Life cycle water use of energy production and its environmental impacts in China

Chao Zhang [a,b,c,*], Laura Diaz Anadon [b]

[a] Mossavar-Rahmani Center for Business and Government, Kennedy School of Government, Harvard University, United States

[b] Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University, United States

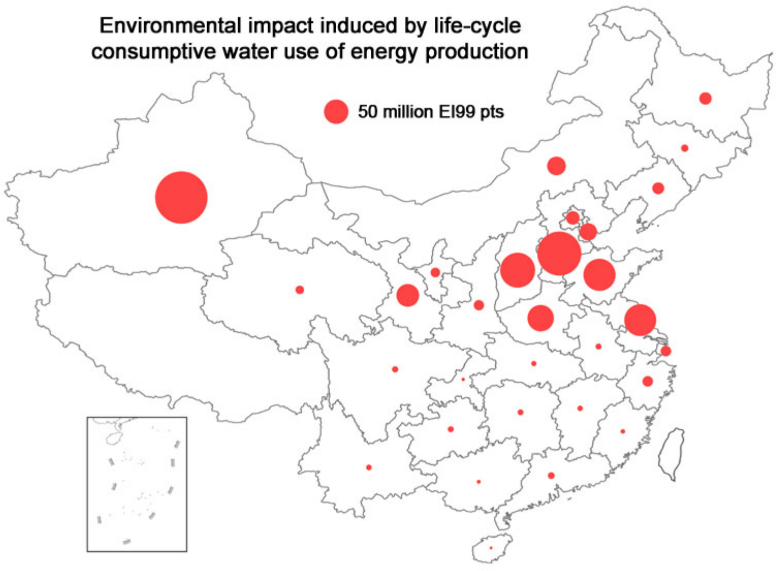
[c] School of Economics and Management, Tongji University, China

Abstract

The energy sector is a major user of fresh water resources in China. We investigate the life cycle water withdrawals, consumptive water use, and wastewater discharge of China's energy sectors and their water-consumption-related environmental impacts, using a mixed-unit multi-regional input-output (MRIO) model and life cycle impact assessment method (LCIA) based on the Eco-indicator 99 framework. Energy production is responsible for 61.4 billion m^3 water withdrawals, 10.8 billion m^3 water consumption and 5.0 billion m^3 wastewater discharges in China, which are equivalent to 12.3%, 4.1% and 8.3% of the national totals, respectively. The most important feature of the energy-water nexus in China is the significantly uneven spatial distribution of consumptive water use and its corresponding environmental impacts caused by the geological discrepancy between fossil fuel resources, fresh water resources and energy demand. More than half of energy-related water withdrawals occur in the east and south coastal regions. However, the arid north and northwest regions have much larger water consumption than the water abundant south region, and bear almost all environmental damages caused by consumptive water use.

Abstract Art

[*] Corresponding author
Phone: +86 21 65984236; fax: +86 21 65986304; e-mail: chao_zhang@tongji.edu.cn, zhangchao03@gmail.com



TOC/Abstract Art

1. Introduction

Energy and water are two fundamental resources that support most aspects of human well-being. It has been increasingly recognized that energy and water sustainability are inextricably intertwined ([1]). The energy sector is the second largest water user in the world in terms of withdrawals, following irrigation ([2]). Almost every stage in the energy supply chain needs water in various ways ([3, 4]), e.g., water is used for drilling and fracturing in oil and gas exploration([5, 6]); large volumes of cooling and processing water are often needed in thermal power generation ([3, 7-9]); some feedstocks for biofuels need considerably large amounts of water ([10-15]). Besides its impact in terms of the magnitude of water consumed and withdrawn, energy production can also cause serious degradation to the local aquatic environment. Fossil fuel extraction, especially coal mining, can pollute aquifers and lead to ecosystem and health damages ([16, 17]).

A water-constrained future makes water an increasingly important vulnerability in the energy sectors ([18, 19]). Water shortages caused by an over exploitation of freshwater resources and drought have already affected the electric generation in some parts of the world ([2]). On the one hand, such an impact is likely to occur with more frequency in the future due to climate change ([19, 20]). On the other hand, driven by growing population and economic growth, the energy sector will continue to expand and this expansion will continue to increase the pressures on fresh water demand in many nations([20-22]). For example, Davies et al. ([23]) shows that global consumptive water use by electric power generation could increase by 4-5 times from 2005 to 2095.

As a reflection of the growing concerns about the growing pressures of energy production on water resources, an increasing number of studies aimed to systematically quantifying the energy-water nexus in water scarce nations and regions, such as the Middle East and North Africa([24]); Mexico([25]); Spain([26]); and the United States([27-30]) . However, no comprehensive study is currently available for China, even though China's energy-water nexus presents some distinct features. First, China is already suffering from severe water shortages. The average annual per capita renewable water resources in China are only about one third of the world's average ([31]). The annual per capita water resources in the 10 provincial jurisdictions, where 34% of China's population live, are well below 1000 m^3([32]), which is the widely regarded water scarcity threshold (See Figure S1 in the Supporting Information). Second, driven by China's unprecedented economic boom over the past decade, total primary energy production has more than doubled between 2000 and 2010 ([33]). The competition for limited water resources between users in the energy industry, other industries, and other users (e.g., irrigation and domestic use) is intensifying. Third, there exists a significant geological mismatch between the distribution of coal resources, the dominant primary energy source in China, and that of water resources. The three provinces with the largest coal outputs in China, namely, Shanxi, Shaanxi and Inner Mongolia, contribute more than half of the total national coal output and 16% of thermal power generation, but are only endowed with 3% of national water resources ([33]). Fourth, China is a major player in the world energy market, with 17.3% of global energy production and 17.5% of global consumption in 2010([34]).

Most previous studies on investigating the energy-water nexus have used technology-based bottom up accounting methods to calculate water use (water withdrawals and/or consumptive water use) in energy sectors. These studies multiply activity levels of different energy production technologies with corresponding water intensity ([24, 30]). While these studies calculate the direct water withdrawals and/or consumption of the energy sector, indirect water use embodied in the upstream supply chains of energy production are usually not included. Furthermore, few studies accounting for the life-cycle water withdrawal, consumption, and discharge (mainly using input output analysis techniques) have assessed the environmental impact of water use in the energy sector.

In this study, we focus on the life cycle water use of energy production and its environmental impact in China. We quantify life cycle freshwater withdrawals, consumptive water use and wastewater discharge of eight energy products (namely, coal, crude oil, natural gas, petroleum products, coke, electricity, heat and gases) at the provincial level. The definition of consumptive water use adopted in this study is also consistent with the widely accepted notion of blue water footprint ([35]). In order to cover the full supply chain of energy production, we base our analysis on a mixed-unit multi-regional input-output (MRIO) model, in which data on energy consumption and water use in physical units are merged with monetary input-output (IO) tables. In the impact assessment step, the method and data provided in Pfister and colleagues ([36]) is used to quantify damages to human health, ecosystem quality and resources caused by life cycle water consumption of energy production. This provides insights to researchers and policy makers interested in: (1) understanding the spatial characteristics of China's energy-water nexus; (2) mitigating environmental impacts related to consumptive water use caused by energy production in hotspot regions and (3) identifying the water-related implications of future energy plans and of severe droughts.

2. Methodology and Data

2.1 Mixed unit MRIO model

The multi-regional input-output analysis model (MRIO) is widely used to trace the supply chain environmental impacts embodied in trade activities from a consumption-based perspective ([37-40]), with plenty studies conducted at both global ([41-43]) and national scales ([44-47]). The basic equation of a MRIO model containing R regions can be expressed as follows:

$$W=f^{*}X^{*}=f^{*}\left(I-A^{*}\right)^{-1}Y^{*} \tag{1}$$

where $X^{*}=\left[x^{1},\cdots,x^{r},\cdots,x^{R}\right]^{T}$ is the aggregated output vector of all sectors in all regions; $A^{*}=\begin{pmatrix} A^{11} & A^{12} & \cdots & A^{1R} \\ A^{21} & A^{22} & \cdots & A^{2R} \\ \vdots & \vdots & \ddots & \vdots \\ A^{R1} & A^{R2} & \cdots & A^{RR} \end{pmatrix}$ is the aggregated inter-regional direct requirement coefficient matrix; $Y^{*}=\left[\sum_{s} y^{1s}+ex^{1},\sum_{s} y^{2s}+ex^{2},\cdots,\sum_{s} y^{Rs}+ex^{R}\right]^{T}$ is the aggregated final use vector; y^{rs} is a column vector represents goods or services produced in region r and consumed in region s; ex^{r} is a column vector represents exports from region r; and $f^{*}=\left[f^{1},\ldots,f^{r},\ldots,f^{R}\right]$ is the water use coefficient vector, referring to water withdrawal, water consumption, or wastewater discharge intensities in different calculations. W is the total water withdrawals, water consumption or wastewater discharges driven by the final demand Y^{*}.

Mixed-unit input-output models are an extension of standard monetary IO analysis. They integrate monetary input-output data and mass flows expressed in physical units into a consistent framework and capture the characteristics of both economic transactions and material flows in an economy ([48, 49]). This study constructed mixed-unit IO tables for each province. Monetary input-output data of energy and water sectors in the original IO tables are replaced by sector-wise energy consumption and water use data in physical units extracted from various data sources. Then, provincial IO tables are compiled into a mixed-unit MRIO table by using a gravity model ([50, 51]) to estimate inter-regional trade flows. In order to extract supply chain water use by different energy products produced in different regions, we use a deduction approach in the calculation. More methodological details are presented in the Supporting Information.

2.2 Data sources

We put together a mixed-unit MRIO table of China for 2007 (the latest year with data available), including 30 provincial jurisdictions, eight energy products in physical units, one water production and distribution sector in physical units and 22 non-energy and non-water sectors in monetary units. Three groups of data are used in this research: (1) provincial monetary IO tables; (2) provincial and sectoral energy production, consumption, and trade data; and (3) provincial and sectoral freshwater withdrawal, water consumption and wastewater discharge data.

The monetary IO tables of each province ([52]) are first transformed into a mixed-unit IO table with energy and water data. Five energy sectors in the original monetary IO tables are removed and replaced by eight energy products expressed in physical units (Table 1 presents the mapping between monetary sectors and physical accounts). Production, consumption and trade amounts of energy products are sourced from the provincial energy balance tables ([53]) and the energy consumption surveys reported in China's second national economic census ([54]).

Table 1. Mapping the relationship between monetary sectors and energy and water products

	Original monetary sectors in the IO tables	Corresponding physical accounts in the mixed-unit IO tables
Energy	Coal mining	Coal
	Crude oil and natural gas extraction	Crude oil
		Natural gas
	Oil refining and coking	Petroleum products
		Coke
	Electric and heat production	Electricity
		Heat
	Gas production and distribution	Gases [a]
Water	Water production and distribution	Tap water

[a] "Gases" includes coal gas and all kinds of recovered gases from industrial processes, such as coke oven gas, blast furnace gas and converter gas.

Water use data collection and estimation takes many steps. Water withdrawal and wastewater discharge by industrial sectors are reported in the first national pollution source census in China conducted by Ministry of Environmental Protection (MEP) and National Bureau of Statistics (NBS) ([55]). This is the most comprehensive dataset currently available that provides sector-wise statistics of water withdrawal and wastewater discharge in each province. Information on irrigation water withdrawal and water consumption in the agriculture sector is extracted from the various provincial water resources bulletins. Precipitation, or green water use, is not included, since green water is usually not subjected to competitive demand. The sector-wise water consumption is not reported in the different industrial sectors. Thus, except for the "electricity" sector, we assume that the water consumption of the different industrial sectors equals their water withdrawal minus wastewater discharge. This means that the water withdrawals that do not return back to the environment in the form of wastewater (either treated or untreated) is 'consumed' through evaporation, absorption by products, and/or other losses. Consumptive water use by the "electricity" sector in each province needs to be estimated separately. Because of the lack of information to provide reliable estimates at provincial level, water consumption related to hydropower generation due to evaporation is not included in this study. Therefore, consumptive water use of "electricity" sector in this study is related to thermal power generation. Three types of cooling technologies are used in China, i.e., once-through cooling, closed-loop cooling and air cooling, and they have very different water consumption performance profiles. We first estimate the proportions of the three cooling technologies in each province based on a literature survey and our own calculations. Then, we use data on the average water consumption factor of the different cooling technologies reported in the China Electricity Council's Thermal Power Unit Benchmarking and Competition Dataset ([56, 57]) to calculate total water consumption by thermal power generation in each province. Details about the steps of estimating water consumption data are provided in the Supporting Information. After compiling provincial mixed-unit IO tables, we balance the provincial IO tables at the national level and extend these single-province IO tables to a MRIO table based on the method of estimating inter-regional trade flows presented by Zhang and Qi ([58]).

3. Results

3.1 Life cycle water use per unit energy products

National average values of life cycle water use for each of the eight energy products by unit energy are presented in Table 2. Electricity has the highest water intensity across all indicators. Life cycle water withdrawals, water consumption and wastewater discharge intensities of electricity are 5263 m^3/TJ, 234.2 m^3/TJ, 656.7 m^3/TJ respectively (or 18.9 m^3/MWh, 0.84 m^3/MWh and 2.36 m^3/MWh). Direct water use accounts for 82% of the electricity life cycle water withdrawal, 63% of life cycle water consumption and 39% of life cycle wastewater discharge.

The life cycle water use of all other energy products is much lower than that of electricity. Large proportions of their life cycle water use are embodied in the upstream supply chains of the other seven energy products. Coal is the dominant primary energy source in China. Life cycle water withdrawals, water consumption and wastewater discharge intensity of coal are 106.4 m^3/TJ, 41.5 m^3/TJ and 38.4 m^3/TJ respectively (or 2.22 m^3/tonne, 0.87 m^3/tonne, and 0.8 m^3/tonne), in which 17%, 22% and 74% are direct water use. It is noteworthy that coal is the only energy product whose direct wastewater discharge intensity exceeds its direct water withdrawal intensity. This is because large volumes of mine drainage are generated and discharged during coal mining process. The water intensity of the "Gases" products is the smallest. This is because a large proportion of gases are recovered as by-products in industrial production processes, such as coking, and iron and steel making. Water use in the main production processes is not allocated to the recovered gases, since their economic values are rather small when compared with the main products and the recovering of gases has a negligible impact on the water use of the main production process.

Table 2. National average life cycle water use per unit energy products (m^3/TJ)

		Coal	Crude oil	Natural gas	Petroleum products	Coke	Electricity [a]	Heat	Gases
Water withdrawal	Direct	18.4	37.2	13.6	87.2	36.1	4306.5	609.4	7.0
	Life-cycle	106.4	257.9	104.5	446.8	217.7	5263.0	901.3	42.4
Water consumption	Direct	8.9	26.3	9.5	37.9	26.2	410.9	81.2	4.5
	Life-cycle	41.5	99.1	41.2	168.3	95.4	656.7	172.7	18.4
Wastewater discharge	Direct	28.3	11.0	4.1	49.3	9.9	90.6	15.7	2.4
	Life-cycle	38.4	42.8	18.7	104.3	52.7	234.2	81.8	8.6

[a] Including both coal-fired thermal power generation and non-coal power generation.

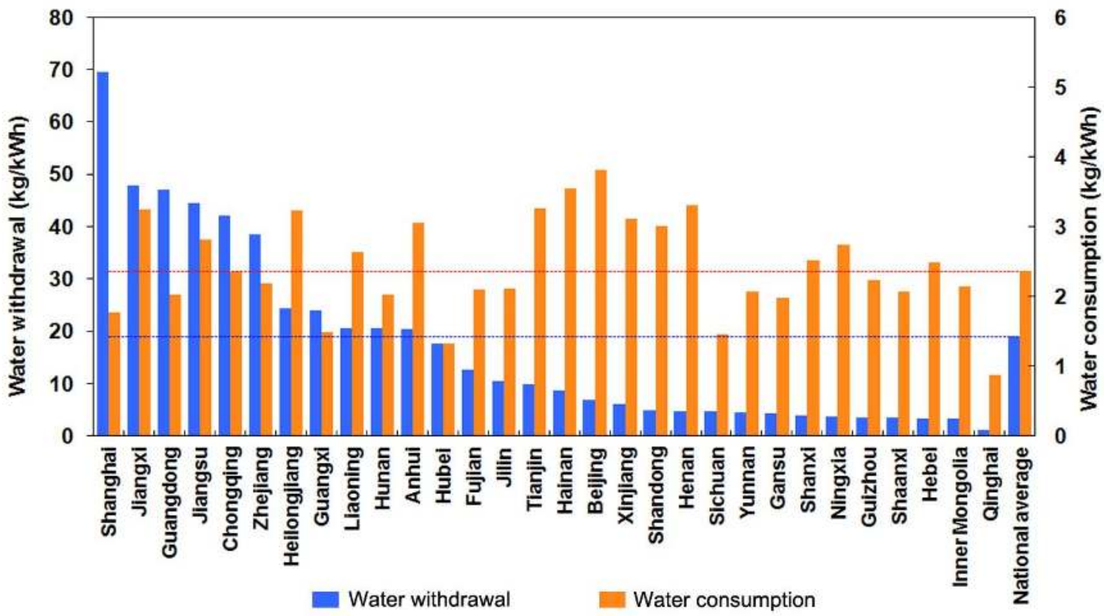


Figure 1. Life cycle water withdrawal and water consumption per kWh of electricity by region.

Figure 1. Life cycle water withdrawal and water consumption per kWh of electricity by region.

Regional differences of water use intensity are significant, especially for water withdrawals. Taking electricity for example, as illustrated in Figure 1, life cycle water withdrawal intensity can be as high as 69.5 m^3/MWh in Shanghai and as low as 1.2 m^3/MWh in Qinghai. Such a large difference is driven by a multiplicity of factors, e.g., the mix of power generation technologies, the adoption of different cooling methods in thermal power plants, and the structure of intermediate inputs of the power sector. In Shanghai, all electricity is produced by thermal power plants, but hydropower plays a dominant role in Qinghai. Since in-stream water use and evaporation from reservoirs related to hydropower generation are not considered in this study, the average water withdrawal and consumption intensity of electricity production in Qinghai are both the lowest. In terms of water consumption intensity, Beijing has the highest value of 3.81 m^3/MWh. Generally speaking, areas with poor water availability and a higher proportion of thermal power generation tend to have lower water withdrawals and higher water consumption intensity of electricity. Places with such characteristics are mainly located in northern China where water resources are scarce, such as Beijing, Tianjin, Shandong, Henan and Shanxi province.

3.2 Sector disaggregation of total life cycle water use related to energy production

The energy sector is a significant water user in China. Table 3 presents total life cycle water use of energy production and its sectoral disaggregation. Total life cycle water withdrawal, water consumption and wastewater discharge in 2007 amount to 61.4 billion m^3, 10.8 billion m^3 and 4.95 billion m^3, respectively, which equivalent to 12.3%, 4.1% and 8.3% of national totals, respectively. The proportion of direct water use by energy sectors is 87.3% for water withdrawal, 59.5% for water consumption and 72.1% for wastewater discharge. Electricity generation plays a very significant role in both in terms of water withdrawal and water consumption, as it accounts for 79.3% of total withdrawal and 47.0% of total consumption. For wastewater discharge, coal production makes up the largest contribution, with 32% of total wastewater water discharge. Among other non-energy sectors, agriculture is the major source of embodied water use, with 9.4% of total life cycle water withdrawal and 34.7% of water consumption. As expected given China's heavy reliance on coal, the energy-water nexus in China is dominated by coal-fired power generation.

Table 3. Sectoral disaggregation of life cycle water use of energy production in China

Sectors	Water withdrawal [a]		Wastewater discharge		Water consumption	
	million m^3	%	million m^3	%	million m^3	%
National total	**504,208**	**-**	**59,545**	**-**	**266,195**	**-**
Total life cycle water use	**61,356**	**100**	**4,952**	**100**	**10,839**	**100**
Direct use by energy sectors	**53,560**	**87.3**	**3,568**	**72.1**	**6,453**	**59.5**
Coal	1025.9	1.67	1584.4	32.00	495.5	0.85
Crude oil	296.9	0.48	87.6	1.77	210.3	1.91
Natural gas	39.3	0.06	11.8	0.24	27.5	0.25
Petroleum products	1234.2	2.01	697.4	14.08	536.8	4.88
Coke	344.0	0.56	94.6	1.91	249.4	2.27
Electricity	48635.9	79.28	1023.6	20.67	4641.4	47.01
Heat	1923.5	3.13	49.4	1.00	256.3	2.59
Other gases	55.4	0.09	19.3	0.39	36.1	0.33
Indirect use by other sectors	**7796**	**12.7**	**1383**	**27.9**	**4386**	**40.5**
Agriculture	5788.8	9.44	0.0	0.00	3761.3	34.70
Metal ores mining	106.5	0.17	42.2	0.85	64.3	0.59
Nonmetal ores mining	19.6	0.03	4.8	0.10	15.4	0.14
Food, beverage and tobacco	37.1	0.06	27.5	0.56	9.6	0.09

Textile	38.8	0.06	31.3	0.63	7.6	0.07
Wearing apparel and leather products	11.8	0.02	8.8	0.18	3.0	0.03
Timber processing and furniture	4.6	0.01	2.6	0.05	2.0	0.02
Paper products and education articles	223.1	0.36	179.8	3.63	43.3	0.40
Chemical products	388.7	0.63	231.7	4.68	157.0	1.45
Non-metallic mineral products	25.9	0.04	7.1	0.14	18.8	0.17
Ferrous and non-ferrous metals	235.1	0.38	85.0	1.72	150.0	1.38
Metal products	14.4	0.02	10.3	0.21	4.1	0.04
General and special purpose machineries	23.4	0.04	13.5	0.27	9.9	0.09
Transport equipments	14.0	0.02	8.6	0.17	5.4	0.05
Electrical equipments	8.6	0.01	5.0	0.10	3.6	0.03
Communication and electronic equipments	4.6	0.01	3.3	0.07	1.3	0.01
Measuring instruments and office supplies	2.3	0.00	1.3	0.03	1.0	0.01
Other industrial products	4.1	0.01	2.7	0.06	1.3	0.01
Construction	22.1	0.04	18.8	0.38	3.3	0.03
Transportation, storage and postal services	128.4	0.21	109.2	2.20	19.3	0.18
Wholesale, retail, lodging and catering	215.5	0.35	183.1	3.70	32.3	0.30
Other services	478.6	0.78	406.9	8.22	71.8	0.66

[a] Tap water withdrawals are included in the water withdrawals by each sector.

3.3 Spatial distribution of life cycle water use related to energy production

In arid areas where water resources are scarce, thermal power plants generally adopt closed-loop cooling systems to avoid the need to withdraw large amounts of water. Consequently, consumptive water use has increased dramatically due to evaporation. This leads to further depletion of the local water resources and intensifies water shortages. The tradeoff between water withdrawal and water consumption is explicitly revealed in our calculation. Subplot (a) and (b) in Figure 2 illustrates the provincial breakdown of water withdrawal and water consumption related to energy production in China.

Most energy-related water withdrawals occur in the eastern and southern coastal regions of China. Water withdrawal in Guangdong, Jiangsu, Zhejiang and Shanghai are 10.6, 10.5, 7.0 and 4.5 billion m^3, respectively, which are equivalent to 23%, 24%, 30% and 49% of their total local water withdrawal for all sectors and account for 53% of the national total energy-related water withdrawal. The Yangzi River Delta in the east coast and the Pearl River Delta in the south coast are China's major manufacturing hubs and most populated areas. Electricity production and consumption are high in these regions. In addition, their better water resources availability, compared with northern regions, results in a greater penetration of once-through cooling technology, thereby leading to large water withdrawals in the four aforementioned provinces.

The spatial distribution of energy-related water consumption differs tremendously from that of water withdrawals. There is generally an inverse pattern between the spatial distribution of water consumption and freshwater resources in China. The first five provinces with the largest energy-related water consumption are Shandong (995 million m^3), Shanxi (879 million m^3), Henan (855 million m^3), Hebei (718 million m^3) and Jiangsu (713 million m^3), which together account for 38.4% of the national total. Most areas of these provinces are located in the Huang-Huai-Hai River Bain, where the most severe water shortage problems in China occur.

The spatial distribution of wastewater discharge is quite similar to that of water consumption. As shown in the subplot (c) in Figure 2, northern China also bears a large proportion of energy-related wastewater discharges. Liaoning has the biggest discharge amount, i.e., 526 million m^3, which accounts for 10.6% of the nation total. Other major contributors include Henan (422 million m^3), Shandong (402 million m^3) and Hebei (334 million m^3).

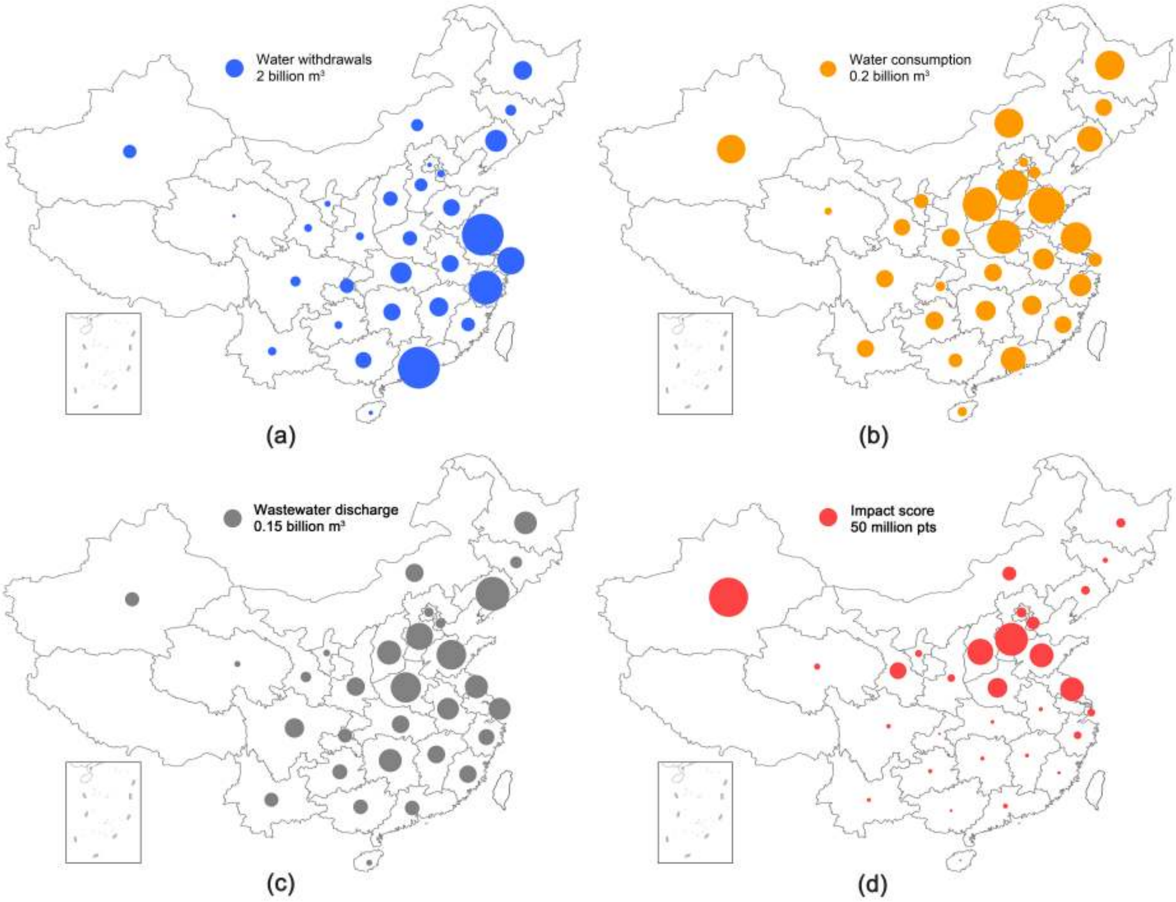


Figure 2. Spatial distribution of life cycle water withdrawal, water consumption, wastewater discharge and environmental impacts related to consumptive water use of energy production in China (Values are proportional to the area of corresponding circles—the scales are different).

Figure 2. Spatial distribution of life cycle water withdrawals, water consumption, wastewater discharge and environmental impacts related to consumptive water use of energy production in China (Values are proportional to the area of corresponding circles—the scales are different).

3.4 Environmental impacts of life cycle consumptive water use of energy production

The environmental impact needs to be understood to inform policy making on water resources management ([59]). The same volume of water consumption may have more significant impacts on human wellbeing and ecosystem health in water scarce regions than in water abundant regions. Considering China's large territory and significant differences in spatial water resource distribution, integrating the volumetric amount of water use by energy production with regional specific environmental impacts is critical to identifying the areas in China where the energy infrastructure is posing or may pose the most difficult water resource challenges.

In this section, we use the impact assessment method developed by Pfister and colleagues ([36]) to estimate the water-consumption-related environmental impacts induced by energy production at the provincial level. This method, based on the framework of Eco-indicator 99(EI99) ([60]), quantifies potential damages per cubic meter of water consumption on three aspects: (1) human health measured as disability-adjusted life years (DALY) caused by malnutrition due to water shortages for irrigation; (2) ecosystem quality measured as water-shortage related potentially disappeared fraction (PDF) of species in an area over a period of time; and (3) resources represented by energy requirements of desalination as a backup technology to replace the depleted water resources. Damages per unit water consumption, i.e., the characterization factors, and equivalent EI99 scores of the three impact categories at the watershed level provided in the literature ([36]) are aggregated at the provincial level (See Supporting Information for details of data aggregation). Life cycle freshwater consumption by energy production in each province is then multiplied with corresponding characterization factors and EI99 scores to calculate total damages.

National total damage to human health, ecosystem quality and resources related to life cycle water consumption by energy production in China are 4,027 DALY, 3.1×10^9 [PDF • m^2 • yr], and 25.2 PJ, respectively. The aggregate impact translated into EI99 points (pts) of the three categories are 104.7, 240.7 and 598.7 million pts, respectively. Potential damage to resources (which accounts for 63.4% of the country's total water-consumption-related damages of energy production) is larger than damages to ecosystem quality (accounts for 25.5%) and human health (accounts for 11.1%). A main reason is that over-withdrawals of freshwater resources widely occur in many watersheds in north China, where major energy production bases are located. Huge amounts of energy are potentially needed if the depleted water resources in those regions are to be replaced by sea water desalination, which is regarded as a backup technology for freshwater provision.

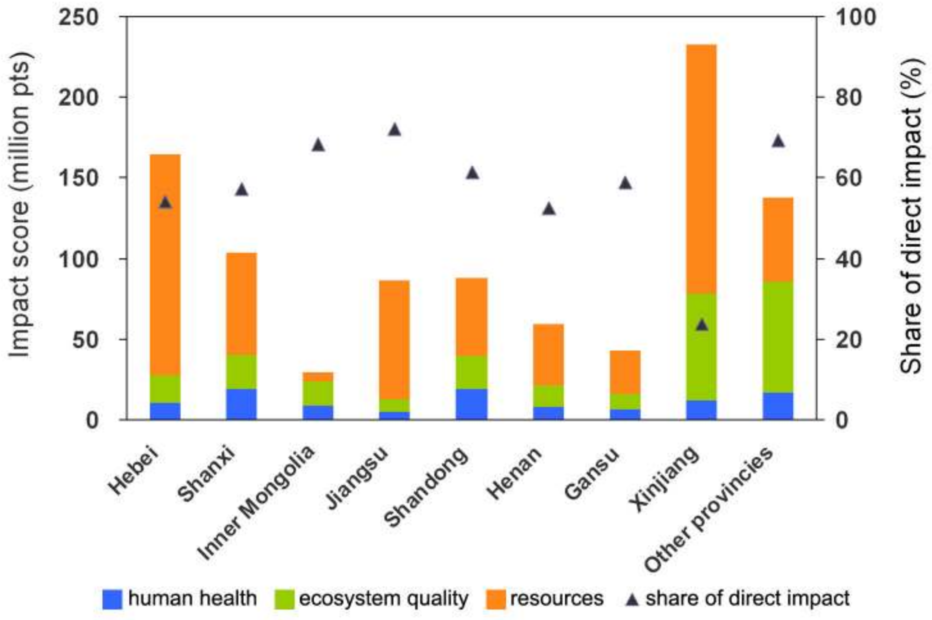


Figure 3. Composition of environmental impact and share of direct impact attributed to energy production in hotspot regions. Column bars represent impact scores (left scale) and triangles represent share of direct impact of energy production (right scale).

Figure 3. Composition of environmental impact and share of direct impact attributed to energy production in hotspot regions. Column bars represent impact scores (left scale) and triangles represent share of direct impact of energy production (right scale).

As shown in the subplot (d) in Figure 2, the spatial distribution of the environmental impacts caused by consumptive water use is much more uneven than the distribution of water consumption itself. Xinjiang, Hebei, Shanxi, Jiangsu, Shandong, Henan, Gansu and Inner Mongolia altogether bear 85.4% of the total environmental impacts, while energy-related consumptive water use occurred in these provinces account for 51.4% of the national total. Compositions of impacts in these hotspot regions are presented in Figure 3. The largest human health impacts occur in Shandong, while the largest damage to ecosystem quality and resources both occur in Xinjiang. However, indirect water consumption embodied in the upstream supply chain of energy production is responsible for most (76.2%) of the impacts in Xinjiang. In southern China, water consumption-related environmental impacts are almost negligible, compared with northern China. More details of the water use in energy production and its corresponding impacts by province are presented in the Supporting Information.

4 Discussion

In this study, life cycle water use and corresponding environmental impacts caused by water consumption in China are investigated. Overall, China's energy sectors are responsible for 12.3%, 4.1% and 8.3% of the national total water withdrawals, water consumption (excluding that of hydropower) and wastewater discharge, respectively. Coal-fired power generation plays a dominate role in both energy-related water withdrawals and water consumption. When compared to other regions throughout the world, the share of China's energy sectors in the total national water use is much larger than that of other arid countries such as countries in the Middle East([24]), but smaller than some water abundant countries such as the United States, where nearly half of the total water withdrawals are directly used by thermal power generation([61]). The most important feature of energy-water nexus in China is the significantly uneven spatial distributions of water use and its environmental impacts caused by the geological discrepancy between fossil fuel resources, water resources and economic activities. While more than half of energy-related water withdrawals occur in the eastern and southern coastal regions, the arid northern region has much larger water consumption than the water abundant southern region. The environmental impacts related to the consumptive water use concentrate in several hotspots provinces in northern China.

China is likely to continue to experience rapid expansion of coal-based thermal power generation along with its rapid economic development. According to the national 12th five-year (2011-2015) development plan of China's power sector ([62]), total capacity of coal-based thermal power is expected to reach 0.93 TW in 2015 and 1.17 TW in 2020, compared with 0.71 TW in 2010, and accounts for 63.5% and 60.5% of the total installed capacity respectively. Stimulated by the enormous impulse of developing local economy, local governments in major energy production provinces have outlined even more ambitious blueprints for their energy sectors. For example, the planned incremental capacities of coal-fired electricity during the 12th five-year in eight provinces in north and northwest regions, i.e., Hebei, Shanxi, Inner Mongolia, Shandong, Henan, Shaanxi, Ningxia and Xinjiang, add up to 0.23 TW, which, surprisingly, exceeds China's national plan (See Figure S3 in the Supporting Information for planned incremental capacities in these provinces). Coal-based thermal power capacity is planned to more than double in Shanxi, Shaanxi and Ningxia during 2010-2015. In Xinjiang, fourfold increase may be achieved in 2015 compared with 2010. Considering that the existing environment impacts caused by energy production are already significant in these regions, these electricity generation plans involving significant expansions could potentially contribute to more serious water-related environmental damages if the planned expansion does not rely on air-cooling technology.

Relieving the pressure of growing energy production on water resources in China is likely to require comprehensive measures. Wide adoption of water-saving technologies in the power sector in northern China, such as air cooling technology, is of key importance ([63]). Many advanced power technologies, such as ultra-supercritical coal power systems, large-scale circulating fluidized bed (CFB) technology and integrated gasification combined cycle (IGCC) plants with higher conversion efficiency and lower water intensities have started to be deployed since late 2000s ([64-66]). Compared with traditional subcritical thermal power generation, ultra supercritical technology can reduce water consumption intensity by more than 10% and IGCC by 40% ([67]).

Over the longer term, the challenge posed by the geographic mismatch of water resources and energy production requires a strategy of increased decoupling between the energy sector and freshwater resource demand, especially in regions with high environmental impacts. Options include (but are not limited to) the increased deployment of wind power and solar photovoltaic power, which have started receiving government support in the mid-2000s ([68-71]); nontraditional water resources utilization in the energy sector, e.g., using treated municipal wastewater; and a larger role for the construction of coastal power plants to allow the use of sea water for cooling ([72, 73]). Which of these options is preferable (or is even an option) depends on the context, but the long-term plans for the energy sector discussed above do not consider water resources limitations in areas where water is already scarce. As a top-down approach, this study still has some limitations in terms of spatial resolution (for example, we were unable to identify basin level water use). If comprehensive plant-level information of water use in energy production facilities in China becomes available, more detailed analysis could be conducted. Combined with an energy planning model, this type of dataset could provide important insights for energy and water planning.

In summary, we have shown that energy is a major component of China's water scarcity challenge. Our spatially disaggregated analysis allowed a better understanding of the coupling characteristics between energy development and water resources in China and identifying hotspot regions suffering most severe impacts, which provide important inputs to both energy and water plans.

Supporting Information Available

Additional information as noted in the text is included in the Supporting Information. This material is available free of charge via the Internet at http://pubs.acs.org/.

Acknowledgements

This work was conducted while Chao Zhang was a joint Giorgio Ruffolo fellow in the Sustainability Science Program in the Mossavar-Rahmani Center for Business and Government and Energy Technology Innovation Policy Fellow at the Belfer Center for Science and International Affairs, both at the Harvard University Kennedy School of Government. Support from Italy's Ministry for Environment, Land and Sea is gratefully acknowledged. The authors appreciate comments on the early version of the manuscript from Henry Lee, Sai Liang and Zhu Liu.

References

1. Schnoor, J. L. Water Energy nexus. *Environ. Sci. Technol.* **2011**, 45, 5065.
2. Hightower, M.; Pierce, S. A. The energy challenge. *Nature* **2008**, 452, 285-286.
3. Mielke, E.; Anadon, L. D.; Narayanamurti, V. *Water consumption of energy resource extraction, processing, and conversion*. Energy Technology Innovation Policy Discussion Paper No. 2010-15, Belfer Center for Science and International Affairs, Harvard Kennedy School, **2010**, belfercenter.ksg.harvard.edu/files/ETIP-DP-2010-15-final-4.pdf.
4. *Energy demands on water resources：Report to congress on the interdependency of energy and water*; U.S. Department of Energy: Washington, DC, **2006**, www.sandia.gov/energy-water/docs/121-RptToCongress-EWwEIAcomments-FINAL.pdf.
5. *Lifecycle Analysis of Water Use and Intensity of Noble Energy Oil and Gas Recovery in the Wattenberg Field of Northern Colorado*; Noble Energy, Inc., Colorado State University: **2012**, cewc.colostate.edu/wp-content/uploads/2012/04/Water-Intensity-Report-Final.pdf.
6. Jordaan, S.; Anadon, L.; Mielke, E.; Schrag, D. Regional water- and land-use implications of reducing oil imports with natural gas, shale oil, or biofuels in the United States. *Environ. Sci. Technol*. 2013, Just accepted manuscript; DOI: 10.1021/es404130v.
7. Sovacool, B. K.; Sovacool, K. E. Identifying future electricity-water tradeoffs in the United States. *Energ. Policy* **2009**, 37, 2763-2773.
8. Macknick, J.; Newmark, R.; Heath, G.; Hallett, K. *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*; Technical Report NREL/TP-6A20-50900; U.S. National Renewable Energy Laboratory: Golden, **2011**; www.nrel.gov/docs/fy11osti/50900.pdf.
9. DiPietro, P.; Gerdes, K.; Nichols, C. *Water Requirements for Existing and Emerging Thermoelectric Plant Technologies*; Technical Report DOE/NETL-402/080108; U.S. National Energy Technology Laboratory: Morgantown, **2008**; www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=137.
10. Dominguez-Faus, R.; Powers, S. E.; Burken, J. G.; Alvarez, P. J. The water footprint of Biofuels: A drink or drive issue? *Environ. Sci. Technol.* **2009**, 43, 3005-3010.
11. Gerbens-Leenes, W.; Hoekstra, A. Y.; Meer, T. H. v. d. The water footprint of bioenergy. *Proc. Natl. Acad. Sci. USA* **2009**, 106, (25), 10219-10223.
12. Gheewala, S. H.; Berndes, G.; Jewitt, G. The bioenergy and water nexus. *Biofuel Bioprod. Bior*. **2011**, 5, (4), 353-360.
13. Gerbens-Leenes, P. W.; Hoekstra, A. Y.; Meer, T. v. d. The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply. *Ecol. Econ*. **2009**, 68, (4), 1052-1060.
14. Mishra, G. S.; Yeh, S. Life Cycle Water Consumption and Withdrawal Requirements of Ethanol from Corn Grain and Residues. *Environ. Sci. Technol.* **2011**, 45, 4563-4569.
15. Murphy, C. F.; Allen, D. T. Energy-Water Nexus for Mass Cultivation of Algae. *Environ. Sci. Technol.* **2011**, 45, 5861-5868.
16. *Thirsty coal*: *a water crisis exacerbated by China's new mega coal power bases*; Green Peace: Beijing, **2012**; www.greenpeace.org/eastasia/Global/eastasia/publications/reports/climate-energy/2012/Greenpeace%20Thirsty%20Coal%20Report.pdf.
17. Mishra, V. K.; Upadhyaya, A. R.; Pandey, S. K.; Tripathi, B. D. Heavy metal pollution

induced due to coal mining effluent on surrounding aquatic ecosystem and its management through naturally occurring aquatic macrophytes. *Bioresource Technol*. **2008**, 99, 930-936.

18. Schaeffer, R.; Szklo, A. S.; Lucena, A. F. P. d.; Borba, B. S. M. C.; Nogueira, L. P. P.; Fleming, F. P.; Troccoli, A.; Harrison, M.; Boulahya, M. S. Energy sector vulnerability to climate change: A review. *Energy* **2012**, 38, 1-12.
19. Vliet, M. T. H. v.; Yearsley, J. R.; Ludwig, F.; Vögele, S.; Lettenmaier, D. P.; Kabat, P. Vulnerability of US and European electricity supply to climate change. *Nature Climate Change* **2012**, 2, 676-681.
20. Chandel, M. K.; Pratson, L. F.; Jackson, R. B., The potential impacts of climate-change policy on freshwater use in thermoelectric power generation. *Energ*. *Policy* **2011**, 39, 6234-6242.
21. *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements*; Technical Report DOE/NETL-400/2008/1339; U.S. National Energy Technology Laboratory: Morgantown, **2008**; www.netl.doe.gov/technologies/coalpower/ewr/pubs/2008_Water_Needs_Analysis-Final_10-2-2008.pdf.
22. Carrillo, A. M. R.; Frei, C. Water: A key resource in energy production. *Energ*. *Policy* **2009**, 37, 4303-4312.
23. Davies, E. G. R.; Kyle, P.; Edmonds, J. A. An integrated assessment of global and regional water demands for electricity generation to 2095. *Adv*. *Water Resour*. **2013**, 52, 296-313.
24. Siddiqi, A.; Anadon, L. D. The water-energy nexus in Middle East and North Africa. *Energ*. *Policy* **2011**, 39, 4529-4540.
25. Scott, C. A. The water-energy-climate nexus: Resources and policy outlook for aquifers in Mexico. *Water*. *Resour*. *Re*s. 2011, 48(6); doi: 10.1029/2011WR010805.
26. Hardy, L.; Garrido, A.; Juana, L. Evaluation of Spain's Water-Energy Nexus. *Int*. *J*. *Water Resour*. *D*. **2012**, 28, 151-170.
27. Klein, G.; Krebs, M.; Hall, V.; O'Brien, T.; Blevins, B. B. *California's water-energy relationship*; CEC-700-2005-011-SF; California Energy Commission: Sacramento, **2005**, www.energy.ca.gov/2005publications/CEC-700-2005-011/CEC-700-2005-011-SF.PDF.
28. Scott, C. A.; Pierce, S. A.; Pasqualetti, M. J.; Jones, A. L.; Montz, B. E.; Hoover, J. H. Policy and institutional dimensions of the water-energy nexus. *Energ*. *Policy* **2011**, 39, 6622-6630.
29. Stillwell, A. S.; King, C. W.; Webber, M. E.; Duncan, I. J.; Hardberger, A., The Energy-Water Nexus in Texas. *Ecol*. *Soc*. **2011**, 16(1): 2.
30. Kenney, D. S. and R. Wilkinson, Eds. The Water-Energy Nexus in the American West. 2011, Northampton, Edward Elgar Publishing, Inc.
31. *World development indicators 2012*; World Bank: Washington, DC, **2012**; data.worldbank.org/sites/default/files/wdi-2012-ebook.pdf.
32. NBSC(National Bureau of Statistics of China); MEP(Ministry of Environmental Protection) *China Statistical Yearbook on Environment 2010*. China Statistics Press: Beijing, **2011**.
33. NBSC, *China Energy Statistical Yearbook 2010*. China Statistics Press: Beijing, **2011**.
34. *Key World Energy Statistics 2012*; International Energy Agency: Paris, **2012**; www.iea.org/publications/freepublications/publication/kwes.pdf.
35. Hoekstra, A. Y.; Chapagain, A. K.; Aldaya, M. M.; Mekonnen, M. M. *The Water Footprint Assessment Manual: Setting the Global Standard*. Earthscan: London, 2011.
36. Pfister, S.; Koehler, A.; Hellweg, S. Assessing the environmental impacts of freshwater

consumption in LCA. *Environ. Sci. Technol.* 2009, 43, 4098-4104.
37. Wiedmann, T.; Lenzen, M.; Turner, K.; Barrett, J. Examining the global environmental impact of regional consumption activities - Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade. *Ecol. Econ.* **2007**, 61, 15-26.
38. Wiedmann, T. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecol. Econ.* **2009**, 69, 211-222.
39. Wiedmann, T.; Wilting, H. C.; Lenzen, M.; Lutter, S.; Palm, V. Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. *Ecol. Econ.* **2011**, 70, 1937-1945.
40. Ewing, B. R.; Hawkins, T. R.; Wiedmann, T. O.; Galli, A.; Ercin, A. E.; Weinzettel, J.; Steen-Olsen, K. Integrating ecological and water footprint accounting in a multi-regional input–output framework. *Ecol. Indic.* **2012**, 23, 1-8.
41. Peters, G. P.; Minx, J. C.; Weber, C. L.; Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. USA* **2011**, 108, 8903-8908.
42. Lenzen, M.; Kanemoto, K.; Moran, D.; Geschke, A. Mapping the Structure of the World Economy. *Environ. Sci. Technol.* **2012**, 46, 8374-8381.
43. Davis, S. J.; Peters, G. P.; Caldeira, K. The supply chain of CO_2 emissions. *Proc. Natl. Acad. Sci.* **2011**, 108, (45), 18554-18559.
44. Wiedmanna, T.; Wood, R.; Minx, J. C.; Lenzen, M.; Guan, D.; Harris, R. A carbon footprint time series of the UK – results from a multi-region input-output model. *Economic Systems Research* **2010**, 22, 19-42.
45. Liang, Q.-M.; Fan, Y.; Wei, Y.-M. Multi-regional input–output model for regional energy requirements and CO_2 emissions in China. *Energ. Policy* **2007**, 35, 1685-1700.
46. Zhang, Z.; Yang, H.; Shi, M., Analyses of water footprint of Beijing in an interregional input–output framework. *Ecol. Econ.* **2011**, 70, 2494-2502.
47. Feng, K.; Siu, Y. L.; Guan, D.; Hubacek, K. Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: A consumption based approach. *Appl. Geogr.* **2011**, 32, 691-701.
48. Weisz, H.; Duchin, F. Physical and monetary input–output analysis: What makes the difference? *Ecol. Econ.* **2006**, 57, 534-541.
49. Hawkins, T.; Hendrickson, C.; Higgins, C.; Matthews, H. S. A Mixed-Unit Input-Output Model for Environmental Life-Cycle Assessment and Material Flow Analysis. *Environ. Sci. Technol.* **2007**, 41, 1024-1031.
50. Batten, D. F.; Boyce, D. E. Spatial interaction, transportation, and interregional commodity flow models. In *Handbook of Regional and Urban Economics, Volume 1*, Nijkamp, P., Ed. North Holland: Amsterdam, **1987**; pp 357-406.
51. Erlander, S.; Stewart, N. F. *The gravity model in transportation analysis*: *Theory and extensions*. VSP: Utrecht, The Netherlands, **1990**.
52. *China Regional Input-output tables*. China Statistics Press: Beijing, **2011**. (In Chinese)
53. *China Energy Statistical Yearbook 2007*. China Statistics Press: Beijing, **2008**. (In Chinese)
54. *China Economic Census Yearbook*. China Statistics Press: Beijing, **2010**. (In Chinese)
55. *Dataset of China pollution source census*. China Environmental Science Press: Beijng, **2011**. (In Chinese)
56. *National 600 MWe-scale thermal power unit benchmarking and competition dataset*; China

Electricity Council: Beijing, 2010. (In Chinese)

57. *National 300 MWe-scale thermal power unit benchmarking and competition dataset*; China Electricity Council: Beijing, 2010. (In Chinese)

58. Zhang, Y.; Qi, S., *China Multi-Regional Input-Output Models: 2002 and 2007*. China Statistics Press: Beijing, 2012.

59. Ridoutt, B. G.; Huang, J. Environmental relevance—the key to understanding water footprints. *Proc. Natl. Acad. Sci. USA* **2012,** 109 (22), E1424.

60. Goedkoop, M.; Spriensma, R. *The Eco-indicator 99: A damage oriented method for life cycle impact assessment, methodology report*; PR`e Consultants.: Amersfoort, the Netherlands, 2000.

61. Kenny, J. F.; Barber, N. L.; Hutson, S. S.; Linsey, K. S.; Lovelace, J. K.; Maupin, M. A. *Estimated use of water in the United States in 2005*; U.S. Geological Survey Circular 1344; U.S. Department of the Interior: Washington, DC, **2009**; pubs.usgs.gov/circ/1344/.

62. *Research report on the 12th year (2011-2015) plan of electric sector*; China Electricity Council: Beijing, **2012**. (In Chinese)

63. Wang, P. Innovation and development of direct air cooling technology for thermal power generation in China. *Electrical Equipment* **2008**, (3), 270-272. (In Chinese)

64. Zhao, L.; Gallagher, K. S. Research, development, demonstration, and early deployment policies for advanced-coal technology in China. *Energ*. *Policy* **2007**, 35, 6467-6477.

65. Liu, H.; Ni, W.; Li, Z.; Ma, L. Strategic thinking on IGCC development in China. *Energ. Policy* **2008**, 36, 1-11.

66. Chen, W.; Xu, R. Clean coal technology development in China. *Energ*. *Policy* **2010**, 38, 2123-2130.

67. DiPietro, P.; Gerdes, K.; Nichols, C. Water Requirements for Existing and Emerging Thermoelectric Plant Technologies; Technical Report DOE/NETL-402/080108; U.S. National Energy Technology Laboratory: Morgantown, 2008, www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=137.

68. Wang, Z.; Qin, H.; Lewis, J. I. China's wind power industry: Policy support, technological achievements, and emerging challenges. *Energ*. *Policy* **2012**, 51, 80-88.

67. *Twelfth five year (2011-2015) plan of energy development*; China State Council: Beijing, **2013**. (In Chinese)

70. Grau, T.; MolinHuo; Neuhoff, K. Survey of photovoltaic industry and policy in Germany and China. *Energ*. *Policy* **2012**, 51, 20-37.

71. Hua, Z.; Wang, J.; Byrne, J.; Kurdgelashvili, L. Review of wind power tariff policies in China. *Energ*. *Policy* **2013**, 53, 41-50.

72. Li, H.; Chien, S.-H.; Hsieh, M.-K.; Dzombak, D. A.; Vidic, R. D. Escalating Water Demand for Energy Production and the Potential for Use of Treated Municipal Wastewater. *Environ*. *Sci*. *Technol*. **2011**, 45, 4195-4200.

73. Shen, M.; Han, M. Environmental pollution and water resources utilization in coal-fired power industry. *China Environmental Protection Industry* **2011**, (1), 43-48. (In Chinese)