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

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# Chapter 1

## General Introduction

## 1.1 Energy security challenges worldwide

Energy is essential to human society and energy security is vital in maintaining many services, from health to education. Energy demand has been growing rapidly around the world over recent decades, due to rapid industrialization and population growth. Meeting this demand is a crucial but challenging task in many regions [1]. Energy infrastructure is inadequate in some developing countries and 11% of the global population still lacks access to a reliable electricity supply [2]. This issue was recognised by Sustainable Development Goal 7 (SDG 7), which calls for universal access to affordable, reliable, and modern energy services by 2030[3].

However, improving the supply and security of energy is challenging for a number of reasons. With the global energy system still largely reliant on fossil fuels, there is a direct conflict with the ambitions to limit climate change[4]. Moreover, an energy system based on fossil fuels also creates other environmental problems, such as biodiversity threats due to extraction of fossil fuel resources; emission of toxic substances, such as PM2.5, during use; and water stress due to both the use of water for cooling in power plants and the impact of hydropower plants on water systems [5, 6]. In recent decades, many studies have focused on the air pollution caused by energy production, while lately the conflict between energy and water resources is also raising concerns around the world [7, 8]. Given that both energy and water are key resources for human development, understanding their nexus is an important step toward achieving both SDG7 and several other, interconnected SDGs. Yet this nexus between energy and water resources is still insufficiently understood, especially for key, highly populous regions, such as China.

## 1.2 Energy-water nexus

In the past, resource governance mostly focused on single resource categories, such as water, land, or energy, but policymakers and researchers are now increasingly aware of the interdependencies of resources and the need to manage resources from a nexus perspective. The ‘nexus’ concept was formulated in response to siloed thinking, and emphasizes the examination of critical linkages across resources [9]. The nexus between water and energy is one of the most critical [10]. Analyses of problems and solutions for current and future energy-water nexus challenges are of significant interest to policy and research [11-14]. The energy-water nexus can be investigated in two directions, that is ‘energy for water’ and ‘water for energy’. The former focuses on energy inputs needed at various elements of the water system, including extraction from lakes, rivers, and aquifers, desalination, and water treatment [15]. The latter focuses on the water required at every stage of the energy cycle, from the extraction and processing of fossil fuels to the generation of electricity [16]. Compared with the energy constraints on water, the water constraints on energy are more prominent and have raised many concerns. Water shortages have already impacted national energy systems quite regularly in recent years, forcing reductions in energy supply [17]. This situation is likely to become worse in the future, due to growing national water consumption and climate change [18-20]. In view of this important challenge, the focus of this thesis is the water requirement for energy.

The energy system comprises various energy types, with both primary and secondary energy sources. Primary energy sources are available in many forms, including nuclear energy, fossil energy – such as oil, coal, and natural gas – and renewable sources, such as wind, solar, geothermal, and hydropower. These primary sources can be converted to electricity, a secondary energy source. Electricity is becoming increasingly important, since the ambitions to reduce greenhouse gas emissions are prompting the world to shift to a much more electrified energy system, for instance by replacing the direct use of fossil fuels for mobility and home heating with electricity-based solutions, such as electric vehicles and heat pumps [21]. At the same time, the electric power sector has become the largest water user among all energy types [22, 23]. Water is an essential requirement for operating the global power plant fleet and, as mentioned above, this has knock-on implications for energy security[5, 16, 24, 25]. Power plants face water stress and even reductions in usable capacity if their water withdrawal requirements cannot be met [26]. For example, numerous power plants in Europe had to be throttled back in the summers between 2015-2018 due to water shortages [17]. Understanding the water-electricity nexus is therefore essential to the sustainable development of water and energy systems.

It is worth noting that the impact of using water for electricity production does not end at water resources but often extends to other systems. Water resources are a major carrier of ecosystems. The impact of the increase in human water use on ecosystems is already a deep concern in many regions [27]. The water use of electric power results in freshwater ecosystem impacts caused by its water consumption and pollution [28, 29], which have often been neglected. Assessing the associated ecosystem impacts of the water use of electricity production is an important step toward ecosystem protection.

## 1.3 Cross-regional transfers of the impacts of electricity production on water resources

The picture is complicated by electricity transmission, which can separate the users from the producers of energy products and services. Depending on the extent of transmission, electricity produced at power plants can be transported over long distances for eventual use by consumers. National and regional grid systems balance the supply and demand and enable the development of power plants that are remote from centers of energy use. Electricity transmission is becoming increasingly important for global energy security [5, 30, 31], but this also creates a situation where the production-related impacts occur in a different location than the electricity use.

This 'telecoupling' of impacts via transmission has attracted much attention. Via the electricity grid, electricity users consume 'virtual' water, i.e., water used in electricity production; this is also referred to as 'virtual water transfer via power transmission' [32, 33]. The virtual water concept, first introduced by Allan (1993), is the water required for the production of goods and services along their supply chains [34, 35]. Water-scarce regions can import electricity to satisfy their domestic consumption instead of producing it locally and can thus conserve their domestic water resources [36], whereas electricity-exporting regions see the water available in their region providing services for other regions. Understanding virtual water use in relation to power transmission is highly relevant for water management and should be assessed in grid planning.

## 1.4 China's water-electricity nexus

Globally, electricity generation grew by 1.3% in 2019 – around half its 10-year average. Growth was weak or negative in most regions and mainly occurred in China, which increased electricity generation by 340 TWh (4.7%), accounting for 95% of net global growth (360 TWh) [37, 38]. In China, the electric power sector has become the second-largest water user, after irrigation [39]. Water availability is therefore a key component of China's electricity production [16, 24]. Of the total human water withdrawal, a lower percentage is used for electricity in China than in other countries, but China is one of the world's most water-stressed regions. That is, water availability per capita is classified as close to the international warning level of water stress (1700 $m^3$ per capita) [40], and the situation is likely to be further exacerbated by economic development and urbanization [41]. Additionally, studies have shown that there is a severe geographic mismatch between available water resources and thermal power plant locations across China [42]. Thus, there is an urgent need to understand the current and future conflicts between China's power production and water resources.

As the world's largest carbon dioxide ($CO_2$) emitter [43], China has set a carbon-neutral target of 2060 [44]. Many scenarios suggest that this will be met with substantial carbon capture and storage (CCS) [45, 46], potentially making the carbon available for use in the power sector (which emitted 4.2 $GtCO_2$ in 2019, comprising 41% of China's emissions) [45, 47, 48]. Most power systems modelling research has been aimed at optimising the energy mix for $CO_2$ reduction or optimising cost for various low-carbon goals [49], while the water impacts and challenges of water use for power production have not been incorporated into power system planning.

It is also of specific interest to examine the impacts on biodiversity related to the water-electricity nexus, as biodiversity conservation is attracting attention in China, where the new *Biodiversity Conservation in China* regulation [50] was implemented in 2021, with an emphasis on water biodiversity protection.

China is not only a large electricity producer but also has a large-scale power transmission infrastructure. It exchanges very little electricity internationally, but the scale of interprovincial power transmission within China is large and increasing (it increased 220% between 2008 and 2019 [51]). Interprovincial electricity transmission increased more rapidly than electricity generation, with 19.7% of the total electricity transmitted across provinces in 2019, mainly from the west to the east [48], although water scarcity is generally more severe in the west than in the east. Electricity-importing provinces are outsourcing water stress and water biodiversity impacts via transmission to other provinces, which may aggravate the water issues for some exporters. In assessments, it is increasingly important to quantify the virtual water embedded in transmission systems to provide insights for mitigating water stress across the country.

Although water and electricity are closely connected in China, the water-electricity nexus has not been fully incorporated into the country's water and electricity planning, due to a lack of information on this nexus. There is a need to depict a more detailed and complete map of the current water-electricity nexus and also its changes in the future.

## 1.5 Research questions

As discussed above, electric power production requires water resources and many power plants around the world are facing water stress. The situation is especially problematic in China due to the high water stress in most subnational regions and a geographic mismatch between water resources and the large-scale, water-intensive power production. The main research question posed in this thesis is: *What are the impacts and challenges of water use of electric power production in China?*

Investigating this question requires several studies at different stages, and prompts several further subquestions, which are listed below.

First, there are many types of electricity technologies, which have different requirements for water resources. These requirements can differ across countries due to different geographic conditions. It is necessary to understand the water requirements of various technologies across different regions.

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

To answer this question, a literature review of the existing research is needed. This also requires an assessment of the data availability and results of data on water use of power production. Here there is a focus on what country-specific data are available, because different technologies require different amounts of water.

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

To answer this question, an inventory of power production, transmission, and China-specific water intensity is used. On the basis of the answers, we can move on to the next stage, i.e., to assess the impacts of power production on the water system.

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

To answer this question, both freshwater consumption and freshwater thermal pollution of power production need to be quantified. Freshwater biodiversity loss will be estimated, to assess the extent of the impacts. The above three stages show the impacts of power production on water resources and the related biodiversity; on the other hand, power production faces challenges from water resources if its water requirements cannot be met. This issue is studied in the next stage.

***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?*

To answer this question, we combine a hydrological model and a thermoelectric power model. We assess the water stress faced by thermal power in the future and the impact that CCS as a solution for net-zero carbon emissions could have on water issues faced by the power sector.

## 1.6 Guide to this thesis

This thesis consists of 6 chapters (Figure 1.1). This first chapter gives a general introduction, describing the motivation, research questions, and outline of the thesis.

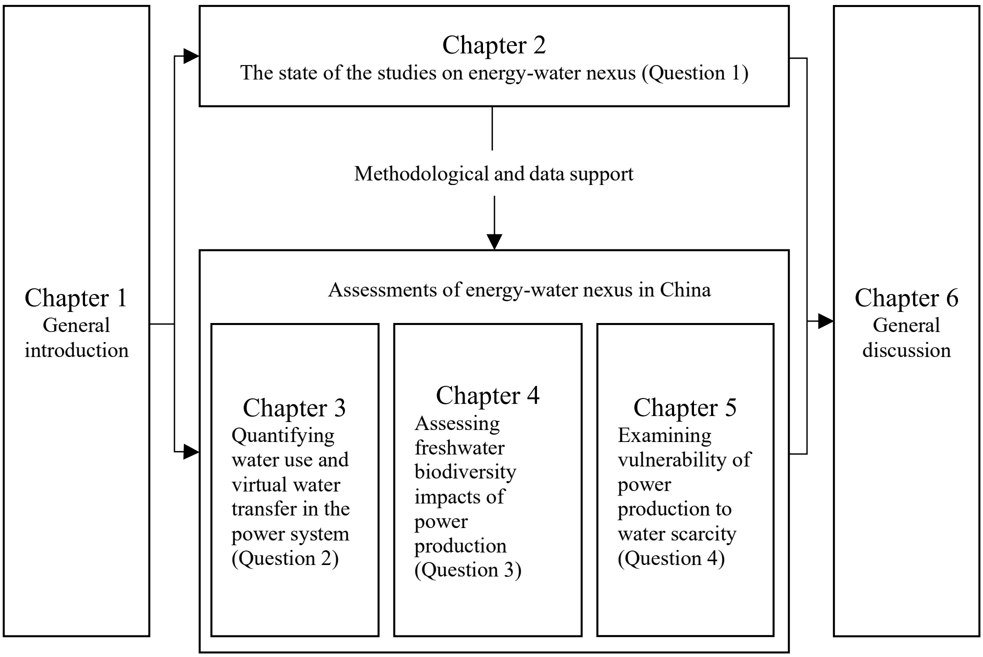


**Figure 1.1** Outline of this thesis.

**Chapter 2** addresses the first research question. It presents the available data on water use of power production at different life cycle stages, gathered by conducting a global meta-analysis. The differences in water use estimates within and across power types are reported, and the key drivers behind them are analyzed. We then analyze the uncertainties in assessments from the perspective of both methodological theories and the data inventory that we compiled. Finally, gaps in knowledge are identified to guide future studies.

**Chapter 3** addresses the second research question. It quantifies the water use of power production and virtual water transfer via power transmission across China, using information on numerous renewable and non-renewable power-generating units and interprovincial power transmission. On this basis, it investigates the spatial and seasonal variations in water use and virtual water, and the impacts of power production and transmission on provincial water stress.

**Chapter 4** addresses the third research question. It assesses the freshwater biodiversity loss caused by China's power production and the embodied biodiversity loss in power transmission. In this process, the characterization factors of water use impacts on freshwater biodiversity are developed for China. Further, based on the results, we analyze the decoupling relationship between biodiversity loss and electricity and the driving factors of the changing biodiversity loss.

**Chapter 5** addresses the fourth research question. It examines the vulnerability of power production to water scarcity in China by developing a hydrology-electricity modelling framework, which quantifies the impacts of the changes in water availability and climate change mitigation actions of power plants (i.e., CCS) on power production. It also tests a set of adaptation options that have the potential to mitigate the vulnerabilities of power production.

**Chapter 6** presents a synthesis of the answers to the research questions given in the preceding chapters, followed by a general discussion and outlook for future work.