	10.96	20.99	0.82
	Sum	33.58	0.44	13.52	31.07	1.52
Shanghai	Internal	0.00	0.00	3.44	16.14	2.57
	External	74.77	12.42	12.99	20.85	0.57
	Sum	74.77	12.42	16.43	36.99	3.14
Chongqing	Internal	0.04	0.00	0.03	0.84	0.11
	External	0.86	1.48	4.24	3.56	0.31
	Sum	0.89	1.48	4.27	4.40	0.42
Guangzhou	Internal	0.00	0.00	0.09	0.57	0.02
	External	16.68	3.81	10.12	3.87	0.89
	Sum	16.68	3.81	10.22	4.45	0.91
Shenzhen	Internal	0.00	0.00	0.01	0.11	0.00
	External	6.48	0.22	4.49	1.62	0.41
	Sum	6.48	0.22	4.51	1.73	0.41

S2 = Coal mining and dressing; S3 = Petroleum and Natural Gas Extraction; S11 = Petroleum Processing and Coking; S22 = Electricity and Heating Power Production and Supply; S23 = Gas and Water Production and Supply.