Chapter 5

Climate change and CCS increase the water vulnerability of China's thermoelectric power fleet

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Abstract: Large numbers of China's thermal power plants are in water-stressed regions. Changes in the availability of water resources due to climate change may impact the vulnerability of regional and national electricity generation. Here we explore this vulnerability for coal-fired power units (CPUs) as the generation-type most exposed to climate risk. We find many plants are already experiencing water scarcity and 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 CPUs will increase slightly, mainly due to an increase in water availability for power plants in northern China under all climate scenarios except RCP8.5. However, CCS systems have been identified as essential in China's national roadmap for carbon neutrality and their use represents high water requirements. The addition of CCS significantly exacerbates water vulnerability, leading to further usable-capacity reductions of 7.4-7.7%. We assess several adaptations and find that early retirement of power plants is most effective, with interregional power transmission also playing an important mitigating role. Our work highlights the need for improved awareness of water resources in electricity planning.

5.1 Introduction

Despite efforts to increase renewable energy and reduce coal power, 67% of global electric power in 2018 was produced by thermal power with 38% from coal-fired power plants[37]. Global electricity demand is expected to increase with a growing world population and, more significantly, with increasing consumption levels[19, 20, 26]. Water is an essential requirement for operating the global power plant fleet and has knock-on implications for energy security[5, 16, 24, 25]. However, climate change and water shortages have increased the sensitivity of power production to water availability[189], raising both research and policy concerns[299]. During 2011-2015, 43% of the global coal-fired power plant capacity experienced water scarcity for at least one month per year and 32% experienced scarcity for five or more months per year[292]. Severe water shortages can result in power curtailments and reduce the reliability of the electrical power system[53, 300].

China produced 26% of the total global electric power in 2018[37], with thermal power as the main contributor (accounting for 72% nationally[264]). In 2007, thermal power was responsible for roughly 10% of the total national freshwater withdrawal[23, 39, 168,

[201]. This proportion is relatively low compared to other regions, such as the US (45%)[238] and Europe (43%)[239] for the same decade. However, there is a severe geographical mismatch between water resources and thermal-power plant locations across China[42], as many thermal power plants are located in water-stressed regions. Research has focused on the water use of thermal power production[23, 168, 202], but few have connected plants' water use to water availability to assess vulnerability under climate change. Zheng et al.[301] made a step forward by identifying regions where power production is vulnerable to water scarcity, but did not capture finer-scale spatial-temporal variations in water availability, potential usable-capacity reductions of power plants, or the impact of power transmission.

Power plants face reductions in usable capacity if the required water withdrawal – the volume of water diverted from a water source for use – cannot be met[26]. Research on the vulnerability of thermal power to changes in water resources for the US[300, 302] and Europe[26, 241] indicate reductions in usable capacity and power supply shortages under future climate change. Previous studies simulated the available water resources for thermal power, but changes in water use for other sectors (e.g. irrigation) are not often incorporated. These other sectors often result in additional constraints for the electricity sector[53]. While previous work has been conducted on the level of the river basin[53], water scarcity is at the plant level and a higher spatial resolution is needed for localized assessments of water scarcity and its impacts on power production. This is important in China's case, since the power sector sees heavy water competition with other users. For example 84% of China's CPUs being close to residential areas and farmland (Figure S7.4.1).

A plant-level analysis is essential to a vulnerability analysis since individual plants can be significant withdrawers and consumers of water within a region. This requires knowledge of the cooling type for each unit within a plant (since the cooling type is a strong determinant of water use[13, 16]). There are three common cooling types: once-through cooling, closed-loop (wet tower) cooling, and air cooling[200]. A further complication is that there are four main types of cooling water used in China: surface water, groundwater, reclaimed water, and seawater. Distinguishing these different cooling and water types can be a challenge due to data availability, but they are important if we are to gain a deeper understanding of the vulnerability of power production to water scarcity.

We can expect many policy and technological responses to water constraints in the power system, so it is also important to assess adaptation and mitigation strategies. Van Vliet et al.[26] considered strategies for power plants globally but did not include the role of the power transmission network. Interprovincial power transmission plays an increasingly important role in China's energy system (increasing 220% between 2008 and 2019[48]). Increased power transmission facilitates the shifting of generation away from highly water-scarce regions.

Climate change mitigation (e.g. carbon emission reduction) can also have direct and large impacts on water scarcity issues. Zhang et al. indicated that there are conflicts between water conservation and carbon emission reduction of China's thermal power[303]. Tang et al. showed that peaking China's power sector carbon emissions before 2030 may increase the water consumption due to the expansion of nuclear power according to their simulation results[304]. While renewables have much lower water requirements, urgent emission-reduction requirements, political trade-offs, and existing infrastructure mean that China's energy transition strategy utilizes large amounts of carbon capture and storage (CCS) during the 2030s[45, 46, 305]. Many proposed scenarios for meeting Net-Zero carbon by 2060 require significant amounts of CCS, with one model proposing 850 GW coal, gas, and biofuels be retro-fitted with CCS[45]. While CCS is regularly promoted for thermal power plants (which emitted 4.2 $GtCO_2$ in 2019, comprising 41% of China's emissions)[45, 47, 48] and there are some demonstration stage projects [306] CCS will require additional water resources[292]. Reliance on CCS may place significant additional stress on water-scarce regions. There are other CCS approaches with lower water requirements, such as oxyfuel and pre-combustion, but it is generally thought that post-combustion capture technology will be the most common by far, given its ease of implementation and technological maturity[109, 307]. For this reason, we focus on post-combustion technology here.

To address these issues, we developed a hydrological-electricity modelling framework. This framework examines the vulnerability of power production to climate change and water scarcity at a monthly time step and a 5-arcmin spatial resolution of the river network. This contrasts with existing macro-scale studies that typically use a 0.5°-resolution[26, 53, 241]. We include individual water uses of power plants, four water types, electricity-specific water availability and the national transmission grid. We use two indicators to measure the impacts of future water availability on power production: the number of months that CPUs face water scarcity and the usable capacity reduction. The former reflects the time span of impacts and the latter reflects the severity of impacts.

We also tested 5 adaptation options to mitigate power system vulnerabilities that may be exacerbated by CCS. An adaptation is considered effective if the usable capacity increases after its implementation and include: (1) Switching to seawater cooling for all CPUs close to the coast (within 10 km and already encouraged for these geographical areas in national policies)[53, 237]; (2) Replacement of once-through cooling systems with closed-loop systems that decrease water withdrawals; (3) Increasing all power plants' water use efficiency to the same level as today's state-of-the-art units[286]; (4) Improving power transmission between regions of low and high water stress, allowing for closure of generation in water-stressed regions and new generation in regions of lower water stress[53, 308, 309]; and, (5) Closing coal units after 30 years, rather than 40 [304, 307, 310] due to additional energy transition policy pressures (we assume no new CPUs will be built to compensate and that the gap will be filled by low-water intensity renewables).

This study makes several contributions: First, we built and solved an electricity-hydrology model at the individual plant level and a monthly time scale and assess the vulnerability of power production to water scarcity in China under climate change. This provides a template for similar analyses in other nations (previous assessments focused on the USA [308] and the European Union [53]). Second, CCS may be used for power plants but its impacts on power production have not been examined (Zhu et al. investigated overall water use by CCS but did not assess the influence on electricity generation [311]). Here, we quantified the impacts of CCS on the vulnerability of plants. Finally, we quantitatively evaluated the efficacy of several flexible adaptation strategies whereas previous studies only qualitatively analyzed them[301, 312].

5.2 Materials and Methods

The overall modelling approach is shown in Figure 5.1 and we present detailed steps in Sections 5.2.1-5.2.5. Impacts of water scarcity on thermoelectric usable capacity were quantified for the 2030s under four different climate scenarios (Representative

Concentration Pathway (RCP) 2.6, 4.5, 6.0, and 8.5) relative to a reference period 1992-2001.

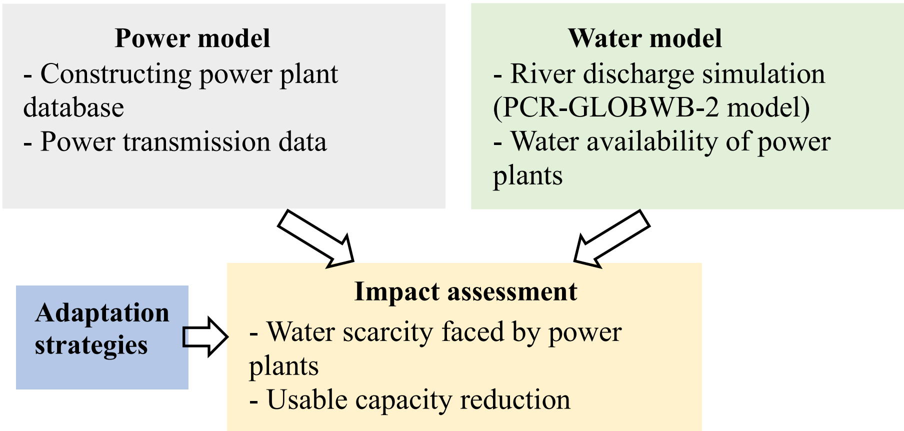

Figure 5.1 Model framework used in this study. The different colors indicate the different models used in the framework.

5.2.1 Power model

We compiled a database of coal-fired power units (CPUs) including plant name, installed capacity, the beginning year of operation, unit type, location, operation status, and cooling system. Data were sourced from the Global Coal Plant Tracker[38], World Electric Power Plants Database[215], and the China Electricity Council[217]. Coal dominates China's thermal power production with gas power plants accounting for less than 5% of the total (Oil power is not included in this assessment due to its very small contribution at only 0.05% of production). In total, 3050 power production units were included (accounting for 98% of the national total installed CPU capacity in 2017). To verify CPU cooling systems, we used Google satellite imagery cross-checked with information from the China Electricity Council[217]. We obtained the water type for cooling from the China Electricity Council[217] and the Power Industry Statistical Information System[222]. This study focuses on plants using surface water rather than groundwater, seawater and reclaimed water, thus 2265 units were investigated (in total 749.8 GW, 75.2% of the total capacity of CPUs). We used China-specific water use factors for power plants (specific water use for 95% of CPUs were obtained from the China Electricity Council[217] and 5% from previous research[16]). Once-through cooling water withdrawals were obtained from Zhang et al.[23], who used the monitoring data of withdrawals for some plants with once-through cooling systems in the Yangtze River basin.

To examine adaptation options using the power transmission network we compiled an inventory of inter-provincial power transmission for 2008-2017 with data from the China Electricity Council[51]. These data are mostly reported in the form of province-to-province transmission. Additionally, there are some data covering transmission from provinces to the subnational grid. We disaggregate these data into the province-to-province transmissions based on actual electricity transmission lines[8, 220]. China's provinces and river basins are shown in Figure S7.4.3.

5.2.2 Water model

Monthly available surface water (WA) at a spatial resolution of 5-arcmin was calculated as the difference between monthly river discharge and the environmental flow requirement. Monthly river discharge was simulated using the PCR-GLOBWB-2 model[313]. For current conditions, we use the PCR-GLOBWB-2 run based on the European Union Water and Global Change (EUWATCH) data where the actual meteorological observation datasets are used. For future conditions we use PCR-GLOBWB-2 runs based on the data from five different global climate models (GCMs) forced with the four representative concentration pathways (RCPs)[314]. The five GCMs are MIROC-ESM-CHEM, IPSLCM5A-LR, HadGEM2-ES, NorESM1-M, and GFDL-ESM2M and their ensemble means are then applied for the final water availability. We obtained the bias-corrected future conditions (based on EUWATCH and GCM runs). The correction procedure is given by:

$$future\_corrected = present\_watch + (future\_gcm - present\_gcm) \qquad (1)$$

Where the *present_watch* represents present-day values based on the EUWATCH run; *present_gcm* and *future_gcm* represent values obtained from GCM runs in historical (under present-day greenhouse gas concentration forcing) and future (for various RCP scenarios) simulation periods.

Environmental flow is defined as the minimum freshwater flow required to sustain ecosystem functions[292]. For the rivers that supply water for human use in China, 60% of the average discharge needs to be preserved for environmental flow[315]. Environmental flow requirements are the most important factor that influences water availability for power production. Rose et al. showed little sensitivity of water scarcity to different environmental flow requirements[292]. Here, we tested the sensitivity of usable capacity changes and adaptations to environmental flow requirements. Upstream water consumption and reduced availability for downstream uses were accounted for by considering all water uses (irrigation, livestock, households, and industry). The water use for thermoelectric cooling of power plants is not included in PCR-GLOBWB-2[313]. Water consumption was assessed by multiplying the withdrawal and the corresponding China-specific factors (sector-specific consumption-to-withdrawal ratios [225, 316]). Factors for agricultural, industrial and domestic sectors are 0.65, 0.23 and 0.40, respectively. Ratios of surface water consumption to total water consumption were obtained using provincial data. We further assessed surface water consumption by multiplying consumption and the above ratios. The proportion was obtained from the Ministry of Water Resources at the provincial level[225]. We made assessments for RCP2.6, 4.5, 6.0 and 8.5 climate scenarios, capturing the largest range of uncertainties in the future greenhouse gas concentration scenarios. RCP2.6 describes a world in which global warming is kept well below 2 °C by 2100 relative to pre-industrial temperatures. RCP8.5 depicts a future that excludes any climate mitigation policies, leading to nearly 5 °C of warming by the end of the century. RCP8.5 should be considered as an unlikely worst case[317].

5.2.3 Impact of water availability changes on power production

The monthly water scarcity (WS) for each grid cell was assessed using the monthly availability and consumption of surface water resources. We extracted river discharge for each grid cell in which each power plant is situated. For cases in which the power plant and river are not in the same grid cell, the river discharge of the grid cell where the river is located is used. In this way, the available river discharge of 566 units (25% of the total) is corrected. CPUs are located in water-scarce areas if the ratio between water consumption (WC) and available water (WA) is > 1 (after the removal of environmental flow requirements and for renewable water availability only)[318].

$$WS = \frac{WC}{WA} > 1 \qquad (2)$$

Koch and Vögele[319] and Wang et al.[320] built models to assess the thermoelectric power usable capacity reduction caused by water scarcity. Since these studies do not consider competition for water between the electricity sector and other sectors, we further modified these models. Additionally, the water withdrawals of CPUs in these studies were calculated based on cooling water temperature regulations and power-plant-specific characteristics. There is no regulation on cooling water temperature in China so we did not estimate the withdrawal based on temperature restrictions but used the unit-specific withdrawal data obtained from the sources mentioned above. The equations for estimating the usable capacity reduction are:

$$q = KW \cdot t \cdot WW \tag{3}$$

$$P = \min\,(Q - NEW, q) \cdot \frac{1}{t \cdot WW} \tag{4}$$

Where q = monthly required water withdrawal (m^3); KW = installed capacity of CPU (MW); t = The number of hours in each month (h); WW = water withdrawal factor (m^3/MWh); P = usable capacity of CPUs (MW); Q = monthly river discharge (m^3); NEW = water consumption of non-electricity sectors (m^3).

5.2.4 Assessing the impact of CCS on the vulnerability of thermal power

The use of large amounts of CCS to meet climate targets represents a significant potential threat to water scarcity. Here we assume a CO_2 capture efficiency of 90% based on previous work[307, 310, 311, 321, 322]. Considering that small (≤100 MW) CPUs will probably be shut down before being retrofitted with expensive CCS technologies, we assume that only large (>100 MW) CPUs will be retrofitted (in total 733 GW). Although 100% adoption of CCS is unlikely, this assumption allows us to assess the impacts of CCS retrofit on water future vulnerability. This assumption is in line with the urgent need for rapid carbon reductions to meet climate targets[292]. We assess the above adaptation options for both the non-CCS and CCS scenarios. The water requirements of power production with CCS are obtained from Jin et al. 2019[16]. We assessed the cost of CCS-related usable capacity reductions by assuming that the reduced capacity needs to be compensated by building new capacity. The cost is assessed as:

$$CC = CR \cdot IC \tag{5}$$

Where CC = the cost of new capacity (US$); CR = total usable capacity reduction (kW); IC = the investment cost of CPU (US$/kW). The investment cost of China's CPU is US$617/kW [310].

5.2.5 Adaptation options

We tested five adaptation option. Four options focus on thermal power plants due to their large water withdrawal, while one is based on the transmission:
(1) Switching to seawater cooling for all CPUs close to the coast (within 10 km)[53].

(2) Replacement of once-through cooling systems with closed-loop systems (which have lower surface water withdrawal requirements for all power plants).

(3) Increasing power plant water use efficiency to the same level as today's state-of-the-art units (where the state-of-the-art is defined as the average of the 10% most water-efficient plants per MWh generated for each cooling type)[286].

(4) Improving power transmission between low-vulnerability and high-vulnerability regions.[53, 308, 309]. We assume the plants facing water scarcity in vulnerable regions (those experience significant reductions of >2 GW under all scenarios) will be closed, and the generation displaced to regions with low water scarcity. This reallocation is made in proportion to the transmission capacity between those regions based on 2017 data (the latest available year). Within each low-vulnerability region, generation will be allocated to power plants in proportion to, but not exceeding, the plant capacity.

(5) In the absence of early retirement, 86% of current CPUs will be in operation in the 2030s with an average operation time of 40 years. We assume that plant lifetimes will decrease to 30 years due to additional policy pressures[53, 323]. Older plants with higher water intensity and lower energy efficiency are retired earlier [308]. Under the International Energy Agency's (IEA's) sustainable development scenario, China's wind and solar PV will experience a rapid increase by 4600 TWh during 2019-2040, equal to the total coal power production in 2019[285]. This indicates a possibility fill the power gaps in an early retirement scenario where 58% of current freshwater-using CPUs retire. Energy storage technologies work well with variable renewables and there is a growing trend of pairing battery storage with solar PV and wind. Energy storage typically has little to no water requirements except for pumped hydro and hydrogen [324]. However, it is expected that growing battery capacities will provide most storage requirements [285].

To examine the efficacy of adaptation options when CCS is implemented, the usable capacity changes in the 2030s relative to the reference period are calculated for six scenarios separately: baseline (i.e. without adaptation options) and the five adaptation options. We use the expression:

$$C = (P_{2030} - P_r)/P_r \quad (6)$$

Where P_r = usable capacity in the reference period (MW); P_{2030} = usable capacity in 2030 (MW) for each scenario; C = usable capacity change. If C of an adaptation option is larger than that of the baseline, the adaptation option is considered effective; if C of an adaptation option is larger than not only that of the baseline but also 0, the option is effective enough to offset the impacts of CCS and water scarcity under climate change.

5.3 Results

5.3.1 The impact of water availability changes on thermal power

Nationally, annual river discharge increases in the 2030s relative to the reference period (1992-2001) for all scenarios. The Yellow and Yangtze river basins feed 23% and 22% of CPUs respectively and also see increases in annual river discharge under all climate scenarios (Figure S7.4.2). The Southeast basin experiences significant decreases in river discharge but feeds only 1% of total CPUs. However, existing policies already account for some heterogeneity in water availability[325]. Nationally, once-through cooling, air cooling, and closed-loop cooling account for 14%, 29%, and 57% of the total CPU capacity, respectively. Closed-loop cooling systems are used throughout the country. Once-through cooling systems are mainly located along the Yangtze River (due to the need for large water withdrawals). By contrast, air cooling systems are mainly in the north, especially in Continental and Yellow river basins (Figures S7.4.3 and S7.4.4).

Our results show that 40% of CPUs experience water scarcity for at least one month and 22% experience severe water scarcity (six or more months) in the reference period (Figure 2). These historical difficulties are often underreported in media and industry. However, a 2012 *Greenpeace* report highlights some instances where China's CPUs are facing water shortage risks[326]. Of the CPUs starting operations before 2000, 36% face water scarcity, and of the CPUs starting operations after 2000, 41% face water scarcity. This suggests a significant mismatch between water availability and demand for the recently built plants. For most rivers in China, water flow is higher in summer than in winter[327]. Accordingly, February is the most acute month for water scarcity overall with 32% of CPUs facing water availability issues, while September sees only 9%. Large amounts of generation see severe water scarcity across Inner Mongolia and Shandong provinces (22 and 20 GW, respectively). On net, CPU capacity experiencing water scarcity will increase by 43-82 GW in the 2030s, relative to the reference period (ranges indicate the minimum and maximum combinations of scarcity and capacity availability). This net result shows 43-56 GW of capacity faceing water scarcity for at least one fewer month a year, and 120-176 GW of capacity exposed to water scarcity for at least one additional month a year.

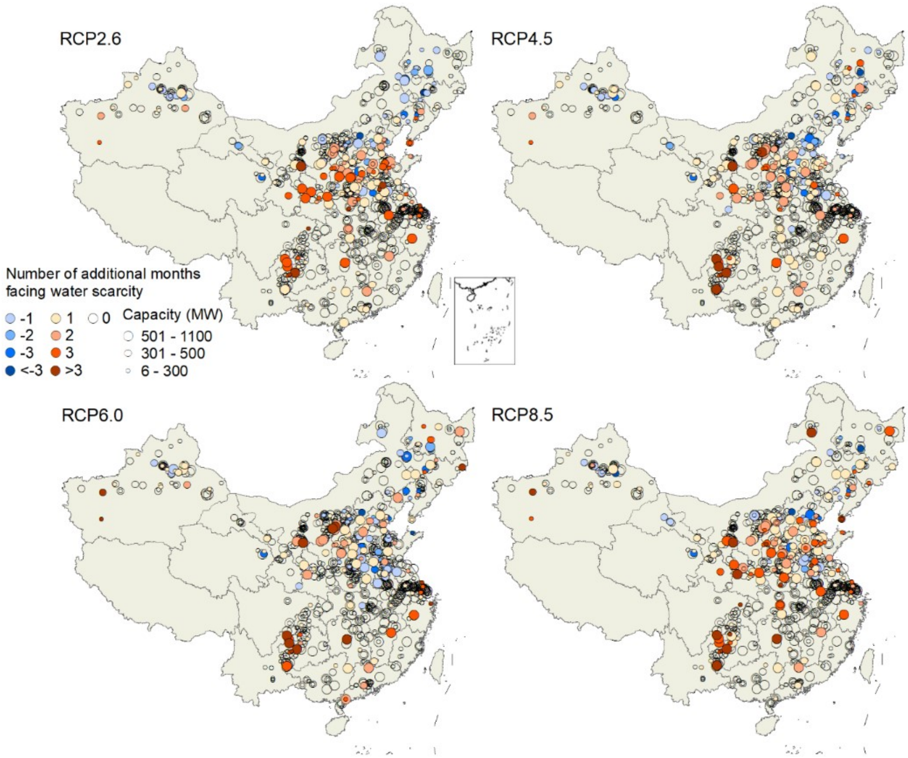

Figure 5.2 Additional water scarcity faced by CPUs. The number of additional months per year when coal-fired units face water scarcity in the 2030s compared to the reference period. Negative values refer to the number of fewer months of water scarcity per year that CPUs face.

Nationally, CPUs experience an increase in the usable capacity of 0.3-1.4% in the 2030s relative to the reference period for RCP2.6, RCP4.5, RCP6.0, whereas RCP8.5 sees a decrease of 1.0%. The impact of water availability changes on usable capacity differs across plants and provinces (Figure 5.3). We show that 22-34% of CPUs face usable capacity reductions and 3-6% face severe reductions (>30%). Between 30 and 38% of CPUs face usable capacity increases. Xinjiang, Hebei and Inner Mongolia provinces experience remarkable usable capacity increases (>0.5 GW), while Guizhou and Shaanxi experience remarkable reductions (>0.5 GW) in all scenarios (Table S7.4.1). There are also seasonal variations in usable capacity reductions (Figures S7.4.5- S7.4.8). Summer sees usable capacity reductions by 0-6.4 GW in all scenarios. Winter sees an increase of usable capacity by 6.5-12 GW in RCP2.6, 4.5 and 6.0, and a decrease by 2.5 GW in RCP8.5.

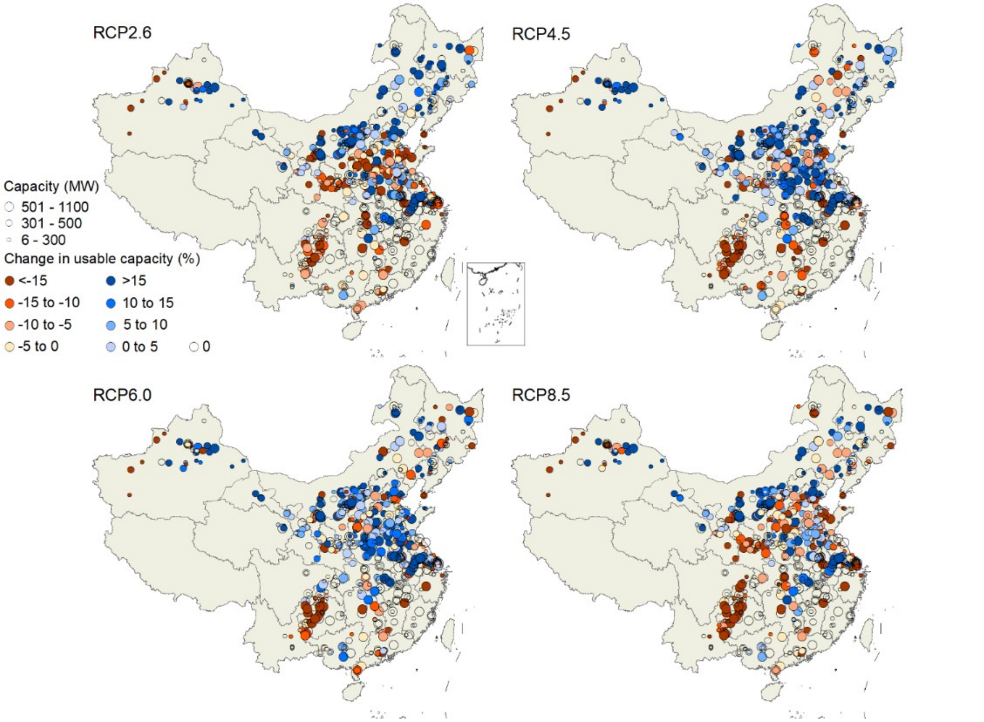

Figure 5.3 Impacts of climate and water resources change on annual usable capacity of CPUs. The changes in the annual usable capacity under four climate scenarios in the 2030s compared to the reference period.

5.3.2 The impact of CCS and adaptation options

The water requirement of power production with CCS can be 53-77% higher, depending on CPU configuration [16]. We find that requirements can be as high as 14.8 billion m^3 per $GtCO_2$ sequestered. Given these water requirements, the addition of CCS increases vulnerability to water stress broadly across all plants. Our results show that adding CCS to plants leads to additional usable capacity reductions of 7.4-7.7%. Between 49 to 55% of CPUs face usable capacity reductions and 15-21% of CPUs face severe reductions (>30%) (Figure S7.4.9). All provinces experience CCS-related capacity reductions except Xinjiang, Qinghai, and Beijing. Several provinces including Guizhou, Henan, Shaanxi and Jiangsu experience significant reductions (>2 GW) under all scenarios (Table S7.4.2).

Given these CCS-related reductions, out of all adaptation strategies only early retirement can increase usable capacity across all RCP scenarios (by 2.8-4.5%, Figure 5.4). Retrofitting the existing plants for seawater use can only slightly mitigate the vulnerability. Cooling type switches and increased water use efficiency may help but are not sufficient to increase capacity compared to the reference period (when CCS is implemented). Increases in transmission can effectively mitigate the CCS-related vulnerability. Water availability is the largest factor affecting our findings. Here, the environmental flow, defined as the minimum freshwater flow required to sustain ecosystem functions, is the most important factor that influences water availability for human purposes[292]. We find little sensitivity to the changes in environmental flow requirements for all adaptation strategies (within 2% of variations) except for early retirement. When the level of protection for ecosystems is high, e.g., 80% of discharge, the efficacy of retirement is extremely high.

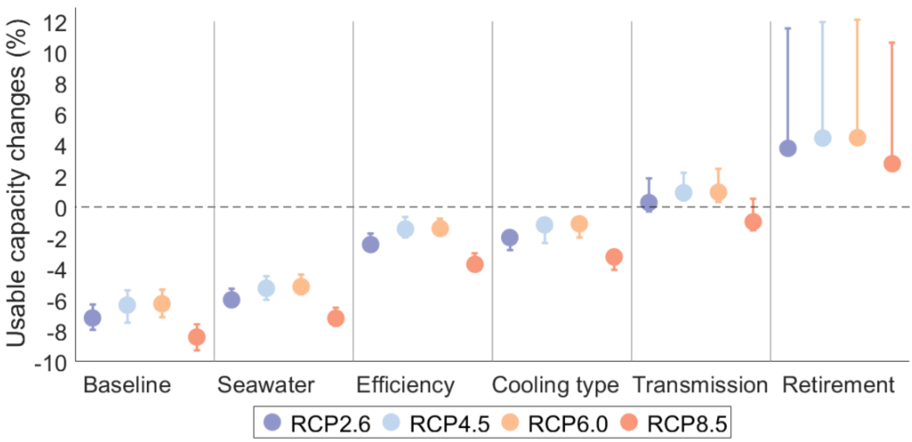

Figure 5.4 Impacts of adaptation on CCS-related CPU vulnerability to water constraints. Usable capacity changes in the 2030s relative to the reference period for the baseline settings (i.e., without adaptation options) and various adaptation options are shown as markers per climate scenario. Ranges indicate the sensitivity of usable capacity to the changes in environmental flow requirements (40-80% of river discharge for environmental flows).

5.4 Discussion

5.4.1 Comparisons with previous studies

On an aggregated, national level, we show that 40% of installed capacity experiences water scarcity for at least one month during the reference period (1992-2001). For comparison, Rosa et al.[292] found that 47% of installed capacity experience water scarcity in China during a later period (2011-2015). Water availability of power production can significantly influence vulnerability. Rosa et al assumed 80% of the monthly river discharge for environmental flow which may be high. According to Han et al.[315], an 80% proportion is recommended for protected rivers, reservoirs, and national parks, whereas 60% is considered sufficient for rivers that supply water for human use (and is the value used here). In terms of usable capacity reductions, van Vliet et al.[26] show reductions in usable capacity for 81-86% of the thermoelectric power plants worldwide in 2040-2069 relative to 1971-2000, with reductions in Asia lower than the world's average. Our results show that 22-34% of China's CPUs will face usable capacity reductions in the 2030s relative to the reference period, depending on future climate changes.

5.4.2 Challenges of mitigating vulnerability

Policymakers are becoming increasingly aware of water supply issues and, in some cases, have implemented water-saving regulations. For instance, there are now restrictions for adding new capacity to the Jing-Jin-Ji area (Beijing, Tianjin, and Hebei). We show that while this key area should be of focus, policies could be expanded to surrounding areas (e.g., Shaanxi, Shanxi, Shandong, and Guizhou). The most effective adaptation, early retirement, faces challenges. If plant lifetime is limited to 30 years, 58% of current CPUs will retire in 2040, resulting in a large power generation gap that would have to be rapidly met with alternatives. However, this assumption of early retirement is less radical than other scenarios. Under the IEA's sustainable development scenario, Chinese coal power production would decrease by 69% in 2040 relative to 2019[285]. In another, faster phaseout, Cui et al.[328] proposed a scenario whereby conventional coal-fired power plants without CCS decline by more than 90% in 2040. If the power gap caused by the shutdown of thermal power plants is filled by water-intensive energy technologies rather than renewables (e.g., wind and solar power, which generally consume orders of magnitude less water than thermoelectric generation), the effect of early retirement on water resources will be lower than expected. Early retirement also has economic and social issues, i.e., the impacts on profitability and employment of coal-fired power plants and coal mining[328]. Cooling technology is also a policy concern, with the share of air cooling systems increasing quickly since it became a government requirement for water-scarce regions in 2004[231]. Air cooling is effective in water-saving but does require higher investment and has a lower energy efficiency[200]. Using seawater is also a useful adaptation strategy and China's power sector is already the largest seawater user, accounting for more than 90% of the national total volume of seawater utilization[23]. However, the price of desalinated seawater is still higher than freshwater[329]. Although constructing coastal power plants can save freshwater, there is a challenge for coal resources far from the coast. Long-distance coal transport from inland to coastal regions is also energy- and water-consuming, to an extent that is not fully understood[330]. The trade-offs between water use and other environmental and economic issues need to be weighed before plant and cooling system construction. Power transmission enables the shifting of generation away from highly water-scarce regions. At the national scale, power transmission enables a lower water requirement for power production. An estimated 10 billion m^3 of withdrawal is saved due to current power transmission[8].The vulnerability decreases in power-importing regions but increases in power-exporting regions. If the closure of highly vulnerable thermal power plants can be compensated for by using wind and solar power in power-exporting regions and increasing power transmission, water vulnerabilities would see further mitigation. With the proposed development of west-to-east transmission lines and hydropower in the southwest[236, 331], power transmission will play a more important role in vulnerability mitigation for water-scarce regions.

China has pledged to make efforts to be carbon neutral before 2060[44, 332], which could be realized with several different energy system choices. Renewables will play an important role in achieving the target. Previous research indicated that China would have to ramp up solar and wind capacity over the next 40 years, including a 16-fold increase in solar and a 9-fold increase in wind, which would represent a significant shift in the temporal and spatial supply of electrical power and require further efforts to ensure energy supply, including short- and long-term energy storage[45, 333]. Hydropower is the second largest electricity supplier in China, it contributes to a low-carbon system but also relies on water resources. As an effective technology for carbon emission reduction, CCS has not been widely adopted in large part because of its high investment[45]. From the perspective of economic costs, the usable capacity reduction caused by CCS should be accounted for in CCS investments. In this case, the capacity-related cost due to water-scarcity of large-scale CCS adoption is US$34-36 billion (or approximately US$10 per tCO_2 sequestered). Fan et al. compared the investment benefits of CCS retrofitting of coal-fired power plants and renewable power generation projects in China, finding that Ningxia, Xinjiang, and Gansu Provinces would be most suitable for the development of CCS retrofitting pilot projects[334]. We suggest that the capacity-related costs of CCS be included in future economic assessments, as should several other factors such as air pollution and ash disposal. In reality, policymakers and entrepreneurs need to incorporate several different adaptation options simultaneously to achieve multiple objectives in terms of, among other factors, power system reliability, economic cost, and compliance with regulations.

5.4.3 Limitations and implications

Although this work integrates water and electricity models and we assess different scenarios, we are unable to exactly predict power production or new power transmission lines due to the difficulty of predicting the capacity, cooling type and location of future CPUs. The optimization of the transmission network is not only important for the reliability of the power supply but can also mitigate the vulnerability of power production to water scarcity. Further research is needed to optimize the network with the consideration of future transmission lines, regional electricity mix, economic cost, etc. The water use factors of thermal plants, specific to China's power plants, were assumed to be constant throughout the year, yet plants often have higher water requirements in summer than in winter due to lower thermodynamic efficiencies[16, 241]. This assumption may lead to an underestimation of the seasonal variations in power-related water use.

In this study, we focus on showing the changes in the performance of thermal power when faced with changing climate and water resources under different climate scenarios rather than the situation in a reference period. Each RCP runs for the period 2006-2099 with different trajectories in radiative forcing and temperature. The reference period used in our study makes the impacts under different RCPs comparable and enables us to see the impacts of changing water availability on power plants. As such the actual water availability in 2021/2022 is not an input of our model, having been calibrated until the end of our reference period in 2001. Further research could use a more recent reference period as and when sufficient meteorological data are available. Other future work could investigate the role of China's power plants in exacerbating water scarcity threats of other nations and the electricity-hydrology model can be used for the nations where the data on power plants are available. Further, more adaptation strategies should be tested according to the local conditions such as resources, infrastructure, and policies. Early decommissioning of coal in China would likely preclude the possibility of RCP8.5 and potentially even RCP6.0. However, given disagreements in the literature between energy and climate modellers we include the full spectrum of results[317, 335]. While updated pathways for carbon emissions are available, PCR_GLOBWB-2 was produced with bias-corrected RCP trajectories. It would be useful to update the analysis using Shared Socioeconomic Pathways in future analyses.

We recommend three actions to further mitigate the vulnerability of thermal power plants. First, it is important to take into account climate and water-scarcity changes when planning the power plant construction. Thermal power plants generally have a long lifetime, which requires assessments on both current and future water resources. Second, the competition for water between the energy sector and other users (agricultural, industrial, domestic, and environmental water requirements) needs to be considered in water resources assessments. Third, the role of adaptation strategies should be considered from the perspective of both individual plants and the power system as a whole, since early retirement is key to reducing water vulnerabilities. With the improvement in transmission technologies and the lowering of transmission costs[336], it is becoming more feasible and important to replace vulnerable power plants in water-scarce regions with ones in regions with sufficient water resources.

5.5 Conclusion

This study presents an assessment of the vulnerability of China's thermal power production to changing climate and water resources using a coupled hydrological-electricity modelling framework. The following conclusions are reached:

China sees a significant spatial heterogeneity in water resources. Nearly half of freshwater-using plants are located in the two major river basins (Yellow and Yangtze) due to their need for water withdrawals. Many plants are close to residential areas and farmland, and are already facing the challenge of competing water with other users, which is an issue that has become worse for the newer power plants over the last two decades. Further, there are seasonal variations in water scarcity, with February the most acute month and September the least. The plant capacity experiencing water scarcity will increase in the 2030s.

The main contributions of the study are showing the water scarcity faced by power production in China, and to what extent CCS will exacerbate the issue.. On the national scale, power production experiences slight changes in the usable capacity in the 2030s relative to the reference period. When CCS is implemented, the vulnerability of power production increases, with additional usable capacity reductions of 7.4-7.7%. Early retirement and interregional power transmission are more effective in vulnerability mitigation than other adaptation strategies from the perspective of usable capacity. However, strategies may also face other challenges from economic, energy security, employment etc. Policymakers and industry will need to be cognizant of the challenges when implementing these adaptation options.