The Water–Energy Nexus of Megacities Extends Beyond Geographic Boundaries: A Case of Beijing

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Abstract

The water–energy nexus (WEN) is dynamic and complicated in megacities, most of which are challenged by water scarcity and the mandate to reduce energy consumption. A salient feature of water and energy services in megacities is that they are supported by a web of regional infrastructure, extending far beyond the geographic boundaries of the cities, resulting in a strong dependence on resources imported from outside. Understanding the WEN of megacities has implications not only for more efficient resource utilization but also for synergistic regional development and corporation. This study provides a quantitative assessment of the WEN of Beijing within and beyond its geographic boundaries. Results show that water for local internal energy production and transformation accounts for 220 million m^3/year, or 5.6% of its total freshwater use in 2016, and the energy for local water abstraction, supply, and treatment is 3.06 billion kWh, accounting for 1.1% of its total energy consumption for the same year. The external water for "imported" energy is 290 million m^3/year, 1.3 times of Beijing's freshwater use for internal energy. This means that more water for energy is consumed outside Beijing than that within Beijing. The energy for external water is negligible because the bulk of the water transfer into Beijing relies on gravity and because the energy for construction of the transfer infrastructure is not included. Analysis of the WEN revealed the contradiction between the two independently conceived policies of Beijing: to meet the "three-red-line" target in the water sector, recycled water and transferred water use will rise, making it more difficult to meet the carbon emission control targets. Therefore, adopting low energy intensity, nature-based water recycling is a wise policy choice.

Keywords: Beijing; megacity; recycled water; sustainable regional development; water–energy nexus

Introduction

CITIES ARE POWERFUL engines of economic growth. However, the high degrees of social and economic activities meant massive amounts of concentrated resources consumption, such as energy and water, resulting in various degrees of dependence on "imported" resources from outside the geographic boundaries of cities (Sun *et al.*, 2015; Zhao *et al.*, 2016a, 2016b). Urban population already accounts for 54% of the world's total population (United Nations, 2014) and is expected to reach 70% by 2050 (United Nations, 2008). It has been estimated that 75% of global energy consumption and 10% of water consumption were by cities (United Nations, 2008; WWAP, 2014). Therefore, many cities around the world have undertaken arduous tasks of saving energy and water.

The efficient use and coordinated management of water and energy resources is crucial for the sustainable growth of cities. Historically, different government agencies manage water and energy resources separately. As the result, efforts to improve the efficiency of water and energy use are independently driven by needs in each sector. When devising energy policies and plans, policymakers often consider water

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demand for energy development but rarely consider the impacts of energy development plans on local water resources, neglecting the potential impact on other regions. Likewise, in formulation of water resources policies and plans, little attention is paid to energy consumption for water resources development and utilization, let alone energy efficiency in urban water systems (Wen *et al.*, 2014). For example, Beijing, China's political, economic, and cultural center and a megacity with superlative energy consumption and severe water scarcity (Zeng *et al.*, 2013), depends highly on external resources (Beijing Bureaus of Statistics, 1980–2011, 2016). To address the water and energy issues, Beijing has made great yet separate efforts to improve water and energy use efficiencies that can be contradictory to each other. To alleviate water stress in Beijing, multiple water sources are being secured among which groundwater, recycled water, and transferred water are all significant. Unfortunately, these water sources all have higher energy intensity compared with local surface water (Wen *et al.*, 2014; Li *et al.*, 2016b).

Recently, the interdependence of water and energy, captured through the concept of "water–energy nexus" (WEN), is being recognized as worthy of examination to seek simultaneous improvement in efficiency in managing both resources (USDOE, 2006, 2007; Marsh, 2008; Retamal *et al.*, 2008; Cammerman, 2009; Bartos and Chester, 2014; Hamiche *et al.*, 2016; Liu *et al.*, 2017). In addition to formulating the general concept and framework of WEN (Bazilian *et al.*, 2011; Hoff, 2011; Kenway *et al.*, 2011a, 2011b), researchers have explored how specific production processes or technology of one sector affect the other (Lofman *et al.*, 2002; Gao, 2012; Cai *et al.*, 2014; Liu *et al.*, 2015a, 2015b). Given that cities are foci of energy consumption, it is surprising that very few WEN studies have examined urban areas (Fang and Chen, 2017). Wen *et al.* (2014) analyzed the WEN of Qingdao, China, from the perspective of energy consumption of various water sources. They have found that with improvements of water quality and utilization of unconventional water resources including reclaimed water, energy requirement of the urban water system may surge. Hu *et al.* (2013) analyzed the WEN of Beijing for 2009 by quantifying the water used in electricity production and supply, as well as the electricity used for water supply, treatment, utilization, and postuse, before the delivery of water from the South to North Water Diversion (SNWD) project. A critical aspect that is missing in the aforementioned studies is that the spatial dimension of the WEN, that is, the nexus of the imported resources, remains an area to be explored.

This study seeks to enhance the understanding of the WEN of megacities and its reach beyond the city's geographic boundary, which is essential for sustainable resource use and management toward a synergistic urban and regional development. Because nearly 96% of the primary energy supply to Beijing is "imported" from other provinces or countries (National Bureau of Statistics, 2016), the energy mix of Beijing's supply network outside its geographic boundaries are considered in this study. Furthermore, to address the water scarcity of Beijing, the SNWD project has been delivering about 4 billion m^3 water to Beijing since December 2014. This amount is equivalent to the total annual water consumption of Beijing. This study investigates the WEN of Beijing after the arrival of water from the SNWD to illustrate

the complexities of the WEN of megacities. The reliance of Beijing on external water and energy to sustain its rapid pace of urbanization in the context of WEN has implications for adopting strategies to meet a set of stringent policy targets set forth by Beijing's municipal government.

Materials and Methods

Beijing: water, energy, and urbanization

Located in the monsoon-influenced humid continental climate zone, Beijing encompasses a total area of 16,410 km^2 with a population of 21.73 million (Beijing Bureau of Statistics, 2013). Average annual precipitation is 585 mm/year, with nearly 75% of precipitation in June, July, and August. The local surface water and groundwater resources are about 3.5 billion m^3, and the water resource per capita in Beijing is only 161 m^3 (Beijing Water Authority, 2016), far below the national and the world averages. The rapid expansion of urban land use from 9% in 1990 to 15% in 2015 (Fig. 1), and the doubling of population from 11 million to nearly 22 million in the same period (Beijing Bureau of Statistics. 2013), is accompanied by massive investment in infrastructure. This included the water and energy supply sectors (Fan *et al.*, 2017). Public outcry to poor air quality has led Beijing to reduce its coal-sourced energy to only 9.8% of its total energy supply at 69.6 million tons of standard coal equivalent (TCE) in 2016 [Beijing Statistical Yearbook, 2016 (Beijing Bureau of Statistics 1980–2011, 2016)], the lowest in China.
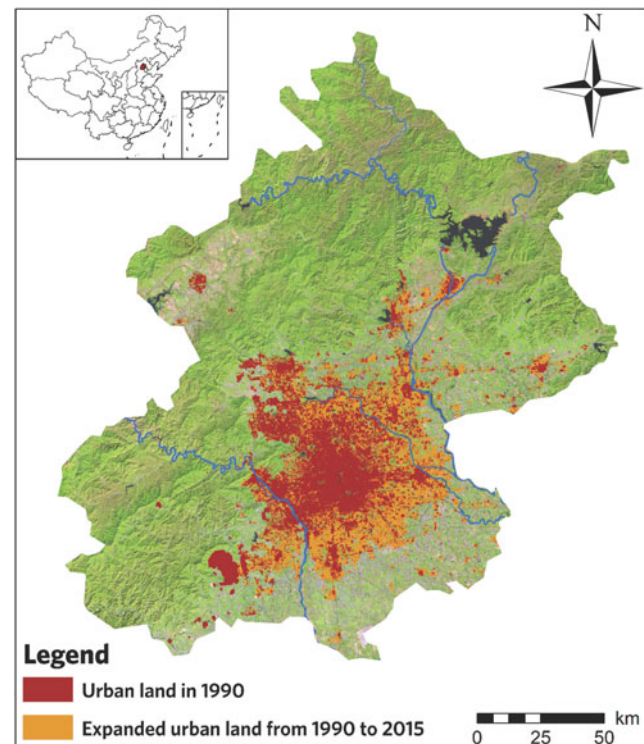
FIG. 1. Location of Beijing and its urban land changes (Landsat TM data downloaded from USGS Earth Explorer; Urban land data in 1990 and 2005 are from Liu *et al.* [2018]).

Methods and data sources

With trade, regional and global economic integration, the spatial separation where things are produced differ from where they are consumed is increasingly the norm, water and energy included. To illustrate the extent of megacities' reliance on ''imported'' water and energy resources and to shed light on the interaction between the two, simple but consistent accounting was applied to ''local'' and ''imported'' energy and water resources, supply, and consumption that took place within and beyond the geographic boundaries of Beijing, respectively. Data sources that enabled such accounting are described below.

Energy for water. Energy used by the water sector includes constructional use and operational use. Constructional use refers to the energy used in constructing water-related infrastructures, and operational use refers to the energy used to extract, convey, treat, and distribute water. The former category is usually counted as energy used by the industrial sectors and therefore is not considered in water sectors of this study. The operational energy use for extracting, conveying, and treating water is considered in this study as the ''energy for water'' (EFW) (Rothausen and Conway, 2011). Plappally and Lienhard (2012) and Wakeel *et al.* (2016) provided comprehensive reviews on energy requirements for water production, treatment, end use, reclamation and disposal, and representative values of the energy consumed per unit water were given for a broad range of processes. However, most of the available values are for the Western countries with limited data for Asia and even less for China. The energy intensity data for all water-related processes used in this study were collected from Chinese government-authorized sources, academic reports, and journal articles (Table 1) and are ex-

pressed in terms of kilowatt hour per cubic meter of water (kWh/m^3). To reduce the discrepancies of data from different studies, the mean value of energy intensity data was adopted here. Detailed explanations on how the values were obtained can be found in Li *et al.* (2016a, 2016b). The water quantity data were collected from the Water Resources Bulletin published by Beijing Water Authority (2016). In this study, the energy for the SNWD considers only the operational energy after the transferred water enters Beijing because before that the middle route of SNWD is gravity driven. The SNWD water comes through the Hui-Nan-Zhuang pumping station located at the southwestern corner of Beijing where about 18% of transferred water is pumped up through nine pumping stations with a total lift of 133 m and a channel of 103 km to reach the Mi-Yun reservoir for storage.

Water for energy. Water for energy (WFE) sectors include water consumption for primary energy production (e.g., mining of fossil fuels) and energy transformation (e.g., electricity generation) (Perera and Zhong, 2017). In this study, the water consumption for coal mining, oil refining, power generation, and heating, which account for more than 90% of the energy production and transformation of Beijing, is considered as the ''water for energy''. Lacking the actual water intensity data but considering that water is the limiting factor for energy sectors, we assume that the energy sectors utilize water according to the water quota assigned to them by the government. The Guideline for Beijing Industrial Energy Consumption and Water Consumption mandates a water quota (Q) for 10,000 Yuan of various energy production. Based on the unit price (P) of the energy categories, the water intensity per unit of energy production is calculated (Table 2). Based on energy production data (E) obtained from the 2016 Energy

TABLE 1.   ENERGY FOR WATER IN BEIJING WITHIN ITS BOUNDARY (2016)

Items		Quantity (million m³/year)	Energy intensity (kWh/m³)	EFW (million kWh/TCE)	Data sources
Surface water extraction	Rivers and reservoir	291	0.20	58/0.015 (2%)	Liu *et al.* (2013) Shao *et al.* (2003)
	SNWD	838	0.0045 kWh/(m³ · km) (for water conveying) 0.0027 kWh/(m³ · m) (for water lifting)	575/0.15 (19%)	Plappally and Lienhard (2012) Rothausen and Conway (2011) Gao (2012) Wen *et al.* (2014)
Groundwater extraction		1,748	0.49	857/0.22 (28%)	China Geological Environmental Monitoring Institute (2012) Wang *et al.* (2012)
Public water supply		1,942	0.30	583/0.15 (19%)	China Urban Water Association (2012)
Recycled water treatment		1,004	0.82	823/0.21 (27%)	Wen *et al.* (2014)
Wastewater treatment		524	0.32	168/0.04 (5%)	Fu and Zhong (2014) Gu (2017)
Total				3,063/0.79	1.1% of 69.6 million TCE total energy consumption

EFW, energy for water; TCE, tons of standard coal equivalent; SNWD, South to North Water Diversion.

TABLE 2. WATER FOR ENERGY IN BEIJING WITHIN ITS BOUNDARY (2016)

Item	Water quota (m³/10⁴ Yuan)[a]	Unit price (Yuan/TCE)[b]	Energy produced (10⁴ TCE)[c]	WFE (million m³)	
Coal mining	55	803	257	11.4 (5%)	
Oil refining	1.62	3,836	1171.5	7.2 (3%)	
Power generation	77	1,809	1157.8	161.3 (74%)	
Heating	35	2,037	548.7	39.1 (18%)	
Total				219	5.6% of the 3,880 million m³ total water use

Data sources: [a]Guideline for Beijing Industrial Energy Consumption and Water Consumption.
[b]Unit energy price for coal mining is 650 Yuan/ton, for oil refining is 5.5 Yuan/L, for power generation is 0.5 Yuan/kWh, for heating is 69.45 Yuan/GJ; they are converted Yuan/TCE.
[c]Energy Statistics Yearbook, Beijing, 2016.
WFE, water for energy.

Statistics Yearbook of Beijing in 2016, the water consumption for various energy production processes is calculated by Equation (1):

$$WFE = Q \times P \times E \qquad (1)$$

where WFE is the water for energy production (m³), Q is the water quota for 10,000 Yuan energy production (m³/Yuan), P is the unit price of energy (Yuan/TCE), and E is the energy production (TCE).

Results

Compositions of water flows in Beijing

Figure 2 illustrates the water supplies in Beijing at the left-hand side and the water uses at the right-hand side. At 45% of Beijing's water supply, groundwater dwarfs other sources of water supply. Recycled water and the SNWD water account for 25.9% and 21.6% of Beijing's water supply, respectively, with only 7.5% coming from non-SNWD surface water. From the water use perspective, 46.2% of the water consumption is for domestic purpose. Environmental water uses (28.6% of total water use) primarily sourced water from recycled water, so is industrial water use. Curiously, agricultural water use (15.6% of total water use) still relies entirely on groundwater and not at all on recycled water. In comparison, nearly 60% of industrial water use comes from recycled water, with the rest from surface water.

Groundwater is not only the most abundant water source but also has the most diverse use, providing water for domestic, agricultural, and environmental purposes, with each accounting for 47%, 35%, and 18% of extracted groundwater (Fig. 2). In contrast, the SNDW has one and only use for domestic purposes. Not surprisingly, domestic water consumption is dominated by SNDW at 47%, although groundwater remains important, accounting for 45% of domestic water use. About
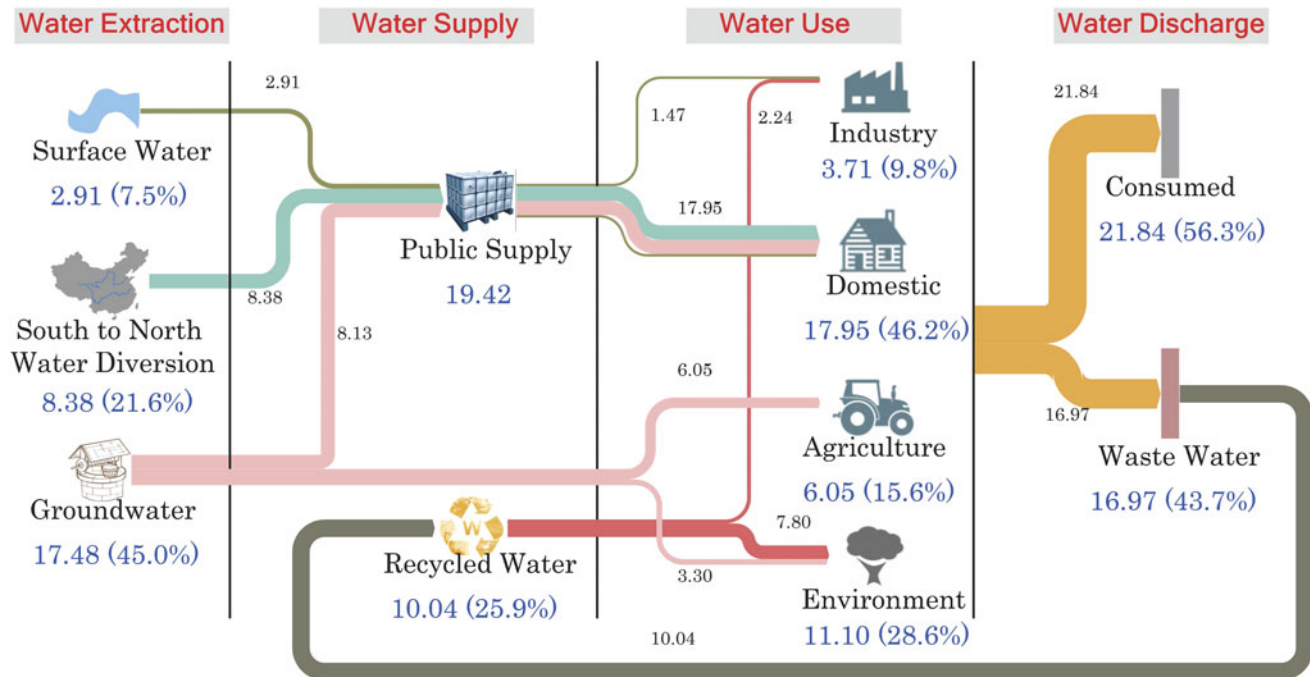
FIG. 2. Sankey diagram of water flows in Beijing, 2016 (Unit: 10⁸ m³, Data source: Beijing Water Authority, 2016). Sankey diagram is made by eSankey, and the widths of the bands are directly proportional to the water quantity (Sankey, 1898; Schmidt, 2008).

half of the surface water goes to domestic use and the other half goes to industrial use.

Beijing's water use pattern has its distinctive feature and is significantly different from the national norm. The proportions of agricultural (15.6%) and industrial (9.8%) water use are low, whereas the national average for agricultural and industrial water use is 62.4% and 21.6%, respectively (Ministry of Water Resources, 2016). The proportions of water for domestic (46.2%) and environmental uses (28.6%) are much higher than the national average, which is 13.6% and 2.4%, respectively (Ministry of Water Resources, 2016). Such water use pattern is consistent with a high degree of urbanization of Beijing with limited farmland and a high degree of environmental awareness.

Compositions of energy flows in Beijing

The energy mix of Beijing continues to be optimized to meet the ''double control'' targets for both quantity and intensity of energy consumption (Beijing Bureau of Statistics, Beijing Municipal Development and Reform Commission, Beijing Municipal Water Affairs Bureau, 2016). In 2016, Beijing's total energy consumption was 69.6 million TCE, below the annual cap of 71 million TCE set by the 13th Five-Year Energy Development Plan of Beijing (2016). The energy intensity measured by energy consumption per 10,000 Yuan GDP was 0.28 TCE and the lowest in the country [Beijing Statistical Yearbook, 2016; (Beijing Bureau of Statistics, 1980–2011, 2016)], less than half of the nation average value of 0.58 TCE.

Beijing's energy supply system is embedded in a regional distribution network. The city relies heavily on direct energy supplies from outside, importing nearly 96% of the primary energy from other provinces or countries (Fig. 3). Beijing not only imports 100% of the oil and natural gas it needs but also 60% of its electricity. In 2016, oil and gas have already exceeded coal in the total energy consumption of the city. The percentage of coal in the total energy consumption was 9.8%, whereas this number in most developed countries is below 5% (Wu *et al.*, 2014); oil and natural gas accounted for 32.9% and 31.7%, respectively, of the total energy consumption of Beijing [Beijing Statistical Yearbook, 2016 (Beijing Bureau of Statistics, 1980–2011, 2016)]. In 2016, Beijing generated 40% of thermal electricity locally, with gas-fired power plants accounting for the vast majority (86%). In 2017, all the coal-fired power plants in Beijing were shut down as part of the air pollution control measures (Clean Air Action Plan of Beijing, 2013–2017), and this remains effective in 2018, further lowering coal consumption in Beijing.

From the energy end use perspective, all four sectors except for agriculture are significant players, consuming 99% of the energy (Fig. 3). The commercial sector comes in at first place, accounting for 31.6% of the total energy consumption in 2016. Domestic, industrial, and transportation uses are roughly equal players, accounting for 24.1%, 23.1%, and 20%, respectively, of the total energy consumption in 2016. Of the 23.1% energy consumed by the industrial sector, manufacture contributed 13.6%. Compared with the year 2000, when more than 60% of the energy consumption in Beijing went to industrial sectors, the energy end use structure has
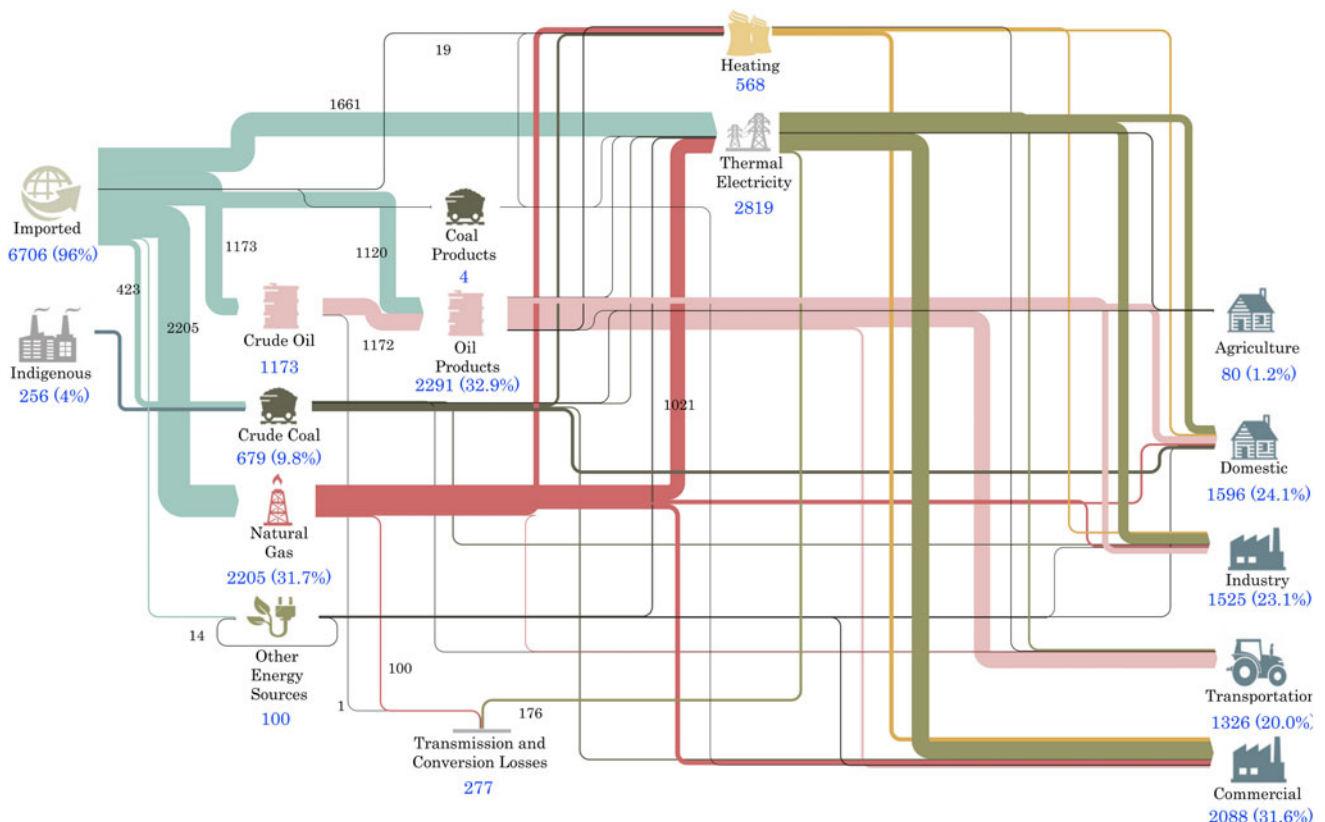
FIG. 3. Sankey diagram of energy flows in Beijing, 2016 (Unit: 10^4 TCE). The widths of the bands are directly proportional to energy production, utilization, and losses. TCE, tons of standard coal equivalent.

evolved due to modernization in manufacturing and growth in service industries.

Accounting of the WEN

Based on the analysis of the water and energy flows above, the energy and water intensity of each individual sector, the EFW and WFE are calculated to illustrate the WEN in Beijing.

Energy for water. The total EFW sectors of Beijing is 3.06 billion kWh or 0.79 million TCE in 2016 (Table 1), accounting for 3% of the city's total electricity use (102 billion kWh) or 1.1% of the city's total energy consumption (69.6 million TCE). This value did not include the EFW end use at household level (e.g., the energy for heating water, running washing machines, or dishwashers). A previous study by Li (2012) estimated the household-level EFW of Beijing in 2010 as 4.88 billion kWh, which is greater than the EFW in this study. But it is still debated (see the Section "Energy associated with the SNWD project and water end use") whether the EFW at household level should be included or not in the calculation of the total EFW chain (Hu *et al.*, 2013).

The processes of EFW (Fig. 4) include extracting water from sources, conveying water directly to end users (e.g., irrigation) or through public water supply, and treating wastewater before discharge or reuse (Water in the West, 2013). Local EFW within Beijing's boundary is split roughly equally into four ways among recycled (27%) and waste (5%) water treatment for a total of 32%, groundwater extraction (28%), pumping and conveying the water from the SNWD (19%) and from local reservoirs (2%) for a total of 21% for

surface water extraction, and finally public water supply (19%) (Table 1). In comparison, EFW is 64% for water abstraction, 29% for public water supply, and 7% for wastewater treatment for China (Li *et al.*, 2016a, 2016b). It is worth noting that the percentage of energy for recycling and treating wastewater in Beijing (32%) is much higher than that of the national average (7%).

From water use perspective, Fig. 4 shows that more than half of EFW goes to the domestic sector, and this only considers the water-related energy from the water utility perspective and does not include the water-related energy use in households. The potential to save energy, and possibly water, in the domestic sector has not been fully exploited. For China as a whole, the energy for agricultural use ranks first and accounts for 41% of the total EFW (Li *et al.*, 2016a). While in Beijing, the energy for agricultural water use is only 10%, only slightly more than that for industrial use (Fig. 4). The external energy for imported water is discussed in the Section "Energy associated with the SNWD project and water end use."

Water for energy. The total water consumption for internal energy production is about 220 million m³, accounting for 5.6% of the total freshwater consumption of Beijing in 2016 (Table 2). Power generation (mainly for cooling water use) consumes the largest amount of water in part due to the highest water intensity among the categories of energy considered, accounting for 74% of the total WFE.

We also estimate the WFE imported to Beijing in 2016. Assuming the water intensities of energy production outside Beijing are the same as inside the city, the amount of WFE occurred outside Beijing is estimated to be about 290 million
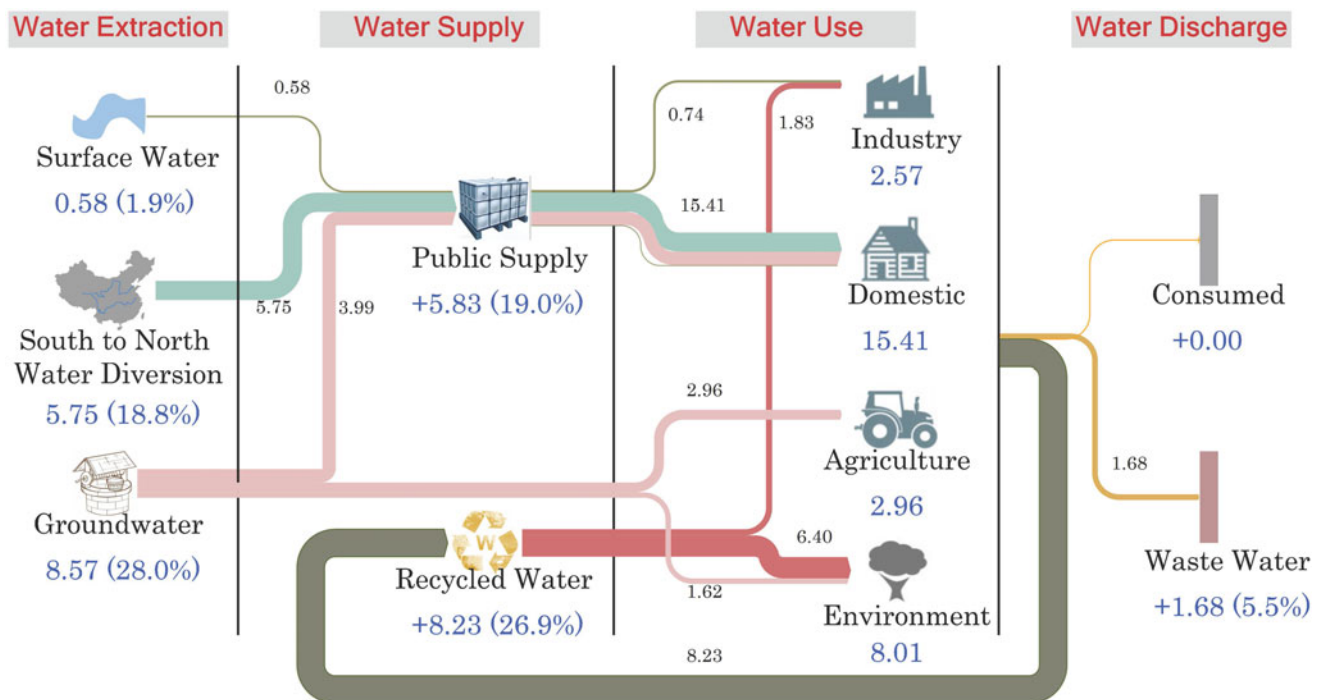
FIG. 4. Energy for water in Beijing in 2016 (10⁸ kWh). The numbers in *blue* indicate the EFW in each sector and/or process, and the numbers with "+" indicate the energy added for that specific process. The widths of the bands are directly proportional to EFW, with the quantity marked by numbers in *black*. EFW, energy for water.

m^3, based on the ratio between indigenous and imported energy as well as the energy mix. This implies that much of the water demand for energy is outsourced. Similar to the WFE pattern inside Beijing, water for the imported power generation consumes the largest amount of water, accounting for 80% of total outside water use. It should be noted that the accurate quantification of WFE of the imported energy needs the specific water intensity information for energy production in the energy export regions. Considering the water intensity for unit energy production in Beijing is likely the lowest in China due to the most advanced technologies used by Beijing's utility companies, the 290 million m^3 water outsourced is a conservative estimate, as a crucial initial step to unravel the outsourced water stress in nearby regions that also do not have abundant water supply (Cao et al., 2014; Wang et al., 2013).

Figure 5 illustrates the water and energy nexus internal and external to Beijing. Energy of Beijing depends more on external sources and is reflected by the external WFE of at least 290 million m^3 per year. Water supply in Beijing depends on groundwater, recycled water, and surface water sourced locally, with 22% transferred from outside through the SNWD project that has an embedded energy content (see Discussion: "Energy associated with the SNWD project and water end use"). The local EFW is 0.79 million TCE, accounting for 1.1% of Beijing's total energy consumption. Hu et al. (2013) found that electricity required for water supply, treatment, utilization, and postuse comprised about 5–7% of total electricity consumption for 2009. The reason that our results are different is because Hu et al. (2013) took into account the energy for urban and rural household water end use in addition.

Discussion

Nature-based solutions to recycle wastewater for protection of groundwater resource

A surprising result is that despite the availability of 0.84 billion m^3 of transferred water from the SNWD annually
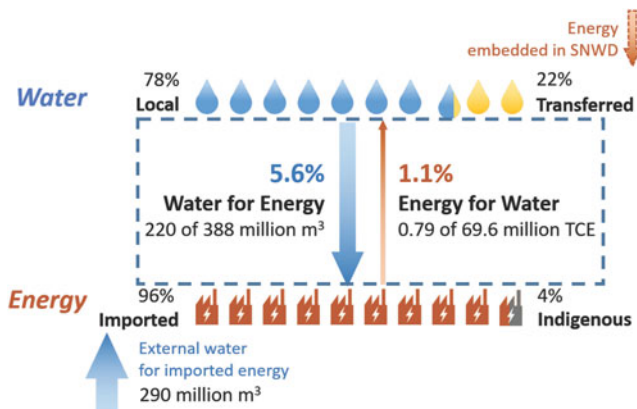
FIG. 5. Water and energy nexus of Beijing. Energy production, mostly for generating electricity, is water intensive, consuming 220 million m^3 of water within the boundary of Beijing and 290 million m^3 of water outside the boundary of Beijing. In contrast, 0.79 million TCE or 1.1% of total energy consumed within the boundary of Beijing is used to abstract, supply, and treat water. This value did not consider EFW at household level. The external energy consumption of the South to North Water Diversion is estimated as 0.06 million TCE based on Liu et al. (2015a, 2015b).

(Fig. 1), groundwater still accounts for the largest portion of Beijing's water supply (45%). In 2016, the groundwater level increased by 0.52 m and the aquifer storage increased by 0.27 billion m^3 on average compared with 2015. However, if compared with the values in 1980s and 1990s, the groundwater level and storage still exhibited significant decline (Beijing Water Authority, 2016), with an average drop of groundwater level of 17.99 and 13.35 m, and a storage decline of 9.21 and 6.84 billion m^3, respectively (Beijing Water Authority, 2016). To restore aquifer storage, the 13th Five-Year Plan has set a target to reduce groundwater pumping by 0.4 billion m^3 per year, although the efficacy of this policy still needs assessment because the groundwater supplied was 1.8 billion m^3 in 2015 (Beijing Water Authority, 2015) compared with 1.75 billion m^3 in 2016 (Fig. 2), suggesting that the target to reduce groundwater extraction was barely met.

A further reduction in groundwater pumping is desirable, although it would require significant water conservation efforts and/or more recycling of wastewater. In 2016, about 1 billion m^3 out of a total 1.7 billion m^3 of wastewater, or 59% of wastewater, is recycled. Yet recycling more wastewater would mean higher energy use because the energy intensity to recycle wastewater is about 2.5 times higher than that to treat wastewater for discharge (Table 1). In addition, most of the recycled water is for eco-environmental use (Fig. 1), which has not only enhanced the flow in surface water but also infiltration into groundwater, resulting in increasing chloride concentration if the recharge is unmanaged (Yu et al., 2014; Zheng et al. 2015). Therefore, it seems wise to consider low energy intensity, nature-based solutions (Palmer et al., 2015) such as wetland and managed aquifer recharge techniques to polish treated wastewater so that the recycled water can be used for purposes other than environment. Such nature-based solutions still have a long way to go in China. In a recent global assessment, China purposefully recharges and recovers only 0.1% of 112 billion m^3 of groundwater it extracts annually, whereas the global average is 2.4% of 415 billion m^3 of worldwide groundwater extraction (Dillon et al., 2019). Although conjunctive surface water and groundwater management has been highlighted in the 13th Five-Year Plan, our analysis show that a critical missing link in the surface water and groundwater conjunctive management is the fate of treated wastewater, which by now has become a significant component of the surface water and groundwater systems in megacities thus requiring further research to understand the fate of the treated wastewater and the constituents within.

In addition, development of renewable energy to upgrade wastewater treatment can make the siting of the two be simultaneously considered for potential savings. Renewable energy in Beijing includes wind and solar. The capacity is very limited and is distributed in the mountainous regions (Fig. 1) and roofs of high-rise buildings. The renewable energy plan again calls for such areas through the construction of wind power plants (Wu et al., 2014). The siting of renewable energy development should simultaneously consider wastewater treatment needs.

Energy associated with the SNWD project and water end use

The energy associated with the SNWD project includes the operational energy and the embedded energy. For the middle

route of the SNWD, the operational energy is negligible as the elevation of areas receiving water is almost 100 m lower than the elevation of the water source (Smith *et al.*, 2018). The infrastructures to transfer water over long distances require significant amounts of concrete and steel, which in turn means large energy inputs due to high embedded energy intensity of water provision (Kahrl and Roland-Holst, 2008), but usually, they are counted as constructional energy use. Liu *et al.* (2015a, 2015b) calculated the carbon footprint for the SNWD project considering the material production (concrete, steel etc.), material transportation, operation, and maintenance. Their study found that the carbon emissions during the operation stage consisted of a small fraction of total carbon footprint, or 5% of 0.179 kg CO_2 per m^3 of water if the operation period is 30 years. Thus, the annual carbon footprint of the 0.84 billion m^3 SNWD water is estimated to be 0.15 Mt CO_2 if the operation period is 30 years, which is about 0.06 million TCE embodied energy annually (based on the factor of 2.54 tCO_2/TCE; Tu and Liu, 2014).

The energy associated with water end use activities (especially the residential sector) can be more than that for the delivery of water and the treatment of wastewater (Kenway *et al.*, 2008, 2011b; Rothausen and Conway, 2011; Plappally and Lienhard, 2012; Binks *et al.*, 2016; Wakeel *et al.*, 2016). However, this part of energy is less studied than other stages of the water use cycle (Wakeel *et al.*, 2016). Furthermore, it is still an open question whether this part of energy should be included in the calculation of EFW (Hu *et al.*, 2013; Wakeel *et al.*, 2016). In this study, we did not consider the EFW end use due to data availability at household level, although it is worth noting that domestic water use accounted for nearly half of the total water use in Beijing, suggesting that water conservation at household level can be the most effective way to reduce both water and energy consumption (Wakeel *et al.*, 2016). In the United States, 14% of California's electricity and 31% of its natural gas are consumed for water end use activities, which is larger than 5% of its electricity consumption used in treatment and supply processes (Wakeel *et al.*, 2016). In Australia, the residential end use of water is responsible for ∼30% of energy used throughout the urban water cycle (Kenway *et al.*, 2011a). Water conservation is equivalent to energy conservation, taking Australia as an example, the water conservation in 2006/2007 by households led to a 15% reduction in energy use (Kenway *et al.*, 2008). At the household level, water heating and cloth washing are the most energy-intensive uses, among which the energy used for water heating constitutes 14–25% of total energy consumption at domestic level (Siddiqi and Fletcher, 2015). Experiences from other countries suggest that water conservation at household level deserves great attention and is also where more WEN study is needed.

The WEN of megacities beyond geographical boundaries

Accounting of the WEN for megacities needs to explicitly define boundaries within and beyond which both water and energy are produced and consumed to facilitate comparison of results with WEN studies at national and global levels and to assess how sustainable cities are. Globally, the WFE production is 10% of the total water consumption (International Energy Agency, 2014). And, the EFW accounts for 1.7–2.7% of total global primary energy consumption (Liu *et al.*, 2016). In the United States, the WFE or energy-related water consumption accounts for about 10% of both total and freshwater United States water consumption (Grubert and Sanders, 2018), whereas the EFW or water-related energy use accounts for 1.0–1.9% of total primary energy consumption (Liu *et al.*, 2016). Li *et al.* (2016a, 2016b) estimated that on average 4% of China's electricity is used for various water sectors in 2011, with surface water abstraction accounting for 41% of the total electricity-for-water. Li *et al.* (2016a, 2016b) considered interbasin water transfer projects over the country, which require intensive operational energy.

Beijing's internal WFE (5.6%) is less than the world average. This may be misinterpreted as megacities like Beijing are more "sustainable," whereas the reality is simply incomplete accounting of the imported water and energy (Fig. 5). It is not surprising that water and energy stress of megacities is outsourced to regions far beyond the geographic boundaries of these cities. Zhao *et al.* (2016a, 2016b) made a similar argument through investigating the megacity Shanghai, which draws water resources from all over China and outsources 79% of freshwater consumption, 82.9% of chemical oxygen demand, and 82.5% of NH_3-N to other regions through virtual quantity and quality water flows associated with trade. Wang and Chen (2016) explored the WEN of urban agglomeration using a case study in the Beijing-Tianjin-Hebei region. Their findings show the differences of direct energy/water and embodied energy/water consumption between sectors and regions, and the nexus effect on energy and water networks for Beijing is bigger than those of Tianjin and Hebei, that is, Beijing is more dependent on outside for water and energy resources, whereas Hebei is more self-sufficient. Once we considered the external WFE of Beijing, which at 290 million m^3 is 1.3 times higher than the internal WFE (Fig. 5), the proportion of Beijing's WFE will rise to be comparable to the world average WFE at 10%.

The proportion of internal EFW of Beijing at 1.1% (Fig. 5) is quite close to the United States (1.0–1.9%) and the world EFW (1.7–2.7%) (Liu *et al.*, 2016). It is worth noting that the water-related processes considered in this study and in Liu *et al.* (2016) include withdrawal from the sources, conveyance, treatment, distribution, wastewater treatment, and discharge. While there are other studies like Sanders and Webber (2012) that also claimed the energy applied to water end uses—including the residential, commercial, industrial, and even electric power sector—as the "energy for water," therefore they estimated a much higher EFW as 12.6% of the United States's primary energy consumption. Kyle *et al.* (2016) and Liu *et al.* (2016) argued that the type of energy actually is the energy applied to "water for other purposes" and should not be included as the "energy for water." The controversial about this indicates that different definition of the system boundaries of EFW will lead to different results of the EFW accounting.

In the future, it is unlikely that Beijing can "import" more water to meet its rising water demand. Because importing energy or developing renewable energy is easier than importing water, it makes sense for Beijing to boost wastewater treatment capacity to recover and reuse this valuable resource as discussed in the Section "Nature-based solutions to recycle wastewater for protection of groundwater resource".

Table 3. Water Energy Nexus in 2020

Item	Energy mix[a] (million TCE)	% of Energy mix	Water intensity[b] (m³/TCE)	WFE (million m³)	% of Total WFE
Coal	3.6	4.7	4.42	15.9	4.3
Electricity	23	30.3	13.93	320.5	85.9
Natural gas	24	31.6	0.94	22.6	6
Oil refining	23.2	30.5	0.61	14.3	3.8
Others	2.2	2.9			
Total	76	100		373	100

[a]Energy mix data were sources from the 13th Five-Year Energy Development Plan of Beijing (2016–2020), with coal being 5 million tons, electricity being 77 billion kWh, natural gas being 19 billion m³, and oil refining being 22 billion L.
[b]Water intensities for energy production is calculated by water quota per 10,000 Yuan and the unit energy price in Table 2.

WEN in 2020 and policy implication

Based on the planned energy mix in the 13th Five-Year Energy Development Plan of Beijing (2016–2020) and the current water intensity levels, the WFE is estimated to reach 373 million m³ by 2020 (Table 3). In alignment with the ''Strategy on Energy Production and Consumption Reform (2016–2030)'' policy released by China's central government (NDRC, 2016) to cap total energy consumption nationwide, Beijing's 13th Five-Year Plan has placed a target cap of its energy consumption, with coal consumption reduced to <5% and the proportion of high-quality energy (i.e., electricity, natural gas, refined oil, renewable energy, and new energy) consumption increased to >95% (Table 3).

It is worth noting that reduced local coal consumption in Beijing is to be made up by imported electricity mainly from Shanxi and the western Inner Mongolia. Multiple gas sources, including coal-gas from Inner Mongolia and liquefied natural gas from Tangshan, Hebei Province and Shaanxi Province, will be utilized to replace local coal consumption of Beijing. Because coal-gas production and liquefied natural gas are water intensive, with every 1,000 m³ gas consuming 6.9 tons of freshwater and every ton of liquefied gas consuming 11 tons of freshwater (CPCIA, 2017), this will cause the external WFE to increase and aggravate the already serious water scarcity of Inner Mongolia and Shaanxi.

Based on the target of water use in the 13th Five-Year Water Development Plan of Beijing (2016–2020), the EFW is expected to rise. The water use cap of 4.3 billion m³ is planned to allocate to agricultural, industrial, domestic, and environmental uses of 0.5, 0.51, 1.82, and 1.47 billion m³, respectively. Assuming the current average energy intensity of each water using sector and the water supply structure remain unchanged, by 2020, the total EFW is estimated to increase by 40 million kWh, or 1.3% higher than current EFW. To meet the ''three-red-line'' target (Liu et al., 2013), Beijing's water supply and water quality control will be more reliant on energy-intensive approaches, which could put more pressure on achieving the energy conservation targets. The recycled water use will be accelerated, and by 2020, the total recycled water use will increase to 1.2 billion m³, to replace 0.4 billion m³ freshwater annually. And the transferred water will be increased too with the extension of the SNWD eastern route to Beijing. All these changes will lead to continued increase of the EFW. This trend is understandable as water has become the biggest limiting factor for Beijing's growth, and various water suppliers pursue to guarantee water security even at the expense of consume more energy.

Although the percentage of EFW may not appear significant for now, it nevertheless represents a large amount of energy (3.06 billion kWh in 2016) and therefore also a significant source of greenhouse gas emissions. Moreover, this part of energy demand and emissions stand to grow substantially in the future with increasing water scarcity and higher water quality requirements (Liu et al., 2016).

Limitations

Although a time-series analysis is more desirable, this study evaluates the water and energy flow for the year 2016, the first year of the 13th Five-Year Development Plan, due to data availability. It nevertheless provides an updated assessment of the WEN of Beijing after the arrival of SNWD water in the end of 2014. In addition, for the imported nexus analysis, the water intensity and energy intensity were assumed to be the same as inside Beijing, this will likely result in underestimation of imported WFE and EFW.

Conclusions

The analysis of the WEN finds that Beijing is outsourcing its water stress through importing both water and energy, and this outsourcing will rise further in the future. The physical water scarcity in Beijing led to not only importing water through the SNWD but also importing energy due to difficulty to allocate WFE production locally. Furthermore, air pollution control measures invoke a replacement of coal by higher quality energy sources especially natural gases, resulting in also an increase in energy imported. Finally, after all ''imported'' water from the SNWD reaches Beijing, the only underutilized source of water is wastewater. Enhancing wastewater treatment and recycling through imported energy, or newly developed renewable energy, or adopting low energy intensity nature-based green solutions, appears to be a good option to alleviate future water stress in Beijing. The best solution emerged from this WEN analysis is to adopt nature-based solutions to recycle wastewater and recharge aquifers that would address both water scarcity and meet energy governance targets of Beijing simultaneously.

The WEN of megacities like Beijing is beyond its geographic boundary and needs to be evaluated accordingly. It is recommended that future water and energy policies consider the nexus within and beyond Beijing's geographic boundaries. The contradiction between the two independently conceived policies is evident: to meet the ''three-red-line'' target in the water sector, recycled water and transferred water use will rise,

making it more difficult to meet the emission control and low-carbon development targets. Yet outsourcing energy production is equivalent to outsourcing water stress to the energy exporting regions that also experience water scarcity. Considering the WEN beyond the geographical boundaries will help megacities toward sustainable urban development and promote synergetic regional development.

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