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Long-term transition of China's power sector under carbon neutrality target and water withdrawal constraint

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ABSTRACT

Deep carbon mitigation and water resources conservation are two interacted environmental challenges that China's power sector is facing. We investigate long-term transition pathways (2020–2050) of China's power sector under carbon neutrality target and water withdrawal constraint using an integrated capacity expansion and dispatch model: SWITCH-China. We find that achieving carbon neutrality before 2060 under moderate cost decline of renewables by 10–20% depends heavily on large scale deployment of coal-fired power generation with carbon capture and storage (CCS) since 2035 in China's water-deficient northwestern regions, which may incur significant water penalties in arid catchments. Introducing water withdrawal constraints at the secondary river basin level can reduce the reliance on coal-CCS power generation to achieve carbon neutrality, promote the application of air-cooling technology, and reallocate newly built coal power capacities from northwestern regions to northeastern and southern regions. If levelized cost of renewables can decline rapidly by about 70%, demand for coal power generation with CCS will be significantly reduced by more than 80% and solar photovoltaic (PV) and wind could account for about 70% of the national total power generation by 2050. The transition pathway under low-cost renewables also creates water conservation co-benefits of around 10 billion m^3 annually compared to the reference scenario.

1. Introduction

The development of power sector is increasingly facing multiple environmental challenges, among which tightening carbon budget for achieving climate targets and more competitive water availability driven by growing demand are prominent ones. The former requires commitment to a commonly shared global environmental issue and the latter is a typical local or regional resource constraint. Addressing both problems calls for fundamental transitions of the electric power system. Studies in the recent decade have begun to consider both carbon mitigation and water conservation targets in power system planning and operation, framing an active emerging research field of electricity/energy-water nexus (Frumhoff et al., 2015; Sanders, 2015; Szinai et al., 2020), or an extended electricity/energy-carbon-water nexus (Li et al., 2019; Meng et al., 2019). This framework aims at understanding the implications of carbon mitigation in power sector on water use and water stress, as well as the impacts of water constraints on low carbon technological change, thus revealing synergies and tradeoffs between these two important environmental targets. Extensive modeling-based researches have been conducted for developed countries, especially the United States (e.g., Dodder et al., 2016; Liu et al., 2019; Miara et al., 2019; Voisin et al., 2016; Webster et al., 2013) and European countries (e.g., Behrens et al., 2017; Fernandez-Blanco et al., 2017; Murrant et al., 2017) with various spatial and temporal scopes and resolutions.

Low-carbon transition is at the center of sustainable development of China's power system. China's coal-dominated power sector emitted 4.6 Gt of carbon dioxide in 2018, contributing 13% of the global total energy related carbon emissions (IEA, 2021). Sustained by cheap coal in

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some northwestern and northern provinces, such as Xinjiang, Inner Mongolia, Shaanxi and Shanxi, coal power capacity is still in growth. Newly commissioned coal power plants amounted to 233 GW between 2015 and 2019, which account for 61% of the global total new coal power capacity during that period (Global Energy Monitor, 2020). China has pledged to peak its carbon emissions before 2030 (Liu et al., 2015) and achieve carbon neutrality by 2060. Fundamental transitions of the power sector is essential for achieving these carbon mitigation targets. Key measures include phasing out existing carbon-intensive coal power plants more rapidly (Cui et al., 2021), accelerating the deployment and utilization of renewable power technologies (Zhang et al., 2018; Cui et al., 2020), and possibly adopting negative emission technologies in the far future (Xing et al., 2021).

Power generation is also the largest industrial sector for freshwater withdrawal in China, ranking after agriculture irrigation (MWR, 2021). For example, total thermoelectric freshwater withdrawal in 2015 is estimated at 57.6 billion m^3, accounting for 43% of the total industrial water withdrawal (Zhang et al., 2018). It was revealed that coal power generation in catchments under high water stress (mainly located in northern and northwestern China with a withdrawal-to-availability ratio larger than 0.4) has grown by more than fourfold during 2000–2015, leading to increased water stress in coal mining and power production bases in western China (Zhang et al., 2016a, 2018). Capping water withdrawals has been determined as a key management measure in China's water conservation policies, known as the "red line" for total water withdrawals (Nickum et al., 2017). Using water constraint as a leverage to guide industry development and technology choice has been emphasized in river basin or regional development strategies (Xiang et al., 2017). For example, in 2019, Chinese President Xi Jinping launched an important talk on the ecological conservation and high-quality development of the Yellow River Basin, and required to make water resources as the most rigid constraint on urban and industry planning in the basin. As water conservation has become the highest priority in coordinating ecology and social development, mage coal mining and coal power production bases in the Yellow River Basin will face more stringent water withdrawal quotas in the future.

These two environmental constraints, i.e., carbon mitigation and water conservation, will interact with each other in many ways. Low carbon power technologies can have either co-benefits or tradeoffs on water conservation and vice versa. Generally speaking, achieving carbon mitigation through renewable technologies such as wind power and solar photovoltaic (PV) can reduce pressures on scarce water resources (Fan et al., 2018). But retrofitting coal power plants with carbon capture and storage (CCS) may double water use intensity per unit net electricity generation (Zhai and Rubin, 2015) and could be constrained by water scarcity especially in northern China, middle U.S., and India (Rosa et al., 2020). Water conservation technologies may also incur additional energy consumption and CO_2 emissions. A typical example is adopting air-cooling technology in coal power plants to save water in northwestern and northern China, which has led to more than 10 million tons of additional CO_2 emissions annually (Zhang et al., 2014).

The tightening interactions in China's electricity-carbon-water nexus have raised wide attentions in recent years. Historical trend and/or status-quo of water use and water stress by power generation are investigated by top-down accounting methods, such as environmentally extended input-output analysis (EE-IOA) (Feng et al., 2014; Zhang and Anadon, 2013), and bottom-up inventory analysis at various spatial scales (Liao et al., 2016; Zhang et al., 2016a; Zheng et al., 2016). Policy-relevant researches have focused on the mutual influences of low-carbon development and water conservation based on power capacity expansion models or computable general equilibrium (CGE) models. Various approaches were adopted to represent different policy contexts, for instance, introducing carbon emission and water withdrawal/consumption constraints into energy system optimization models (Liao et al., 2021; Lv et al., 2018; Peng et al., 2018; Tang et al., 2020), assigning targets for the national average water intensity of coal power generation (Yu et al., 2011), minimizing weighted average water stress index of the power generation mix (Zhang et al., 2020); setting water price or tax to consider water use cost in energy technology choice (Fan et al., 2018; Huang et al., 2017), defining step-wise water supply cost curves for energy production to model increasing water cost (Li and Chen, 2019), coupling power planning model and water supply model in an integrated framework (Sharifzadeh et al., 2019), or simply calculating water use based on the results from energy models exogenously (Li et al., 2017; Zhou et al., 2016). Early studies mostly generalize China's power system at rather coarse spatial and temporal resolutions. Aggregated national or sub-national spatial scales and yearly time-step are most common model configurations. Water intensity or cooling technology structure for coal-fired power generation was often exogenously fixed in many previous studies. Under these assumptions, fuel mix will respond quite sensitively to water constraints, since the only adaptive approach to reduced water availability is to significantly decrease the output of coal power generation.

In order to get more reliable capacity expansion pathway, it is important to incorporate more technological and spatio-temporal details of the coupled electricity-water system into modeling such as the spatio-temporal heterogeneity of water resources (Zhang et al., 2016a), the significant temporal intermittency of renewable electricity (He and Kammen, 2014, 2016), demand for power storage facility under high renewable electricity penetration, and endogenous cooling technology selection. These factors have begun to be taken into consideration in electricity-water nexus studies in recent years. For example, Miara et al. (2019) coupled the Regional Energy Deployment System (ReEDS), which has intra-day temporal resolution, with a hydrological model and used an iterative calculation approach to explore robust development pathways under climate-water variations for future U.S. electricity sector (Miara et al., 2019). Li et al. (2021) investigated detailed catchment-level water stress risk of power system transition up to 2050 under 2 °C and 1.5 °C targets and disaggregated the calculation results of a provincial-level capacity expansion model into catchments based on spatial location of existing and proposed power plants (Li et al., 2021).

It is unclear how China's latest announced carbon neutrality target will affect freshwater withdrawal by power generation at regional level and how freshwater withdrawal constraints will interact with this carbon mitigation target to change the technology structure, spatial distribution and operation of the power system. In order to fill these knowledge gaps, we upgrade the SWITCH-China model (He et al., 2016, 2020), an integrated capacity expansion and electricity dispatch model, to allow endogenous cooling technology selection by thermal power plants and to exert freshwater withdrawal constraints at river basin level. Power system transition under carbon and water constraints are modeled under four scenarios. Section 2 introduces the method and data of the modeling work, Section 3 presents calculation results, Section 4 discusses implications and then conclusions are summarized in Section 5.

2. Method and data

2.1. SWITCH-China

To effectively model the impact of low carbon development and water constraints on China's power system, we utilized the SWITCH-China capacity expansion and electricity dispatch model. SWITCH, which is a loose acronym for investment in solar, wind, hydro, and conventional technologies, is an optimization model that has the objective function of minimizing the cost of producing and delivering electricity based on projected demand through the construction and retirement of various power generation, storage, and transmission options available currently and at future target dates. The SWITCH-China model provides high resolution in both temporal and spatial dimensions, to simulate the effect of dramatically decreasing cost for incorporating renewable energy into the power grid (He et al., 2016; Li et al., 2021).

The structure of power system is modeled based on power plants/electric generating units (EGUs), and inter-provincial transmission lines. SWITCH-China optimizes both the long-term investment and short-term operation of the grid. Infrastructure investment, electricity production, transmission and consumption are optimized and balanced at provincial level and with hourly time step under various operational constraints. The model incorporates a combination of current and advanced grid assets. Optimization is subject to reliability, constraints on operations, and resource availability, as well as on current and potential climate policies and environmental regulations (Fripp, 2012; Johnston et al., 2019; Mileva et al., 2013; Nelson et al., 2012; Sanchez et al., 2015). SWITCH-China's modeling decisions regarding system expansion are based on optimizing capital costs, operation and maintenance costs, and variable costs for installed power plant capacities and transmission lines. Compared with models used in previous studies, SWITCH-China has several merits: 1) the framework of integrated capacity expansion and electricity dispatch can reflect more realistic characteristics of power system operation, 2) higher spatial and temporal resolutions can provide more reliable simulation results under the condition of high penetration of renewable technologies, and 3) detailed model configuration at the power plant/EGU level enables flexible mapping of the spatial unit between jurisdictions and river basins.

2.2. Model configurations

Energy administration and water resources management have different authorities and spatial units in China. While National Energy Administration (NEA) and provincial government are responsible for the approval of power plant projects, Ministry of Water Resources (MWR) and river basin management branches review and issue water withdrawal permits and implement the gross water withdrawal cap policy. Therefore, electricity supply and demand are balanced at the province level, and water withdrawal constraints are exerted at the river basin level in our model. Thermal power plants are disaggregated into electric generating units (EGUs) with detailed geographic location and technological information such as year of commissioning, unit size, cooling technology. It is flexible to get the summation of power generation, CO_2 emission and water withdrawal at different spatial units in different constraint conditions. We choose the secondary river basins as the basic unit to assign water constraints, since they are neither too large as the 10 primary river basins in China, nor too small as more than 1000 basic catchments. The division of secondary river basins is presented in Supplementary Fig. S1. The entire mainland China is divided into 76 secondary river basins according to China's water resources management authority. Thermal power plants exist in 67 secondary river basins, covering almost all territories except a few regions in western China, mainly in the Tibet Plateau. Intersecting these 67 secondary river basins with 32 provinces (Inner Mongolia is divided into West Inner Mongolia and East Inner Mongolia in this study since their electric grids are operated by different companies), we obtain 108 spatial units. All existing power plants/generating units in the base year are assigned to the spatial unit where they are located.

Feasible cooling technologies for newly commissioned thermal power plants in each spatial unit are defined according to river basin characteristics and policy restrictions (see Table S1 in SI). For coal and natural gas-fired power generation, recirculating cooling technology has the widest application range and is feasible in all spatial units. Seawater cooling technology can only be adopted in coastal regions. Air-cooling technology is only used in the water-scarce northern China. Due to its higher investment and operation costs, air-cooling technology is economically infeasible to be used in southern China without mandatory requirement by the government. Freshwater once-through cooling has been restricted by water resources management authorities due to its thermal pollution and disturbance to flow regime. Very few newly built or proposed power plants adopt freshwater once-through cooling system in recent years. Therefore, we assume this cooling technology will no longer be considered in new plants in the future. Some other policy restrictions are also considered, for example, new coal power plants are not allowed to be built in Beijing and Shanghai for the purpose of air pollution control.

Nuclear power generation has the lowest levelized cost of electricity (LCOE) of all technologies. If the model does not limit its total capacity, nuclear power plants will expand unreasonably. The planning and construction of nuclear power plants take very long period and are highly controlled by the central government. Therefore, we set maximum allowed nuclear power capacity according to the Nuclear Development Planning Research by the China Nuclear Development Center (CNDC) and State Grid Energy Research Institute (SGERI), i.e., 58 GW in 2020, 128 GW in 2030, 221 GW in 2040 and 334 GW in 2050 (CNDC and SGERI, 2019). Locations that are feasible to build nuclear power plants are assigned according to the information of all currently proposed and planned projects collected by the World Nuclear Association (World Nuclear Association, 2020). Coastal nuclear power plants must use seawater cooling and inland plants must use re-circulating cooling.

Hydroelectric and pumped hydroelectric generators include constraints derived from historical monthly generation data. For non-pumped hydroelectric generators in China, monthly net generation data from the China Electricity Council is employed. Hydroelectric and non-pumped hydroelectric plants that are less than 1 GW are aggregated to the load area level to reduce the number of decision variables. For pumped hydroelectric generators, the use of net generation data is insufficient, as it considers both electricity generated from in-stream flows and efficiency losses from the pumping process. We configure pumped hydro data by applying a 74% round trip efficiency to each plant's total electricity input, and set monthly in-stream flows to values from corresponding non-pumped projects. Hydro plants that are under construction or in plan are assumed to be online as planned. New hydroelectric facilities are not built in the current version of the model.

Electricity demand is exogenously assigned according to projections made by State Grid Energy Research Institute, the national total electricity demand is expected to reach 9808 TWh in 2030, and 14300 TWh in 2050 (Hu et al., 2011).

2.3. Data compilation

We updated the power plants database of SWITCH-China. Data for coal power generation are improved with coal power units classified by nameplate capacity and cooling technology. All thermal power plants or generating units in 2015 are updated according to a comprehensive thermoelectric water use inventory developed by Zhang and colleagues (Zhang et al., 2018). Coal power generating units larger than or equal to 100 MW are classified into four typical capacity groups, i.e., 100 MW, 300 MW, 600 MW and 1000 MW, and modeled individually. There are 2176 large units in operation in 2015 altogether, adding up to 809 GW. Location, cooling technology, nameplate capacity and year of commissioning are determined for each units. Small units less than 100 MW are aggregated as representative power plants by spatial unit and by cooling technology. These small units add up to 57 GW, or 6.6% of the total coal power capacity in 2015. Natural gas-fired and nuclear power plants are not further disaggregated into individual units and are modeled at plant level. Moreover, to make the capacity expansion scheme for 2020 close to the actual situation as much as possible, we further collected information of thermal power units that have already been commissioned during 2016–2020. 229 coal power units (141.4 GW) and 22 natural gas-fired power plants (16.5 GW) are included. We assume that these new plants must be on-line in the base year of 2020.

Average heat rate and water withdrawal factor for different coal power generation technologies are assigned according to the data reported in the Energy Efficiency Benchmarking Competition of Coal-fired Power Generating Units organized by China Electricity Council (CEC, 2018). Heat rate and water withdrawal factor for natural gas-fired and nuclear power plants are collected from relevant literature and actual data reported (Table S2 in SI). Investment cost of different coal power generating units are determined by information collected from the inspection and approval announcement for environmental protection measures of newly commissioned power plants issued by the Ministry of Environment (Table S3 in SI). These data reflect the actual investment cost for each kind of new projects. Assumptions for future investment costs of renewable power technologies (wind power, solar PV and battery storage) through 2050 used in the LCR scenario are obtained from the latest U.S. National Renewable Energy Laboratory (NREL) Annual Technology Baseline (ATB) updated in 2020 (available at https://atb.nrel.gov). The declining trend of renewable power costs are also plotted in Fig. S2 in SI.

Provincial wind and solar capacities are updated to year 2018 using historical capacity data. The hourly capacity factors of wind and solar projects are derived from He and Kammen (He and Kammen, 2014, 2016) that were used in the earlier version of SWITCH-China. Wind and solar capacities are set to meet existing 2020 provincial installed capacity plans. Transmission lines, capacities, and costs are set consistent as the earlier version of SWITCH-China (He et al., 2020).

2.4. Scenario design

Interactions between carbon mitigation and water conservation in the long-term (2020–2050) are investigated under four scenarios: 1) pledged climate change policies of peaking CO_2 emission by 2030 and achieving carbon neutrality by 2060 are defined as a reference carbon constraint scenario (S1, CC); 2) a water constraint scenario in which water withdrawal quotas for power generation are reduced by 50% by 2050 in all secondary river basin units in addition to carbon constraints (S2, CC + WC); 3) a low-cost-renewables scenario representing more rapid technology advancement of renewable power and energy storage technologies (S3, CC + LCR); and 4) a combined scenario introducing both water constraints and low cost renewables (S4, CC + WC + LCR).

China has pledged to peak carbon emission by 2030, but it is not specified how large will the peak emission be. To assume a reasonable potential emission peak for the power sector, before running the above four scenarios, we tested a scenario zero (S0) in which no emission constraint is exerted. We assume the modeled carbon emission in 2030 under S0 is the upper limit of the potential emission peak, and set this number as the emission constraint for 2030 in S1–S4. The emission pathway of power sector beyond 2030 is much uncertain depending on the stringency of mitigation policies and future technology trends. Quite several studies have explored future emission pathways of China's power sector consistent with the Paris Agreement or carbon neutrality target. For example, modeling work by Jiang et al. (2018) suggested a radical mitigation pathway that the power sector will reach net zero emission in 2040 under the 1.5 °C target. Wang et al. (2020) also modeled a zero emission in 2040 under deep decarbonization scenario. Study by Yu et al. (2021) shows China's power sector to reach zero emission in 2050 to realize carbon neutrality by 2060 under a medium GDP development and implementation strength scenario. Researchers in China Energy Group projected that thermal power sector will still emit 1.3 billion tons of CO_2 when China achieves carbon neutrality (Zhu et al., 2021). These results reflect that there is a lack of consensus on the emission pathway of power sector beyond 2030. Since the focal point of this study is the interactions between carbon mitigation and water constraint, we tend to make a conservative assumption that the national total CO_2 emissions by power sector will approach zero in 2060. For simplicity, a linear decrease is assumed during 2030–2060, which looks similar to the shape of many modeled post-peak pathways.

In terms of water constraint, a principal goal of the "Three Red Line" mechanism is to cease the growth of freshwater withdrawal in the near term and to alleviate water stress and restoring aquatic eco-system in the long term. Based on this principal, we assume the maximum freshwater withdrawal quotas at the secondary river basins for power generation in the first calculation year 2025 will keep at the base year level and will decrease linearly to 50% of the base year level by 2050. Sensitivity analysis is conducted to show the responses of technology mix to different water constraint levels. More rapid decrease in costs of renewable power and energy storage technologies according to the latest forecast made by U.S. National Renewable Energy Laboratory's Annual Technology Baseline (ATB) is modeled in the low-cost-renewables (LCR) scenario.

3. Results

3.1. Power sector transition under carbon neutrality target

The reference scenario (S1) provides an outlook of the plausible future of power sector transition in China under current emission reduction commitment. Total electricity generation in China will reach 16,739 TWh in 2050, growing by 123% compared to 7511 TWh in 2020 (see Fig. 1). Carbon neutrality target will drive significant changes in fuel mix in China's power sector. Reaching emission peak by 2030 does not allow further expansion of traditional coal power generation (without carbon capture and storage, CCS). Its output will keep roughly stable during 2020 and 2030. Rapidly decreasing carbon emission constraint after 2030 will basically eliminate traditional coal power fleet by 2050, when its share in total generation will only remain 3.6%. Coal power generation with CCS plays a considerable role in achieving China's carbon neutrality target in the long-term. It needs to be deployed in large quantity after 2030 to substitute for traditional coal power. Power generation by CCS plants will peak in 2040 (5021 TWh), accounting for 39% of the total generation. At that period, all coal-fired power generation (with and without CCS) will reach a maximum level of 7844 TWh, or 61% of the total generation. In 2050, CCS plants will contribute 22% of the total generation (3638 TWh), their total scale is comparable to traditional coal power generation in the base year. Wind and Solar PV will grow most rapidly after 2040, and account for 19% (3244 TWh) and 32% (5342 TWh) of the total generation in 2050, respectively. Nuclear power can reach the expected maximum output in all periods due to its cost advantage over other technologies.

Carbon constraint is tight in the long term (after 2040), but loose in the near term. All maximum allowed carbon emissions will be met after 2040, but the potential emission peak of 5.13 billion tonnes set in 2030 will not be reached. Modeling results show that total carbon emissions by the power sector will enter a plateau around 4.6 billion tonnes during 2020–2030. This means that stopping the expansion of traditional coal power capacity immediately and capping its scale around the base year level in the near decade is an economic way to approach near zero emission before 2060. Otherwise, newly built traditional coal power plants will be forced to retire earlier, which would increase the stranded assets of achieving carbon neutrality.

National total water withdrawal by power generation presents a declining trend even without constraining water withdrawal (see Fig. 2). Water withdrawal will continuously decrease to 12.1 billion m^3 in 2050 compared to 63.8 billion m^3 in 2025 and 58.8 billion m^3 in 2015. The significant water saving effect is mainly caused by the shrinking share of coal power fleet, especially the retirement of existing once-through cooling plants, which need large volumes of cooling water withdrawal. Nearly all (98%) newly commissioned CCS power plants will adopt recirculating cooling system if water quota is not a limiting factor (see Fig. 3). Despite the declining overall water withdrawal, deploying CCS power plants will definitely cause additional water demands in specific river basins (to be elaborated in spatial distribution analysis below).

Unit cost of renewables are assumed to only decrease by 10–20% by 2050 under the S1 and S2 scenario. As shown in Fig. 4, under S1, national average levelized cost of electricity (LCOE) is modeled at 73.3 USD/MWh in 2025 (measured as per unit net electricity supply) and will fluctuate around this level through 2040, and then increase from 71.9

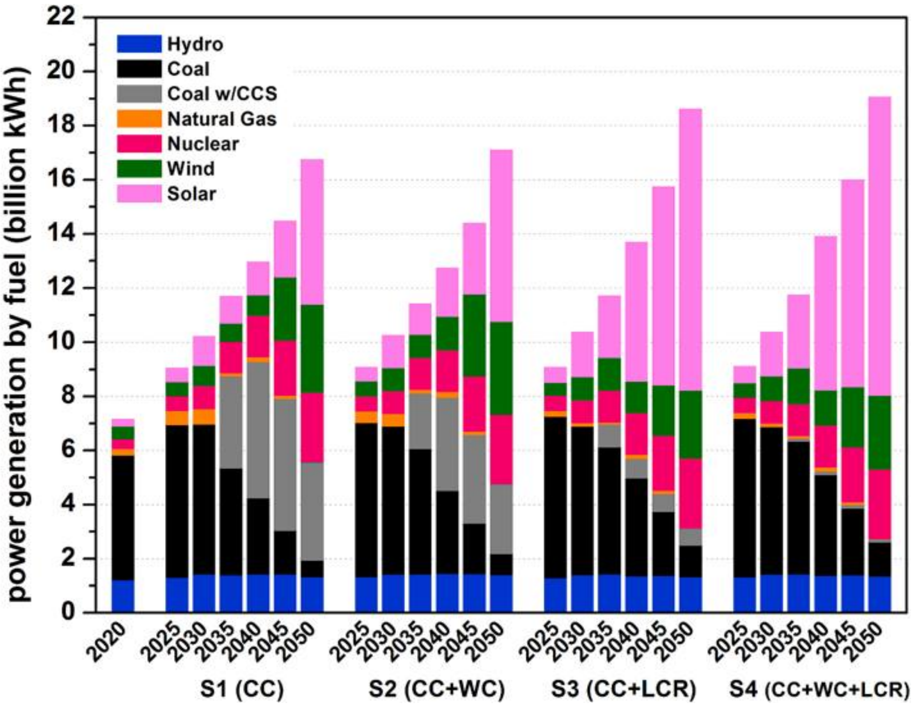

Fig. 1. Fuel mix of electricity generation under four scenarios. S1, carbon constraint (CC), S2, carbon constraint plus water constraint (CC + WC), S3, carbon constraint with low-cost renewables (CC + LCR), S4, carbon constraint plus water constraint with low-cost renewables (CC + WC + LCR). Also see fuel mix of installed capacity under four scenarios in Supplementary Fig. S3.

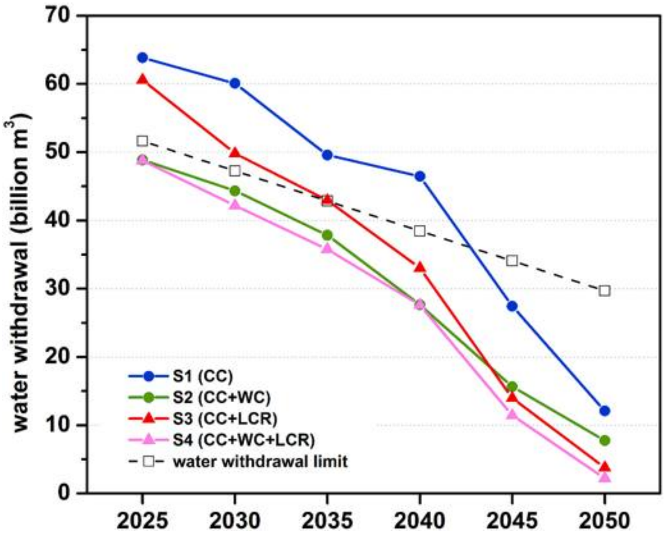

Fig. 2. Total water withdrawals under different scenarios.

USD/MWh to 86.0 USD/MWh (by about 20%) during 2040–2050. The rapid increase of LCOE in the last decade of the study period is driven by fast penetration of non-hydro renewable electricity (wind and solar PV) and storage capacity, which account for 44.3% and 10.3% of the LCOE in 2050, compared to 15.6% and 1.8% in 2035.

3.2. Overall impacts of water constraints and low cost renewables

Exerting water withdrawal constraints will largely limit water intensive generation technologies and lead to overall structure changes in fuel and technology mix. First, due to lower thermal efficiency and additional water use in the carbon capture stage, CCS power plants have much higher water intensity than traditional coal power plants. It is estimated that when equipped with CCS, the facility water withdrawal factor of a 600 MW recirculating cooling generating unit increases from 2.09 m^3/MWh to 3.88 m^3/MWh (Table S2 in SI). With reduced water quotas at secondary river basins, rooms for deploying new CCS power plants will be limited, especially in water-deficient regions. The capacity of CCS power plants can be reduced by 40% in 2035 and 29% in 2050 compared to the S1 scenario (Supplementary Fig. S3), thus shrinking the overall coal power generation by 9.2% and 21%, respectively. Wind and Solar PV power generation with negligible water use during operation will increasingly substitute for coal. Second, cooling technology choice will favor water conservation technologies. Once-through cooling power plants will be phased out more rapidly. Existing air-cooling power plants will remain in operation for longer periods, and more than half of the newly built CCS power plants (52%) will also select air-cooling technology. Its contribution to the total coal-fired power generation will keep around 30% after 2035.

These structure changes can reduce water withdrawal significantly. As for 2025, total water withdrawal will be 48.9 billion m^3 under S2 scenario, 23% lower than the S1 scenario and 5.3% below the total withdrawal limitation. The withdrawal gap will become smaller in the long term as the scale of thermal power generation is shrinking. It is also noteworthy that limiting water withdrawal could trigger a tradeoff effect of more carbon emissions in the early period of CCS deployment. Total carbon emission will reach the cap of 4 billion tonnes in 2035, which is 0.36 billion tonnes higher than S1 scenario. This is caused by more generation of traditional coal-fired power to make up for the reduced amount of CCS power generation. For example, traditional coal-fired power generation will be 4641 TWh in 2035 under S2, compared to 3959 TWh under S1 scenario.

Rapidly declining renewable energy costs as projected by U.S. National Renewable Energy Laboratory's Annual Technology Baseline (modeled as low-cost-renewables scenario, S3) have more fundamental effects to boost transition away from coal. Unit investment cost of central solar PV and battery storage will decline most significantly and be more than 70% lower than the base year level. This makes solar PV more competitive than coal-fired power plants both with and without CCS in

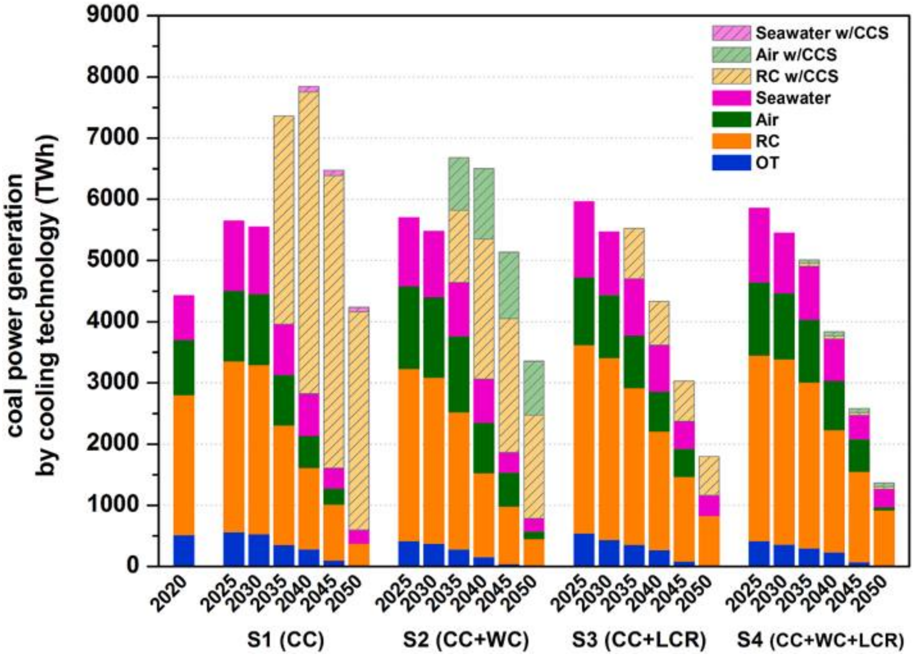

Fig. 3. Cooling technology mix of coal power generation in different scenarios.

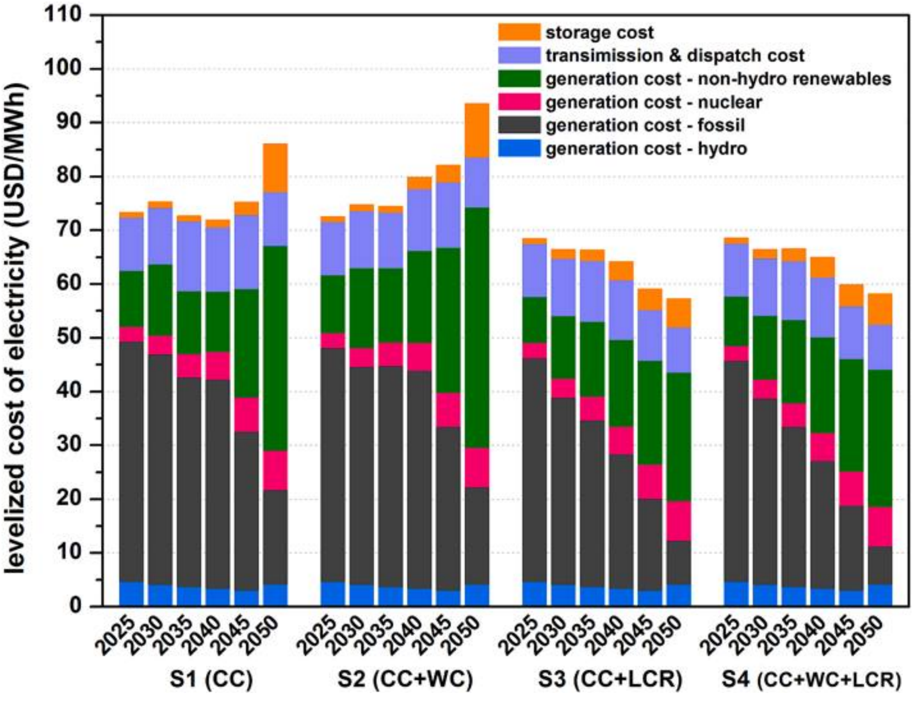

Fig. 4. Levelized cost of electricity (LCOE) under four scenarios.

the future, and deemphasizes the necessity of deploying new CCS power plants. The total installed capacity of CCS power plants will be less than one fifth of the amount under S1 scenario and its contribution to total power generation will be reduced to only 7.0% in 2035 and 3.4% in 2050. Solar PV will replace coal to become the dominant fuel type in China's electricity mix (accounting for 56% of the total generation). The installed capacity of power storage under S3 scenario will also double in 2050 compared to S1, increasing from 777 GW to 1505 GW (See Supplementary Fig. S3). Larger penetration rate of renewable electricity brings co-benefits of water conservation. Total water withdrawal under S3 scenario will be about 7–13 billion m^3 lower than S1 in different calculation years. The impact on the average electricity cost is also tremendous. LCOE under S3 scenario will follow a decreasing trend that declines to 57.2 USD/MWh in 2050, 33% lower than that of S1 scenario.

Further applying water constraint to low-cost-renewables scenario will almost eliminate CCS power plants (S4). Although traditional coal power generation can be remained to a slightly larger extent within the emission cap after 2040, the share of all coal power generation will be further reduced to 43% in 2035 and 7.2% (with only 0.5% CCS power generation) in 2050. The overall water conservation effect is quite obvious in the initial calculation period (12 billion m^3), but will continuously decrease over time (1.6 billion m^3), as the fleet of coal power plants will shrink quickly after 2035. The tradeoff effect of temporary boost of carbon emission in 2035 still exist under S4 scenario, but with a much smaller extent (0.07 billion tonnes).

3.3. Impacts on the spatial distribution of power generation

The uneven spatial distribution of coal, renewable energy and water resources leads to large disparities in regional capacity expansion. Northwestern China is rich in cheap coal resources, but is suffering

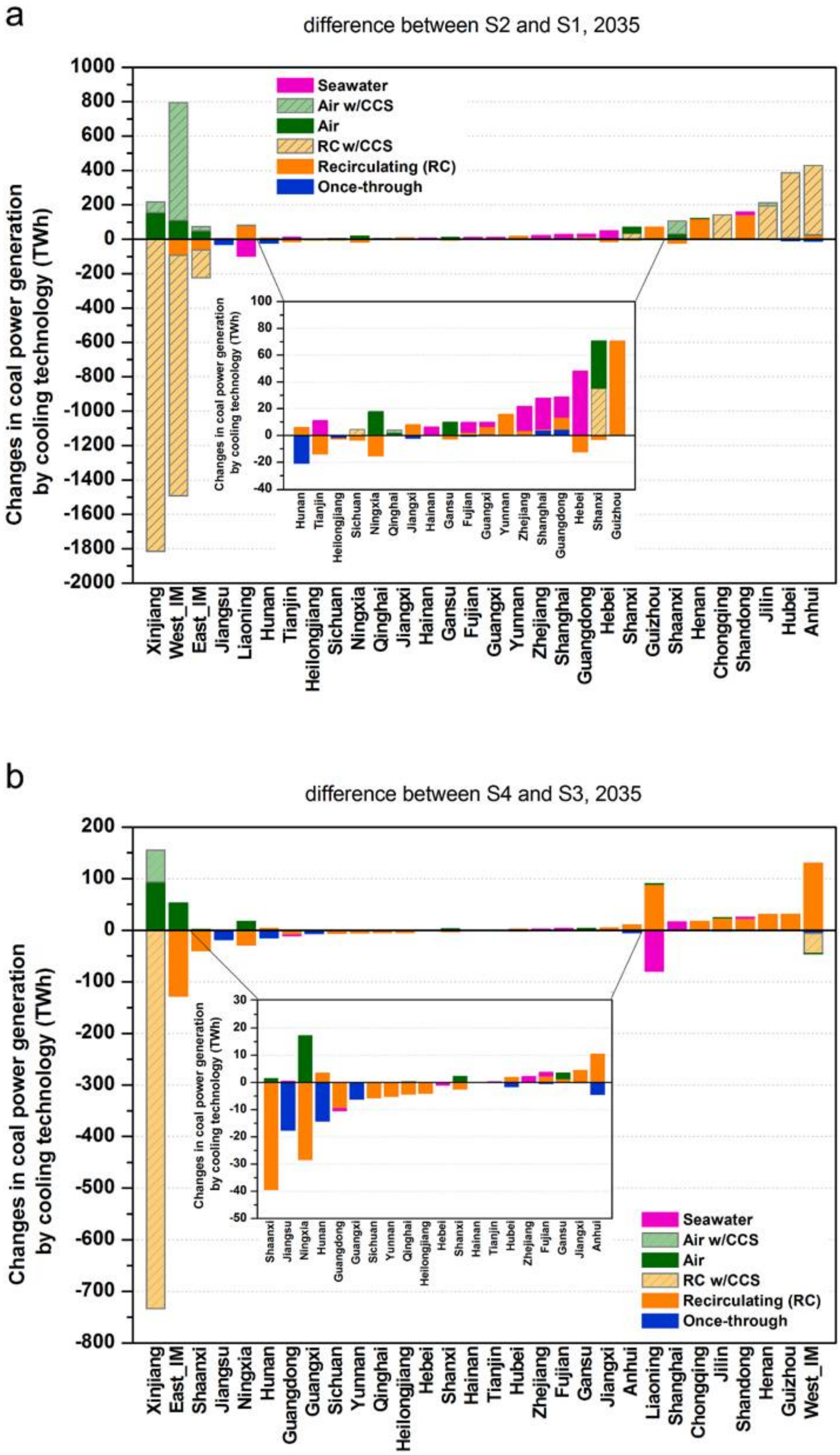

Fig. 5. Changes in coal power generation by province and by cooling technology between scenarios with and without water constraint in 2035. a, changes between S2 (CC + WC) and S1(CC) scenario in 2035; **b,** changes between S4 (CC + WC + LCR) and S3 (CC + LCR) scenario in 2035.

severe water scarcity. Under S1 scenario more than 90% of newly built CCS power capacity will be concentrated in West Inner Mongolia (520 GW) and Xinjiang (326 GW), with the remaining in East Inner Mongolia (36 GW), Liaoning (19 GW) and Jilin (18 GW). Coal power generation (both with and without CCS) in West Inner Mongolia, Xinjiang and East Inner Mongolia will rank the top three among all provinces, contributing 24% (1790 TWh), 25% (1836 TWh) and 6.8% (499 TWh) to the total generation in 2035, and increase to 50% (2118 TWh), 30% (1262 TWh), and 7.5% (320 TWh) in 2050, respectively.

Exerting water withdrawal constraint (S2) has a strong effect of limiting the development of coal power industry in northwestern China. In addition to reduce the total capacity of CCS power plants, water withdrawal constraint also makes the spatial distribution of CCS power plants spread to some water-abundant provinces in central and eastern China, such as Anhui, Hubei and Chongqing, where capacity of CCS power plants will reach 190 GW, 139 GW and 30 GW and contribute 20% (403 TWh), 18% (379 TWh) and 6.8% (138 TWh) of the total CCS power generation in 2035, respectively (see Fig. 5a for changes in coal power generation by province in 2035 and SI Fig. S4 for results in 2050). Reallocation of water-intensive CCS power plants depends on the possibility of releasing water quotas from existing coal power plants. Early retirement or reduced output of once-through cooling plants in these water-abundant provinces can make considerable rooms for newly built CCS power plants. In the arid northwestern regions, the substitution potential is much lower and therefore air-cooling technology is needed in Inner Mongolia, Xinjiang, and Shaanxi to meet local water constraint, despite its higher capital and fuel cost. In most provinces, traditional coal power generation will increase after 2035. This substitution effect is most obvious in four neighboring provinces in northern China, i.e., Hebei, Henan, Shanxi, and Shandong. Traditional coal power generation in these four provinces will altogether increase 348 TWh in 2035, accounting for half of the national total increment. Northern China receives large amounts of west-to-east electricity transmission from northwestern China. When the scale of inter-regional transmission decreases, this region needs to retain more local power generation to improve the self-sufficiency of electricity. The spatial shift of coal power further promotes renewable electricity in western China to make up for the reduced output. This fuel substitution effect is most significant in the far future in West Inner Mongolia, Shaanxi, East Inner Mongolia, and Xinjiang, where wind and solar PV power generation will increase 1508 TWh in all in 2050.

Under the prospect of low-cost renewables (S3), CCS power plants will only be built in Xinjiang (138 GW) and West Inner Mongolia (18 GW). The impacts on provincial power generation of introducing water constraints represented by S4 scenario has many similarities with S2 scenario, but with lower degree due to much smaller share of coal power generation (see Fig. 5b). All CCS plants in Xinjiang should adopt air-cooling technology and the total capacity will decrease tremendously to 15 GW. Traditional coal power generation will decrease in East Inner Mongolia and increase mostly in West Inner Mongolia. Increase in non-hydro renewable electricity generation will mainly take place in northwestern provinces, including Gansu, Qinghai, Ningxia, and Xinjiang, which altogether amount to 813 TWh in 2050.

3.4. Impacts on the spatial distribution of water withdrawals

The spatial mismatch between coal resources and water resources is an outstanding feature of China's energy-water nexus (Zhang et al., 2016b). Without water constraint, new CCS coal power capacity will expand in river basins that are rich in coal resources, including the Northwestern Rivers, Yellow River Basin and Liao River Basin, all located in northern regions. Consequently, water withdrawals in the above basins will increase in the future and peak in 2040 when power generation by CCS plants reach the maximum level (see SI Table S4 for water withdrawal by river basin). Water withdrawal in the Northwestern Rivers will amount to 8.8 billion m^3 (19% of the national total) in 2040, a nine-fold increase compared to the base year. Water withdrawal in the Yellow River Basin and Liao River Basin will also have 4-fold and 2-fold increase, respectively. In contrast, volume of water withdrawals in the Yangtze River Basin is currently the largest among all basins (~70% of the national total in the base year), but will decrease most significantly due to retirement of many once-through cooling plants. As show in Fig. 6a and e, the most important trend of the changing spatial distribution of thermoelectric water withdrawal under S1 scenario is a northwestward shift of water withdrawal burdens. Water withdrawal volumes in secondary basins will be larger than 500 million m^3 in almost the entire Northwestern Rivers, middle reach of the Yellow River Basin and west part of the Liao River Basin. Although withdrawals in the lower and middle reach of the Yangtze River Basin will still be the largest in 2035, but will decline rapidly during the latter half of the study period. Actually, the model forces nearly all coal power capacities in the Yangtze River Basin, Southeastern River Basin and Pearl River Basin to retire in 2050 in order to meet the carbon neutrality target.

The impacts of introducing water withdrawal constraint (S2) are presented in Fig. 6b and f, and differences between S1 and S2 are highlighted in Fig. 6i and j. As a result of reallocating CCS coal power capacities, water withdrawals will decrease to less than 50 million m^3 in almost all western catchments. Water constraints are also tight in the middle and lower reach of the Yangtze River Basin during the first half of the study period. In 2035, the following three regions will have obviously increased water withdrawals as they take a majority of the shifted coal power capacities: most catchments in the Songhua River Basin in northeastern China, the south part of the Hai River Basin and the neighboring Huai River Basin, and the upper reach of the Yangtze River Basin. In 2050, regions with increased water withdrawals will further expand to catchments covering stem stream of the middle and lower reach of the Yangtze River. The reallocation effect of water constraints will not spread to areas south to the Yangtze River, thus electricity mix and corresponding water withdrawals will barely change in the south part of the Yangtze River Basin, Pearl River Basin and Southeastern Rivers.

Under the Low-Cost Renewables scenario (S3), the spatial distribution pattern of water withdrawals is quite similar to that under S1 scenario, but with lower volumes due to higher penetration of renewables (Fig. 6c and g). Introducing water constraints (S4) will also shift coal power capacities and the associated water withdrawals from northwestern catchments to northeastern and southern catchments. In 2035, incremental water withdrawals will be between 100 and 200 million m^3 in northeastern catchments, and less than 100 million m^3 in most southern catchments, with a similar pattern but much more moderate changes (Fig. 6k). Moreover, differences between Fig. 6j and l shows that the degree of renewable electricity development can affect the direction of reallocation of water-intensive coal power capacity. In Fig. 6l, catchment with the largest volume of incremental water withdrawal will appear in the east corner of the Northwestern Rivers, roughly located in the east part of West Inner Mongolia. Incremental water withdrawals in the Hai River Basin, Huai River Basin and Yangtze River Basin will be reduced to a large extent compared with Fig. 6j. Low-cost renewable electricity results in higher penetration of wind and solar PV power and smaller scale of coal power generation in northwestern regions, thus making the water constraints looser in some catchments. On the other hand, self-sufficiency of electricity in southern regions can be enhanced due to more economically feasible local renewable power, thus reducing the dependence on importing electricity from northwestern. The combined effect of these two factors is to reallocate coal power generation to neighboring catchments within the northwestern region in priority, instead of reallocating to further catchments in southern regions.

3.5. Sensitivity analysis

Sensitivity analyses are further conducted to understand the responses of technology selection of China's power system facing different

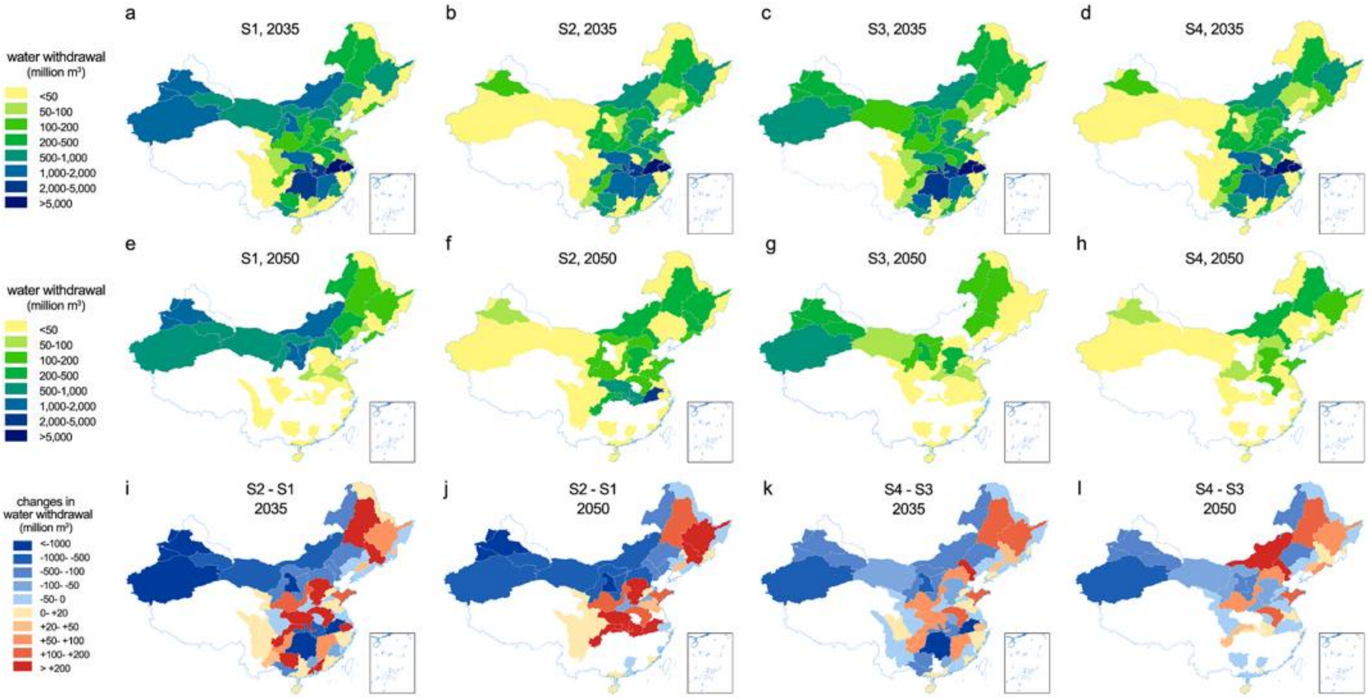

Fig. 6. Spatial distribution of water withdrawal at the secondary river basin level in 2035 and 2050 under different scenarios and changes in water withdrawal between scenarios with and without water constraints. Division of secondary river basins is illustrated in more details in Supplementary Fig. S1.

level of water availability. Additional water constraint scenarios that linearly reduce water quotas by 30% (a loser water constraint) and 70% (a stricter constraint) by 2050 are calculated to compare with the 50% scenario. Given other conditions unchanged, stricter level of water constraint leads to lower level of CCS coal power generation (Fig. 7a). The maximum amount of CCS coal power generation is 3618 TWh in 2040 if reducing water quotas by 30%, compared to 3084 TWh under the 70% scenario. The maximum variation range from the base scenario S2 (50% reduction in water quotas) is around ±5% in 2040. It is also evident that even introducing moderate water constraint can lead to significant cut in CCS coal power generation, and the variation ranges among different water constraint scenarios are much smaller than the differences between scenarios with and without water constraint. Besides reduced scale of CCS power generation, more stringent water constraint will promote water-efficient cooling technologies. For example, the share of traditional coal power generation with once-through cooling and recirculating cooling technology in 2035 under the 70% reduction scenario will decrease by 0.94 (69 TWh) and 3.4 (271 TWh) percentage points compared to the 30% reduction scenario, meanwhile air cooling and seawater cooling power generation will increase by 4.2 (248 TWh) and 2.0 (113 TWh) percentage points, respectively (Fig. 7b). Shrinking scale of coal power generation and changing cooling technology mix lead to lower water withdrawal under more stringent water constraint. Differences in total water withdrawal between the 30% reduction and 70% reduction scenario are between 5.5 and 9.2 billion m^3 during 2025–2040, but the gap will be quickly narrowed in the far future as once-through cooling plants are eliminated in all scenarios (Fig. 7c).

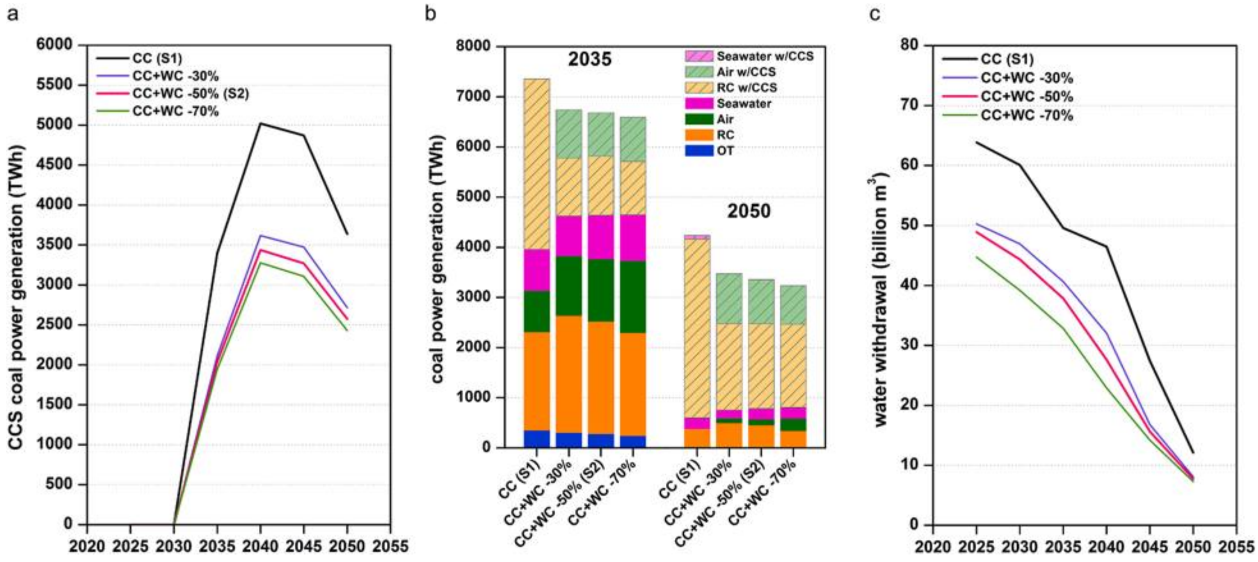

Fig. 7. Sensitivity of CCS coal power generation(a), cooling technology mix(b), and total water withdrawals(c) to different levels of water constraint.

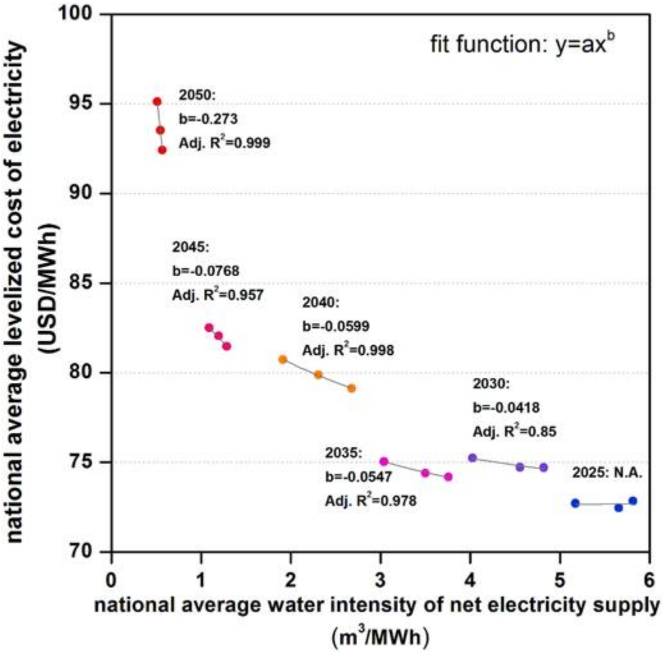

Fig. 8. Sensitivity of national average levelized cost of electricity (LCOE) to national average water intensity of net electricity supply in each calculation period. The three dots in each calculation period represent sensitivity analysis results of reducing water quotas by 30%, 50% and 70% in 2050, respectively. Each group is fitted by a power function, and the estimated parameter b represents the elasticity of LCOE to average water intensity.

Sensitivity of LCOE to the national average water intensity of net electricity supply is presented in Fig. 8. A power function is used to fit the sensitivity analysis results in each calculation period, so that the estimated parameter b in the function reflects the elasticity of LCOE to water intensity. LCOE becomes more and more sensitive to water intensity changes in the latter calculation periods when water intensity decreases. For example, 1 percentage point decrease in the national average water intensity of net electricity supply incurs 0.0547 percentage point increase in LCOE in 2035, and this value quadruples to 0.273 percentage point in 2050. The marginal cost of conserving additional 1 m^3 of water withdrawal based on the level of S2 scenario is 0.69 USD in 2030, 1.16 USD in 2035, and increases tremendously to 46.8 USD in 2050. The rapidly increasing marginal cost indicates that low-cost water conservation measures will be used in priority in earlier periods according to the least-cost rule, such as reducing the output of once-through cooling plants, and further constraining water withdrawal in a decarbonized power system will be very expansive if the cost of renewable electricity doesn't decline sharply.

4. Discussion

We investigate the long-term transition of China's power sector under both carbon and water constraints using an integrated high-resolution capacity expansion and dispatch model. By considering spatiotemporal variations of renewable resources, endogenous cooling technology choice by individual thermal power generation plants/units, and intersected river basin and province spatial unit configuration, this study reflects both temporal intermittence of renewable energy and spatial variations of thermoelectric water use. New information regarding adaptive responses to tightening carbon budget and water quotas, including fuel mix changes, capacity reallocation and cooling technology switch, can support decision-making for both energy and water resources management.

The secondary river basin level is a suitable spatial unit to introduce water withdrawal constraints. Primary river basins can cover large territories with very different socioeconomic conditions and water resources pressure. For example, the Yangtze River Basin intersects with 19 provinces from the most developed metropolitan Shanghai to the underpopulated Tibet. Thermal power plants are concentrated around the trunk stream in the lower reaches and the Yangtze River Delta area (belonging to secondary river basin no. 611 and 612). It is more practical and meaningful to regulate thermoelectric water withdrawal in a smaller spatial unit around the delta area, where large volumes of once-through cooling water withdrawal contribute obvious water stress, instead of the entire Yangtze River Basin. Therefore, the secondary river basins classified by China's water resources management authority not only reflect local characteristics of water resources, but also have convenience in implementing water withdrawal caps.

Study results show that pathways of realizing carbon neutrality in China's power sector depend on the prospect of declining cost of renewable electricity technologies, i.e., solar PV, wind power and battery storage. If LCOE of renewable electricity will only reduce by around 10–20% from the current level, CCS coal power plants will play a major role in achieving carbon neutrality after 2035, and total coal power generation will continue to grow until 2040. The water penalties of CCS coal power generation can incur a trade-off between decarbonization and water conservation; this phenomena has been proved by previous studies in the context of the United States (Chandel et al., 2011; Macknick et al., 2012; Talati et al., 2014). Moreover, the carbon-water trade-off tends to be more prominent in China because of the spatial mismatch between coal resources and water resources. A large fleet of CCS coal power plants has potential to be built in the arid catchments in northwestern China, which could exacerbate the already-high water stress in this region (Zhang et al., 2018). Rapidly declining cost of renewable electricity by more than 70% up to 2050 (as projected by the U.S. National Renewable Energy Laboratory) will lead to a very different carbon mitigation pathway, which mainly relies on solar PV, wind, and battery storage in the far future and only a small amount of CCS coal power capacity is needed. The pathway driven by low-cost renewables can bring co-benefits in three aspects: reducing the overall economic cost for achieving the carbon neutrality target; reducing dependence on coal earlier and thus alleviating pollution problems associated with the entire coal supply chains; and releasing more scarce water resources to create water conservation synergies.

Adaptation responses to reduced water availability are mainly reflected in three aspects of structural changes. First, fuel mix has moderate changes to reduce the scale of newly built CCS coal power generation. Second, cooling technology mix has corresponding changes that limit once-through cooling and recirculating cooling and promote air cooling technology. Third, shift in the spatial distribution of coal power generation is prominent. New coal power plants will be reallocated from water-scarce northwestern basins to water-abundant southern and northeastern basins where retired once-through cooling power plants release spare water quotas. Although decarbonizing China's power system can reduce the aggregate volumes of water withdrawal in the long-term, it may also incur more fierce water resources competition at local level. For example, a previous study showed that current thermoelectric water withdrawal in a number of northwestern catchments has already exceed 60% of the long-term average blue water availability, imposing high water stress on local catchments (Zhang et al., 2016a). Carbon mitigation under S1 scenario without consideration for water conservation may tremendously increase water withdrawal in those areas. More stringent water resources management is necessary to address the looming negative impacts in northwestern China. Existing water conservation policies mainly focus on improving the technical efficiency of water use by coal power generation, for example, promoting the application of water-saving technologies (Zhang et al., 2016b) and strengthening water withdrawal standards (MWR, 2019). However, efficiency improvement only is not enough to offset the effect of scale expansion, especially when large capacities of CCS coal power generation are needed. Both water efficiency measures and strengthening water withdrawal quota management should be considered to prevent local water crisis while achieving carbon neutrality.

The water limit for CCS technology deserves more attention by policy makers. Our results show that additional water withdrawals by CCS power plants will mostly occur in the arid northwestern China. This could be a potential water-carbon conflict when pursuing deep emission mitigation. This finding is consistent with the study on water limit to CCS by Rosa et al. (2020). The water penalty of CCS is to a large extent overlooked in current policy discussions in China, while hot topics are technical potential and economic feasibility of CCS.

The current study has some limitations in terms of coverage of novel technologies. We only include mainstream power generation technologies in this study. Some emerging renewable technologies or negative emission technologies, such as concentrated solar power (CSP) (Meldrum et al., 2013) and bioenergy with carbon capture and storage (BECCS) (Fajardy and Dowell, 2017), are not considered. These technologies may provide new alternative pathways for carbon neutrality and have important water implications as well. However, studies on the feasibility and potential of these novel technologies in China are still at the beginning stage and not sufficient to incorporate them into the current SWITCH-China framework with enough spatial resolution. Enriching technological details is a direction worthy of future research. Moreover, long-term technology projections are subjected to many uncertainties. We only explored two representative changing trends of renewable power cost. Moreover, there are also many uncertainties in the future carbon emission pathway of China's power sector to achieve carbon neutrality, depending on the scale of carbon sink, emissions by other sectors, electrification level, etc. Exploring water implications under alternative emission pathways for carbon neutrality could be an interesting point in future studies. Therefore, the calculation results in this study should not be viewed as a forecast for future structure of China's power system, but rather a what-if investigation on the responding characteristics and adaptation mechanisms of the power system facing environmental limitations and policy interventions. This study has shown both the general features and spatiotemporal details of power sector transition under carbon and water constraints.

5. Conclusion

In order to investigate the impacts of CO_2 emission constraints and water withdrawal constraints on the long term transition of China's power system, we updated the SWITCH-China model to include water constraints and endogenous cooling technologies choice. Achieving carbon neutrality by 2060 may depend on building coal-fired power plants with CCS after 2035 in the water-deficient northwestern China. Introducing water withdrawal constraints at the secondary river basin level will promote the application of air-cooling technology, reduce the scale of CCS power plants and reallocate new coal power capacities to northeastern and southern regions. Rapidly decreasing renewable costs could have large co-benefits of reducing both CO_2 emissions and freshwater withdrawals at much lower system cost. When setting carbon mitigation target for China's power sector, the spillover effect on water conservation should be considered due to the spatial mismatch between fossil fuel resources and freshwater resources. Co-coordinated policy design is necessary to avoid water penalties in the arid northwestern region.

CRediT authorship contribution statement

Chao Zhang: Conceptualization, Data curation, Methodology, Formal analysis, Writing – original draft, preparation, Writing – review & editing. **Gang He:** Conceptualization, Software, Methodology, Formal analysis, Data curation, Writing – review & editing. **Josiah Johnston:** Software, Validation. **Lijin Zhong:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.129765.

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