The ‘thirsty’ water-electricity nexus: field data on the scale and seasonality of thermoelectric power generation’s water intensity in China

2015 Environ. Res. Lett. 10 024015

(http://iopscience.iop.org/1748-9326/10/2/024015)

Environmental Research Letters

OPEN ACCESS

RECEIVED
15 October 2014

REVISED
21 January 2015

ACCEPTED FOR PUBLICATION
22 January 2015

PUBLISHED
20 February 2015

LETTER

The 'thirsty' water-electricity nexus: field data on the scale and seasonality of thermoelectric power generation's water intensity in China

Daqian Jiang and Anuradha Ramaswami

Humphrey School of Public Affairs, University of Minnesota, 301 19th Ave S., Minneapolis, MN 55455, USA

E-mail: jiang102@umn.edu

Keywords: water-electricity nexus, water intensity, thermoelectric power plants, China, seasonality, water withdrawal, water consumption

Abstract

There is a lack of field data on the water withdrawal and consumption intensity of thermoelectric power plants in China. With China's ambitious electricity capacity expansion and ever-growing water deficit, the overlooked water dimension of thermoelectric power generation could soon have significant water sustainability implications, and field data on water intensity of thermoelectric power plants will be essential to further our understanding of China's water-electricity nexus. To address this knowledge gap, this paper presents field data on the water withdrawal intensity and water balance of 19 coal-fired power plants in Shandong, China, categorized by different generator capacities (<100 MW ~ >600 MW) and boiler technologies (subcritical, supercritical and ultra supercritical). This paper suggests that the annual average water withdrawal intensity of coal-fired power plants in Shandong (1.50–3.75 L kWh^{-1}) is within the range of values reported for other countries, and that the distinction between water withdrawal and water consumption effectively vanishes since very little water is returned from withdrawal. This paper also suggests that there is quite significant seasonality in power plants' water intensity whereby the water intensity in July can be approximately 15–28% higher than the annual average. The seasonality is on a similar scale across all generator capacities, except for a small co-generation plant (<100 MW), which had substantially lower water intensity in January when a heat exchanger was used to provide heating.

1. Introduction

The strategic importance of water for power plants is widely recognized only recently. In fact, thermoelectric power plants withdraw a large amount of water in their operation, thus giving rise to the concept of water-electricity nexus (Dennen *et al* 2007, Sovacool 2009, Sovacool and Sovacool 2009). In countries like the USA, the power sector has long been the largest water-withdrawing sector, accounting for approximately 40% of the country's total freshwater withdrawal (Solley *et al* 1998, Kenny *et al* 2009, Maupin *et al* 2014,). Such magnitude of water demands has exposed thermoelectric power plants to high water supply chain risks and given them unique importance in water sustainability and climate change adaptation. In the past decade, water-related power plant service disruptions were not uncommon: US, France, Spain and Germany (Kimmell and Veil 2009, Förster and Lilliestam 2010, Rogers *et al* 2013), all experienced cooling-related shutdowns due to fluctuation in water availability or increase in water temperature.

The water dimension of electricity generation is perhaps even less recognized in emerging economies like China. Besides the institutional disconnect between energy and water planning, another reason is that the water withdrawal by the power sector is dwarfed by the agriculture sector in China. As the world's second largest agricultural irrigator (Wang *et al* 2012), agricultural irrigation is responsible for a predominant 65% of China's total freshwater withdrawal (NDRC 2005), whereas the power sector withdraws only 1/6 of agriculture's (Wai-Shin Chan 2012). As such, the water-electricity tradeoff in the agricultural sector, e.g. the carbon emissions from agricultural water pumping (Wang *et al* 2012), has drawn earlier attention than the water-electricity tradeoff in the power generation sector. Water-related electric power plant dysfunctions were reported occasionally (CCTV 2001) but failed to raise enough attention to motivate the coupling of electricity and water from a resource management perspective. However, with China's ever-increasing water deficit (which is estimated to be 40 billion cubic metres annually) (NDRC 2005, Liu and Diamond 2005) and its plan to add 1.2 TW water-reliant power capacity by 2030 (which is double Russia's and 5.9 times India's entire power generation capacity in 2009) (Wai-Shin Chan 2012), it is not inconceivable that China's electricity sector may soon reach a point where it will face stringent water constraints.

Compounding the inadequate awareness, the geographical distribution of China's water resource is disproportionate to the electricity generation capacity: North of Yangtze River is home to over 60% of China's generation capacity with only 17% of China's water resources (National Bureau of Statistics of China 2011). In the metropolitan Beijing area (including Tianjin, Shandong and Hebei), the per capita water availability is well below the 500 m^3/person extreme water scarcity threshold (Wai-Shin Chan 2012), while this area also happens to be where the electricity demand and production are highest and growing fastest. The major water sources in the region, Huang, Huai and Hai Rivers, are already over-exploited with use-availability ratios as high as 59%–123% (Kahrl and Roland-Holst 2008).

In US and Europe, there are growing interests and efforts in managing water and electricity in tandem (Sovacool 2009, Tidwell *et al* 2011). Unfortunately, even with the heightened policy interest and public concern, people have yet to find a way to overcome the accumulated institutional inertia and coordinate the competing use. Early awareness and intervention on water-electricity nexus in China may help to circumvent a much larger scale reinvention of infrastructure and policies in the future and alleviate the tension between water and electricity before the rapid growth in electricity production and the uneven spatial distribution of water resources cause irreversible sustainability issues.

Thus far, there is limited information in literature on the water intensity of the electric power sector in China. Water intensities of one or two thermoelectric power plants were reported occasionally in Chinese literature from a unit operation efficiency perspective (Li and Mo 2002, Chen *et al* 2008), but there is not yet a regionalized, field-data-based assessment of the electric power sector's water dependence and its water policy implications in China.

The lack of information, particularly the lack of field data on water intensity by different generator capacities, cooling technologies and water sources, has precluded further exploration of the water-electricity nexus challenge in China, which is the knowledge gap we intended to address in this study. Central to our study is the first field data on water intensities and seasonality of thermoelectric power plants in Shandong, China and a comparison of the annual average and seasonality of power plants' water intensities in Shandong with that in other countries.

Shandong Province makes a uniquely important case study for water-electricity nexus in China for two reasons: (1) Shandong is an extremely water-scarce area where the per capita water availability is only 1/6 of China's average and well below the extreme scarcity level (<500 m^3/capita) (Wai-Shin Chan 2012); (2) Shandong has the largest installed capacity of coal-fired power plants in China, including two of the largest coal-fired power plants that are already in operation, and one coal-fired power plant that is designed to be the largest coal-fired power plant in China (NBS 2011). The growing gap between water availability and electric power capacity expansion makes Shandong emblematic and representative of China's challenge. Given Shandong's unique position in China's electricity and water management, our study will bring to light China's water-electricity nexus challenge and provide data for future water-electricity nexus research on the national or global scale.

2. Methods

2.1. Water use in coal-fired power plants

Coal-fired power plants contribute more than 70% to China's electricity portfolio (Wang 2007). Coal-fueled electricity generation uses water throughout the life cycle, including the operation phase (e.g., cooling, flue gas scrubbing) and the non-operation phases (e.g., the upstream fuel acquisition and downstream discharge) (Fthenakis and Kim 2010). In this study, we focused on the water intensity in the operation phase and excluded water used in the non-operation phase.

2.2. Type of cooling systems

The cooling process is the largest water-withdrawing step in the operation phase of thermoelectric power plants. Four types of cooling systems are commonly used: a once-through system, a cooling pond, a wet cooling tower and a dry cooling tower (Fthenakis and Kim 2010). Except for dry cooling towers, water is used in the other three cooling processes to condense steam and dissipate waste heat.

In Shandong, wet cooling towers are the most commonly used type of cooling system. In a wet tower, the water withdrawal is known as the makeup water and is used to compensate for water losses in three processes: (1) evaporation, which usually accounts for the majority of the water loss in wet towers; (2) blowdown, which refers to the water discharged to prevent buildup of solids; (3) drift and blow-out, which are losses caused by exhaust air and wind (Feeley *et al* 2008). The cycles of concentration is an indicator used to control the accumulation of minerals in the cooling water and is directly related to the amount of blowdown needed (Feeley *et al* 2008).

2.3. Water withdrawal and water consumption

Similar to USGS, we distinguish the general concept of water use as water withdrawal and water consumption (Cohen and Ramaswami 2014). Water withdrawal refers to the total amount of water that is taken from water sources, including what is consumed and later returned to the original source without significantly lowering the water quality. In contrast, water consumption refers to processes in which water is diverted from its original source permanently or substantially damaged in terms of quality. The implications of distinguishing between water withdrawal and water consumption have been discussed in literature (Cohen and Ramaswami 2014). In particular, the distinction between water withdrawal and consumption is most used for future water-shed planning, addressing return flow management and multiple competing uses (Cohen and Ramaswami 2014).

2.4. Data collection

We personally networked with 19 electric power plants in Shandong, China and collected water intensity data via on-site interviews. We chose plants with different generator capacities and locations in order for the data to be representative of the entire region. Data collected included generator capacity (MW), electricity production (kWh), type of boiler (subcritical, supercritical, and ultra supercritical), type of cooling technologies, water balance within the thermoelectric power plant, annual average water intensity in 2013 (which was defined as the amount of water withdrawn to produce a unit of electricity, L kWh^{-1}), and water intensities in January and July (L kWh^{-1}) in 2013.

All 19 plants have measurement-based cooling water withdrawal intensities as plant-aggregates. Five out of 19 plants have provided measurement-based per generator cooling water withdrawal intensities and seven out of 19 plants have provided measurement-based water balance tables. In other plants, the best estimates made by the technical staff were used to construct the water intensity and water balance tables.

3. Results and discussion

3.1. Source of makeup water of power plants in Shandong

In Shandong, thermoelectric power plants use wet cooling towers and withdraw makeup water from a variety of sources (table 1). The most common source is surface water (14 out of 19 plants use 15 ~ 100% of surface water), of which the most commonly used source is the Huang River. Groundwater is another source of makeup water (used by 3 of 19 plants), although the use of groundwater for cooling has been strictly prohibited for newly constructed electric power plants. Use of grey water for cooling is becoming increasingly popular and encouraged in recent years. 10 out of 19 plants have a certain percentage of grey water as water source (5% ~ 80%). However, feedback from plants indicates that grey water is currently subject to much higher quantity and quality variations than surface and groundwater, and is only economically feasible for plants in the close vicinity of metropolitan areas. Seawater is another source of cooling water for power plants located on the coast line. In unique cases, small power plants with generators less than 100 MW may rely completely on wastewater (1 out 19) or tap water (1 out of 19) as the source of makeup water.

3.2. Cooling technologies

Dry cooling towers are not used in Shandong and rarely used in China for cost considerations. The extremely low water availability has practically prohibited electric power plants in Shandong from using once-through or pond cooling except for power plants that use seawater for cooling (table 1). To reduce the water withdrawal, thermoelectric power plants try to maximize the cycle of concentrations. In our survey, the cycles of concentrations ranges between 2 and 6.5, which are largely determined by the quality of the water source.

3.3. Return flow of makeup water

It is estimated that the evaporative loss accounts for 80%–90% of water withdrawal per the technical staff (figure 1). The remaining 10–20% blowdown is high in salt concentrations and is usually used for flue gas scrubbing (and/or ash flushing), which is then sold to construction companies as a raw material (figure 1). There is usually little blowdown remaining after flue gas scrubbing (less than 5% of total withdrawal), which is then treated through constructed wetlands and discharged to the environment (figure 1). However, when there is extreme water shortage in the summer, the remaining blowdown is sometimes used as irrigation water. Given the insignificant return flow, the water consumption intensity is effectively numerically equivalent to the water withdrawal intensity for thermoelectric power plants in Shandong from a water balance perspective (figure 1).

3.4. Annual average water withdrawal intensity in the operation phase of coal-fired power plants in Shandong

Overall, the water withdrawal intensity of thermoelectric power plants in Shandong is within the range of values reported for US coal-fired power plants (Macknick *et al* 2011, Woldeyesus 2012) and elsewhere (table 2). The water intensity of once-through cooling is lower than wet towers, although the water intensity of once-through cooling reported here is the

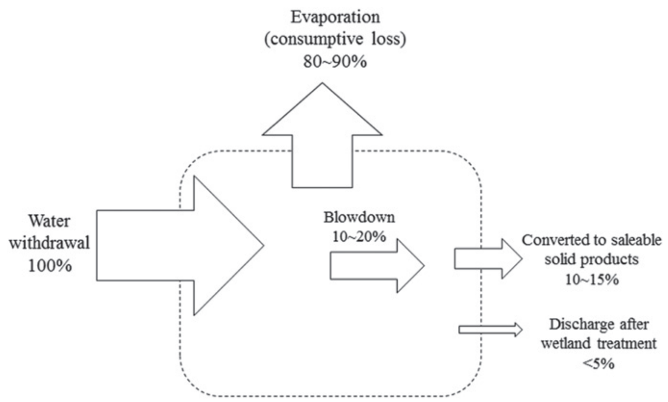

Figure 1. Water balance in a typical coal-fired power plant in Shandong, China. There is virtually no return water (<5%) and 10–15% of water withdrawal is usefully transformed to saleable solid products.

water loss in cooling auxiliary equipment, rather than the evaporative loss as reported elsewhere (Macknick *et al* 2011). The annual average water intensity is lower and more consistent for larger plants and larger generators (>100 MW) while small plants (<100 MW) appear to have higher variability, which seems to suggest a lower cooling efficiency in smaller plants (table 1).

When linearly scaling up our field data, we project an annual total water withdrawal of approximately 7×10^8 m^3 by the thermoelectric power sector in Shandong (total electricity production data taken from *Shandong Statistical Yearbook* 2013), which agree with the sectoral water withdrawal data reported in *Shandong Statistical Yearbook* 2013. With the planned capacity expansion and increased electricity consumption in China (Shiu and Lam 2004, Crompton and Wu 2005), the annual total withdrawal will soon reach the order of billion cubic metres before 2030, putting additional pressure on the already over-exploited water resource in the area.

3.5. Seasonal water intensities in the operation phase of coal-fired power plants in Shandong

The water withdrawal intensity of power plants in July was significantly higher than in January in Shandong (figure 2). On average, the water withdrawal intensity in summer is 15–28% higher than annual average water withdrawal intensity while in winter, the water withdrawal intensity tends to be 12–24% lower than annual average (figure 2). The seasonality of water withdrawal intensity tends to be higher in small plants (<100 MW), particularly in a small co-gen plant which has significantly lower water intensity in winter. The seasonal variability reported here seems to be on par with Macknick *et al* 2007 (Macknick *et al* 2011), but less significant than reported by Koch and Vogele (Koch and Vögele 2009) based on actual data and by Yang and Dziegielewski (Yang and Dziegielewski 2007) based on a regression analysis.

The higher water intensity from power generation coincides in time with the peak electricity demand (Gnansounou and Dong 2004) and the highest irrigation water demand in Shandong (Zhen *et al* 2005). Assuming a 25% increase in the average water intensity in the summer, the water withdrawal by thermoelectric power plants in Shandong could be as high as 90 million m^3/month in the summer of 2013, which highlights the importance of peak water demand management in addition to the total annual demand management.

4. Conclusion

Overall, our data indicate that the water withdrawal intensity and water consumption intensity of coal-fired power plants are effectively numerically equivalent in Shandong. An insignificant amount of water is discharged as a result of cross-using blowdown water for flue gas scrubbing, although 10–15% of the water withdrawal is usefully transformed into a saleable product during flue gas scrubbing. The annual average water intensity is ~2 L kWh^{-1} for coal-fired power plants in Shandong, which is on par with water withdrawal intensities of thermoelectric power plants worldwide using similar cooling technologies.

Our results also indicate quite significant intra-plant seasonality and plant-to-plant variability in thermoelectric power plants' water intensity. Overall, smaller thermoelectric power plants (<100 MW) tend to have larger annual average water withdrawal intensity and seasonality, particularly if they are co-generation plants. The higher water withdrawal intensity from thermoelectric power plants in the summer coincides in time with the peak electricity demand and peak irrigation water demand in Shandong, which makes peak water demand management in summer potentially more critical than the total annual demand management from a water management perspective.

Table 1. Water withdrawal intensity of thermoelectric power plants in Shandong, China (some plants have multiple types of boilers).

Generator capacity	Fuel	Boiler type	Cooling technology	Fuel efficiency (g coal equivalent/kWh)	Sample size	Annual average consumption water loss (L kWh^{-1})	Water source
	Coal	Ultra supercritical[c]		260 ~ 275	3	1.88–2.21	
>600 MW	Coal	Super critical		280 ~ 290	2	2.00–2.18	
	Coal	Supercritical		290 ~ 310	5	2.08–2.5	Groundwater' surface water, and grey water[b]
300 ~ 600 MW	Coal	Supercritical[d]	Wet tower	290 ~ 310	3	1.76–2.80	
100 ~ 300 MW	Coal	Supercritical		290 ~ 320	6	1.50–2.78	
<100 MW	Coal	Supercritical		290 ~ 320	2	2.16–3.75	
>100 MW	Coal	Generic	Once-through	260 ~ 340	2	0.15 ~ 0.45[a]	Seawater

[a] Water loss in cooling auxiliary equipment.

[b] A mix of surface water and grey water is used in most power plants. Use of groundwater for cooling has been prohibited for new power plants.

[c] Thermoefficiency 41% ~ 43%.

[d] Thermoefficiency 37% ~ 40%.

Table 2. Water intensity of thermoelectric power plants in different countries.

Country	Fuel and boiler	Cooling technology	Water withdrawal intensity (L kWh^{-1})	Water consumption intensity (L kWh^{-1})	Source
US	Coal, generic	Wet tower	1.89–4.54	1.82–4.16	(Macknick *et al* 2011)
China	Coal, subcritical	Wet tower	1.50–3.75	1.50–3.75	This paper
US	Coal, subcritical	Wet tower	1.75–2.57	1.49–2.51	(Macknick *et al* 2011)
China	Coal, supercritical	Wet tower	2.00–2.18	2.00–2.18	This paper
US	Coal, supercritical	Wet tower	2.20–2.53	1.73–2.25	(Macknick *et al* 2011)
China	Coal, generic	Once-through	NA	0.15–0.45	This paper
US	Coal, generic	Once-through	75.71–189.3	0.38–1.20	(Macknick *et al* 2011)
US	Coal, subcritical	Once-through	102.4–102.6	0.27–0.52	(Macknick *et al* 2011)
US	Coal	Wet tower	1.90–4.43	1.70–4.43	(Fthenakis and Kim 2010)
US	Coal	Wet tower	1.75–19.96	1.49–4.2	(Woldeyesus 2012)
Australia	Coal	NA	1.70		(Marsh 2008)
Spain	Coal	NA	31.05	1.55	(Rio Carrillo and Frei 2009)
France	Nuclear/coal/gas	NA	94		(Innovation for Energy 2011)
UK	Coal	Wet tower	2.11	1.77	(Byers *et al* 2014)
EU	Coal	NA		1.70–2.00	(Koulouri and Moccia 2014)

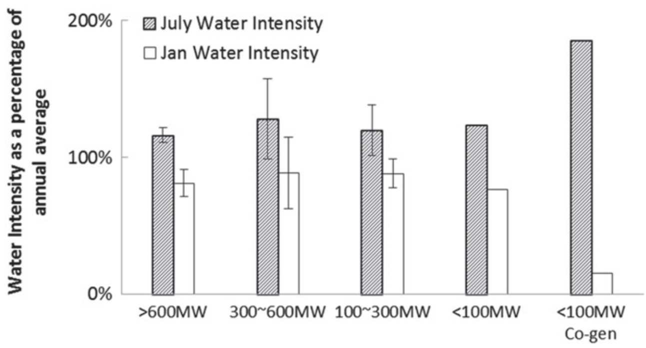

Figure 2. Water withdrawal intensity in January and July for power plants using wet towers in Shandong, China.

Acknowledgments

The authors would like to thank NSF PIRE (grant number PIRE-1243525), University of Minnesota Global Spotlight Research Grant for financial support. The authors would also like to thank the anonymous reviewers for their very helpful comments.

References

Byers E A, Hall J W and Amezaga J M 2014 Electricity generation and cooling water use: UK pathways to 2050 *Glob. Environ. Change* **25** 16–30

CCTV News 2001 In drought: tap water more than 40 RMB/ton (www.cctv.com/financial/jingji/sanji/gazz/20010618/108.html) Accessed October 5th 2014

Chan W-S, Robins N and Knight Z 2012 No water, no power: Is there enough water to fuel China's power expansion? HSBC Global Research, Climate Change

Chen H, Xu Y and He Y 2008 Review of progress on cooling water operation in coal and nuclear power plants (火核电厂冷却水试验研究 年的进展和体验)*J. China Inst. Water Resour. Hydropower Res.* **6** 288–98

Cohen E and Ramaswami A 2014 The water withdrawal footprint of energy supply to cities *J. Ind. Ecology* **18** 26–39

Crompton P and Wu Y 2005 Energy consumption in China: past trends and future directions *Energy Econ.* **27** 195–208

Dennen B, Larson D, Lee C, Lee J and Tellinghuisen S 2007 California's energy-water nexus: water use in electricity generation *MESM Thesis* Bren School of Environmental Science and Management, University of California Santa Barbara, CA 93106

Innovation for Energy 2011 Panorama 2011: water for electricity (www.ifpenergiesnouvelles.com/Publications/Available-studies/Panorama-technical-reports/Panorama-2011) Accessed February 6th 2015

Feeley T J I I I, Skone T J, Stiegel G J Jr, McNemar A, Nemeth M, Schimmoller B, Murphy J T and Manfredo L 2008 Water: a critical resource in the thermoelectric power industry *Energy* **33** 1–11

Fthenakis V and Kim H C 2010 Life-cycle uses of water in US electricity generation *Renew. Sustainable Energy Rev.* **14** 2039–48

Förster H and Lilliestam J 2010 Modeling thermoelectric power generation in view of climate change *Reg. Environ. Change* **10** 327–38

Gnansounou E and Dong J 2004 Opportunity for inter-regional integration of electricity markets: the case of Shandong and Shanghai in East China *Energy Policy* **32** 1737–51

Kahrl F and Roland-Holst D 2008 China's water-energy nexus *Water Policy* **10** 51

Kenny J F, Barber N L, Hutson S S, Linsey K S, Lovelace J K and Maupin M A 2009 Estimated use of water in the United States in 2005 (Reston, VA: US Geological Survey) 1344

Kimmell T A and Veil J A 2009 Impact of drought on US steam electric power plamt cooling water intakes and related water resource management issues No DOE/NETL-2009/1364 Argonne National Laboratory (ANL)

Koch H and Vögele S 2009 Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change *Ecological Econ.* **68** 2031–9

Koulouri A and Moccia J 2014 Saving water with wind energy. The European Wind Energy Association

Li H and Mo N 2002 Preliminary analysis on water conservation technology of circulating cooling tower in thermal power plant *North China Electric Power* 9–12

Liu J and Diamond J 2005 China's environment in a globalizing world *Nature* **435** 1179–86

Macknick J, Newmark R, Heath G and Hallett K 2011 A review of operational water consumption and withdrawal factors for electricity generating technologies *Contract* **303** 275–3000

Marsh D M 2008 The water-energy nexus: a comprehensive analysis in the context of New South Wales *PhD Dissertation* University of Technology Sydney

Maupin M A, Kenny J F, Hutson S S, Lovelace J K, Barber N L and Linsey K S 2014 Estimated use of water in the United States in 2010 US Geological Survey Circular 1405 56

National Bureau of Statistics of China 2011 Chinese Statistics Yearbook 2011

National Development and Reform Commission (NDRC) 2005 China Water Policy Conservation Technology Outline (中国节水技术政策大纲). Announcement No.17

Rio Carrillo A M and Frei C 2009 Water: a key resource in energy production *Energy Policy* **37** 4303–12

Rogers J, Averyt K, Clemmer S, Davis M, Flores-Lopez F, Frumhoff P, Kenney D, Macknick J, Madden N and Meldrum J 2013 Water-mart power: strengthening the US electricity system in a warming world (Cambridge, MA: Union of Concerned Scientists)

Shiu A and Lam P-L 2004 Electricity consumption and economic growth in China *Energy Policy* **32** 47–54

Solley W B, Pierce R R and Perlman H A 1998 Estimated use of water in the United States in 1995 (Menlo Park, CA: United States Geological Survey)

Sovacool B K 2009 Running on empty: the electricity-water nexus and the US electric utility sector *Energy Law J.* **30** 11

Sovacool B K and Sovacool K E 2009 Identifying future electricity-water tradeoffs in the United States *Energy Policy* **37** 2763–73

Tidwell V C, Kobos P H, Malczynski L A, Klise G and Castillo C R 2011 Exploring the water-thermoelectric power Nexus *J. Water Resour. Plan. Manag.* **138** 491–501

Wang B 2007 An imbalanced development of coal and electricity industries in China *Energy Policy* **35** 4959–68

Wang J, Rothausen S G A, Conway D, Zhang L, Xiong W, Holman I P and Li Y 2012 China's water-energy nexus: greenhouse-gas emissions from groundwater use for agriculture *Environ. Res. Lett.* **7** 014035

Woldeyesus T A 2012 Electric portfolio modeling with stochastic water-climate interactions: implications for co-management of water and electric utilities *PhD Dissertation* Department of Civil and Environmental Engineering, University of Colorado at Denver

Yang X and Dziegielewski B 2007 *Water Use by Thermoelectric Power Plants in the United States* 1 (New York: Wiley)

Zhen L, Routray J K, Zoebisch M A, Chen G, Xie G and Cheng S 2005 Three-dimensions of sustainability of farming practices in the North China Plain: a case study from Ningjin County of Shandong Province, PR China *Agric. Ecosystems Environ.* **105** 507–22