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Catchment-level water stress risk of coal power transition in China under 2℃/1.5℃ targets

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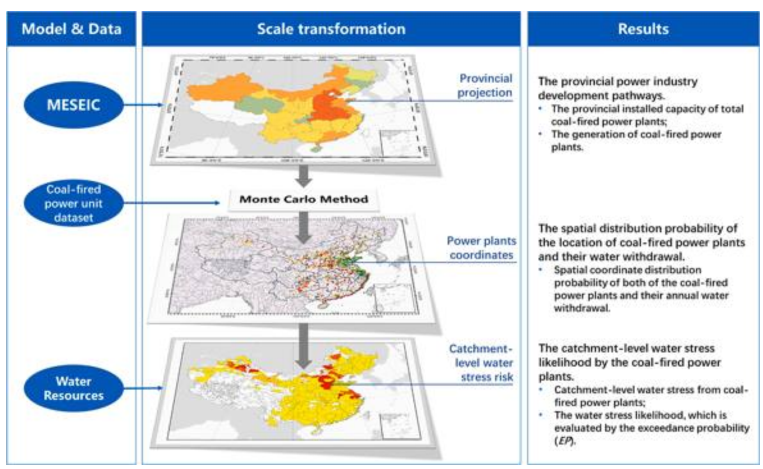
HIGHLIGHTS

- This study breaks the scale gap between energy model and natural water resources.
- This study provides a method to assess water stress risk due to power plants.
- 2℃/1.5℃ targets obviously affect China's power transition pathways.
- Achieving the 1.5℃ target is a key to release the water stress risk in catchment scale.

GRAPHICAL ABSTRACT



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ABSTRACT

Coal power production is the second largest source of water demand in China. However, as coal power would undergo significant changes under ambitious climate goals (2℃ or 1.5℃), it's not clear how the low-carbon transition of the power sector made at the provincial level would affect the catchment-level water resources in the future. With a power system model (MESEIC) and a unit-level coal-fired power unit dataset, this study explores different power sector transition pathways from 2020 to 2050, and maps out the catchment-level water stress risk of China's coal power with Monte Carlo method. Results show that the future power supply mix varies much under the shared socio-economic pathways (SSPs) and carbon emission targets. Without carbon emission

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targets, coal power would continue to dominate the power supply mix advantage and would cause severe risk of water stress. Under SSP1-5, the national water withdrawal from coal power in 2050 would be 12.2–176.2 billion m^3 under the reference scenario, but would decline to 10.7–59.2 billion m^3 with 2℃ target and 0.11–35.5 billion m^3 with 1.5℃ target. Compared with the 2℃ target, the catchment-level water stress risk generated by coal-fired power plants in north China would be significantly reduced under the stricter target of 1.5℃. However, the benefits would be reduced under SSP5 because of the application of carbon capture and storage. This study reveals the strong synergies between reducing carbon emissions and alleviating water stress risk in China's power sector, but regional risk should be noted while achieving the carbon reduction targets.

1. Introduction

Globally, the power industry is the key sector producing the most greenhouse gases (GHGs) [1] and the second-largest water use sector after agriculture [2,3], with the cooling water demand of coal-fired power plants accounting for the vast majority of the total water demand [4,5]. The existing power plants in many parts of the world, including Europe [6,7], USA [8], and China [9,10], have significant impacts on water resources and may be affected by the changes of water resources in the future [11]. Meanwhile, coal power developments in some areas like China [12] and India [13], the top two countries with the largest installed capacity, are still very prosperous and facing the pressure of future transformation. During the past several years, the coal power capacity and generation in China have increased by 66.4% and 43.6%, respectively, from 2010 [14] to 2020 [15], and there are also ambitious power development plans in certain Chinese provinces like Xinjiang [16], Inner Mongolia [17], Ningxia [18], Gansu [19], Shaanxi [20], etc. For example, Shaanxi has made plans to build large clean coal power bases, including a low-calorific coal power plant for each of its coal mining areas [20]. Moreover, the carbon emissions originating from coal power generation are increasing, and water withdrawal for coal power generation has caused water scarcity issues in some certain areas because of the unbalanced water resource supply and demand in China [9,10]. If the above plans are implemented, these new coal-fired power plants will potentially produce additional CO_2 and are likely to exacerbate the water scarcity issues in those regions. The good news is that China has vigorously promoted many advanced coal power generation techniques, such as high-capacity and high-efficiency coal-fired power units and air cooling technologies, which has achieved remarkable effects. Hence, there has been a freshwater withdrawal decoupling trend from coal-fired power generation growth in China during the past 15 years (2000–2015) [21], which has prevented a major increase in the amount of water withdrawal in the Chinese coal power generation industry.

China has joined the Paris Agreement and committed to carbon emission reduction targets. China has also pledged to try to achieve carbon neutrality by 2060 at the General Assembly of the United Nations in 2020 [22] and issued plans to promote carbon emission reduction actions, such as the 14th Five-Year Plan [23], which are very likely to change the future development trend of coal power in China. Meanwhile, China's electricity demand is still growing with increasing societal and economic development, and improvement of the water use efficiency does not indicate the reduction in the total water demand of coal-fired power plants [24,25]. Over the past ten years (2010–2019), approximately 490GW of new coal-fired power plants have been built and put into operation, thus creating a vast fossil-energy lock-in infrastructure. Moreover, approximately 491 GW additional reserved and planned coal-fired power plants are planned because of multiple economic and social benefits [26]. Over a long-term outlook, the future development pathway of coal power is controversial, including the construction, decommissioning, and application of new techniques. According to projections of previous studies, even in the case of deep decarbonization, China's coal-fired power generation is expected to change by the range of −30% to 79.7% in 2030 and −50% to 87.2% in 2050 compared with it in 2015 [27–33]. Given the pressure on the future power sector to reach carbon neutrality before society as a whole, coal power is likely to dramatically change. What is the future of coal power under policy pressures and technological development? Where are the new or retired plants and what generation techniques will be adopted? Will future coal power development exacerbate the stress on water resources or not? All these key questions must be answered by countries with large coal power capacity before the formulation of future policies regarding coal-fired power development and water resource protection.

Previous studies have focused on water-energy nexus with different methods or models, such as Computable General Equilibrium (CGE) model [34,35], Multiregional Input-Output (MRIO) model [36–39], technology-economic model of energy system [40–44], or scenario accounting [45]. However, these studies have usually been carried out at administrative scales in China [27,34,40,43,46,47] or other countries [38,48], and the coarse spatial accuracy is not consistent with the real catchment-level distribution pattern of water resources. Therefore, the water stress in certain catchments have been likely ignored or the irreversibly high local risks of water resources have been omitted. In addition, there are also some studies based on power units, which have focused on past or future environmental impacts from power systems at the sub-provincial [21,49] or grid-level scale [9,10] under fixed pathways. These studies have simulated changes in the environmental impacts of coal-fired power plants, but it is difficult to comprehensively reflect various environmental, energy, and economic policies, and technological progress, etc. [49], such as the constraint of carbon dioxide emission reduction, renewable energy incentives, and generation technology progress. Moreover, it is challenging to reveal the impacts of the above indirect factors on water resources. In other words, there exists a gap between the administrative management of power development pathways and the geographical changes of water resources.

This paper crosses the above-mentioned research gap through considering the socioeconomic policies, technological progress, spatial locations of coal-fired power plants, etc. to map out Chinese power sector development under multiple scenarios. To remedy the shortcomings of the existing research on the spatial likelihood of coal-fired power plant locations and the response to multiple policies and technological factors, we combine provincial projection analysis from a technology optimization model with the spatial locations of coal-fired power plants. The bottom-up model of China's power industry (Multiregional model for Energy Supply system and their Environmental Impacts, or MESEIC) is employed to simulate the total amount and layout changes in China's coal-fired power sector under multiple socioeconomic development pathways and carbon emission reduction targets. And, we build a coal-fired power unit dataset that provides the potential locations of future coal-fired power plants. To reveal the risk of catchment-level water stress originating from coal-fired power plants in the future, including existing operational and planned reserve plants, this study adopts the Monte Carlo method to determine the probability spatial distribution of plants.

The remainder of this paper is organized as follows. Section 2 introduces the study method and data, including the model framework used in the study, the coal-fired power unit dataset and how to evaluate the water stress risk. In Section 3, we describe the scenario assumptions and pathways in this study. In Section 4, we discuss the development pathways of the power sector and the water stress risk under different scenarios. Finally, in section 5, we conclude the findings and offer policy implications for China's power development with water resource consideration.

2. Method and data

2.1. Overview

This study combines a provincial power model, coal-fired power unit dataset, and catchment-level water resources, considering future natural and socioeconomic scenarios. The China's coal-fired power unit dataset supports the development of MESEIC, and the socioeconomic development scenarios drive the provincial power model (MESEIC) in regard to the future development pathways of the Chinese power sector. The spatial distribution probability of power plants is determined with the Monte Carlo method based on the unit dataset and provincial projections obtained with the model. Then, both the water resources at the catchment-level and the spatial distribution probability of the power plants are considered to calculate the water stress risk originating from China's coal power generation sector in the future. The framework is shown in Fig. 1.

2.2. Model description

The MESEIC model is a bottom-up, technology, optimization model for China based on an former version BOMECES_ED, which considers six regions [50]. In this study, the MESEIC model is developed as a province-scale model that Chinese mainland is divided into 32 provincial regions (Mongolia is divided into East Inner Mongolia and West Inner Mongolia), based on the previous six-region model [32,51]. The model mainly focuses on the power sector in this study and contains the energy demand, electricity transmission across provinces, and electricity conversion and supply.

The model is developed in yearly intervals from 2015 to 2050 and output the provincial power supply at 5-year intervals. In the optimization module of the MESEIC model, 86 technology mixes are considered consisting of 14 power generation techniques and 101 interprovincial power transmission channels. Moreover, specific environmental and energy policies, such as carbon emission reduction targets, coal consumption constraints, and subsidy policies for renewable power resources, are considered, which enable the model to project different policy combinations. The objective function of the model minimizes the discounted value of the accumulated total cost over the planning horizon, including the total generation cost (C_{GEN}), interregional power transmission cost (C_{TRANS}), and other policy costs or income (environmental costs, subsidies, etc.) (C_{POLICY}).

$$Objective = min\left\{\sum_t \left[\sum_n (C_{GEN\,n,t} + C_{TRANS\,n,t} + C_{POLICY\,n,t})/(1+i)^{t-1}\right]\right\} \quad (1)$$

where i denotes the discount rate which equals 8% per year; n denotes the power generation technology; and t denotes the year.

The decision variables of this model are the provincial power generation ($GELEC_{n,p,t}$), the provincial installed capacity ($QCAP_{n,p,t}$) of each power generation technology, as well as the annual electricity transmission ($TRANSGELEC_{n,t}$) and average annual transmission capacity ($TRANSQCAP_{m,t}$) of each transmission channel (Table 1). The other model description in detail will be explained in Support Information.

2.3. Coal-fired power unit dataset

We established a dataset of the coal-fired power units in China by

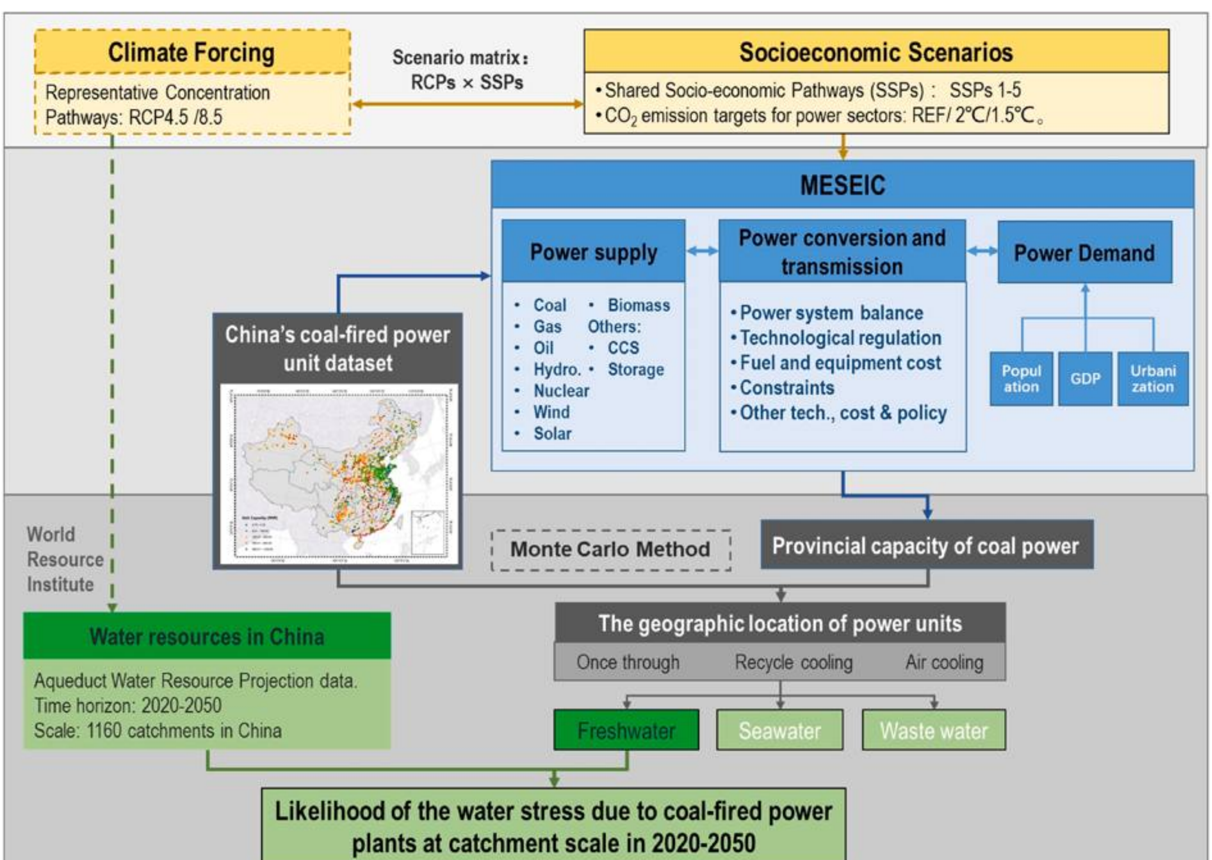


Fig. 1. Risk assessment framework of the water stress due to coal-fired power plants.

Table 1
The decision variables of MESEIC model.

The variables	Variable declaration
$GELEC_{n,p,t}$	The annual generation by each generation technology in each province.
$QCAP_{n,p,t}$	The installed capacity of each generation technology in each province.
$TRANSGELEC_{m,t}$	The annual transmission electricity of each transmission channel.
$TRANSQCAP_{m,t}$	The average annual transmission capacity between two regional grids.

where *n* denotes the power generation technology; *m* denotes the transmission channel; *p* denotes the province; and *t* denotes the year.

integrating different data sources, which contains more than 7,800 units (including retired, operational, and planned units) and covers more than 98% of the total operational capacity in 2015. The dataset covers various attributes of each unit such as the status, nameplate capacity, commissioning year, boiler type, heating or not, cooling technique, permitted water withdrawal, water source, longitude and latitude. The dataset has been validated in our previous studies [52]. The main data sources included:

- List of Desulfurization and Denitrification Units acquired from the Ministry of Environmental Protection [53];
- Energy Efficiency Benchmarking Report compiled by the China Electricity Council (CEC) [54];
- World Electric Power Plants Database (WEPP) [55];
- Global Coal Plant Tracker [56];
- Other data sources such as water withdrawal permits issued to power plants by several water conservancy commissions [57], technical proposals and environmental impact analyses of power plant projects, newspapers or website, financial statements of listed companies, and government announcement;
- Additionally, the locations of certain units were acquired from the Baidu Pick-up Coordinate System. We integrated and across-validated the above data.

Based on the above multiple sources, we cross-validated the acquired data and ensured that no repeated nor incompatible data occurred (please refer to the Supporting Information for details). In 2015, there were approximately 4,500 operational units whose total installed capacity reached approximately 890.1 GW according to the database. In addition, there were approximately 1,600 planned units or units under construction with a total capacity of 901.4 GW and retired units with a total capacity of 88.9 GW. The planned units were determined based on different regional administrative permits or long-term plans, which exceed common estimates of the coal-fired power development scale in recent decades. Hence, there is an assumption that the units to be put into operation in the future will not exceed the scope of the database. It should be noted that in regard to the planned units or those under construction, uncertain technical parameters were determined mainly based on current technical parameters, planning reports, policies, regulations, etc. For example, in terms of the planned cooling and water source-type units, according to regulations [18,58,59], the new units in northern China are recommended to adopt air cooling technique. In regard to the units located in southern and northeastern China, such as the Yangtze River basin, the considered cooling type involves recycling cooling unless alternative credible information is acquired or their geographical location is close to major rivers and oceans. Regarding the future water withdrawal of coal-fired power plants, we determined the future annual water withdrawal of each unit according to their historical water withdrawal intensity (m^3/kWh) and the provincial utilization hours of coal power determined with the MESEIC model.

2.4. Water resources at the catchment scale

The World Resources Institute (WRI) provided a global water risk map (Aqueduct) at the catchment level for 2010 and projections from 2020 to 2040 [60]. We performed calculations via extrapolation to determine the water resources in 2050. In summary, there are a total of 1,129 catchments in China, many of which are located on the Qinghai-Tibet Plateau, and the average area of the remaining catchments is approximately 17,000 km^2. Based on the catchment level, water resource data were calculated under the RCP4.5 and RCP8.5 scenarios using 6 global circulation models (GCMs) retrieved from the Coupled Model Intercomparison Project Phase 5 (CMIP5). This dataset includes the freshwater availability (blue water), water withdrawal (total water extracted from the water catchment), and water consumption (total water consumed in the water basin). In addition, the dataset reveals the changes in water resources in the different regions of China; for example, the annual water resources in the North China Plain and most regions of Northwest China have increased more than 20% over the average value in recent decades.

2.5. Water stress likelihood

There are several different mean values and indices to evaluate water scarcity, such as: the per capita available water, water stress index (WSI) [8,61], and water vulnerability [6,62]. To evaluate the impacts of water withdrawal in the coal power sector on water resources, the WSI is a more suitable index than the other indices. The WSI is defined as the ratio of the total annual water withdrawal to the average annual available blue water (open water source) in a given catchment as follows:

$$\mathrm{WSI} = Ut/Ba \tag{2}$$

where *Ut* denotes the total annual water withdrawal in a given year, and *Ba* represents the available blue water as an estimate of the surface water availability minus the upstream consumption use, which is the mean value of the blue water supply over the several decades. The WSI is divided into the following classifications [60,63](Table 2).

Usually, the development pathways of the power sector are managed and estimated by the administrative regions, as indicated by the MESEIC model. However, the water resources and water scarcity level are evaluated at the catchment scale because of the geographical impacts. Here, we overcome the scale gap between these two assessments by confirming the locations of the coal-fired power units. In general, this process involves downscaling the provincial-scale projection from MESEIC model to the coal-fired power plants (each plant has its certain coordinate) and then summarizing the catchment-scale water stress by the total water withdrawal from those plants within a certain catchment. Since it is not clear which units will be in operation in a certain area in the future, we use the Monte Carlo method to do multiple sampling to give the probability distribution of water stress in each catchment.

Firstly, all units are divided into three states of "operating", "reserved" and "retired" (among which units under construction in 2015 will be marked "operating" after 2020).for the units in operation in a certain year, once the units exceed their operating life, they will be eliminated and classified as decommissioned units. Meanwhile, in order to construct the probability distribution function (PDF) of the units, we give each coal-fired power unit a "P-value" (no matter whether they have been put into operation or not) according to its technical parameters and other factors, including the capacity, boiler types, cooling types, heating or not, and fuel sources (equation (3)). The P-value

Table 2
Water stress classifications.

$<$10%	10%~20%	20%~40%	40%~80%	greater than80%
Low	Low to medium	Medium to high	High	Extremely high

indicates the relative priority of different units within the same state. Units with a higher P-value will have a relatively higher probability of being retained or put into operation. Please read the details in section 3.2 of Supporting Information.

$$P_{unit} = f(capacity, boiler, coolingtype, heating, fuelsource) \quad (3)$$

$$\begin{cases} PDF_{operating} = g_1(P_{unit}, operatinglife) \\ PDF_{reserved} = g_2(P_{unit}) \\ PDF_{retired} = g_3(P_{unit}) \end{cases} \quad (4)$$

Then, the PDF of units in different states will be mainly constructed based on the *P*-value as shown by equation (4). The probability distribution function of operating units will be combined with the *P*-value and operating life, while the reserved and retired units will mainly rely on the P-value. If the total capacity of these "operating" units is larger than the projection of provincial coal-fired power capacity from MESEIC, the retained operating units will be determined by $PDF_{operating}$. On the contrary, if the total capacity of these "operating" units is lower than the projected provincial capacity, the whole "operating" units will be preserved and the new-units demand will be met by the "reserved" units based on $PDF_{reserved}$. If there is still a shortage, "retired" units will also be considered reserved units and put into operation according to $PDF_{retired}$. The above process is taken as a sampling of the Monte Carlo method (Fig. 2). In each sampling, we will get a spatial map of coal-fired power plants, as well as the coordinate-based water withdrawal when considering the provincial average annual utilization hours of coal-fired power generation technologies from MESEIC. Therefore, we determined the water withdrawal amount in each catchment and calculated the catchment-level water stress combined with the available water resources. The water stress is divided into five intervals by WRI [64]: low (<0.1), low to medium (0.1–0.2), medium to high (0.2–0.4), high (0.4–0.8), extremely high (greater than0.8). Based on the division we further subdivide two intervals of 0–0.05 and 0.05–0.1. We used the Monte Carlo method to perform 5000 samplings. And compared with the results of 3000 sampling times, it proves the stability of the sampling probability.

where CA_p: capacity of the province by MESEIC model; *U*: units in some one province; *unit*: the coal-fired power unit; *op*: operating; *rv*: reserved; *rt*: retired.

In addition, the probability of water stress was measured by the concept of the exceedance probability (*EP*) (5), which is the probability that the value exceeds a given value, to illustrate the likelihood of water stress in the future. It is calculated as the probability of the occurrence of water stress greater than a certain critical value in all samplings. For example, an exceedance probability higher than 0.2 was denoted as $EP_{0.2}$. The *EP*-values were divided into five intervals: 0 (no risk), 0 ~ 25% (low risk), 25%~50% (moderate risk), 50%~75% (high risk), 75% ~100% (extremely high risk), and 100% (inevitable risk) (Table 3).

$$EP_r = P(WSI_{coalpower} > WSI_{level}) \quad (5)$$

3. Scenario description

In this paper, we consider socioeconomic scenarios (shared socioeconomic pathways, SSPs and carbon emission reduction targets) and climate change scenarios (representative concentration pathways, or RCPs) to determine the combined effects of socioeconomic and climate change projections on water resources. SSPs comprise the scenario framework for future social development proposed by the

Table 3
The risk (Exceedance Probability) classification.

0 ~ 25%	25%~50%	50%~75%	75%~100%	100%
Low	Moderate	High	Extremely high	Inevitable

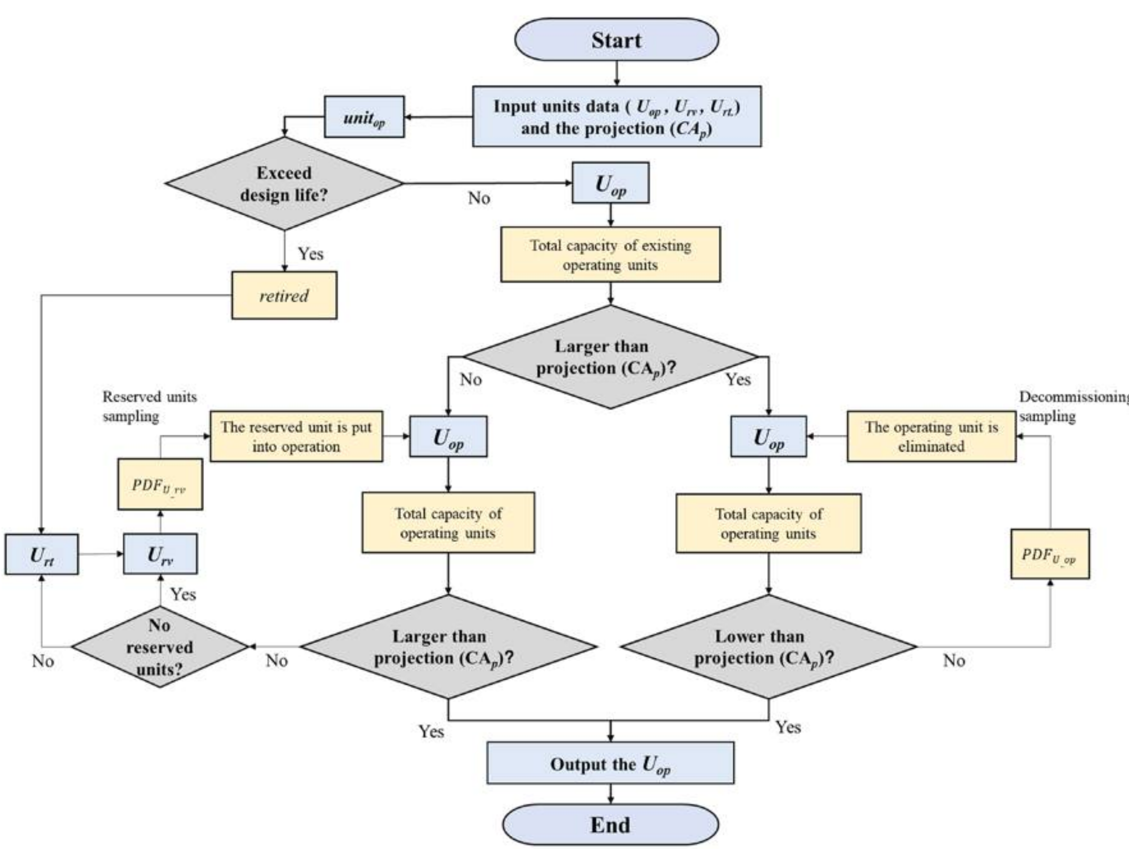


Fig. 2. The flow chart of units confirmation of Monte Carlo sampling.

Intergovernmental Panel on Climate Change (IPCC) in 2010 [65–68], which provides a general view of climate change. There are 5 development scenarios, namely, SSP1-5, which represent different pathways: SSP1 (Low for mitigation and adaptation); SSP2 (Moderate); SSP3 (High for mitigation and adaptation); SSP4 (High for adaptation, low for mitigation); SSP5 (High for mitigation, low for adaptation) [69]. These five pathways represent the low, intermediate, and high challenges to both mitigation and adaptation. In addition, the key variables within the framework are qualitatively displayed. SSP1, SSP2, and SSP3 represent the low, intermediate and high challenges, respectively, to both adaptation and mitigation. SSP4 represents the unbalanced development scenario. SSP5 is similar to SSP3, but it greatly relies on traditional fossil fuels and considers higher mitigation challenges than those under SSP3 [42,67,69–71]. Table 4 shows the designed SSPs in this study, which yield a detailed qualitative description of the future socio-economic and power sector development pathways.

In this study, we consider numerous indicators of power industry to describe the future development pathways. Under these SSP scenarios, the electricity demand intensity, cost reduction curves, technology progress rates and other social and economic components are included to describe the different development pathways. In addition, it should be clarified that renewable energy, including wind, solar and hydropower, is intermittent and unstable. The application of energy storage could address this uncertainty to a great extent, but coal power still represents a stable and more controllable power supply for the grid system. Therefore, no mandatory decommissioning policy of coal is considered in the model. Details of the scenarios setting are presented in Supporting Information.

To compare the influences from the different CO_2 emission targets, we designed three carbon emission targets, namely, the reference scenario (REF), deep decarbonization pathway (2℃) [72], and net-zero emission target (1.5℃) [73](Table 5). Under the REF scenario, there is no carbon emission reduction constraint in the power sector, while the carbon emission intensity of the power sector is reduced by 89% in 2050 over 2010 level under 2℃ target and decreases to zero under the 1.5℃ target. Moreover, as indicated shown in Table 6, the scenario matrix is constituted by the SSPs, RCPs and three CO_2 reduction emission targets in this paper, which refers to the framework for comprehensive assessments of climate policy [69,74]. Parameter settings are contained in the Supporting Information.

Table 5
Scenarios of the carbon emission reduction targets.

	Reference scenario (REF)	2℃ target	1.5℃ target
SSPs	No carbon emission control target.	In 2050, the carbon emission intensity of the power industry is reduced by 65% over the 2010 level[72].	Net-zero CO_2 emission in the electric power industry by 2050 to achieve the carbon neutrality[73].

4. Results

4.1. China's electricity demand before 2050 under the SSPs

The electricity demand of China in 2019 is 7,249 TWh [14], which has continued increasing in recent years. And it is derived by the joint influence of the gross domestic product (GDP), population, urbanization and power demand intensity under the various SSP scenarios in the future [75]. The electricity demand will continue to grow under SSP2-5, except that the electricity demand will peak in the 2035 s under SSP1 (Fig. 3a). The national electricity demands in 2050 under all 5 scenarios are higher than that in the base year of 2015. Among the five scenarios, SSP5 exhibits the highest electricity demand (19,383 TWh) in 2050, which is approximately 3.4 times higher than that in 2015. The electricity demand under SSP1 will peak (8,026 TWh) in about 2035 and then gradually decrease to the value of 7,058 TWh in 2050, which is approximately 1.3 times higher than that in 2015.

Regardless of the scenario and carbon emission target, the electricity demands in most provinces will continue to increase, especially in specific provinces, such as Guangdong, Shandong, Henan, Hebei, and Jiangsu. (Fig. 3b). The total national power demands under the SSP2 and SSP4 scenarios are similar, but there are differences among the provinces, and they are mainly affected by the increasing differentiation between social and economic development under SSP4. Between SSP3 and SSP5, the mitigation challenges are similar, and SSP3 faces high adaptation challenges, which indicates that the energy demand under SSP5 is higher than under SSP3 [71]. Generally, electricity consumption is more concentrated in developed and densely populated areas, such as the coastal areas and provinces in Central and East China. This pattern is similar to the situation in 2015 and does not change in 2050. So the local electricity demand will have to be satisfied either by increasing local generation or transmission across provinces.

4.2. The development pathways of the China's power sector under the SSPs

4.2.1. China's future power supply pathways

In this study, the changes and balance between the consumption and production sides of the power industry are examined within the SSP scenario framework, while three carbon emission targets are considered under each pathway. Fig. 4 shows power generation mixes and annual coal-fired power generation curves of the Chinese national power sources under the various scenarios involving the SSPs and CO_2 emission targets from 2015 to 2050. The SSPs provide five general future development pathways, including the electricity demand and advances in power generation. It is clear that the electricity demand imposes a positive effect on nearly all types of power generation techniques. There are also certain new techniques, such as carbon capture and storage (CCS) and biomass, applied under some scenarios to achieve the set carbon emission targets.

Under the SSP1 scenario (low adaptation and mitigation), the generation of coal power will peak in either 2025 or 2030, which is earlier than the peak year of the electricity demand (2035). Thereafter, wind,

Table 4
The qualitative description of shared socio-economic pathways (SSPs).

	SSP1	SSP2	SSP3		SSP4		SSP5
GDP	Middle	Middle	High		Middle		High
Population	Low	Middle	High		Low		High
Urbanization	High	Middle	High		High		High
Power demand intensity	Low	Middle	Middle		Low	Middle	High
Fossil energy supply	Middle	Middle	Low	High	Low	High	High
Fossil energy conversion technology progress	Middle	Middle	Low		Low	High	High
Biomass energy conversion technology advancement	High	Middle	Low		High		Middle
Renewable energy conversion technology advances	High	Middle	Low		High		Middle
CCS	Middle	Middle	Middle		High		High

Note: The quantification of each indicator is determined through literature and experience.

Table 6
Scenario matrix (SSPs, RCPs and carbon emission targets).

SSPs	SSP1		SSP2		SSP3		SSP4		SSP5	
Emission	REF	2°C/1.5°C	REF	2°C/1.5°C	REF	2°C/1.5°C	REF	2°C/1.5°C	REF	2°C/1.5°C
RCP8.5	×	×	×	×	×	×	×	×	√	√
RCP4.5	√	√	√	√	√	√	√	√	×	×

Note: The symbols of "√"mean the mixes are selected as the future scenarios while the symbols of "×" mean not.

solar and nuclear power generation will quickly replace fossil-fueled power generation, while hydropower remains stable. Compared with the REF scenario, the above substitution occurs sooner under the 2℃ and 1.5℃ targets.

Under the SSP2 scenario (moderate challenge), power generation will quickly increase before 2030 and gradually stabilize thereafter. If no CO_2 emission targets are considered, coal-fired power generation will increase 0.6 times to 5,300 TWh in 2025 and will remain relatively stable thereafter. However, the CO_2 emission targets highly influence fossil fuel consumption. To meet the 2℃ and 1.5℃ targets, zero-carbon power resources such as wind, solar, and nuclear power will mostly replace coal, and the remaining coal power will require CCS to reduce carbon emissions. In addition, bioelectricity with CCS will be applied after 2040, which mitigates the carbon emissions originating from coal power generation through CCS.

Under the SSP3 scenario (high mitigation and adaptation), the electricity demand continues to increase until 2050, which is 3 times that in 2015. Because low-carbon energy resources do not provide enough advantages over fossil fuel under SSP3, the additional electricity demand is satisfied by coal-fired power generation. However, the power supply will transition to low-carbon energy considering the CO_2 emission constraints of 2℃ and 1.5℃. Under SSP3, biomass and coal power with CCS will play irreplaceable roles. Nearly the entirety of the generated coal-fired power of approximately 2,700 TWh (15.5% of the total generated power) is produced by coal-fired power units equipped with CCS under SSP3 and the 1.5℃ target.

The SSP4 (high adaptation and low mitigation) and SSP5 (low adaptation and high mitigation) scenarios are similar to the SSP3 scenario in certain ways. Under SSP4, a relatively rapid technological development occurs in low-carbon energy resources in certain provinces and slow development in other regions. Therefore, low-carbon energy resources, such as solar, wind, and nuclear energy, occupy a larger proportion than that under SSP2. Under SSP5, it is clear that coal power with CCS still accounts for a major proportion of the electricity supply. Due to the technological advances and falling cost of traditional fossil fuels, coal power with CCS will rapidly increase after 2030 and will meet nearly half of the power demand in 2050.

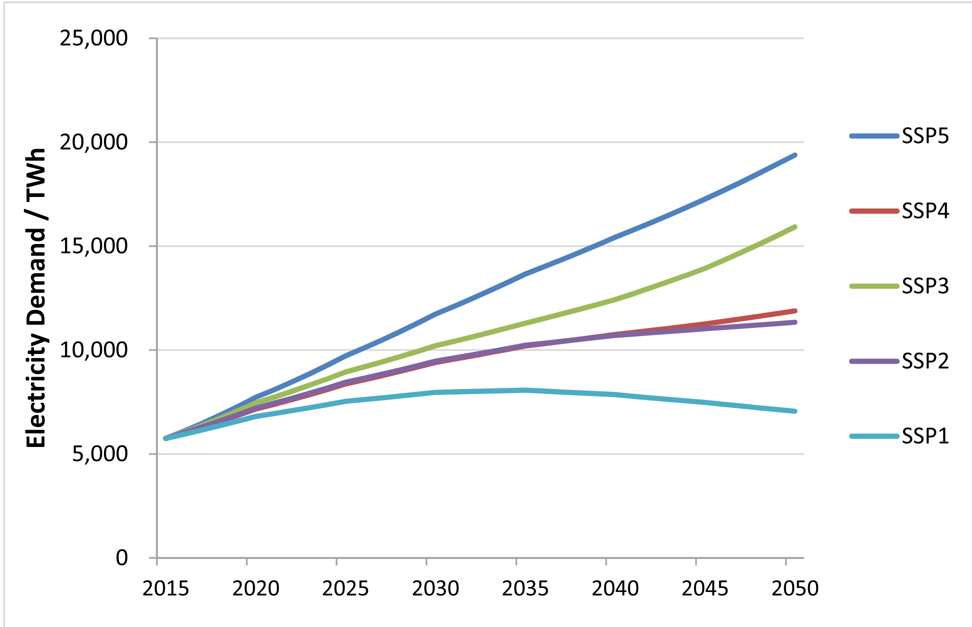
4.2.2. Coal power development in China

The development pathways of China's coal power are quite different under the various combination of the SSPs and CO_2 emission targets (Fig. 5). By 2050, the generation of coal power will reach a wide range from 288 to 16,650 TWh under the different scenario. Under SSP1, SSP2, SSP3, and SSP4, coal power generation will peak in either 2025 or 2030 and will begin to decline thereafter, except under SSP3 with the REF scenario. To achieve the carbon emission reduction targets, coal power generation under SSP1 will be reduced from 3,893 TWh in 2015 to [288, 1,551] TWh in 2050, while the installed capacity will be reduced from 895 GW to [323, 527] GW. However, regardless whether the above CO_2 emission target constraints are considered under the SSP5 scenario, coal power generation will always continue to grow, and coal power generation will reach 2.3–4.2 times that in 2015. However, it should be noted that to achieve the carbon emission targets of 2℃ and 1.5℃ by 2050, the carbon intensity of coal power generation will have to be reduced by including the CCS technique. Under SSP3, coal power generation is greatly influenced by the CO_2 emission targets, and coal power with CCS is applied in 2040 because of these targets. Compared with SSP3, the trends of coal power generation under SSP2 and SSP4 are similar. The difference is that the cost of renewable energy under SSP4 decreases faster and renewable energy resources occupy a larger share than that of coal power, thus reducing the generation of coal power.

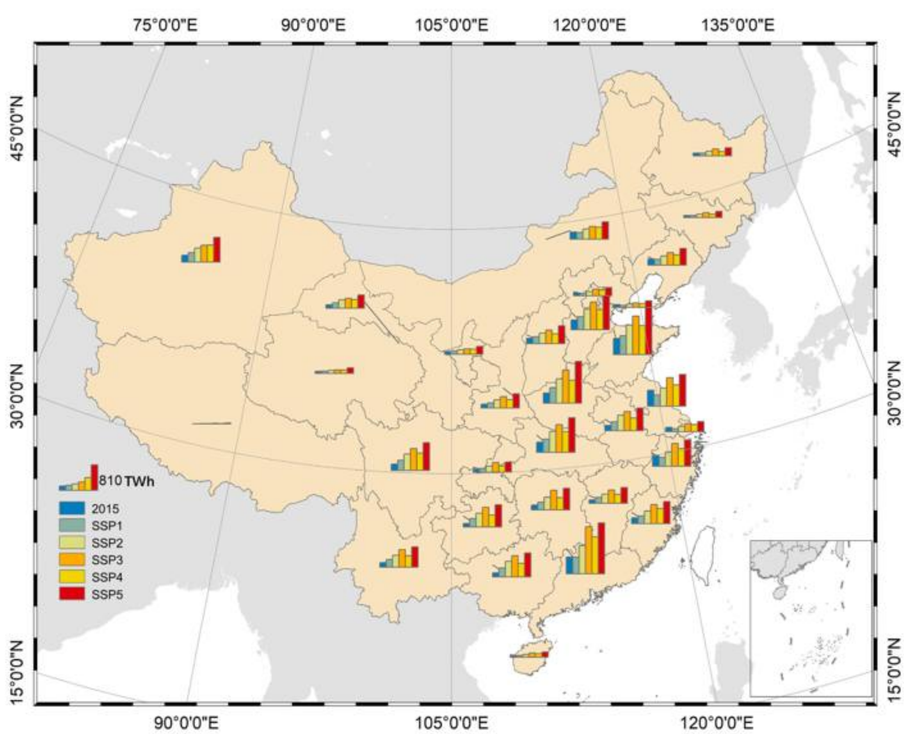
The above differences in coal power generation directly affect the total installed capacity (Fig. 6a). Among all 32 provincial-level regions, the installed capacity of coal-fired power plants in 17, 22 and 28 provinces will increase in 2050 over 2015 under the SS2, SSP3, and SSP5 scenarios, respectively, with the REF scenario, while only 4 and 5 provinces exhibit an increase under the SSP1 and SSP4 scenarios, respectively (Fig. 6b). When considering the stringent carbon emission targets, the number of provinces with an increased coal-fired installed capacity under the SSP1-5 scenarios is 1, 5, 11, 3, and 18 provinces (2 °C) and 2, 3, 7, 2, and 7 provinces (1.5 °C), respectively. The more stringent carbon emission targets drive the reduction in coal-fired power in most regions, in which the electricity consumption is satisfied through more low-carbon power and cross-regional electricity transmission. However, not all provinces will become coal free and there will still be a few regions with increased coal power installed capacity (most of the coal power is installed with CCS), such as Xinjiang and Inner Mongolia. This shift may be due to the advantages of coal resource endowment. To ensure the stability of the power grid, the whole country needs a certain stable power supply to provide support for the power grid. In this case, the relative concentration of coal power distribution is higher, which means that it is important to pay attention to the water stress risk in areas like Inner Mongolia and Xinjiang, where the coal power capacity still increases despite the carbon emission reduction constraints.

Moreover, the spatial distribution of the coal-fired power plants shows that the increase in installed capacity will occur more in Northwest and North China. In 2015, the top 10 provinces, among which 6 provinces to the north of the Yangtze River, supplied more than 62.8% of the national coal-fired power capacity. In 2050, this percentage will increase to 67%-99% under all scenarios. Although the national capacity of coal-fired power is the lowest under the 1.5℃ target, the concentration in the top 10 provinces is the highest over that under the REF and 2℃ targets, which is higher than 90%. Inner Mongolia, Xinjiang, Henan, and Shandong will always account for a notable share of the Chinese installed coal power capacity, and Guangdong, Shanxi, and Guizhou, also play important roles under certain scenarios.

There are two representative provinces reflecting the shift in power structure. Guangdong is always an electricity importer whose power consumption will be largely supplied by local coal-fired power plants under SSP3 (73.0%) and SSP5 (75.7%) with the REF scenario in 2050. However, the supply relies on other power sources, such as interprovincial power import, wind, solar power, and nuclear power, under the other scenarios. For example, the local coal power supply will be reduced to nearly 0 under the 1.5℃ target (Fig. 7a). In Inner Mongolia, an electricity exporting province in 2050, the share of coal power will increase from 64.8% in 2015 to 78.9% (SSP2), 86.7% (SSP3), and 90.4% (SSP5) under the REF scenario. Under both the 2℃ and 1.5℃ targets, the proportion of coal power will decrease to below 30%, except under the SSP4 scenario (23%~43%). As a net power exporter, the average export capacity percentage in Inner Mongolia will change from [47.5%, 58.0%] (REF) to [28.9%, 37.6%] (2℃) and [24.2%, 42.8%] (1.5℃) (Fig. 7b). Although the proportion of the export capacity appears to be decreasing, it should be emphasized that the export capacity does not actually decrease. Moreover, the annual utilization hours of renewable



(a) Projection of the national electricity demand before 2050



(b) Provincial electricity demand in 2050 under the 5 scenarios

Fig. 3. China's electricity demand under the five SSPs from 2015 to 2050. (a) The national electricity demand under SSP1-5 during 2015–2050; (b) The provincial electricity demand under SSP1-5 in 2050.

energy sources such as wind and solar energy are far below the available hours of transmission lines.

4.3. The likelihood of the water stress due to coal-fired power plants

4.3.1. Total water demand of the coal-fired power plants

In 2015, the national water withdrawal of coal-fired power plants reached nearly 54.0 billion m^3 according to our coal-fired power unit dataset, of which 49.4 billion m^3 came from once-through cooling units (similar to the value reported in the 2015 China Water Resources Bulletin). In 2050, the national water withdrawal by coal-fired power plants would vary greatly among five shared socio-economic development scenarios and the three carbon emission reduction targets (Fig. 8). The development pathways will have large influence on the water

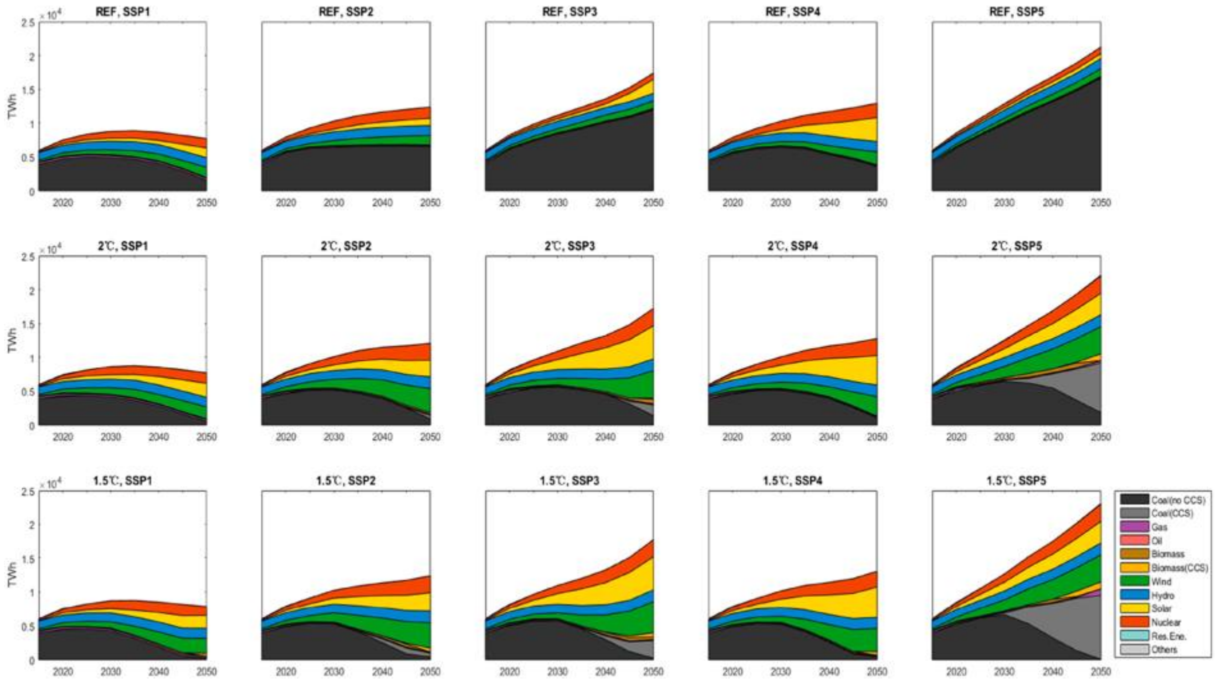


Fig. 4. National power generation based on the power sources under the SSPs and CO_2 emission targets from 2015 to 2050.

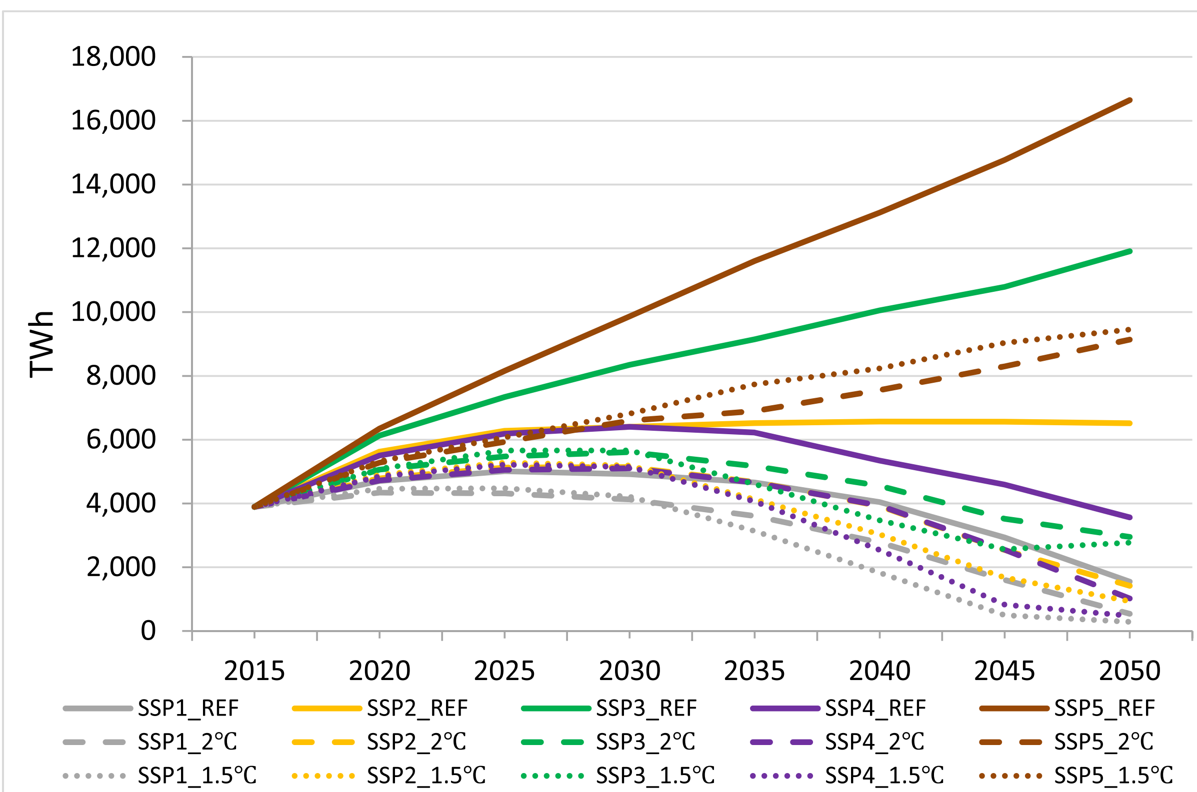
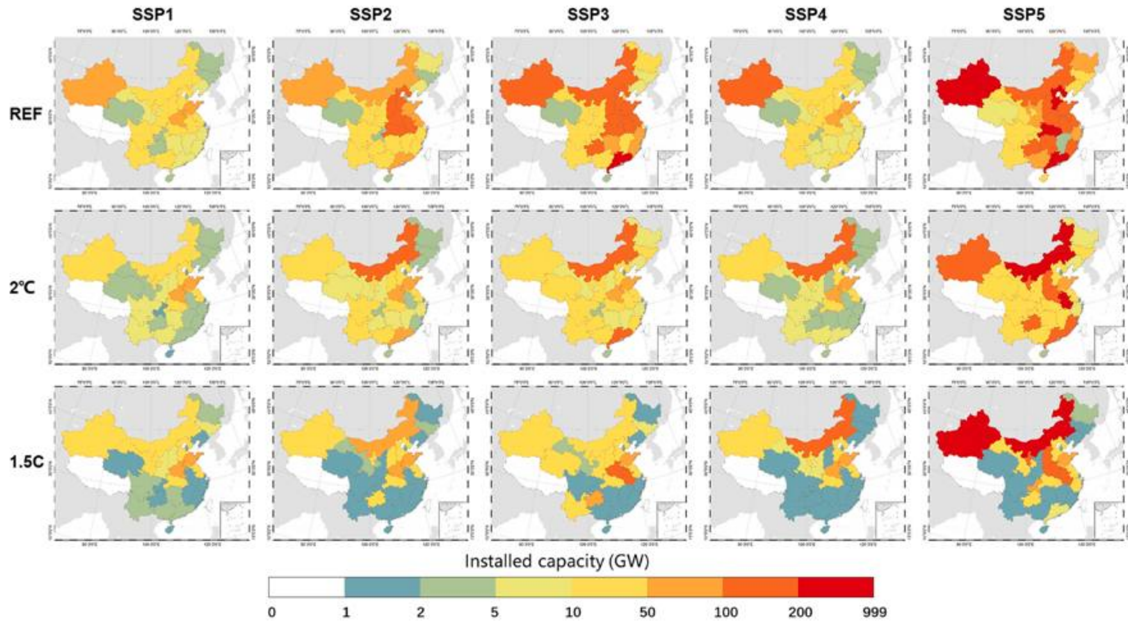
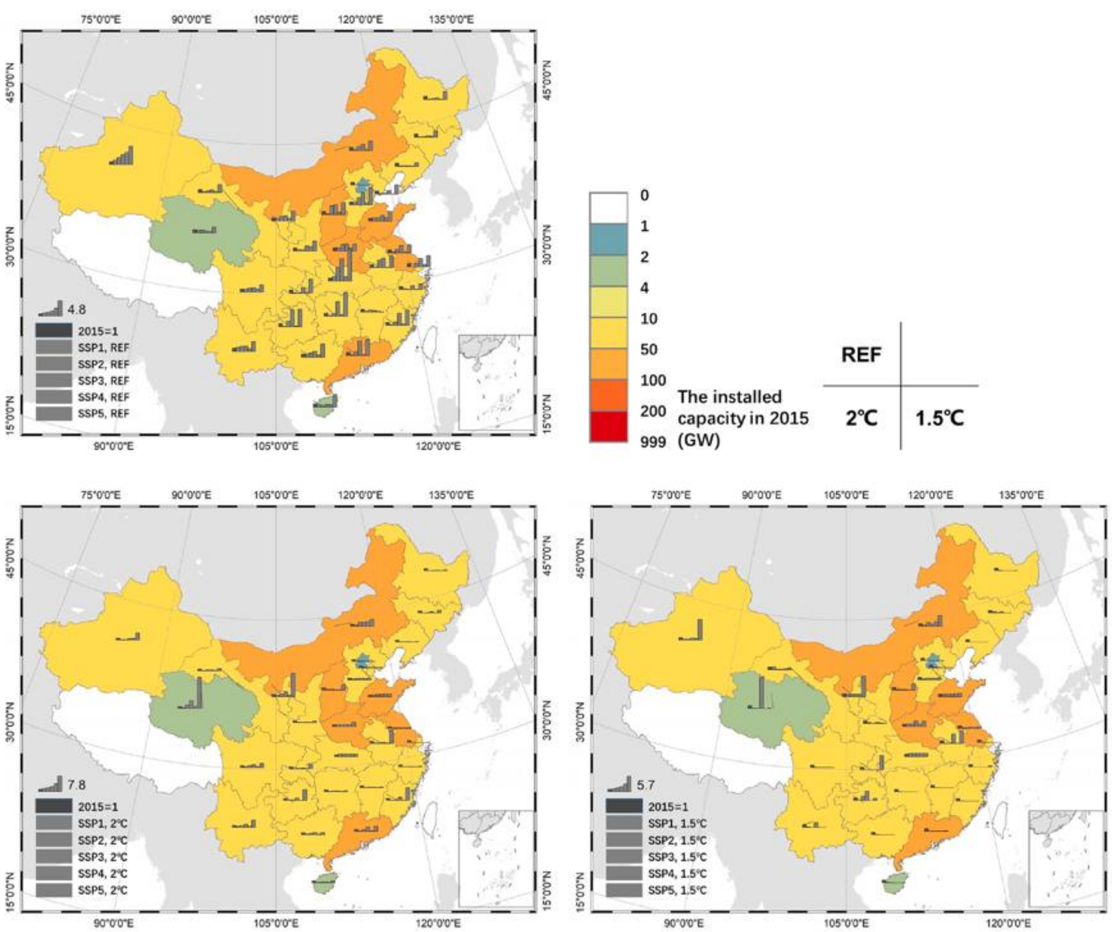


Fig. 5. Annual generation of coal power from 2015 to 2050 under SSPs and the carbon emission reduction targets.

withdrawal. Under the REF scenario, the national coal power water withdrawal under SSP2 scenario in 2050 will be almost the same as it in 2015, while it will decrease under SSP1 and SSP4, and increase significantly under SSP3 and SSP5. When carbon emission targets of 2℃ and 1.5℃ are considered, there will be significant synergies between carbon emission reduction and water withdrawal reduction. Under the REF, 2℃, and 1.5℃ targets, the average national water withdrawal in 2050 will range from 12.2 to 176.2 billion m^3, 10.7–59.3 billion m^3, and 0.12–35.5 billion m^3 under SSP1-5 respectively. The stricter constraints of carbon emission targets on coal power greatly reduces the corresponding water withdrawal except SSP3 scenario. Moreover, since new power units will mainly adopt recycling cooling systems or use seawater

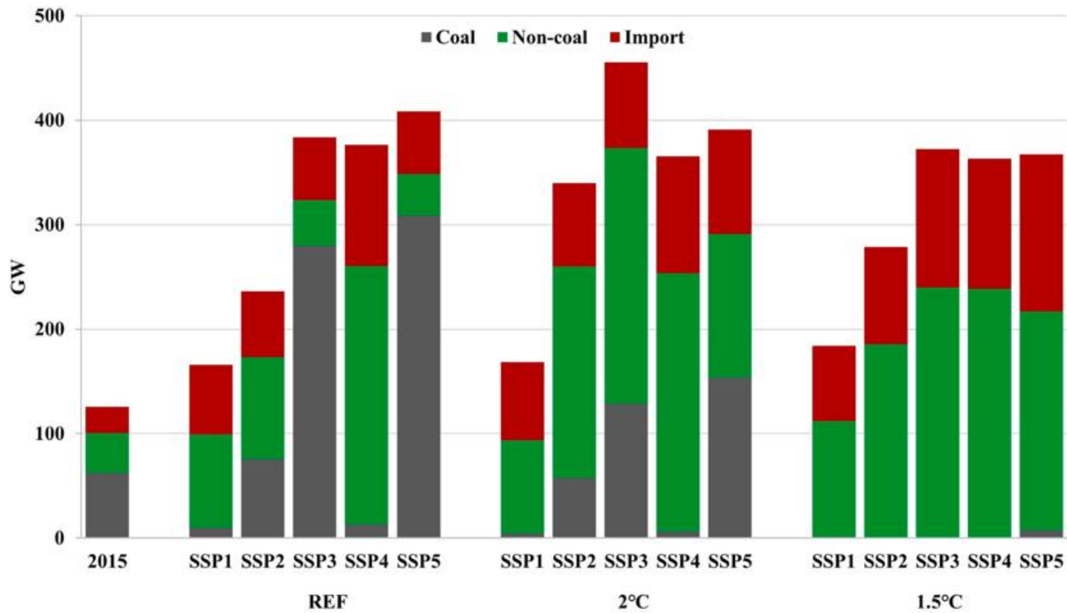


(a) The provincial installed capacity of coal-fired power plants in 2050.

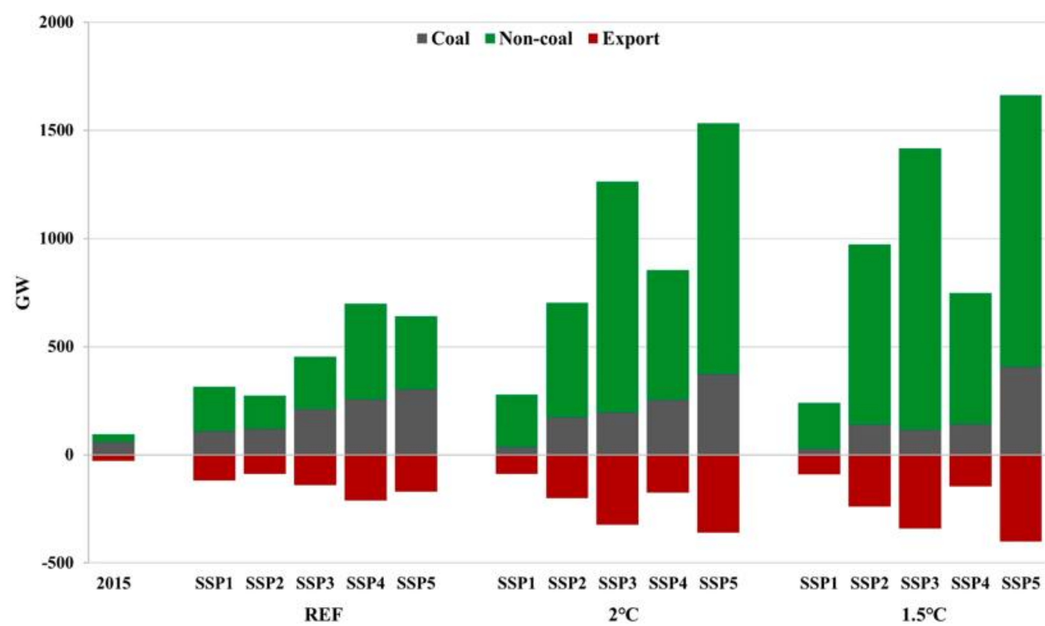


(b) The provincial relative installed capacity values in 2050 compared with it in 2015.

Fig. 6. Projection and the relative values of provincial coal-fired power plants capacity in 2050. (a) The projection of coal-fired power plants under the SSPs and three carbon emission targets by MESEIC; (b) The relative provincial installed capacity values of coal-fired power plants in 2050 compared to it in 2015. The black bar represents the capacity in 2015, and the grey bars represent the ratios between 2050 and 2015.



(a) Example province of electricity importer: Guangdong in 2015 and 2050



(b) Example province of electricity exporter: Inner Mongolia in 2015 and 2050

Fig. 7. Example provinces of the electricity importer and exporter in 2015 and 2050: (a) Guangdong; (b) Inner Mongolia.

as cooling water source in the future, the water withdrawal of once-through cooling units will account for 10.8%-21.4%, 17.6%-24.5%, and 20.5%-90.6% of the total water withdrawal with the three carbon emission targets, which indicates that the proportion of the remaining consumed water withdrawal by recycling cooling and air cooling units will be relatively lower.

In 2015, China contained 2,690 billion m^3 of available water resources [3], and the water withdrawal for coal power generation accounted for approximately 2.00% of the total water supply. In 2050, under the RCP4.5 and RCP8.5 scenarios, China's water resources are likely to decrease by approximately 3.60%~3.80%. If measured at the national scale, the variation in water withdrawal may only account for 0.04%~6.81% of the total water resources. The national variation in water resource stress buries the characteristics of the spatial distribution differentiation of the water resources in China.

4.3.2. Risk assessment of the water stress in catchments

The risks of the water stress in space originating from China's coal-fired power plants under the five SSP scenarios and three carbon emission targets are shown in Fig. 9. In 2015, the areas facing a water stress level of 0.05 due to coal-fired power plants were mainly concentrated in Northwest and North China, including catchments in Xinjiang, Gansu, Hebei, Shanxi, and Shandong. In particular, in certain basins in North and Northwest China, the water stress caused by coal power generation

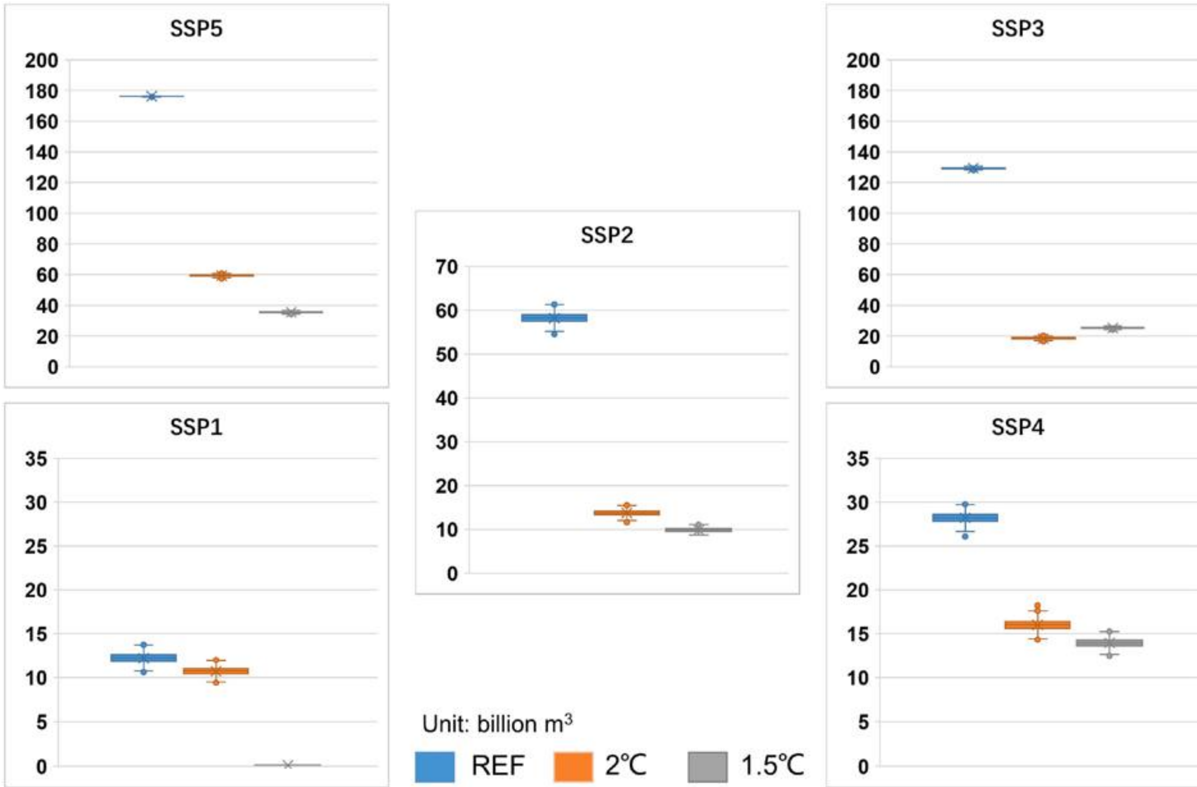
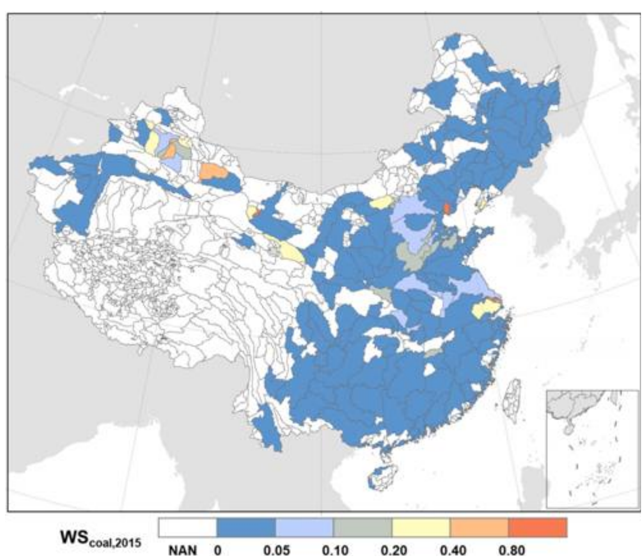


Fig. 8. Total water withdrawal of China's coal-fired power plants. The boxes represent the upper and lower quartiles of total water withdrawal.

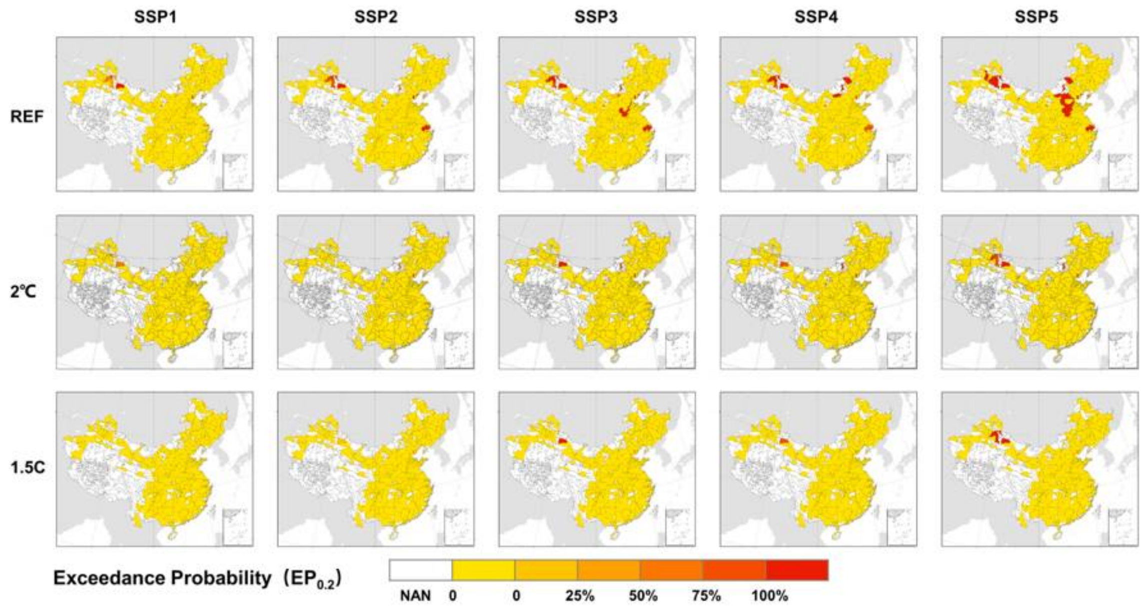


(a)$WSI_{coal,\ 2015}$

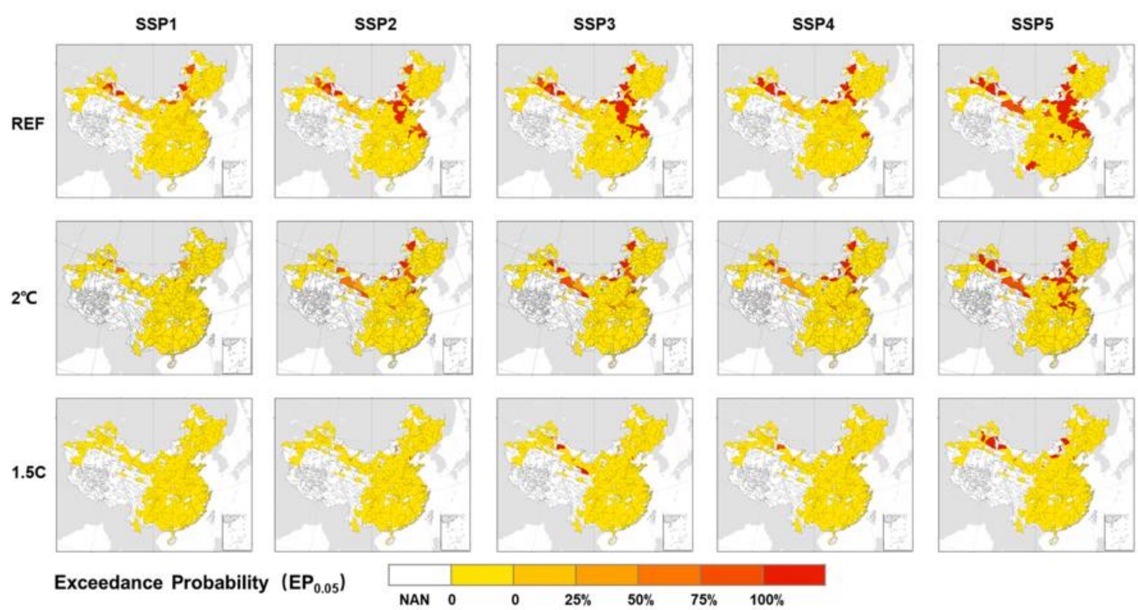
Fig. 9. Risk maps of the water stress due to coal-fired power plants in 2015 and 2050 under the five SSPs and three carbon emission reduction targets. (a)$WSI_{coal,2015}$, the water stress due to coal-fired power plants in 2015; (b) and (c) $EP_{0.2}$ and $EP_{0.05}$ in 2050, the exceedance probability of water stress for 0.2 and 0.05.

was high, even higher than 0.2. In southern China, despite the very large water withdrawal amount, almost no notable water stress occurred due to the abundant water resources, except for several catchments near the Yangtze River or the sea.

Under the REF scenario with no carbon emission reduction constraints, the installed capacity of coal-fired power plants increases or remains at a certain level, which directly affects water withdrawal. Under the five SSP scenarios, the coal-fired power plants are mainly located in the provinces in North and Northwest China, and there are also some certain plants in South China under SSP3 and SSP5. The high-risk areas ($EP_{0.2}$ greater than 50%) are mainly located in Northwest and North China, such as Xinjiang, Hebei, and Inner Mongolia. Especially in certain catchments, the risk (WSI greater than 0.2) is shown to be inevitable. If we focus on a water stress level of 0.05, it is found that the



(b)$EP_{0.2}$ in 2050



(c)$EP_{0.05}$ in 2050

Fig. 9. (*continued*).

catchments affected by coal power generation rapidly increase. Almost all the water catchments in North and Northwest China will face an extremely high or inevitable risk of water stress. The obvious contrast is that the coal-fired power plants in southern China will not exert major impacts on the local water resources. The risk maps under the REF scenario reveal that without the carbon emission constraints, China will not avoid the risk of water stress due to coal power generation, especially in Xinjiang and Inner Mongolia, even if we reduce the future power demand (SSP1).

Under the 2℃ target, the risk of water stress due to coal-fired power plants decreases in most areas of North China. The $EP_{0.2}$ value in most catchments in North China is reduced to 0, which indicates that the risk is mitigated, and only a few catchments still face a high risk of an extremely high water stress exceeding 0.2. In regard to a water stress level of 0.05, the high-risk areas greatly decrease, and the regional catchments in northern China with a high or even inevitable risk under the REF scenario become discontiguous. For example, under the SSP5 scenario, the number of areas with an $EP_{0.05}$ value higher than 50% is more than 46% smaller than that under the REF scenario. Moreover, it cannot be ignored that there are still some catchments facing high and extremely high risks of water stress in North China. Only the catchment risk under SSP1 was greatly reduced, and no catchment faces a high risk. This indicates, however, that the electricity demand will have to be reduced.

Under the 1.5℃ target and stricter carbon emission reduction constraints, the water stress will have been greatly eased in most catchments in China. Except for several catchments (the areas are sensitive to water withdrawal because of water scarcity) in Xinjiang under SSP3, SSP4, and SSP5, nearly no catchments will suffer a water stress level of 0.2. Similarly, under the SSP3 and SSP5 scenarios, the areas facing a high risk of a water stress exceeding 0.05 will expand, containing some catchments in Gansu and Inner Mongolia. Under SSP2 and SSP4, only a few catchments will face a moderate risk of water stress, and no catchments will face a moderate risk of water stress under SSP1. The risk maps under the 1.5 °C target demonstrate that the majority of areas will be able to avoid water stress risks while meeting their electricity demand.

Under the constraints of the considered carbon emission reduction targets, either 1.5℃ or 2℃, there is no catchment with a water stress probability due to coal-fired power plants higher than 0.2, except in certain areas in Xinjiang. When we focus on a water stress level higher than 0.05, the carbon emission reduction targets are also important for the reduction in water stress risk in most areas. The water stress (WS greater than 0.05) in some catchments in Northeast and North China decreases under the 1.5 °C targets. However, there are also certain catchments that experience a certain water stress risk, such as the catchments in Inner Mongolia.

The water withdrawal of the current coal-fired power plants in 2015 was approximately 54.0 billion m^3 (excluding seawater). By 2050, the total water demand is projected to range from $0.12 \sim 176.2$ billion m^3 under SSP1-5 and the 3 carbon emission targets. The range is large because there are diverse projections of the future electricity demand under the 5 SSPs, various stringency levels of national or regional coal consumption control measures and different levels of low-carbon energy penetration.

Under SSPs 1–5, there are 6, 11, 21, 10 and 37 catchments that would very likely (a probability higher than 50%) face a high water stress (indicating that the potential water withdrawal of only coal-fired power plants would account for more than 40% of the total water availability, thus matching the definition of a high water stress level) in 2050. These catchments are concentrated in the central and eastern parts of Xinjiang, the North China Plain, and specific catchments in Inner Mongolia, Shanxi, and Gansu provinces. This indicates that they should be designated as focus or restricted zones in regard to the construction of new coal-fired power plants in these catchments or the water supply should be replaced with that in other sectors to avoid an even higher water stress in these regions.

5. Conclusion

The purpose of the current study was to focus on the development pathways and the water stress risks of China's coal power sector under Shared Socio-economic Pathways (SSPs) and three carbon emission reduction targets. To address the resolution limitation of previous studies, this study gives the spatial distribution probabilities of the coal-fired power plants combining the provincial-level coal power projection and the unit-level coal-fired power plants dataset, as well as the risk maps of water stress due to the transition of coal power in China. Electricity demand is the original driver of power sector and technological development and carbon emission targets are the key factors to change the structure of electricity production. China's electricity demand will keep growing before 2050, except for the SSP1 scenario due to the suppressed demand intensity and population. However, the growth of electricity demand in various provinces is quite different, and the future power supply pattern might also have great changes from it now.

The following conclusions could be drawn from the present study. Carbon emission targets have a significant impact on China's coal power scale, and also both the inter-provincial differences and the proportion of some northern provinces in China's coal power production would increase. Without carbon emission constraint under REF scenario, coal power will still play an indispensable role in electricity supply in 2050 (SSP2, SSP3, and SSP5), unless the electricity demand is suppressed (SSP1) or the cost advantage of renewable energy is greater than that of coal power (SSP4). Under the 2℃ and 1.5℃ targets, coal power will be obviously restricted because of the carbon emission constraint, except for SSP5 where coal power with carbon capture and storage (CCS) technology has achieved rapid development. Compared with the 2℃ target, coal power development under 1.5℃ target is subject to stricter restrictions of carbon emission and therefore has little capacity for development. Although the national capacity of coal-fired power plants is restricted, there are still some provinces in the north of China, such as Inner Mongolia and Ningxia, where the installed capacity of coal power would maintain a relatively large scale. It means that coal-fired power plants would be more concentrated in some regions with sufficient resource endowment and significant cost advantages.

The water stress risk caused by coal-fired power plants would be alleviated more comprehensively under 1.5℃ target than it under 2℃ target, but the application of CCS might weaken the synergistic benefits. The carbon emission targets directly restrict the development of coal power in China. However, the 2℃ target is not strong enough to help release the water stress risk caused by coal-fired power plants, especially for some catchments in northwestern China. Under the stricter target of 1.5℃, only a few catchments will still face high risk of severe water stress due to coal-fired power plants, which indicates that there is a synergy between the carbon reduction targets and water stress mitigation. However, when the technology progress and cost reduction of CCS are more accepted in the future, coal power will still be retained and generate high water stress risks in a few catchments, such as the pathways of SSP5 and SSP3.

In summary, there are synergies between carbon emission targets and water stress mitigation. The 2℃ target is not strong enough to completely reduce the high water stress risk of some catchments in north China in 2050, while the risk could be significantly alleviated under stricter constraint of the 1.5℃ target. However, it needs to be noted that the large-scale application of CCS could maintain high capacity for coal power and weaken the synergies above. Therefore, it needs to pay more attention to those areas with high water stress risk and take additional measures, such as limiting coal power development in some regions. The operation of coal-fired power plants with CCS in the northern regions should be more cautious because CCS cannot solve the water stress issues caused by coal power.

This study spans the scale differences between administrative planning and catchment-level water resources by mapping out the spatial distribution probability of coal-fired power plants, and provides more reliable findings of the water stress risks caused by coal power under social and economic development pathways and climate change. The study could help policymakers and researchers take water stress risks (rather than providing a fixed water stress index) into account more reliably and refine the transition pathway of the coal-fired power plants. The research framework also provides a reference for other areas and similar issues. Also, there are some limitations in this study. For instance, the bearing capacity of the water stress generated by coal-fired power plants actually differs across the various regions, which is affected by the water demand from other sectors and beyond the scope of the study. Also, water consumption by the plants has not been considered separately because of the need for more detailed data. Besides, the determination of the plants location mainly takes the technical factors and fuel source of the units into account, and it might be influenced by more factors in practice. Notwithstanding these limitations, likelihood estimation describes the possible risks of future coal-fired power plants development, which has a notable reference for the formulation of future development strategies of coal power based on macroscale policies and regional characteristics.

CRediT authorship contribution statement

Haoran Li: Conceptualization, Methodology, Data, Analysis, Writing original draft. **Xueqin Cui:** Methodology, Writing - review & editing. **Jingxuan Hui:** Methodology, Writing - review & editing. **Gang He:** Methodology, Writing - review & editing. **Yuwei Weng:** Writing - review & editing. **Yaoyu Nie:** Visualization. **Can Wang:** Conceptualization, Supervision. **Wenjia Cai:** Conceptualization, Funding acquisition, Project administration, Supervision, 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.apenergy.2021.116986.

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