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Quantifying the “Water–Carbon–Sulfur” Nexus for Coal Power Plants in China

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Abstract: China has implemented strict policies for the installation of desulfurization facilities in coal power plants in order to mitigate their negative environmental and human health impacts. However, it is rarely acknowledged that desulfurization processes lead to increased water consumption and carbon emissions from the coal power sector. By using a bottom-up approach, we quantified that the desulfurization facilities in all of China’s coal power plants together avoided emissions of 29.52 Mt of SO_2 in 2014, with expenses of 550.26 million m^3 of increased water consumption, and 53.28 Mt of additional CO_2 emissions. Such conflicts were especially pronounced in the North China Grid, where 9.77 Mt of SO_2 emission reductions were realized at expenses of 132.15 million m^3 of water consumption, and 14.25 Mt of CO_2 emissions. The provinces in the North China Grid were already facing extreme water scarcity. Furthermore, while more than 90% of China’s coal power plants have installed desulfurization facilities, the application of full desulfurization would further reduce the greatest amount of SO_2 emissions with the smallest amounts of additional water consumption and carbon emissions in the Northwest Grid. Replacing all wet desulfurization facilities with dry ones saves 498.38 million m^3 of water consumption in total, and reduces 26.65 Mt of CO_2 emissions; however, this is at an expense of 14.33 Mt of SO_2 emissions. These conflicts are most pronounced in Shanxi Province in the North Grid, and in Guangdong Province in the South Grid.

Keywords: water–energy nexus; desulfurization; coal power plants; water resource management; carbon emissions

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1. Introduction

Sulfur dioxide (SO_2) is a short-lived gas that has severe and harmful impacts on human health, ecosystems, and the environment. Direct exposure to SO_2 can cause human respiratory system problems. SO_2 emissions also contribute to particulate matter (PM) air pollution [1], which is a leading cause of death and disability worldwide. Together with NOx, SO_2 is also a major pollutant that causes acid rain, which is harmful to ecosystems both on land and under water, and which can cause the corrosion and weathering of infrastructure systems, as well as affect human health. SO_2 is emitted both naturally (e.g., by volcanoes) and by human activities [2]. Globally, the largest source of anthropogenic SO_2 emissions to the atmosphere is from the fossil fuel combustion of power plants and other industrial facilities.

According to NASA’s data [3], during the last 150 years, anthropogenic SO_2 emissions have increased from 2.06 million tons (Mt) in 1850, to 115.51 Mt in 2005, which is an increase of more than 55 times. Global SO_2 emissions peaked in the 1970s at around 140 Mt annually. Since 1993, China has overtaken the United States and has become the world’s largest SO_2 emitter. In 2005, China alone emitted 32.67 Mt of SO_2, which was more than the United States, India, and Russia combined. According to different sources, coal burning contributed the majority (more than 50%) of the anthropogenic SO_2 emissions worldwide. Specifically, coal burning in China contributed one-quarter of the total global SO_2 emissions.

Therefore, SO_2 emission reduction in China can generate significant local, regional, and global benefits.

Starting from the late 1970s, acid rain emerged as a major environmental problem for China [4]. The estimates on the economic costs that have been caused by acid rain in China range from USD 13 billion every year, according to the Chinese State Environmental Protection Administration (SEPA), to USD 11–32 billion, according to the World Bank, depending on the different valuation methods [5]. However, despite the large variations, all of the figures were high, which indicates the severity of the problem. In response, the Chinese government has taken a series of measures, starting from the early 1990s, in order to curb the soaring SO_2 emissions [6]. Coal power production is responsible for the largest share of coal consumption in China, which is followed by manufacturing. In 1996, the State Environmental Protection Administration issued the "Emission Standard of air pollutants for thermal power plants", which was subsequently amended in 2003 and 2011 [7–9]. The current standards (GB13223-2011) set the requirement for the SO_2 emissions from Chinese coal-fired power plants at 100 mg per m^3, which is low compared to even global standards [10]. Since the "Technical Specifications for Flue Gas Desulfurization Engineering of Thermal Power Plant" was issued by the SPEA in 2005, desulfurization facilities have been widely applied in China's coal power plants, and the sulfur dioxide emission intensity has been reduced from 6.4 g/kWh to 2.26 g/kWh, which is even lower than in the United States [11]. In 2014, China further introduced an ultralow emissions (ULE) standards policy for renovating coal-fired power-generating units in order to limit the SO_2 emissions to $35\,\mathrm{mg/m^3}$. These policies have been effective. Tang's research found that the annual emissions of SO_2 from the power plants in China were reduced by 65% from 2014 to 2017, on the basis of the results from a national unit-level emission monitoring system [10].

However, desulfurization processes (flue gas desulfurization (FGD)) often create unintended costs for the environment, which have received much less attention. FGD is a set of technologies that are used to remove the SO_2 from the exhausted flue gases of power plants and other industrial processes. Overall, these technologies can be categorized into dry, semidry, and wet systems, where wet FGD accounts for the predominant share. Wet FGD uses water to create limestone slurry to absorb SO_2, while dry FGD injects dry lime ash for the same purpose. Dry FGD methods normally have lower SO_2 removal efficiencies. However, these FGD processes lead to additional carbon emissions and water consumption. In addition to the additional CO_2 emissions that are caused by the parasitic loads, CO_2 is also emitted as a byproduct of using lime or limestone to neutralize the absorbed SO_2 in the FGD process. Furthermore, wet FGD is the largest water-consuming process at coal power plants with open-loop and air-cooling systems, while the second largest water-consuming process at plants with closed-loop cooling systems, following water consumption for cooling purposes [12].

Because China has made ambitious carbon reduction commitments as the world's largest CO_2 emitter, and because it also faces a national water crisis, reducing anthropogenic SO_2 emissions may create conflicts with these environmental objectives. To better understand the unintended environmental trade-offs that are caused by desulfurization processes, and to inform the decision-making processes going forward, we make novel contributions in this study by: (i) Quantifying the SO_2 emissions that are avoided by the desulfurization processes that have been adopted by China's coal power plants, and the resultant additional carbon emissions and water consumption on the basis of a desulfurization technology inventory database that was published by the Ministry of Environmental Protection of China in 2014; (ii) Estimating the further carbon emissions and water consumption that are required to install and operate desulfurization facilities at all of the coal power plants; and (iii) Since dry desulfurization technology offers multiple benefits, including reduced water consumption and carbon emissions at the expense of a lower SO_2 removal efficiency, we also conduct a scenario analysis to quantify the CO_2 emission reduction, the water consumption reduction, and the increased SO_2 emissions if all of the wet desulfurization facilities were retrofitted to dry ones.

2. Method and Data

2.1. CO_2 Emissions and Water Consumption for Desulfurization

The generation of CO_2 for desulfurization is due to two mechanisms: (i) CO_2 is emitted through fossil fuel combustion to generate electricity; and (ii) CO_2 is also emitted in the process of desulfurization through chemical reactions. The CO_2 emissions that are generated by the first mechanism can be calculated by the electricity consumption for the desulfurization process and the carbon emission intensity, as in Equation (1). The CO_2 emissions that are generated from the second mechanism can be calculated according to the chemical reaction equation, as in Equation (2), which is the calculation equation that is mentioned in the "Guidelines for Accounting Methods and Reporting of Greenhouse Gas Emissions by Chinese Power Generation Companies":

$$E = U \times T \times r \times I \tag{1}$$

$$E_f = \sum\nolimits_k CAL_k \times EF_k \tag{2}$$

where *E* refers to the CO_2 emissions from the electricity consumption by the desulfurization process; *U* denotes the capacity of the electricity generation unit; *T* refers to the running hours of the unit; and *r* represents the electricity consumption rate for the desulfurization facilities. Moreover, *I* represents the carbon emission intensity per unit of electricity generated (ton/kWh); *EF* refers to the CO_2 emissions from the process of desulfurization through chemical reactions; *k* refers to the types of desulfurizer; *CAL* refers to the consumption amount of the carbonate in the desulfurizer; and EF_k refers to the emission factor of the carbonate in the desulfurizer of type *k*.

Similarly, the water consumption for the desulfurization can be calculated according to Equation (3) below:

$$W = U \times T \times F \tag{3}$$

where *W* represents the water consumption for the desulfurization; *U* denotes the capacity of the electricity generation unit; *T* refers to the running hours of the unit; and *F* represents the desulfurization-related water consumption factor per unit of electricity generated (m^3/kWh).

2.2. SO_2 Emissions

In order to calculate the benefits of reducing SO_2 emissions, as well as the additional SO_2 emissions in a hypothetical scenario, where all of the wet desulfurization facilities are retrofitted to dry desulfurization facilities (similar to Tang et al., 2019), we calculate the SO_2 emissions with a bottom-up approach, according to Equations (4) and (5), as seen below:

$$EF_{i,h} = C_{i,h} \times V_i \tag{4}$$

$$E_{SO_2,i,h} = A_{i,h} \times EF_{i,h} \tag{5}$$

where *EF* is the SO_2 emission factor; *C* denotes the stack concentration in the flue gas on the basis of a standard oxygen level; *V* is the theoretical flue gas rate; *A* represents the activity level (i.e., the electricity generation); *i* represents the different types of desulfurization technologies, which include wet desulfurization facilities and dry desulfurization facilities; and *h* is the operation hour of the electricity generating units.

2.3. Data Sources

We obtained the inventory of the desulfurization facilities for China's coal power plants in 2014 from the Ministry of Environment and Ecology. This inventory list includes the capacity and desulfurization technologies of China's coal power plants, which was

756.9 GW in total, and which occupied 90.94% of China's total coal power capacity in 2014. The data on the carbon emission intensity of the electricity production are from the National Center for Climate Change Strategy and International Cooperation [13], and they include six electric power system regions' carbon emission intensities in China (North Grid: 0.8843 $KgCO_2/kWh$; East Grid: 0.7769 $KgCO_2/kWh$; Northeast Grid: 0.7035 $KgCO_2/kWh$; Central Grid: 0.5257 $KgCO_2/kWh$; South Grid: 0.5271 $KgCO_2/kWh$; and Northwest Grid: 0.6671 $KgCO_2/kWh$). The water consumption intensity for the desulfurization process is taken from Liao's paper (i.e., 0.175 m^3/kWh) [14]; the SO_2 emission factors are from Tang's research [10]; and the operation hours of the coal power plants in the different provinces in China are from the National Bureau of Statistics of China [15].

3. Results

3.1. Water Consumption and Carbon Emissions for Desulfurization

In total, the desulfurization facilities in all of China's coal power plants together avoided emissions of 29.52 Mt of SO_2 in 2014; however, this was at expenses of 550.26 million m^3 of increased water consumption, and 53.28 Mt of additional CO_2 emissions. The largest SO_2 emission reduction was realized in Shanxi Province (4.2 Mt) in the North China Grid (Figure 1). The North China Grid includes the Jing-Jin-Ji megaregion, where China's capital city of Beijing is located. It is home to a large population and industrial activities that require large amounts of electricity. Since the North China Grid is coal abundant but water scarce, coal power plants supply more than 95% of the electricity in this grid. The SO_2 emission reduction in the North China Grid amounted to 9.77 Mt, which occupied 33.1% of the national total. Similarly, because of North China Grid has the largest coal power capacity, the water consumption that was caused by the desulfurization was also the highest in the North China Grid, where it amounted to 132.15 million m^3. Presumably because of its dry natural conditions, the water consumption from the wet FGD processes occupied the lowest share (96.4%) in the North China Grid, compared to 97.4 to 99.3% in the other regional grids, with the additional water consumption resulting from semidry FGD processes.

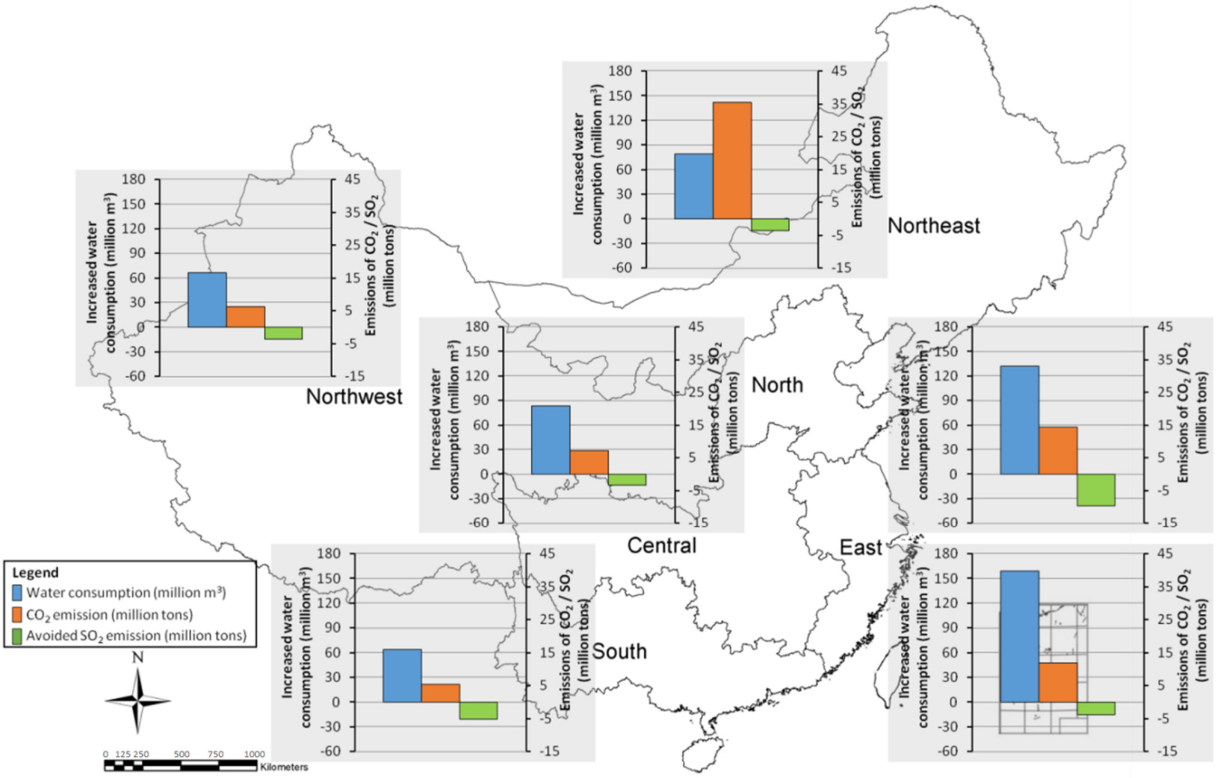

Figure 1. Regional water consumption and carbon emissions for SO_2 reduction in China.

In terms of the carbon emissions from the desulfurization processes, the largest amount of CO_2 was emitted in the North China Grid (14.25 Mt), which was followed by the East Grid (11.78 Mt), the Northeast Grid (8.33 Mt), the Central Grid (7.25 Mt), the Northwest Grid (6.26 Mt), and the Southwest Grid (5.41 Mt) (Figure 2). Overall, the Southwest, North, and Northwest Grids had the highest water and carbon efficiencies for the SO_2 reduction (i.e., the lowest amounts of water consumption and CO_2 emissions per ton of SO_2 reduction). In the Southwest Grid, the avoidance of one ton of SO_2 emissions leads to 12.32 m^3 of water consumption and 1.04 tons of CO_2 emissions, which is followed by 13.52m^3 and 1.46 tons, respectively, in the North China Grid. By comparison, a reduction of one ton of SO_2 requires the largest amounts of water consumption (32.19 m^3) and CO_2 emissions (3.01 tons) in the East China Grid.

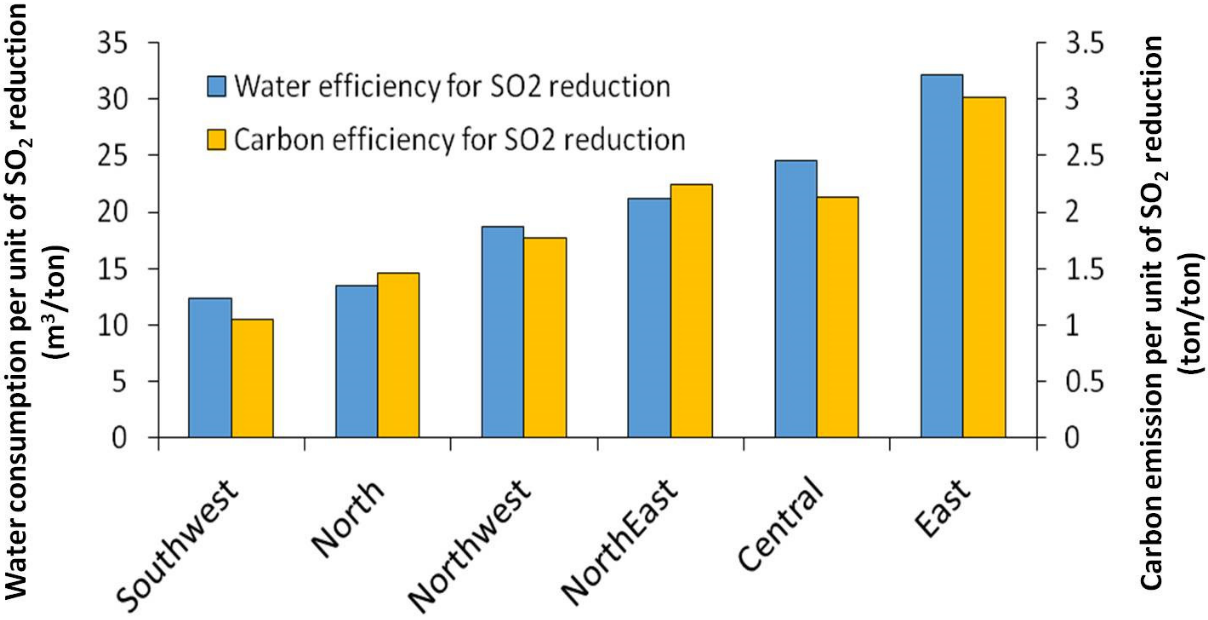

Figure 2. Regional water efficiency and carbon efficiency for SO_2 reduction in China.

3.2. Water and Carbon Cost of Applying Full Desulfurization

By comparing the inventory list of the desulfurization facilities and the coal power plant list that was compiled by Tang et al. (2019), it is found that the desulfurization rate of China’s coal power plants has reached more than 90% overall, but with substantial provincial and regional differences, with the lowest rate (82.93%) in the northwest, and the highest rate (98.59%) in the southwest. Nearly 66 GW of the coal-power-generating capacity has yet to install desulfurization facilities, nationwide. The application of the full coverage of desulfurization facilities would further reduce 2.21 Mt of the SO_2 emissions nationally, with the highest reduction coming from the Northwest Grid (0.73 Mt), followed by Northeast (0.52 Mt), North (0.32 Mt), East (0.38 Mt), Central (0.18 Mt), and Southwest (0.07 Mt) Grids.

It can be seen from Figure 3 that, while the reduction potential is much higher in the northwest than in the east, almost the same amounts of water consumption (13.53 million m^3) and carbon emissions (1.28 Mt) would be induced in the East Grid as in the Northwest Grid. Therefore, priorities should be given to the Northwest Grid, where the largest SO_2 reduction potential can be realized with the smallest amounts of water consumption and carbon emissions. Although, in general, water consumption for desulfurization does not occupy large shares of industrial water allowances, according to China’s relevant water management policies, it makes up nearly 5% of that allowance in Shanxi Province, and nearly 4% in Ningxia Province. Water is extremely scarce in both provinces.

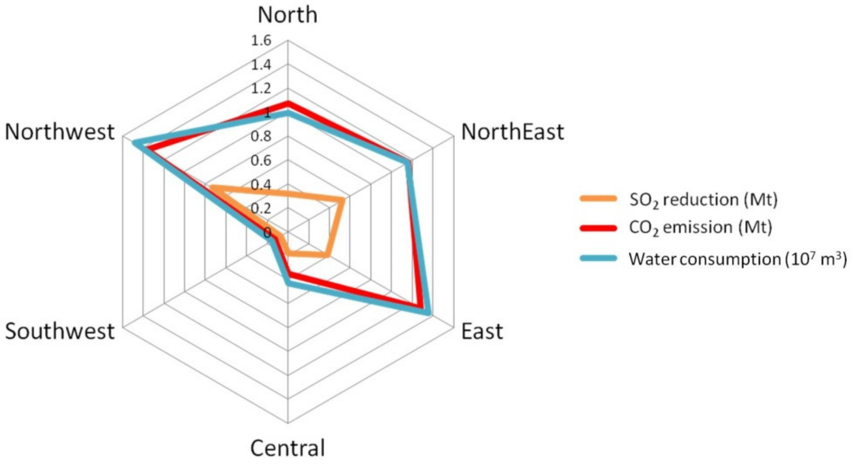

Figure 3. Water consumption and carbon emissions for full desulfurization coverage.

3.3. Water–Carbon–Sulfur Trade-Offs of Applying Dry Desulfurization Process

In water-scarce regions (WSI > 0.5) (i.e., the north and northwest), switching cooling systems from wet cooling to dry cooling reduces over 1.5 km^3 of the water consumption. However, because air-cooling systems are faced with efficiency and energy penalties, such a water consumption reduction would be realized at an expense of 31.08 million tons of CO_2 emissions.

According to our analysis, replacing all of the wet desulfurization facilities with dry ones would save 498.38 million m^3 of water consumption in total, and would reduce 26.65 Mt of CO_2 emissions; however, this would be at an expense of 14.33 Mt of SO_2 emissions. It can be seen from Figure 4 that it would be most beneficial to retrofit the desulfurization facilities in Jiangsu, Inner Mongolia, and Henan, where 48.70, 43.98, and 36.01 million m^3 of water consumption could be saved, respectively, as well as 1.31, 2.48, and 1.98 Mt of CO_2, respectively, which would lead to only relatively small amounts of additional SO_2 emissions (i.e., 0.52, 0.58, and 0.46 Mt, respectively). Although the water-consumption-savings and carbon-emission-reduction effects are also significant in Shanxi and Guangdong (at 34.34 and 27.70 million m^3 of water consumption reductions, respectively, and 2.00 and 1.58 Mt of CO_2 emission reductions, respectively), they cause substantial SO_2 emissions in these two provinces, at 3.17 and 2.23 Mt, respectively.

As is shown in Table 1, on the regional grid level, the highest water consumption savings (114.87 million m^3) are realized in the East Grid, together with a 4.55 Mt CO_2 reduction, at an expense of merely 1.26 Mt of SO_2 emissions, whereas, in the North Grid, a similar amount of water consumption savings (111.21 million m^3) need to be realized at an expense of 6.54 Mt of SO_2. Further cost–benefit analyses that consider the social, environmental, and economic impacts per unit of water consumption, the carbon emissions, and the SO_2 emissions, need to be conducted in order to facilitate these trade-offs.

Table 1. Regional summaries of water–carbon–sulfur trade-offs of changing desulfurization technologies.

Region	SO_2 Emissions (Mt)	CO_2 Emissions Reduction (Mt)	Water Consumption Savings (Million m^3)
Central	1.10	−4.45	−80.41
East	1.26	−4.55	−114.87
North	6.54	−6.79	−111.21
NorthEast	1.15	−4.25	−74.33
Northwest	1.12	−3.41	−59.93
Southwest	3.16	−3.20	−57.64

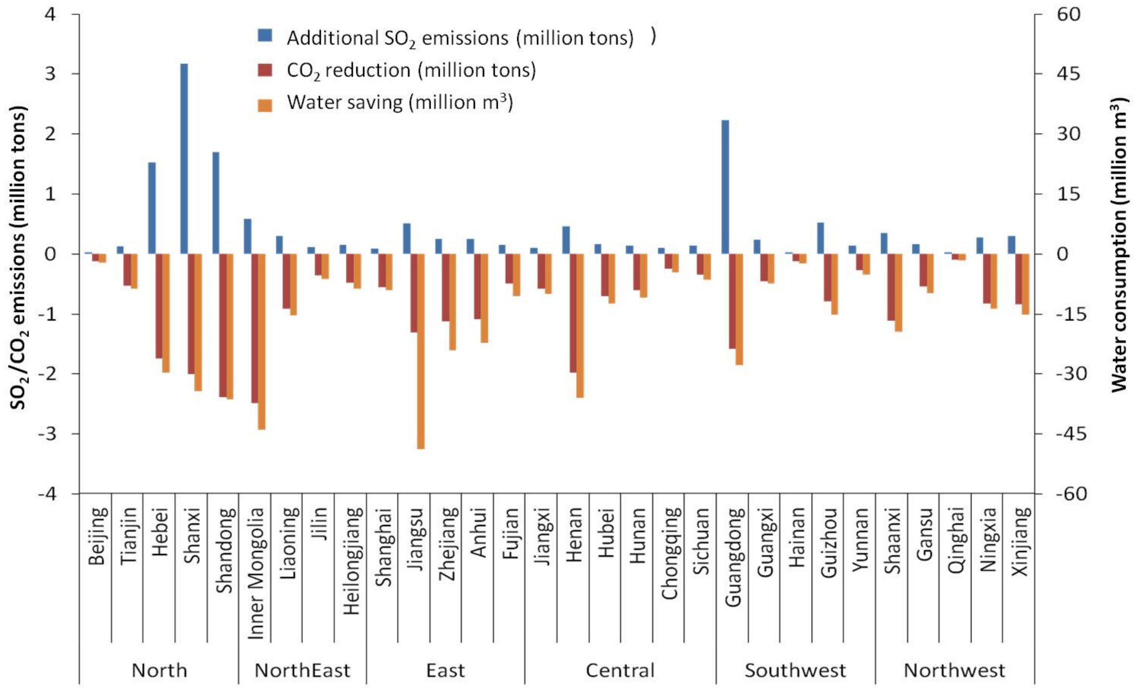

Figure 4. Water–carbon–SO_2 trade-offs of changing desulfurization technologies.

4. Conclusions and Discussions

4.1. Conclusions

On the basis of the plant-level data and by using a bottom-up approach, we have quantified that the desulfurization facilities in all of China's coal power plants together avoided emissions of 29.52 Mt of SO_2 in 2014, at expenses of 550.26 million m^3 of increased water consumption, and 53.28 Mt of additional CO_2 emissions. Such conflicts were especially pronounced in the North China Grid, where 9.77 Mt of SO_2 emission reductions were realized at expenses of 132.15 million m^3 of water consumption, and 14.25 Mt of CO_2 emissions, while the provinces in the North China Grid were already facing extreme water scarcity. Furthermore, while more than 90% of China's coal power plants have installed desulfurization facilities, the application of full desulfurization would further reduce the largest SO_2 emissions, with the smallest amounts of additional water consumption and carbon emissions in the Northwest Grid. Replacing all of the wet desulfurization facilities with dry ones would save 498.38 million m^3 of water consumption in total, and would reduce 26.65 Mt of CO_2 emissions; however, this would be at an expense of 14.33 Mt of SO_2 emissions, with such conflicts most pronounced in Shanxi Province in the North Grid, and Guangdong Province in the South Grid.

4.2. Water Consumption and Carbon Emissions for Desulfurization

The water-for-energy nexus has gained increasing appreciation in the last two decades [16]. It is acknowledged that significant volumes of water are used at thermoelectric power plants, and primarily for cooling purposes [17]. However, it is rarely acknowledged that the desulfurization process leads to around 30% of the water consumption of coal power plants [12]. Similarly, the desulfurization process also leads to additional carbon emissions. According to our calculation, the desulfurization facilities in all of China's coal power plants together avoided emissions of 29.52 Mt of SO_2 in 2014, at expenses of 550.26 million m^3 of increased water consumption, and 53.28 Mt of additional CO_2 emissions. As the world's largest CO_2 emitter, China has pledged to peak its carbon emissions by 2030 [18]. The reduction in SO_2 emissions introduces conflicts with China's climate change mitigation agenda.

Similarly, China is not abundant in water, with an average per capita water resource endowment that only amounts to one-third of the global average, with its northern regions especially facing dire water challenges. Among the thirty-one mainland Chinese provinces, eight of them are facing extreme water scarcity, with less than 500 m^3 per person. Seven of them are located in the northern regions, and all five provinces in the North China Grid fall into this category [19]. The North China Grid is identified as facing the highest water risks for power generation in the world [20]. Meanwhile, desulfurization led to the largest amount of water consumption in the North China Grid, where it amounted to 132.15 million m^3.

4.3. Water–Carbon Trade-Offs and Synergies at Coal Power Plants

Besides the trade-offs between water and SO_2, and between CO_2 and SO_2, there are also trade-offs between water and carbon. Water-saving technologies at coal power plants are often carbon intensive. For example, compared to wet-cooling technologies, which use water as a cooling medium, air-cooling technologies use air for cooling purposes, thereby significantly reducing the water use of coal power plants. However, air-cooling technologies suffer from 5 to 10% efficiency losses, and they therefore lead to additional carbon emissions [21]. On the other hand, technologies that are used to mitigate carbon emissions can be water intensive. For example, while carbon capture and storage (CCS) offer the potential to cut the carbon emissions from coal power plants, they require additional water use because of the parasitic loads [22].

It is, therefore, important to realize the opportunities to reap the cobenefits of water savings and carbon reductions. Transforming the power sector to low-carbon sources, such as solar PV and wind power, will realize such synergies [23]. Our study shows that the retrofitting of desulfurization facilities is also able to reduce the water consumption and carbon emissions at the same time. Replacing all current wet desulfurization facilities with dry ones would reduce 498.38 million m^3 of the water consumption and 26.65 Mt of the carbon emissions, in total. Such benefits are especially significant in the provinces of Jiangsu, Inner Mongolia, and Henan, where large amounts of water consumption and carbon emissions could be reduced at an expense of relatively small amounts of SO_2 emissions.

4.4. Outlook and Future Directions

As a cheap and abundant resource, coal power production has fueled China's development miracle over the last few decades. However, the negative social environmental consequences that are caused by coal power plants are gaining increasing amounts of attention. Coal power plants are not only major contributors to CO_2 and SO_2, but they also generate other air pollutants, such as PM2.5, which lead to negative human health impacts. According to the estimates from the Global Burden of Disease study [24], air pollution is the fourth leading cause of death and disability in China. In recent years, hazy air, which is caused by the particular matters, PM2.5 and PM10, has given rise to increasing social unrest in China. The research estimates that coal pollution cuts the life expectancy in northern China by 5.5 years [25]. It is therefore useful to incorporate other pollutants from coal power plants into the holistic evaluation and trade-offs. Furthermore, in order to facilitate the decision making on technology choices when considering these various trade-offs, economic analyses could perhaps be adopted in order to monetize the social, environmental, and health impacts of various coal power plants. Although it should be acknowledged that not all externalities can be monetized, monetization enables comparisons between the different dimensions, and it can be used in conjunction with other decision-making methods, such as multicriteria analyses.

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