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

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Chapter 6

General Discussion

Energy and water systems are often perceived as unconnected and managed separately. However, electric power is the main water consumer in energy systems and is already a major driver of water stress worldwide. Due to the significant spatial heterogeneity of power production and its water requirement, such problems have not been well addressed by national- and regional-level analyses. This thesis attempted to examine the energy-water nexus at a higher resolution using China as an example, with the aim of answering the following overarching research question:

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

This chapter first reviews the progress made toward the specific research questions proposed in Chapter 1 and then answers the overall research question (section 6.1).

6.1 Answers to the research questions

SQ1. *What are the water requirements of different electricity technologies and what is the availability of regionally specific data? (Chapter 2)*

The literature reported large differences in water requirements of electricity generation technologies. This was a barrier to decision-making. In Chapter 2, we presented a meta-analysis, compiled an inventory of the water use of power production, and investigated the characteristics of water use and uncertainties in assessments. 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. The deployment location of power production has an important effect on water use of power systems in a country, because of different climate conditions and available types of water resources. Coal power plants have relatively low variability in life cycle water consumption compared with hydropower, which has significant variability due to factors like reservoir area and evaporation factor, with a coefficient of variation of 634% across the water intensity of hydropower assessed in the literature. For thermal power plants, the operational water consumption increases by up to 81% (natural gas) if carbon capture and storage (CCS) is added.

Inconsistent system boundaries caused uncertainties in water use estimates across studies. The fuel cycles of biomass and shale gas merit further consideration in the future because they are large water consumers, driven by the irrigation required to grow plants for biomass and water use in the fracturing process of shale gas extraction. Current studies focus on showing the results of assessments rather than the key influencing factors, such as the conversion efficiency, capacity factor, and lifetime of energy systems. Moreover, the type of water use (consumption vs. withdrawal: as explained in Chapter 1, these are different concepts and need to be distinguished in research) was often not clarified, creating barriers to understanding the results and comparing different studies. Water withdrawal refers to the volume of water diverted from a water source for use, all or part of which may be returned, while consumption refers to the volume of water not returned to the water body due to evaporation, transpiration, or incorporation into products. Clarification of the water sources would also help in interpreting values for water use estimates for biomass (precipitation vs. irrigation), geothermal (geofluid vs. freshwater), and fuel-based thermal and nuclear power (seawater vs. freshwater). The emphasis for future studies should be to increase the transparency and clarity of such factors and terminologies.

***SQ2**. How much water is required for power production in China and how much water is virtually transferred via power transmission? (Chapter 3)*

We assessed the water use of power production in China from the perspective of both water consumption and water withdrawal at the power plant level and then aggregated it to the regional and national levels. Chapter 3 showed that China's power production withdrew 62.7 billion m^3 of freshwater in 2017, of which 13 billion m^3 was consumed. The extensive inventory of plant information allowed for a detailed analysis of the drivers of water use. There were large heterogeneities in the water use of power production across plants. Hydropower plants with large reservoirs were large freshwater consumers due to evaporation, whereas thermal power plants with once-through cooling systems were large freshwater withdrawers. This study showed that it is important to distinguish water sources (surface water, groundwater, reclaimed water, and seawater). Hydropower was the main consumer of surface water, while all nuclear power plants in China were located along the coastline and used seawater for cooling.

Interprovincial electricity transmission increased more rapidly than electricity generation in the last decade. Approximately 16% of China's water consumption for power generation was driven by demand in other provinces and 'virtually used' via power transmission. Power transmission led to a more equal distribution of water stress across provinces. Compared with the east, the west generally had a larger water consumption factor but a lower withdrawal factor. Power generation that consumed large amounts of water was often transmitted from west to east, consequently reducing water withdrawal but increasing water consumption nationally. The impact of power transmission is expected to grow with the rapid development of transmission infrastructure.

SQ3. *What are the impacts of power production on freshwater biodiversity in China? (Chapter 4)*

Current electric power systems require large amounts of freshwater in the thermodynamic conversion of heat to work or the water held in hydropower reservoirs. These processes can result in the consumption of water and warming of the water in the environment (termed 'thermal emissions'). Both freshwater consumption and thermal emissions have impacts on water systems. Chapter 4 assessed the impacts from the perspective of freshwater biodiversity loss.

We found that the total biodiversity loss caused by China's electricity generation increased by 45% during 2008-2017, while the biodiversity impact per unit of electricity generation decreased by 23%. 62% of the biodiversity loss was due to thermal pollution, while 38% was due to freshwater consumption. Electricity transmission resulted in the shifting of biodiversity impacts across regions. The results showed that 15% of total biodiversity loss was driven by electricity transmission to provinces other than those where electricity production and hence biodiversity loss took place. 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). Our results highlighted the need to assess the biodiversity impacts of electricity generation and to incorporate them in power system planning. For example, in the future it is important to shift electricity generation from regions with high biodiversity intensities to those with low biodiversity intensities by taking into account the provincial biodiversity factors of electricity generation that we found.

SQ4. *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? (Chapter 5)*

Thermal power production requires large amounts of water, therefore changes in the availability of water resources due to climate change may affect the vulnerability of power production. Chapter 5 examined the current and future water availability in China based on the outputs of a global hydrological model (PCRGLOBWB-2) under various climate scenarios, and geographically matched this availability to thermal power plants to reveal the impacts on power production. The results showed that there are quite some plants already experiencing water stress, while the impact will be slightly mitigated before 2040 due to an increase in water availability for power plants in northern China in all climate scenarios except one extreme case (Representative Concentration Pathway 8.5).

Many proposed scenarios for meeting China's net-zero carbon targets require that a large number of existing power plants are retrofitted with CCS. Yet the water requirements of CCS mean that its addition exacerbates vulnerability to water constraints compared with the existing situation, leading to additional usable-capacity reductions of 7.4-7.7%. To mitigate such negative implications, we assessed several measures that can enhance usable capacity. We found that early retirement of older, generally more water-intensive power plants and interregional power transmission were more effective in vulnerability mitigation than other adaptation strategies, such as retrofitting cooling systems and switching to seawater cooling. However, strategies may also face other challenges from the economic, energy security, and employment perspectives. Policymakers and industry will need to have insight into such challenges when implementing these adaptation options.

In addressing these research questions, this thesis offers several answers to the overall research question: *What are the impacts and challenges of water use of electric power production in China?*

The thesis answered this question by first providing a meta-analysis of previous assessments of the water requirement of electricity generation. The analysis showed that there were large differences in water requirements of electricity technologies (Chapter 2). Large amounts of water were needed because of the large-scale thermal and hydropower production in China. Water was used for power production and then transferred, virtually, across the power transmission. Water stress was found to be more equally distributed due to the virtual water transfer via power transmission (Chapter 3). In addition to water use, the heat released into water from power plants also had impacts on the water system. We showed that both freshwater consumption and thermal emissions can result in freshwater biodiversity loss (Chapter 4). As a result of the large demand for water, changes in the availability of water resources can affect the vulnerability of electricity generation, with further uncertainties arising from the changing climate and countermeasures (Chapter 5). Both the meta-analysis in Chapter 2 and Chinese case studies in Chapters 3, 4, and 5 showed the importance of increasing transparency in electricity and water systems, and the importance of a joint, spatiotemporally explicit analysis of the electricity and water systems to understand problems and solutions in their nexus.

6.2 Limitations and future research

During our research, we found limitations of data, methods, and scopes that formed barriers to understanding the energy-water nexus. Here we discuss these issues in depth and give some suggestions for future research.

6.2.1 Data limitations

Although energy and water are important resources supporting human activities, data for the two systems are not easily accessible, which limits the scope and transparency of studies.

First, the power system is often divided into three stages when assessing its water use: 1) the fuel cycle, referring to fuel extraction, refining, and transport; 2) the operational stage, referring to the process of electricity production; and 3) plant infrastructure, referring to all the material inputs for plant construction. The operational stage is the focus of the existing research because of its large water requirements, especially for thermal power and hydropower. Yet studies still face many challenges in the availability of high-quality data, which may result in large uncertainties. For example, while the volume of electricity generation is required for making operational water use calculations, it is not usually available and is often estimated by multiplying the installed capacity by a capacity factor. However, capacity factors are seldom reported. If inaccurate values are used, they can lead to substantial uncertainties in the final results. In addition to the capacity factor, key information such as plant location, generator type, and cooling type is also generally not publicly available, which makes it difficult to perform detailed analyses for the operational stage. Information on the other two stages (fuel cycle and plant infrastructure) is also under-reported by governments and businesses, although partly included in some Life Cycle Inventory (LCI) databases, such as *ecoinvent*. Our own study focused on the operational water use rather than lifecycle water use. For some power types, however, the fuel cycle (e.g., biomass) and plant infrastructure (e.g., wind power) may require large amounts of freshwater [16]. Future work needs to enhance data availability of, for example, the location and impacts on water use of extraction of fossil fuels, impacts on water use embodied in materials used for electricity infrastructure, and so on.

Second, information on the type of water is another major source of uncertainty in energy-water studies, and a clear differentiation should also be made between water withdrawal and consumption. Power systems can use various types of water (surface water, groundwater, reclaimed water, and seawater). This thesis mainly distinguished water sources for hydropower, nuclear power, and coal-based thermal power, while more information on water sources for other power technologies (e.g., biomass-based power plants, geothermal power) will be required.

6.2.2 Method limitations

Methodological differences may also yield different results. For example, input-output analysis (IOA) and lifecycle assessment (LCA)-based process analysis have been widely used for assessing water footprints. IOA often leads to larger lifecycle water withdrawal and consumption estimates for most power types, especially wind and photovoltaic (PV). This is because there is an additional water input from economic sectors not covered by LCA-based process analysis [16]. Our studies are mainly based on process data and largely neglect water use in supply chains of fuels and infrastructures, so our estimates could lead to underestimations or represent a lower bound of potential water stresses. Researchers have been attempting to link the two methods in hybrid LCAs for a more comprehensive assessment. However, some issues still need to be addressed. For example, using IO-based hybrid LCA presents a challenge in sector disaggregation. Power production is a homogenous sector in many IO tables, even though each power type has a distinctive water use, as shown in Chapter 2. Work is needed to isolate the targeted power type from the power production sector. IO tables are also normally released later than process-based data, which is an issue for emerging energy technologies. There is a growing trend for battery storage to be paired with renewables, such as solar PV and wind, but these installations are not separated from the power sector in IO tables. Future research could put more effort into disaggregating generation and storage across datasets.

In Chapter 5 we examined the future changes in water availability due to climate change and the associated impacts on electric power production, taking into account the competition for water resources between various sectors. There are still some aspects that need to be improved for the climate, water, and energy models used in the thesis:

- It would be useful to update our analysis using other climate and socioeconomic scenarios, e.g., Shared Socioeconomic Pathways.
- Most power plants withdraw water from the rivers on which they are built, therefore water scarcity is at the plant level rather than the regional and river basin level. In our work, we simulated the water availability at grid cell level at a 5-arcmin spatial resolution, so there are still opportunities to improve the spatial resolution of hydrological simulation in order to obtain more accurate results of the energy-water nexus.
- Our reference period for the hydrological simulation is 1992-2001. Further research could use a more recent reference period as and when sufficient meteorological data become available.
- Our study links a water model with a power production model, while in reality power demand is also important in the power system and affects power production. It would be better to take account of the variations in power demand and the balance between power production and demand when analyzing the relations in the water-electricity nexus.

6.2.3 Scope limitations

Analyzing water and electricity systems may not be enough for assessing how we can realise sustainable development related to these two resources. For example, the energy transition faces constraints with regard to e.g. required greenhouse gas emissions and limitations related to land use. Moreover, the water system is influenced by other developments, such as expansion of agriculture and industrial production. Researchers have been trying to perform analyses with the addition of other nexuses, such as energy-water-CO_2 [337], energy-water-land [338], and energy-water-food [339]. But even with such additions, the system boundary is still limited. Combining the water-electricity nexus with other nexuses requires an integrated assessment model (IAM) that fully integrates environmental systems and economic systems. At the same time, water-electricity models can offer insights into water and electricity systems at a much higher resolution than is possible in IAMs. It would be interesting and important for future research to combine the highly spatiotemporal water-electricity nexus with a traditional IAM to gain a comprehensive view of all nexuses.

The studies presented here mainly analyzed the two systems – water and energy – from the environmental perspective, yet solving environmental issues sometimes involves conflicts with the demands of governments, industries, and residents for economic developments. For example, energy transition and water conservation strategies sometimes require adjustments in other industries [160], which is a serious challenge because of the different policymaking bodies that deal with these issues in most political systems. Industries also face challenges in addressing environmental issues. For example, the regulations on reducing carbon emissions require energy industries to add carbon capture facilities, thus increasing the energy suppliers' costs, which they may partly pass on to consumers. Measures to protect freshwater biodiversity can have impacts on people who live from fishing. For example, the Chinese government imposed a ten-year ban on fishing in the Yangtze River [340] in 2020 to alleviate the reduction in fish stocks. This meant that 111,000 fishing boats, providing the livelihood of 231,000 fishers, had to cease activities. Future research in this area needs to have a wider perspective, addressing but not limited to the challenges above, since many issues extend beyond the natural environment and require trade-offs across various systems.

6.3 Scientific and policy implications

6.3.1 Scientific implications

This thesis provides scientific contributions to both methods and databases in this field. First, in terms of methodological contributions, we conducted a global meta-analysis and concluded that analyses could improve on the terminologies (withdrawal versus consumption), data (which type of water is used), and system boundaries (fuel supply, power production stage, infrastructure). We also provide a methodology to study the impacts of power production and transmission on water resources and biodiversity, which may be useful for similar research in other countries. In addition, we built and implemented an electricity-hydrology model to examine the water vulnerability of power production, with a new research framework for taking account of water competition among various users and evaluating the effectiveness of adaptation strategies for the power system. Second, in terms of data contributions, the data on water requirements of electricity technologies provided by our global meta-analysis can be used for future research on the water-electricity nexus and extended to other related issues, such as studies on the food-water-energy nexus. Further, the information on water use and power production and transmission for China, as one of the major energy users worldwide, can make an important contribution to a database of global energy and water use.

6.3.2 Policy implications

To address global development challenges, the United Nations has set Sustainable Development Goals (SDGs) for 2030, including goals related to the provision of energy and water. Achieving the SDGs requires all relevant stakeholders to work together and manage the synergies and trade-offs among different resources [3]. Currently, energy and water are often managed separately, although there are many connections between them. Understanding the energy-water nexus is an important step toward both a sustainable energy transition and sustainable water management. Against this background, this thesis may provide the following policy-relevant information.

First, from the perspective of guiding the development of energy and water systems, an effective way for policymakers to mitigate energy-water conflicts is to facilitate decoupling of the two systems. We can reduce the water demand of power by developing photovoltaics and wind power, which is also an approach to achieving a low-carbon energy system. However, there is still a long way to go, despite the progress that has been made. Global power production remains dominated by water-intensive technologies. Since freshwater is not the only option, using other, alternative types of water (e.g., seawater and reclaimed water) is an effective way to save freshwater. For example, building coastal power plants with seawater desalination systems can mitigate the reliance of power production on freshwater, and the plant could even become a freshwater supplier. If a region cannot overcome the challenges by itself, using these methods, it could receive assistance from other regions via power transmission. By improving the interconnectivity of electricity grids, power production capacity in water-scarce regions can be downsized and made less susceptible to water stress. The options mentioned here are not the only ones that can help optimize energy and water systems. However, we need to be aware that several options may have trade-offs. For example, air cooling saves water but reduces the energy efficiency of power plants [200]. Wind and solar PV consume negligible amounts of water but face issues in terms of output variability, often creating a need for storage infrastructure. In such cases it is necessary to combine information on the energy-water nexus with other aspects to optimize policy decisions for sustainable development.

Second, from the perspective of supporting further research, an emphasis of future policies should be to increase the availability of data relevant for assessing water and energy systems. Global electricity generation is growing rapidly, dominated by thermal power (77% of the total) and hydropower (16%) [37]. Both are water-intensive energy technologies. Their carbon emissions have been widely monitored and assessed at the power plant level, whereas their water use has not been fully identified and reported. It is important to increase the transparency of water use (quantity, source), as it can vary greatly across power plants of the same type. For example, hydropower is a large water consumer with significant variations across plants, but currently the transparency of its water consumption-related characteristics (e.g., reservoir area, evaporation) is relatively low. Compared with the energy system, the information on the water system is somewhat more difficult to obtain. Improving the accessibility of official data on observational water discharge is a straightforward way to contribute to the nexus studies.

Third, policymakers themselves need to strengthen the links across units responsible for policy development of different resources. At present, resources such as energy and water are often managed by different departments. For example, in China, energy is mainly managed by the National Energy Administration, whereas water is managed by the Ministry of Water Resources. Considering the intractable nexus, it is necessary to develop mechanisms for cooperation between different agencies and ministries, so that synergies in resources conservation can be achieved. In addition, as discussed above, extending the links to departments responsible for socioeconomic topics would provide comprehensive insights and improve policy effectiveness. Furthermore, international collaboration on resources policies is important in transboundary river basins, where environmental impacts may take place across borders.