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Sustainable or Not for Water Consumption after Implementing CCS in China's Coal-Fired Power Plants for Achieving 2 °C Target

Feiyin Wang [1], Pengtao Wang [2] and Mao Xu [3,*]

[1] College of Safety Science and Engineering, Civil Aviation University of China, Tianjin 300300, China; fy_wang@cauc.edu.cn
[2] College of Mining Engineering, North China University of Science and Technology, Tangshan 063210, China
[3] School of Environment, Tsinghua University, Beijing 100084, China
* Correspondence: xumao951225@163.com

Abstract: The shortage of urban water caused by CCS retrofitting over coal-fired power plants has become an emerging issue, especially in China where water resources are scarce. In this study, we quantified the impact of CCS retrofitting on water resources and analyzed the increased water pressures due to CCS retrofits in 234 cities of China. We identified 54 cities with 165 power plants that would face water pressure due to CCS retrofitting for achieving 2 °C targets. The results show that the average water withdrawal and water consumption of power plants in 234 cities would increase by 1.63 times and 1.49 times, respectively, involving 480 million people in China. The ratio of freshwater withdrawal to available water (WTA) and the ratio of freshwater consumption to available water (CTA) at the city-level increased by 0.2 and 0.06 under 2 °C constraints respectively, involving a population of 84 million people. Moreover, CO_2-EWR technology does not provide relief from urban water stress. This paper assesses the water demand for carbon capture technologies and provides a basis for siting future large-scale deployment of carbon capture technologies in China.

Keywords: CCS; coal-fired power plant; withdrawal water; consumption water

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1. Introduction

Carbon dioxide capture and storage (CCS) technology is regarded as one of the most promising measures for the low-carbon development in the power [1] and industrial sectors, as well as for mitigating climate change [2,3]. Existing studies have discussed the effectiveness of CCS development in the power sector for achieving the temperature-limiting goal. There are already some CCS projects that have been put into practice or under construction. However, due to the additional cooling demand of the heat exchanger and the CO_2 compressor, the implementation of CCS in power plants will further increase the water consumption.

In terms of the difference between power generation technology and carbon capture technology, the water consumption of a retrofitted power plant with CCS is expected to increase by 33% to 90% [4–6]. Schakel et al. find that with the large-scale promotion of carbon capture technology in Europe, the water load in many regions would increase significantly by 2050 [7]. Sathre et al. researched the county-level water consumption pressure in the United States. They concluded that the implementation of CCS in U.S. power plants might upset the balance of water supply and demand and would cause severe impact on water supply in some counties [8]. Different from Europe and the United States, power plants in China are dominated by coal-fired plants which account for about 60% of the total power generation and contribute to approximately 40~50% of total CO_2 emissions in China [9]. In this sense, the impact of China is expected to be far greater than that of other countries if large-scale CCS technologies are equipped in coal-fired power plants.

Moreover, China is plagued by water shortages, with uneven spatial and temporal distribution of water resources. The average surface water resources for many years in China is 2.81 trillion m^3, and the water resource per capita is less than one-quarter of the world average. The average annual precipitation for recent years is 6.2 trillion m^3, equivalent to 648 mm depth of precipitation, which is approximately 20% lower than the global average [10]. Even worse, the geographical distribution of coal-fired power plants in China does not match with the water resource distribution. In particular, cities with abundant water are located in the south of the Yangtze River, while large coal-fired power plants are concentrated in North and Northwest cities. Several studies have shown that, with global climate change, the contradiction between increased water consumption for power generation and severe water shortage will continue to intensify [11,12]. For the cost of implementing CCS in the power plants, the closer a coal-fired power plants with carbon capture equipment is to the CO_2 storage site, the lower the cost would be in general [13]. However, areas suitable for CO_2 storage in China generally lack water resources, which means adopting CCS in these areas is not a good option. In summary, the spatial distribution of coal-fired power plants (carbon sources), suitable CO_2 storage sites (carbon sink) and water resources in China are inconsistent [14,15]. Therefore, it is of great significance to study the impact of implementing CCS in coal-fired power plants on the water consumption in China. It is also essential to further develop an optimal and feasible CCS deployment strategy to achieve the climate mitigation targets with the lowest cost and minimum water use.

Existing studies have begun to focus on water withdrawal and consumption in China's power plants [16–20]. The ratio of freshwater withdrawal/consumption to available flow (WTA/CTA) at the catchment level is used to measure the water stress [16]. However, few studies have investigated the impact of CCS on city-level water load, which is more informative for the water resource policy design in practice. The reasons hindering the city-level analysis mainly include the following three aspects. First, there is no unified statistics on China's urban water resource data, which requires researchers to calculate and calibrate the data of water resources for each city. Second, there is a lack of information on the geographical location, construction time, power generation type, and cooling method of each coal-fired power plant in China. Third, not all coal-fired power plants are suitable for implementing CCS. Therefore, it is also necessary to evaluate whether the power plants are suitable for CCS deployment. This requires not only detailed technical information on the power plants, but also detailed geographical information on the basins available for CO_2 sequestration.

To explore the impact of CCS on water consumption in cities of China for large coal-fired power plants, this study uses a bottom-up approach. First, large-scale coal-fired power plants suitable for CCS retrofitting were screened by suitability standard [21]. The screening process is shown in Figure 1. We summarized the annual average water resources of 234 cities where 596 power plants are located. Second, the installed scale of CCS retrofitting for power plants is given under 2 °C constraints. And the water withdrawal and water consumption of CCS retrofitted power plants are calculated. Finally, countermeasures are proposed to mitigate the additional water consumption in these cities.

This study goes beyond prior literature to investigate the impact of CCS on the urban water consumption of large coal-fired power plants in China and explore the optimum CCS deployment strategy for achieving the 2 °C warming target with minimum cost and water consumption. To that end, we first pick out 591 large-scale coal-fired power plants appropriate for equipping CCS based on a series of retrofitting criteria. Then, we compile the inventory of the total annual water resource of the identified 234 cities where those 591 power plants are located and discuss the mismatching of the spatial distribution between power plants and water resources in China. Second, the question of how serious the situation would be for urban water consumption if different types of CCS technologies are implemented in each city is further answered. Finally, the optimum deployment of CCS in China for achieving the 2 °C temperature limit target is proposed, which displays the information on installed capacity of the power plants, the cities that can implement CCS, and the increase of water consumption. Policy instruments for alleviating the increasing water consumption due to CCS in these cities are further given.

This article aims to address the following three issues in the context of China: (1) which coal-fired power plants are suitable for implementing CCS technologies? (2) what is the impact of implementing CCS on the city-level water consumption? (3) how to reduce the water pressure in the city?

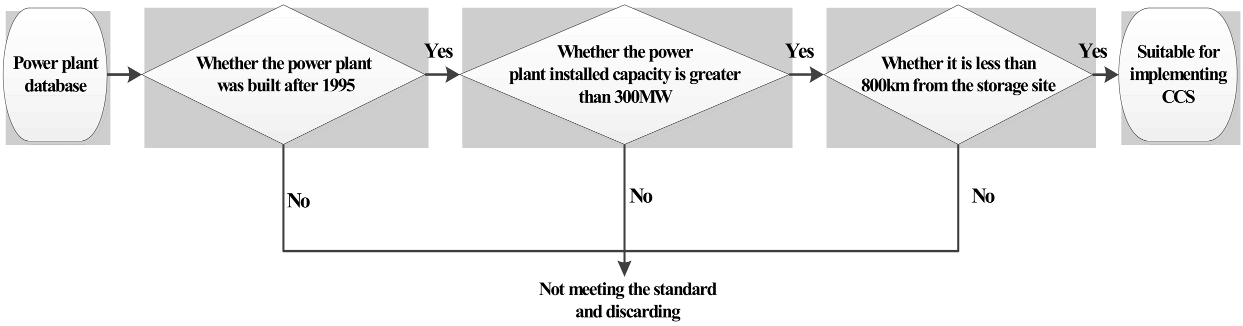

Figure 1. The screening process of available plants for CCS implementation.

2. Data and Methods

2.1. Power Plant Data Acquisition

First, we obtain the name, address, installed capacity, annual power generation, construction time, and steam turbine type of each power plant from the power plant survey dataset. Then, we screen the power plants suitable for CCS according to the transformation standard [21]. The screening rules include: (1) The power plant must be built after 1995; (2) the installed capacity is greater than 300 WM and within 800 km from the available sealed basin. The specific screening process can be seen in Figure 1. After the primary screening, 596 power plants that meet the above rules with a total installed capacity of about 664 GW are selected across 236 prefecture-level cities. Through Google satellite maps, we collect the geographic coordinates of each power plant according to the information on the power plant address, whether they have cooling towers, whether there is air-cooling equipment, and how they would work. Finally, based on the different cooling methods and the water consumption of power generation units with and without the CCS, the water consumption of each power plant under different technologies can be estimated. Water withdrawal and consumption of per unit power generation in different power plants with/without CCS (Table 1).

Table 1. Water withdrawal and consumption of per unit power generation in different power plants with/without CCS (m^3/MWh).

Power Generation Technology	Cooling Method	Withdrawal	Consumption	Data Sources
SBC	Once-trough cooling	116.48	1.24	[22,23]
SBC + CCS	Once-trough cooling	199.11	1.77	[22,23]
SPC	Once-trough cooling	88.9	0.69	[22,23]
SPC + CCS	Once-trough cooling	161.49	0.85	[22,23]
USPC	Once-trough cooling	82.8	0.228	[24]
USPC + CCS	Once-trough cooling	143.2	0.344	[25]
SBC	Recirculating cooling	2.31	2.01	[22,23]
SBC + CCS	Recirculating cooling	4.51	3.65	[22,23]
SPC	Recirculating cooling	2.19	1.61	[22,23]
SPC + CCS	Recirculating cooling	4.14	3.06	[22,23]
USPC	Recirculating cooling	1.58	1.26	[22,23]
USPC + CCS	Recirculating cooling	3.44	2.53	[22,23]

Table 1. *Cont.*

Power Generation Technology	Cooling Method	Withdrawal	Consumption	Data Sources
SBC	Dry cooling	0.23	0.2	[22,23]
SBC + CCS	Dry cooling	0.45	0.36	[22,23]
SPC	Dry cooling	0.21	0.16	[22,23]
SPC + CCS	Dry cooling	0.41	0.31	[22,23]
USPC	Dry cooling	0.15	0.12	[22,23]
USPC + CCS	Dry cooling	0.34	0.25	[22,23]

Note: SBC stands for subcritical power plant; SPC stands for supercritical power plant; USPC stands for ultra-supercritical power plant.

The water resource data of prefecture-level cities are derived from the Water Resources Bulletin of each province. Heilongjiang Province has no water resources bulletin, and its water data comes from the Heilongjiang Statistical Yearbook. Due to the inconsistency in the release time of water resources data in different provinces, the study selects the data published during 2016–2017. The data obtained for the city's water resources are averaged over the last 20 years and included the average annual amount of water available to the city over the last 20 years, the average 20-year rainfall, and the current rainfall in 2015. The calculation formula (1) for the water resources of each prefecture-level city is as follows.

$$\text{Average water resources} = \frac{\text{Water resources} \times \text{Average rainfall}}{\text{Current rainfall}} \tag{1}$$

The flow chart of this paper is shown in Figure 2. First, the data of coal-fired power plants and sequestration sites are established; second, a CCS source-sink matching model is established to determine the distribution of coal-fired power plants that need to be retrofitted with CCS technology under the 2 °C target constraint; third, a database of urban water resources is established and the increase in water withdrawal and consumption required by the city after the implementation of CCS is calculated; finally, the water stress index of coal-fired power plants is assessed for the city with and without CCS.

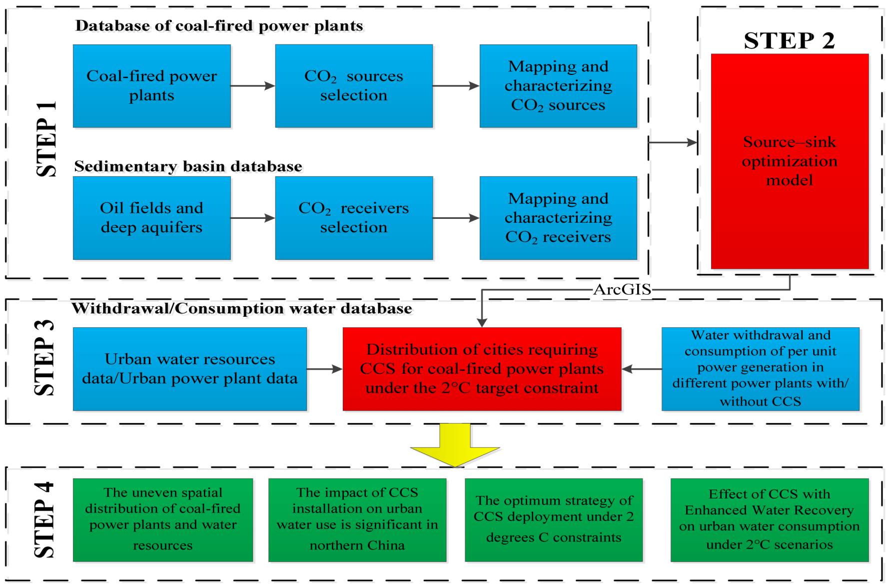

Figure 2. The research framework of this study.

2.2. Source–Sink Matching Model

The objective of the source–sink matching model [26] is to minimize the total mitigation cost estimated using Equation (2). This study defines total mitigation cost as the difference between the total costs and the profits from by-products. The planning period for the CCS project is assumed to be 30 years:

$$f = \min\left(\sum_{i \in S} C_i^s \cdot a_i + \sum_i \sum_j C_{ij}^d \cdot x_{ij} + \sum_{j \in R} C_j^r \cdot b_j - \sum_{j \in R} P_j \cdot k_j \cdot l_j \cdot b_j\right) \quad (2)$$

where total cost f includes capture cost C_i^s, transport cost C_{ij}^d, and storage cost C_j^r; P_j is the oil price; k_j is ton-to-barrel conversion ratio; l_j is CO_2 replacement oil rate in sink j; a_j is CO_2 captured by node i, which is the decision variable of the optimization model; b_j is CO_2 storage capacity for node j, which is also the decision variable; x_{ij} is CO_2 transport volume from node i to node j, which is also the decision variable. When CO_2-EOR is not implemented, the value of the crude oil revenue ($\sum_{j \in R} P_j \cdot k_j \cdot l_j \cdot b_j$) is set to 0, which means that there is no income.

(1) The mass conservation constraint

This study defines a mass conservation constraint, where for any capture (storage) point, the capture (storage) amount of the node is equal to the amount of CO_2 inflow from other points minus the CO_2 outflow:

$$\sum_{j \neq i} x_{ij} - \sum_{j \neq i} x_{ji} - a_i = 0 \quad \forall i \in S, \forall j \in N_i \quad (3)$$

$$\sum_{i \neq j} x_{ij} - \sum_{i \neq j} x_{ij} + b_j = 0 \quad \forall j \in R, \forall i \in N_i \quad (4)$$

(2) The capture (storage) capacity constraint

The maximum capture amount constraint for a single capture (storage) point is observed when the CO_2 capture (storage) of each capture (storage) node is less than the emission from the power plant (storage capacity of the sink):

$$a_i - Q_i^s \leq 0 \quad \forall i \in S \quad (5)$$

$$b_j - Q_j^r \leq 0 \quad \forall j \in R \quad (6)$$

where Q_i^s is the CO_2 capture amount for source i; Q_j^r is the CO_2 amount stored in sink j.

(3) The CO_2 emissions reductions target constraint

In the capture (storage) scale constraint, T is the target amount of CO_2 to be sequestered, the capture volume of CO_2 is equal to total CO_2 captured or total CO_2 stored:

$$\sum_i a_i = T \quad \forall j \in S \quad (7)$$

$$\sum_j b_j = T \quad \forall j \in R \quad (8)$$

(4) The non-negative constraints

The volumes of CO_2 transportation, capture, and storage are non-negative:

$$x_{ij} \geq 0 \quad \forall i \in N_i, \forall j \in N_i \quad (9)$$

$$a_i \geq 0 \quad \forall i \in S \quad (10)$$

$$b_j \geq 0 \quad \forall j \in R \quad (11)$$

The parameters in the CCS source–sink matching model were divided into sets and variables. Table 2 presents the model parameters and decision variables.

Table 2. Parameters and variables of the source–sink matching model.

Set or Variable	Definition	Unit	Value
Set			
$N_i(N_j)$	Nodes adjacent to nodes i or j		
R	Power plant nodes		
S	Basin nodes		
Parameter			
C_i^s	Capture cost for source i	$/t CO_2	46
C_{ij}^d	Transportation cost for route i to j	$/t CO_2/km	0.18
C_i^r	Injection and storage cost for sink j	$/t CO_2	15
P_j	Oil price in sink j	$/barrel	50
K_j	Ton-to-barrel conversion ratio in sink j	t Oil/barrel	7.30
l_j	CO_2 replacement oil rate in sink j	t Oil/t CO_2	0.25
T	Target amount of CO_2 to be sequestered	Gt CO_2	17.42
Q_i^s	CO_2 capture amount for source i	t	-
Q_j^r	CO_2 amount stored in sink j	t	-
x_{ij}	CO_2 transported from node i to node j	t	
a_i	CO_2 captured by node i	t	
b_j	CO_2 storage capacity for node j	t	

Note: All costs are estimated at 2013 constant prices.

2.3. The Calculation of CO_2-Enhanced Deep Saline Water Production

Within the constraints of carbon neutrality targets, CO_2 is widely used in geological development [27], for instance, in CO_2 polymer fracturing fluids to enhance oil recovery [28,29], CO_2 to replace methane [30], CO_2 enhanced water recovery(EWR), etc. To estimate the amount of salt water obtained by EWR, under the condition of supercritical CO_2 density of 0.60 ton/m^3, it is assumed that each ton of CO_2 can be displaced into the same volume of water after being injected into the deep saline layers, i.e., the displacement ratio of the CO_2 and the salt water is 0.6:1 [31]. Because the water withdrawn from the deep saline layers is salt water that could not be used directly, a desalting process is necessary where reverse osmosis is extensively used. Based on the existing data, the converted ratio of the salt water to the fresh water is assumed to be 1:0.5 [8,32,33]. Therefore, the amount of fresh water finally obtained by CO_2-EWR is substantially equal to the mass of stored CO_2. In addition, it is assumed that all the water obtained through CO_2-EWR is used for the CCS coal-fired power plants in the cities.

3. Results and Discussion

3.1. The Uneven Spatial Distribution of Coal-Fired Power Plants and Water Resources

There are mainly four cooling technologies in power plants, which are once-through cooling, recirculating cooling, dry cooling, and seawater cooling, with installed capacity accounting for 18.3%, 60.7%, 8.1%, and 12.9%, respectively (Table 3). Our calculation indicates that the total water consumption of the power plants without CCS is expected to be 4.6 billion tons, of which power plants with circular towers for cooling consume the most water resource, accounting for 86.4% of the total water consumption. The main reason is that the circulating tower cooling has the highest water consumption per unit compared to other cooling methods. On the one hand, the power plants using cyclic cooling are mostly subcritical. Compared to supercritical and ultra-supercritical power plants, under the same cooling mode, the water consumption per unit of subcritical power generation is 40–80% higher.

Table 3. Technical statistics of different cooling types on power plants without CCS [26,34].

Power Plant Parameters	Once-Through	Recirculating	Dry	Seawater	Sum
Capacity (GW)	121.4	403	53.8	86	664.2
Generation (billion kW·h)	588.6	1968.5	257.9	468	3283
CO_2 emissions (100 Mt/Year)	5.9	19.7	2.6	4.7	23.3
Water withdrawal (100 Mt)	585.2	48.4	1.3	350	984.8
Water Consumption (100 Mt)	1.8	40.1	1.3	3.2	46.5

It can be found that large-scale coal-fired power plants suitable for CCS equipment are concentrated in the central and northern cities where water resources are scarce with less than 5 billion tons of annual available water consumption (Figure 3a–c). The cooling mode of these power plants is mainly based on the circulating tower with higher water consumption per unit, and the power generation technology is mainly subcritical power plant with higher water consumption per unit (Figure 3a–c). Without CCS, coal-fired power plants in central and northern cities accounted for about 60% of the total electricity generation in the identified 234 cities, while total water resources account for only 27%. The water consumption of power plants in the central and northern cities with severe water resource shortage is 72% higher than that of the southeastern cities with abundant water resources (Figure 3d). In the central and northern cities where most of the power plants are equipped with circulating tower cooling, the implementation of CCS will further increase the water consumption and aggravate the water shortage in those cities. The mismatching between the distribution of CCS power plants and water resources has become a tough issue when the authorities weigh the pros and cons of the carbon emissions reductions and the water safety.

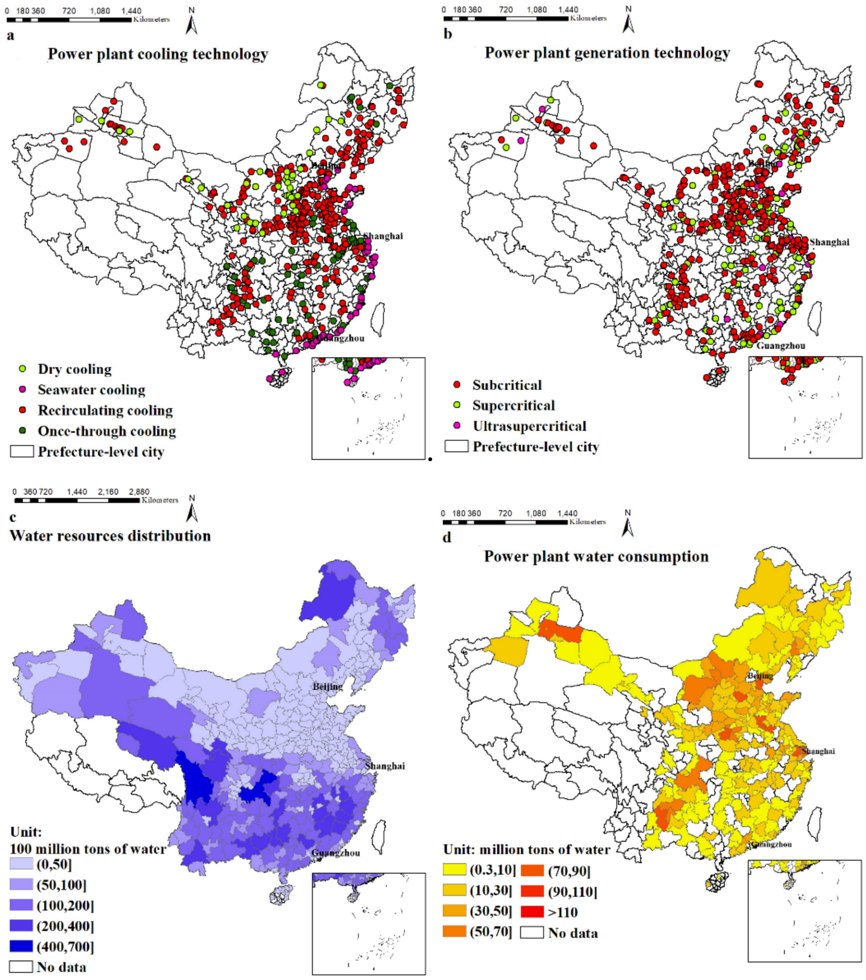

Figure 3. Distribution of qualified power plants and their water consumption. (**a**) The distribution of 591 qualified power plants by different cooling technologies, namely once-through cooling, recirculating cooling, dry cooling, and seawater cooling. (**b**) The distribution of power plants by different power generation technologies, namely subcritical, supercritical, and super-supercritical power plants. (**c**) The average water resource distribution of prefecture-level cities in China, see calculation in Equation (1), for the calculation process. (**d**) The spatial distribution of water consumption without CCS implementation in 234 cities where 591 qualified power plants are located.

3.2. The Impact of CCS Installation on Urban Water Use Is Significant in Northern China

After retrofitting power plants with CCS, the WTA and the CTA at the city-level will increase by 0.03 and 0.02, respectively. This situation means that the water withdrawal (water supply) will increase by approximately 6.5 billion tons, the water consumption will increase by about 2 billion tons, yearly, which will be 1.63 and 1.49 times the total water consumption and consumption of coal-fired power plants in 2016. It can be found from Figure 4 that the water supply pressure in northern cities (cities across the north of the Yangtze River) will be much greater than that in southern cities (cities across the south of the Yangtze River). The average water withdrawal pressure index of power plants in northern cities is seven times that of southern cities. The average water consumption pressure index in northern cities is 35 times that of southern cities. These indicate that the water safety of about 48 million people will be affected. This is because the water resources of northern cities are relatively scarce compared with those of southern cities. The annual water resources of 121 cities in the north are less than 2.5 billion tons, and the per capita water resources are less than one-third of those in southern cities.

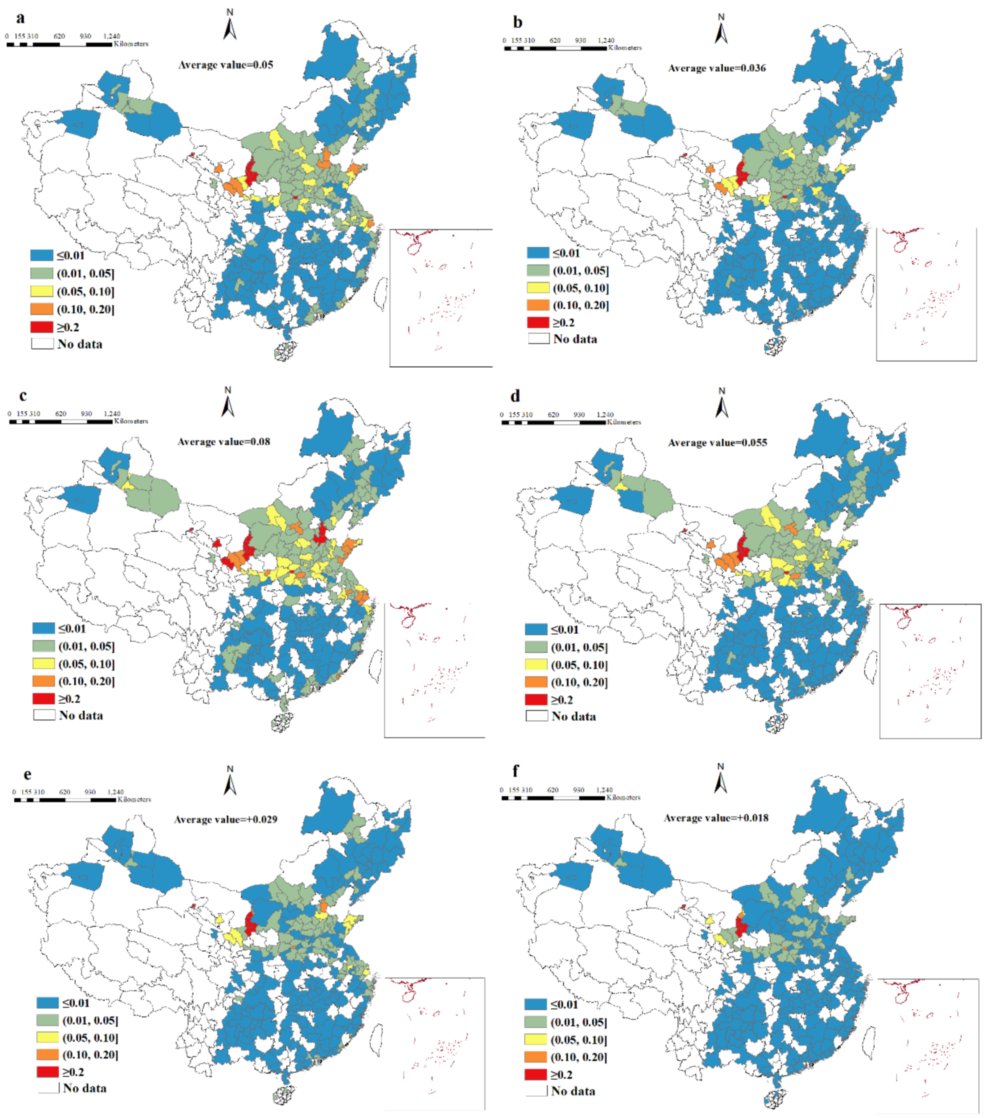

Figure 4. Withdrawal- and consumption-based water stress index levels of 234 cities in China in 2018; (**a**) withdrawal based current water stress index levels without CCS. (**b**) Consumption-based water

stress index levels without CCS. (**c**) Withdrawal-based water stress index levels with CCS. (**d**) Consumption-based water stress index levels with CCS. (**e**) Changes in WTA with CCS. (**f**) Changes in WTA with CCS. Water stresses are classified into six categories according to their WTA or CTA ratio, that is, low (<0.1), low to medium (0.1–0.2), medium to high (0.2–0.4), high (0.4–0.8), extremely high (>0.8), and arid and low water use.

In addition, the number of coal-fired power plants suitable for CCS retrofitting is larger in the north with abundant coal resources than that of southern cities. Without the constraints of water resources, coal-fired power plants in the north are more suitable for CCS retrofitting. More importantly, the study found that the richer the city's water resources, the higher the proportion of coal-fired power plants using once-through cooling. Due to the CCS retrofits, the water withdrawal of the power plant with once-through cooling technology has increased significantly, but the change in water consumption is small because 90% water resources will return to the river through circulation. Therefore, the overall impact on urban water is smaller for power plants with once-through cooling technology. Moreover, we also found that the more scarce the urban water resources, the higher the coal-fired power plants with circulating towers cooling. The water withdrawal and water consumption of the power plants with circulating towers cooling technology have increased significantly, which seriously impacts the urban water pressure.

3.3. The Optimum Strategy of CCS Deployment under 2 °C Constraints

The IEA states that China needs to reduce 26 GtCO_2 using CCS by 2050, about 67% of which comes from the power industry, to achieve the goal of limiting global warming below 2 °C [35]. The source-sink matching model is established based on suitable storage sites and identified power plants under the goal of minimizing the total cost of CO_2 abatement. Through the calculation of the model, we selected 165 coal-fired power plants requiring CCS retrofits among 591 power plants identified above, involving a total of 54 cities. The detailed source-sink matching models and visualized results are presented in the method section. For these 54 cities, about 87% are located north of the Yangtze River, and most of these cities have relatively scarce water resources. This is largely because the basins suitable for CO_2 storage on land are mainly distributed in northern regions such as the Ordos Basin, the Bohai Bay Basin, and the Tarim Basin. The CO_2 captured in areas with abundant water resources south of the Yangtze River mainly depends on the Sichuan Basin and Subei Basin for storage. The oil and gas reserves in these two basins are not abundant, so the benefits that can be brought by CO_2-EOR projects are relatively small. Compared with the northern region with rich oil and gas reservoirs, CO_2 storage in the south does not have a cost advantage.

The spatial distributions of coal-fired power plants, water resources, and CO_2 storage basins are mismatched. In particular, the implementation of the post-combustion capture technology in 165 power plants will increase total water withdrawal by approximately 58 billion tons and increase water consumption by 660 million tons. It can be seen that the conflict between water resources and carbon emissions reductions caused by CCS technology has further intensified. If there is no change in urban water resources, it is necessary to increase the amount of water supplied by electricity, affecting the consumption of other industries (agriculture, industry, and residents, etc.,). This is because the water withdrawal per unit of power generation after the implementation of CCS in power plants has increased significantly.

Figure 5a,b show the water withdrawal and consumption pressure of a power plant without CCS. Without CCS, the average water withdrawal pressure index of 54 cities is 0.36, which is already at the middle level. The average water consumption pressure index is 0.13, and the water consumption pressure is between low and medium pressure. Considering that the implementation of CCS will increase the water withdrawal and water consumption of power plants, the pressure on water resources in cities will face greater challenges.

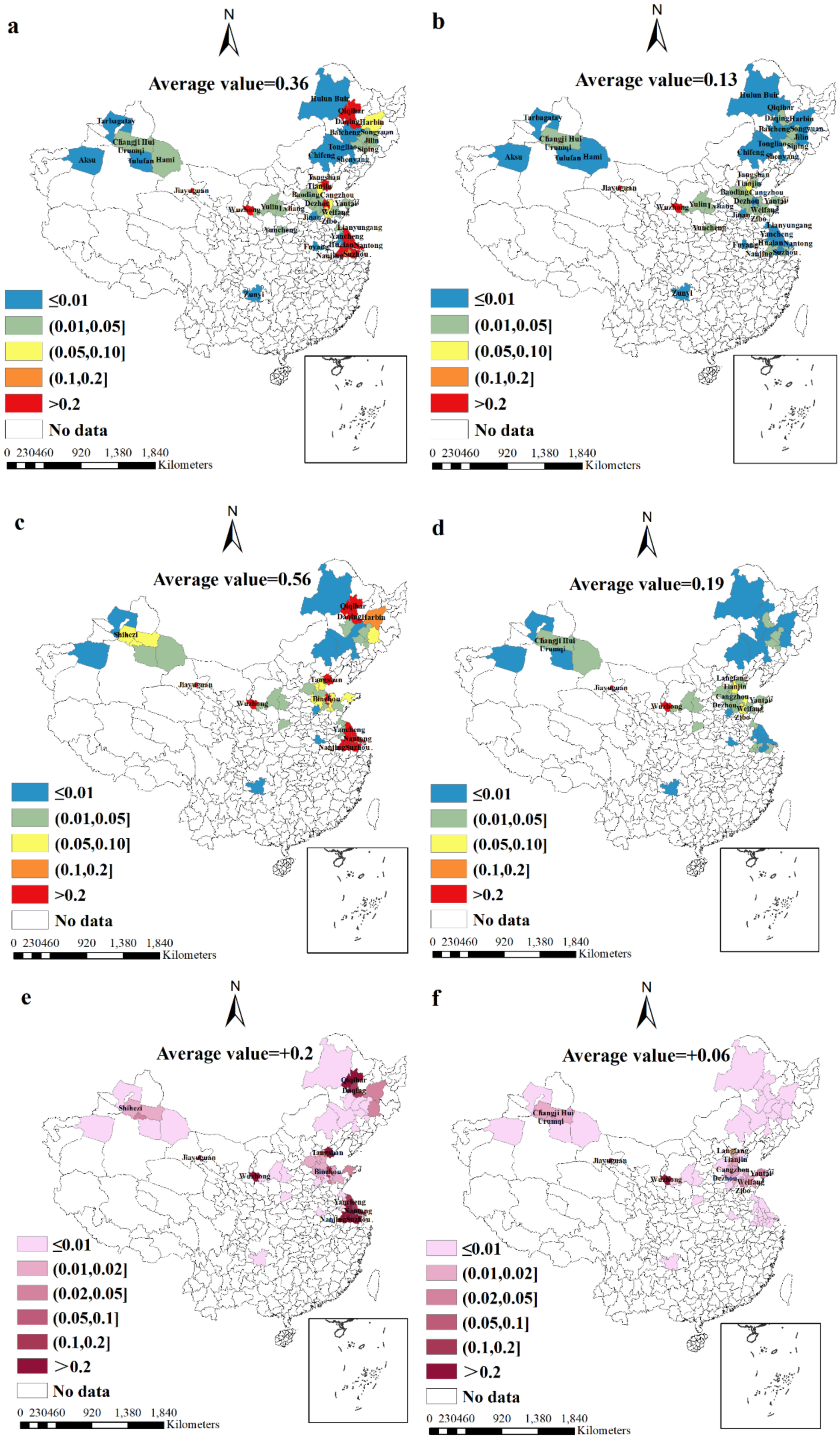

Figure 5. Withdrawal- and consumption-based water stress index levels under 2 °C scenarios in China in 2018; (**a**) Withdrawal based water stress index levels without CCS. (**b**) Consumption-based

water stress index levels without CCS. (**c**) Withdrawal based water stress index levels with CCS. (**d**) Consumption-based water stress index levels with CCS. (**e**) Changes in WTA with CCS. (**f**) Changes in WTA with CCS. Water stresses are classified into six categories according to their WTA or CTA ratio, that is, low (<0.1), low to medium (0.1–0.2), medium to high (0.2–0.4), high (0.4–0.8), extremely high (>0.8) and arid and low water use.

The water withdrawal of 54 power plants has increased after retrofitting with post-combustion capture technology, and the average WTA value will increase by 0.2 (Figure 5e). This means that more cities will have medium to high water pressure. Geographically, the water stresses will be medium to high level or high levels in 12 cities, where about 85 million people will be affected. These 12 cities are mainly concentrated in north of the Yangtze River Delta Economic Zone, the Bohai Rim region, north of the Songliao Basin, and near the Ordos Basin (Figure 5c).

Unlike the water withdrawal, the water consumption is pure evaporation and cannot be recycled. Cities with large water consumption have a more serious issue on urban water use. The average increase in CTA values of 54 cities is 0.06. Although this increase is not high, it will still have a serious impact on water security in some cities. The reason is that cities with large power consumption are concentrated in North and Northwest China. These power plants mainly use circulating tower cooling technology, and a large amount of water is evaporated through the cooling tower. However, the power plants in southern cities mainly use once-through cooling technology which consumes very little water. Therefore, the average increase in CTA nationwide is not high, but the water consumption of northern cities using circulation tower cooling technology increases sharply. There are six cities with a water consumption pressure greater than the medium to low level, including Wuzhong, Changji, and Jiayuguan, involving a total population of about 20 million.

Comparing the WTA and the CTA values (Figure 5e,f), the results of the two indicators are quite different. In particular, the power plants with once-through cooling technology, which are concentrated in the Yangtze River Basin, where the two evaluation results are even the opposite. The main reason is that, after CCS is implemented with once-through cooling technology in power plants, although the amount of water required for unit power generation of coal-fired power plants is huge, the actual amount of evaporated water is small. Therefore, most water resources can be recycled. For the power plant adopting circulation tower cooling technology, although the water consumption per unit of power generation is small, the actual water consumption for evaporation is very high. A lot of water resources are evaporated through the cooling tower, and the cooling tower needs to be replenished. The impact of post-combustion capture on urban water use in once-through cooling power plants will be overestimated by WTA. However, only using CTA may ignore the thermal pollution caused by water circulation. The discharge of circulating water into rivers will cause river water temperature to rise and other environmental pollutions. This thermal pollution will be further aggravated after the implementation of CCS.

3.4. Effect of CCS with Enhanced Water Recovery on Urban Water Consumption under 2 °C Scenarios

Under the 2 °C target constraint, 76% of the power plants that require implementing CCS are located in the arid areas of Northwest or North China. How to make up for the increase in urban water consumption due to CCS implementation in power plants is an issue that cities with insufficient water resources must solve in the future. Without changing the cooling mode of power plants, CO_2-EWR technology has become a countermeasure [36–38]. Therefore, we further estimated the impact of CO_2-EWR on the urban water use of power plants.

When power plants implement post-combustion capture technology, some cities can use CO_2-EWR to make up for the additional water consumption (Figure 6). The power plants in these cities mainly use once-through cooling, which is mainly distributed in the Yangtze River Basin, such as Zhenjiang and Nantong. The water resources obtained through CO_2-EWR cannot make up for the increased water consumption cities. The power plants in these cities mostly use circulating cooling, and they are concentrated in North China and Northeast China. It is found that the proportion of the newly increased water consumption and the water resources increased by CO_2-EWR in cities where CO_2-EWR technology is used to make up about 30% of the new water consumption in the Northwest and North China. It means that the implementation of CO_2-EWR in power plants cannot fundamentally solve the problem of the increased water consumption, but can only relieve the pressure on urban power water.

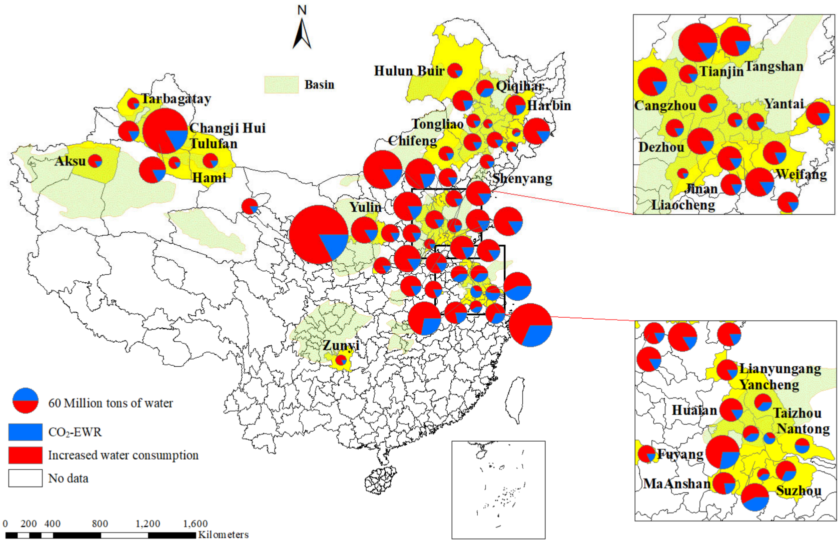

Figure 6. The ratio of water obtained by CO_2-EWR over the annual increased water consumption caused by the post-combustion capture.

4. Conclusions

Water security and carbon reductions are important issues for China's sustainable development. This study confirms that there is a spatial mismatch between water resources and power plants suitable for CCS implementation, and between water resources and suitable CO_2 storage sites in China. This objective spatial distribution has exacerbated the contradiction between the emission reductions of large coal-fired power plants and the water scarcity in China.

(1) Our research shows that after CCS is implemented in power plants, the urban water withdrawal and water consumption will increase significantly, and the contradiction between carbon emissions reductions and water resources will further intensify. Specifically, 165 coal-fired power plants are required for achieving the 2 °C temperature control target, with a total installed capacity of about 175 GW. These power plants are situated in 54 cities, of which 76% are located in water-scarce areas north of the Yangtze River. The use of post-combustion capture technology in power plants will increase the total water withdrawal of electricity generation by more than 74%, resulting in 19 cities with moderate or higher water pressure and affecting water supply of 84.57 million people.

(2) With abundant coal resources in the north, there are more coal-fired power plants suitable for CCS retrofitting than those in the south. Without the constraints of water resources, coal-fired power plants in the north are more suitable for CCS retrofits. Furthermore, the study found that the more abundant the water resources, the higher the proportion of coal-fired power plants with primary cooling. As a result of CCS retrofits, power plants with primary cooling technology have significantly higher water withdrawals, but the change in water consumption is minimal as 90% of the water is recycled back into the river. Therefore, the overall impact of power plants with primary cooling technology on urban water use is low. It was also found that the

further the scarcity of urban water resources, the higher the coal-fired power plants using recirculating tower cooling. The power plants with recirculating tower cooling technology have significantly higher water withdrawals and water consumption, which have serious implications for urban water stress.

(3) The WTA value is calculated based on water intake, and it does not involve water consumption. It results in a greater impact on WTA for plants with direct cooling (very high recovery and low consumption) than for plants with cooling towers (medium recovery and high consumption) [7]. The power plants in cities adjacent to rivers mostly use DC cooling, this reveals why these cities still have high water pressure for power despite abundant water resources. Although the amount of water consumed by once-through cooling technology in power plants is smaller than that consumed by cooling towers, the amount of water consumed by once-through cooling technology is high. Therefore, the implementation of CCS in power plants will limit the water consumption of other industries, which will exacerbate the urban water pressure. On the other hand, the once-through cooling system will cause water and heat pollution, which will reduce the quality of water resources and increase the pressure on urban water resources. In summary, the water pressure of electricity generation in cities in southern China (cities with a high proportion of once-through cooling power plants) may be overestimated, but it still reflects the degree of change in urban water use pressures.

(4) Some municipalities can use CO_2-EWR to compensate for the additional water consumption when post-combustion capture technology is implemented in power plants. The power plants in these cities mainly employ primary cooling and are mainly located in the Yangtze River basin, such as Zhenjiang and Nantong. In other cities, the water resources obtained through CO_2-EWR cannot offset the increased water consumption resulting from the implementation of CCS technology. This is because most of the power plants in these cities use recirculating cooling, mainly in northern and north-eastern China. The study found that in the north-western and northern cities, 30% of the additional water use could be compensated by CO_2-EOR. This implies that the implementation of CO_2-EOR at power plants will not fundamentally solve the problem of increased water use, but will only relieve the pressure on urban electricity consumption.

(5) For the mismatch between water resources and suitable storage sites for CO_2, on the one hand, we should actively explore the offshore CO_2 storage potential along the southeast coast, so that the CO_2 captured by power plants on the southeast coast can be stored nearby. On the other hand, it is necessary to build transport pipeline networks to transport CO_2 to a suitable basin in Northwest China for CO_2 onshore storage.

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