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Four years after, marked by these words here, this journey, probably the most rewarding journey in my life so far, is coming to an end. The last four years are filled with both highs and lows in my life. Being able to walk through it, I am forever in debt to so many wonderful human beings I have had the fortune to cross path with.

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Abstract

Electricity use is indispensible for almost every aspect of modern human society, from agricultural and industrial production to household consumption. It is increasingly recognized that, besides hydropower, water resources are also required for thermoelectric power production that provides the majority of the world's electricity use. Therefore, water security can have serious impacts on electricity security. Electric power curtailments caused by water-related issues have been reported all around the world.

China, the world largest electric power producer, faces pronounced challenges in this respect as its electric power sector heavily relies on coal-fired power plants that are located at inland water ways. Water shortages may induce substantial cost for under-serving electricity to its large population and fast growing economy. However, such risks, including their magnitudes and spatiotemporal characteristics, are not well understood, especially under future climate change.

Against this backdrop, this dissertation, for the first time, examines water shortage risks facing China's electric power sector on plant-level and monthly bases within a comprehensive framework. It first develops a comprehensive inventory of plant-level water-using technology dataset and, based on which, quantifies the electric power

sector’s water demands in China. Water availability is then simulated with a calibrated hydrological model that incorporates human interventions during the current period (1984-2014) and future period 2050s (2035-2065) under two carbon emission scenarios RCP 2.6 and 8.5. Spatial and temporal water risks can be identified where water availability falls short of water demands. Finally, using the concept of virtual water within the Input-Output framework, water uses for electric power productions are attributed to different end users whose electricity use could be disrupted should those above-identified risks arise.

From 2000 to 2015, water withdrawal and consumption in China’s electric power sector, excluding hydropower, have increased from 40.75 and 1.25 billion m^3, respectively, to 124.06 and 4.86 billion m^3. Freshwater use withdrawal and consumption are projected to exceed 280 and 15 billion m^3 respectively by 2050 if China does not implement any new policies, up from current levels of 65.2 and 4.64 billion m^3 (2014). At a regional level, central and eastern China account for the majority of the power sector’s water withdrawals because open-loop cooling systems are widely adopted, while water consumption is significantly higher in the current dry northern regions because closed-loop cooling systems are more popular.

It is found that around 10% of China’s coal-fired power capacity is facing low flow water risks from July to October, and 20% the rest of the year. Particularly in the north, 40% to 60% of its regional coal-fired power capacity is at risks of not having enough water for cooling purposes from February to June. Under climate change, available water in the river system is expected to increase significantly in the current dry north and decrease significantly in the northwest and slightly in the south, which is expected to alleviate the low flow water risks facing China's coal power plants except in the northwest Inland River Basin. In the east and south, if their growing electricity demands continue depending on coal, increasing utilization rate of coal power facilities can lead to the increase of demand-driven water shortage risks.

Lastly, this dissertation includes water consumption by both thermoelectric and hydropower plants to reveal the virtual water flows from power producers to consumers using Multi-Regional Input-Output analysis. From 2002 to 2012, the share virtual water embodied in the final consumption of electricity, e.g. household, increased from 24.6% to 39.8%. Nearly half (47.5% in 2010) of the physical water inputs into the power sector were virtually transferred across provincial boundaries in the form of virtual water embodied in the electricity produced, mainly from provinces in northeast, central and south China to those in east and north China.

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Chapter 1. Introduction

1.1 Background

Electricity (hereinafter used interchangeably with electric power and power) provision underpins modern human society's development and prosperity. Driving and also driven by growing population, industrialization and urbanization, the increasing demand and production of electricity trigger growing concerns regarding its environmental externalities, which are mostly focused on air pollution and greenhouse gas emissions from burning fossil fuels (Zhao et al. 2008; Akorede et al. 2012). Moreover, electricity production also uses another essential commodity, i.e. water (Gleick 1994). Such dependency has gained increasing appreciation and been brought to the forefront of scientific and policy discussions in the last two decades (Vassolo and Doll 2005; van Vliet et al. 2012; Ackerman and Fisher 2013; Byers et al. 2014; van Vliet et al. 2016).

Water is a fundamental resource that often goes underappreciated. People start to pay close attention only when there is either too much or too little of it (Sadoff et al. 2015). Driven by growing population, available water resources may not be able to meet human needs has been identified as a top global risk facing humanity over the next decade (World Economic Forum 2015). In addition, climate change is expected to alter the availability and variability of water resources, both geographically and seasonally, which may further intensify the abovementioned risks (van Vliet et al. 2012; van Vliet et al. 2016; Zheng et al. 2016). Scientists have predicted reductions in usable capacity for over 60% of the global hydropower and over 80% of the thermoelectric power from 2040 to 2069 due to climate change (Van Vliet et al. 2016).

Hence research on water use for electricity production, the so called 'water-for-electricity nexus', is of paramount importance as cross-sector risks are posed for the reliable provision of an indispensible input to almost every aspect of modern society - namely, electricity - from industrial processes to household consumption. Electricity curtailments due to water-induced risks have already been recorded all over the world, which raises water-for-electricity nexus as an emergent challenge globally (McCall et al. 2016).

On the other hand, being constrained by limited planetary boundaries, there is a growing consensus that all anthropogenic activities should take into account and strive to minimize their environmental impacts. In some water-scarce regions, if the business continues as usual, electricity production is set to compete with other basic human needs, e.g. food, and the ecological system for limited water resources in the hydrologic system (Bazilian et al. 2011; Byers et al. 2016).

One way to alleviate local water pressure imposed by electricity production is to import electricity from other areas. As Bai (2016) has pointed out, any anthropogenic ecosystem depends on natural resources locally as well externally. Water can be redistributed in the form of virtual water embodied in goods transmitted across geographical boundaries (Zhao et al. 2015). Such telecoupling means electricity consumption in one region not only has impacts on its local water resources but also has impacts beyond its territories (Liu et al. 2015).

The abovementioned impacts and risks are particularly pronounced in China, a country that has seen remarkable economic growth and urbanization in the last few decades. Such development is accompanied by markedly increased electricity production. For example, starting from the 21st century, China's electric power production has more than quadrupled from 1,328 billion KWh in 2000 to 5,810 billion KWh in 2015 and has overtaken the US as the biggest electricity producer in the world. About 75% of China's electricity demand is met by thermoelectric power productions (National Bureau of Statistics of China 2016).

The trend is concerning due to the prevalence of thermoelectric power plants on inland waterways that are potentially at risk of water shortages in China, which is further exacerbated by the uneven geographical distribution of China's water endowments and their mismatch with energy reserves, particularly coal (Zhang and

Anadon 2013). A large amount of thermoelectric power plants are located in water-stressed regions, as well as over half of the country's proposed coal-fired power plants (China Water Risk 2012; World Resource Institute 2014).

1.2 Research objective

Against this backdrop, the objectives of this research are to better understand the electric power sector's dependencies on water resources and the corresponding water risks in China. Accordingly, this DPhil research aims to answer the four following research questions sequentially:

1) How has China's water-for-electricity nexus evolved historically and what are the underlying drivers?

2) How much water is used for China's thermoelectric power productions on a provincial level and how is China's water-for-electricity expected to change in the future?

3) What are the spatial and seasonal water risks for China's thermoelectric power sector and how those risks will be affected by future climate change?

4) Who are the final consumers of the abovementioned water-for-electricity and thus bear the potential risks?

It should be noted that various actors, e.g. electricity end users, power companies and so forth, bear different types of risks facing the thermoelectric power plants, such as coal supply, climate change mitigation policies and so on, we focus on the water shortage risks facing electricity end users in this chapter.

Before proceeding further, it is necessary to differentiate two key concepts: water withdrawal and water consumption. Water withdrawal refers to water abstracted from the natural environment while water consumption is defined as the water withdrawn but not discharged back to any water bodies (AQUASTAT 1998). They are collectively referred to as water use in this dissertation.

1.3 Dissertation structure

This dissertation consists of seven chapters: Chapter 1 introduces the background of this research, along with research objectives. Chapter 2 reviews the exiting literature and identifies major research gaps. Chapter 3 looks back at the historical trajectory of water use in China's electric power sector and analyzes the impacts of the underlying drivers, i.e. (1) population, (2) power production per capita, (3) electric power sector's generation mix and (4) cooling technology configurations. Chapter 4 quantifies the current water uses in China's thermoelectric power sector on a provincial level as well as future contingencies under different scenarios of the electric power sector’s generation mix and cooling technology configurations. It demonstrates the geographical characteristics of China’s water-for-electricity nexus as well as potential cross-sector policy conflicts. Building on water demand data from Chapter 4, Chapter 5 analyzes the spatial and temporal water risks facing China’s thermoelectric power plants using water availability data simulated from a hydrological model, H08. Chapter 6 attributes water use in China’s electric power sector to different electricity users in different provinces and quantifies the inter-provincial virtual water transfers embodied in electricity transmissions. Chapter 7 discusses the major findings of this dissertation and their real world implications. Finally, it concludes with research outlooks.

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Chapter 2: Literature Review

Based on "Liao, X.W., Hall, J.W. and Eyre, N. (2017) Water for energy in China. In Laura M.P., McElroy, C., Littaye, A. and Girard, A.M. (Eds.), Food, Energy and Water Sustainability: Emergent Governance Strategies!. Earthscan, Routledge"

In this chapter, I aim to answer the four following questions before proceeding further:

1) What are the interconnections between water and energy systems and why this dissertation focuses on water use in the electric power sector, i.e. 'water-for-electricity nexus'? (Section 2.1)
2) Why do we need to further our understanding in the context of China? What are the research gaps and questions? (Section 2.2)
3) What are the research methods that have been prevalently used in this field? (Section 2.3)
4) What are the main contributions of this dissertation? (Section 2.4)

2.1 Water-energy nexus

Water and energy are both critical and fundamental to human society. They are also intrinsically and inextricably interlinked. Energy is required to produce, deliver, and distribute fresh water resources (e.g. seawater desalination, groundwater pumping), as well as treating wastewater (Gleick 1994; Stokes and Horvath 2009; Siddiqi and Anadon 2011; Wang et al. 2012; Sanders and Webber 2012). Conversely, water is an indispensible input in the production processes of various energy resources, from primary sources, e.g. oil and coal, to electricity (Gleick 1994; Marsh 2008; Rio and Frei 2009).

2.1.1 Water-for-energy nexus

In 2010, IEA estimated that energy production is responsible for 15% of the global water withdrawal, at 583 billion m^3 (BCM), of which 66 BCM is consumed (IEA 2012). Water is directly used in the extraction and process of raw energy resources, as well as the conversion and transportation (Williams and Simmons 2013). For example, during coal mining, water is mainly used to control dust and to cool down underground mining equipment. Depending on the quality, coal sometimes then needs to be washed to remove its impurities and sulphur before it can be burned to generate electricity, which requires more water use (Department of Energy 2006). After extraction, transport can also be water intensive with slurry pipelines being used (Meldrum et al. 2013). Water is also used for drilling and fracturing in oil and gas extraction, as well as desalting, distillation, hydrotreatment in oil refinery (Gleick 1994; Clark et al. 2013). Water uses for the production of biomass and unconventional gas are described in Table 1.

Table 1 Water use for the production of biomass and unconventional gas

Energy source	Water use for energy productions
Biofuel	By far the most water-intensive fuel to produce. A substantial amount of water is consumed due to the evaporation when growing the stock, e.g. corn.
Unconventional Gas	Gas-To-Liquids of Natural gas and Coal-to-Liquids of coal involve a large amount of water input. China has thus abandoned its plans to build dozens of coal-to-liquid (CTL) plants in 2008 presumably due to the local water scarcity (IEA, 2012). Hydra fracturing for non-conventional fossil fuels, e.g. shale gas, raises an increasing concern. Even though the exploitation of shale gas is not anticipated in China in the near future, China has one of the largest shale gas reserves in the world, the development of it should be carried out with caution.

Many scholars have thus spared efforts to quantify energy production's water use at various geographical locations. Spang et al. (2014) compared energy production's water consumption in over 150 countries using water intensity (hereinafter used interchangeably with water factor) data, measured as water use (either consumption or withdrawal) per unit of energy product produced, synthesized from the existing literature. Tidwell and Moreland (2016) mapped out water consumption for energy production in 21 Asia-Pacific Economic Cooperation economies' 12000 watersheds. According to Mielke et al. (2010), energy production is responsible for 27% of the US society's total water consumption, only second to the Agriculture sector. Cai et al. (2014) calculated that water withdrawal for energy production in China has increased from 8.98 BCM in 2000 to 28.78 BCM in 2011, and is projected to further grow by 77% by 2030.

In addition to the water uses on the production sites, a certain amount of water is used in the upstream supply chain of energy supply, e.g. manufacturing infrastructure materials such as wind turbines and solar panels. Lastly, the life span of power plants, normally ranging between 30 to 50 years, can also lead to further water consumption: building and dismantling a power plant after its retirement needs water input for various reasons, including dust control, domestic uses, and so forth. Pan et al. (2012) conducted a supply chain analysis in China's coal industry and concluded that water is becoming a constraint for coal development in North and West China.

Besides water quantity, energy production, especially fossil fuel extraction, discharges a significant amount of water pollutants (Mishra et al. 2008), which receives far less attention so far. Zhang and Anadon (2013) calculated that energy productions in China discharge 8.3% of the national wastewater. However, as crucial information such as wastewater pollutant concentrations and water pollutant types is all unknown, the real world implications of their results are limited.

Given the abovementioned background, global institutional efforts have been initiated. Several examples include the ‘Water and Energy’ World Water Day in 2014 (United Nations 2014), Water for Energy Framework launched at the 6th World Water Forum (European Innovation Partnership 2015) and Thirsty Energy Program by the World Bank (World Bank 2013).

2.1.2 Water-for-electricity nexus

Among all energy productions, potential water risks for electricity production are especially dire as electricity production has to balance demand instantaneously due to limited capacity for storage to date. Since water is often required for electricity production, reliable electricity provision can be vulnerable to be disrupted by water-related risks.

Life-cycle water use for electricity production

Many scholars have shed light on the life-cycle water use for electricity production in various locations. With bottom-up life-cycle inventory analysis, Fthenakis and Kim (2010) estimated water intensities of both conventional and renewable electric power plants’ life cycle, including fuel acquisition, preparation, plant construction and operation, in the US based on data from the existing literature. Mekonnen et al. (2015) completed a similar study on a global scale. Grubert et al. (2012) found that replacing coal-fired power plants with natural gas combined cycle plants (NGCCs) can reduce Texas coal power's water footprint by 60%, 0.2 BCM per year. Although Natural Gas may play a significant role in China's future energy mix as demonstrated in the future scenario analysis in Chapter 4, we do not consider Natural Gas in the current inventory analysis because it only occupies a small proportion in China's thermoelectric power production, less than 4% in by 2015 (China Electricity Council 2015). Meldrum et al. (2013) broadened the study scope by including power plant decommissioning and harmonized literature estimates. They concluded that (1) thermoelectric power productions are more water intensive than PV and Wind; (2) Operational phase dominates electric power production's life-cycle water uses. Feng et al. (2014)'s study on China using hybrid Life-Cycle and Input-Output analysis also came to similar conclusion, except they have also included biomass and found that life-cycle water consumption of biomass tops the list, of which crop production accounts for 95%. Also using an Input-Output approach, Wan et al. (2016) found that Intended Nationally Determined Contributions (INDC) will lead to more life-cycle water consumption for the power sector in China, India and Russia because their renewable energy development require substantial upstream water inputs.

Operational water use for electricity production

According to Meldrum et al. (2013), a very small amount of water is need for the operational stage of wind and PV electricity production, mostly for dust control and cleaning. For thermoelectric power productions, including coal, nuclear, natural gas, geothermal, Concentrated Solar Power (CSP), water used for cooling at the operational phase dominates their life cycle water use.

Water is heavily used or consumed in various processes in the operational phase (within the power plants) of electricity production. According to the UN (2014), about 90 per cent of global power generation depends intensively on water. And thermoelectric cooling is estimated to be responsible for around 43 per cent and 50 per cent of total fresh water withdrawals within the EU and the US, respectively (United Nations 2014). In 2005, Vassolo and Doll made the first attempt to estimate the water use by power generation via a bottom-up approach using the 1995 data of 63,590 thermal power stations located around the world. Taking coal-fired power plants for example, water is used to clean the coal, remove the lime-ash, for desulfurization, and for cooling the steam turbine as well as different auxiliary units. The water-consuming processes in a typical coal-fired power plant can be categorized as below:

1) Industrial water use: which undergoes clarification and can then be used for different industrial purposes, such as lime-ash removal and wet desulfurization, as well as cooling of the steam that drives the turbine and other auxiliary engines (including induced air fan, forced draft fan, primary air fan, and so forth). Cooling

water constitutes the biggest part of thermoelectric power production's water uses.

2) Domestic water use: it is used to meet the living needs of power plant workers.

3) Chemical water use: Due to salinity enrichment, water boilers need to be regularly emptied and replenished with demineralised water of the highest quality.

The abovementioned water flows and related energy flows are illustrated as in Figure 1 below:

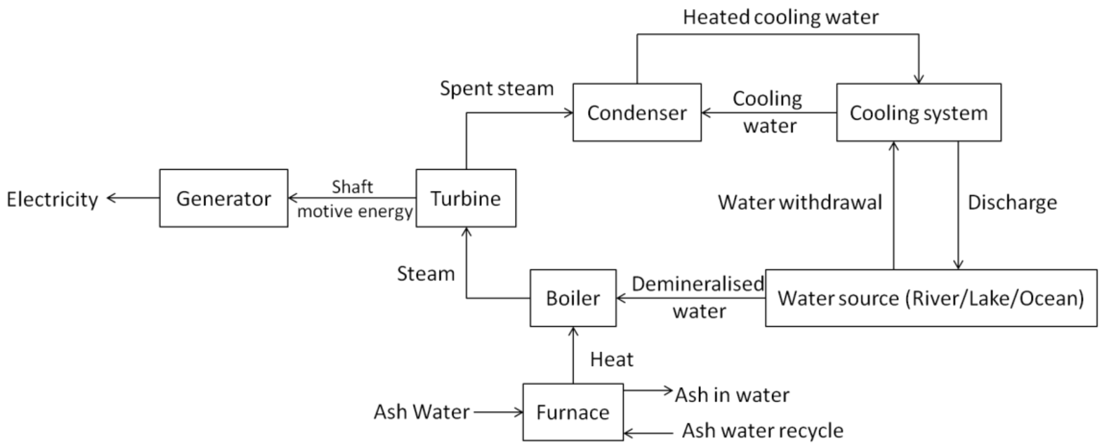

Figure 1 Water and energy flows in a coal-fired power plant (Stone et al. 1982)

Below, four main factors that have significant impacts on power plants' water intensities, namely (1) cooling technology, (2) energy source, (3) generating technology and (4) environmental factors, are described in detail.

Cooling technology

As it can be seen from Table 2 and 3, which detail the water consumption factors of different processes in typical coal power plants, water usage is primarily determined by the cooling system utilized. Cooling systems are needed to dissipate the residual heat of the steam exiting the turbine. Water is often used as the medium.

Table 2 Designed water consumption factor of power plants with open-loop cooling system of different capacities. Source: East China Electric Power Design Institute (2012)

Capacity (MW)	Wet desulfurization (without GGH, m^3/h)	Dry ash/lime-ash removal (m^3/h)	Coal transport (m^3/h)	Boiler make-up (m^3/h)	Domestic water use (m^3/h)	Total (m^3/h)	m3/MWh
2×300	100-110	109-195	46-83	80-150	5-10	340-548	0.567-0.913
2×600	190-230	155-247	60-107	90-170	5-10	500-764	0.416-0.637
2×1000	270-320	265-380	77-146	150-270	5-12	767-1128	0.384-0.564

Table 3 Designed water consumption factor of power plants with closed-loop cooling system of different capacities. Source: East China Electric Power Design Institute (2012)

Capacity (MW)	Wet desulfurization (without GGH, m^3/h)	Dry ash/lime-ash removal (m^3/h)	Coal transport (m^3/h)	Boiler make up (m^3/h)	Domestic water use (m^3/h)	Cooling tower make-up (m^3/h)	Total (m^3/h)	m3/MWh
2×600	190-230	155-247	60-107	90-170	5-10	2092-2692	2592-3456	2.16-2.88

There are three types of cooling systems being used: open-loop and closed-loop wet cooling, and air-cooling. Open-loop cooling systems, also called once-through, withdraw the largest amount of water but more than 99% of which is returned to the water source; closed-loop, or recirculated cooling, withdraws significantly less water; however a larger proportion is consumed due to evaporation, either in cooling ponds or cooling towers. Power plants with air-cooling systems, also called dry cooling, have the lowest water consumption and withdrawal intensities as they do not need any water for cooling purposes. However, water is still required for other on-site uses, e.g. cleaning. Moreover, reducing water use by deploying air cooling systems comes at a price. First of all, capital cost of power plants with dry cooling systems can be at around 2.5 times of that of plants with wet cooling systems. And the levelized cost ratio is close to two (Zhai and Rubin 2010). Secondly, as air cooling systems have lower cooling efficiencies, the steam leaving the turbine has a higher temperature, which creates a back pressure. As a result, power plants with air cooling systems face 5% -10% of thermal efficiency losses (Electric Power Research Institute 2004). Consequently, the deployment of air-cooled power plants in China contributed to an additional 24.3 – 31.9 million tonnes of CO_2 emissions in 2012 (Zhang et al. 2014).

Cooling technology affects the water consumption factors in two ways: first, nearly 100 per cent of water abstracted by closed-loop cooling system evaporates during the cooling circles while only 3 per cent of water withdrawal of open-loop system is consumed. Therefore, when compared to closed-loop cooling system, consumptive water use in an open-loop system is 70-80 percent lower than in a closed-loop system, but water withdrawal is 30-60 times higher (World Resource Institute 2015). Secondly, since cooling systems marginally impact the plant's efficiency, power plants with an open-loop cooling system consume less water in other processes due to its higher efficiency. Due to the large share of ancillary water uses, air cooling systems' water consumption is on par with that of open-loop cooling systems.

Energy source

Macknick et al. (2012) reviewed a large amount of existing literature and technical documents in the US. According to their work, apart from cooling technologies, fuel types also bear a significant impact on power production's water use mostly due to the differences in thermal efficiencies. To generate a certain amount of electricity, gas-fired power requires the least water while nuclear power needs the most.

Last but not least, in terms of hydropower, although Mekonnen and Hoekstra (2012) have highlighted that hydropower is a significant water consumer, mainly due to water evaporation in the dammed reservoirs, there exist many methodological disputes, especially on how to attribute the water consumption to different uses, e.g. hydropower, agriculture, navigation, flood control, in multi-purpose reservoirs (Bakken et al. 2013; Bakken et al. 2016). As a result, the literature estimates exhibit huge uncertainties (Zhang and Anadon 2013; Bakken et al. 2017). Nonetheless, continuous efforts have been made in this respect. Zhao and Liu (2015) proposed to allocate the water consumption to reservoirs' different uses according to their ecosystem services. Based on this allocation method, Liu et al. (2015) calculated the water consumption factors for electricity production of China's 209 hydropower plants.

Generating technology

Several hundred power plants were required to report their water consumption factors to China Electricity Council (CEC) (CEC 2012, 2013). A summary of the reported values is presented as below in Table 4:

Table 4 Average water consumption factors of units of different capacities with different cooling systems in China

Capacity (MW)	Cooling system	Water consumption factor
<300	Closed-loop	2.25
<300	Open-loop	1.23
<300	Air cooling	0.47
300-600	Closed-loop	1.93
300-600	Open-loop	0.52
300-600	Air cooling	0.41
>600	Closed-loop	1.79
>600	Open-loop	0.29
>600	Air cooling	0.31

For small-scale units, closed-loop cooling systems consume the most water while air-cooling systems consume the least. However, when the capacity exceeds 600 MW, air-cooling systems lose their advantage to open-loop systems in terms of water consumption, presumably because air-cooling systems are less efficient and require more electricity for the plant's own use. Moreover, water uses also differ by generating technology. For instance, application of Carbon Capture and Sequestration (CCS) results in increases of both water consumption and withdrawal (Webster et al. 2013; Byers et al. 2016).

Environmental factors, e.g. ambient and river temperature

In addition, Jiang and Ramaswami (2015) highlighted the significant seasonality in power plants' water intensities from field data of 19 coal-fired power plants in Shandong, China. Power plants water intensities are higher in July. The reason is presumably due to the higher temperature of river water and thus lower cooling efficiencies. Assuming a heat engine as in the Diagram below:

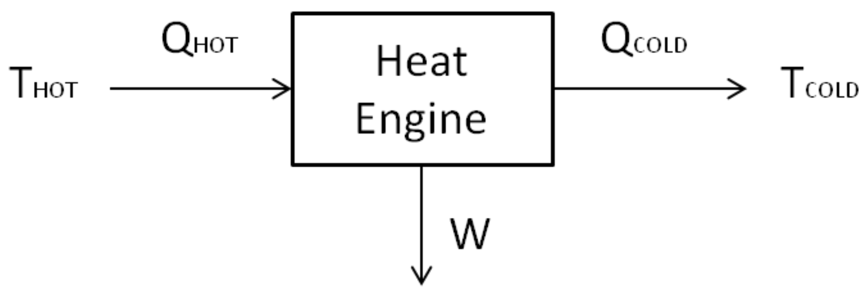

Figure 2 A heat engine operating between two temperatures

Where W is the work/output of the engine, Q_{HOT} is the Heat input at a high temperature, Q_{COLD} is the heat rejected at a low temperature. W equals to Q_{HOT} minus Q_{COLD}. According to Carnot (1824), the ration between Q_{HOT} and Q_{COLD} equals the ratio between the high temperature T_{HOT} and low temperature T_{COLD}. As a result, air cooling systems' efficiency decreases as ambient air temperature increases, whereas open-loop cooling systems are mostly vulnerable to increased river water temperature, especially when the maximum discharged water temperature is regulated (Forster and Lilliestam 2009). France and Southern California had to curtail their electricity productions in 2003 and 2007 respectively due to increased river water temperature. Moreover, several studies have shed light on the thermal pollutions from thermoelectric power plants with open-loop cooling systems (Raptis and Pfister 2016; Raptis et al. 2016; Raptis et al. 2017).As cooling water is used to dissipate the residual heat from the heat engine, cooling water use intensity is affected by the cooling water temperatures. However, we do not consider water temperature's effects in this dissertation, which should be investigated in future studies.

Scholars around the world have utilized abovementioned datasets to quantify the electric power system's water use in different places in the world, e.g. China (Qin et al. 2015; Zhang et al. 2016; Zhang et al. 2017), UK (Byers et al. 2014), US (Macknick et al. 2012; Averyt et al. 2013), Middle East and North Africa (Damerau et al. 2015), as well as some sub-national regions (Scanlon et al. 2013; DeNooyer et al. 2016).

2.1.3 Water risks for and conflicts with electricity production

Water demand by electricity production is likely to increase along with electricity demand by a developing world with a growing population. The growth rate is expected to be especially sharp in some fast developing regions. However, water resource is finite. Some studies examined the water pressure imposed by electricity production based on current water stress data (Cai et al. 2014; Zhang et al. 2016).

Moreover, future climate change is expected to alter the availability and variability of water resources, both geographically and seasonally. Increased drought periods and enlarged drought-affected areas are foreseen (Gerten et al. 2013; Doell and Schmied 2012). Water has been recognized as the top global risk for the next decade (World Economic Forum 2015). Future climate change can affect or constrain future electricity production in four ways: (1) by reducing river flows available for cooling uses at power production sites (Sovacool and Sovacool 2009; Byers et al. 2016; Zheng et al. 2016): for example, Byers et al. (2016) projected that, with Carbon Capture and Storage (CCS) development, water available in UK's river Trent is likely to fall short of cooling water demand for the basin's electricity generation by the 2030s-2040s; (2)

by increasing water temperature and thus reducing thermoelectric power plants' usable capacity due to legal thresholds for heat discharges (Hoffmann et al. 2012; van Vliet et al. 2012). The usable capacity of global thermoelectric power plants is projected to be reduced by 81-86% during 2040-2069 due to a compounded effect of changed water availability and increased water temperature (van Vliet et al. 2016); (3) 61-74% of hydropower capacity reduction is also projected due to reduced river flows brought by future climate change (van Vliet et al. 2016); (4) Lastly, Tarroja et al. (2018) pointed out that water availability can also limit the development of thermally based renewable energies, e.g. geothermal, CSP, in water-stressed regions.

2.1.4 Water uses for electricity transmission

Electricity can be transmitted across geographical boundaries, e.g. administrative and river basin. Accordingly, water is used in electric power production processes and then transmitted in the form of virtual water embodied in the power transmissions (Ruddell et al. 2014; Zhu et al. 2015; Guo et al. 2016; Wang and Chen 2017). Importing virtual water through electricity transmissions helps alleviate water stresses in the importing regions, however, water scarcity in virtual water exporting, i.e. electricity exporting, regions need to carefully examined and incorporated into future electricity transmission planning (Zhang et al. 2017). Consequently, citizens and industries in electric power importing regions are exposed to water risks for electricity production in electric power exporting regions (Wang et al. 2017).

2.1.5 Institutional dimension of water-for-electricity nexus

Impacts of institutional arrangements, from cultural practice to policy formulations, on water-for-electricity nexus shall not be overlooked (Scott et al. 2011). Sanders (2010) has pointed out that five variables of the electricity sector have impacts on its water uses: (1) generation mix; (2) cooling technologies; (3) climate change; (4) electric power grid; and (5) regulatory environment. Particularly, it has been recognized that policies in the energy sector may have spill-over effects on the water sector (Zhou et al. 2016). For example, Webster et al. (2013) found that, in Texas, a restriction on CO_2 emissions would also reduce water withdrawals by the power sector. Bartos and Chester (2014) demonstrated that the implementation of Arizona's Energy Efficiency Mandate and Renewable Portfolio Standard also helped to reduce its power sector's water usage.

2.2 The significance of China

2.2.1 Electricity and water in China

The abovementioned issues are especially pronounced in China, the world biggest electricity producer and consumer. China's economy is heavily based on coal, with coal-fired electricity production accounting for approximately 75 per cent of the nation's total electricity generation (National Bureau of Statistics 2016). Over the last decade, electricity consumption in China has almost quadrupled from 1,347 TWh in 2000 to 4,976 TWh in 2012. This rising trend is projected to continue with China's growing economy and population (Zhang et al. 2016). Even though China has several pledges about decarbonising its electric power system, including improving coal efficiency and expanding the use of natural gas and renewable energies (National Development and Reform Commission 2015), coal is still expected to dominate the electric power sector's energy portfolio.

China's water resources are not abundant. In 2012, it was calculated that even though the country's total surface water endowment ranked sixth in the world, the amount per capita stood at only one third of the global average, at around 2100 cubic meters per person (Ye and Zhang 2013). In 2011, China issued its 'strictest' water management mechanism called the 'three red-line' policy, setting targets on total water use, industry and agriculture water efficiency, and water quality improvements. The first 'red-line' sets the water withdrawal cap at 635, 670, and 700 billion m^3 in 2015, 2020, and 2030, respectively.

2.2.2 Two features of China's water resources

Two features of China's water resources further exacerbate the potential water-for-electricity challenge:

(1) Uneven spatial distribution and geographical mismatch with energy reserves:

More than 80 per cent of China's rivers are in the South while the Northern areas, that contain 37 per cent of China's population and 45 per cent of its farmland, have only 12 per cent of the country's water resources. However, a large amount of thermoelectric power generation capacities are installed in regions facing the most severe water shortages and over half of the country's proposed coal-fired power plants are placed in areas with high water stresses (China Water Risk 2012; World Resource Institute 2014). This geographical mismatch is particularly significant with coal energy as coal extraction and coal-fired power production are done close to coal reserves to reduce transportation cost, despite using large quantities of scarce water. As a result, eleven Chinese provinces, mainly in the Northeast, already face water scarcity (<1000 m^3 per capita per year) (Francis et al. 2013). For instance, Shanxi, Shaanxi, and Inner Mongolia, the three provinces with the most coal reserves in China, contribute over half of China's coal output and a quarter of the thermal power generation with only 3 per cent of the total water resources (Zhang and Anadon

2013).

2) Uneven intra-year temporal distribution:

The seasonal distribution of China's water resources within a year is heavily impacted by its monsoon climate. In the south of the Yangtze River, precipitation between March and June makes up about 60 per cent of the annual total, while precipitation between June and September accounts for around 80 per cent in the north of the Yangtze River (Ye and Zhang 2013). The least precipitation occurs in the winter, which means the hydropower capacity is also the lowest. However, China's national power demand also peaks in winter, as central heating is provided by Combined Heat and Power (CHP) plants in Northern China and heating pumps is widely used in Southern China.

2.2.3 Climate change impacts on China's water resources

Hydrological models with climate scenarios predict an overall increase of river flows over China (Zhang and Wang 2007). However, the current predictions embody substantial uncertainties (Piao et al. 2010). Taking the water-stressed Yellow River Basin for example, Zhang et al. (2007) predicts increases in its river runoff in both IPCC A2 and B2 scenarios (Nakicenovic et al. 2000). However, research using high-resolution regional climate model predicts a decreasing or unchanged trend

(Gao et al. 2008). Nonetheless, it is widely acknowledged that increasing anthropogenic water use imposes severe pressures on the river systems (Grafton et al. 2013).

To simulate the hydrological system as well as related climate change impacts in China, previous studies have mostly applied Variable Infiltration Capacity (VIC) model on different geographical locations, e.g. Hanjiang Basin (Guo et al. 2009), north-western China (Zhao et al. 2012), Huang-Huai-Hai region (Dan et al. 2012), as well as the whole country (Zhang and Wang 2007). Furthermore, based on water availability data from Zhang and Wang (2007), Zheng et al. (2016) calculated future water stresses faced by the electricity sector in China. However, two significant research gaps emerge: (1) there is no national study on the electricity sector's water risks using water availability data simulated by hydrological model with climate scenarios beyond 2050; (2) while VIC model, as well as many other rainfall-runoff models, does not consider human interventions (Liang et al. 2994), heavy anthropogenic impacts on the hydrological cycle in China require more holistic approach. In light of this, an integrated water management model - H08 - that simulates both natural and anthropogenic water flows on a monthly basis at a very high resolution is suitable (Hanasaki et al. 2008a, b).

2.2.4 China's water and electricity institutions

The institutional arrangements for China's water and energy resources have gone through noticeable changes. In 1949, the Ministry of Water Resources and Ministry of Electric Power Industry were established with the People's Republic of China. In 1958, the Ministry of Water Resources and Ministry of Electric Power Industry were merged into the Ministry of Water and Electricity, which was divided again in 1979, combined again in 1982, and finally re-divided in 1988 until now. The repeated institutional transformation shows that governance of water and electricity has been an ongoing challenge in China.

Later in 2002, the Bureau of Electricity was divided into five electricity production corporations and two grid companies. The five power production companies, namely, Guodian, Datang, Huaneng, Huadian, and State Power Investment, own about 50 per cent of China's electricity generation capacity and are responsible for power generation. The two grid companies, State Grid and China Southern Power Grid, are responsible for electricity dispatch, transmission, and delivery. The National Development and Reform Commission (NDRC) and local DRCs are responsible for short, medium, and long-term power construction and development plans while the Ministry of Industry and Information Technology and the local Commissions of Economy and Information Technology are responsible for electricity production coordination, demand management, and so forth.

Water resources are governed by the Ministry of Water Resources in China. The Ministry of Water Resources develops water utilization plans and provincial water quotas that are implemented by local water resource bureaus. Although there is a River Basin Committee set up for each river basin, water quotas set by River Basin Committees are usually used as a reference and their main responsibility is to coordinate if any conflicts over water uses between different provinces within a same river basin occur. The fragmented and contested authority of water resource management in China complicates and, sometimes, invalidates the enforcement of related polices and thus weakens the credibility of respective institutions.

After a power plant's construction is proposed by a power production corporation, it requires permission from the local DRC in order for power generation to fit into the overall power development plans and from the Water Resources Bureau so that its water consumption conforms to the regional water quota scheme. Zhang et al. (2016) have comprehensively reviewed China's existing policies managing water resources in its power industry.

Many institutional barriers can hinder good management of water resources in China's power sector: (1) Local protectionism: the central government of China has delegated the power to permit construction of power plants to provincial governments. As provincial cadres' political performance is still evaluated based on their province's economic growth rather than environmental sustainability, power plants permission and construction are prioritized over water resources conservation and environmental protection; (2) Fragmented authoritarianism: China's political system has been coded as 'fragmented authoritarianism'. There are two lines of organizing the government: horizontally (by territory) and vertically (by function). Although provincial and local water bureaus are supposed to report to both their corresponding provincial government (horizontal) and Ministry of Water Resources (vertical). Funding and personnel of provincial and local water bureaus are decided only by the provincial governments. Therefore, there lacks incentives for provincial and local water bureaus to implement any regulations or policies made by the Ministry of Water Resources when they contradict the interests of the provincial or local governments; (3) Political ranking system: Chinese political actors are ranked hierarchically and their bargaining powers are correspondent to their political rankings. Some energy State-Owned Enterprises (SOE) rank the same as the Ministry of Water Resources, therefore, in another word, the polluter has the same power as the regulator, which creates immense resistance for the Ministry of Water Resources to formulate and implement water resource management policies in the power sector.

2.3 Methodologies

This research gains its intellectual roots from multiple disciplines and adopts a mix-method approach. Two important methods used in this dissertation are Hydrological Modelling and Input-Output Analysis.

2.3.1 Hydrological Modeling

Hydrologic models are simplified conceptual representations of the real-world hydrological cycle. Many scholars have used hydrological models to assess water available for power productions around the world, e.g. the UK (Byers et al. 2016), the US and Europe (van Vliet et al. 2012) and worldwide (van Vliet et al. 2016). It should be noted that many traditional hydrological rainfall-runoff models do not consider human interventions (Wada et al. 2011; Gerten et al. 2013; Doll and Schmied 2012). However, heavy anthropogenic impacts on the hydrological cycle in China require more holistic approach. In light of this, an integrated water management model, H08, which simulates both natural and anthropogenic water flows is suitable (Hanasaki et al. 2008).

2.3.2 Input-Output Analysis

First proposed by Allan (1993), virtual water refers to water resources that have been used in production processes and then embodied in the final products or services. Virtual water can be transferred among economic sectors and geographic regions embodied in traded goods. Studies of virtual water provide insights into production, trade and consumption's cross-sector and trans-boundary impacts on water resources. A widely used tool to quantify virtual water uses is Environmental Extended Input-Output Analysis (Lenzen and Foran 2001; Lenzen 2009; Zhang et al. 2011). Input-Output Models is first proposed by Leontief (1941) to depict the interdependencies and monetary flows among different economic sectors. Environmental Extended Input-Output models incorporate natural resources use as an additional row to quantify virtual resource flows from production in one sector to consumption in another. A group of studies have utilized the Multi-Regional Input-Output (MRIO) model to estimate the water uses throughout the energy sector's supply chain in China on various geographical scales (Zhang and Anadon 2013; Wang et al. 2017; Okadera et al. 2015; Wang and Chen 2016). Same approach is used to study energy trade's water impacts in different areas, either globally (Holland et al. 2015) or regionally (Duan and Chen 2017).

2.4 Major research gaps and contributions of this research

Overall, this dissertation will build on and extend the literature on water conflicts/trade-offs in the electric power sector, especially in China. The main contributions based on major research gaps are summarized as below:

Significance of the research region:

Due to its rapidly growing economy and population, China's power demand has had massive growth in recent decades and the trend is projected to continue. In contrast, its water resources are limited and unevenly distributed. While water is required for power production, water security risks in China's power sector are not well understood. Moreover, as the biggest CO_2 emitter in the world (Guan et al. 2009), China is facing considerable pressure participating in the global climate change mitigation. Studies demonstrating water conservation co-benefits of climate change mitigation measures, e.g. improving energy efficiency, demand management and developing renewable energies, are able to advance the agenda.

Integrity of research perspectives:

The water-for-electricity nexus in China has been widely discussed during the last few years. However, most studies have focused on either water availability or demands by the electric power sector. This DPhil dissertation aims to construct an integrated framework to quantify the water risks in China's power sector with consistent analyses. Regarding water demands for power production, this dissertation will investigate from both a producer as well as consumer's perspective, thus enabling policy makers to better identify effective water conservation policies in the power sector. Rigorous analyses on water availability offer more robust estimations of the potential future water risks for electricity production in China.

Effectiveness of research methodologies:

Based on a straight-forward bottom-up model, Chapter 3 attributes the historical change of China's electric power sector's water use to four underlying driving factors, i.e. population, power production per capita, the power sector's generation mix and cooling technology, using a completed Index Decomposition Analysis; Chapter 4 quantifies the current water use in China's thermoelectric power sector and demonstrates future contingencies under different scenarios of the power sector's generation mixes and cooling technology configurations; Chapter 5 quantifies water risks in China's power sector based on water demand data from Chapter 4 and water availability data simulated by an Integrated Water Management Model, H08, at a monthly and half degree x half degree resolution; finally, Chapter 6 attributes the abovementioned water demand in China's power sector to different water users (sectors) in 30 Chinese provinces with a Multi-Regional Input-Output Model.

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Chapter 3. Drivers of water use in China's electric power sector from 2000 to 2015

Based on "Liao, X. and Hall, J.W. (2018) Drivers of water use in China's electric power sector from 2000 to 2015. *Environmental Research Letters* 13: 094010"

3.1 Introduction:

In the past few decades, the rapid economic growth of China has been accompanied by markedly increased electric power (hereinafter used interchangeably with 'power') production, resulting from extensive industrialization, urbanization and growing population. Starting from the 21st century, China's power production has more than quadrupled from 1,328 billion KWh in 2000 to 5,810 billion KWh in 2015 and has overtaken the US as the biggest power producer in the world (National Bureau of Statistics of China 2016). This expansion has notable externalities, for air quality, greenhouse gas emissions and water usage. Due to several recent water-induced power curtailments around the world (McCall et al. 2016; Gjorgiev and Sansavini 2018), water use for electricity production, the so-called 'water-for-electricity' nexus, as well as potential corresponding conflicts and trade-offs have raised growing concerns.

Besides hydropower, a large amount of water is used at thermoelectric power facilities for cooling purposes (Vassolo and Doll 2005; Stillwell et al. 2011; Byers et al. 2014; Sanders 2015; Grubert and Webber 2015; Stillwell et al. 2017). Consequently, global power productions may be exposed to water-related risks, especially under a changing climate (van Vliet et al. 2012; van Vliet et al. 2016; Byers et al. 2016).

China is particularly prone to potential water-electricity conflicts due to its unevenly distributed water endowments (Zhang and Anadon 2013) and the prevalence of thermoelectric power plants on inland waterways (Liao et al. 2016). Moreover, potential changes in water availability and variability, both geographically and seasonally, induced by future climate change may further expose some Chinese regions, e.g. Northern China, to intensified water risks in the power sector (Sadoff et al. 2015; Zheng et al. 2017).

A growing amount of scholarly work has paid attention to China's water-for-electricity nexus. Some studies have quantified the current water use in China's power sector (Zhang et al. 2016; Liao et al. 2016; Zhang et al. 2017) and identified areas that are vulnerable to water risks for power generation, e.g. Jing-Jin-Ji megalopolises (Zheng et al. 2017), whilst others have addressed the future possibility of China's power sector competing with water users in other sectors (Cai et al. 2014; Li et al. 2017) and potential conflicts due to uncoordinated policies (Qin et al. 2015; Liao et al. 2016). Yu et al. (2011) concluded that facilitating and adopting water-saving technologies is the key to avoiding such conflicts. However, in order to better understand such complexity and to inform future policy formulations, it is of great importance to look back into the past trajectories of China's water-for-electricity nexus and to identify the impacts of the factors driving its historical changes.

According to the Impact=Population x Affluence x Technology (IPAT) model (Ehrlich and Holdren 1971; Mi et al. 2017), we attribute China's historical water-for-electricity change to three corresponding factors: (1) population, (2) power production[1] per capita (MWh/p) and (3) water intensities, measured as water use, either withdrawal or consumption, per unit of electricity generated (m^3/MWh). Individual power plant's water intensities vary primarily by its generation technology and cooling technology (Macknick et al. 2012). Prevalent generation technologies include coal, solar PV, wind, hydro and so on. This study does not consider hydropower because the quantification of its water use embodies many methodological disputes and uncertainties, especially regarding the attribution of water use in multi-purpose

[1] Power production is a dependent variable driven by power demand. Because we do not consider inter-regional power transmission in this study, so power production equals power demand.

reservoirs (Bakken et al. 2016). In terms of cooling technologies in thermoelectric power plants, air cooling systems, which use air to cool down the steam exiting turbines, use the least water. Closed-loop cooling systems, where cooling water is recirculated, have much higher consumptive water use but significantly lower water withdrawal than open-loop cooling systems that use running water. Power plants water intensities are also affected by other technological factors, for example, boiler technology. However, compared with plant type and cooling technologies, their effects are much smaller by an order of magnitude for water consumption and three orders of magnitude for water withdrawal (Macknick et al. 2012). Therefore we only consider plant type and cooling technology in this study.

Considering the significant regional variations highlighted by previous studies (Cai et al. 2014; Liao et al. 2016; Zhang et al. 2016), this study is conducted on China's six regional power grids: Northeast, Northwest, North, East, South and Central Grids. Inter-regional power transmissions only occupied a small proportion of energy demand (5% in 2014, China Electricity Council 2015a), so we do not account for these transfers in our regional allocation of water use.

3.2 Method and data

3.2.1 Methods

Until 2015, China's non-hydro electricity was almost entirely produced from fossil fuels (coal and gas), nuclear, wind and solar PV (China Electric Power Statistic Yearbook Editorial Board 2015). We focus on the water use of fossil fuel thermoelectric power plants in this study for two reasons: (1) all China's existing nuclear power plants are located along the coast and utilize sea water for cooling purposes; (2) solar PV and wind power use negligible amount of water (Macknick et al. 2012). Furthermore, gas-fired power generation only reached 3.9% in 2015 (China Electricity Council 2015b) and data are limited to a regional level, so we use the same cooling water usage factors for gas as for coal.

Therefore, water use in the power sector can be quantified according to Eq. (3-1) below:

$$W_i = E_i \cdot P_i \cdot S_{thermal,i} \cdot I_i \qquad (3\text{-}1)$$

Where, *W* is the total water use; *E* denotes the electric power production per capita in the six regional grids; *P* and $S_{thermal}$ represent population and the share of thermal power production, respectively; *I* is thermoelectric power production's water intensities for either withdrawal or consumption, which are approximated by those of coal-fired power plants; *i* represents the region.

According to Eq. (3-1), changes in the power sector's water use can be attributed to four underlying determinants: electric power production per capita *E*, population *P*, the share of thermoelectric power production $S_{thermal}$ and water intensity *I*. In order to assess the influences of various social, economic and technological factors on environmental issues, Index Decomposition Analysis (IDA) has been widely employed (Hoekstra and van der Bergh 2003). We adopt the additive mathematical form as its results are easier to interpret and thus more commonly used in the existing literature (Su and Ang 2012). Accordingly, the power sector's water use change, ΔW_i, can be expressed as Eq. (3-2):

$$\Delta W_i = E_i^e + P_i^e + S_{thermal,i}^e + I_i^e \quad (3\text{-}2)$$

Where E_i^e, P_i^e, $S_{thermal,i}^e$ and I_i^e represent the impacts brought by changes in each factor *E*, *P*, $S_{thermal}$ and *I* respectively. During the time interval [*0, t*], ΔW_i can also be expressed as Eq. (3-3):

$$\Delta W_i = W_i^t - W_i^0 = E_i^t \cdot P_i^t \cdot S_{thermal,i}^t \cdot I_i^t - E_i^0 \cdot P_i^0 \cdot S_{thermal,i}^0 \cdot I_i^0 = (E_i^0 + \Delta E_i) \cdot (P_i^0 + \Delta P_i) \cdot \left(S_{thermal,i}^0 + \Delta S_{thermal,i}\right) \cdot (I_i^0 + \Delta I_i) - E_i^0 \cdot P_i^0 \cdot S_{thermal,i}^0 \cdot I_i^0 \quad (3\text{-}3)$$

In early studies, the effect of each changed factor in Eq. (3-2) was quantified by keeping the other factors the same as either in the starting year (Laspeyres method) or in the ending year (Paasche method), or the mean values (Marshall-Edgeworth method). Take EP_i^e for example, EP_i^e was estimated as$\Delta E_i \cdot P_i^0 \cdot S_{thermal,i}^0 \cdot I_i^0$, $\Delta E_i \cdot P_i^t \cdot S_{thermal,i}^t \cdot I_i^t$ or $\Delta E_i \cdot 1/2 \cdot (P_i^0 \cdot S_{thermal,i}^0 \cdot I_i^0 + P_i^t \cdot S_{thermal,i}^t \cdot I_i^t)$. However, these decomposition methods created residual terms from Eq. (3-3), namely, all terms including changes from more than one factor, for example$\Delta E_i \cdot \Delta P_i \cdot S_{thermal,i}^0 \cdot I_i^0$.

Following the 'jointly created and equally distributed' principle in Sun (1996), Sun (1998) developed the S/S method for attributing effects jointly created by two or more factors, e.g. $\Delta E_i \cdot \Delta P_i \cdot S_{thermal,i}^0 \cdot I_i^0$, equally among the changed factors, i.e. ΔE_i and ΔP_i. In this way, the residual errors are avoided. The S/S method is thus called complete decomposition and is employed in this study. Accordingly, each term in Eq. (3-2) can be derived by breaking down Eq. (3-3) mathematically. Taking E_i^e for example, it can be estimated by Eq. (3-4) below:

$E_i^e = \Delta E_i \cdot P_i^0 \cdot S_{thermal,i}^0 \cdot I_i^0 + \frac{1}{2} \cdot \Delta E_i \cdot \big(\Delta P_i \cdot S_{thermal,i}^0 \cdot I_i^0 + P_i^0 \cdot \Delta S_{thermal,i} \cdot$

Ii0+Pi0·Sthermal,i0·ΔIi+13·ΔEi·ΔPi·ΔSthermal,i·Ii0+ΔPi·Sthermal,i0·ΔIi+Pi0

·ΔSthermal,i·ΔIi+14·ΔEi·ΔPi·ΔSthermal,i·ΔIi (3-4)

Similarly, P_i^e, $S_{thermal,i}^e$ and I_i^e can be attributed (More detailed description of the method can be found in the Supplementary Information)

However, as interactions between different factors are unknown, such assumption generates uncertainties. In order to demonstrate such uncertainties, we calculate the effect of each driving factor under two additional scenarios: (i) without considering joint terms; and (ii) fully accounting unweighted joint terms. Taking E_i^e as an example, the range of uncertainties $[E_i^{e\prime}, E_i^{e\prime\prime}]$ can be calculated as in Eq. (3-5) and (3-6).

$$E_i^{e\prime} = \Delta E_i \cdot P_i^0 \cdot S_{thermal,i}^0 \cdot I_i^0 \quad (3\text{-}5)$$

$$E_i^{e\prime\prime} = \Delta E_i \cdot P_i^0 \cdot S_{thermal,i}^0 \cdot I_i^0 + \Delta E_i \cdot \left(\Delta P_i \cdot S_{thermal,i}^0 \cdot I_i^0 + P_i^0 \cdot \Delta S_{thermal,i} \cdot I_i^0 + P_i^0 \cdot S_{thermal,i}^0 \cdot \Delta I_i\right) + \Delta E_i \cdot \left(\Delta P_i \cdot \Delta S_{thermal,i} \cdot I_i^0 + \Delta P_i \cdot S_{thermal,i}^0 \cdot \Delta I_i + P_i^0 \cdot \Delta S_{thermal,i} \cdot \Delta I_i\right) + \Delta EP_i \cdot \Delta P_i \cdot \Delta S_{thermal,i} \cdot \Delta I_i \quad (3\text{-}6)$$

3.2.2 Data sources and treatment

China's historical provincial electricity generation, thermal power production and population data were obtained from the National Bureau of Statistics (2016) and aggregated to the regional level. A comprehensive dataset of China's coal-fired electricity generation units (EGUs) is compiled from Carbon Monitoring for Action

(CARMA) (The Center for Global Development 2015), World Electric Power Plants Data Base (WEPP) (Utility Data Institute of Platts Energy InforStore 2015), Global Coal Plant Tracker (CPT) (CoalSwarm 2015) and Enipedia (Davis et al. 2015), which includes all coal-fired units' capacities, commissioned years and boiler technologies. Cooling technologies employed by individual power plants are identified via Google Earth satellite imagery in a similar way to the U.S. Geological Survey (Deihl et al. 2013) following two main rules: (i) closed-loop cooling towers can be visually identified; (ii) power plants without such cooling towers but located close to water bodies, primarily in the southern regions, and with discharge outlets are equipped with open-loop cooling systems, otherwise with air-cooling ones. Data acquired from the steps above are then crosschecked with existing information on power plants' cooling technologies in the above-mentioned datasets as well as individual power plant's websites. Over 2300 coal-fired EGUs are included whose aggregate capacity amounts to 870 GW, which equals to about 96.7% of the nation's total in 2015. Although water withdrawal intensities are not available in China, China's technology is on par with that in the US (Zhang et al. 2016), so water withdrawal and consumption intensities of EGUs of a certain cooling type are approximated by those compiled by Macknick et al. (2012) for the US. Regional water withdrawal and consumption are calculated assuming that all coal-fired power plants in a same province have the same running hours each year. This assumption is reasonable because China's generator dispatch mechanism seeks to assure all contracted power generators comparable running hours (Kahrl et al. 2016). The historical changes of the four driving factors can be found in the Supplementary Information.

3.3 Results and discussion

3.3.1 Historical trajectories of water uses in China's electric power sector

As shown in Fig. 3, from 2000 to 2015, the national total water consumption and withdrawal for power production in China grew from 1.25 and 40.75 billion m^3 to 4.86 and 124.06 billion m^3, respectively. Water withdrawal peaked in 2013 at 129.82 billion m^3, which is because power productions in regions with large water withdrawal intensities, i.e. south, east and central, peaked in that year. In 2013, southern China suffered from record-high heat waves that could have contributed to these regions' electricity demand peaking (USA Today 2013). Open-loop cooling systems are prevalently utilized in these abovementioned regions where water is abundant (Liao et al. 2016). As a result, the largest amount of water was withdrawn in the east, from 18.28 billion m^3 in 2000 to 65.01 billion m^3 in 2015 and peaking at 68.16 billion m^3 in 2013, which is followed by the south. While in the northern regions (north, northeast and northwest), particularly northwest, the amount of water withdrawn for power production was substantially smaller.

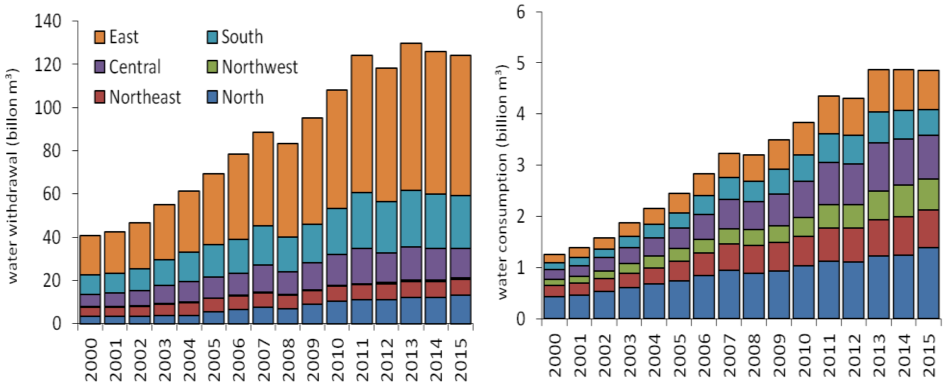

Figure 3 China's electric power sector's water use change from 2000 to 2015

Regarding water consumption, the largest amount of water was consistently consumed in the north, from 434.13 million m^3 in 2000 to 1.39 billion m^3 in 2015, aggravating the region's continuous severe water scarcity. When population is taken into account, the power sector in the northwest has the highest water consumption per capita, 6.00 m^3/p, while the lowest water withdrawal per capita, 7.22 m^3/p. In comparison, the power sector's water withdrawal per capita in the east is the highest, amounting to 250.87 m^3 per person.

3.3.2 Drivers of historical changes in China's electric power sector's water use

3.3.2.1 Effects of population and power production per capita

It can be seen from Fig. 4 that the increases of population and power production per capita both have had positive effects on the power sector's water use increases. In total, from 2000 to 2015, population increase contributed to 8.43 billion m^3 and 295.99 million m^3 of water withdrawal and consumption increases, respectively, compared with 103.40 and 3.84 billion m^3 triggered by the rise of power production per capita. Population played the least important role, which is not surprising considering China's population has stabilized during this period at an average annual growth rate of 0.56%, while power production per capita has kept an annual growth rate of around 10% during the same period. In the east, population growth had made a visible contribution to the water withdrawal increases, at 1.1, 2.0 and 1.5 billion m^3 during the three consecutive five-year periods respectively. Whereas the population effect on water consumption was the highest in the north. The north and the east are homes to China's two rapidly expanding urban agglomerations, Jing-Jin-Ji and the Yangtze Delta region respectively. Both regions have attracted significant numbers of inward migrations for better jobs and opportunities (Wang et al. 2017), which has resulted in heightened pressure on its local resources.

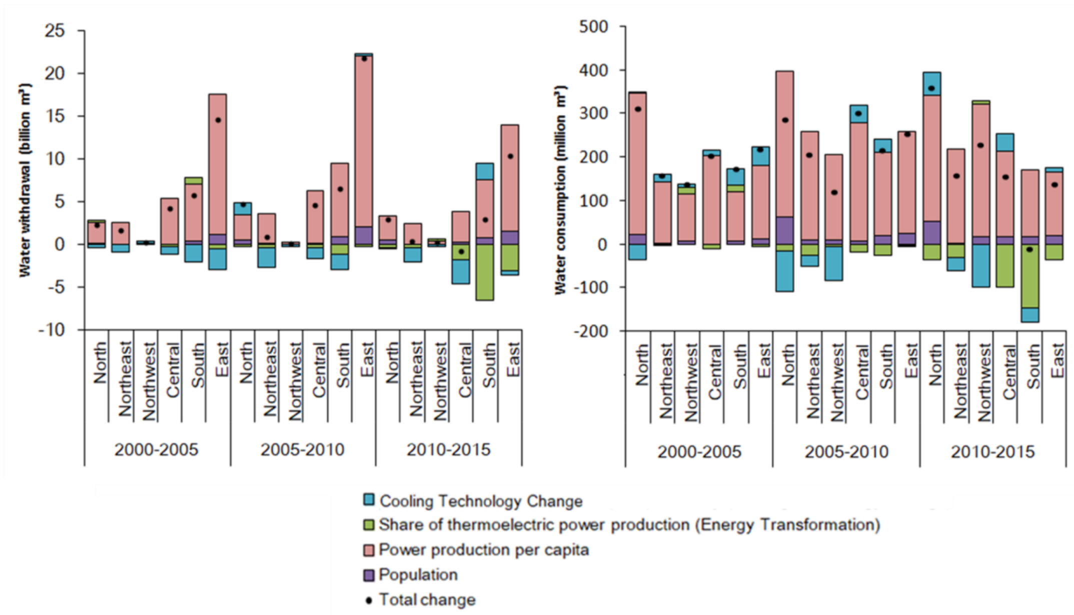

Figure 4 Drivers of China's electric power sector's water use changes from 2000 to 2015 (Detailed results can be found in the Supplementary Information)

Growth in power production per capita played the dominant role in every region. Particularly, it had substantial effects in central, south and east China contributing to their water withdrawal increases of 15.09, 22.07 and 48.96 billion m^3 respectively from 2000 to 2015. Such significant effects can be explained by the large base values of water withdrawal intensities in those regions as they are relatively abundant in water resources and therefore open-loop cooling systems are commonly adopted. Regarding water consumption, the effects are relatively similar across different regions. In each region, about 100 to 300 million m^3 of water consumption growth was triggered by power production per capita increase every five years.

3.3.2.2 Effects of energy transformation

According to Fig. 2, energy transition - the change of the power sector's energy portfolio – has mitigated 14.46 billion m^3 of water withdrawal increase and 429.30 million m^3 of water consumption increase in the power sector during the study period. The effect was especially significant from 2010 to 2015, contributing to 83.67% and 80.00% of the total, respectively. During this period, transforming the energy structure offset 6.56 and 3.06 billion m^3 of water withdrawal increase in south and east China, respectively.

As the world's biggest CO_2 emitter, China pledged to increase the share of its non-fossil fuel to around 15% by 2020 at Copenhagen in 2009. It first proposed to diversify the energy portfolio in its 10th Five-Year Plan (2001-2005) (National People's Congress of China 2001) and the 12th Five-Year Plan (2011-2015) (National People's Congress of China 2011) made more specific targets aiming to decrease the share of coal in the country's energy structure to 63%.

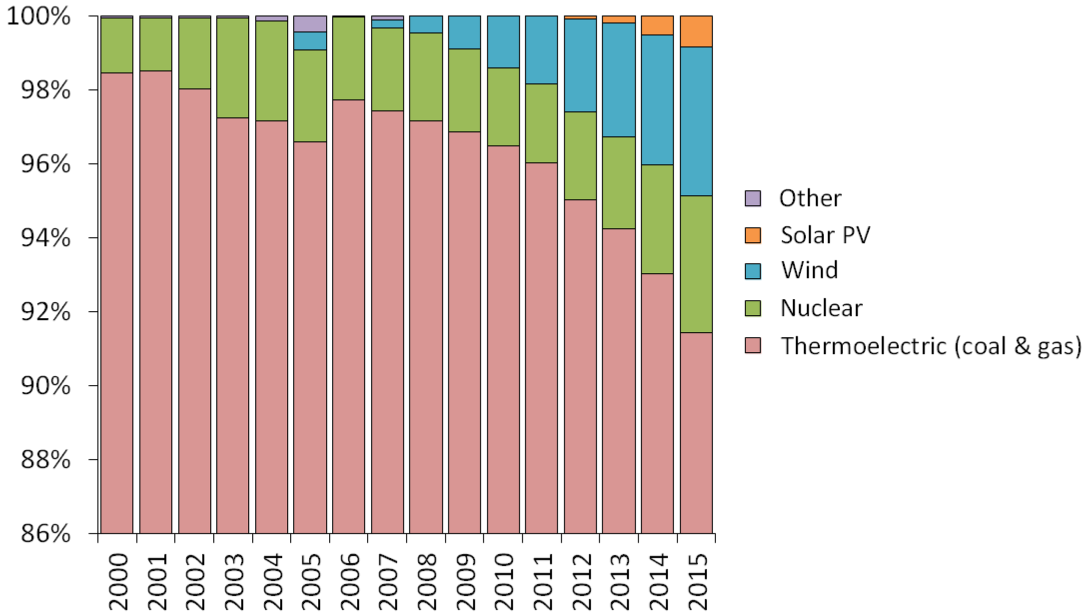

Figure 5 Energy structure of China's electric power productions (excl. hydro) from 2000 to 2015 (Note: wind power and solar PV were included in 'Other' before 2005) (Source: China Electric Statistic Yearbook 2015)

While China's hydropower has occupied a relatively stable proportion of the total power production (at just below 20%), it can be seen from Fig. 5 that, besides hydropower, during the study period (2000-2015), even though the sheer amount of electricity produced from fossil fuel has increased drastically from 1088.48 to 4241.93 TWh, the percentage it occupies has gone down from 98.5% to just over 91.4%, which was gradually taken over by nuclear, wind power and solar PV.

The power sector is the major source of air pollution and greenhouse gas emissions in China due to its intensive coal combustion. Facing pressing local health penalties and global climate change pressures, China has taken actions to reduce its power sector's reliance on coal, by either transforming its energy portfolio or improving coal-burning efficiencies. Sanders (2015) has conducted a meta-analysis of existing publications in the water-electricity field and identified five main aspects of the power sector that have impacts on its water uses: (1) fuel consumption structure; (2) cooling technology deployment; (3) relevant regulations; (4) changing climate and (5) power grid characteristics. Therefore, apart from policies that directly regulate the sector's water uses, those targeting at any one of the five domains may deliver corresponding co-benefits. For example, Webster et al. (2013) found that a restriction on CO_2 emissions in the energy sector would also reduce water withdrawals by the power sector in Texas; Bartos and Chester (2014) have shown that Arizona's Energy Efficiency Mandate and Renewable Portfolio Standard have resulted in considerable water savings.

It needs noticing that some technologies that can curb the power sector's carbon emissions may lead to increased water uses. For example, Carbon Capture and Storage (CCS) offers the opportunity to minimize carbon emissions from fossil fuel power plants. However, as carbon capture is an energy intensive process, the parasitic loads of CCS power plants could result in larger water uses (Zhai et al. 2011; Byers et al. 2016). Although Concentrated Solar Power (CSP) and inland nuclear power are both feasible alternatives to reduce carbon emissions of China's electric power sector, their on-site water uses are substantial, whereas bio-fuels require the largest amount of water inputs throughout the life cycle, mainly for crop cultivation (Meldrum et al. 2013). On the contrary, thermoelectric power plants equipped with air cooling systems that are used to minimize their water uses emit more carbon due to lower thermal efficiencies and thus increased coal use (European Commission Joint Research Center 2001).

3.3.2.3 Effects of cooling technology change

The effects of water intensity changes as in Fig. 4 are primarily determined by the plant fleets' cooling technology configuration changes as demonstrated in Fig. 6. In total, changing cooling technologies mitigated 14.07 billion m^3 of water withdrawal increase and 101.34 million m^3 of water consumption increase, which varied among regions. For instance, cooling technology change contributed to 93.94 million of water consumption increase but 5.10 billion m^3 of water withdrawal decrease in central China. While in northwest China, the percentage of closed-loop cooling systems has gone down from 86.6% in 2000 to 52.7% in 2015 being replaced by air cooling ones, which resulted in 169.97 million m^3 of water consumption reductions. In the southern regions (central, south and east), closed-loop cooling systems are gradually replacing open-loop ones to reduce the power sector's water withdrawals thus dependence on water supplies, but at the cost of water consumption increase. Reducing water withdrawal can reduce the power plants' dependency on reliable water supplies and corresponding water shortage risks. While in the northern regions (north, northwest and northeast), in response to severe local water stresses, defined as available water sources being difficult to meet water demands, air cooling systems have been gradually adopted to cut both water withdrawal and consumption.

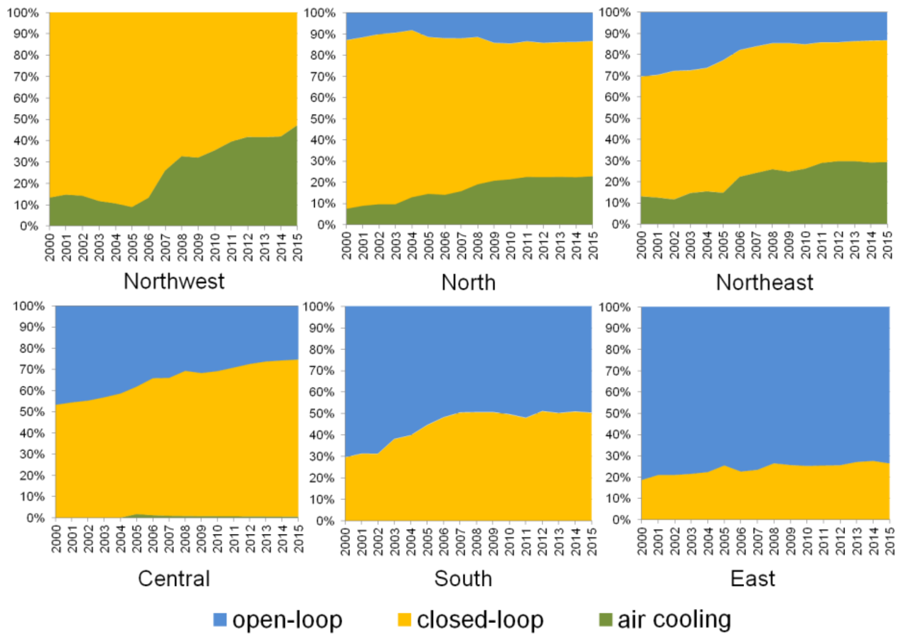

Figure 6 Historical changes of cooling technology configurations in China's six regional grids

The abovementioned changes in the cooling technology configurations in China's different regions resulted from various policies in the power sector directly and specifically targeting its water usage. At a national level, in 2012, a new national water withdrawal standard (GB/T 18916.1-2012) replaced "GB/T 18916.1-2002" and set more stringent requirements regarding water uses by coal power plants with closed-loop cooling systems (General Administration of Quality Supervision, Inspection and Quarantine of China 2002, 2012). Moreover, in water scarce areas, new plants are not allowed to extract groundwater and required to employ large air-cooling units with water withdrawal intensities less than 0.18 m^3/(s GW) (National Development and Reform Commission 2004). As a result, new power plants equipped with air cooling systems need much less time to acquire environmental permits and thus have proliferated during the last decade. Nationally, the percentage of air cooling systems has increased from 6.4% in 2000 to 14.5% in 2015 while that of wet cooling systems, including both closed-loop and open-loop cooling, has decreased accordingly.

There are also other official but non-mandatory guidelines for water-using practices in the coal power sector, such as 'Guidelines for water saving in thermal power plants' issued by the State Economic and Trade Committee, 'China water conservation technology policy outline' by the NDRC and 'Water efficiency guide for key industrial sectors' by the Ministry of Industry and Information Technology (Zhang et al. 2016).

Some trade-offs need to be made regarding choosing cooling technologies. While replacing open-loop cooling systems with closed-loop ones reduces the power sector's dependency on water supplies and thus enhances its resilience to extreme weather events (e.g. droughts), it also markedly increases the power sector's consumptive water use and therefore competes with other water users, e.g. agriculture and domestic. Moreover, besides larger capital investment (for land and cooling towers), more water efficient technologies lead to lower power production efficiencies, which results in larger coal inputs and higher emissions, including carbon and other pollutants. Future infrastructure planning and investment need to consider those trade-offs prudently.

Although not considered in this study, upgrading boiler technology may also contribute to the power sector's water savings. As Zhang et al. (2016) has demonstrated based on field data in China, EGUs with larger capacities are more water efficient. The reason is because larger EGUs tend to adopt more advanced boiler technologies, e.g. supercritical, with higher efficiencies, which means more heat is converted from the primary energy carrier, e.g. coal, to electricity, and therefore less residual heat needs to be dissipated by cooling water. Nonetheless their effects on water use are much smaller compared with plant types and cooling technologies (Macknick et al. 2012).

3.3.3 Uncertainties in the driver effects attribution

Uncertainties resulted from the decomposition method are illustrated in Fig. 7 using water withdrawal as an example. It can be seen that the average uncertainties in attributing the effects of population change, demand change, energy structure change and water intensity change are [-18.0%, +16.0%], ± 7.1%, [-20.2%, +18.9%] and ± 22.8%, respectively. It is the highest for population factor in the northwest from 2000-2005, [-35.6%, +36.5%], and the lowest for demand factor in the north from 2010-2015, [-0.36%, +0.31%].

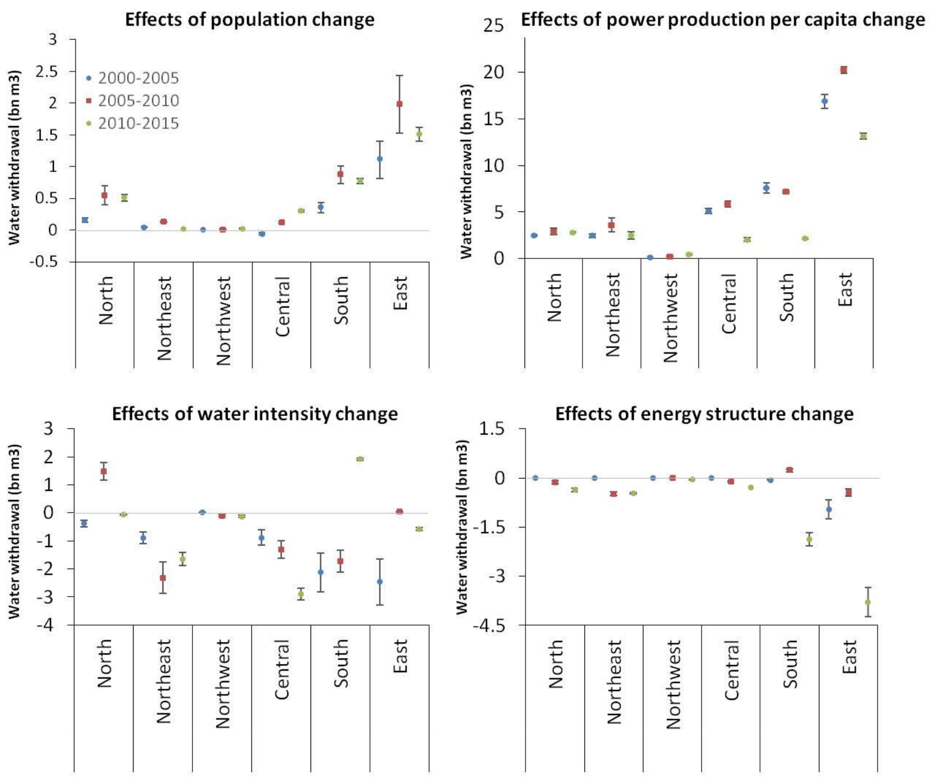

Figure 7 Uncertainties in attributing driver effects of the power sector's water withdrawals in China

In absolute terms, different ways of accounting the joint terms could result in uncertainties of ± 0.08, ± 0.27, ± 0.07 and ± 0.24 billion m^3 of water withdrawals triggered by the changes of population, power production per capita, energy structure and water withdrawal intensity, respectively.

3.4 Conclusions

Water scarcity has already hindered China's energy development, manifested by plans to build coal-to-liquids (CTL) plants being abandoned in 2008. Qin et al. (2015) and Liao et al. (2016) have also demonstrated that, with uncoordinated policies, power production may violate industrial water policies in the future, on both national and regional scales. While previous studies have revealed the current status and future contingencies of China's water-for-electricity nexus issues, this study has, for the first time, shed light on its past trajectories as well as driving factors on a regional level.

Both water withdrawal and consumption have more than tripled in China's power sector from 2000 to 2015 and this study shows that power production per capita was the primary force driving the power sector's water use increases. However, China's national average power production per capita is still low, amounting to only 4153 KWh in 2014 and ranked around 70^{th} in the world, against 7995 KWh in OECD countries and 12987 KWh in the United States (World Bank 2017). Furthermore, we have demonstrated that a series of China's policies primarily aimed to reduce carbon emissions and other air pollutants have generated co-benefits of offsetting the power sector's water use increases. Although inter-regional power transmissions were small in the past and thus not considered in this study, China has embarked on building long-distance power transmission lines, especially ultra-high voltage ones, to facilitate transmitting electricity generated by renewable energies in inland regions to densely populated coastal regions. Their possible effects on the national as well as regional water resources need to be further researched.

Through studying the historical trajectories and driving factors, we highlight two features of China's water-for-electricity nexus: its geographical disparities and potential cross-sectoral conflicts or synergies. How to take these geographical differences into account prudently, and to maximize potential synergies and minimize conflicts remain pivotal for future policy formulations and implementations, as well as infrastructure planning and investments in both power and water sectors in China for a sustainable future.

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Supplementary Information:

S 3-1, Derivation of Index Decomposition Equation

After the driving factors being identified, according to the additive mathematical form commonly used in the literature (Hoekstra and van der Bergh, 2003; Su and Ang, 2012; Mi et al., 2017), region *i*'s power sector's water use change, ΔW_i, can be expressed as:

$$\Delta W_i = E_i^e + P_i^e + S_{thermal,i}^e + I_i^e \quad \text{(S3-1)}$$

Where E_i^e, P_i^e, $S_{thermal,i}^e$ and I_i^e represent the impacts brought by changes in each underlying determinant E, P, $S_{thermal}$ and I respectively.

Alternatively, ΔW_i can also be expressed as Eq. (S3-2) below:

$$\Delta W_i = {W_i}^t - {W_i}^0 = E_i^t P_i^t S_{thermal,i}^t I_i^t - E_i^0 P_i^0 S_{thermal,i}^0 I_i^0$$

$$= (E_i^0 + \Delta E_i)(P_i^0 + \Delta P_i)\left(S_{thermal,i}^0 + \Delta S_{thermal,i}\right)(I_i^0 + \Delta I_i) - E_i^0 P_i^0 S_{thermal,i}^0 I_i^0$$

$$= (E_i^0 P_i^0 + E_i^0 \Delta P_i + \Delta E_i P_i^0 + \Delta E_i \Delta P_i)\left(S_{thermal,i}^0 I_i^0 + S_{thermal,i}^0 \Delta I_i + \Delta S_{thermal,i} I_i^0 + \Delta S_{thermal,i} \Delta I_i\right) - E_i^0 P_i^0 S_{thermal,i}^0 I_i^0$$

$$= E_i^0 P_i^0 S_{thermal,i}^0 I_i^0 + E_i^0 P_i^0 S_{thermal,i}^0 \Delta I_i + E_i^0 P_i^0 \Delta S_{thermal,i} I_i^0 + E_i^0 P_i^0 \Delta S_{thermal,i} \Delta I_i + E_i^0 \Delta P_i S_{thermal,i}^0 I_i^0 + E_i^0 \Delta P_i S_{thermal,i}^0 \Delta I_i + E_i^0 \Delta P_i \Delta S_{thermal,i} I_i^0 + E_i^0 \Delta P_i \Delta S_{thermal,i} \Delta I_i + \Delta E_i P_i^0 S_{thermal,i}^0 I_i^0 + \Delta E_i P_i^0 S_{thermal,i}^0 \Delta I_i + \Delta E_i P_i^0 \Delta S_{thermal,i} I_i^0 + \Delta E_i P_i^0 \Delta S_{thermal,i} \Delta I_i + \Delta E_i \Delta P_i S_{thermal,i}^0 I_i^0 + \Delta E_i \Delta P_i S_{thermal,i}^0 \Delta I_i + \Delta E_i \Delta P_i \Delta S_{thermal,i} I_i^0 + \Delta E_i \Delta P_i \Delta S_{thermal,i} \Delta I_i - E_i^0 P_i^0 S_{thermal,i}^0 I_i^0$$

$$= E_i^0 P_i^0 S_{thermal,i}^0 \Delta I_i + E_i^0 P_i^0 \Delta S_{thermal,i} I_i^0 + E_i^0 P_i^0 \Delta S_{thermal,i} \Delta I_i + E_i^0 \Delta P_i S_{thermal,i}^0 I_i^0 + E_i^0 \Delta P_i S_{thermal,i}^0 \Delta I_i + E_i^0 \Delta P_i \Delta S_{thermal,i} I_i^0 + E_i^0 \Delta P_i \Delta S_{thermal,i} \Delta I_i + \Delta E_i P_i^0 S_{thermal,i}^0 I_i^0 + \Delta E_i P_i^0 S_{thermal,i}^0 \Delta I_i + \Delta E_i P_i^0 \Delta S_{thermal,i} I_i^0 + \Delta E_i P_i^0 \Delta S_{thermal,i} \Delta I_i + \Delta E_i \Delta L S_{thermal,i}^0 I_i^0 + \Delta E_i \Delta P_i S_{thermal,i}^0 \Delta I_i + \Delta E_i \Delta P_i \Delta S_{thermal,i} I_i^0 + \Delta E_i \Delta P_i \Delta S_{thermal,i} \Delta I_i \quad \text{(S3-2)}$$

In Eq. (S3-2), $\Delta E_i P_i^0 S_{thermal,i}^0 I_i^0$, $\mathrm{E_i^0} \Delta P_i S_{thermal,i}^0 I_i^0$, $\mathrm{E_i^0} P_i^0 \Delta S_{thermal,i} I_i^0$ and $\mathrm{E_i^0} P_i^0 S_{thermal,i}^0 \Delta I_i$ are fully attributed to E_i^e, P_i^e, $S_{thermal,i}^e$ and I_i^e, respectively. According to 'jointly created and equally attributed' principle (Sun, 1996), joint change terms, for instance, $\Delta E_i \Delta P_i S_{thermal,i}^0 I_i^0$, are equally attributed to the changed factors, i.e. E_i^e and P_i^e in this case. Therefore, E_i^e, the impacts of changes of E_i, includes

$$\Delta E_i P_i^0 S_{thermal,i}^0 I_i^0;$$

half of $\Delta E_i \Delta P_i S_{thermal,i}^0 I_i^0$, $\Delta E_i P_i^0 \Delta S_{thermal,i} I_i^0$ and $\Delta E_i P_i^0 S_{thermal,i}^0 \Delta I_i$;

one third of $\Delta E_i P_i^0 \Delta S_{thermal,i} \Delta I_i$, $\Delta E_i \Delta P_i \Delta S_{thermal,i} I_i^0$ and $\Delta E_i \Delta P_i S_{thermal,i}^0 \Delta I_i$;

one fourth of $\Delta E_i \Delta P_i \Delta S_{thermal,i} \Delta I_i$.

Therefore, combining Eq. (S3-1) and (S3-2), E_i^e can be expressed in Eq. (S3-3):

$$E_i^e = \Delta E_i \cdot P_i^0 \cdot S_{thermal,i}^0 \cdot I_i^0 + \frac{1}{2} \cdot \Delta E_i \cdot \left(\Delta P_i \cdot S_{thermal,i}^0 \cdot I_i^0 + P_i^0 \cdot \Delta S_{thermal,i} \cdot I_i^0 + P_i^0 \cdot S_{thermal,i}^0 \cdot \Delta I_i\right) + \frac{1}{3} \cdot \Delta E_i \cdot \left(\Delta P_i \cdot \Delta S_{thermal,i} \cdot I_i^0 +\right.$$

$$\Delta Pi \cdot Sthermal,i0 \cdot \Delta Ii + Pi0 \cdot \Delta Sthermal,i \cdot \Delta Ii + 14 \cdot \Delta Ei \cdot \Delta Pi \cdot \Delta Sthermal,i \cdot \Delta Ii \qquad \text{(S3-3)}$$

The other three items P_i^e, $S_{thermal,i}^e$ and I_i^e can be quantified in the same way as Eq. (S3-3).

It should be noted that analysis using S/S method described above is a non-chaining analysis (Su and Ang 2012). Which means, for example, if we have year 1, 2 and 3, there are two ways to conduct the index decomposition analysis throughout the whole period: (1) we can use year 1 and 3 as starting and ending point to study the effects covering the whole period *[1, 3]*; (2) we can conduct the analysis during period 1 *[1, 2]* and period 2 *[2, 3]* respectively, and combine the results for the whole period. The results given by the two ways are not exactly the same. We choose the second way because we want to present the periodical change of the driving factors' effects. Moreover, in the table presented below, using analysis on water consumption as an example, we show that the two different ways do not generate significantly different results nor change the general patterns of the results.

Table S 3-1 Different ways of temporal aggregating in a non-chaining IDA analysis

Driving factors	population		water consumption intensity		thermoelectric power percentage		power production per capita	
Means of temporal aggregating	1	2	1	2	1	2	1	2
North	133.28	134.11	-112.71	-76.52	-44.68	-52.80	979.52	950.61
Northeast	15.24	13.75	-17.06	-35.98	-69.27	-79.25	590.48	620.88
Northwest	38.89	32.74	-167.03	-171.05	-44.48	-50.17	657.81	673.67
Central	11.91	19.67	84.93	93.60	-15.05	-21.11	574.69	564.33
South	33.91	43.21	57.35	34.37	-22.77	-37.72	308.43	337.05
East	51.14	52.44	79.31	53.33	-50.84	-59.77	530.19	563.80

S 3-2. Historical changes of the four driving factors from 2000 to 2015 in China

N-North; NE-Northeast; NW-Northwest; C-Central; S-South; E-East

Table S 3-2. Population in China's 6 power grids from 2000 to 2015 (million) (Source: National Bureau of Statistics 2016)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
N	212.84	214.01	215.41	216.75	218.41	220.35	222.58	224.94	227.64	230.19	236.17	238.45	240.66	242.83	244.9	246.54
NE	130.45	130.77	130.99	131.15	131.36	131.6	132.32	132.81	133.18	133.65	134.27	134.48	134.63	134.74	134.81	134.58
NW	90.79	91.38	91.99	92.57	93.12	93.84	94.48	95.13	95.72	96.23	96.76	97.23	97.84	98.42	99.09	100.09
C	370.23	369.67	370.6	372.48	372.8	367.37	367.43	367.25	368.97	370.89	370.95	371.99	373.49	375.02	376.62	379.02
S	221.87	224.03	226.37	228.77	231.37	228.62	231.7	234.19	237.02	239.58	240.01	241.27	243.06	244.47	246.03	248.28
E	231.19	233.29	235.15	237.46	240.4	241.46	243.87	246.72	248.89	250.93	252.69	253.97	255.13	256.56	257.83	259.13

Table S 3-3. Non-hydro power production per capita in China's 6 regions from 2000 to 2015 (MWh/p) (Source: National Bureau of Statistics 2016)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
N	1.32	1.42	1.61	1.81	2.08	2.32	2.62	2.96	2.88	3.09	3.39	3.64	3.68	3.95	3.99	4.31
NE	1.34	1.37	1.46	1.70	1.87	2.15	2.56	3.09	3.38	3.41	3.71	4.29	4.40	4.83	5.18	5.24
NW	0.76	0.89	1.01	1.22	1.42	1.55	1.75	2.07	2.37	2.41	2.90	3.78	4.20	5.07	5.70	6.00
C	0.43	0.48	0.54	0.66	0.74	0.84	0.97	1.14	1.10	1.20	1.37	1.60	1.51	1.72	1.63	1.58
S	0.75	0.80	0.91	1.11	1.27	1.42	1.61	1.82	1.70	1.90	2.13	2.42	2.37	2.53	2.44	2.34
E	1.12	1.21	1.35	1.67	1.86	2.19	2.52	2.75	2.88	3.19	3.52	4.03	4.03	4.42	4.38	4.39

Table S 3-4. The percentage thermoelectric power occupies in non-hydro electricity production (%) (Source: National Bureau of Statistics 2016)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
N	99.99	98.71	99.94	100.00	99.83	99.93	99.73	99.80	97.48	98.74	98.24	98.20	95.94	96.84	95.64	95.26
NE	99.75	99.78	99.84	99.89	99.70	99.77	99.60	98.44	94.37	95.22	92.69	91.32	91.28	89.72	88.46	86.75
NW	99.71	98.18	99.80	99.82	99.71	99.55	99.29	99.28	97.85	98.12	97.28	97.01	92.80	92.73	91.18	89.39
C	99.90	99.64	99.87	99.69	99.88	99.98	99.94	99.84	96.10	99.61	99.05	99.29	96.31	99.51	98.19	96.99
S	91.07	91.43	89.97	88.08	90.04	90.60	91.57	92.77	88.92	92.34	91.77	91.95	89.71	90.60	87.73	84.57
E	99.21	98.30	98.33	96.22	94.96	95.56	96.02	95.18	93.87	94.45	94.60	94.88	92.70	93.90	91.72	88.82

Table S 3-5. Water consumption intensity in China's 6 power grids (m^3 /MWh) (Source: Data sources and treatment section)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
N	1.55	1.54	1.54	1.54	1.52	1.46	1.46	1.43	1.39	1.33	1.31	1.32	1.31	1.33	1.34	1.37
NE	1.24	1.26	1.29	1.25	1.26	1.32	1.29	1.28	1.27	1.29	1.26	1.22	1.21	1.20	1.21	1.20
NW	1.67	1.65	1.66	1.69	1.70	1.74	1.67	1.50	1.41	1.42	1.37	1.28	1.23	1.22	1.21	1.12
C	1.24	1.24	1.29	1.28	1.30	1.30	1.38	1.36	1.40	1.41	1.39	1.40	1.45	1.46	1.48	1.47
S	0.85	0.92	0.94	0.97	0.99	1.02	1.09	1.10	1.11	1.16	1.10	1.05	1.09	1.08	1.06	1.03
E	0.64	0.69	0.70	0.71	0.73	0.76	0.72	0.72	0.76	0.75	0.76	0.75	0.76	0.77	0.78	0.77

Table S 3-6. Water withdrawal intensity in China's 6 power grids (m^3 /MWh) (Source: Data sources and treatment section)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
N	3.33	3.28	3.41	3.62	3.85	5.58	6.57	7.45	6.74	8.94	10.37	10.87	11.15	12.03	12.03	13.28
NE	4.37	4.42	4.64	5.44	5.73	5.98	6.30	6.65	6.33	6.40	6.90	7.10	7.19	7.31	7.44	7.27
NW	0.14	0.16	0.19	0.23	0.28	0.31	0.34	0.36	0.38	0.39	0.45	0.55	0.57	0.68	0.75	0.72
C	5.63	6.33	7.06	8.32	9.51	9.80	9.89	12.55	10.38	12.35	14.34	16.09	13.75	15.47	14.45	13.49
S	9.00	9.10	10.17	11.81	13.74	14.75	15.82	18.09	16.06	17.82	21.33	26.06	23.91	26.18	25.24	24.29
E	18.28	19.00	21.15	25.68	28.18	32.85	39.46	43.38	43.54	49.14	54.69	63.33	61.77	68.16	65.97	65.01

S 3-3. Impacts of the four driving factors on China's historical water-for-electricity change

The impacts of the four driving factors on China's water-for-electricity change, both water withdrawal and consumption can be quantified by Eq. (7) and (4) with input data from Table S-1 to Table S-5, the results are presented in Table S-7 and Table S-8.

Table S 3-7. The impacts of four driving factors on the water withdrawal change in China's power sector (billion m^3)

	North	Northeast	Northwest	Central	South	East
2000-2005						
Population	0.155	0.046	0.007	-0.061	0.359	1.118
Power production per capita	2.465	2.514	0.134	5.382	6.665	16.419
Share of thermoelectric power (Energy Transformation)	0.012	-0.050	0.018	-0.267	0.841	-0.509
Water withdrawal intensity (Cooling Technology Change)	-0.378	-0.897	0.010	-0.885	-2.109	-2.462
Total change	2.254	1.613	0.169	4.170	5.756	14.567
2005-2010						
	North	Northeast	Northwest	Central	South	East
Population	0.542	0.134	0.012	0.118	0.884	1.980
Power production per capita	2.908	3.481	0.239	6.160	8.607	20.100
Share of thermoelectric power (Energy Transformation)	-0.133	-0.368	-0.009	-0.434	-1.181	-0.281
Water withdrawal intensity (Cooling Technology Change)	1.467	-2.329	-0.100	-1.304	-1.736	0.038
Total change	4.784	0.917	0.143	4.540	6.574	21.836
2010-2015						
	North	Northeast	Northwest	Central	South	East
Population	0.508	0.017	0.020	0.303	0.783	1.508
Power production per capita	2.823	2.363	0.368	3.543	6.793	12.439
Share of thermoelectric power (Energy Transformation)	-0.352	-0.354	0.008	-1.791	-6.555	-3.058
Water withdrawal intensity (Cooling Technology Change)	-0.065	-1.655	-0.128	-2.908	1.942	-0.569
Total change	2.914	0.370	0.269	-0.853	2.963	10.320

Table S-8. The impacts of four driving factors on the water consumption change in China's power sector (million m^3)

	2000-2005					
	North	Northeast	Northwest	Central	South	East
Population	20.472	2.576	5.964	-2.310	6.234	11.617
Power production per capita	325.322	139.320	109.050	202.404	113.993	168.437
Share of thermoelectric power (Energy Transformation)	1.544	-2.786	14.410	-10.122	14.587	-5.292
Water withdrawal intensity (Cooling Technology Change)	-36.015	17.883	7.529	13.211	37.516	43.793
Total change	311.324	156.993	136.952	203.183	172.330	218.554
	2005-2010					
	North	Northeast	Northwest	Central	South	East
Population	61.773	9.631	9.802	5.306	19.727	23.043
Power production per capita	333.812	248.008	195.350	274.240	190.959	233.937
Share of thermoelectric power (Energy Transformation)	-15.120	-26.597	-7.293	-19.487	-26.395	-3.274
Water withdrawal intensity (Cooling Technology Change)	-94.024	-25.416	-77.538	39.706	30.888	-0.671
Total change	286.441	205.626	120.321	299.764	215.179	253.035
	2010-2015					
	North	Northeast	Northwest	Central	South	East
Population	51.860	1.523	16.731	16.754	17.545	17.745
Power production per capita	288.209	216.195	304.230	195.244	152.778	146.349
Share of thermoelectric power (Energy Transformation)	-35.955	-32.586	6.920	-99.480	-146.369	-35.998
Water withdrawal intensity (Cooling Technology Change)	53.533	-28.359	-99.961	41.019	-34.547	10.116
Total change	357.646	156.772	227.920	153.536	-10.593	138.212

Chapter 4. Water use in China's electric power sector

Based on "Liao, X., Hall, J.W. and Eyre, N. (2016) Water use in China's thermoelectric power sector. *Global Environmental Change* 41: 142-152."

4.1 Introduction

4.1.1. 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; Meldrum et al. 2013).

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 m^3 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).

4.1.2 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 billion m^3, its water resource per capita, 2100 m^3 in 2012, only amounts to one third 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 billion m^3 for 2015, 2020 and 2030, respectively, against the level of 609.5 billion m^3 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) concluded 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 km^3, 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) concluded 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.

4.2 Methodology and data

4.2.1 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:

$A=E*a$ (4-1)

$C = E*c$ (4-2)

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. (4-1) and (4-2) can be expressed as:

$A=\sum_{1}^{n}\sum_{1}^{k}E_{g,m}a_{g,m}$ (4-3)

$C=\sum_{1}^{n}\sum_{1}^{k}E_{g,m}c_{g,m}$ (4-4)

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.

4.2.1.1 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 5. 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 CO_2 emitter, it has pledged to peak its emissions around 2030 and lower its CO_2 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.

Table 5 Studies on China's long-term power development (TWh)

Year	Source	National power demand	Hydro	Gas	Nuclear	Wind	PV	CSP	Coal
	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
2020	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 NDRC & WWF scenarios	Min	6271	1088	263	525	200	70	10	4040
		Max	9577	1260	320	622	439	140	16	6896
	State Grid (2011)		9808							
	Sino-Danish Roadmap (2014) Basic						800	420	90	
	Sino-Danish Roadmap (2014) Positive						2400	840	180	
2030	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 NDRC & WWF scenarios	Min	9808				462	70	16	
		Max	15043				800	420	90	
2035	IEA (2010)		10802	1512	972	800	756	820		5941
	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 NDRC & WWF scenarios	Min	8735	1326	263	777	376	70		5091
		Max	17614	1512	972	1050	756	820		14549
2040	IEA (2014)		10762	1469	861	1076	807	915		5596
	State Grid (2011)		14300							
	Sino-Danish Roadmap (2014) Basic						2000	1400	720	
2050	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 NDRC & WWF scenarios	Min	10665	1320	263	777	512	70	16	5820
	Max	24377	2891	945	2400	2444	11139	4700	21258

Table 6 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

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

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.

4.2.1.2 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 modeled 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. (4-5) as below:

$$E_{demand,i}=E_{coal.i}+E_{gas,i}+E_{PV,i}+E_{CSP,i}+E_{wind,i}+E_{nuclear,i}+E_{hydro,i} \quad (4\text{-}5)$$

Where $E_{demand,i}$ is the projected electricity demand in province i, $E_{coal.i}$, $E_{gas,i}$, $E_{PV,i}$, $E_{CSP,i}$, $E_{wind,i}$, $E_{nuclear,i}$ and $E_{hydro,i}$ 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.

4.2.1.3 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).

4.2.2 Data

The framework of the approach and data used in this study are presented in Fig. 8. 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.

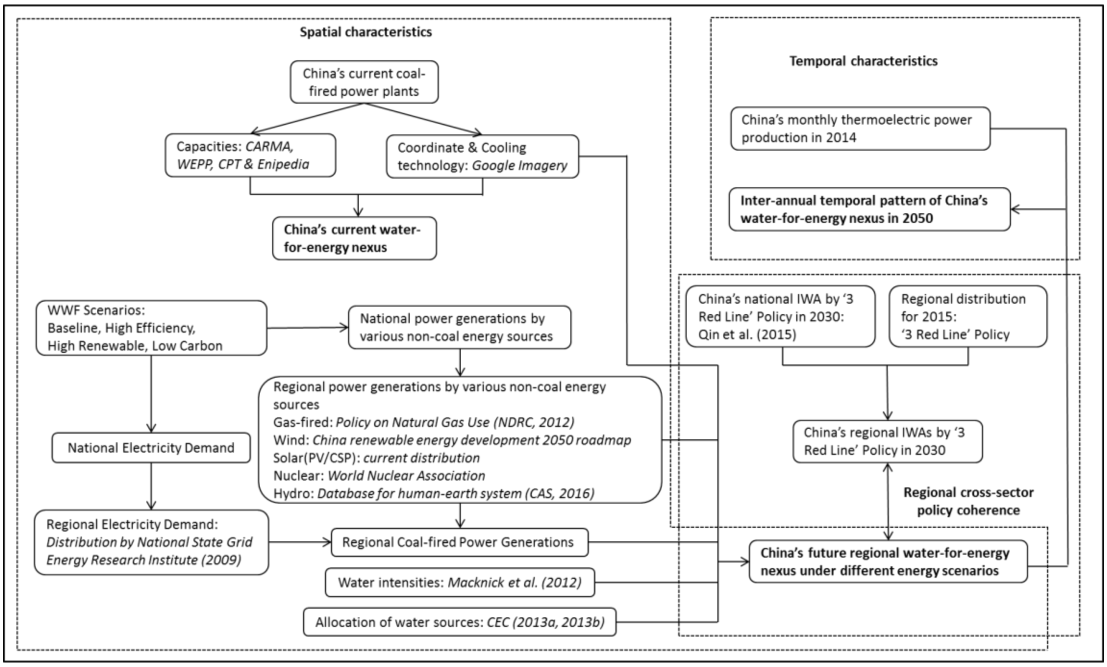

Figure 8 Approach and data framework

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 6.

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).

4.3 Results

4.3.1 Water use in China's thermoelectric power sector in 2014

Fig. 9 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.

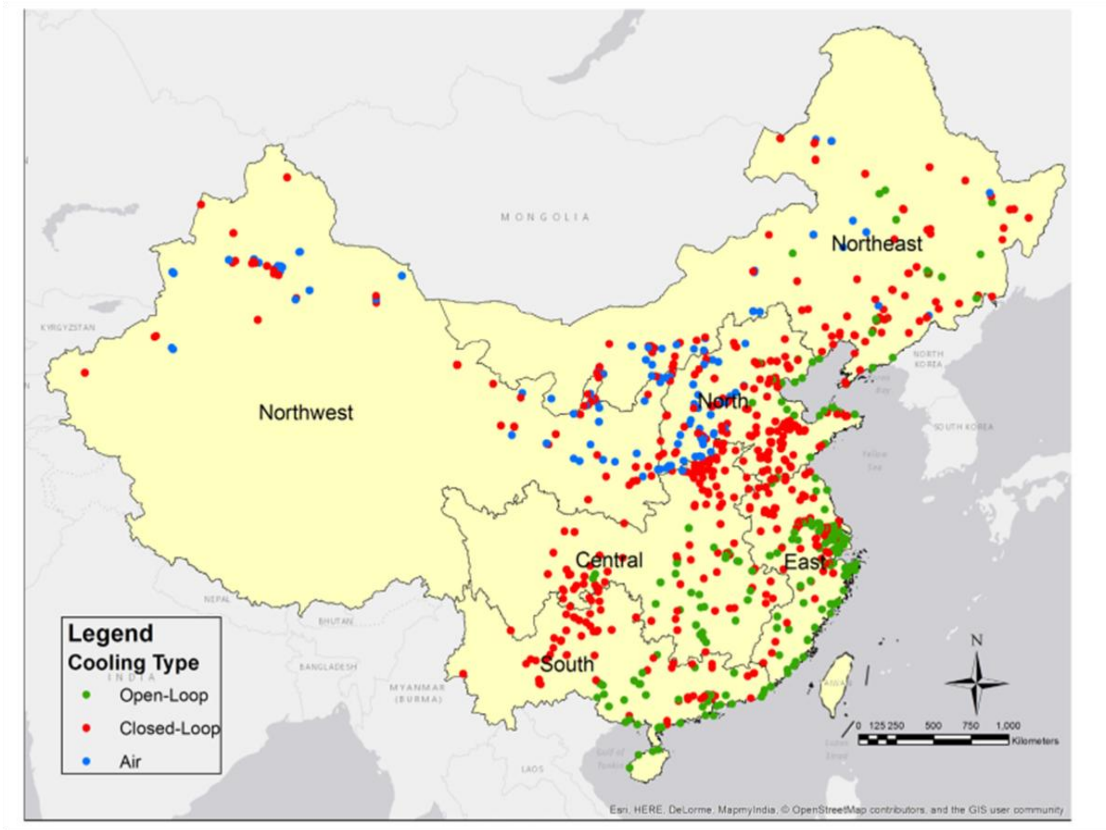

Figure 9 China's current coal-fired power plants with different cooling types

Water consumption from four sources (surface water, ground water, reclaimed water and seawater) by power generation in 2014 is presented in Fig. 10. Two major hot spots of surface water consumption can be identified in the Yellow River basin in northern China and the Yangtze River basin in eastern 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.

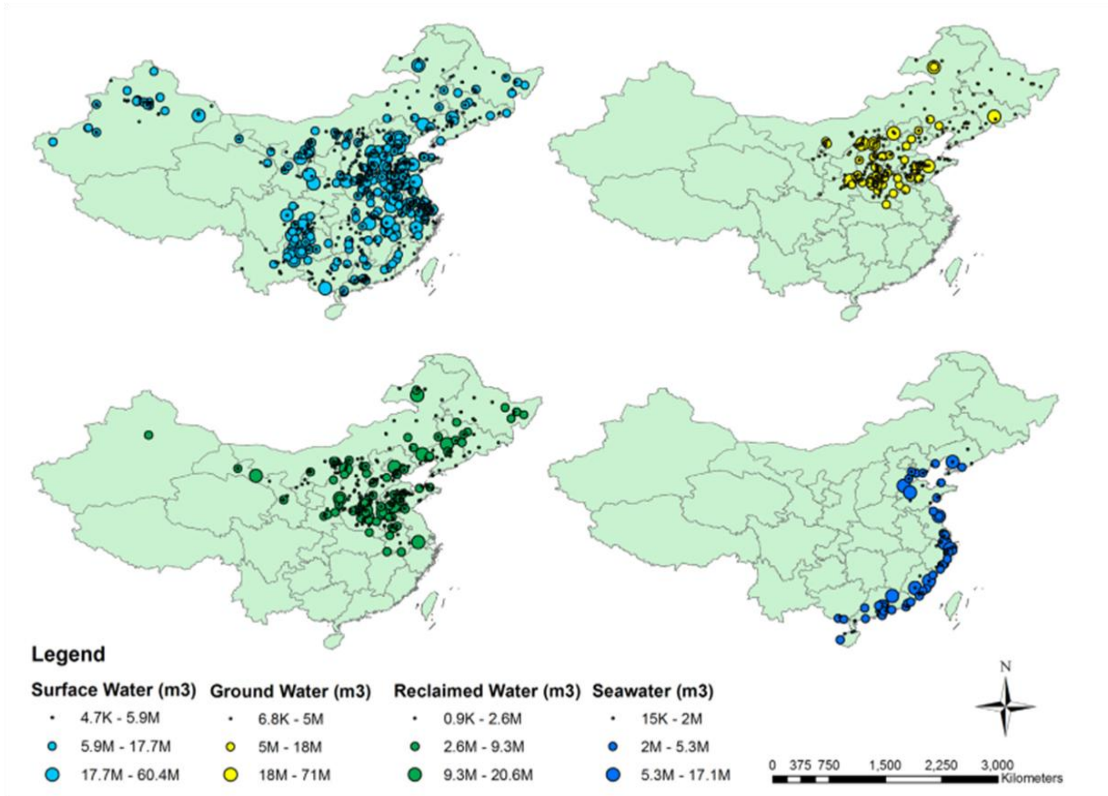

Figure 10 Power sector's water consumption of various water sources

The national surface water, reclaimed water and ground water consumption amount to 4.64, 0.79 and 1.05 billion m^3 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 billion m^3, is therefore proportionate to the generating capacities examined in each study.

4.3.2 China's future water demand by the thermoelectric power sector

4.3.2.1 National results

The results of scenario analysis of China's future fresh water use by the power sector are demonstrated in Fig. 11. Further information on reclaimed water and seawater uses in China's thermoelectric power sector is provided in the Supplementary materials on a regional scale.

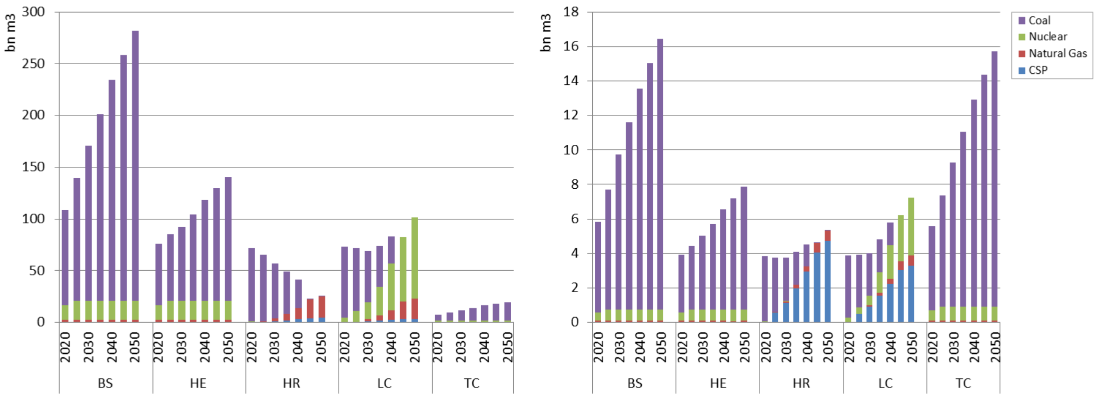

Figure 11 Fresh water withdrawal (left) and consumption (right) by China's thermoelectric power sector under different scenarios (billion m^3).

Significant increases in water withdrawal and consumption can be seen in the baseline scenario to over 280 and 16 billion m^3 respectively by 2050. Improving energy efficiency reduces the magnitudes of water withdrawal and consumption by over 50% to about 140 and 8 billion m^3 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 billion m^3 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.

4.3.2.2 Regional patterns

Fig. 12 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.

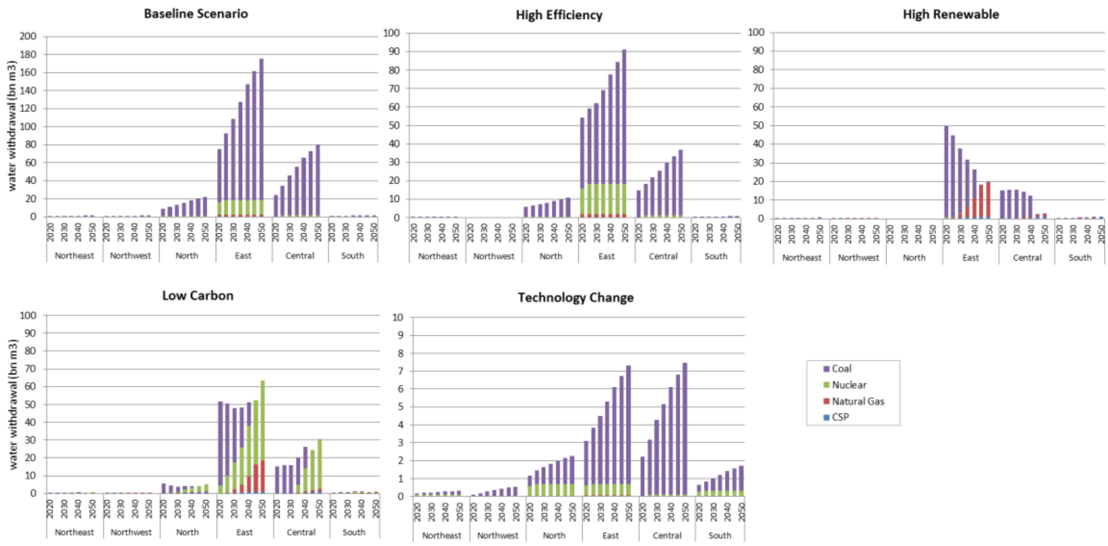

Figure 12 Regional surface water withdrawal under different scenarios (billion m^3)

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. 13. Under a baseline scenario, water consumption is the highest in north China at just below 6 billion m^3 in 2050 and the lowest in the northwest at about 0.73 billion m^3. 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.

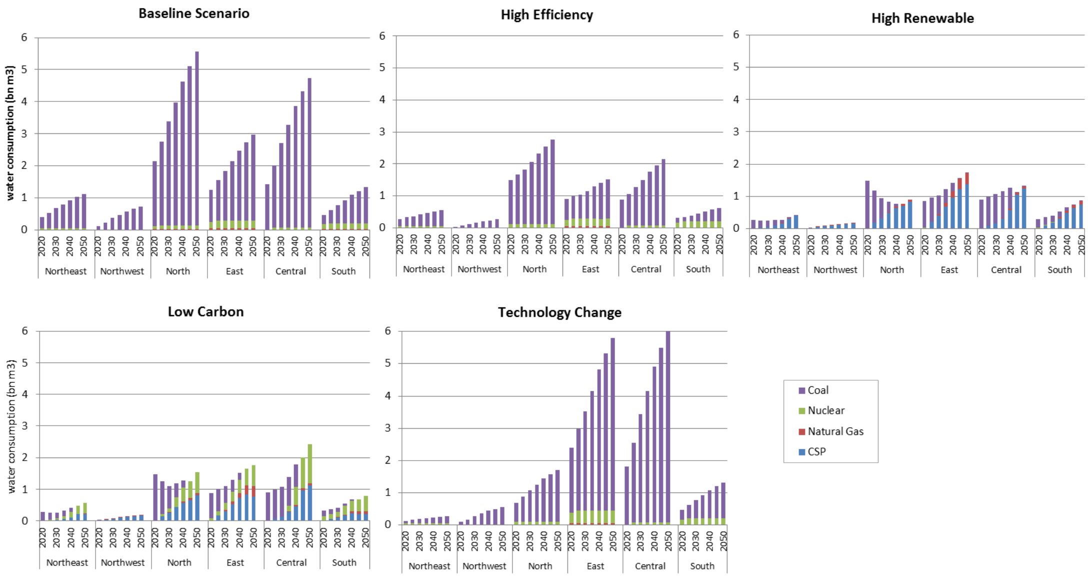

Figure 13 Regional surface water consumption under different scenarios (billion m^3)

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 billion m^3 under a baseline scenario to 5.80 billion m^3 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.

4.4 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. 14. 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.

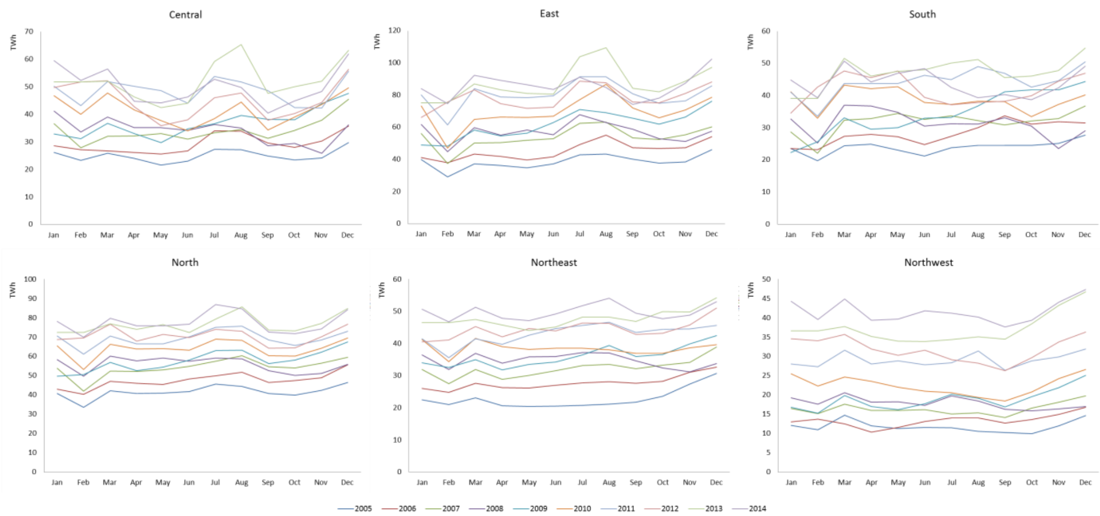

Figure 14 China's regional monthly thermal power productions from 2005 to 2014 (TWh)

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. 15 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 billion m^3 under a baseline scenario.

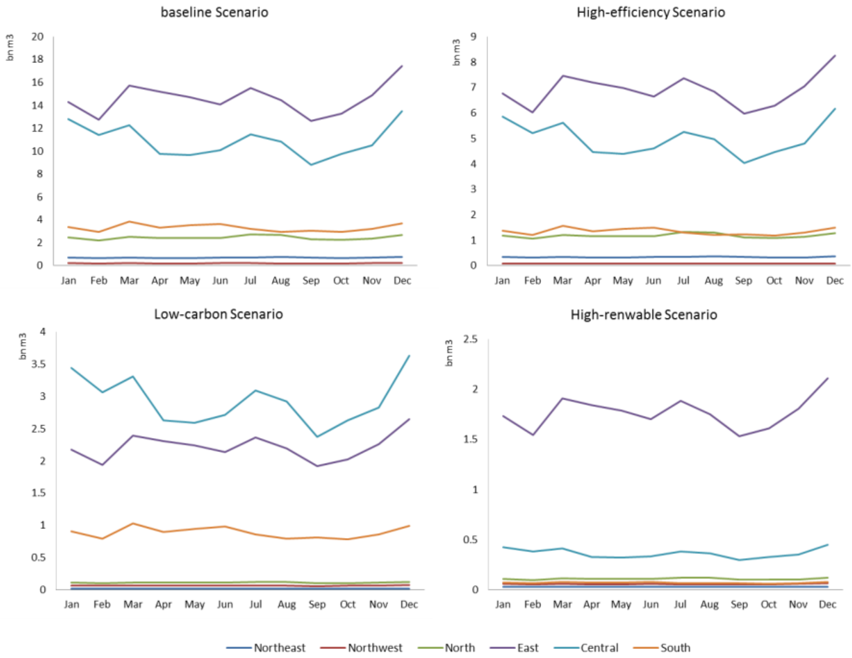

Figure 15 China's regional monthly water uses by power sector in 2050 (bn m^3)

4.5 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.

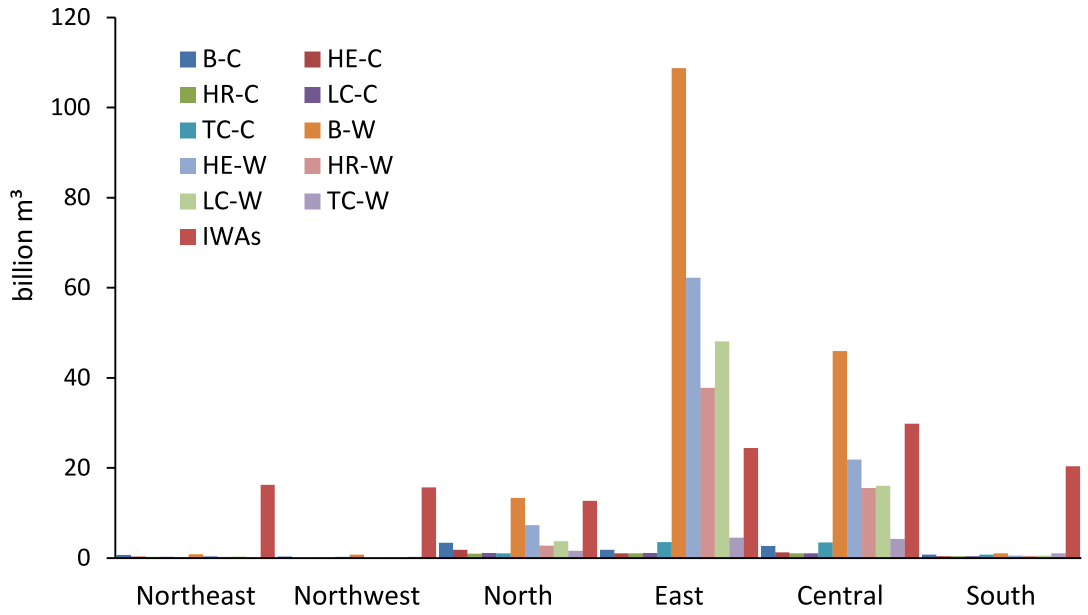

Figure 16 Comparison between regional water demands by power sector with water targets set by the '3 Red Line' policy in 2030 (W-Fresh water withdrawal in 2030; C-Fresh water consumption in 2030; B-Baseline Scenario; HE-High Efficiency Scenario; HR-High Renewable Scenario; LC-Low Carbon Scenario; TC-Technology Change Scenario; IWA-Industrial Water Allowed

The results in Fig. 16 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.

4.6 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 billion m^3 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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Supplementary materials:

S 4-1 Disaggregating China's future energy scenarios to different regions

China's future regional future portfolios can be estimated through the equations below:

(S4-1) $E_{demand,i} = E_{demand} * P_{demand,i}$

Where: E_{demand} is the national electricity demand which is given by WWF scenarios. $P_{demand,i}$ is the electricity demand percentage of Region i (including north, northeast, northwest, east, central, south), which can be accessed in National State Grid Energy Research Institute (2009). $E_{demand,i}$ is therefore Region i's electricity demand.

(S4-2) $E_{gas,i} = E_{gas} * P_{gas,i}$

Where: E_{gas} is the national gas-fired electricity production which is given by WWF scenarios. $P_{gas,i}$ is the gas-fired electricity production percentage of Region i, which equals $P_{demand,i}$ according to "gas-fired electricity should be developed according to the regional electricity consumption" (NDRC, 2012). $E_{gas,i}$ is therefore Region i's gas-fired electricity production.

(S4-3) $E_{PV/CSP,\,i} = E_{PV/CSP} * P_{PV/CSP,i}$

Where: $E_{PV/CSP}$ is the national solar PV or CSP electricity production which is given by WWF scenarios. $P_{PV/CSP,i}$ is the solar PV or CSP electricity production percentage of Region i, which is approximated by the current value. $E_{PV/CSP, i}$ is therefore Region i's solar PV or CSP electricity production.

(S4-4) $E_{wind, i} = E_{wind} * P_{wind,i}$

Where: E_{wind} is the national wind power production which is given by WWF scenarios. $P_{wind,i}$ is the wind power production percentage of Region i, which is given by "China renewable energy development 2050 roadmap" (Sino-Danish Renewable Energy Development Program, 2014). $E_{wind, i}$ is therefore Region i's wind power production.

(S4-5) $E_{nuclear, i} = E_{nuclear} * P_{nuclear,i}$

Where: $E_{nuclear}$ is the national nuclear power production which is given by WWF scenarios. $P_{nuclear,i}$ is the nuclear power production percentage of Region i, which is derived from "World Nuclear Association (2015). China's current, constructing, planned and proposed nuclear power plants are documented. We assume the growing capacity of nuclear power will be met according to this order. When the estimated capacity exceeds the total documented capacity, including current, constructing, planned and proposed nuclear power plants, we assume the further capacity will be met by expanding the capacities of existing plants instead of building new ones. $E_{nuclear, i}$ is therefore Region i's nuclear power production.

(S4-6) $E_{hydro,\ i} = E_{hydro} * P_{hydro,i}$

Where: E_{hydro} is the national hydro power production which is given by WWF scenarios. $P_{hydro,i}$ is the hydro power production percentage of Region i, which is in proportion to the hydropower endowments documented by the "Database for Human-earth System" of Chinese Academy of Sciences (2016). $E_{hydro,\ i}$ is therefore Region i's hydro power production.

(S4-7) $E_{coal.i} = E_{demand,i} - (E_{gas,i}+E_{PV,i}+E_{CSP,i}+E_{wind,i}+E_{nuclear,i}+E_{hydro,i})$

Where: $E_{coal.i}$ is the coal-fired power production of region i, which is used to meet the unmet electricity demand after supplying gas-fired, solar PV, CSP, wind, nuclear and hydro power.

S 4-2 China's current water consumption by coal-fired power plants by water source by region (bn m3)

Region	Surface water	Ground water	Reclaimed water	Seawater
Central	0.95961	0.263741	0.127018	-
East	0.855737	-	0.06794	0.10361
North	0.851781	0.481749	0.225032	0.04315
Northeast	0.613973	0.197354	0.259389	0.032218
Northwest	0.69322	0.110719	0.111378	-
South	0.667615	-	-	0.072036

S 4-3 Extrapolation of China's regional Industrial Water Allowances (IWAs) by "3 Red Line" policy

China's regional IWAs for 2030 can be extrapolated through the equation below:

(S4-8) $IWA_i = IWA*P_i$

Where: IWAi is the IWA of region I; IWA is the national total industrial water allowances by "3 Red Line" policy in 2030, which is given by Qin *et al.* (2015); P_i is the percentage of region i's IWA. As regional total water allowances for 2015 are given by "3 Red Line" policy, P_i can be approximated by the distribution in 2015.

Chapter 5. Water shortage risks in China's coal power industry under climate change

Based on "Liao, X., Hall, J.W., Naota, H., Lim, W.H. and Paltan, H. (Submitted to *Environmental Science & Technology*) Water shortage risks in China's coal power industry under climate change"

5.1 Introduction

Thermoelectric power generation, which meets more than 60% of global electricity demand, uses significant volumes of water, primarily to cool steam turbines (Gleick 1994). Water withdrawn by thermoelectric power plants is responsible for over 40% and 50% of the total freshwater withdrawal in the EU and US respectively (United Nations 2014). In China, thermoelectric power plants account for over 70% of the country's total electricity production and over 10% of the national freshwater withdrawal (Liao et al. 2016). Such close interdependency means that power provision can be exposed to and disrupted by water-related risks, for example reduced water availability and increased water temperature during low flows (van Vliet et al. 2012), which has been documented throughout the world (McCall et al. 2016) and raises growing concerns in the energy sector.

Climate and hydrological models help us better anticipate and prepare for the future contingencies of such risks. For example, Van Vliet et al. (2012) showed a 6.3-19%

and 4.4-16% capacity decrease for European and American power plants respectively during summers for the period between 2013 and 2060. Furthermore, they found that over 80% of global thermal power plants' annual usable capacity can be reduced due to climate change during the period from 2040 to 2069. Zhou et al. (2018) estimated a similar trend by incorporating changes in water demand by thermal electric power production.

China may face particularly pronounced challenges in this regard because of its electric power sector's substantial and growing demands as well as its significant reliance on thermoelectric power plants that are prevalently located on inland waterways. The risks are further aggravated by China's uneven temporal and spatial distributions of water resources (Zhang and Anadon 2013; Ye and Zhang 2013), as well as their mismatch with energy reserves. For example, Northern China is endowed with coal and has large capacities of coal-fired power plants, yet on the other hand, it is not rich in water and has thus been identified as facing the highest water risks for power generation in the world (Sadoff et al. 2015). Zheng et al. (2016) conducted a high-resolution (0.5^{o}) quantification of China's thermoelectric power plants future vulnerability to water scarcity and pointed out that it would increase in the Northwest by 2030. However, their work has four significant drawbacks: (1) they acquired water withdrawal data from aggregate statistics whose quality can be improved by using plant-level water-using technology data; (2) water withdrawal of each geographical cell was calculated by adding up all power plants' water withdrawals. That may overestimate the vulnerabilities because the water withdrawal of upstream power plants can be returned to the water body and reused by downstream power plants within the same half-degree geographical cell; (3) the quantification was conducted annually therefore risks on shorter timescales may be overlooked; (4) water availability data were calculated from the Variable Infiltration Capacity (VIC) hydrological model (Liang et al. 2994) that does not take into account other anthropogenic water interventions, e.g. agriculture, domestic and reservoir operation, therefore water available for thermoelectric power production was overestimated.

Against this backdrop, we assess the current and future (2050s) water shortage risks (hereinafter used interchangeably with water risks) facing China's thermoelectric power plants at a plant level and a monthly basis. Water risks for thermoelectric power plants' are defined as circumstances where their water availability falls short of their water demand. Water demand is calculated based on plant-level technology data. Water availability is simulated on a 0.5^{o} x 0.5^{o} spatial resolution with a hydrological model H08 that incorporates agriculture and domestic water uses, as well as reservoir operations. Because plants are identified individually, the return flows of cooling water are adequately accounted for within each 0.5^{o} x 0.5^{o} cell.

5.2 Results

5.2.1 Climate change impacts on China's water resources

Figure 17 (a) and (b) demonstrate the average of monthly mean stream flow and monthly 10-year return low flow respectively during the base period (1981-2014). The spatial patterns of the monthly mean flow and 10-year return low flow overlap largely. It can be seen that Southern and Northeastern China are endowed with relatively rich water resources. Large areas in provinces in the north and northwest, namely, Xinjiang, Ningxia, Gansu, Shaanxi, Qinghai and Inner Mongolia have very low stream flow values.

The changes of the monthly mean stream flow and monthly 10-year return low flow between the base period and future period 2050s (2035-2065) under the RCP 2.6 scenario are demonstrated in Fig. 15 (c) and (d) respectively. The results of ensemble mean of five ISI-MIP GCMs are demonstrated. Both monthly mean flow and monthly 10-year return low flow are projected to increase significantly in most part of Northern China and decrease significantly in the inland river basin in northwestern China and slightly in southern China. There is no apparent difference in the simulated flow regimes found between the two future periods, 2030s and 2050s, or the two emission scenarios, RCP 8.5 and RCP 2.6.

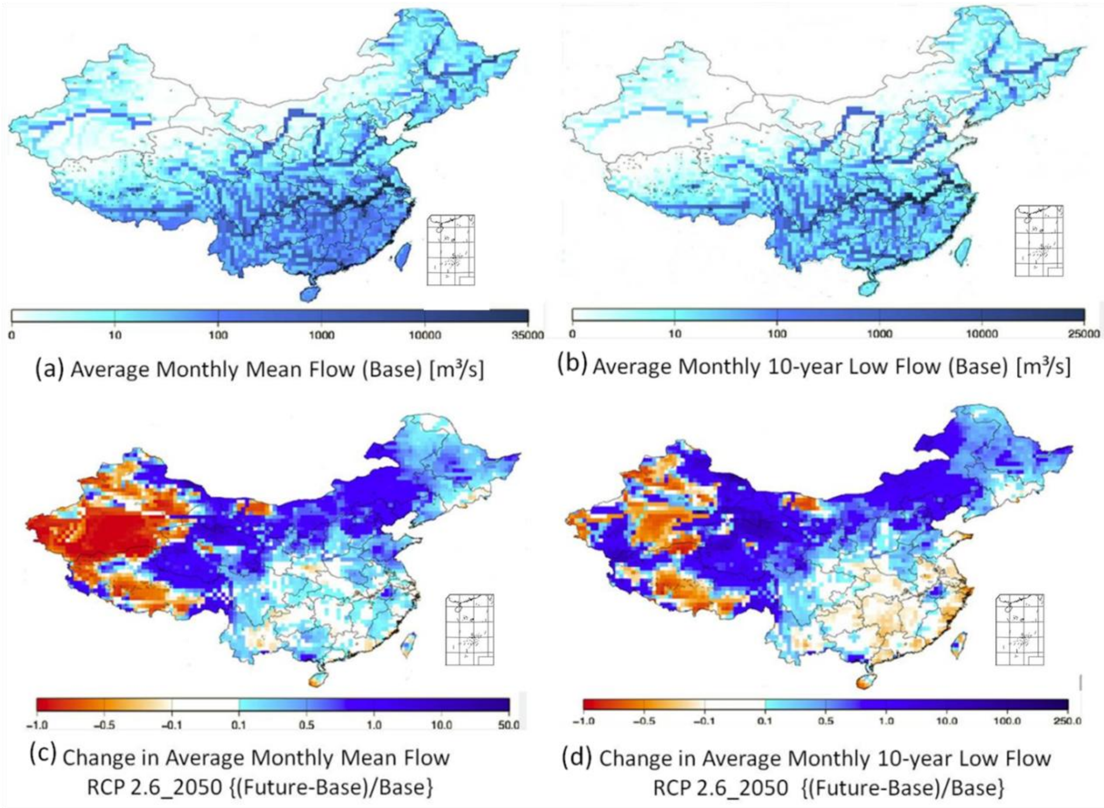

Figure 17 Average monthly mean flow and average monthly 10-year return low flow during the base period (1981-2014) (Upper); Changes in monthly mean flow and monthly 10-year return low flow between the base period and the future (2035-2065). The results of ensemble mean of five ISI-MIP GCMs are shown.

Hydrographs of the 10-year return low flow at four selected stations in China's four driest river basins, namely, Yellow, Huai, Hai and Inland River Basins, that are all located in the north and northwest, are demonstrated in Fig. 5-2. It can be seen that, overall, wetter future conditions projected by the GCMs are expected to increase the mean water availability during low flows in the four river basins. The changing climate, at the projected time scale and for these analyzed scenarios, is not expected to alter the seasonal variability of river flows in these basins significantly. The driest month in the Huai and Inland River Basin is January and February respectively, and May in both Hai and Yellow River Basin.

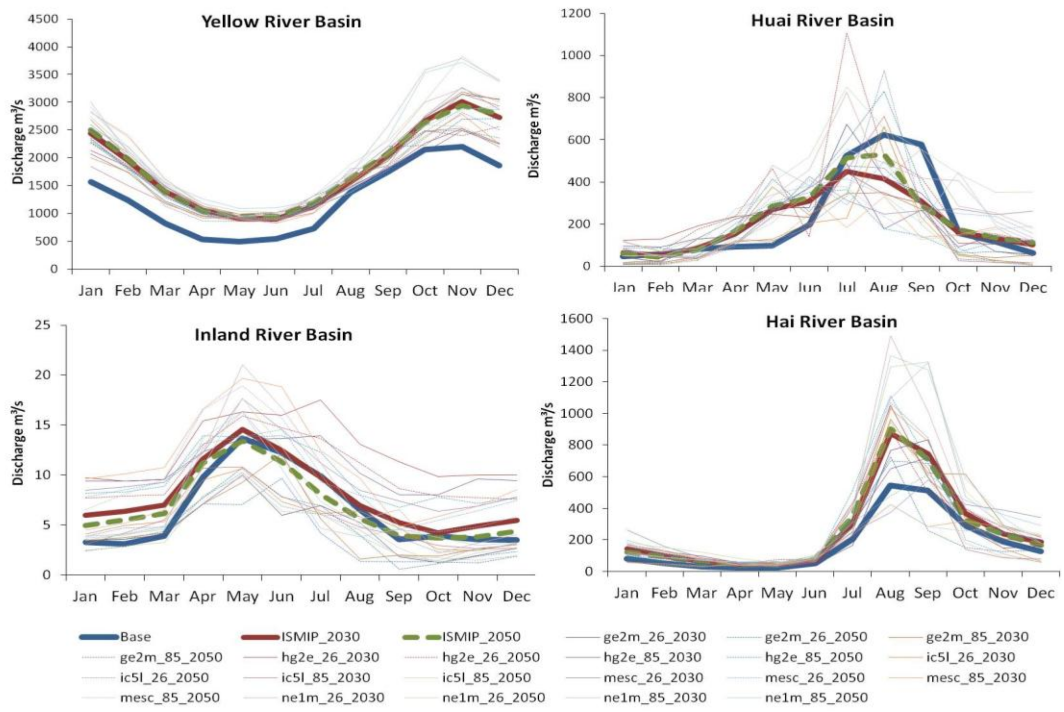

Figure 18 Monthly 10-year return low flow regimes in China's four driest river basins during the base period (1981-2014) and future periods, 2030s (2015-2045) and 2050s (2035-2065). The results of five ISI-MIP GCMs are shown.

The availability and variability of China's future river discharges simulated in this study agree with the study of Leng et al. (2015) that focuses on China's future surface water change using the VIC model that does not consider any human interventions.

5.2.2 Water risks for coal power industry in China

5.2.2.1 Current low-flow water risks for China's coal power industry

At any given site of a power plant, if the water available during 10-year return low flow is not enough to meet the water withdrawal demand by the power plant, we consider the power plant facing low-flow water risks. Our results indicate that, during the base period, as shown in Fig. 19, over 50% of power generation capacities, whose aggregated capacity is larger than 100 GW, in the north are facing low-flow water risks if surface water is the only water source available, i.e. no groundwater utilization nor reclaimed water use (coal power plants close to the coast are excluded from this study). According to China Electricity Council (2013a,b), 16.2% and 12.2% of China's coal power plants' current water uses are groundwater and reclaimed water respectively. Nationally, about 30% of power generation capacities face low-flow water risks in April and around 10% face low-flow water risks from July to October. These risks are concentrated during the winter NDJ (November, December and January) and spring FMA (February, March and April) seasons because (1) due to the monsoon repercussions in the region, water availability is lower during NDJ and FMA throughout the whole China; (2) electricity water demand is higher during these two seasons because household require higher electricity consumption for heating purposes. It should be noted that although the water intensity (both withdrawal and consumption) for power generation varies by season due to different water and air temperatures, we do not take such heterogeneity into account in this study. During colder times, water intensity decreases because its cooling efficiency increases. Therefore, the differences between water risks in winter/spring seasons and summer/autumn seasons are overestimated.

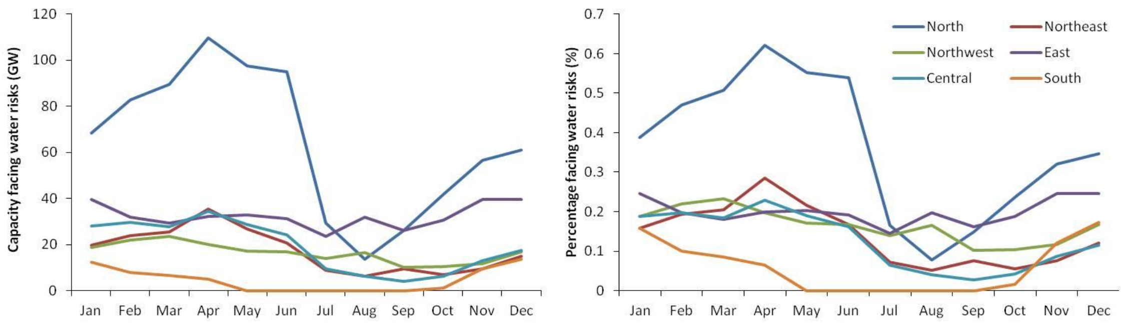

Figure 19 Monthly low-flow water risks for China's regional coal power plants

During the base period, Northern China faces the highest water risks for its power generation in April (Fig. 20). It can be seen that such risks are concentrated in the Jing-Jin-Ji mega region. While the risks for Southern China peak in December and mainly concentrate in the Yangtze Delta region. The Jing-jin-ji and Yangtze Delta mega regions are China's two biggest and fastest growing urban agglomerations. They are home to 111 and 158 million people respectively, of which the urban population represents 62.5% and 69.8%. In 2016, these two regions generated over 10% and 20% of national GDP respectively (National Bureau of Statistics 2016).

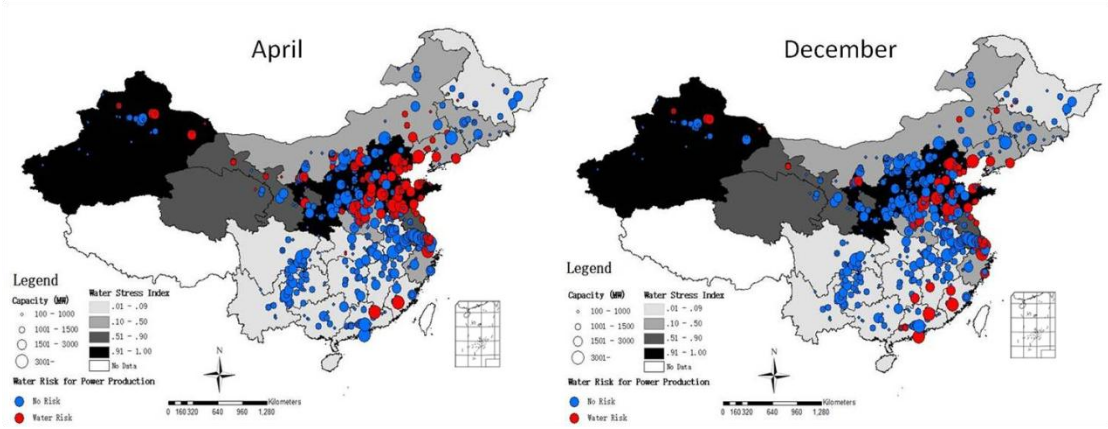

Figure 20 Low-flow water risks for coal power industry in China's northern and southern regions are the highest in April and December respectively

Although closed-loop cooling systems have higher capital cost and lower cooling efficiency than open-loop ones, because Northern China is water-scarce, closed-loop cooling systems that require relatively small water withdrawals are prevalently used in the north. Water risks in the north are therefore mostly due to low water availability as cooling technologies already seek to minimise water use. Power plants switching to air cooling systems can reduce their water risks. However, air cooling systems result in higher energy and emission penalties because of their low cooling efficiency (Zhang et al. 2014). In comparison, water risks in the south are primarily demand driven. Located at the mouth of the mighty Yangtze River, coal power plants in the Yangtze Delta megalopolis predominantly employ open-loop cooling systems where a large amount of water needs to be available for power plants withdrawal.

5.2.2.2 Climate change impacts on the low-flow water risks for China's coal power industry

As it can be seen from Fig. 21, the wetter conditions projected to the area are expected to attenuate low-flow water risks in China's coal power industry since water availability is widely increased. Only in the northwestern Inland River Basin, climate change is expected to intensify low-flow water risks in the coal power industry from May to August unless the utilization rate of coal power facilities is lowered. Yet, an additional 5 to 10 GW of coal power facilities within this region will risk not having enough water for cooling during summer months if their utilization rate is kept the same or increased.

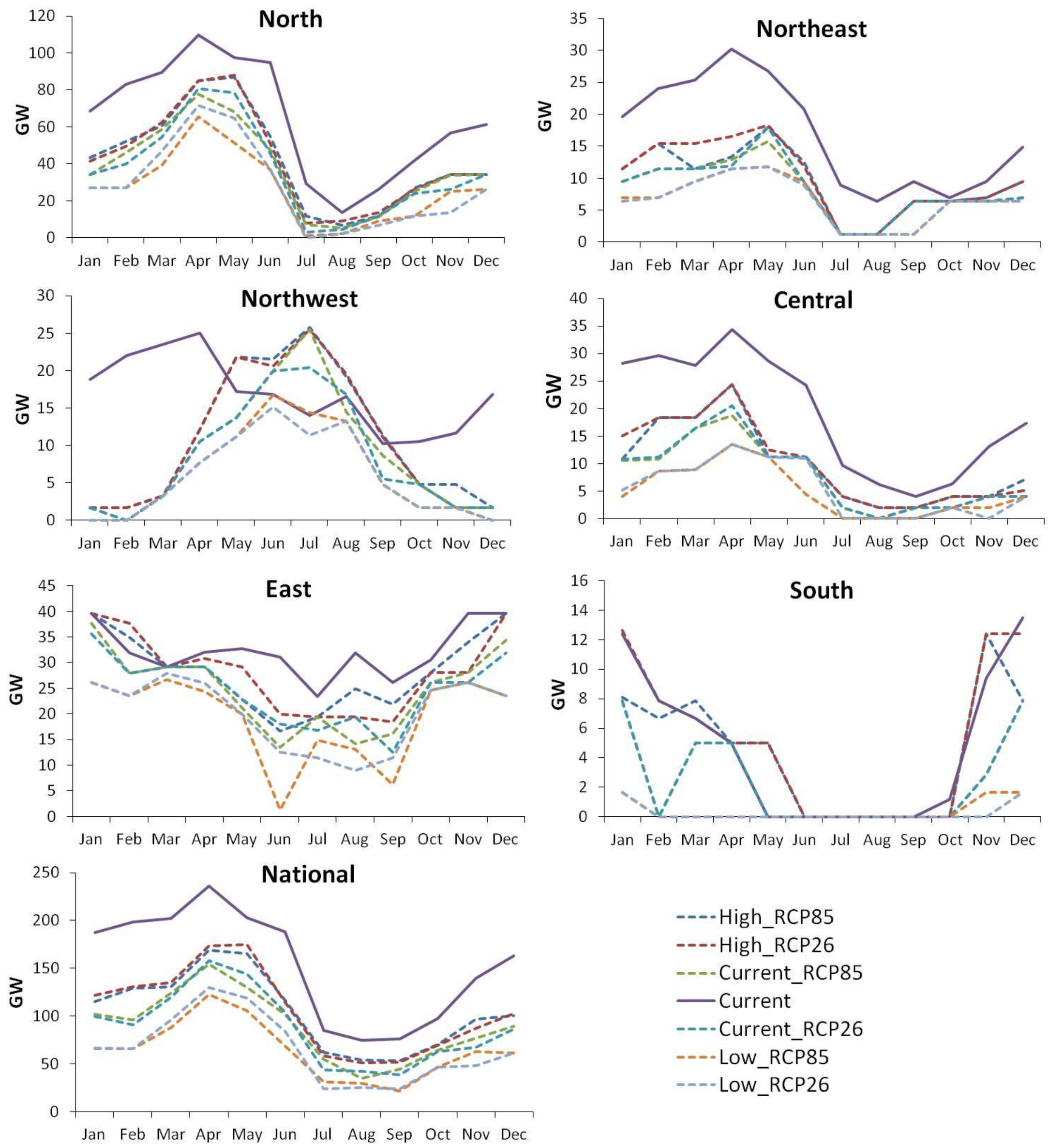

Figure 21 Capacity of China's coal power plants facing low-flow water risks during the base (2000s) and future (2050s) periods

Moreover, in the east and south, if the utilization rates of their coal power plants are increased, for example, under circumstances where their increasing regional electricity demands remain highly dependent on coal, their coal power plants are expected to face heightened risks of low river flows not being enough to meet their withdrawal demands, in February in the east and in March and November in the south. Power plants are threatened to curtail their production and at the risk of not getting their cost recovered. Retrofitting open-loop cooling systems to closed-loop ones in the south and east is an effective investment to reduce their corresponding water risks and potential economic lost.

5.3 Conclusion and discussion

In order to understand if there are potential water shortage risks for China's electric power sector, especially under future climate change, and if there are, what are the spatiotemporal characteristic of such risks, we simulated China’s monthly river discharges on a 0.5° × 0.5° spatial resolution using a calibrated global hydrological model H08 that incorporates human interventions during the current period (1981-2014) and future period 2050s (2035-2065) under two carbon emission scenarios RCP 2.6 and 8.5. We then identified the spatiotemporal pattern of low flow water risks for China’s coal power plants, which is defined as the 10-year return low flow in the river falling short of power plants’ water withdrawal requirements. We found that (1) around 10% of China’s coal-fired power capacity is facing low flow water risks from July to October, and 20% the rest of the year. Particularly in the north, 40% to 60% of its regional coal-fired power capacity is at risks of not having enough water for cooling purposes from February to June; (2) global climate change would alter the water availability in China through changing precipitation and evaporation patterns. Available water in the river system would increase significantly in the current dry north and decrease significantly in the northwest and slightly in the south; (3) climate change would alleviate the water shortage risks facing China's coal power plants except in the northwest Inland River Basin. In the east and south, if their growing electricity demands continue depending on coal, increasing utilization rate of coal power facilities could lead to the increase of demand-driven water risks.

However, while climate change may alleviate the impacts of low flows in the coal power sector, rising global temperatures are thought to importantly impact regional high flows and floods. Hu et al. (2015) pointed out that China's power infrastructures are also vulnerable to flood risks, which is likely to increase under climate change (Paltan et al. 2018). Apart from water availability and variability, climate change would also affect the power sector's water uses and risks through other mechanisms: warmer stream flows and increased electricity demand due to warmer weather are two prominent examples. Van Vliet et al. (2012, 2016) found that thermoelectric power plants' usable capacity can be reduced due to higher stream flow temperature combined with regulations on power plant's discharge water temperature. Moreover, possible warmer weather and increased heat waves will increase household electricity demands for air conditioning. These two effects both contribute to potentially heightened water risks in the electric power sector.

In this study, we assumed surface water is the only available water source for inland coal power plants. It overestimated their current water risks because other water sources could also be utilized. For example, thermoelectric power plants in the north commonly rely on ground water, reclaimed water from industrial and municipal wastewater as well as reservoirs. However, utilization of groundwater by newly built coal power plants is outlawed since 2004 (National Development and Reform Commission 2004). Using reclaimed water incurs higher cost. Our study constitutes a baseline study for further cost comparison between curtailing power production due to surface water shortages and using reclaimed water. In the south, it has also been reported that, due to drought situations, many power plants with open-loop cooling systems have faced water shortage problems (China Electricity Council 2012).

As renewable energies, i.e. Solar PV and Wind, require negligible amount of water for on-site use, changes in power generation technologies has offset the increase of water use in China's electric power sector (Liao and Hall 2018). This study showed that, without transformation on power supply technologies, if China's growing electricity demands continue to rely on coal, even with our projected increase in water availability, coal-fired power plants might encounter higher water risks, especially in the northwest, south and east, in the future, though elsewhere cooling water risks might decrease.

It needs noticing that while this study showed that water risks for coal power generation is particularly dire in the northwest China, previous work has pointed out that, electricity production as well as its embodied water consumption in the northwest has been transmitted to support the relatively developed coastal regions in the east (Zhang et al. 2017; Liao et al. 2018). Similar to the case of the US (Wang et al. 2017), water shortages in the northwest can engender impacts beyond its boundaries on electricity-consuming activities, from household to industrial uses, in the more developed and populated regions. Such trans-boundary effects would magnify with China's ongoing efforts on building more electricity transmission infrastructures and increasing the electricity sector's connectivity (National Energy Administration 2014; National Development and Reform Commission 2016).

5.4 Methods and models

5.4.1 Water availability for thermoelectric power plants

5.4.1.1 Hydrological model

We use a hydrological model H08 (Hanasaki et al. 2008a,b) to simulate water available for thermoelectric power plants cooling use, which equals natural river discharge deducting agriculture and domestic withdrawals while also taking reservoir operation into account. The H08 model consists of five primary modules: (1) The Land Surface Module calculates the energy and water balances at the land surface level, and estimates hydrological variables such as evapotranspiration, soil moisture, and runoff; (2) The River Routing Module transports runoff through a digital river network in order to estimate gridded river flows; (3) The Crop Growth Module estimates irrigation water requirements and (4) Water Abstraction Module represents water abstraction for agriculture and domestic uses; (5) Finally, the Reservoir Module simulates reservoir operations. Further detailed description of these modules can be found in Hanasaki et al. (2008a,b). This national simulation on China is conducted on a 0.5° × 0.5° spatial resolution at a daily interval. Daily gridded global climate data of Weedon et al. (2014), including surface pressure, rainfall, snow fall, wind speed, long-wave downward radiation, short-wave downward radiation, specific or relative humidity and air temperature, are used as inputs. From here, the monthly average results are presented and analyzed.

Calibration and validation

First, we obtain river discharge data of 35 stations in China from the Global Runoff Data Centre (GRDC) (The Global Runoff Data Centre 2017). For calibration and validation processes, we select 22 gauging stations where monthly data of the longest overlapping period, 1981-1986, are available. These 22 stations are located in six major river basins in China (Table 1).

For calibration, a natural hydrological simulation (land surface module and river routing module) on China is conducted with 864 combinations of four key parameters, soil depth (SD), Drug Coefficient (CD), the shape parameter γ and the time constant τ for subsurface flow generation (GAMMA and TAU), from predetermined ranges (for more details see Hanasaki et al. 2014). Human interventions are not included for calibration due to computational capacity and time limitations. The optimal set of parameters is estimated according to the Nash-Sutcliffe Efficiency test (Nash and Sutcliffe 1970) at each station against the monthly observational records at the 22 gauging stations from January 1981 to December 1983. In order to better capture low flows, the test is performed on the log transformed flows (NSE_{log}). Observation data is not naturalized due to lack of reliable water use data, which is a deficiency in our approach, because it means our framework cannot be used to analyse the effects of changing water withdrawals in future, but it is a reasonable approach to estimate water shortage risks assuming constant withdrawals. From this evaluation, the NSE_{log} of the optimal parameter set is found to be greater than zero in all 22 gauging stations as shown in Table 7.

Table 7 Calibration (1981-1983) and validation (1984-1986) results against monthly discharge data at 22 gauging stations using NSE_{log} and NBIAS

GRDC ID	Basin	NSE_{log} _Calibration	NSE_{log} _Validation	NBIAS _Validation	GRDC ID	Basin	NSE_{log} _Calibration	NSE_{log} _Validation	NBIAS _Validation
2106500	HRB	0.523	0.766	0.007	2181900	YTRB	0.549	0.288	0.013
2106600	HRB	0.052	-0.088	-0.027	2182050	YTRB	0.179	0.490	0.020
2180400	YRB	0.609	0.551	-0.030	2182100	YTRB	0.892	0.866	-0.004
2180500	YRB	0.100	-0.062	0.042	2182250	YTRB	0.738	0.600	0.016
2180711	YRB	0.426	0.238	0.020	2180800	HUB	0.213	-0.438	0.033
2180750	YRB	0.717	0.539	-0.058	2181950	HUB	0.823	0.826	-0.036
2181200	YTRB	0.768	0.705	0.013	2181951	HUB	0.847	0.440	-0.068
2181300	YTRB	0.649	0.770	0.007	2178200	SRB	0.877	0.814	-0.018
2181500	YTRB	0.205	0.009	0.003	2186800	PRB	0.825	0.907	-0.001
2181600	YTRB	0.629	0.564	0.002	2186900	PRB	0.874	0.866	0.002
2181800	YTRB	0.670	0.560	0.003	2186950	PRB	0.825	0.559	-0.005

Criteria	**Station No.**	**Criteria**	**Station No.**	**Criteria**	**Station No.**
$NSE_{log}>0$	19	$NSE_{log}>0.5$	14	$-0.2<NBIAS<0.2$	22

Note: HRB – Heilongjiang River Basin; YRB – Yellow River Basin; Yangtze River Basin – YTRB; Huai River Basin – HUB; Southeast River Basin – SRB; Pearl River Basin – PRB

For validation, river discharge is first simulated taking irrigation and domestic water uses into account as well. The simulated monthly discharge data from 1984 to 1986 are validated at the 22 gauging stations based on NSE_{log} and Normalized Bias of Mean Annual Discharge (NBIAS) (Details see Hanasaki et al. 2008b). The results are presented in Table 1. All stations met the criteria for NBIAS. NSE_{log} agreed with the criteria for 19 of the 22 gauging stations, among which, 14 had NSE_{log} value larger than 0.5.

42 large reservoirs (e.g. location, capacity, surface area) with > 1 km^3 capacity in

China are included in the simulation. The storage and release of these reservoirs are controlled by the generic reservoir operation algorithm implemented in H08 (Hanasaki et al. 2008a). It can be seen from Fig. 22 that incorporating reservoir operation improves NSE_{log} performance at station 2106600 (Heilongjiang River Basin) from -0.088 to 0.319 (Hydrograph is demonstrated as Figure 1). It should be noted that two stations in the Yellow River Basin still fail the NSE_{log} test even with reservoir operation module enabled, which implies the need, in future studies, to incorporate more observational data for this one of the most developed basins in the world.

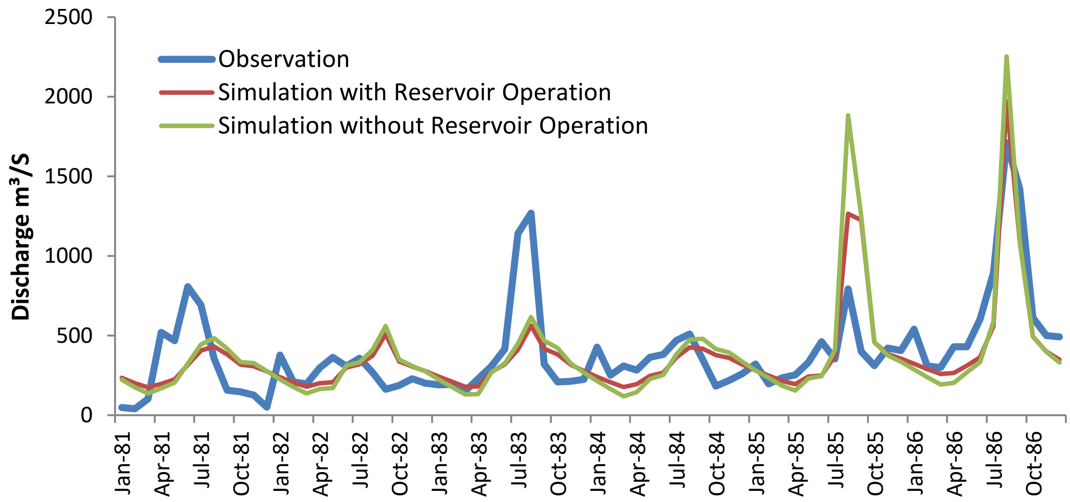

Figure 22 Hydrographs of the simulations with and without reservoir operation against the observation data at station 2106600 (Heilongjiang Basin) for the period from January 1981 to December 1986

5.4.1.2 Future climate projections

In order to simulate China's future river discharge in the 2050s (2035-2065), we use the bias-corrected meteorological forcing data from 5 General Circulation Models (GCMs) provided by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): HadGEM2-ES, GFDL-ESM2M, IPSL-CM5A-LR, MIROCESM-CHEM, and NorESM1-M (Hempel et al. 2013). ISI-MIP aims to quantify the uncertainty in projecting climate change impacts on water and other sectors using a minimal setting that covers uncertainties in climate models and climate scenarios. According to McSweeney and Jones (2016), these five ISI-MIP GCMs adequately capture the inter-quartile range of the climate uncertainties embodied in the entire CMIP5 models over the continental China. Two emission scenarios are selected: Representative Concentration Pathways (RCP) 2.6 and 8.5, in which the anthropogenic radiative forcing equals 2.6 and 8.5 W m^{-2} by 2100, respectively (IPCC 2014). We select these two scenarios because they correspond to low emission and high emission scenarios in the future and represent the widest range of climate outcomes.

5.4.2 Water demand by thermoelectric power plants

Thermoelectric power plants are used interchangeably with coal-fired power plants in this study because (1) we do not have information on gas-fired power plants in

China; (2) gas-fired power generation only provides less than 4% of the thermoelectric power generation in China (China Electricity Council 2015). We exclude power plants that are located on the coast, so likey to use sea water for cooling. Water use at coal-fired power plants can be quantified by multiplying their generational outputs (MWh) and water intensity, measured as water use per unit of electricity produced (m^3/MWh). Water use includes both water withdrawal and consumption. Water withdrawn initially from but not discharged back to the river system is defined as water consumption (AQUASTAT 1998). Power plants' generation output is the product of power plants' capacity (MW) and annual running hours (h). Different types of cooling technologies dictate coal power plants water intensities (Macknick et al. 2012): Air-cooling has the least water use; open-loop cooling systems use running water and have larger water withdrawal but less water consumption compared to closed-loop cooling ones because the latter use re-circulated water. We recap on our previous work that compiled the capacity and cooling technology of China's over 2300 coal-fired Electricity Generation Units (EGU) whose aggregate capacity amounts to 870 GW, which equals to about 96.7% of the nation's total in 2015 (Liao et al. 2016). Because China's unique dispatch mechanism tries to assure all EGUs have the same running hours (The Regulatory Assistance Project 2016), we assume all EGUs within the same province have the same annual running hours. The current coal power plants water demands are calculated based on the provincial running hours in 2015. The future utilization of coal power plants in

China depends on many social-economic factors, including future energy demand, capacity of new power plants built, generation and cooling technologies adopted for new plants and the decommissioning of old plants. Its estimation requires further elaborate work that is beyond the scope of this study. We introduce three simple scenarios of coal power plants' different utilization rates in the future. Under the Business As Usual (BAU) scenario, coal power plants will have the same annual running hours in each province as in 2015. Under the High utilization scenario and Low utilization scenario, power plants will have 60% and 140% of the BAU running hours respectively. Low utilization scenario encompasses potential future scenarios where China reduces its dependence on coal and transforms to other energy sources, e.g. hydro, nuclear and renewable; High utilization scenario corresponds to potential future scenarios where China's increasing high electricity demand will still be met by coal power facilities primarily.

5.4.3 Water risks for coal power plants in China

We define that if the simulated monthly 10-year return low flow (monthly stream flow value that is exceeded 90% of the time in the same month) in the rivers falls short of the power plants water withdrawal demand, the power plants are considered as facing water risks. Agricultural and domestic water uses are deducted from the natural river flows to acquire water available for coal power plants, which is to say coal power production has priority over other industrial water uses. Reservoir operation is also incorporated in our simulations. If there is more than one power plant located within the same geographical cell, water available for downstream power plants equals water available for upstream power plants minus the upstream power plants' consumptive water uses.

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Chapter 6. Categorising virtual water transfers through China's electric power sector

Based on "Liao, X., Zhao, X., Hall, J.W. and Guan, D. Categorising virtual water transfers through China's electric power sector. *Applied Energy* 226: 252-260"

6.1 Introduction

While electric power is crucial to modern human society's development and prosperity, production of electricity uses another essential commodity, i.e. water (Gleick 1994; Macknick et al. 2012; Meldrum et al. 2013). Episodic water-related issues have curtailed power production around the globe (McCall et al. 2016). With water being recognized as the top global risk facing humanity over the next decade (World Economic Forum 2015), water challenges for the energy sector are set to intensify (Howells and Rogner 2014).

Although water is required throughout the life cycle of electricity production, the operational phase plays a dominant role (Meldrum et al. 2013; Fthenakis et al. 2010; Zhang and Anadon 2013). Apart from some forms of renewable electricity production, e.g. solar PV and wind, which require negligible amounts of on-site water inputs, many studies have shed light on the water uses for thermoelectric power production, primarily for cooling purposes, on global, national and regional scales

(Vassolo and Doll 2005; Byers et al. 2014; Zhang et al. 2016; Liao et al. 2016; Hu et al. 2012). However, little work has been done to reveal how the physical water inputs to the electric power sector in one region turn into virtual water embodied in the power produced traversing geographical boundaries and then being used by different sectors, e.g. households, industries, in another region.

Virtual water refers to water used for the production of goods and services, which can then be transferred among economic sectors and regions through trade (Liu et al. 2015; Feng et al. 2011). Studies of virtual water provide insights into how production, trade and consumption in other regions and sectors can exacerbate or alleviate over-exploitation of water resources (Allan 1993; Vorosmarty et al. 2015). However, existing studies quantifying sub-national virtual water fluxes within China's electric power system have adopted a production-based bottom-up approach (Zhu et al. 2015; Guo et al. 2016; Wang et al. 2017; Zhang et al. 2017). Their work failed to address the inter-sectoral contributions among the final electricity users. Incorporating insights from a consumption-based perspective analyzing virtual water embodiments in the electric power consumed by different sectors can help to provide a more complete picture of the water footprint of different sectors and of the geographical fluxes of virtual water. Furthermore, although Liu et al. (2015) have shed light on the water consumption in China's hydroelectric power plants and pointed out that they have a higher water consumption factor, measured as water consumption per unit of electricity produced, than other types of electricity production, hydropower production's water consumption has not been examined on a provincial scale.

We propose a framework that maps out the water flows related to the power sector, from physical water inputs to virtual water embodiments:

1. To produce electricity, physical water is directly consumed in (i) thermoelectric power plants for cooling and other purposes; (ii) hydroelectric power plants through evaporation from dammed water.
2. After power production, abovementioned physical water inputs are transformed into virtual water embodiments in (i) electricity consumption by final demand, including urban and rural household consumption, the public sector and so forth (VWEF) and (ii) electricity as intermediate inputs into other industrial sectors (VWEI).

This framework can be illustrated by the Sankey diagram (Fig. 23) demonstrating the corresponding water fluxes from physical water consumption to virtual water embodiments in China's power sector in 2010 (see data section for data sources):

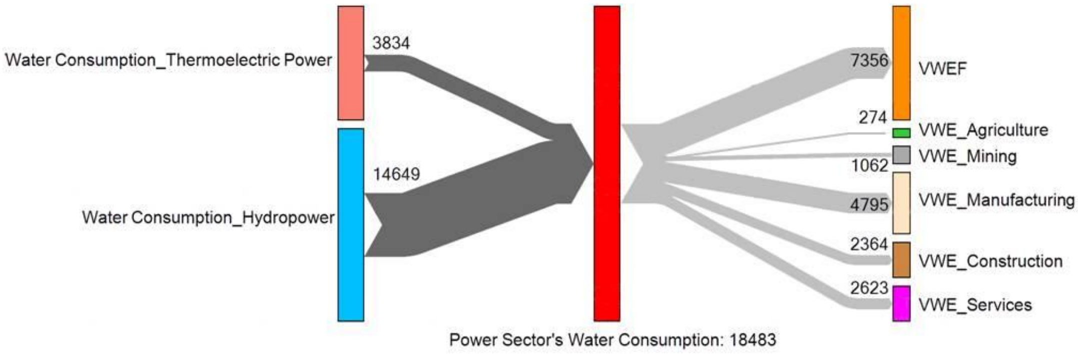

Figure 23 Water fluxes from physical water consumption to virtual water embodiments in China's power sector (million m³) (Dark Grey – Physical Water; Light Grey – Virtual Water; the width of the fluxes are proportionate to the amount of water)

A Water Embodied in Trade model (WET) based on the data from Multi-Regional Input-Output (MRIO) tables (see Data section) is used to quantify the two categories of virtual water flows among China's thirty province in 2002, 2007, 2010 and 2030. We focus on water consumption by the power sector in this study.

In summary, this study distinguishes itself from existing literature with four significant contributions: (i) including water consumption by both thermoelectric and hydropower productions at a provincial level; (ii) quantifying virtual water embodiments in the electricity consumed by the final demand as well as intermediate input to industries; (iii) quantifying the inter-provincial virtual water transfers based on this improved categorisation; (iv) investigating the future possibilities of water consumption by China's power sector and consequential virtual water transfers under various future scenarios of different provincial generation mixes and technology configurations in the electric power sector.

6.2 Method and data

6.2.1 Quantifying water consumption for power production

Water consumption for both thermoelectric power production and hydroelectric power production are quantified in this study. Regarding thermoelectric power production, coal-fired power production is used as a proxy for two reasons: (i) electric power generated from natural gas occupied only 3.1% of thermoelectric power production in China in 2014; (ii) provincial energy statistics do not differentiate gas-fired and coal-fired power generations.

This study focuses on the operational phase of coal-fired power production, which needs water for cleaning, cooling, boiler make up and other on-site water-requiring processes, e.g. flue gas desulfurization (FGD), coal transport and domestic uses. Coal-fired power plants' water consumption factors differ significantly depending on the cooling technology used (Macknick et al. 2012). Three commonly used cooling technologies in China are: open-loop cooling, closed-loop cooling and air cooling. Closed-loop cooling systems consume the largest amount of water because of the evaporative loss of recirculated water in cooling towers, whereas open-loop cooling systems use running water and thus have much lower water consumption. Air cooling systems require the least amount of water as they do not need water for cooling purposes. According to Liao et al. (2017), in a typical coal-fired power plant equipped with closed-loop cooling systems, evaporative water loss accounts for around 80% of its total operational water consumption. Thermoelectric power plants' water consumption can be calculated by equation (6-1):

$$W_{it} = WF_{it} \cdot P_{it} \qquad (6\text{-}1)$$

Where WF_{it} indicates water consumption factor for thermoelectric power production in province *i*; P_{it} is province *i*'s thermoelectric power production and W_{it} is the water consumption for province *i*'s thermoelectric power generation.

According to Liao et al. (2016), coal-fired power plants equipped with closed-loop, open-loop and air-cooled systems occupy 56.6%, 30.8% and 12.6%, respectively, in China. Further provincial distributions can be obtained from their study (Liao et al. 2016). Regarding water consumption factors of coal-fired power plants equipped with different cooling technologies, only a small number of coal-fired power plants reported their water consumption factors in China (China Electricity Council 2013a, b). For plants with closed-loop and open-loop cooling systems, we use the median values (1.87 and 0.39 m^3 /MWh, respectively) in the US as reviewed by Macknick et al. (2012). They are on par with the reported values from Chinese power plants (Liao et al. 2016). Regarding coal-fired power plants with air cooling systems, as they are not included in Macknick et al. (2012), we use the median water consumption factor

(0.32 m^3 /MWh) reported by Chinese power plants (China Electricity Council 2013a, b). It is worth noting that although cooling tower's water evaporation will be affected by ambient temperature and relative humidity change, those effects are not considered in this study. China's provincial thermoelectric power sector's water consumption factors can then be estimated assuming that all power plants in the same province have the same running hours. This assumption is valid because of China's unique generator dispatch mechanism trying to assure all contracted power generators comparable running hours (The Regulatory Project 106). Furthermore, provincial seawater uses by the thermoelectric power sector are calculated in Liao et al. (2016) and since we are only concerned with freshwater consumption, seawater use is not included in this study.

In terms of hydropower, its provincial water consumption can be calculated by equation (6-2) below:

$$W_{ih} = WF_{ih} \bullet P_{ih} \qquad (6\text{-}2)$$

where WF_{ih} denotes water consumption factor for hydropower in province *i*, which is the water evaporated per unit of hydropower produced; P_{ih} is province *i*'s hydropower output and W_{ih} is the water consumption for province *i*'s hydropower production.

Liu et al. (2015) compiled the water consumption factors for 209 major hydropower plants in China based on their reservoir area, measured annual evaporation and primary use. We extrapolate WF_{ih} based on the average value of water consumption factors of all hydropower plants within province *i*. Run-of-river hydro electricity is not included in this study due to lack of data availability. There is no data on what percentage of China's hydropower capacity is run-of-river, which indicates that run-of-river hydro electricity does not occupy a significant share in China's hydropower profile.

Provincial thermoelectric and hydroelectric power productions for 2002, 2007 and 2010 are obtained from China's national statistics bureau (2014). More detailed description of the methods and corresponding limitations are presented in Appendix of Supporting Information.

6.2.2 Quantifying virtual water embodied in all sectors using Water Embodied in Trade model

When local water was physically abstracted and consumed in the production process of a sector, this water is then turned into virtual water embodied in that sector, and redistributed through the supply chain consumed by final demand of this sector and other sectors. Hence, the physical water consumption of a sector does not equal to the virtual water consumption of final demand in that sector, but the sum of the total physical water consumption of all sectors equals to the sum of the virtual water consumption of all sectors, which is shown as followed.

$$\sum PW_j = \sum VW_j \tag{6-3}$$

The virtual water redistribution among sectors can be quantified using an input-output analysis. We applied the ‘Water Embodied in Trade’ (WET) model to study the virtual water embodied in final consumption of different regions for all sectors (Feng et al. 2011; Zhao et al. 2016). The assumption in a WET framework is that bilateral trade between regions is all directed towards final consumption (Peters and Hertwich 2008). This means the international purchase of intermediate consumption is assigned to the international purchase of final consumption. For region *r*, the local total output was assigned to intermediate demand, domestic final demand and export to other regions.

$$\mathbf{x}^r = \mathbf{A}^{rr}\mathbf{x}^r + \mathbf{y}^{rr} + \sum_{s \neq r} \mathbf{e}^{rs} \tag{6-4}$$

where $\mathbf{x}^r$ is the total output in region *r*, $\mathbf{A}^{rr}$ the technical coefficient, representing the intermediate inputs of each sector per unit of their output, $\mathbf{y}^{rr}$ is the domestic purchase of final demand in region *r*, and $\sum_{s \neq r} \mathbf{e}^{rs}$ is the international purchase of final demand from regions. Noting that in a WET framework, the local output in region *r* does not contain imports from other regions, because the assumption in WET that intermediate demand is all from local production.

Equation (6-4) can be solved as follows:

$$\mathbf{x}^r = (\mathbf{I}\text{-}\mathbf{A}^{rr})^{-1}(\mathbf{y}^{rr} + \sum_{s \neq r} \mathbf{e}^{rs}) \quad (6\text{-}5)$$

where $\mathbf{L} = (\mathbf{I}\text{-}\mathbf{A}^{rr})^{-1}$ is the Leontief inverse matrix which measuring both direct and indirect input in each sector to satisfy one unit of final consumption.

Combining equation (6-3) and (6-5), the virtual water embodiment in final demand can be expressed as followed.

$$\mathbf{VW}^r = \frac{\mathbf{pw}^r}{\mathbf{x}^r}(\mathbf{I}\text{-}\mathbf{A}^{rr})^{-1}(\mathbf{y}^{rr} + \sum_{s \neq r} \mathbf{e}^{rs}) \quad (6\text{-}6)$$

where $\mathbf{VW}^r$ is the matrix form of virtual water embodiment. $\mathbf{d}^r = \mathbf{pw}^r / \mathbf{x}^r$ is the vector of direct physical water use intensity of region *r* that represents the direct physical water use per unit of output in each sector. $\mathbf{pw}^r$ is the vector of direct physical water consumption in each sector of region *r*. $\mathbf{m}^r = \mathbf{d}^r(\mathbf{I}\text{-}\mathbf{A}^{rr})^{-1}$ represents the vector of total direct and indirect water input from region *r* to produce one unit of final consumption.

The virtual water related to region *r* can be classified into two groups. First, region *r* consumes physical water to produce the goods and services within the region, this physical water all turns into virtual water embodied the goods and services, and will be further distributed through the supply chain for local final consumption $\mathbf{y}^{rr}$

($\mathbf{vw}^{rr} = \mathbf{m}^{r} \times \mathbf{y}^{rr}$) and for export $\mathbf{e}^{rs}$ ($\mathbf{vw}^{rs} = \mathbf{m}^{r} \times \sum_{s \neq r} \mathbf{e}^{rs}$).

6.2.3 Quantifying virtual water consumption embodied in the power demands

For region *r* with *n* sectors, the virtual water embodied in power sector *k* (vwe^{r}) can be divided into electricity consumption by final demand ($vwef^{r}$) and electricity as intermediate inputs into other industrial sectors ($vwei^{r}$).

$$vwe_{k}^{r} = vwef_{k}^{r} + vwei_{k}^{r} \qquad (6\text{-}7)$$

The elements in equation (7) can be calculated as followed

$$vwe_{k}^{r} = \sum_{p=1}^{\mathrm{n}} \mathrm{VW}_{kp}^{rr} + \sum_{s \neq r} \sum_{p=1}^{n} \mathrm{VW}_{kp}^{rs} \qquad (6\text{-}8)$$

$$vwef_{k}^{r} = \mathrm{VW}_{kk}^{rr} + \sum_{s \neq r} \mathrm{VW}_{kk}^{rs} \qquad (6\text{-}9)$$

$$vwei_{k}^{r} = \sum_{p=1}^{n} \mathrm{VW}_{kp}^{rr} + \sum_{s \neq r} \sum_{p=1}^{n} \mathrm{VW}_{kp}^{rs} \quad (k \neq p) \qquad (6\text{-}10)$$

6.2.4 Data sources, availability and treatment

Two sets of data are needed in this study, i.e. time series MRIO tables and corresponding sectoral specific water consumption data. China’s MRIO tables for years 2002, 2007, and 2010 are available from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (Liu et al. 2009, 2012, 2014). China’s MRIO table of 2030 is obtained from Zhao et al. (2015). In Zhao et al. (2015), final demands of each sector, e.g. the electric power sector, include five components: rural household consumption, urban household consumption, government consumption, gross fixed capital formation, and stock changes. First, sectoral rural and urban household consumption are estimated using income elasticity and revenue growth following the projections from Guan et al. (2008). Then the other three components of sectoral final demands as well as sectoral total outputs are estimated assuming they have the same change rate as sectoral rural and urban household consumption.

Apart from the power sector’s water consumption that is calculated above, two following steps are undertaken to match water use statistic data with sectors in MRIO tables: (1) regarding primary and tertiary industries, water withdrawal data can be obtained from the Water Resource Bulletin in different Provinces (2007). It should be noted that, water withdrawal in tertiary industry (service sectors) and for domestic water use are aggregated in the Water Resource Bulletins. As about 50% of national urban domestic water use was for water use in service sectors, we assume the total water withdrawal of all service sectors in each province is 50% of its urban domestic water use. Then the distribution of different service sectors’ water withdrawal is the same as in Zhao et al. (2015); (2) Water withdrawal data of all industrial sectors (secondary industry), except the power sector, in different provinces are taken from the China Economic Census Yearbook (2008), whose 39 industrial sectors are aggregated to 22 industrial sectors as in MRIO tables (detailed sector aggregation is shown in Supporting Information). Water withdrawal data are then converted to water consumption by multiplying the corresponding sectoral water consumption coefficient from provincial Water Resource Bulletins (2007).

The power sector in IO tables includes Thermoelectric Power, Hydropower, Renewable and Heat production. According to Zhang and Anadon (2013), water use for heat production is negligible compared to that of power production. Therefore, we do not disaggregate Power and Heat Production. Combined Heat and Power (CHP) production is also not considered in this study because: (i) there is no statistical data for CHP capacity and heat generation for 2002 and 2007; (ii) although cogeneration can reduce coal-fired power plants' water consumption and neglecting it could result in overestimation of thermoelectric power sector's water usage. However, as China's current CHP units are mostly of small capacities and lower efficiencies and only provide heat during the winter, on an annual base, their total water consumption factors are on par with that of large non-heat generating coal-fired units (China Electricity Council 2013a, b). The latter is adopted for estimations in this study. (Self-reported total water consumption factors of over 700 coal-fired power generation units in China, which include both CHP units and non-heat-generating units, are discussed in Supporting Information). Renewable energy sources, e.g. solar

PV and wind, which contribute to rather small amount of China's electricity (less than 5%) and use a negligible amount of water during the operation phase, are also not included (Meldrum et al. 2013). Last but not least, we only include freshwater consumption in this study.

6.3 Results

6.3.1 Physical water consumption by electricity production

Hydropower makes up about 20% of China's power production (National Bureau of Statistic 2014), yet little attention has been paid to its water loss. Water is consumed in hydropower primarily as evaporative loss from reservoirs. Hydropower's water consumption grew substantially from 6.1 to 14.6 billion m^3 between 2002 and 2010, which represented some 80% of the power sector's total water consumption. Hydropower's water consumption in a certain region is decided by the region's hydropower production and its water consumption factor. According to Liu et al. (2015), hydropower has higher water consumption factor than other energy sources, especially in provinces in the north and northwest, where water scarcity is particularly pronounced, because of the local climatic and land surface conditions, e.g. high wind and little vegetation (Liu et al. 2015). Despite the upward trend at a national scale, hydropower production has gone down in the north from 2007 to 2010. When hydropower production of multipurpose reservoirs reduces, a greater proportion of their water use will be attributed to other purposes, including agriculture and flood control, hence the amount of water use attributed to hydropower decreases.

Regarding the water consumption for thermoelectric power production, this study recaps on methods and results from the authors' previous analysis of the water use in China's thermoelectric power plants (Liao et al. 2016). By multiplying provincial water consumption factors of thermoelectric power and power outputs, we calculate that, from 2002 to 2010, China's thermoelectric power production's consumptive water use has increased markedly from 1.6 to 3.8 billion m³.

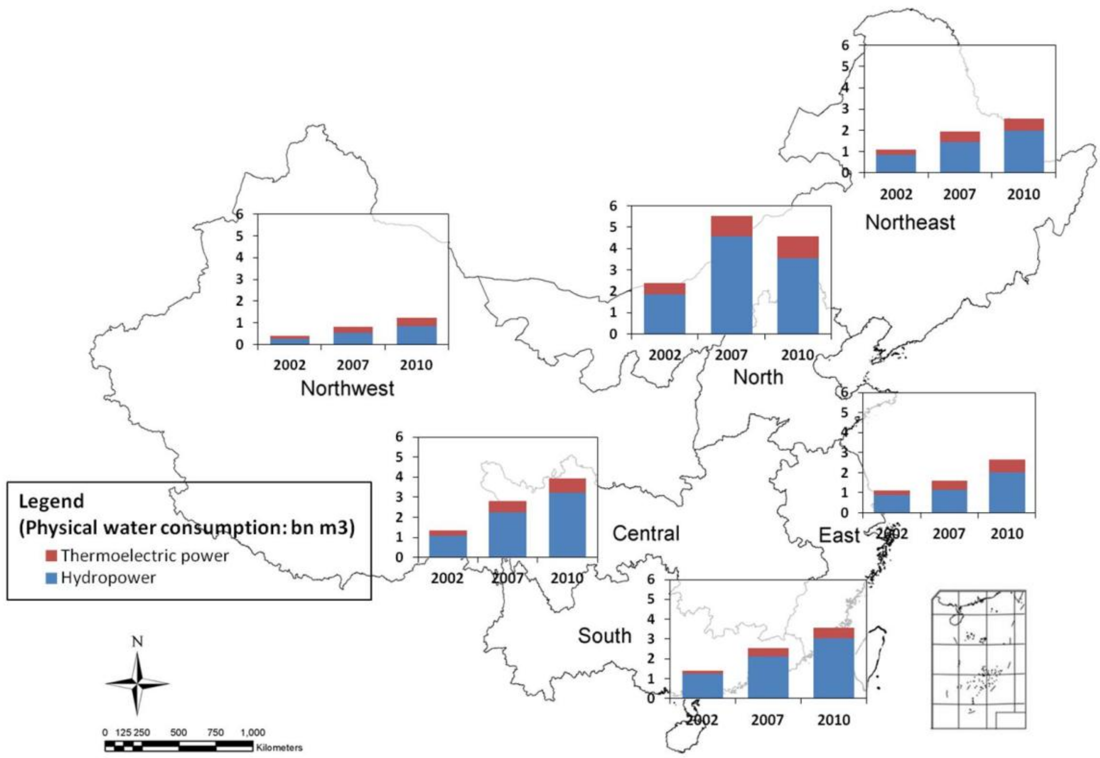

Figure 24 Water consumption for power production in 2010 in China's six grids: North, Northeast,

Northwest, East, Central and South

As shown in Fig. 24, nationally, water consumed to generate electricity in China has more than doubled from 7.72 billion m^3 in 2002 to 18.48 billion m^3 in 2010. Unlike other regions, there is a downward trend in the north from 2007 to 2010. This could possibly be attributed to either decrease in local electricity consumption or increase in virtual water imports, which will be further discussed in the following sections.

6.3.2 Virtual water embodiments in electricity consumption

The largest proportion of electric power supplied was consumed by final demand, accounting for 39.8% in 2010. The remainder of electricity was used by industries, in the following proportions: Manufacturing (25.5%), Services (14.2%), Construction (12.8%), Mining (5.7%) and Agriculture (1.5%). Consumption of virtual water in electricity (VWE) follows these proportions, with some minor regional variations (see Appendix of Supporting Information). Nationally, VWEF has increased from 1.91 billion m^3 in 2002 to 7.36 billion m^3 in 2010; meanwhile VWEI also grew from 5.82 to 11.13 billion m^3. The share VWEI occupied has steadily decreased from 75.4% in 2002 to 61.2% and 60.2% in 2007 and 2010, respectively. This reflects growing final electricity demand, such as by households and government, associated with rapid urbanization and economic development, alongside increasing electricity efficiency in industry and a gradual shift in economic activity from manufacturing, mining and agriculture to service industries.

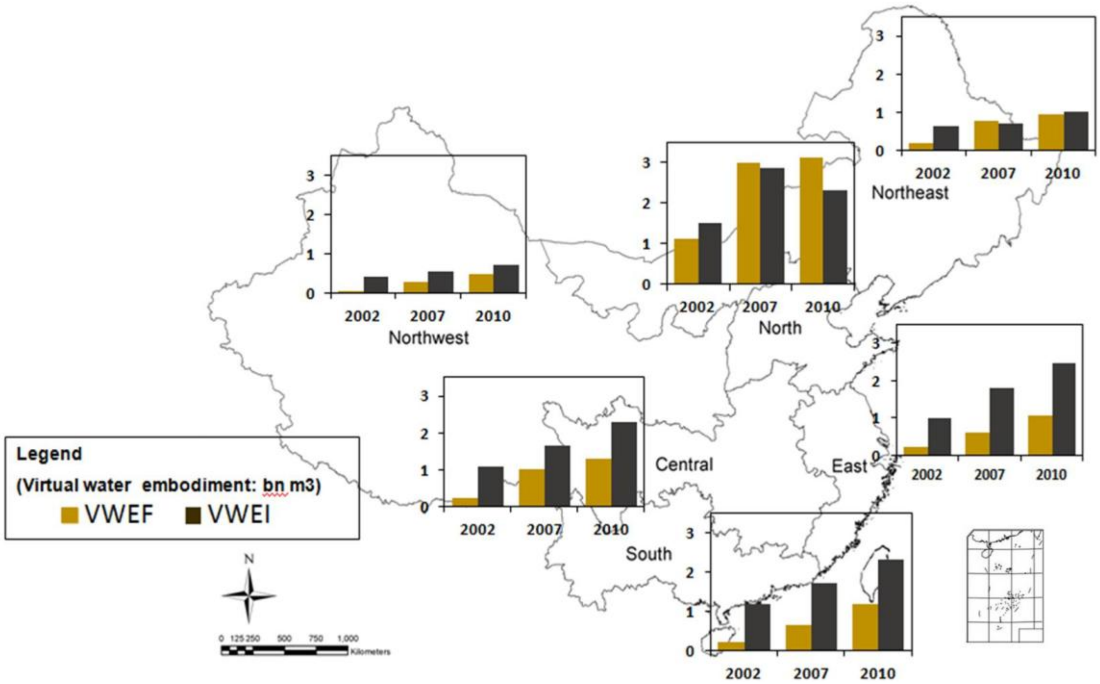

Figure 25 Virtual water embodiment in electric power use in China's six grids in 2010

Due to either relocation of industries or improvement in their energy efficiency, it can be seen from Fig. 25 that despite a slight increase in VWEF, the north has had a significant decrease in its VWEI from 2007 to 2010, which partially explains the decreasing water consumption of its power production illustrated in Fig. 22.

6.3.3 Virtual water trade via the electric power sector

When goods and services in different sectors are traded among different provinces, they carry a certain amount of virtual water embodiments that can be traced back from the physical water input into its production. Consequently, the physical water consumption in power sector is virtually redistributed across administrative boundaries. The differences in regional pattern of virtual water embodied in different electricity uses, either by final demand or other industries (Fig. 25), compared to electricity production (Fig. 24) illustrates how power demands in some regions are driving water consumption in some other regions. For example, in 2010, 4.58 billion m^3 of water was consumed for power production in the north, while all power demands in the north required 5.22 billion m^3 of water inputs in total, which means power demands in the north, which is relatively water scarce, also induced water consumption in other regions.

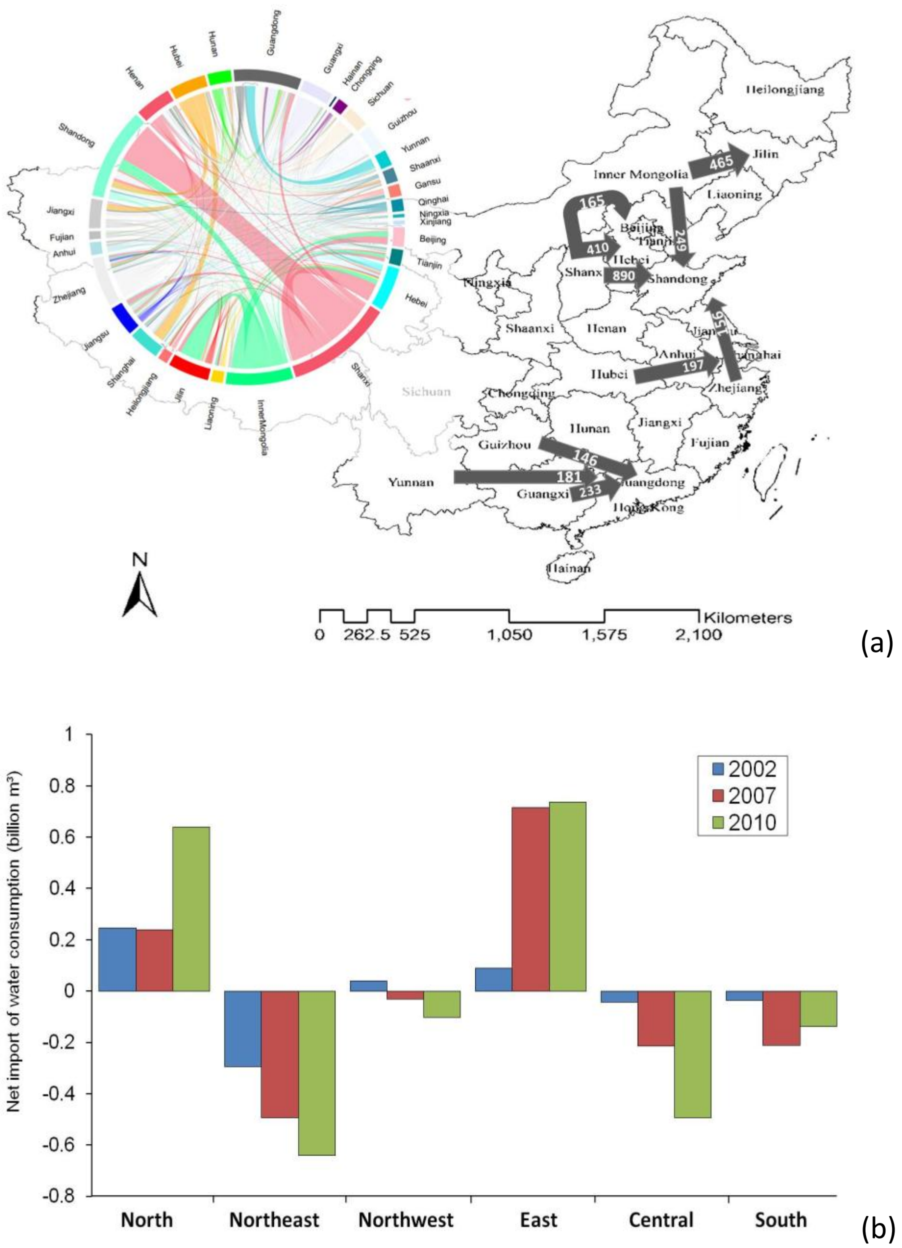

Figure 26 (a) Inter-provincial virtual water trade and the top-10 flows through the power sector in 2010 (million m^3); (b) Inter-regional net import of virtual water embodied in the power sector in China's six grids

Inter-provincial virtual water transfer via the power sector has increased from 2.81 billion m^3 in 2002 to 8.77 billion m^3 in 2010. The percentage in the power sector's total water consumption has gone up from 36.4% to 47.5%. This is to say, nearly half of the power sector's physical water inputs were finally used for inter-provincial trading purposes in 2010. According to Fig. 26 (a), it can be seen that virtual water was predominantly transferred eastward to coastal provinces, where there is more dense population and more developed economy, from their nearby inland provinces.

The amount of inter-regional virtual water transfers through the power sector has increased steadily from 1.48 billion m^3 in 2002 to 4.92 billion m^3 in 2010. Fig. 26 (b) shows water has been primarily transferred from the northeast and the central, whose net virtual water export was 0.64 and 0.49 billion m^3, respectively, while the north and the east were the main net virtual water importers, whose respective net water import was 0.64 and 0.74 billion m^3 in 2010.

6.3.4 Outlook to 2030

To look at the future possibilities of China's power sector's virtual water embodiments as well as the associated sub-national water transfers, four scenarios of different provincial power generation mixes and technology configurations are investigated: no new policies are implemented besides the existing ones in the Baseline scenario (Scenario 1: BS); Energy demands are met with renewable or low-carbon energy sources, respectively, in High Renewable (Scenario 2: HR) and Low Carbon (Scenario 3: LC) scenarios; Thermoelectric power plants' cooling technologies are altered in Technology Change (Scenario 4: TC) scenario, i.e. all closed-loop cooling systems in the north (north, northeast and northwest) and open-loop cooling systems in the south (south, east and central) are replaced by air cooling and closed-loop ones respectively. According to Fig. 27, in addition to thermoelectric power generation, we project hydropower is likely to use 17.04 to 18.65 billion m³ of freshwater resources, mostly in central, south and northwest China, depending on its different levels of development (Further method see Appendix of Supporting Information). In total, 20.79 to 26.87 billion m³ of freshwater resources is projected to be consumed in China's power sector.

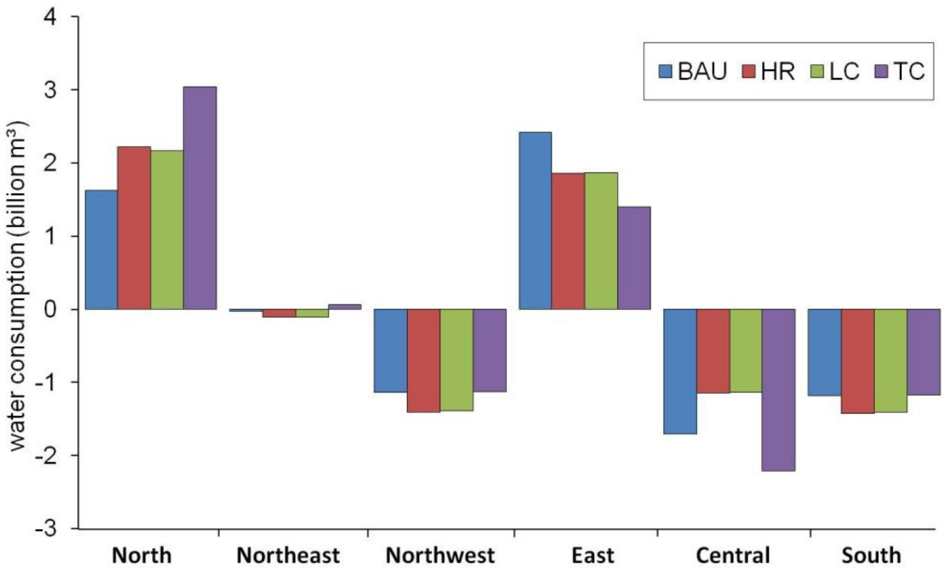

Figure 27 Virtual water transfers via the power sector in China's six grids in 2030 (BS – Baseline Scenario; HR-High Renewable Scenario; LC-Low Carbon Scenario; TC-Technology Change Scenario)

Among all the water consumption for power production, the total amount of inter-regional virtual water transfers via the power sector will increase to 10.46 to 13.14 billion m^3. Compared with the Baseline Scenario, the High Renewable and Low Carbon Scenarios will increase virtual water exports from northwest and south China as, especially, hydropower is favourably developed in these regions. Under the Technology Change scenario, water consumption is increased in east and central China as open-loop cooling systems are replaced by closed-loop ones, while in northern China (north, northeast and northwest), employing air cooling systems reduces water consumption. Consequently, virtual water export from central China increases and virtual water import by east China decreases.

With these scenario studies, we demonstrate that climate change mitigation and water conservation measures may impose different water pressures on different regions. These inter-regional contingencies need close examination when future policies are formulated and implemented. It should be noted that improving energy efficiency may also contribute to both climate change mitigation and water conservation throughout the whole country. However, these improvements are not incorporated in the input-output table for 2030 that we used, so we have not been able to evaluate the co-benefits of further enhancing energy efficiency.

6.4 Discussion

Consumption-based inter-sectoral analysis

For the first time, we have considered water embodied in the power production for intermediate inputs to other economic sectors from a consumption-based perspective. More than half, 60.2% in 2010, of the water consumed for power production was driven by power demands from industries, i.e. VWEI, particularly manufacturing, construction and services. The inter-sectoral analysis on virtual water flows demonstrates the importance of joint accountability throughout all sectors and regions for sustainable use of water resources. Potential risks for water shortages for the power sector can be reduced by either improved water efficiency in the power sector or reductions in the economy's electricity use, which can bring other co-benefits of carbon emissions reduction from the power sector and savings for energy users.

Hydropower's water consumption

From 2002 to 2010, hydropower production in China almost tripled from 283.7 TWh to 722.2 TWh (National Bureau of Statistics 2014). To mitigate climate change while securing power provision, hydropower is often considered as the most favourable alternative to fossil fuels (Liu et al. 2015). In 2012, China planned to increase its hydropower capacity by 70% by 2020 to 420 GW (Information Office of State Council

2012). However, its impact on water resources is seldom talked about in the energy community. Our results show that hydropower's water consumption made up the largest part of the power sector's water demands, which underscores the importance of incorporating hydropower's water loss into future life-cycle energy development, from energy planning to power plants operation.

Virtual water transfers through the power sector

Virtual water trades driven by the spatial mismatch between power demands and production can be revealed by virtual water analysis. According to our quantification, nearly half of water consumption for power production (8.77 billion m^3 in 2010) was used for inter-provincial trading purposes in China, i.e. driven by power demands from other provinces. The top-five inter-provincial virtual water flows highlight China's West-to-East Power Transmission Project (WEPT), Guangxi to Guangdong in the south corridor and Shanxi to Hebei/Shandong and Inner Mongolia to Jilin/Shandong in the north corridor. The WEPT was initiated in China's Tenth Five-year Plan (2000-2005) (National People's Congress 2001) and designed to bring economic development to the lagging west while alleviate the resources pressure in the east, where dense population, heavy industrialization and rapid urbanization require substantial power supplies and thus put enormous pressure on local resources. However, the associated environment pressures in the inland west, especially the water-stressed northwest, brought by this spatial shift of power provision need to be evaluated. Moreover, similar to China's south-to-north water diversion project, water transfer, either virtually or physically, raises the question of spatial inequalities of development and opportunities (Pohlner 2016), especially when virtual water is transferred outward from water-scarce regions.

Electricity transmissions and regional water scarcities

As shown in Fig. 28, most coastal provinces in the east, namely Beijing, Tianjin, Hebei, Shandong, Jiangsu and Shanghai, are facing different levels of water scarcities as a result of large water demands by extensive populations and advanced development. Importing virtual water through their power sector contributes to the alleviation of their physical water scarcities. On the contrary, water scarcities in inland provinces in the north and northwest are aggravated by their power sector's virtual water exports.

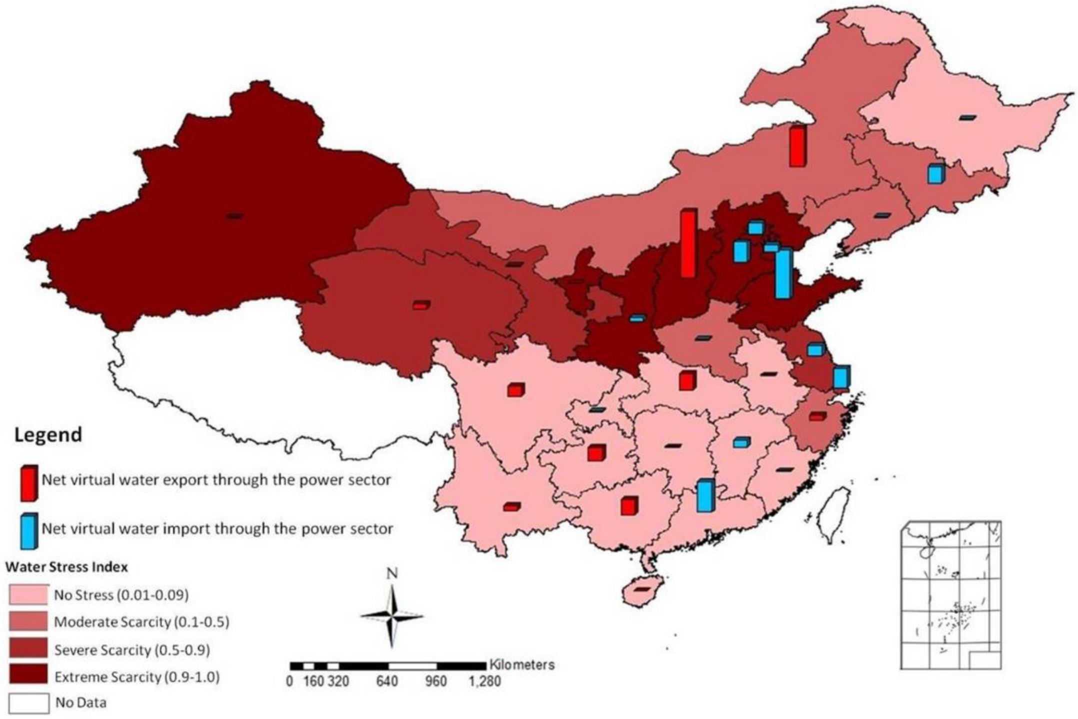

Figure 28 Provincial water scarcities and their net virtual water transfers through the power sector

Although provinces in north and northwest China are suffering from different levels of water scarcities, as they are also home to China's major coal bases, coal-fired electricity exports from those regions through the WEPT Northern corridor to Jin-Jin-Ji (Beijing-Tianjin-Hebei) megalopolis are still encouraged in China's 13th Five-Year Electricity Planning (National Development and Reform Commission 2016). In 2016, the National Energy Administration of China issued a 'Notice on Establishing a Coal-fired Power Planning and Construction Risk Warning Mechanism (hereinafter referred to as 'the mechanism')' (National Energy Administration 2016). The mechanism grades each province for its suitability to further expand its coal-fired power capacity from Red (discouraged development), Orange (cautious development) to Green (normal development) based on three sets of index: bankability, generation capacity adequacy and resource constraints. Although the mechanism explicitly listed water availability as one of the resource constraints, several water-scarce provinces, e.g. Ningxia, Shanxi, Inner Mongolia, are nonetheless not discouraged to develop their coal-fired capacities due to any resource constraints.

Future virtual water transfers through the power sector in China

We expect that the water demands by China's power sector will continue to grow until 2030. Northwest China will become one of the main net water exporters due to the expansion of WETP and development of both hydropower and thermoelectric power in the region (China State Council 2013). The virtual water outflow from the Yellow River basin is likely to grow remarkably in the future. Such planning that lacks comprehensive cross-sector considerations may lead to overexploitation of scarce water resources or energy infrastructure, e.g. coal-fired power plants, being stranded in the electricity-exporting regions. Power provision in the electricity-importing regions, often with dense population and high levels of urbanization and industrialization, may be exposed to risks brought by water scarcities beyond their administrative boundaries.

Limitations and future research needs

This study has certain limitations due to the nature of the method (top-down) and paucity of data. First, the future scenario analysis was built using input-output data from Zhao et al. (2015), which does not account for changes of the upstream supplies and the consequent water uses brought by the power sector's energy structure transformations under different scenarios. Data of higher spatial and sectoral resolution could contribute significantly in this regard. Secondly, it should be noted that Liu et al. (2016) calculated hydropower's water consumption with gross instead of net evaporation (subtracting evaporation from the original rivers before the reservoir is constructed) and, as Bakken et al. (2017) have pointed out, it may exaggerate reservoirs' impacts on local water resources (Several limitations of our calculation of China's hydropower's water consumption are discussed in Appendix of Supporting Information). Lastly, as cooling water consumption makes up about 80% of coal-fired power plants' total water consumption (Liao et al. 2017), utilizing the residual heat by retrofitting large electricity generation units for heat cogeneration could reduce the electric power sector's water uses.

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Appendix: Supporting Information

S 6-1 Physical water consumption by thermoelectric power sector in China

To calculate the physical water consumption of China's thermoelectric power sector, this study builds on methods and data from our previous study (Liao *et al.*, 2016). Thermoelectric power's water consumption factor, measured as water consumption per unit of power produced, varies by energy type, boiler technology and, predominantly, cooling technology. As China's coal-fired power production occupies more than 95% of China's thermoelectric power production, we focus on coal-fired power plants in our study for the current status and include other energy sources, i.e. natural gas, inland nuclear, to assess future scenarios. Therefore, China's thermoelectric power production's water consumption can be calculated by the equation below:

$W_{it} = WF_{it} * P_{it}$ (S6-1)

Where WF_{it} indicates water consumption factor for thermoelectric power production in province i, which is determined by thermoelectric power plants' cooling technology uptakes, including closed-loop cooling, open-loop cooling and air cooling; P_{it} is province i's thermoelectric power production and Wit is the water consumption for province i's thermoelectric power generation.

Similar to Byers et al. (2015), Liao et al. (2016) identified the cooling system of China's 1072 coal-fired power plants whose aggregate capacity amounts to 855 GW through Google imagery. For further details, please refer to Liao et al. (2016).

Combined Heat and Power is not differentiated in this study because according to self-reported water consumption factor (m^3/MWh) data from over 700 power generation units in 2013 whose total capacity amounts to 342.9 GW, 40% of the national total, coal-fired power generation's total water consumption factor shows greater agreement when organized according to cooling technologies as opposed to turbine types (Table A1). Table A2 shows that CHP units are mainly small units with lower efficiencies, which may result in higher non-cooling water uses.

Table S 6-1 Self-reported water consumption factors by China's coal-fired power plants (CEC 2013a, 2013b)

Cooling System	Turbine Type	Boiler Type	Average Water Consumption Factor (m^3/MWh)	Median values by Macknick *et al.* (2012) (m^3/MWh)§
Air cooling	SCT*	Subcritical	0.79	0.32
	CHP	Subcritical	0.54	
	SCT	Supercritical	0.45	
	SCT	Ultra-supercritical	0.43	
Open-loop	SCT	Super High Voltage	1.19	0.39
	CHP	Super High Voltage	1.57	
	SCT	Subcritical	1.45	
	CHP	Subcritical	0.81	
	SCT	Supercritical	0.62	
	CHP	Supercritical	0.42	
	SCT	Ultra-supercritical	0.38	
Closed-loop	CHP	High Voltage	4.80	1.87
	SCT	Super High Voltage	3.17	
	CHP	Super High Voltage	3.37	
	SCT	Subcritical	2.80	
	CHP	Subcritical	2.48	
	SCT	Supercritical	2.38	
	CHP	Supercritical	2.01	
	SCT	Ultra-supercritical	1.91	
	CHP	Ultra-supercritical	2.01	

*: SCT: straight condense turbines do not generate heat; CHP: Combined Heat and Power
§:Water consumption factors used for estimations in this study

Table S 6-2 Boiler type of CHP units and STC (non-heat-generating) units.

Boiler type	**CHP (MW)**	**STC (MW)**	Percentage of CHP units
High Voltage (100-200 MW)	200		100.0%
Super High Voltage (100-200 MW)	3255	4630	41.3%
Subcritical (300-600 MW)	41430	142600	22.5%
Supercritical (300-600 MW)	2700	89200	2.9%
Ultra-supercritical (600 MW -)	1000	57920	1.7%

S 6-2 Physical water consumption by hydropower production in China

Provincial water consumption of hydropower can be calculated by the equation below:

$W_{ih} = WF_{ih} * P_{ih}$ (S6-2)

Where WF_{ih} denotes water consumption factor for hydropower in province i, which is the water evaporated per unit of hydropower produced; P_{ih} is province i's hydropower production and W_{ih} is the water use for province i's hydropower.

Liu et al. (2015) calculated the gross evaporation of China's 875 major reservoirs. Among which, 209 have hydropower production and their hydropower production's water consumption factor, WF_h, is allocated by economic values of their multiple purposes.

Province i's hydropower production's water consumption factor, WF_{ih}, can be extrapolated based on the average WF_h value of all hydropower plants within its territory. For further details, please refer to Liu et al. (2016).

As Bakken et al. (2017) pointed out, any study on hydropower's water consumption should be used with great caution due to many methodological debates. There are three major limitations should be noted:

1, Liu et al. (2016) used gross evaporation instead of net evaporation (subtracting evaporation from the original rivers or lakes before the reservoirs are constructed), it may therefore exaggerate the impacts of constructing the reservoirs on local water resources. This may also explain why our results of China's hydropower's water consumption exceeded that of thermoelectric power markedly.

2, Liu et al. (2016) allocated multi-purpose reservoirs' water consumption to hydropower production by economic values. Consequently, many other values, e.g. social values of entertainment, were neglected. Therefore, hydropower may be assigned larger share of water consumption.

3, Neither the increase of blue water during dry seasons by building reservoirs nor the returned water after evaporation due to reservoirs' microclimate is considered by Liu et al. (2016) and both may contribute to the overestimation of reservoirs' water losses.

4, There is no additional evaporation considered with run-of-river hydropower. However, they are not considered in this study. Using solely hydropower reservoirs' water consumption to calculate the provincial hydropower water consumption factor may result in overestimation.

Table S 6-3 Physical water consumption by hydropower production in China

Province	Hydropower's Water Consumption Factor [m³/GJ]	2002	2007	2010	2002	2007	2010	2002	2007	2010
		Hydropower production (0.1 billion kWh)			Hydropower production (million GJ)			Hydropower water use (million m³)		
Anhui	9.64	10.51	19.67	18.85	3.78	7.08	6.79	36.47	68.26	65.42
Beijing	21.6	4.1	4.93	4.4	1.48	1.77	1.58	31.88	38.34	34.21
Chongqing	3.47	37.48	83.75	169.25	13.49	30.15	60.93	46.77	104.52	211.22
Fujian	2.62	224.35	311.59	453.69	80.77	112.17	163.33	211.21	293.34	427.12
Gansu	2.09	105.74	189.08	262.32	38.07	68.07	94.44	79.61	142.35	197.48
Guangdong	4.24	108.62	241.03	348.86	39.1	86.77	125.59	165.78	367.88	532.46
Guangxi	8.31	184.12	323.52	475.26	66.28	116.47	171.09	550.56	967.39	1421.12
Guizhou	4.04	221.53	340.62	416.58	79.75	122.62	149.97	322.1	495.26	605.71
Hainan	17	13.74	13.09	13.34	4.95	4.71	4.8	84.09	80.11	81.64
Hebei	20.41	3.64	5.68	5.55	1.31	2.04	2	26.74	41.73	40.78
Henan	4.43	15.52	88.53	91.67	5.59	31.87	33	24.77	141.29	146.3
Hubei	2.14	272.58	937.7	1263.83	98.13	337.57	454.98	209.57	720.93	971.66
Hunan	3.72	227.93	312.56	502.53	82.05	112.52	180.91	305.33	418.7	673.19
Inner Mongolia	260.9	6.69	11.86	16.29	2.41	4.27	5.86	628.35	1113.94	1530.02
Jiangxi	10.17	61.51	85.06	117.85	22.14	30.62	42.43	225.1	311.29	431.29
Jilin	6.35	44.57	61.83	105.5	16.05	22.26	37.98	101.89	141.34	241.17
Liaoning	9.98	14.46	43.81	43.98	5.21	15.77	15.83	51.94	157.36	157.97

Ningxia	0.1	7.78	17.47	18.02	2.8	6.29	6.49	0.28	0.63	0.65
Qinghai	3.05	88.97	207.76	371.11	32.03	74.79	133.6	97.72	228.19	407.59
Shaanxi	2.44	25.92	55.45	87.24	9.33	19.96	31.41	22.74	48.65	76.54
Shandong	2.16	0.01	0.77	2.14	0	0.28	0.77	0.01	0.6	1.67
Shanxi	263.5	18.83	47.32	36.63	6.78	17.04	13.19	1786.21	4488.77	3474.72
Sichuan	1.81	409.85	814.13	1213.42	147.55	293.09	436.83	267.75	531.86	792.7
Xinjiang	4.97	29.21	58.84	97.08	10.52	21.18	34.95	52.31	105.36	173.84
Yunnan	1.36	209.24	430.95	814.12	75.33	155.14	293.08	102.75	211.62	399.77
Zhejiang	18.06	95.29	118.15	230.85	34.3	42.53	83.11	619.69	768.35	1501.27
Jiangsu	18.06	2.98	2.95	1.03	1.07	1.06	0.37	19.38	19.18	6.7
Heilongjiang	8.16	22.53	10.41	15.09	8.11	3.75	5.43	66.21	30.59	44.35

S 6-3 Provincial and regional water consumption for power production (million m³)

Table S 6-4 Provincial and regional water consumption for power production (million m³)

million m³	2002		2007		2010			2002			2007			2010		
	Thermo	Hydro	Thermo	Hydro	Thermo	Hydro		Thermo	Hydro	Total	Thermo	Hydro	Total	Thermo	Hydro	Total
Beijing	25.47	31.88	41.73	38.34	48.96	34.21	N	531.06	1844.84	2375.90	949.91	4569.44	5519.35	1031.89	3551.38	4583.27
Tianjin	45.61	0.00	65.26	0.00	82.90	0.00										
Hebei	155.32	26.74	223.01	41.73	251.51	40.78										
Shanxi	94.40	1786.21	169.71	4488.77	159.89	3474.72										
Shandong	210.27	0.01	450.20	0.60	488.64	1.67										
Inner Mongolia	60.47	628.35	216.98	1113.94	245.51	1530.02	NE	247.47	848.39	1095.86	515.89	1443.23	1959.12	579.09	1973.50	2552.60
Liaoning	79.43	51.94	126.80	157.36	147.94	157.97										
Jilin	38.10	101.89	64.20	141.34	69.84	241.17										
Heilongjiang	69.47	66.21	107.91	30.59	115.80	44.35										
Shanghai	40.12	0.00	43.57	0.00	44.16	0.00	E	219.68	886.75	1106.43	463.16	1149.14	1612.30	635.81	2000.50	2636.30
Jiangsu	76.16	19.38	196.03	19.18	242.45	6.70										
Zhejiang	29.28	619.69	81.36	768.35	122.92	1501.27										
Anhui	62.08	36.47	109.21	68.26	180.38	65.42										
Fujian	12.03	211.21	32.98	293.34	45.90	427.12										
Jiangxi	18.26	225.10	49.05	311.29	69.50	431.29	C	258.52	1079.29	1337.82	569.41	2228.58	2798.00	699.16	3226.36	3925.52
Henan	146.97	24.77	317.76	141.29	371.70	146.30										
Hubei	24.06	209.57	56.66	720.93	71.92	971.66										

Hunan	7.71	305.33	29.72	418.70	41.19	673.19										
Chongqing	8.11	46.77	32.34	104.52	38.23	211.22										
Sichuan	53.42	267.75	83.89	531.86	106.63	792.70										
Guangdong	76.56	165.78	157.77	367.88	187.58	532.46	S	174.34	1225.28	1399.62	431.90	2122.26	2554.16	515.82	3040.70	3556.52
Guangxi	4.82	550.56	27.20	967.39	39.51	1421.12										
Hainan	1.42	84.09	3.96	80.11	5.36	81.64										
Guizhou	60.89	322.10	154.41	495.26	181.21	605.71										
Yunnan	30.65	102.75	88.55	211.62	102.15	399.77										
Shaanxi	41.19	22.74	73.85	48.65	114.42	76.54	NW	154.10	252.65	406.75	294.01	525.18	819.19	372.69	856.11	1228.80
Gansu	43.81	79.61	71.39	142.35	71.10	197.48										
Qinghai	9.45	97.72	18.68	228.19	18.17	407.59										
Ningxia	30.53	0.28	68.38	0.63	73.43	0.65										
Xinjiang	29.13	52.31	61.72	105.36	95.57	173.84										

(Note: N – North; NE – Northeast; E – East; C – Central; S – South; NW – Northwest)

S 6-4 Categorization of sectors and provinces

The sectors of this input-output analysis are categorized as below:

Table S 6-5 Categorization of sectors and provinces

Tier 1 Classification	Tier 2 Classification	Tier 1 Classification	Tier 2 Classification
Agriculture	Agriculture, Forestry, Husbandry and Fishery	Construction	Construction
Mining	Coal Mining and Dressing	Power Provision	Power and Heat Production and Provision
	Oil and Natural Gas Mining	Services	Gas and Water Production and Provision
	Metal Mining and Dressing		Transport and Storage
	Non-Metal and Other Mining and Dressing		Wholesale and Retail
Manufacturing	Food and Tobacco		Accomodation and Catering
	Textile		Rental and Commercial Service
	Cloth, Footwear and Leather Products		Research and Experimental Development
	Timber and Furniture		Other Services
	Paper, Cultural, Educational and Sports Products		
	Petroleum processing, coking and nuclear fuel processing		
	Chemical Industry		

	Non-metalic Mineral Products
	Smelting and Pressing of Metals
	Metalic Mineral Products
	General and Special Equipment Manufacturing
	Transport Equipment
	Electric Machinery and Equipment
	Communication, Computer and Other Electronic Equipment
	Instruments, Meters and other cultural, office equipment
	Other Manufacturing

Table S 6-6 Sector aggregation between water use statistic data and MRIO tables

Industry	Sectors in China Economic Year Book 2008	Sectors in MRIO tables
Primary	Agriculture	Agriculture
	Coal Mining and Dressing	Coal Mining and Dressing
	Petroleum and Natural Gas Extraction	Petroleum and Natural Gas Extraction
	Ferrous Metals Mining and Dressing	Metals Mining and Dressing
	Nonferrous Metals Mining and Dressing	
	Non-metal Minerals Mining and Dressing	Non-metal Minerals Mining and Dressing
	Other Minerals Mining and Dressing	
	Food Processing	Food and Tobacco Processing
	Food Production	
	Beverage Production	
	Tobacco Processing	
Secondary	Textile Industry	Textile Industry
	Garments and Other Fibre Products	Garments, Leather, Furs, Down and Related Products
	Leather, Furs, Down and Related Products	
	Timber Processing, Bamboo, Cane, Palm & Straw Products	Timber Processing and Furniture Manufacturing
	Furniture Manufacturing	
	Papermaking and Paper Products	Papermaking, Cultural, Educational and Sports Articles
	Printing and Record Medium Reproduction	
	Cultural, Educational and Sports Articles	
	Petroleum Processing and Coking	Petroleum Processing and Coking
	Raw Chemical Materials and Chemical Products	Chemicals
	Medical and Pharmaceutical Products	

	Chemical Fibre	
	Rubber Products	
	Plastic Products	
	Non-metal Mineral Products	Non-metal Mineral Products
	Smelting and Pressing of Ferrous Metals	Smelting and Pressing of Metals
	Smelting and Pressing of Nonferrous Metals	
	Metal Products	Metal Products
	Ordinary Machinery	General and Specialized Machinery
	Equipment for Special Purpose	
	Transportation Equipment	Transportation Equipment
	Electric Equipment and Machinery	Electric Equipment and Machinery
	Electronic and Telecommunications Equipment	Electronic and Telecommunications Equipment
	Instruments, Meters Cultural and Office Machinery	Instruments, Meters Cultural and Office Machinery
	Other Manufacturing Industry	Other Manufacturing Products
	Scrap and waste	
	Electric Power, Steam and Hot Water Production and Supply	Electricity and Heating Power Production and Supply
	Gas Production and Supply	Gas and Water Production and Supply
	Tap Water Production and Supply	
	Construction	Construction
Tertiary	Freight Transport and Warehousing	Freight Transport and Warehousing
	Wholesale and Retail Trade	Wholesale and Retail Trade
	Hotels, Food and Beverage Places	Hotels, Food and Beverage Places
	Real Estate and Social Services	Real Estate and Social Services
	Scientific Research	Scientific Research

Other Services	Other Services

S 6-5 Provincial distribution of sectoral power demands (%)

Nationally speaking, final sectors consume the largest proportion of electric power supplied: 39.9%, in 2010. The remainder of electricity was used by industries, in the following proportions: Services (27.8%), Manufacturing (25.5%), Mining (5.5%) and Agriculture (1.3%). Consumption of virtual water in electricity (VWE) follows these proportions. It should be noted there are significant regional variations in terms of the distribution of sectoral power demands and associated virtual water consumption. In provinces (cities) like Beijing, the final sectors, e.g. households, constitute the dominant power consumer, occupying over 60% of the total power demand, while in provinces like Liaoning, manufacturing makes up almost 70% of the power demands.

Table S 6-7 Provincial distribution of sectoral power demands (%)

	2002						2007						2010					
	Agriculture	Mining	Manufacture	Construction	Final Sector	Service	Agriculture	Mining	Manufacture	Construction	Final Sector	Service	Agriculture	Mining	Manufacture	Construction	Final Sector	Service
Beijing	1.98	2.55	15.91	2.79	59.74	17.04	1.39	0.6	19.75	2.16	67.83	8.27	1.01	1.89	20.65	2.22	62.25	11.98
Tianjin	0.87	2.48	16.38	1.01	65.27	13.99	1.9	4.73	30.51	2.56	50.81	9.48	1.31	9.95	27.75	5.78	41.21	13.99
Hebei	1.29	10.93	20.55	2.99	50.23	14.01	0.88	23.22	20.81	2.2	45.91	6.98	0.82	30.24	17.65	3.8	39.79	7.69
Shanxi	1.63	2.88	18.12	23.56	20.01	33.8	1.36	2.05	23.78	28.18	17.61	27.01	1.72	1.52	9.16	16.9	37.24	33.45
Inner Mongolia	4.53	5.91	17.75	20.87	28.35	22.6	1.82	2.15	24.56	20.49	23.41	27.58	1.87	1.4	17.33	27.74	33.21	18.46
Liaoning	4.61	4.21	27.5	8.4	25.18	30.1	1.6	6.39	43.73	8.19	12.27	27.82	0.97	9.29	45.71	12.3	15.8	15.92
Jilin	1.55	5.9	47.73	8.18	7.78	28.85	0.78	0.81	10.2	1.96	80.56	5.7	0.36	1.01	12.44	5.58	74.09	6.52
Heilongjiang	0.98	8.65	53.17	4.4	13.92	18.87	1.75	3.91	34.3	5	33.51	21.53	1.56	3.93	33.81	6	31.03	23.67
Shanghai	2.35	1.71	53.65	2.05	14.26	25.98	2.49	6.43	35.7	1.13	46.78	7.47	1.33	8.91	29.52	0.59	51.96	7.69
Jiangsu	21.2	0.77	29.18	9.64	21.89	17.32	1.7	13.71	57.55	4.42	15.19	7.43	1.39	19.43	51.94	3.36	15.03	8.85
Zhejiang	1.86	0.65	47.48	14.4	13.6	22.02	1.24	2.79	57.42	10.6	17.97	9.98	0.79	3.5	47.66	15.48	18.96	13.6
Anhui	3.24	1.65	49.42	9.86	17.68	18.15	3.61	4.62	41.64	9.06	11.78	29.29	1.97	6.02	43.31	14.08	15.22	19.39
Fujian	2.05	3.08	51.78	7.61	25.66	9.82	1.71	1.49	43.26	8.27	18.53	26.75	0.99	1.54	32.55	11.31	37.54	16.08
Jiangxi	4.24	1.36	34.38	17.26	12.66	30.1	1.5	1.99	16.26	15.84	53.55	10.86	0.58	0.9	16.5	15.32	59.28	7.41
Shandong	16.63	0.77	33.73	11.07	20.3	17.5	0.75	0.34	11.64	2.49	81.31	3.47	0.74	0.36	13.68	3.84	78.89	2.49
Heinan	6.7	3.08	35.12	11.16	18.95	24.99	1.92	5.4	31.31	7.7	42.45	11.21	1.73	5.6	31.98	9.03	40.53	11.12
Hubei	2.52	4.63	33.21	16.5	19.3	23.85	3.91	4.54	41.2	16.61	15.11	18.63	2.23	5.58	32.23	19.99	19.56	20.42
Hunan	3.24	2.4	36.19	25.44	10.52	22.21	2.72	5.32	26.52	12.65	31.29	21.51	2.58	3.57	27.63	18.11	26.01	22.11
Guangdong	4.9	1.16	39.41	8.26	15.64	30.63	1.44	8.6	44.71	7.56	30	7.69	0.83	10.24	41.89	9.29	32.13	5.62

Guangxi	2.33	1.62	39.03	19.59	14.54	22.89	2.65	5.05	16.58	19.58	21.71	34.43	1.44	1.6	17.97	24.95	36.86	17.18
Hainan	12.28	1.31	47.41	8.97	2.86	27.16	2.44	2.39	14.69	46.73	10.89	22.86	1.29	3.62	15.06	46.69	9.47	23.87
Chongqing	2.7	1.12	38.86	13.94	12.85	30.52	1.84	4.83	28.33	12.64	37.02	15.35	2.18	5.73	25.05	28.25	29.61	9.18
Sichuan	4.29	1.45	22.97	25.64	17.78	27.87	3.09	1.96	25.92	15.7	33.12	20.22	3.9	2.44	32.31	19.04	20.3	22.01
Guizhou	7.18	3.09	35.9	29.52	12.07	12.24	2.77	3.12	20.17	15.39	24.82	33.73	2.33	1.17	13.8	22.35	23.07	37.28
Yunnan	7.7	1.03	35.23	18.24	13.37	24.42	4.75	3.52	29.24	17.85	22.21	22.42	3.4	2.54	24.43	22.59	34.59	12.45
Shaanxi	4.25	4.41	59.19	6.51	4.9	20.74	2.2	1.84	39.77	4.79	35.14	16.25	1.82	2.47	32.97	7.91	40.13	14.7
Gansu	6.14	4.31	45.71	8.97	12.27	22.59	2.84	14.87	14.18	16.43	24.24	27.44	3.71	28.79	12.31	20.56	18.99	15.63
Qinghai	4.26	3.65	35.29	37.3	8.44	11.07	1.36	6.76	19.36	12.78	45.3	14.44	3.53	2.14	8.8	21.14	43.27	21.13
Ningxia	2.35	6.16	48.9	18.65	6.84	17.1	1.62	4.28	29.53	16.05	26.9	21.61	0.94	8.23	22.91	26.91	27.16	13.85
Xinjiang	1.89	0.09	27.71	19.01	18.13	33.18	3.63	1.01	28.77	10.22	15.87	40.51	4.27	0.7	22.36	11.62	40.83	20.22

S 6-6 Provincial and regional virtual water embodiments in power demands (million m³)

Table S 6-8 Provincial and regional virtual water embodiments in power demands (million m³)

Million m³	2002		2007		2010			2002			2007			2010		
	VWEI	VWEF	VWEI	VWEF	VWEI	VWEF		VWEI	VWEF	Total	VWEI	VWEF	Total	VWEI	VWEF	Total
Beijing	91.84	368.85	144.90	305.51	165.42	272.77	N	1520.04	1101.59	2621.63	2880.64	2876.59	5757.23	2317.19	2905.17	5222.36
Tianjin	85.28	160.25	152.82	157.88	191.67	134.34										
Hebei	310.34	313.23	529.41	449.33	547.85	362.01										
Shanxi	838.85	209.89	1684.77	360.12	999.44	593.11										
Shandong	193.73	49.36	368.74	1603.75	412.82	1542.94										
Inner Mongolia	250.14	98.97	244.05	74.60	395.66	196.71	NE	627.74	172.88	800.63	719.34	744.77	1464.11	1016.25	894.61	1910.86
Liaoning	116.47	39.21	230.98	32.32	279.21	52.41										
Jilin	97.32	8.21	141.38	585.97	204.11	583.72										
Heilongjiang	163.82	26.49	102.93	51.88	137.27	61.77										
Shanghai	115.12	19.15	223.55	196.52	297.96	322.30	E	988.09	206.67	1194.76	1810.92	516.77	2327.69	2471.72	902.02	3373.75
Jiangsu	125.06	35.05	406.68	72.85	502.52	88.92										
Zhejiang	495.19	77.93	753.92	165.11	1154.26	270.13										
Anhui	97.19	20.87	157.34	21.01	213.56	38.34										
Fujian	155.52	53.67	269.44	61.28	303.43	182.33										
Jiangxi	205.58	29.79	267.24	308.03	283.24	412.27	C	1097.53	197.55	1295.08	1649.68	934.22	2583.90	2282.47	1148.94	3431.41
Henan	176.67	41.30	264.18	194.90	353.98	241.26										
Hubei	153.82	36.79	384.48	68.45	456.87	111.13										

Hunan	275.71	32.41	303.05	137.99	507.28	178.30										
Chongqing	65.92	9.72	125.22	73.59	195.53	82.26										
Sichuan	219.83	47.53	305.51	151.27	485.57	123.71										
Guangdong	314.98	58.42	838.35	359.33	1121.27	530.84	S	1181.69	182.65	1364.34	1732.09	610.05	2342.14	2313.44	1104.31	3417.76
Guangxi	402.16	68.44	488.09	135.34	621.38	362.76										
Hainan	94.03	2.77	59.70	7.30	62.86	6.58										
Guizhou	244.21	33.52	208.77	68.92	281.41	84.37										
Yunnan	126.31	19.50	137.18	39.17	226.52	119.77										
Shaanxi	113.15	5.83	135.78	73.58	179.15	120.06	NW	400.21	45.73	445.94	545.44	241.61	787.05	726.09	400.78	1126.87
Gansu	113.39	15.86	127.34	40.74	197.44	46.28										
Qinghai	75.37	6.95	104.25	86.34	144.00	109.84										
Ningxia	31.58	2.32	41.05	15.11	54.17	20.19										
Xinjiang	66.71	14.77	137.02	25.84	151.33	104.41										

S 6-7 Future scenarios

Future input-output tables

We use China's multi-regional input-output table of 2030 from Zhao et al. (2016). There are a few methods to develop input-output tables for a future year and Zhao et al. (2016) applied a branch of the RAS method named GRAS, which was first proposed by Gunluk-Senesen and Bates (1988). For detailed information please refer to Zhao et al. (2016).

An input-output table constitutes inter-industry table, primary inputs and final sectors. An Environmental Extended Input-output table includes natural resources as primary inputs.

To incorporate scenarios of the power sector's water use, we only consider the changes of the primary water inputs to the power sector according to different scenarios on the energy sector's energy and water efficiencies and energy portfolios as in Liao et al. (2016). Due to data paucity, changes in the whole economy's structure and upstream supplies to the power sector, e.g. biofuel, cannot be accounted.

Future physical water consumption in the power sector

This section recaps method in section 1 and 2. Thermoelectric power and hydropower’s water consumption is estimated by multiplying power production and water consumption factors. Future thermoelectric, hydropower productions and corresponding water consumption factors in 2030 under different scenarios are from Liao et al. (2016).

Reference:

Bakken, T.H., Killingtveit, A. and Alfredsen, K. (2017) The water footprint of hydropower production – state of the art and methodological challenges. Global Challenges 1600018.

Byers, E.A., Hall, J.W. and Amezaga, J.M. (2014) Electricity generation and cooling water use: UK pathways to 2050. Global Environmental Change 25: 16-30.

China Electricity Council (CEC) (2013a) National 600 Mw Scale Thermal Power Unit Benchmarking and Competition Dataset (in Chinese). Beijing, China.

China Electricity Council (CEC) (2013b) National 300 Mw Scale Thermal Power Unit Benchmarking and Competition Dataset (in Chinese). Beijing, China.

Gunluk-Senesen G. and Bates, J.M. (1988) Some experiments with methods of adjusting unbalanced data matrices. Journal of the Royal Statistical Society. Series A (Statistics in Society): 473-490.

Liao, X., Hall, J.W. and Eyre, N. (2016) Water use in China’s thermoelectric power sector. Global Environmental Change, 41: 142-52.

Liu, J., Zhao, D., Gerbens-Leenes, P.W. and Guan, D. (2015) China's rising hydropower demand challenges water sector. Scientific Report 5: 11446.

Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, G. and Hubacek, K. (2015) Physical and virtual water transfers for regional water stress alleviation in China. Proc Natl Acad Sci U S A, 112: 1031-35.

Chapter 7. Conclusion

Electricity is crucial to almost all aspects of our modern lives. It has been found to be highly correlated with both population and economic growth (Shi et al. 2018). Its provision is pivotal to a higher standard of living and is directly related to socioeconomic development (International Energy Agency 2016). However, an indispensible production factor for electricity, water, has long been taken for granted. Alarmed by power curtailments caused by water-related risks worldwide, electricity's dependency on water supplies starts to gain growing attention in the last two decades (Gleick 1994; Vassolo and Doll 2005; Macknick et al. 2012; Howells and Rogner 2014; Spang et al. 2014; van Vliet et al. 2016). The concern is further heightened when water was identified as a primary limiting factor for human society and economy during the next decade (World Economic Forum 2015).

This dissertation aims to deepen our understanding of the interconnections between the water and electric power sector, specifically on the electric power sector's impacts and dependencies on water resources, the so-called 'water-for-electricity nexus', on improved spatial and temporal resolutions in the chosen study area, China. It draws its intellectual roots from multiple disciplines and employs a mixed-method approach and research design.

Chapter 3 for the first time investigates the historical changes of the water use in

China's electric power sector from 2000 to 2015 on a regional level. An Index Decomposition Analysis is conducted to quantify the impacts of four driving factors that have influenced the remarkable changes: population, power production per capita, power plants' type and their cooling technology choice.

Chapter 4 presents a high-resolution inventory of the current water uses in China's thermoelectric power sector based on an updated geo-database of spatial information on cooling technologies and water sources employed by coal-fired power plants and estimates the future water use under China's different energy scenarios at both a regional and a national scale. For the first time, it examines the coherence between policies of water and energy sectors at a regional scale and discussed the temporary patterns of China's thermoelectric power sector's water uses.

Chapter 5 identifies water shortage risks for China's coal power plants based on plant-level water demand data from Chapter 4 and water availability data on a 0.5^{o} spatial resolution simulated by a hydrological model H08 that explicitly incorporates human interventions. Climate change impacts are also incorporated in this chapter by running the hydrological model with meteorological forcing data from 5 GCMs provided by the ISI-MIP under two emission scenarios RCP 2.6 and 8.5.

Chapter 6 links electricity production and consumption from a water perspective. It proposes a framework based on Multi-Regional Input-Output model to map out water fluxes from physical water inputs to the power sector, including thermoelectric and hydroelectric power productions, to virtual water embodiments in either final electricity demands, e.g. households, or intermediate inputs to other economic sectors.

These four papers construct an integrated framework of interconnected and consistent analyses evaluating the power sector’s impacts and dependencies on water resources: Paper 1 evaluates the historical trajectories of water-for-electricity in China; Paper 2 highlights the spatial information of the current inventory of China’s water-for-electricity and demonstrates the future contingencies; Paper 3 simulates water availability with a hydrological model and identifies high-spatial-and-temporal-resolution risks for China’s coal power plants; Paper 4 connects electricity production with consumption and discusses the spatial pattern of the final consumption of water-for-electricity use and lays foundation for future studies on electricity users’ exposure and vulnerability to trans-boundary water shortage risks. The framework of this dissertation is illustrated as in Fig. 29.

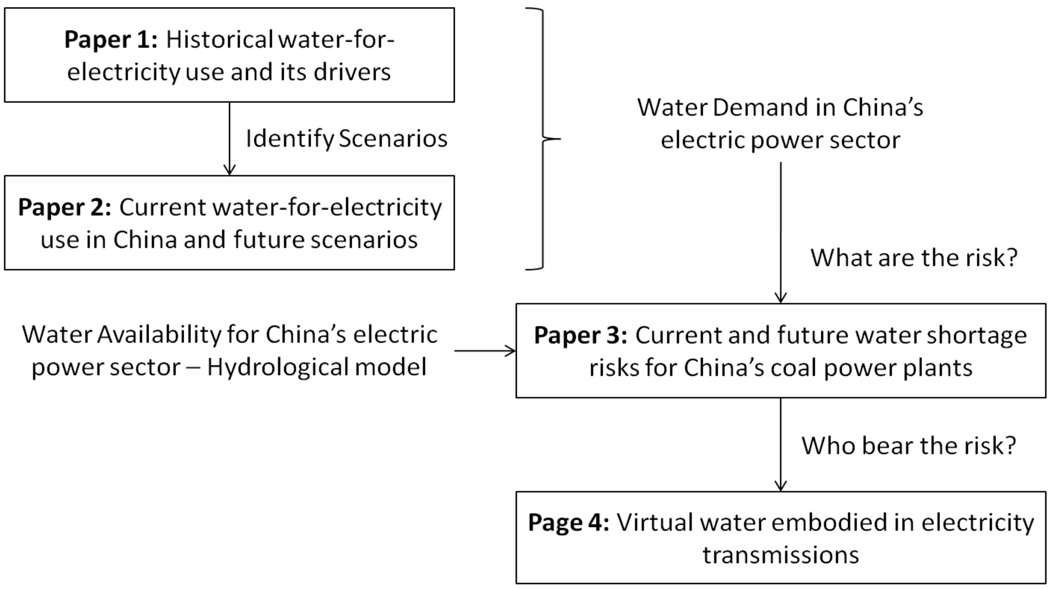

Figure 29 Dissertation framework consisting four separate but interconnected papers

The major findings of this dissertation can be summarised as below:

1) From 2000 to 2015, water withdrawal and consumption in China's electric power sector, excluding hydropower, have increased from 40.75 and 1.25 billion m3, respectively, to 124.06 and 4.86 billion m3;

2) Electricity production per capita has played the most significant role driving the increases of China's power sector's water withdrawal and consumption. Energy transformation to low-carbon sources has had offsetting effects on those increases;

3) Water withdrawal in China's electric power sector is concentrated in the south, particularly the Yangtze Delta region, because Southern China is abundantly endowed with water and power plants prevalently use open-loop cooling

systems, whereas the power sector's water consumption is higher in the north, particularly the Jing-Jin-Ji region, because closed-loop cooling systems that have larger water consumption but lower withdrawal values are commonly employed;

4) Water uses in China's power sector are projected to increase more than fourfold by 2050 if the business carries as usual. Improving energy efficiency or transforming the energy infrastructure to renewable, or low-carbon, sources provides the opportunity to reduce water use by over 50%;

5) 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;

6) Currently, around 10% of China's coal-fired power capacity is facing low flow water risks from July to October, and 20% the rest of the year. Particularly in the north, 40% to 60% of its regional coal-fired power capacity is at risks of not having enough water for cooling purposes from February to June;

7) Global climate change is expected to change water availability in China through changing precipitation and evaporation patterns. Available water in the river system is expected to increase significantly in the current dry north and

decrease significantly in the northwest and slightly in the south;

8) Climate change is expected to alleviate the low flow water risks facing China's coal power plants except in the northwest Inland River Basin. In the east and south, if their growing electricity demands continue depending on coal, increasing utilization rate of coal power facilities can lead to the increase of demand-driven water risks;

9) Hydropower plants consume almost four times water than thermoelectric power plants. Nearly half (47.5% in 2010) of the total physical water inputs into the power sector are virtually transferred across provincial boundaries in the form of virtual water embodied in the electricity produced, mainly from provinces in northeast, central and south China to those in east and north China;

10) While facing increasing water shortage risks for its power production, the northwest of China is expected to become a major virtual water exporter through its power sector by 2030, which means water risks in the northwest can generate trans-boundary impacts on other electric power importing regions.

The work presented in this dissertation provides a comprehensive framework for policy makers, investors and practitioners in the electric power sector to incorporate water resources into their decision making. According to the concept of

Integrated Water Resources Management (IWRM) (UN Water and Global Water Partnership 2007), Economic Efficiency, Social Equity and Environmental Sustainability all have to be included into Integrated Water Resources Management Plans. Four pillars of IWRM include: system analysis, science and technology, biological aspects and planning and policy (Kirshen et al. 2004). Based on the findings above, some policy recommendations can be put forward:

1) First and foremost, the current paradigm where water and energy are governed separately in silo should be improved. Although multiple authorities are inevitable as it's a complex issue, coordinative institutions should be formalized. Energy plans and policies should be formulated in consultation with water departments taking water impacts and constraints into full consideration.

2) To reduce water uses for electricity productions, mandating the change of thermoelectric power plants’ cooling technologies is the most effective policy option. However, policies need to be made within regional contexts. Trade-offs between water withdrawals, water consumption, generation cost and carbon emissions need to be made.

3) Deploying more efficient power plants and renewable energies that do not require on-site water uses, e.g. wind and solar PV, could also reduce the power sector’s water use, which can be realized as co-benefits of endeavours to

reduce the electric power sector's carbon emissions and other air pollutants.

4) Various policy instruments can be utilized to reduce final electricity consumption, including market mechanisms, e.g. subsidies, to promote energy-efficient household appliances. Environmental education to raise environmental awareness as well as environmental information disclosure programs, such as energy labelling, should be encouraged.

5) Thermal power production should be shifted away from coal reserves where water is scarce. Gas-fired power that is more water-efficient could be instrumental in this transformation. For example, Sichuan province in China's south where water is abundant is endowed with a large amount of shale gas that can be further developed after thorough studies.

6) More long-distance electricity transmission infrastructure should be constructed to enhance the connectivity of different power grids in order to fully utilize hydropower, wind power and solar power in different regions to minimize the use of coal.

Although this work for the first time proposes a comprehensive framework to address such an emergent challenge facing China's sustainable development, there exist several limitations and, based on which, future studies are recommended.

This dissertation has not been able to quantify the actual costs of the identified water risks in China's power sector. Future studies could be conducted to quantify the impacts of water risks in a certain region's power sector on electricity prices, industrial productions and social welfares and so forth both within and beyond the regional boundaries.

After identifying the risks and quantifying the potential costs, a sensible next step is to look into possible countermeasures. Future studies should investigate the cost curve of various measures to cope with water shortages in the power sector, namely, curtailing power productions, extracting groundwater, using reclaimed water, transferring water from external sources and so on. Water resources planning and allocation studies are also worthwhile to identify the optimal allocation plans among different water users, e.g. electric power production, agriculture and domestic uses, during water shortages.

It is also advisable for future studies to take both food and carbon emissions into consideration. Although it is impossible to bring all social-economic variables into one framework, several trade-offs between the water-for-electricity nexus and food/carbon emissions are particularly acute: (1) the competition for limited water resources between agriculture and power sectors; (2) the competition for water and land between food and bio-energy; (3) the trade-off between water and carbon emissions to employ air-cooling systems that lower power plants efficiencies; (4)

the trade-off between water and carbon emissions due to the increased water use by Carbon Capture and Storage's parasitic loads. It will be useful to design an optimization model incorporating all these factors to avoid such conflicts and better harness potential synergies.

Despite all those abovementioned limitations, this work has made significant contributions and improvements in advancing our understanding of China's water-for-electricity nexus. It has developed the most comprehensive dataset of China's plant-level cooling technologies to date. It has also for the first time simulated the current and future river discharges under climate change scenarios all over China with a calibrated hydrological model that explicitly incorporates human interventions. The analysis on virtual water flows in China's electric power sector has laid the foundation for future studies on the trans-boundary water impacts and risks for electricity uses. Most importantly, this work underscores the necessity of using nexus approach in both scientific studies and policy formulations. The framework, methods and results presented in this work are useful for China as well as other developing countries to balance their immense development needs and limited natural resources seeking a sustainable development path that also actively addresses climate change mitigation and adaptation needs.

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