University of Groningen

China's coal-fired power plants impose pressure on water resources

Zhang, Xinxin; Liu, Junguo; Tang, Yu; Zhao, Xu; Yang, Hong; Gerbens-Leenes, P. W.; van Vliet, Michelle T. H.; Yan, Jinyue

Published in:
Journal of Cleaner Production

DOI:
10.1016/j.jclepro.2017.04.040

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2017

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Zhang, X., Liu, J., Tang, Y., Zhao, X., Yang, H., Gerbens-Leenes, P. W., van Vliet, M. T. H., & Yan, J. (2017). China's coal-fired power plants impose pressure on water resources. *Journal of Cleaner Production*, *161*, 1171-1179. https://doi.org/10.1016/j.jclepro.2017.04.040

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 19-11-2022

Journal of Cleaner Production 161 (2017) 1171–1179

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

China's coal-fired power plants impose pressure on water resources

Xinxin Zhang [a], Junguo Liu [b, *], Yu Tang [c, **], Xu Zhao [d], Hong Yang [e, f],
P.W. Gerbens-Leenes [g], Michelle T.H. van Vliet [h], Jinyue Yan [i, j]

[a] *School of Nature Conservation, Beijing Forestry University, Qinghua East Road 35, Haidian District, 100083, Beijing, China*
[b] *School of Environmental Science and Engineering, South University of Science and Technology of China, Xueyuan Road 1088, Nanshan Districit, Shenzhen, 518055, Shenzhen, China*
[c] *Graduate School, South University of Science and Technology of China, Shenzhen, 518055, China*
[d] *College of Environment, Hohai University, Nanjing, Jiangsu, China*
[e] *Eawag, Swiss Federal Institute of Aquatic Science and Technology, Ueberlandstrasse 133, 8600, Duebendorf, Switzerland*
[f] *Department of Environmental Science, University of Basel, Petersgraben 35, 4001, Basel, Switzerland*
[g] *Center for Energy and Environmental Studies, University of Groningen, Nijenborg 6, 9747 AG, Groningen, The Netherlands*
[h] *Earth System Science, Wageningen University, P. O. Box 47, 6700 AA, Wageningen, The Netherlands*
[i] *School of Chemical Science and Engineering, Royal Institute of Technology, Teknikringen 42, SE-100 44, Stockholm, Sweden*
[j] *School of Business, Society and Engineering, Mälardalen University, SE-721 23, Västerås, Sweden*

ARTICLE INFO

Article history:
Received 24 February 2017
Received in revised form
29 March 2017
Accepted 6 April 2017
Available online 10 April 2017

Keywords:
Coal-fired power
Water consumption
Water-energy nexus

ABSTRACT

Coal is the dominant fuel for electricity generation around the world. This type of electricity generation uses large amounts of water, increasing pressure on water resources. This calls for an in-depth investigation in the water-energy nexus of coal-fired electricity generation. In China, coal-fired power plants play an important role in the energy supply. Here we assessed water consumption of coal-fired power plants (CPPs) in China using four cooling technologies: closed-cycle cooling, once-through cooling, air cooling, and seawater cooling. The results show that water consumption of CPPs was 3.5 km^3, accounting for 11% of total industrial water consumption in China. Eighty-four percent of this water consumption was from plants with closed-cycle cooling. China's average water intensity of CPPs was 1.15 l/kWh, while the intensity for closed-cycle cooling was 3–10 times higher than that for other cooling technologies. About 75% of water consumption of CPPs was from regions with absolute or chronic water scarcity. The results imply that the development of CPPs needs to explicitly consider their impacts on regional water resources.

1. Introduction

In recent years, the water-energy nexus related to electricity generation has received much attention (Siddiqi and Anadon, 2011; Ackerman and Fisher, 2013). Between 1950 and 2010, global water consumption of the power industry increased 18 times thanks to the rapid expansion of power capacity (Zhang et al., 2014). Improving water use efficiency in electricity generation is becoming an urgent issue in countries like China, which are enduring a growing water stress problem (Zhang and Anadon, 2013). The cooling technologies employed in power plants are the key factor that determines the magnitude of water consumption in electricity generation (Macknick et al., 2012; Meldrum et al., 2013; Mekonnen et al., 2015). The choice for cooling technologies is often influenced by regional specific factors, such as affluence, geographic locations and water availability (Liao et al., 2016; van Vliet et al., 2016). For example, inland areas are difficult to employ seawater cooling. It is thus important to understand the advantages and limitations of certain cooling technologies brought about by regional disparities and implications for freshwater management.

With a growing population and economy, demand for electricity has been increasing over the years (Olsson, 2012; Mertens et al., 2015). It is projected that global electricity generation could increase by a factor of five from 60 EJ/yr (10^{18} J/year) in 2005 to 300 EJ/yr in 2095 under the current structure of electricity generation technologies (Davies et al., 2013). This means an increase in consumptive water use. The limited water availability will cause vulnerability in electric generation, especially in water scarce

---

* Corresponding author.
** Corresponding author.
E-mail addresses: Junguo.liu@gmail.com (J. Liu), tangyu@sustc.edu.cn (Y. Tang).

http://dx.doi.org/10.1016/j.jclepro.2017.04.040

regions and may be exacerbated by increase in drought frequency and intensity under future climate change (van Vliet et al., 2016).

Coal is the primary energy source for electricity generation in the world. According to Key World Energy Statistics (2016), electricity generation from coal-fired power plants (CPPs) accounted for 40.8% of global electricity generated (International Energy Agency, 2016). Electricity generation in China relies heavily on coal. About 75% of China's electricity was generated from CPPs (Zhang and Anadon, 2013; Jia et al., 2016; China Electricity Council, 2013a). According to the National 12th Five-year Plan for the power industry, the target of the installed capacity of CPPs was 0.93 TW in 2015, compared to 0.71 TW in 2010. The figure will increase to 1.17 TW in 2020 (China Electricity Council, 2012). The increase in coal-fired electricity generation is expected to exacerbate water conflicts with other industrial water users (Zhang and Anadon, 2013).

Several studies have quantified water consumption for the renewable and non-renewable (including CPPs) electricity sector at global, regional and national levels (Fethenakis and Kim, 2010; Siddiqi and Anadon, 2011; Macknick et al., 2012; Meldrum et al., 2013; Mekonnen et al., 2015). Few studies however have investigated the water-energy nexus with consideration of spatial locations of CPPs and the water resources status in their localities. Zhang and Anadon (2013) assessed the water use of electricity production and its environmental impacts in China. Feng et al. (2014) investigated the total life-cycle water consumption for eight electricity generation technologies. Both studies were conducted at an aggregated level for energy production from different fuel sources, including coal. These studies were however unable to identify plant-level water consumption for coal-fired electricity generation with different cooling technologies. They also did not specify the spatial distribution of CPPs and associated water consumption. A notable exception is the study by Jiang and Ramaswami (2015) who have assessed the water withdrawal intensity and water balance for Shandong province in China based on 19 CPPs. However, the results were insufficient to represent the whole of China and the linkage to the local water resources status is not discussed. Owing to the important role of the coal-fired electricity production and consumption in China, there is a need for an in-depth investigation and analyses of the water-energy nexus involved in the processes on a spatial dimension. Such study also has global significance due to the large share of coal-fired electricity production in the energy budget in many countries in the world, and the excessive water consumption has put substantial pressure on water resources in these countries, particularly those with water scarcity. Given the growing demand for electricity, such pressure is likely to intensify in the future. An in-depth analysis of the water-energy nexus concerning coal-fired electricity power plants in China can shed lights on the global development of the sector amid the intensification of water scarcity.

In this study, we aim to fill in the gaps specified about by assessing the water consumption of 621 CPPs, accounting for 81% of electricity generated in all CPPs in 2012 in China (79% for installed capacity). Water consumption here refers to the water use or removal from a river basin that renders it unavailable for further use (Liu et al., 2009). It has the same meaning as "water depletion" as defined by Molden (1997) or consumptive water use by Falkenmark and Lannerstad (2005). Four different cooling technologies were assessed, i.e. once-through cooling, closed cycle cooling, air cooling and seawater cooling. We also investigate the sources of water supply (e.g. surface water, groundwater, or the highly treated waste water which can be used for cooling and other uses, i.e. reclaimed water) and link these with water scarcity status of regions where the power plants are located. This comprehensive assessment will make a significant contribution to the improvement of the understanding of the water-energy nexus and provide the information support to the formulation of pertinent policies to address the water scarcity while meeting the growing demand for electricity both in China and in the world.

2. Methods

2.1. Data description

The basic source of the database was from the Annual Compilation of Statistics of the Power Industry (China Electricity Council, 2013a). It contains the key information of 621 CPPs in China by the end of 2012 (Appendix Fig. B1). At the plant level, the data of CPPs included the generated electricity (E), installed capacity and cooling type. Within these CPPs, 77 plants are with once-through cooling system, 358 plants with closed-cycle cooling system, 73 plants with seawater cooling system, and 113 plants with air cooling system (Appendix method and Figs. B2–B.3). The installed capacity of power plants was all higher than 6 MW.

There are two types of CPPs in China, one only generates electricity, the other generates both electricity and heat, named combined heat and power plants (CHP). For both types of plants, we only considered the water consumption for electricity generation. In this study, the water consumption of power plants concerns the total consumption at the operational stage, in which cooling consumes the bulk of the water (Mekonnen et al., 2015). Apart from the cooling purpose, there are other processes, such as dust removal, flue gas desulfurization, boiler water make up, which also consume water.

2.2. Consumptive water intensity and water consumption of CPPs

CWI was defined as the amount of water consumption to produce each unit of electricity. Water consumption of CPPs was calculated through CWI and electricity generated. Hence, the water consumption for CPPs was calculated using the following equation:

$$WC_n = E_n \times CWI_n \tag{1}$$

where WC_n (m^3) is the water consumption for coal-fired power plant n. E_n is the electricity generated by coal-fired power plant n. CWI_n is the consumptive water intensity for coal-fired power plant n.

Among the 621 CPPs included in this study, consumptive water intensity (CWI) of 365 power plants were collected from China Electricity Council (CEC) (China Electricity Council, 2013b). CEC is a joint organization of China's power enterprises and institutions. An annual energy efficiency benchmarking competition for CPPs is organized by CEC. Detailed technical information and water consumption data can be collected from the competition. CWIs of the remaining power plants were derived from our own calculation as shown in Equation (2).

$$CWI_{jk} = \frac{\sum_i cwi_{ijk} \times E_{ijk}}{\sum_i E_{ijk}} \tag{2}$$

where CWI_{jk}(l/kWh) is the average consumptive water intensity of all the CPPs using cooling system k for the level of installed capacity j. cwi_{ijk}(l/kWh) is the consumptive water intensity of coal-fired power plant i employing cooling system k for the level of installed capacity j. E_{ijk}(kWh) is the electricity generated by coal-fired power plant i employing cooling system k for the level of total installed capacity j. The CPPs can be classified into four levels: $j < 250$; $250 \le j < 600$; $600 \le j < 1000$; $j \ge 1000$.

Hence, for those CPPs which have no data of CWI_n, CWI_{jk} is used to the coal-fired power plant according to its cooling system k and total installed capacity j.

2.3. Freshwater sources for CPPs

The percentages of different water sources (surface water, groundwater, and reclaimed water) for CPPs also collected from CEC. Geographic locations of 621 CPPs were identified using Google Earth software by the plant names.

The amount of water consumption from different sources was calculated by multiplying the total water consumption by the percentages of different water sources.

$$FWC_{kr} = \frac{\sum_n WC_{nkr} \times F_{nkr}}{\sum_n WC_{nkr}} \tag{3}$$

where FWC_{kr} (%) is the share of water consumption from certain kind of water resource consumed by CPPs using cooling system k in region r. WC_{nkr} is the water consumption of coal-fired power plant n using cooling system k in region r. F_{nkr} is percentage of water from certain kind of water resource consumed by coal-fired power plant n using cooling system k in region r.

2.4. Water scarcity

We quantified water scarcity at the grid level with the data of water availability (WA) and population (P) based on the long-term average run-off assessment (GWSP Digital Water Atlas, 2008) and population for the year of 2000 (CIESIN, 2005) at a spatial resolution of 30 arc-minutes.

To address the water-energy nexus concerning CPPs, we first assessed the water stress levels at grid level based on their per capita water resources. According to the location of CPPs, we can allocate the information of water stress level to each CPP. We then calculated the water consumption of the 621 CPPs with different cooling technologies in the context of water scarcity.

$$WSI = \frac{WA}{P} \tag{4}$$

$$SWC_{gk} = \sum_n WC_{ngk} \tag{5}$$

where WSI(m^3/cap/yr) is the water stress index, i.e., water availability (WA, m^3/yr) divided by population (P). WC_{nkl} is the water consumption of coal-fired power plant n located in water stress level g using cooling system k. SWC_{kl} is the sum of the amount of water consumption for CPPs located in water stress level g using cooling system k.

The water scarcity here is categorized into four levels: no water stress (>1700 m^3/capita/yr), water stress (1000–1700 m^3/capita/yr), chronic water scarcity (500–1000 m^3/capita/yr), and absolute water scarcity (<500 m^3/capita/yr) (Falkenmark et al., 1989; Liu et al., 2013).

3. Results

3.1. CWI of coal-fired power plants

The CWI varied within and across cooling technology categories (Fig. 1). The average CWI was 1.15 l/kWh for all CPPs. For the power plants with closed-cycle cooling, the CWI was 2.02 l/kWh. For plants with once-through cooling, air cooling and seawater cooling, the averages were 0.34 l/kWh, 0.39 l/kWh, and 0.28 l/kWh, respectively. The highest CWI for all cooling systems was related to

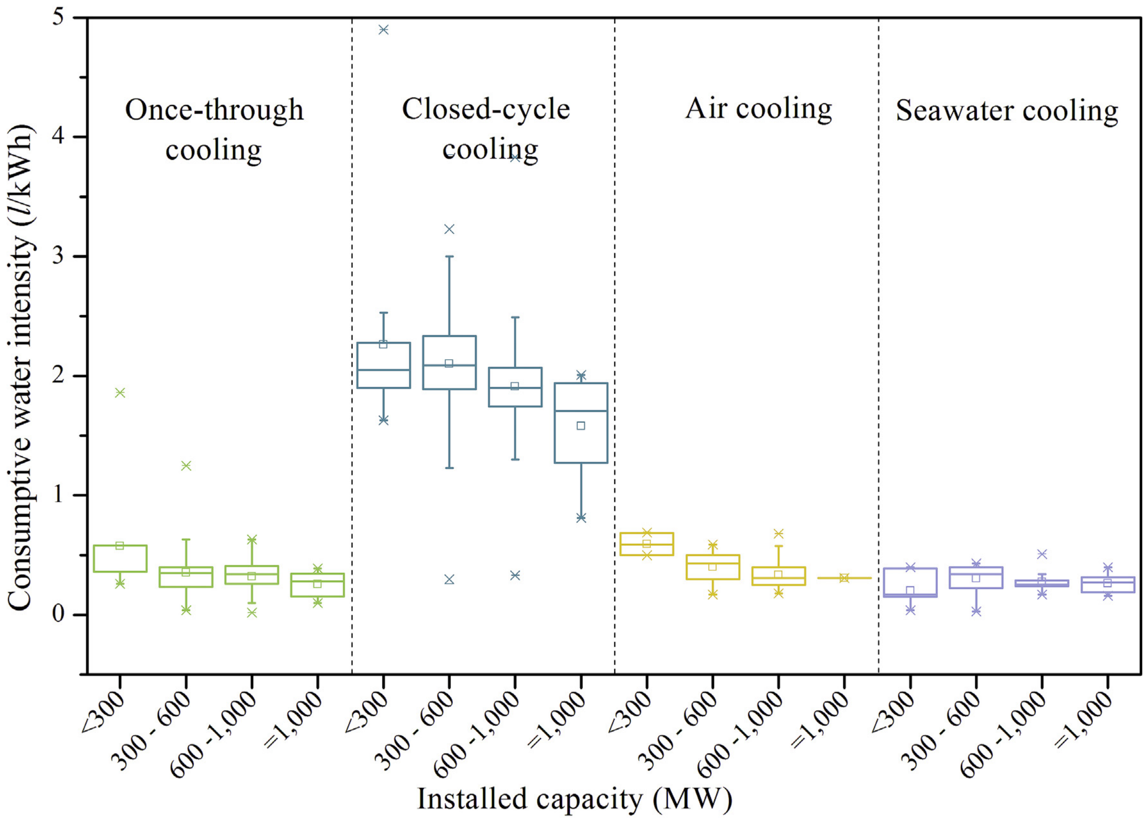


Fig. 1. Water consumption of coal-fired power plants of different sizes of power units and cooling systems.

the use of closed-cycle cooling system, at approximately the upper bound of 2.95 *l*/kWh. The median value of CWI employing closed-cycle cooling system was between 1.71 and 2.09 *l*/kWh depending on the sizes of power units, about 6–7 times higher than that of once-through cooling system and about 3–6 times higher than that of air cooling system. Seawater cooling had the lowest CWI, the median value ranging from 0.16 to 0.39 *l*/kWh for different sizes of power unit, the lowest CWI at the lower bound was 0.02 *l*/kWh. There was a common trend that the median value of CWI decreased with the increase in the size of power units for closed-cycle cooling, once-through cooling and air cooling systems (Fig. 1). The median value of CWI for seawater cooling system with installed capacity lower than 300 MW was the lowest, and for those installed capacity higher than 300 MW, the median value of CWI decreased with the increase in the size of power units.

3.2. Water consumption and freshwater sources for coal-fired power plants

Water consumption of CPPs in China totaled 3.5 km^3 in 2012, accounting for 11% of the total industrial water consumption of 33.1 km^3 of the year (The Ministry of Water Resources of the People's Republic of China, 2012)). Water consumption of CPPs varied widely among plants, from 0.01×10^6 m^3 to 40×10^6 m^3 (Fig. 2). Of the 621 power plants, 358 (58%) plants are with closed-cycle cooling system, accounting for 84% of total water consumption. While those employing once-through cooling, air cooling, and seawater cooling system accounted for 5%, 6%, and 5% of the total water consumption, respectively.

Surface water was the dominant freshwater source for CPPs, accounting for 70% of the total water consumption (Fig. 3a). Interestingly, reclaimed water, which is treated wastewater, was the second important water source of water consumption, accounting for 17%. Groundwater followed closely behind with 13%. In most provinces in southern China, where water is relatively abundant, CPPs consumed mainly surface water. These included Anhui, Guangxi, Hunan, Jiangsu and Shanghai, which accounted for more than 90% of the total water consumption of CPPs in the south. Reclaimed water and groundwater were the alternative choices for CPPs in some provinces in the north where water is scarce, accounting for more than 50% of the total. These included Beijing, Shaanxi, and Hebei. Owing to the cooling technology design, the main water source for once-through cooling system was surface water (Fig. 3b), accounting for more than 90% of the total. For closed-cycle cooling system, the share of water sources was 68% for surface water, 18% for reclaimed water, and 14% for groundwater. For air cooling system, the proportions of surface water, reclaimed water, and groundwater were 64%, 22% and 14%, respectively.

3.3. Regional disparity in water consumption of coal-fired power plants

Most provinces in northern China are under water stress (Fig. 4a). The total water consumption of CPPs in northern China was 2.36 km^3/year, which was twice as high as for southern China (Fig. 4d). The top five largest water consumption provinces in the north were Shandong, Henan, Hebei, Anhui and Inner Mongolia, which together accounted for 59% of the northern total (Fig. 4b). While the top five largest water consumers in the south were Jiangsu, Guangdong, Zhejiang, Guizhou, and Jiangxi, accounting for 56% of the southern total (Fig. 4c). Closed-cycle cooling system is currently the dominant cooling system type in China. About 57% of CPPs assessed applied this system. In the north, closed-cycle cooling system contributed to 88% of the water consumption of CPPs, while the percentage was 78% in the south (Fig. 4d).

As a large water consumer, closed-cycle cooling system consumed 2.9 km^3, of which 75% were located in the regions suffering from absolute or chronic water scarcity. While 82% of total water consumption of air cooling system occurred almost exclusively in the regions with water scarcity. As shown in Fig. 5, 64% of total water consumption of CPPs occurred in the regions with absolute water scarcity, 11% in regions with chronic water scarcity and

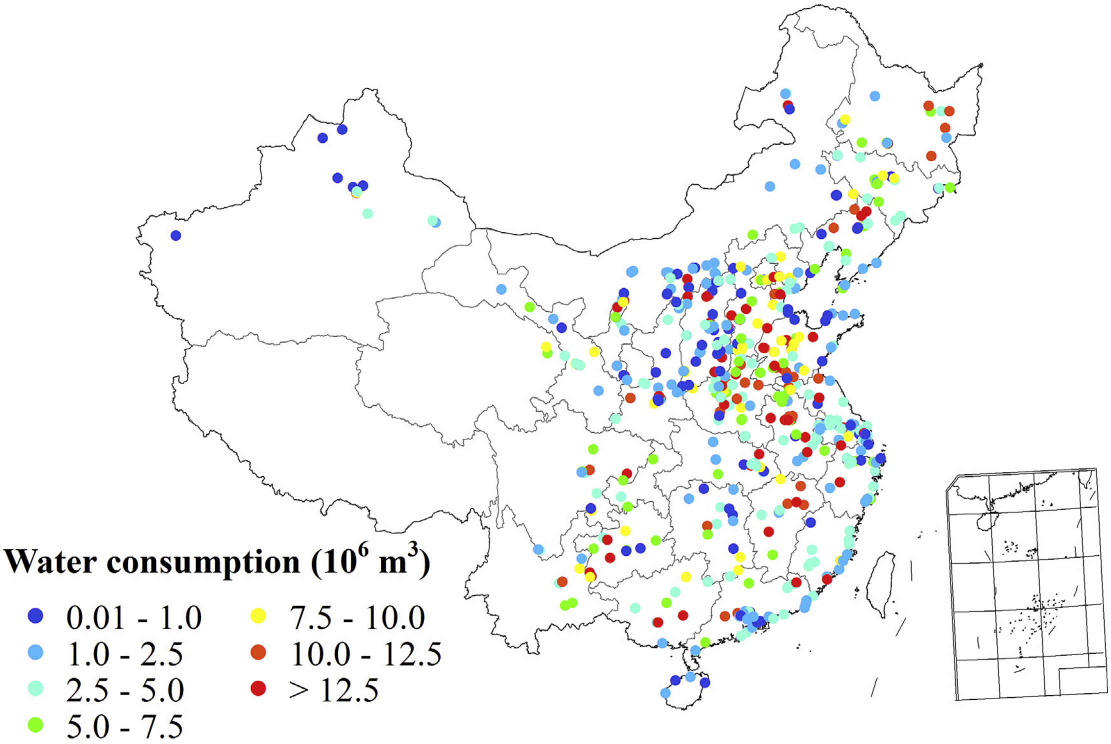


Fig. 2. Spatial distribution of water consumption of coal-fired power plants.

10% in the regions with water stress. Only 15% of total water consumption occurred in regions with no water stress.

4. Discussion

4.1. Comparison of CWI with other countries

Table 1 shows the comparison of the average CWI in CPPs of China from this study with results of the world and other countries from other studies. China's average CWI of CPPs of 1.15 *l*/kWh was lower than several previously reported CWIs: e.g. 1.75 *l*/kWh by Mekonnen et al. (2015) for the global average, 1.8 *l*/kWh for the United States (Torcellini et al., 2004), 1.7–2.00 *l*/kWh for the EU (Koulouri and Moccia, 2014), and 1.55 *l*/kWh for Spain (Rio Carrillo and Frei, 2009). The cooling technology structure may have contributed to the relatively low CWI (Yu et al., 2011) in China. For example, in Spain and the EU, the water-intensive closed-cycle cooling technology is commonly used, leading to high average CWI (Dudgeon et al., 2006; van Vliet et al., 2012). Another reason is that the results of this study reflect the situation of year 2012. The CWI values referenced for other countries in the literature are mostly for years before 2005 (although the publications are in later years). The technological innovation and advances since 2005 may have contributed to the lower CWI in China. This is particularly so because of China's very rapid development in CPPs in recent years, leading to a higher weight of the latest technologies in the respective cooling systems compared with other countries.

4.2. Effects of cooling technologies and national policy

Although once-through cooling system consumes far less water than closed-cycle cooling, water withdrawals (total freshwater taken from surface and ground water) for cooling are much higher. In China, 73% of the CPPs with once-through cooling system were located in the Yangtze River basin (Appendix Fig. B2). Although the return water of once-through cooling system is available for uses downstream, the temperature of the receiving water bodies rises, which can cause additional evaporation and adverse ecological impacts of the receiving bodies, also called "thermal pollution" (Dudgeon et al., 2006; van Vliet et al., 2012). These shortcomings may favor reduced commissioning of once-through cooling system.

Closed-cycle cooling system, the predominant cooling technology in northern China until the late 2000s (Zhang et al., 2014), required relatively less water withdrawal. However, the high water consumption overall increased water stress in northern China. Some policies issued by the Chinese government have promoted air cooling as an alternative measure to relieve water stress in the northern regions since the mid-2000s (National Development and Reform Commission, 2004; 2005). The National Development and Reform Commission has issued the water resource management regulation for thermal power industry to require new CPPs in these regions to adopt air cooling system to meet targets to limit water consumption (National Development and Reform Commission, 2004). According to the latest water resource conservation regulation, air cooling has become a mandatory requirement for new CPPs in water scarce regions (Ministry of Water Resources (2013)).

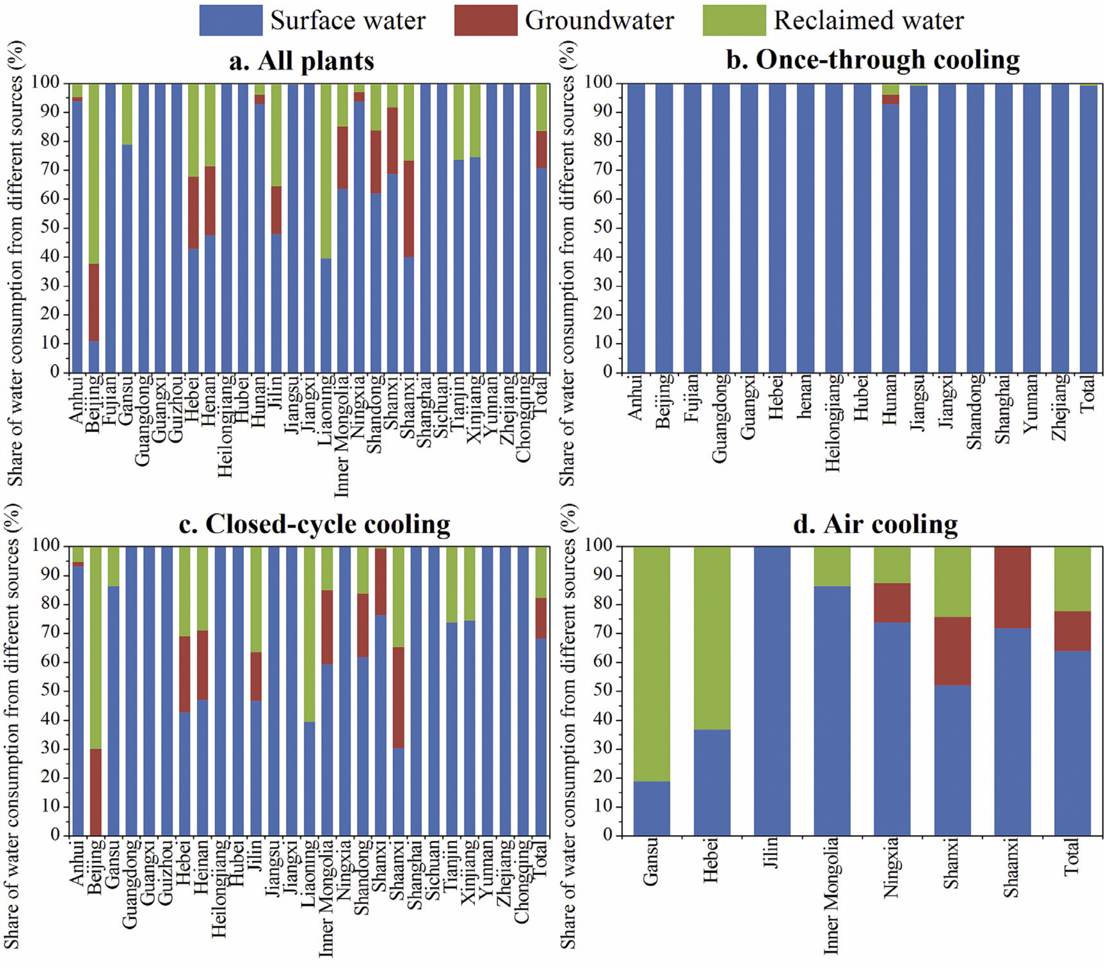


Fig. 3. Share of different water sources in water consumption of coal-fired power plants.

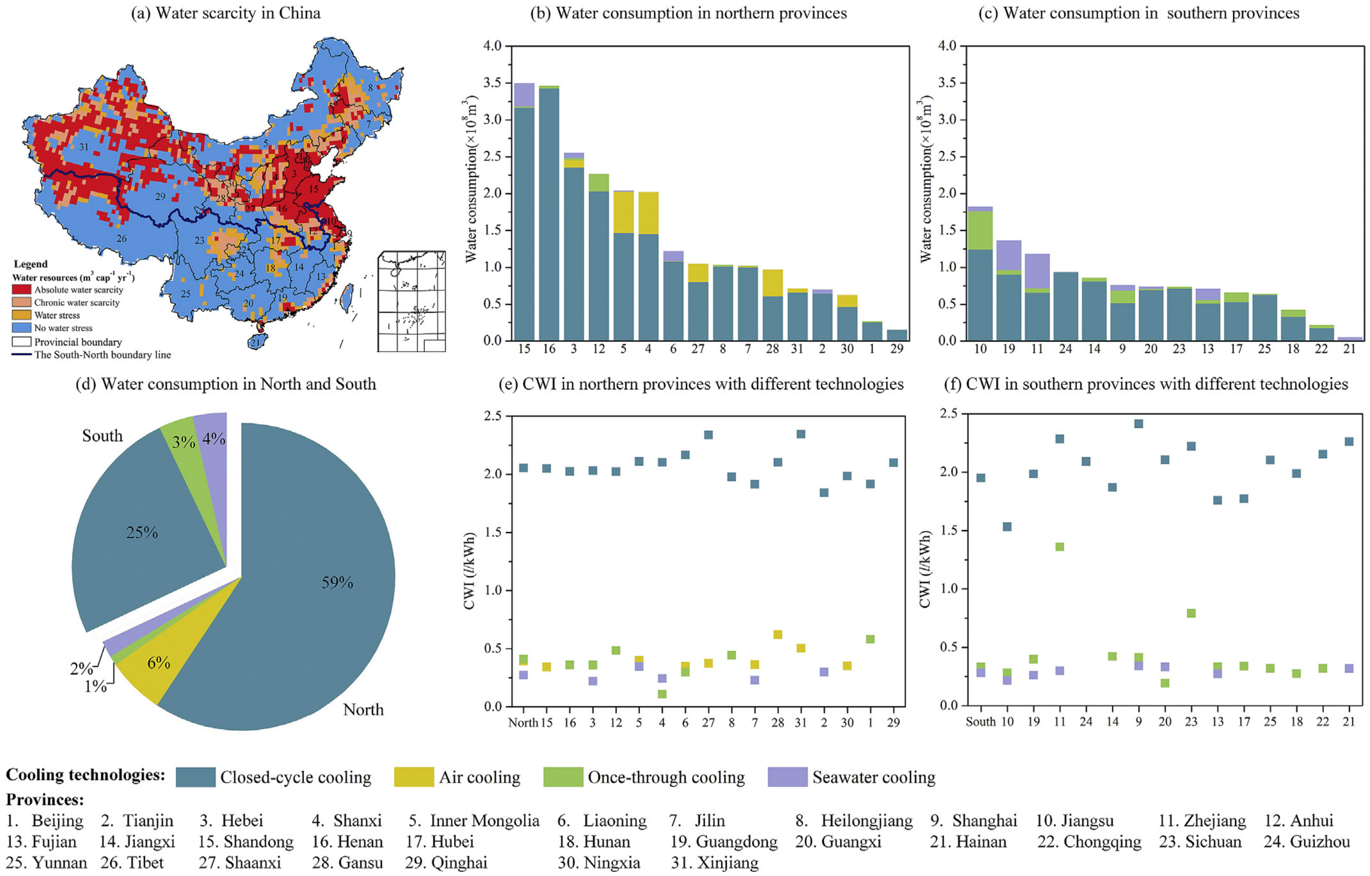


Fig. 4. Water consumption and consumptive water intensity of coal-fired power plants in north and south China. The South-North boundary line for provinces was drawn based on an acknowledged south-north dividing line shown in panel (a) (Xie et al., 2004).

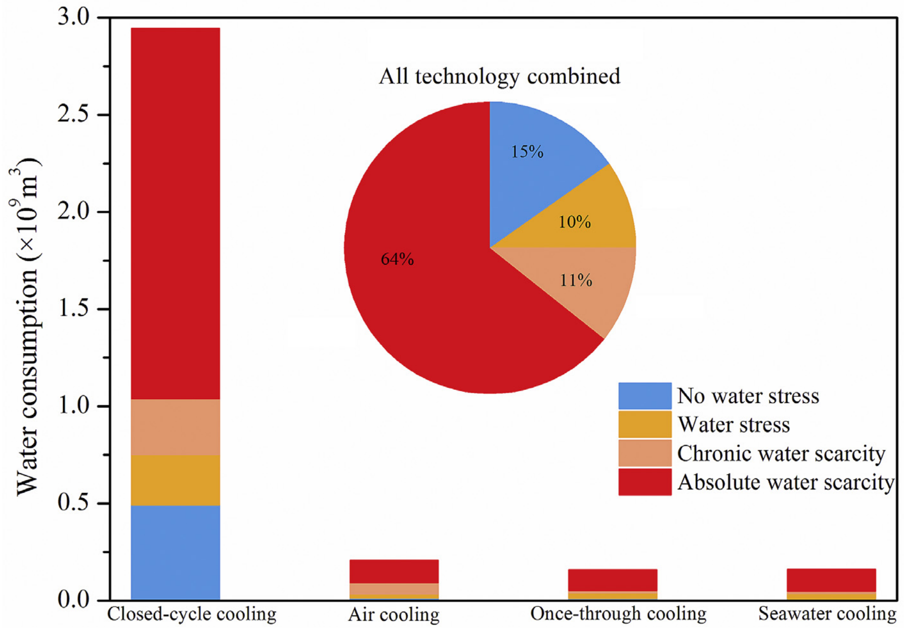


Fig. 5. Water consumption of coal-fired power plants per cooling technology with respect to water stress status of the regions they locate. The pie shows the proportion of total water consumption with respect to water stress.

Amid the increasing water scarcity, the proportion of China's newly installed thermoelectricity power plants with air cooling system increased from 3% in 2004 to 24% in 2010 (China Electricity Council, 2012). The demand for air cooling system in China is expected to increase further in the future amid the increasing water scarcity. According to the National 12th Five-Year Plan and 13th

Table 1
Comparison of CWI of coal-fired power plants from different studies.

Study area	Cooling technology	CWI (*l*/kWh)	References
Global	all technology combined	1.75	Mekonnen et al., 2015
Spain	all technology combined	1.55	Rio Carrillo and Frei, 2009
EU	all technology combined	1.7–2.00	Koulouri and Moccia, 2014
US	all technology combined	1.8	Torcellini et al., 2004
China	once-through	Min: 0.04–0.25 Median: 0.29–0.35 Max: 0.39–0.63	This study
	closed-cycle	Min: 0.82–1.64 Median: 1.71–2.09 Max: 2.01–2.99	
	all technology combined	1.15	

Five-year Plan for the Electricity Industry, there will be an increase of 63%–66% in new CPPs that are mostly located in the water scarce regions, including Songhuajiang, Liaohe, Huaihe, Yellow River, and the Northwest river basins (China Electricity Council, 2012). Air cooling system will dominate these newly developed CPPs.

Several CPPs in China's coastal areas use seawater cooling to relieve fresh water resource stress. By the end of 2013, 88.3 km^3 of seawater was used for cooling in power plants (State Oceanic Administration People's Republic of China, 2014)). Seawater cooling system have the merits of low freshwater withdrawal and discharge, less capital cost and water pollution, which makes them a promising cooling system in coal-fired electricity generation. Apart from these advantages, sea water cooling also has the same problem "thermal pollution", which can cause adverse ecological impacts on the marine ecology.

4.3. Further development of the electricity sector in the context of water scarcity

Relieving the pressure of growing water consumption on water resources requires comprehensive measures. Air cooling and seawater cooling are possible alternatives to closed-cycle cooling or once-through cooling. But these two cooling systems need to conquer some disadvantages, like high capital cost for air cooling system and restriction of region for seawater cooling. It is estimated that air cooling system might increase the cost of electricity generation by 3%–8% compared with closed-cycle cooling system (Turchi et al., 2010). Besides, air cooling system generally have a lower overall thermal efficiency, i.e., the energy consumption is usually higher (Zhang et al., 2014). Seawater cooling system are limited by the locally available salt water. Utilizing reclaimed water is another approach that could relieve water stress in water scarce regions. A switch to renewable energy resources with lower water consumption (e.g. wind, solar and photovoltaic plants) could also reduce water consumption (Mekonnen et al., 2015). According to the national plan, the target for total installed capacity of wind farms was 100 GW in 2015 and it will increase to 180 GW in 2020 (China Electricity Council, 2012). The proportion of installed capacity of wind electricity to total installed capacity will increase from 5% in 2012, 7% in 2015 to 10% in 2020 (China Electricity Council, 2012). In China, wind farms are mainly located in the north and southeast coastal regions. Most provinces in these regions are suffering from severe water stress. Utilizing air cooling system, non-freshwater sources in combination with a shift towards non-hydroelectric renewable energy would reduce water scarcity in these regions.

4.4. Limitation of this study

Our study has several limitations. First, the study is based on 621 CPPs, which contribute 81% of electricity generated from all CPPs in China. We calculated the values only for these CPPs and did not adjust values to the full (100%) power plant coverage. Hence, the results represent conservative estimates of water consumption. Second, this study focuses on water consumption rather than water withdrawal. Water withdrawal rates are also important for understanding the vulnerability of CPPs to limited water availability and in respect to competition for water resources with other sectors. Unfortunately, these cannot be handled by the present analytical approach due to the inconsistent and incomplete water withdrawal data for CPPs. Third, in essence, our study considers only the water consumption during the operation of power plants and addresses the impact on the local water resources. The study did not consider water consumption at other stages, e.g. for coal mining, mainly because of data constraints. At the power plant level, there is no data on the sources of fuel supply, i.e., we do not know the origin of the coal used for each power plant. In reality, the sources of coal supply come from different regions which can be produced by different technologies. This further deterred the effort to include the other stages in the water consumption assessment at the power plant level. Despite the above limitations, this study addresses an important gap in understanding China's water-energy nexus and highlights significant implications for energy and water planning and technological development.

5. Conclusion

Increasing water demand for power production amid water shortages has raised concerns for the water-energy nexus in China and elsewhere in the world. This study provided a thorough assessment on water consumption of CPPs with four different cooling technologies in China, as well as impacts on regional water scarcity. The results have highlighted the spatial heterogeneity of cooling technologies in the context of water endowment in China. Water scarcity in northern China leads to the extensive use of closed-cycle cooling, but the higher water consumption in this technology was often overlooked. The need for increasing electricity supply amid the increasing water stress calls for a water-energy nexus approach in both water and energy management. Other limiting factors that influence the choice of cooling technologies and implications on water and energy consumptions should also be further studied.

Although this study focused on China in addressing the water-energy nexus with specification of regional disparities in water consumption under different types of cooling systems and water scarcity status, the analytical procedures and perspective adopted in this study provide a useful basis for the in-depth investigation of the nexus in other countries in the world, particularly those which heavily rely on coal-fired power plants for electricity supply while facing with increasing water scarcity. The policies and efforts to tackle the relevant problems in China can provide useful references and experience for other countries in developing pertinent measures to deal with their own problems relating to the water-energy nexus.

Acknowledgments

The present work was partially developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS) by the working group "Water Scarcity Assessment: Methodology and Application". This study was supported by the National Natural Science Foundation of China (41571022, 41625001), the Beijing Natural Science

Foundation Grant (8151002), the National Science and Technology Major Project (2015ZX07203-005), the National Natural Science Foundation of China (91325302, 91425303). Additional support was provided by the Southern University of Science and Technology (Grant no. G01296001).

Appendix A. Description of cooling technologies

There are four types of cooling systems: (1) once-through cooling; (2) closed-cycle cooling; (3) air cooling; and (4) seawater cooling. The first two systems use freshwater for cooling, while the last two use air and seawater for cooling, respectively.

(1) Once-through cooling system (Fig. B3a) is the technically simplest cooling system, which requires withdrawing large quantities of water and directly returns that water to its source. Only a small fraction of the water is consumed through evaporation. In China, once-through cooling accounted for 12% of total coal-fired power plants (CPPs). Most CPPs with this technology are located in the Yangtze River basin.

(2) Closed-cycle (wet tower) cooling (Fig. B3b) is the most commonly used cooling system in China. In this cooling system, water goes through the condenser, then goes down the cooling tower where some of the water is consumed through evaporation. The water is cycled for cooling. In China, this system accounts for 58% of the CPPs. More than 65% of the plants with this cooling system are located in the northern regions of China.

(3) Air cooling system (Fig. B3c), sometimes referred to as dry cooling, include direct air cooling and indirect air cooling. This cooling system uses air-cooled condensers and reject the heat from steam to air, which can avoid water evaporative losses compared with water cooling system. In China, this system is mainly used in north and northwest China, accounting for18% of the total CPPs.

(4) Seawater cooling system can be categorized as either once-through cooling or closed-cycle cooling, but using seawater instead of freshwater as a heat transfer fluid to remove waste heat. In China, this system is mainly located along the coast, accounting for 12% of the total.

Appendix B. Figures

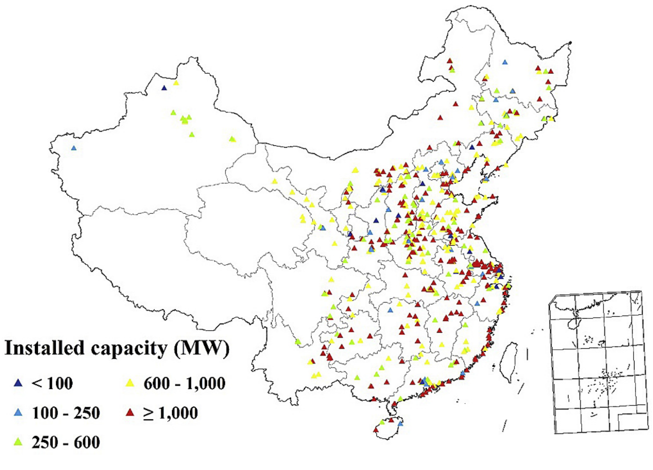


Fig. B.1. Locations of 621 coal-fired power plants studied in the paper.

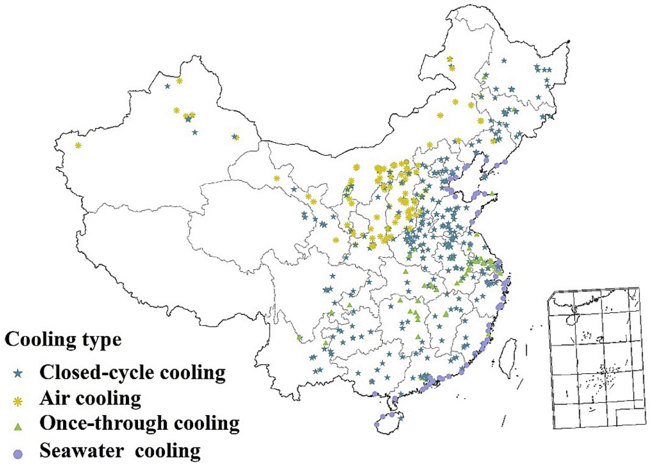
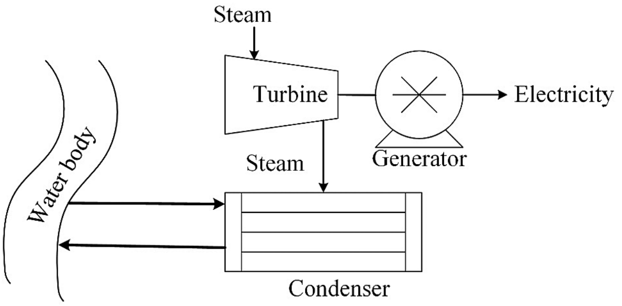
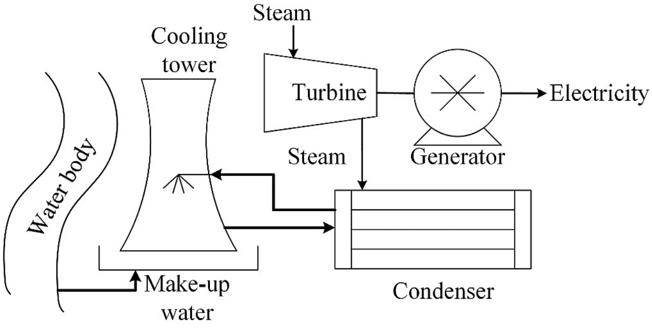


Fig. B.2. Locations of coal-fired power plants with different cooling systems.

a: Once-through cooling system



b: Closed-cycle cooling system



c: Air cooling system

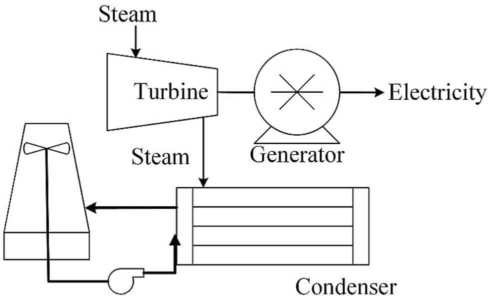


Fig. B.3. Diagram of different cooling system.

References

Ackerman, F., Fisher, J., 2013. Is there a water-energy nexus in electricity generation? Long-term scenarios for the western United State. Energy Policy 59, 235–241.

China Electricity Council, 2012. Research Report on the 12th Fiver-year (2011-2015) Plan of Electricity Sector (Bejing).

China Electricity Council, 2013a. Annual Compilation of Statistics of the Power Industry (Beijing).

China Electricity Council, 2013b. Materials of National Energy Efficiency Benchmarking Completion for Thermal Power Units 2012 (Beijing).

CIESIN, F.A.C., 2005. Gridded Population of the World, Version 3 (GPWv3): Population Count Grid. Center for International Earth Science Information Network (CIESIN), Columbia University; United Nations Food and Agriculture Programme (FAO); and Centro Internacional de Agricultura Tropical (CIAT) Socioeconomic Data and Applications Center (SEDAC), Columbia University, Palisades, NY. http://sedac.ciesin.columbia.edu/gpw.

Davies, E.G.R., Kyle, P., Edmonds, J.A., 2013. An integrated assessment of global and regional water demands for electricity generation to 2095. Adv. Water Resour. 52, 296–313.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.H., Soto, D., Stiassny, M.L., Sullivan, C.A., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81, 163–182.

Falkenmark, M., Lannerstad, M., 2005. Consumptive water use to feed humanity—curing a blind spot. Hydrol. Earth Syst. Sci. 9, 15–28.

Falkenmark, M., Lundqvist, J., Widstrand, C., 1989. Macro-scale water scarcity requires micro-scale approaches. Nat. Res. Forum 13, 258–267.

Feng, K., Hubacek, K., Siu, Y.L., Li, X., 2014. The energy and water nexus in Chines electricity production: a hybrid life cycle analysis. Renew. Sust. Energy Rev. 39, 342–355.

Fethenakis, V., Kim, H.C., 2010. Life-cycle uses of water in U.S. electricity generation. Renew. Sust. Energy Rev. 14, 2039–2048.

GWSP Digital Water Atlas, 2008. Map 7: Water Stress (V1.0). http://atlas.gwsp.org.

International Energy Agency, 2016. Key World Energy Statistics 2016 (France).

Jia, X., Li, Z., Wang, F., Foo, D.C.Y., Tan, R.R., 2016. Multi-dimensional pinch analysis for sustainable power generation sector planning in China. J. Clean. Prod. 112, 2756–2771.

Jiang, D., Ramaswami, A., 2015. The ‘thirsty’ water-electricity nexus: field data on the scale and seasonality of thermoelectricity power generation's water intensity in China. Environ. Res. Lett. 10, 024015.

Koulouri, A., Moccia, J., 2014. Saving Water with Wind Energy. The European Wind Energy Association, Belgium.

Liao, X., Hall, J.W., Eyre, N., 2016. Water use in China's thermoelectric power sector. Glob. Environ. Chang. 41, 142–152.

Liu, J., Zehnder, A.J.B., Hong, Y., 2009. Global consumptive water use for crop production: the importance of green water and virtual water. Water Res. Res. 45, W05428.

Liu, J., Zang, C., Tian, S., Liu, J., Yang, H., Jia, S., You, L., Liu, B., Zhang, M., 2013. Water conservancy projects in China: achievements, challenges and way forward. Glob. Environ. Chang. 23, 33–643.

Macknick, J., Newmark, R., Heath, G., Hallett, K.C., 2012. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ. Res. Lett. 7, 045802.

Mekonnen, M.M., Gerbens-Leenes, P.W., Hoekstra, A.Y., 2015. The consumptive water footprint of electricity and heat: a global assessment. Environ. Sci. Water Res. Technol. 1, 285–297.

Meldrum, J., Nettles-Anderson, S., Heath, G., Macknick, J., 2013. Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environ. Res. Lett. 8, 015031.

Mertens, J., Prieur-Vernat, A., Corbisier, D., Favrot, E., Boon, G., 2015. Water footprinting of electricity generated by combined cycle gas turbines using different cooling technologies: a practitioner's experience. J. Clean. Prod. 86, 201–208.

Ministry of Water Resources, 2013. Regulations on Implementing Water Resources Evaluation for Development Plan of Large Coal Power Bases. http://www.mwr.gov.cn/zwzc/tzgg/tzgs/201312/t20131217_520799.html.

Molden, D., 1997. Accounting for Water Use and Productivity. SWIM Paper 1. International Irrigation Management Institute, Colombo.

National Development and Reform Commission, 2004. Requirement on the Planning and Construction of Coal Power Plants. http://www.nea.gov.cn/2012-01/04/c_131262602.htm.

National Development and Reform Commission, Ministry of Science and Technology, Ministry of Water Resources, Ministry of Construction, Ministry of Agriculture, 2005. China water Conservation Technology Policy Outline. http://bgt.ndrc.gov.cn/zcfb/200506/t20050602_500425.html.

Olsson, G., 2012. Water and Energy: Threats and Opportunities. IWA Publishing, London.

Rio Carrillo, A.M., Frei, C., 2009. Water: a key resource in energy production. Energy Policy 37, 4303–4312.

Siddiqi, S., Anadon, L.D., 2011. The water energy nexus in Middle East and North Africa. Energy Policy 39, 4529–4540.

State Oceanic Administration People's Republic of China, 2014. Report on the Utilization of Seawater 2013 (Beijing).

The Ministry of Water Resources of the People's Republic of China, 2012. China Water Resource Bulletin (Beijing).

Torcellini, P., Long, N., Judkoff, R., 2004. Consumptive water use for U.S. power production. ASHRAE Tran 110, 96.

Turchi, C., Wagner, M., Kutshcer, C., 2010. Water Use in Parabolic Trough Power Plants: Summary Results from WorleyParsons' Analyses. National Renewable Energy Laboratory, Colorado.

van Vliet, M.T.H., Yearsley, J.R., Ludwig, F., Vögele, S., Lettenmaier, D.P., Kabat, P., 2012. Vulnerability of US and European electricity supply to climate change. Nat. Clim. Change 2, 676–681.

van Vliet, M.T.H., Wiberg, D., Leduc, S., Riahi, K., 2016. Power-generation system vulnerability and adaptation to changes in climate and water resources. Nat. Clim. Change 6, 375–380.

Xie, Y., Mackinnon, J., Li, D., 2004. Study on biogeographical divisions of China. Biodivers. Conserv. 13, 1391–1417.

Yu, F., Chen, J., Sun, F., Zeng, S., Wang, C., 2011. Trend of technology innovation in China's coal-fired electricity industry under resource and environmental constraints. Energy Policy 39, 1586–1599.

Zhang, C., Anadon, L.D., 2013. Life cycle water use of energy production and it's environmental impacts in China. Environ. Sci. Technol. 47, 14459–14467.

Zhang, C., Anadon, L.D., Mo, H., Zhao, Z., Liu, Z., 2014. Water-carbon trade-off in China's coal power industry. Environ. Sci. Technol. 48, 11082–11089.