1 **Water use in China's thermoelectric power sector**

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■ ABSTRACT

We quantify the current water use of China's thermoelectric power sector with plant-level data. We also quantify the future implications for cooling water use of different energy supply scenarios at both a regional and national levels. Within China, water withdrawal and consumption are projected to exceed 280 and 15 billion m³ respectively by 2050 if China does not implement any new policies, up from current levels of 65.2 and 4.64 billion m³. Improving energy efficiency or transforming the energy infrastructure to renewable, or low-carbon, sources provides the opportunity to reduce water use by over 50%. At a regional level, central and eastern China account for the majority of the power sector's water withdrawals, but water consumption is projected to increase in many regions under most scenarios. In high-renewable and low-carbon scenarios, concentrated solar power and inland nuclear power, respectively, constitute the primary fresh water users. Changing cooling technology, from open-loop to closed-loop in the south and from closed-loop to air cooling in the north, curtails the power sector's water withdrawal considerably while increasing water consumption, particularly in eastern and central China. The power sector's water use is predicted to exceed the regional industrial water quota under the '3 Red Line' policy in the east under all scenarios, unless cooling technology change is facilitated. The industrial water quota is also likely to be violated in the central and the northern regions under a baseline scenario. Moreover, in line with electricity production, the power sector's water use peaks in the winter when water availability is lowest.

Water-for-energy is a highly contextual issue – a better understanding of its spatio-temporal characteristics is therefore critical for development of policies for sustainable cooling water use in the power sector.

■ 1. Introduction

1.1. Water for thermoelectric power production

Water is an indispensable factor of production throughout the thermoelectric power sector, from upstream fuel extraction and power production to downstream infrastructure dismantling (World Energy Council, 2010). Of these various processes, the operation of power plants contributes the most to total water use (Mekonnen *et al.*, 2015) and cooling to dissipate the residual heat from steam turbines in thermoelectric power production uses the most water (Fthenakis and Kim, 2010 and Meldrum *et al.*, 2013).

Water withdrawal refers to water abstracted from the natural environment while water consumption is defined as the water withdrawn but not discharged back to water bodies (AQUASTAT, 1998). Collectively, they are referred to as water use. Since Vassolo and Doll (2005) made the first attempt at estimating the global thermoelectric power sector's water use and presented a global-gridded estimate of the water uses of 63,590 thermal power stations for the year 1995, there has been a proliferation of studies looking at the water use for power generation over the last decade. It is estimated that thermoelectric cooling is responsible for around 43% and 50% of total fresh water withdrawals in the EU and US, respectively (UN, 2014).

Globally, around 53 billion m³ of fresh water is consumed every year by energy production (Spang *et al.*, 2014). Both water shortage and water temperature increase could lead to reductions of electricity generation, which is manifested by the curtailments of power production or plant shutdowns in Europe, as seen in 2003 in France, and in south eastern US where there was insufficient cooling water availabilities (Van Vliet *et al.*, 2012).

Potential conflict between water availability and demand by the power sector arising from climate change are anticipated in several studies forecasts. Projections based on climate change modelling indicate reductions in usable capacity for over 60% of the global hydropower and over 80% of the thermoelectric power from 2040 to 2069 (Van Vliet *et al.* 2016). Moreover, some climate change mitigation technologies, e.g. carbon capture and storage (CCS), may have the unintended impact of increasing the power sector's water consumptions (Byers *et al.* 2014). However, Kyle *et al.* (2013) argued that increasing water consumption could be offset by water-saving technologies, e.g. open-loop cooling. All the studies highlight the importance of considering future scenarios to avoid unsustainable infrastructure and technological investments.

Amongst various factors impacting the power sector's water intensities, measured as water consumed or withdrawn per unit of electricity produced, the type of thermoelectric plant and the cooling technology they use are the most significant (Macknick *et al.*, 2012). There are primarily three types of cooling technologies: open-loop cooling, which dissipates heat by running water; closed-loop cooling,

which dissipates heat by recirculating water in towers or ponds; and air cooling, which removes heat by air circulation. The consumptive water use in an open-loop system is 70-80 percent lower compared with a closed-loop cooling system, but the water withdrawal is 30-60 times higher (WRI, 2015).

Climate change may alter the availability of water by increasing temperatures (and hence the evapotranspiration of surface water) and increasing the variability of precipitation, e.g. increase of drought periods and expansion of drought-affected areas (Gerten *et al.*, 2013; Hanasaki *et al.*, 2013; Wada *et al.*, 2011 and Doell *et al.*, 2012). The OECD's baseline scenario projects that 3.9 billion people will be subject to severe water stress by 2050 (OECD, 2012). Water-related risks for power industry are estimated to worsen with the changing climate (IPCC, 2013).

1.2. Significance of the study area

Cooling water is a particular issue in China because of the prevalence of thermoelectric power plants on inland waterways that are potentially at risk of water shortages. Over the last decade, electricity consumption in China has almost quadrupled from 1,347 TWh in 2000 to 4,976 TWh in 2012 (National Bureau of Statistics of China, 2014), with this trend projected to continue. More than 80% of the power demand was met by thermoelectric power generation (Zhang, 2012).

Yet, China is not abundant in water. Although the country's total amount of surface water ranks sixth in the world at about 2800 bn m³, its water resource per capita, 2632 m³ in 2012, only amounts to one fourth of the world average (Ye and

Zhang, 2013). In 2011, the Chinese government issued its strictest water management policy called the ‘3 Red Line’ policy. This policy set targets for total water use, industrial and agricultural water use efficiencies and water quality improvements on a national as well as on a regional scale for 2015, 2020 and 2030. Regarding the total water use, the first ‘Red Line’ sets a national water withdrawal cap at 635, 670 and 700 bn m³ for 2015, 2020 and 2030, respectively, against the level of 609.5 bn m³ in 2014 (China water resource bulletin, 2015), which will be enforced through a water permit system. However, without technological changes, the industrial targets for water withdrawals are likely to be exceeded in the energy sector by 2035 (Qin *et al.*, 2015). Accordingly, Yu *et al.* (2011) conclude that technological innovation is critical in terms of water conservation in China’s coal-fired power sector.

China’s water resources are unevenly distributed. The precipitation is highest in the southeast and lowest in the northwest. The total average annual internal renewable surface water resources in northern areas are estimated to be 535.5 km³, which is only 20 percent of the country’s total (AQUASTAT, 2014). Moreover, the precipitation’s inter-annual variations are greater in the north than in the south (Ye and Zhang, 2013). On the other hand, Zhang and Anadon (2013) conclude that the most important feature of China’s thermoelectric power sector’s water use is its uneven spatial distribution. The power sector’s water withdrawal mostly occurs in the east and south, while water consumption by the power sector was higher in the arid northern regions in 2007 (Zhang and Anadon, 2013). Several river basins in the north and northwest, as well as a number of coastal city clusters in the east and south, have

significant water stress (Zhang *et al.*, 2016). Without effective water-saving measures, China's coal industry's water demands could exceed its water availabilities, especially in the north and west (Pan *et al.*, 2012).

China's coal reserves are mostly located in water-scarce areas and, to save cost, a large proportion of power generation capacity is located close to these reserves. Furthermore, over half of China's proposed coal-fired power plants are located in areas with high water stresses (WRI, 2014). According to the assessment by Sadoff *et al.* (2015), northern China stands out as having the highest water security risks in the world for power generation. Given the significant uneven spatial distributions of China's water resources and power productions along with their geographical mismatches, China's thermoelectric power sector's water use needs to be studied on a regional scale.

The power system in China is operated on six regional grids: the northern, northeastern, northwestern, central, eastern and southern grids. Interregional power transmissions are small (Guo *et al.*, 2016) and therefore not considered in this study. It is therefore useful to look into the power sector's water demands against their water quotas by regional grid.

In terms of future projections on a regional scale, Cai *et al.* (2014) has examined China's energy production's water withdrawal, from coal mining to power production, under IEA's future energy scenarios. However, water withdrawal and consumption factors were not differentiated in their calculation. Consequently, Cai *et al.* (2014) underestimated China's energy sector's water withdrawal with results much

lower than that from Qin *et al.* (2015). Moreover, water consumption was not discussed. Water consumption is important especially during dry seasons when upstream power plants' water consumption, instead of water withdrawal, poses the biggest threat to downstream water users.

While power production and its corresponding water demand vary within the year, inter-annual temporal characteristics of China's water for energy are under-studied. Moreover, the spatial patterns of water availability and use are not well understood. This lack of understanding could lead to conflicts between regional energy developments and related water policies. This paper therefore sets to achieve four goals: (1) to better present the current water use by China's power sector with plant-level data that considers different cooling types and water sources; (2) to examine China's future water for energy on a national and regional scales; (3) to examine the regional coherence of China's energy plans and related water policies, i.e. the '3 Red Line' policy; and, (4) to reveal the temporal characteristics of China's power sector's water use.

■ 2. Methodology and data

2.1. Methodology

A bottom-up approach, as in Vassolo and Doll (2015), Yuan *et al.* (2014) and Byers *et al.* (2014), is employed in this study to estimate the water uses in China's thermoelectric power sector:

$$A=E*a \quad (1)$$

$$C=E*c \quad (2)$$

where A and C refer to water abstraction and consumption respectively; E represents the electricity generation and a , c are the water abstraction and consumption intensities.

Water abstraction intensity, a , and water consumption intensity, c , vary by energy source and cooling type. Therefore, the Eqs. (1) and (2) can be expressed as:

$$A=\sum_1^n \sum_1^k E_{g,m} a_{g,m} \quad (3)$$

$$C=\sum_1^n \sum_1^k E_{g,m} c_{g,m} \quad (4)$$

where g indicates the fuel types from 1 to n : nuclear, gas-fired, coal-fired and so forth; m designates cooling types, including open-loop, closed-loop and air-cooling. And k is the number of cooling types.

2.1.1. National scenarios

The coal-fired power sector currently accounts for 75% of power production (National Bureau of Statistics of China, 2014), so is the focus for quantification of water use at present. Other thermal generation, including gas, nuclear and Concentrated Solar Power (CSP), are taken into account to assess future contingencies. Hydropower contributes 17% of China's power production (National Bureau of Statistics of China, 2014), but most reservoirs in China serve multiple purposes, e.g. hydro power, flood control and water supply, and there is no commonly recognized method of allocating the water consumption to different purposes (Bakken *et al.*, 2016), so estimation of hydropower production's water consumption has been

excluded from this study.

As China does not have any holistic plan for future electricity generating technology development or infrastructure expansion (Li, 2015), scenario analysis has been carried out to manage the uncertainties. We reviewed a large number of existing plans, projections and scenarios for China's future energy development as in Table 1. Only World Wide Fund for Nature (WWF) (2014) and National Development and Reform Commission (NDRC) (2009) have done scenario studies on China's future energy development to 2050. With support from the UK Department of Energy and Climate Change (DECC) and the UK Foreign and Commonwealth Office (FCO), NDRC (2009) developed 'China 2050 Pathways' and demonstrate various possible technological routes towards a low-carbon economy in China by 2050. WWF (2014) assesses the maximum potentials for renewable sources in China to 2050 with multiple scenarios. China faces long-term energy challenges as, being the world current largest CO₂ emitter, it has pledged to peak its emissions around 2030 and lower its CO₂ emissions per unit of GDP by 60% to 65% from 2005 levels (NDRC, 2015). It can be seen that the figures given by WWF and NDRC's corresponding scenarios are consistent and the values by all other studies are within a reasonable range. However, as gas-fired power is included separately only in WWF's study and it plays an important role in power sector's water usage, the future energy scenarios in WWF (2014) are employed in this study. In this, the baseline scenario is that China does not implement new policies other than the current ones; under the high-efficiency scenario, China reduces its energy intensity by transforming its

economy from energy-intensive industry to services and adopting state-of-art efficiency technologies. High-renewable and low-carbon scenarios build on high-efficiency demand projections but require the demand to be met with renewable or low-carbon energy sources, respectively. As China's new "Intended National Determined Contribution (2015)" only pledged to raise its share of non-fossil fuels in primary energy to about 20% in 2030, both the high-renewable and low-carbon scenarios adopted in this study are more optimistic than current policy about China's changing fuel mix. This study however is trying to explore the impacts of different future energy portfolios on China's thermoelectric power sector's water uses instead of predicting the future, and WWF's scenarios provide a valuable range. In the abovementioned scenarios, we assume the regional cooling technology shares are the same as current throughout the future. We develop another scenario to explore the effects of cooling technology changes on water use. Building on the demand projections in Baseline Scenario, all closed-loop cooling systems in the north (north, northeast and northwest) are replaced by air cooling systems. Similarly, all open-loop cooling systems in the south (south, east and central) are changed to closed-loop ones.

2.1.2. Regional disaggregation

Electricity demand varies significantly by region throughout China. It is higher in the north and the east currently (National Bureau of Statistics of China, 2014). The regional distribution of future electricity demands is approximated from the Hu et al. (2011). Future regional non-coal-fired power forecasts are extrapolated

from national projections/plans with relevant policies or regulations. Regional natural gas-fired power is developed proportionally to projected electricity consumption according to the “Policy on Natural Gas Use” (NDRC, 2012). Future regional wind power is extracted from the “China renewable energy development 2050 roadmap” (Sino-Danish Renewable Energy Development Program, 2014). Nuclear power development is derived from the World Nuclear Association (2015), including 12 proposed inland nuclear sites. As site selection for nuclear power plants depends on many factors, when the projected capacity exceeds all the existing/planned/proposed nuclear capacity, we assume the further capacity will be met at existing/planned/proposed sites instead of developing new ones. Solar power capacity is projected to grow in proportion to its current distribution and hydropower will be developed proportionately according to the regional hydro resource endowments as in the “Database for Human-earth System” by Chinese Academy of Sciences (2016).

Due to its relatively mature technology and low cost, coal-fired capacity is modelled as filling the discrepancy between total electricity demand and the energy electricity production from other energy sources. Therefore, each region’s electricity generation could be expressed in Eq. (5) as below:

$$E_{\text{demand},i} = E_{\text{coal},i} + E_{\text{gas},i} + E_{\text{PV},i} + E_{\text{CSP},i} + E_{\text{wind},i} + E_{\text{nuclear},i} + E_{\text{hydro},i} \quad (5)$$

Where $E_{\text{demand},i}$ is the projected electricity demand in province i , $E_{\text{coal},i}$, $E_{\text{gas},i}$, $E_{\text{PV},i}$, $E_{\text{CSP},i}$, $E_{\text{wind},i}$, $E_{\text{nuclear},i}$ and $E_{\text{hydro},i}$ refer to electricity generations by coal-fired power, gas-fired power, PV solar power, CSP, wind power, nuclear power and hydropower, respectively. More details about disaggregating China’s future energy scenarios to

different regions are described in Supplementary Materials.

2.1.3. Water sources

Use of groundwater by the power sector has been banned since 2004 (NDRC, 2004), and so we assume in future groundwater will be substituted by surface water from 2020 onwards. We assumed that use of reclaimed water and seawater by the power sector will remain in the same proportion to surface water sources as in China Electricity Council (2013a, b).

2.2. Data

The framework of the approach and data used in this study are presented in Fig. 1. A comprehensive database of China's coal-fired power plants is developed from World Electric Power Plants Data Base (WEPP) (Utility Data Institute of Platts Energy InforStore, 2015). The coordinates and capacities of 1072 coal-fired power plants whose aggregate capacity amounts to 855 GW, which equals about 92% of the nation's total until 2014, are included. Data is crosschecked with other datasets, i.e. Carbon Monitoring for Action (CARMA) (The Center for Global Development, 2015), Global Coal Plant Tracker (CPT) (CoalSwarm, 2015) and Enipedia (Davis et al., 2015). Provincial average running hours of coal-fired power plants in 2014 are used in order to calculate the electricity productions.

Similar to Zhang *et al.* (2016), the cooling technology employed by individual power plants is identified via Google Earth imagery. However, only 769.06 GW of

thermoelectric power plants built by 2011 were included in Zhang *et al.* (2016), while over 850 GW built by 2014 is included in this study.

Apart from coal-fired power, the water intensities of other thermoelectric plants are not available in China. For consistency, the median values of water intensities of various energy sources and cooling types compiled by Macknick *et al.* (2012) are used. Zhang *et al.* (2016) conclude that the average water consumption values of coal power plants in China are comparable to the median values of corresponding American ones. The abovementioned values are summarized in Table 2.

Lastly, the monthly distribution of power sector's water uses is assumed to be in direct proportion to power production. China's monthly regional power production data from 2005 to 2014 is drawn from the National Bureau of Statistics (2014).

■ 3. Results

3.1. Water use in China's thermoelectric power sector in 2014

Fig. 2 presents the current cooling technology used in China, demonstrating the regional prevalence of different cooling technologies. Closed-loop systems are used throughout the whole country; open-loop systems are commonly adopted in the southeast and coastal regions where water - either freshwater or seawater - is abundant and discharged water does not constitute thermal pollution on the downstream; air cooling is mostly used in northern China where it faces the most severe water shortages.

Water consumption from four sources (surface water, ground water, reclaimed water and seawater) by power generation in 2014 is presented in Fig. 3. Two major hot spots of surface water consumption can be identified in the Yellow River basin in eastern China and the Yangtze River basin in southwestern China. As for ground water, even though a ban on its utilization in northern China has been issued in 2004, it is still being intensively consumed in the Huang-Huai-Hai area in northern China where surface water is lacking, together with reclaimed water. Unsurprisingly, seawater is used along the coastline.

The national surface water, reclaimed water and ground water consumption amount to 4.64, 0.79 and 1.05 bn m³ respectively. Further data for regional water consumption are demonstrated in the Supplementary materials. The total fresh water consumption, when compared to the result calculated by Zhao *et al.* (2016) - 4.89 bn m³, is therefore proportionate to the generating capacities examined in each study.

3.2. China's future water demand by the thermoelectric power sector

3.2.1. National results

The results of scenario analysis of China's future fresh water use by the power sector are demonstrated in Fig. 4. Further information on reclaimed water and seawater uses in China's thermoelectric power sector is provided in the Supplementary materials on a regional scale.

Significant increases in water withdrawal and consumption can be seen in the baseline scenario to over 280 and 16 bn m³ respectively by 2050. Improving energy

efficiency reduces the magnitudes of water withdrawal and consumption by over 50% to about 140 and 8 bn m³ by 2050 respectively.

Under high-renewable and low-carbon scenarios, water withdrawal is cut by over 70%, with a decreasing trend. Water consumption is also reduced by over 60% and grows at much lower rates. Under a low-carbon scenario, inland nuclear power is responsible for the growth in water consumption, requiring over 3.3 bn m³ by 2050.

Changing cooling technology significantly reduces water withdrawal due to the elimination of open-loop cooling systems. As for water consumption, phasing out open-loop cooling systems in the south and closed-loop cooling systems in the north, respectively, increases and decreases the sector's water consumption, and in total, little impact is seen on a national scale.

3.2.2. Regional patterns

Fig. 5 demonstrates water abstractions in different regions under all five scenarios. The results show that water is mostly withdrawn in central and eastern China where water resources are sufficient. Intensive utilization of seawater in the south and closed-loop/air cooling technologies in the north lowers their fresh water withdrawals.

Water withdrawal is projected to surge in all regions under a baseline scenario, while the magnitudes are halved under a high-efficiency scenario. Under high-renewable and low-carbon scenarios, water withdrawal is further reduced in all regions, with gas-fired power and inland nuclear, respectively, becoming the main

water abstractors. Most noticeably, switching cooling technologies by phasing out open-loop cooling systems provides the capacity to reduce more than 90% of water withdrawals from a baseline scenario.

The interregional differences in water consumption are not as significant as for water withdrawal, as shown in Fig. 6. Under a baseline scenario, water consumption is the highest in north China at just below 6 bn m³ in 2050 and the lowest in the northwest at about 0.73 bn m³. The total amount is cut by half under a high-efficiency scenario. Water consumption grows substantially from 2020 to 2050, from tripled to quadrupled, in all regions under the two abovementioned scenarios.

If renewable energies are intensively developed, CSP will become the primary reason of water consumption in all regions, together with natural gas in the south and the east. The low-carbon scenario projects a similar pattern with inland nuclear power becoming the major water consumer. In contrast to water withdrawal, technology change increases the power sector's water consumption from 2.96 bn m³ under a baseline scenario to 5.80 bn m³ in the east and from 4.75 to 6.09 in the central. There is a trade-off between water consumption and water withdrawal in switching from open-loop to closed-loop cooling systems.

In conclusion, water is mostly abstracted in the east and central regions due to the widespread penetration of open-loop cooling systems, while the utilization of non-open-loop cooling or seawater lowers fresh water withdrawal in the other regions. A large amount of water consumption occurs in the north, east and central regions

where either electricity demand is especially high or closed-loop cooling is widely used.

Water uses will grow substantially in all regions under a baseline scenario while the magnitudes are cut by more than half under high efficiency, high renewable and low carbon scenarios. Technology change, switching open-loop cooling to closed-loop cooling in the south and closed-loop cooling to air cooling in the north, could markedly reduce water withdrawals but increase water consumptions, especially in the east and central regions.

■ 4. Temporal characteristics of China's power sector's water use

Influenced by latitude and monsoon activities, temperature in China varies considerably by region. In winter, the temperatures in northern areas (north, northwest and northeast) are below 0 °C and above zero in southern regions (central, south and east). In summer, most of the regions have temperatures above 20 °C. Additionally, precipitation is the lowest in the winter and highest in the summer (Ye and Zhang, 2013). As a result, the pattern of annual power demand also varies by region. China's regional power demands from 2005 to 2014 are demonstrated in Fig. 7. It can be seen that power production peaks during winter and summer throughout the whole of China. In winter, central heating by Combined Heat and Power is provided in northern areas from November to March, while heat pumps are prevalent in the other regions, i.e. central, east and south. In the summer, from June to August, thermal power production also increases, especially in central and eastern China, because of

the widespread use of air conditioning. The noticeable drops of power productions in February are presumed due to industrial shutdowns during the Chinese New Year.

As it can be seen, the inter-annual differences of these temporal characteristics are not significant, thus the monthly distribution in 2014 is used to estimate the regional monthly power production in 2050. In line with the power production, the regional power sector's water uses as displayed in Fig. 8 peak in winter and summer. The fluctuation is especially remarkable in eastern and central China with their respective highest water withdrawal in December at nearly 18 and 14 bn m³ under a baseline scenario.

■ 5. Coherence of CHINA's water and energy policies

Since water and energy have historically been governed as two independent issues, related policies have been developed in isolation. Qin *et al.* (2015) showed that, under a 'business as usual' scenario, the energy sector's water use might exceed the Industrial Water Allowed (IWA) on a national scale in China, while the future regional situations remain unknown.

In this section, the thermoelectric power sector's fresh water use in 2030 under different scenarios in different regions are compared with the regional IWAs. The national industrial IWA for 2030 is available in Qin *et al.* (2015). The regional IWAs can be extrapolated assuming its provincial distribution is the same as in 2015, which is specified in the '3 Red Line' policy. More details of the regional IWAs extrapolation are described in the Supplementary materials.

The results in Fig. 9 show that, for the east, water withdrawal will exceed the quota under all scenarios except Technology Change, due to its high economic growth, wide application of open-loop cooling systems and thus substantial water abstractions. Water quotas will also be violated if the business as usual continues in the north and the central regions. Energy efficiency improvement, transformation to low-carbon sources and alteration of power plants' cooling technology could enable both regions to comply with the '3 Red Line' policy. The northeast and northwest have no problem with their compliance due to their relatively low energy demands and high-penetration of air cooling systems; neither does the south due to its use of seawater.

■ 6. Discussion and conclusion

In this study, we have presented current (2014) water use in China's thermoelectric power sector, based on an up-to-date high-resolution inventory of coal-fired power plants. It is shown that closed-loop cooling technology is widely used throughout the whole country, which results in high water consumption. Open-loop cooling systems are prevalent in the southern and eastern regions and lead to large water withdrawals. Two major hot spots for thermoelectric power sector water use are identified, i.e. Huang-huai-hai region and Yangtze Delta, due to their high economic growths and corresponding power and water demands.

We have investigated future possibilities for China's thermoelectric power sector water use to 2050 under different scenarios. At a national level, water

withdrawal and consumption increase significantly under a baseline scenario to over 280 and 16 bn m³ respectively by 2050. Eliminating open-loop cooling in the south and closed-loop cooling in the north could tremendously reduce water withdrawal, but would have little impact on water consumption.

The variations are significant on a regional scale. Fresh water withdrawal mostly occurs in the east and central regions due to the substantial deployment of open-loop cooling systems, while water is mostly consumed in the north because of the application of closed-loop cooling systems. Cooling technology change, promoting closed-loop technology in the south and air-cooling in the north, could drastically reduce the water withdrawal but increase water consumptions, especially in the east and central regions. Thus a trade-off between water consumption and withdrawal has to be made. Moreover, the energy efficiency reduction and fuel use increase by adopting air-cooling technology due to its parasitic energy use have to be considered (Byers *et al.*, 2014). Improving energy efficiency and transforming the structure of the energy supply sector to low-carbon sources offer the possibility of saving more than half of the water uses on both national and regional scales. CSP and inland nuclear power may form the primary water users under high renewable and low carbon scenarios, respectively.

Furthermore, we show that, in eastern China, the power sector's water quota assigned by the '3 Red Line' policy will be violated unless technology change is facilitated. Water quotas would also be exceeded in the north and the south under a baseline scenario. Improving energy efficiency, transforming the energy structure and

changing cooling technologies could enable both regions to comply with the ‘3 Red Line’ policy. Without such change, violation of these policies may lead to the loss of their credibility, which may impede the seriousness of future efforts to enforce such regulations.

Thermal power production peaks in the winter throughout the whole China, so does the corresponding water demand, which is when water availability is especially low. The conflicts between the water demand of China’s thermoelectric power sector and the water availability therefore need to be further studied on a temporal basis.

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Table 1 Studies on China's long-term power development (TWh)

Year	Source	National power demand	Hydro	Gas	Nuclear	Wind	PV	CSP	Coal	
2020	State Grid (2011)	7622								
	Sino-Danish Roadmap (2014) Basic					400	140	10		
	Sino-Danish Roadmap (2014) Positive					600	280	20		
	CEC (2013)	8100								
	NDRC (2009) EEI (Energy Efficiency Improvement)	6271	1088	315	525	200	99		4040	
	NDRC (2009) LC (Low Carbon)	5653	1190	315	700	353	94		2998	
	NDRC (2009) ELC (Enhanced Low Carbon)	5479	1207	315	770	423	99		2662	
	WWF (2014) Baseline	9577	1192	263	622	439	70	16	6896	
	WWF (2014) High Efficiency	6928	1192	263	622	439	70	16	4247	
	WWF (2014) High Renewable	6989	1192	36	68	439	70	16	5089	
	WWF (2014) Low Carbon Mix	6965	1192	36	365	439	70	16	4767	
	Compared with baseline values from	Min	6271	1088	263	525	200	70	10	4040
	NDRC & WWF scenarios	Max	9577	1260	320	622	439	140	16	6896
	2030	State Grid (2011)	9808							
Sino-Danish Roadmap (2014) Basic						800	420	90		
Sino-Danish Roadmap (2014) Positive						2400	840	180		
CEC (2013)		12000								
WWF (2014) Baseline		15043	1377	263	777	462	70	16	11997	
WWF (2014) High Efficiency		8539	1377	263	777	462	70	16	5493	
WWF (2014) High Renewable		8479	1507	279	36	1895	578	670	3392	
WWF (2014) Low Carbon Mix		8472	1507	243	661	1691	501	570	3178	
Compared with baseline values from		Min	9808			462	70	16		
NDRC & WWF scenarios		Max	15043			800	420	90		
2035	IEA (2010)	10802	1512	972	800	756	820		5941	

2040	NDRC (2009) EEI		8735	1326	630	1050	376	262	5091	
	NDRC (2009) LC		7808	1394	630	1470	470	351	3493	
	NDRC (2009) ELC		7704	1394	630	1705	705	462	2763	
	WWF (2014) Baseline		17614	1383	263	777	475	70	16	14549
	WWF (2014) High Efficiency		9529	1383	263	777	475	70	16	6464
	WWF (2014) High Renewable		9493	1577	697	20	2467	966	1089	2544
	WWF (2014) Low Carbon Mix		9488	1261	559	1273	2126	834	918	2383
	Compared with baseline values from	Min	8735	1326	263	777	376	70		5091
	NDRC & WWF scenarios	Max	17614	1512	972	1050	756	820		14549
	IEA (2014)		10762	1469	861	1076	807	915		5596
2050	State Grid (2011)		14300							
	Sino-Danish Roadmap (2014) Basic						2000	1400	720	
	Sino-Danish Roadmap (2014) Positive						4000	2800	2000	
	GEA(2012) for Centrally Planned Asia and China			2694-2891			1028-2444	250-11139		
	CEC (2013)		14000							
	NDRC (2009) EEI		10665	1320	945	2100	805	795	4700	
	NDRC (2009) LC		9857	1485	945	2450	874	1028	3075	
	NDRC (2009) ELC		9271	1551	945	2940	1035	1174	1625	
	WWF (2014) Baseline		24377	1401	263	777	512	70	16	21258
	WWF (2014) High Efficiency		12586	1401	263	777	512	70	16	9466
WWF (2014) High Renewable		12627	1787	2249	0	3962	2051	2412	0	
WWF (2014) Low Carbon Mix		12685	525	2197	3109	3091	1695	1902	0	
Compared with baseline values from	Min	10665	1320	263	777	512	70	16	5820	
NDRC & WWF scenarios	Max	24377	2891	945	2400	2444	11139	4700	21258	

Table 2 water use intensity median values in the U.S. and reported values in China

m3/MWh/Energy source	CSP*		Natural gas*		Nuclear*		Coal*		Coal (China)
Cooling system	Consumption	Withdrawal	Consumption	Withdrawal	Consumption	Withdrawal	Consumption	Withdrawal	Consumption
Closed-loop	3.13	3.13	0.75	0.75	2.5	4.17	1.87	2.31	0.95-3.31
Open-loop	0	0	0.38	0.38	1.02	167.88	0.39	85.51	0.07-0.67
Air-cooled	0.2	0.2	0.01	0.01	0	0	0.32	0.32	0.22-0.63

464 **Note:** * denotes median values of water intensities of various energy sources and cooling types in Macknick *et al.* (2012).

Fig. 1. Approach and data framework

467

468 **Fig. 2. China's current coal-fired power plants with different cooling types**

Fig. 3. Power sector's water consumption of various water sources

Fig. 4. Fresh water withdrawal (left) and consumption (right) by China's thermoelectric power sector under different scenarios (bn m³).

Fig. 5. Regional surface water withdrawal under different scenarios (bn m³).

479 **Fig. 6. Regional surface water consumption under different scenarios (bn m³).**

482 **Fig. 7. China's regional monthly thermal power productions from 2005 to 2014 (TWh).**

483

484 **Fig. 8. China's regional monthly water uses by power sector in 2050 (bn m³).**

485

Fig. 9. Comparison between regional water demands by power sector with water targets set by the '3 Red Line' policy in 2030. (W-Fresh water withdrawal in 2030; C-Fresh water consumption in 2030; B-Baseline Scenario; HE-High Efficiency Scenario; HR-High Renewable Scenario; LC-Low Carbon Scenario; TC-Technology Change Scenario; IWA-Industrial Water

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