# The impacts and challenges of water use of electric power production in China

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## Summary

Electric power production is a major driver of global water stress. With China's rapid increase in energy access and build-out of an electrified energy system, it is now the world's largest electricity producer and is seeing increasing levels of energy-related water stress. The electric power sector has become China's second-largest water user, after irrigation. This thesis investigates the water use of power production and its impacts on water stress across China. Given that the production-related impacts are often transferred via regional power transmission, this thesis also assesses the water embedded in China's national transmission system. The future availability of water for energy generation is set to be threatened not only by the increasing water use of all sectors but also by changes in the climate, raising both research and policy concerns. This thesis therefore puts forward the following overarching research question:

*What are the impacts and challenges of water use of electric power production in China?*

To answer this question, the thesis addresses four subquestions in four chapters.

First, a global meta-analysis investigates the question: *What are the water requirements of different electricity technologies and what is the availability of regionally specific data? (research subquestion 1)*

To further assess the water-electricity nexus, the remaining three subquestions specifically concern the impacts of power production on water resources and the impacts of water stress on power production:

*How much water is required for power production in China and how much water is virtually transferred via power transmission? (research subquestion 2)*

*What are the impacts of power production on freshwater biodiversity in China? (research subquestion 3)*

*What are the changes in water stress and the consequent impacts on power production in the future, and how might future carbon capture and storage (CCS) requirements exacerbate water issues in China? (research subquestion 4)*

To answer the first subquestion, Chapter 2 reviewed the literature on the water

requirements of power production and investigated the characteristics of water use and uncertainties in assessment. There are large differences in water use estimates across power types. Photovoltaics, wind power, and run-of-river hydropower consume relatively little water; concentrated solar power and geothermal power consume intermediate volumes of water; woody and herbaceous biomass and reservoir hydropower may consume considerable water resources. Fossil fuels consume very large amounts of water. However, water use can vary greatly across power plants of the same type, depending on many factors, such as the type of water use, operational efficiency, plant location, and so on. These impacts will change dramatically in the future, contingent upon the climate mitigation strategies chosen. While climate change mitigation via solar and wind power would reduce water stress in the power system, the retrofitting of carbon capture and storage to fossil plants would lead to increases in water stress. For example, the operational water consumption of thermal power plants increases by up to 81% if carbon capture and storage (CCS) is added. Uncertainties arose from inconsistent methodological choices and system boundary definitions among studies. The chapter also highlighted the key points that need to be improved in assessments. For example, clarity on water use type (consumption vs. withdrawal) and water sources (e.g., seawater vs. freshwater) is needed for future research. The review provided methodological and data support for answering the remaining questions.

Chapter 3 answered the second subquestion by assessing the water use of power production in China from the perspective of both water consumption and water withdrawal at the power plant level. China's power production withdrew 62.7 billion $m^3$ of freshwater in 2017, of which 13 billion $m^3$ was consumed. Overall, 6.2 billion $m^3$ of freshwater withdrawal and 2.1 billion $m^3$ of water consumption were virtually traded through the transmission system, with large variations throughout the year. A counterfactual scenario where a region does not import power but satisfies the local demand by producing power itself showed that if transmission does not take place, freshwater withdrawal increases but consumption is reduced. This was because, compared with the east of China, the west generally had a larger water consumption factor but a lower withdrawal factor. Water stress was more equally distributed across provinces through power transmission. This chapter provided an international perspective in terms of the application of methods and results. The methods can be applied to other countries if sufficient data on the power system and water use are available. The results for China, as one of the major energy users worldwide, can make an important contribution to a database of global energy-related water use.

Chapter 4 assessed the impacts on freshwater biodiversity caused by water use for power production in China, in light of the third subquestion. This included the consumption of freshwater and the thermal emissions to freshwater. The total biodiversity loss caused by water consumption and thermal pollution due to China's electricity generation increased by 45% during 2008-2017, while the biodiversity loss caused per unit of electricity generation decreased by 23%. Biodiversity loss from thermal pollution was 60% higher than that driven by freshwater consumption. Electricity transmission resulted in the shifting of biodiversity impacts across regions. The results showed that 15% of total biodiversity loss was embedded in transmission networks. In terms of electric power system drivers of biodiversity loss, the total generation was the main driving factor of the increase in loss (rather than shifts in generation type, for example). This chapter proposed a framework for assessing the freshwater biodiversity impacts of power production, which can be incorporated in electricity and energy planning to reduce the impacts on ecosystems.

Chapter 5 answered the fourth subquestion by exploring the water vulnerability of China's thermoelectric power fleet under climate change by developing a hydrology-electricity modelling framework at a monthly time step and a 5-arcmin spatial resolution of the river network. The results showed that 120-176 GW of capacity will be exposed to water scarcity for at least one additional month per year in the 2030s. In the absence of carbon capture and storage (CCS), the national usable capacity of thermoelectric power will increase slightly, due to slight mitigation of water stress in northern regions, where many plants are located. However, the addition of CCS – which requires more water – would significantly exacerbate water vulnerability, leading to further reductions of 7.4-7.7% in usable capacity. Testing several adaptation options for vulnerability mitigation revealed that early retirement of power plants was most effective, because this significantly reduced water requirements. Interregional power transmission also played an important mitigating role by shifting power production from water-scarce regions to water-abundant regions. The results demonstrated the importance of incorporating climate and water-scarcity changes in electricity planning. It is also important to take account of competition for water between the power sector and other users, and adaptation strategies from the perspective of both individual plants and the power system as a whole.

Based on the above studies, this thesis found several answers to the overarching research question. First, there were large differences in water use of electricity technologies and there was inconsistency in the methods and data used in previous studies. This can lead to substantial uncertainties in water use assessments. In China, large volumes of water were required by the energy system because of large-scale thermal and hydropower production. Due to virtual water transfer via power transmission, water stress was more equally distributed across the country. In addition, China saw increasing freshwater biodiversity loss caused by freshwater consumption and thermal emissions of power production. Power production faces challenges if its water demand cannot be met. In the future, thermal power plants in China would see significant reductions in usable capacity if retrofitted with CCS.

There are many areas on which future research can focus. Specifically, data availability could be improved because data for the two systems – energy and water – are not easily accessible, which limits the scope and transparency of studies. Further, research models of the water-electricity nexus could be improved in terms of several aspects, including water, electricity, and climate simulations. Additionally, the interaction of water demand from governments, industries, and households needs to be further quantified for a deeper understanding of the water-electricity nexus.

To conclude, the new knowledge generated in this thesis advances the understanding of: 1) the water requirements of various types of electricity technologies; 2) the impacts of power production on water resources and the related biodiversity systems; and 3) the impacts of water stress on power production and adaptation. Overall, this thesis provides insights into the impacts and challenges of water use of electric power generation, yields methodological and data support for connecting water and power systems both theoretically and in practice, and offers suggestions for policymakers on how to mitigate energy-water conflicts and support further research.