

# **The Water-Carbon Trade-off for Coal Power Industry in China**

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## **Abstract**

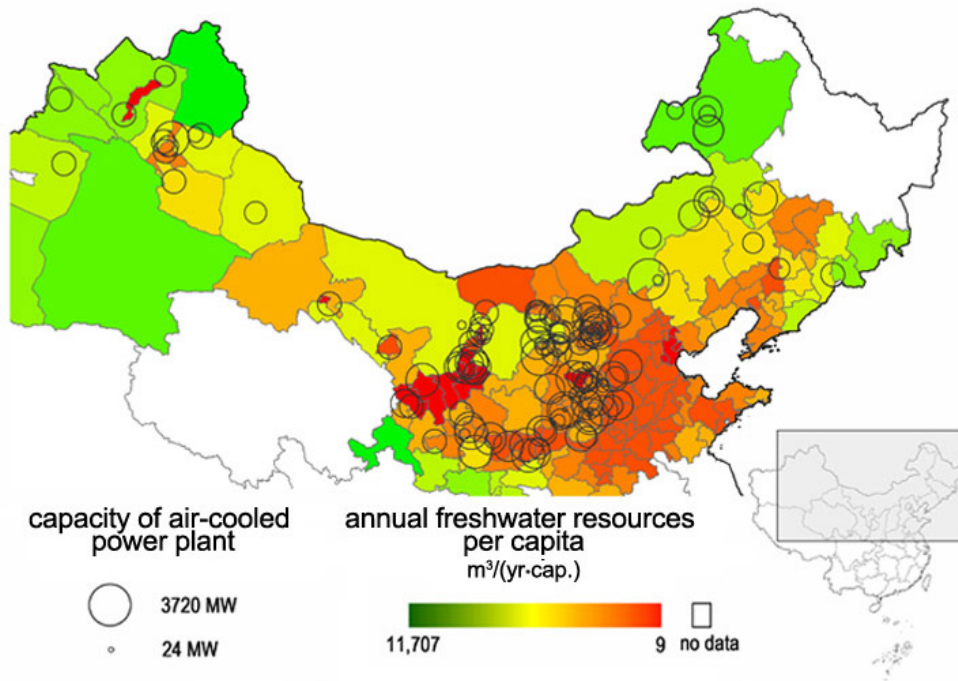
The energy sector is increasingly facing water scarcity constraints in many regions around the globe, especially in China, where the unprecedented large-scale construction of coal-fired thermal power plants is taking place in its extremely arid northwest regions. As a response to water scarcity, air-cooled coal power plants have experienced dramatic diffusion in China since middle 2000s. By the end of 2012, air-cooled coal-fired thermal power plants in China amounted to 112 GW, making up 14% of China's thermal power generation capacity. But the water conservation benefit of air-cooled units is achieved at the cost of lower thermal efficiency and consequently higher carbon emissions intensity. We estimate that in 2012 the deployment of air-cooled units contributed an additional 24.3-31.9 million tonnes of CO<sub>2</sub> emissions (equivalent to 0.7-1.0% of the total CO<sub>2</sub> emissions by China's electric power sector), while saved 832-942 million m<sup>3</sup> of consumptive water use (about 60% of the total annual water use of Beijing) when compared to a scenario with water-cooled plants. Additional CO<sub>2</sub> emissions from air-cooled plants largely offset the CO<sub>2</sub> emissions reduction benefits from Chinese policies retiring small and outdated coal plants. This water-carbon trade-off is poised to become even more significant by 2020, as air-cooled units are expected to grow by a factor of two to 260 GW, accounting for 22% of China's total coal-fired power generation capacity.

## **TOC art**

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## 32 Introduction

33 The rapid expansion of the energy sector is increasingly putting pressure on water resources in  
 34 many places around the globe <sup>1-3</sup>. Water scarcity in arid regions is also starting to affect the  
 35 operation of existing energy infrastructures <sup>4,5</sup> and the choice of technologies for new electricity  
 36 capacity investments and retrofits <sup>6,7</sup>. The complex and various linkages between energy and  
 37 water have posed new challenges for policy makers to achieve secure, efficient and sustainable  
 38 supply of energy in the future <sup>8</sup>, and calls for in-depth and careful assessment on the impacts of  
 39 energy and water policies on one another <sup>9</sup>.

40

41 The thermal power industry is one of the most important foci in the emerging research field of  
 42 energy-water nexus because of its heavy dependence on water resource availability for cooling <sup>10</sup>,  
 43 <sup>11</sup>. Global thermoelectric water consumption increased by a factor of 18 between 1950 and 2010 <sup>12</sup>,  
 44 driven by a tremendous expansion of the power sector and an increasing proportion of circulating  
 45 water cooling systems. Although in theory it is possible to stabilize total water withdrawals by  
 46 relying on different cooling technologies in the future, consumptive water use of thermoelectric  
 47 generation is still likely to experience steady growth during the 21<sup>st</sup> century <sup>13</sup>. The issue of the  
 48 role of water consumption for power production is particularly pressing in countries in which

49 thermal power generation plays a dominant role and with growing water scarcity problems, such  
50 as the United States <sup>14</sup> and China <sup>15</sup>.

51

52 The unprecedented and on-going expansion of coal-fired power in China's arid northwest regions  
53 is a notable case of emerging conflict between energy and water <sup>15</sup>. Driven by China's growing  
54 electricity demand and geographical mismatch between the location of energy resources in  
55 western areas and the load centers of electricity consumption in eastern areas, China initiated a  
56 grand "West to East Electricity Transmission" project in the 1990s. Constructing new coal-fired  
57 power plants in northwest regions is an important part of the northern corridor of the West to East  
58 Electricity Transmission Project <sup>16</sup>. As a result, the total installed thermal power capacity in seven  
59 major coal producing provinces in north and northwest China - i.e., Inner Mongolia, Shanxi, Hebei,  
60 Shaanxi, Gansu, Ningxia and Xinjiang - expanded from 50.4 GW in 2000 to 227 GW in 2012.  
61 Unfortunately, in spite of contributing three quarters of China's coal output and nearly one fourth  
62 of China's total thermal power output, these provinces are only endowed with 8% of China's  
63 freshwater resources <sup>17</sup>. Water scarcity has become the toughest environmental constraint for coal  
64 power production in northwest China.

65

66 Air-cooling (or dry-cooling) technology is a key technological option that can greatly reduce the  
67 water demand of coal power plants. Air-cooling systems employ air-cooled condensers (ACC) and  
68 reject the heat from condensing steam to the atmospheric air passing through finned-tube heat  
69 exchangers <sup>18</sup>. Using this process, air-cooling systems therefore can avoid tremendous water loss  
70 from evaporation compared with the conventional wet-cooling systems using circulating  
71 evaporative towers, which was the predominant cooling technology in the North China until late  
72 2000s. Chinese government has issued a number of policies to promote air cooling technology as a  
73 main measure to relieve the pressures on water resources posed by the expansion of coal power  
74 production in northwest regions since mid-2000s <sup>19, 20</sup>. China has now become the world's largest  
75 market of air-cooling equipment, driven by the high demand from its coal power industry.

76

77 However, the water-saving benefit of air-cooling technology is not a "free-lunch". Air-cooled  
78 power plants are usually designed to operate at higher turbine backpressures than wet-cooling

79 plants. This increases the temperature of the steam entering the condenser, and thereby increasing  
80 heat transfer between inlet steam and ambient air, increasing cooling efficiency. On the other hand,  
81 higher backpressures decrease the efficiency of the steam cycle, leading to a lower overall thermal  
82 efficiency<sup>21,22</sup>. As a result, the energy consumption and consequently carbon emissions per kWh  
83 of net electric power output of air-cooled power plants are usually higher than their wet-cooling  
84 counterparts. The purpose of this study is to reveal the water conservation benefits - i.e., the  
85 savings of consumptive water use - and the corresponding carbon emissions penalty of air-cooled  
86 power plants in China. The scale and structure of the carbon-water tradeoff is estimated based on  
87 plant-level survey data. This study can fill an important gap in understanding the characteristics of  
88 energy-water nexus in China, and therefore provide new information to policy makers in both  
89 fields of energy planning and water resource management.

90

## 91 **Development of air-cooled power plants in China and their energy and water** 92 **efficiency**

### 93 **Data description**

94 We carried out a comprehensive survey on air-cooled power plants in China. A database including  
95 key technological information of all air-cooled power units that have been put into operation and  
96 under construction in China by the end of 2012 was established. Information in the database  
97 comes from a variety of sources:

- 98 1) China Electricity Council (CEC) organizes an annual energy efficiency benchmarking  
99 competition for coal-fired thermal power plants. Materials collected in this competition  
100 provide detailed technical information, and cardinal parameters on energy and water  
101 consumption of power units taking part in the competition. Unit-level data collected in 2011<sup>23</sup>  
102 and 2012<sup>24</sup> reflect status quo technology level of China's thermal power industry. These data  
103 are used for parameter estimation for energy and water consumption models in this study.
- 104 2) CEC also publishes a compilation of statistics of China's power industry annually<sup>25</sup>. Net  
105 electric power output and auxiliary power consumption ratio of all power plants larger than  
106 6MW are reported in the statistics. A list of all new generator units put into commission every  
107 year is also provided.
- 108 3) Data on air-cooled power plants from the above materials are checked with and supplemented

109 by other public available information, such as official permission documents of proposed new  
 110 power plants issued and disclosed by NDRC (National Development and Reform  
 111 Commission), MWR (Ministry of Water Resources), MEP (Ministry of Environmental  
 112 Protection), news report regarding the construction and commission of new air-cooled power  
 113 plants, and information from websites of utility companies.

114 4) Geographic location of power plants is identified by using the Google Earth<sup>®</sup> software.

115

116 **Market penetration of air-cooling technology in thermal power industry**

117 Air-cooling technology has experienced rapid diffusion in China’s thermal power industry in the  
 118 past decade. As shown in subplot (b) of **Figure 1**, total installed capacity of air-cooled power  
 119 plants increased from just 2.3 GW in 2003 to 112.4 GW in 2012. Meanwhile, the share of  
 120 air-cooled coal power capacity increased from less than 1% of national total thermal power  
 121 capacity to 14% of the national total. As shown in **Table 1**, Shanxi province had the largest fleet of  
 122 air-cooled power plants in 2012, i.e. 33.4 GW, which made up 67% of its total thermal power  
 123 capacity. Inner Mongolia ranked the second with 32.3 GW, making up 54% of its total.

124 **Table 1. Installed capacity of air-cooled coal power plants in China in 2012**

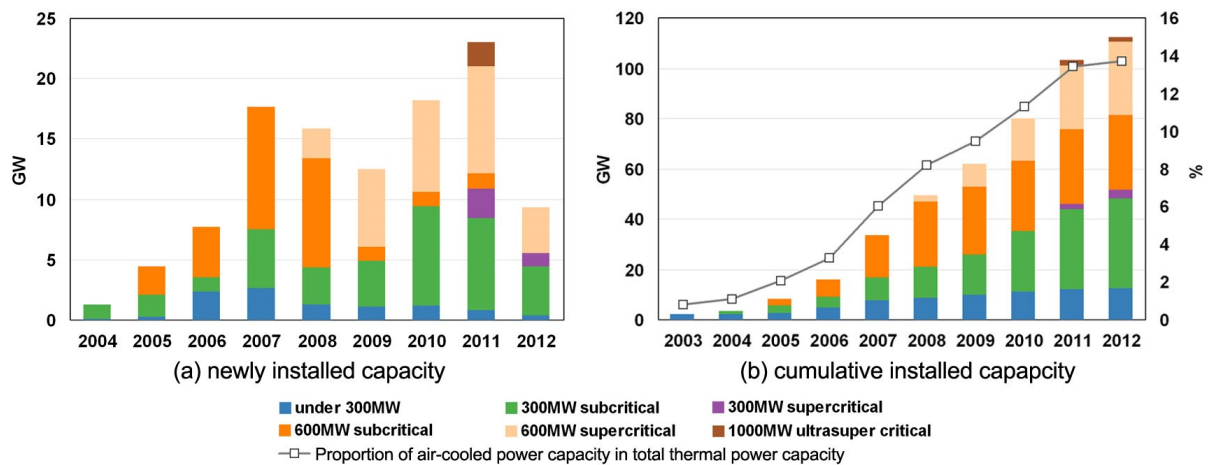
Province	Capacity of air-cooled power GW	Total capacity of coal thermal power GW	Percentage of air-cooled coal power
Hebei	5.6	40.0	14%
Shanxi	33.4	50.1	67%
Inner Mongolia	32.3	60.2	54%
Liaoning	0.6	30.6	2%
Jilin	2.0	16.3	12%
Shaanxi	13.1	22.3	59%
Gansu	7.7	15.5	50%
Ningxia	10.4	16.4	63%
Xinjiang	7.3	22.6	32%
<b>Total</b>	<b>112.4</b>	<b>280.0</b>	<b>40%</b>

125 Note: Total thermal power capacity by province is reported by the China Electricity Council (CEC)  
 126 <sup>25</sup>. Almost all thermal power capacities in these provinces are coal-fired, with less than 1% using  
 127 coalbed methane, natural gas, top gas and other non-coal feed stocks.

128

129 Tremendous technology advancement has been achieved through large-scale deployment of

130 air-cooling technology. In the early stage of diffusion, i.e., before 2007, most power units adopting  
 131 air-cooling system were subcritical units. There were also quite a number of small and medium  
 132 size units under 200 MW being constructed. Most large-size supercritical units were constructed in  
 133 recent years. The first two 600MW supercritical air-cooled units were put into commission in 2008  
 134 in Huaneng Shang'an power plant located in Hebei province. Since then, units of this type  
 135 accounted for nearly 40% of newly built air-cooled coal power capacity. In 2011, the first two  
 136 1000MW ultra supercritical air-cooled units were put into commission in Ningxia Lingwu Power  
 137 Plant. These two units are the largest and most advanced air-cooled power units currently in  
 138 operation in the world, and are regarded as a milestone in the history of air-cooling technology  
 139 development in China. Subplot (a) of **Figure 1** shows how the structure of newly built units  
 140 evolved with time.

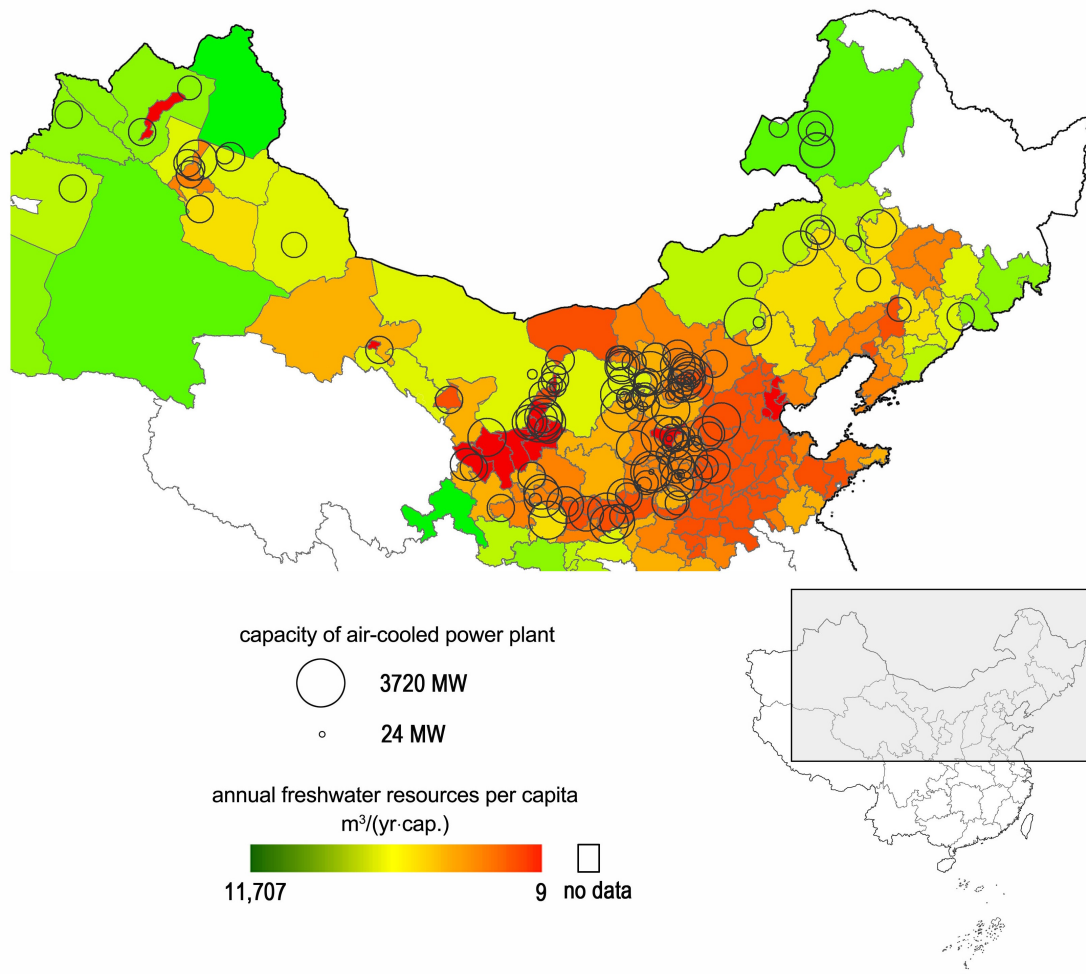


141 **Figure 1. Diffusion of air-cooled thermal power capacity disaggregated by unit types**  
 142 **between 2003 and 2012.** Nuclear power is separately accounted in the energy statistics in China  
 143 and therefore not included in the total thermal power capacity.  
 144

145  
 146 The detailed geographic location of existing air-cooled power plants is presented in **Figure 2**  
 147 along with prefecture-level annual freshwater resources per capita in north and northwest China.  
 148 According to the water resource management regulation for thermal power industry issued by the  
 149 National Development and Reform Commission of China <sup>19</sup>, new coal power plants in arid regions,  
 150 in principle, should adopt air-cooling technology to meet water consumption limitation. It is  
 151 obvious that the distribution of air-cooled power plants is quite concentrated. Many large-size  
 152 plants locate near pithead of coal mines. Therefore the distribution of air-cooled power plants  
 153 generally follows the distribution of large coal bases in northwest China.

154

155



156

157 **Figure 2. Geographic location of air-cooled coal power plants in China and annual**  
158 **freshwater resources per capita at the prefecture-level in north and northwest China.** The  
159 numbers are calculated by dividing total annual freshwater resources by population at  
160 prefecture-level. Total annual freshwater resources at the prefecture-level are reported by the  
161 provincial Water Resources Bulletins issued by provincial water resources management authorities.  
162 Population data come from statistic yearbooks of different provinces.

163

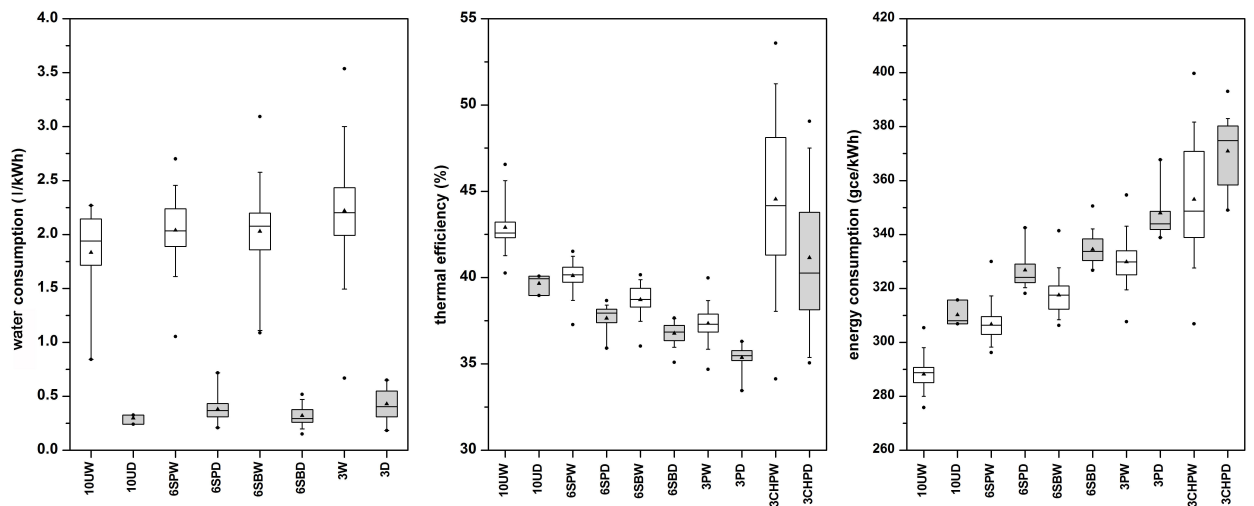
#### 164 **Status quo of energy and water consumption of air-cooled thermal power plants**

165 We use unit-level data collected and reported in the national energy efficiency benchmarking  
166 competition for coal-fired thermal power plants conducted by the China Electricity Council (CEC)  
167 in 2011 and 2012 to measure the state-of-the-art energy and water consumption performance of  
168 air-cooled and wet-cooling units in China. **Figure 3** presents descriptive statistics of water  
169 consumption intensity, energy consumption intensity, and overall thermal efficiency of different  
170 generator unit types with different cooling systems. The median values of water consumption per

171 kWh net electricity output using traditional closed-loop wet-cooling technology are between  
 172 2.0-2.2 l/kWh depending on unit size. These values are about five times higher than that of  
 173 air-cooling technology. For a particular cooling technology, units with greater power ratings have  
 174 higher steam temperatures and pressures therefore higher thermal efficiencies and lower energy  
 175 consumption per unit electricity output.

176

177 The median values of thermal efficiency of 600MW supercritical units, 600MW subcritical units  
 178 and 300MW subcritical units with air-cooling technology are 37.9%, 36.9% and 35.6%,  
 179 respectively, about 1.7-2.2% lower than their wet-cooling counterparts. In terms of energy  
 180 consumption intensity, the median values of the grams of standard coal equivalent per kWh net  
 181 electricity output by 600MW supercritical units, 600MW subcritical units, and 300MW subcritical  
 182 units with air-cooling technology are 324 gce/kWh, 334 gce/kWh and 345 gce/kWh, respectively,  
 183 15-18 gce/kWh higher than their wet-cooling counterparts. Furthermore, we found that a  
 184 substantial part of the energy efficiency benefits of more advanced generator units are being offset  
 185 by the shift to air-cooling technology. For example, the energy intensity of air-cooled 600MW  
 186 subcritical units (6SPD) is statistically higher than that of wet-cooling 300MW subcritical units  
 187 (3W).



188

189 **Figure 3. Water consumption and energy performance of coal-fired power generation plants**  
 190 **for units of different sizes, steam cycles, and cooling technologies in China. (a) Water**  
 191 **consumption per kWh net electricity output; (b) thermal efficiency; (c) energy consumption**  
 192 **per kWh net electricity output.** Each box plot indicates encloses the 25/50/75 percentiles, whisker caps  
 193 denote the 5/95 percentiles, the dots represent minimum/maximum values and the triangles represent mean values.  
 194 10UW and 10UD represent 1000MW ultra supercritical units with closed-loop wet-cooling and air-cooling,

195 respectively; 6SPW and 6SPD represent 600MW supercritical units with closed-loop wet-cooling and air-cooling,  
 196 respectively; 6SBW and 6SBD represent 600MW subcritical units with closed-loop wet-cooling and air-cooling,  
 197 respectively; 3W and 3D represent 300MW units (both conventional generator units and combined heat and power  
 198 units) with closed-loop wet-cooling and dry-cooling, respectively; 3PW and 3PD represent 300MW conventional  
 199 generator units with closed-loop wet-cooling and dry-cooling, respectively; 3CHPW and 3CHPD represent  
 200 300MW combined heat and power units with closed-loop wet-cooling and dry-cooling, respectively.

201

## 202 **Method**

203 Two multiple linear regression models are established to estimate the additional energy  
 204 consumption and water saving effect of coal-fired power units adopting air-cooling technology  
 205 compared to wet-cooling technology, respectively. As shown in [Eq.1](#), energy consumption per  
 206 kWh net electric power output is determined by unit types, cooling technologies and  
 207 heat-to-electricity ratio of the generator unit.

$$208 \quad E_i = \alpha + \sum_k \beta_k \cdot UT_{i,k} + (\sum_k \gamma_k \cdot UT_{i,k}) \cdot CT_i + (\sum_k \lambda_k \cdot UT_{i,k}) \cdot HER_i + \varepsilon_i \quad (1)$$

209 In [Eq.1](#), subscript  $i$  represents the  $i^{\text{th}}$  sample. Subscript  $k$  represents unit types distinguished  
 210 by unit capacity and operating condition. Four types of unit are distinguished, i.e., 1000 MW ultra  
 211 supercritical unit, 600MW supercritical unit, 600MW subcritical unit and 300 MW subcritical unit.

212  $E_i$  is the energy consumption per kWh net power output of the  $i^{\text{th}}$  sample measured in standard  
 213 coal equivalent, i.e., gce/kWh.  $E_i$  is calculated by the following equation ([Eq.2](#)):

$$214 \quad E_i = \frac{TE_i}{NPO_i} \quad (2)$$

215 where  $TE_i$  represents total energy consumption of the  $i^{\text{th}}$  sample in the survey year measured in  
 216 standard coal equivalent;  $NPO_i$  represents net power output of sample  $i$  measured in kWh in  
 217 the survey year, for which in-plant auxiliary power use is excluded. Both  $TE_i$  and  $NPO_i$  are  
 218 reported in the survey conducted by CEC.

219  $UT_{i,k}$  is a binary variable indicates the unit type of sample  $i$ . If sample  $i$  belongs to unit type  
 220  $k$ , then  $UT_{i,k}$  is donated 1, otherwise  $UT_{i,k}$  is donated 0.

221  $CT_i$  is also a binary variable indicates the cooling technology used by sample  $i$ , 0 for  
 222 wet-cooling technology (both once-through and closed-loop cooling technologies), and 1 for

223 air-cooling technology.

224  $HER_i$  is the heat-to-electricity ratio of sample  $i$ , which is a dimensionless variable measuring the  
225 amount of heat output as a ratio to the amount of net power output by a combined heat and power  
226 unit.  $HER_i$  is calculated according to [Eq. 3](#) as follows:

$$227 \quad HER_i = \frac{HO_i}{NPO_i \cdot cf^e} \cdot 100\% \quad (3)$$

228 where  $HO_i$  is the heat output of sample  $i$  in the survey year measured in kJ;  $cf^e$  is a unit  
229 conversion factor, equal to 3600 kJ/kWh. Since total energy consumption and carbon emission by  
230 a unit should be considered in the calculation, for simplicity, we do not allocate fuel consumption  
231 between heat and electricity, but assign all energy consumption to net power output. Therefore it is  
232 necessary to introduce heat-to-electricity ratio as one of the determinants for  $E_i$ . Holding other  
233 conditions unchanged, larger heat-to-electricity ratio, i.e., larger proportion of fuel is used for  
234 supplying heat, usually leads to higher overall thermal efficiency and higher energy consumption  
235 per kWh net power output. Such characteristics is clearly shown in subplot (b) and (c) in [Figure 3](#).

236  $\alpha$ ,  $\beta_k$ ,  $\gamma_k$  and  $\lambda_k$  in [Eq.1](#) are parameters to be estimated.  $\alpha$  is a constant parameter.  $\beta_k$   
237 represents the baseline energy intensity of unit type  $k$  with wet-cooling technology and have no  
238 heat supply.  $\gamma_k$  represents the additional energy consumption attributed to air-cooling  
239 technology for unit type  $k$ , holding other conditions constant.  $\gamma_k$  is the parameter of interest in  
240 this study and is further used to estimate additional carbon emissions due to adopting air-cooling  
241 technology.  $\lambda_k$  is a parameter measuring the impact of supplying heat on energy intensity per  
242 kWh net electric power output of unit type  $k$ .  $\varepsilon_i$  is a random error.

243

244 Linear least square method is used for parameter estimation for the energy consumption model.  
245 Then, total additional energy consumption due to air-cooling technology is calculated by  
246 multiplying parameter  $\gamma_k$  with the corresponding national total net electric power output by unit  
247 type  $k$  as shown in [Eq. 4](#):

248 
$$TAC = \sum_k \gamma_k \cdot X_k \quad (4)$$

249 where  $TAC$  is the total additional energy consumption attributed to adopting air-cooling  
 250 technology in a particular year; and  $X_k$  is the total net electric power output by unit type  $k$  in  
 251 a particular year.

252

253 Finally, energy consumption  $TAC$  is translated into CO<sub>2</sub> emissions by multiplying an emission  
 254 factor of 2.95 tCO<sub>2</sub>/tce derived from a guideline for compiling green house gas emission inventory  
 255 published by NDRC <sup>26</sup>, which is calculated based on the net heating value, carbon content and  
 256 oxidization rate of the raw coal for thermal power generation in China.

257

258 Similar to energy consumption model, water-saving effect of air-cooling technology is estimated  
 259 by the following linear model as shown in **Eq. 5**:

260 
$$W_i = \eta + \left( \sum_k \nu_k \cdot UT_{i,k} \right) \cdot CT_i + \varepsilon_i' \quad (5)$$

261  $W_i$  is the water consumption per kWh net power output of sample  $i$  measured in l/kWh.  $UT_{i,k}$   
 262 and  $CT_i$  have the same definition as in **Eq.1**. But generator units with once-through cooling  
 263 system are not included in the water consumption model, because once-through cooling  
 264 technology is usually not a practical option in arid areas in northwest China. Closed-loop  
 265 wet-cooling technology should be regarded as the baseline for comparing water conservation  
 266 benefits of air-cooling technology.  $\eta$  is a constant parameter in the model.  $\nu_k$  represents the  
 267 water saving effect of adopting air-cooling technology for unit type  $k$ ,  $\varepsilon_i'$  represents the  
 268 random error. After  $\nu_k$  are estimated, total water conservation benefits are calculated by  
 269 multiplying  $\nu_k$  with corresponding total net electric power output  $X_k$ .

270

271 As discussed in Section 2, sample data come from the annual survey conducted by CEC. Not all  
 272 air-cooling units are covered by these samples. For power plants not included in the survey, their  
 273 net power output in particular years are extracted from the Annual Compilation of Statistics of the  
 274 Power Industry published by CEC <sup>25</sup>.

275

## 276 **Results**

### 277 **Parameter estimation**

278 Results of parameter estimation of the energy consumption model and the water consumption  
279 model are presented in **Table 2** and **Table 3**, respectively. The point estimates of additional energy  
280 consumption of 1000 MW ultra-supercritical units, 600MW supercritical units, 600MW subcritical  
281 units, and 300 MW subcritical units with air-cooling technology as compared with wet-cooling  
282 technology are 20.3gce/kWh, 19.3 gce/kWh, 16.0 gce/kWh and 20.2 gce/kWh, respectively. The  
283 corresponding water consumption intensities of those technologies decrease on average by 1.85  
284 l/kWh, 1.77 l/kWh, 1.83 l/kWh and 1.72 l/kWh, respectively.

285 **Table 2 Parameter estimation of the energy consumption model (gce/kWh)**

Parameter <sup>1</sup>	Point estimation	95% confidential interval
$\alpha$	289.87	(288.03, 291.70)
$\beta_1$	0	0
$\beta_2$	17.22	(15.17, 19.27)
$\beta_3$	28.60	(26.40, 30.80)
$\beta_4$	39.37	(37.36, 41.38)
$\gamma_1$	20.34	(11.86, 28.81)
$\gamma_2$	19.32	(16.64, 22.01)
$\gamma_3$	16.01	(13.93, 18.09)
$\gamma_4$	20.21	(17.68, 22.74)
$\lambda_1$	0	0
$\lambda_2$	0.51	(0.09, 0.92)
$\lambda_3$	1.26	(1.05, 1.47)
$\lambda_4$	0.93	(0.89, 0.98)

Number of samples: 982

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R<sup>2</sup>: 0.8776

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286 <sup>1</sup> k=1 for 1000 MW ultra supercritical unit, k=2 for 600MW supercritical unit, k=3 for 600MW  
287 subcritical unit and k=4 for 300 MW subcritical unit.

288

289 **Table 3 Parameter estimation of the water consumption model (l/kWh)**

Parameter	Point estimation	95% confidential interval
$\eta$	2.149	(2.112, 2.186)
$\nu_1$	-1.850	(-2.295, -1.406)
$\nu_2$	-1.768	(-1.903, -1.634)
$\nu_3$	-1.828	(-1.927, -1.728)
$\nu_4$	-1.719	(-1.859, -1.579)

Number of samples: 591  
R<sup>2</sup>: 0.7957

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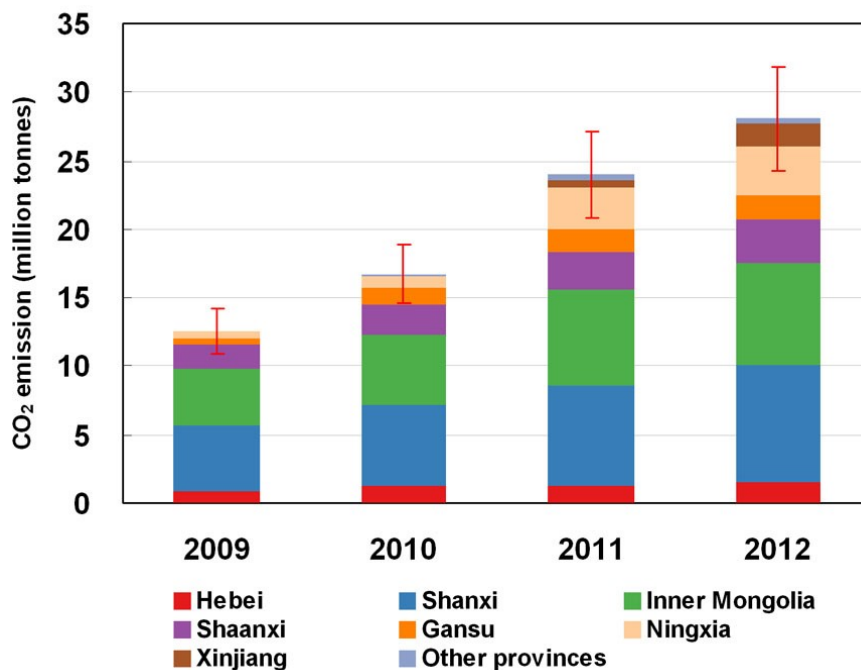
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### 291 **Growing scale of the carbon-water tradeoff**

292 As shown in [Figure 4](#), in 2012, air-cooling technology resulted in consumptive water use savings  
293 of 832-942 million m<sup>3</sup> in China at the cost of additional consumption of 8.22-10.8 million tonnes  
294 of standard coal equivalent, which resulted in 24.3-31.9 million tonnes of CO<sub>2</sub> emissions. The  
295 magnitude of this water-carbon tradeoff has more than doubled from 2009 to 2012 as air-cooled  
296 coal power plants expanded rapidly in China's water scarce north and northwest regions. Shanxi  
297 and Inner Mongolia account for 30% and 27% of the total water-saving benefits and additional  
298 carbon emissions in 2012, respectively, ranking the first and the second among all provinces. The  
299 additional emissions are growing most quickly in the Ningxia and Xinjiang provinces, where quite  
300 a lot of China's new large coal power plants have been under construction in recent years. The  
301 water-savings and additional CO<sub>2</sub> emissions associated with air-cooled coal power plants over  
302 water-cooled plants in Ningxia increased by a factor of six from 2009 to 2012, amounting to 13%  
303 of the national total. In the Xinjiang province, which had its first operational air-cooled power  
304 plant only in 2010, 75% of new installed coal power capacity constructed from 2010 to 2012 relies  
305 on air-cooling technology. The total resulting additional CO<sub>2</sub> emissions in China from the reliance  
306 on air-cooling technology are noteworthy and equivalent to about 0.7-1.0% of the total CO<sub>2</sub>

307 emissions from China's entire power sector<sup>27</sup>. Given that climate change is a stock and not a flow  
 308 problem, decisions about technological choice in these power plants will result in even greater  
 309 carbon dioxide emissions that will accumulate over the life of the plants, which is usually several  
 310 decades. Meanwhile, the avoided yearly consumptive water use is comparable to a large fraction  
 311 of current yearly water consumption by power sector in those arid regions. For example, mean  
 312 values of water-savings resulting from the use of air-cooling technology in Shanxi and Inner  
 313 Mongolia in 2012 are as much as 120% and 58% of the total yearly water consumption of their  
 314 power sector, respectively. It is also comparable to about 60% of the total annual water use of  
 315 Beijing, where a population of 20 million resides. Air-cooling technology has significantly  
 316 relieved the pressure of power sector development on water resources in China's arid northwest  
 317 regions.



318  
 319 **Figure 4. Increase in CO<sub>2</sub> emissions resulting from the use of air-cooling technology when**  
 320 **compared to baseline emissions assuming the use of wet-cooling technology.** Error bars  
 321 represent 95% confidential intervals stemming from the distribution of CO<sub>2</sub> emissions for different  
 322 unit sizes and cooling types.

323

## 324 Discussion

325 The construction of air-cooled coal-fired power plants in the water scarce north and northwest  
 326 regions of China and the resulting increase in CO<sub>2</sub> emissions is a striking and telling example of

327 the growing tradeoffs involved in dealing with energy provision. With 44% of China's total CO<sub>2</sub>  
328 emissions in 2011, the power sector is one of the most important sectors to achieve China's  
329 national greenhouse gas mitigation target, i.e., reducing CO<sub>2</sub> intensity per unit GDP by 40%-45%  
330 in 2020 compared to 2005 level <sup>28,29</sup>. The Chinese government has been successfully phasing out  
331 outdated small units and deploying advanced large scale units which have resulted in a continuous  
332 decline in the national average energy intensity of net electricity output by coal power plants in the  
333 past decade, from 392 gce/kWh in 2000 to 326 gce/kWh in 2012 <sup>30</sup>. However, the energy saving  
334 and emission mitigation potential of retiring small and outdated coal power plants is diminishing.  
335 During 2011 to 2012, the average energy intensity of coal power generation only decreased by 3  
336 gce/kWh, which was equivalent to 34.8 million tonnes of CO<sub>2</sub> mitigation at national level. It is  
337 noteworthy that the additional CO<sub>2</sub> emissions associated with air-cooling technology in 2012  
338 estimated by this study was very similar to the retirement of old coal power plants over the same  
339 period of time, indicating that the decisions taken to address water scarcity are largely erasing the  
340 carbon mitigation benefits of other policies in coal power industry aimed at shutting down small  
341 plants and building bigger ones.

342

343 Further penetration of air-cooling technology could be a major factor hindering efficiency  
344 improvement of coal power generation in China in the future. According to the information we  
345 collected, besides the existing installed capacity, another 20GW of air-cooled coal-fired power  
346 plants were under construction by the end of 2012, and at least 26GW of additional air-cooled  
347 power units have started construction or been in permitting process in 2013(See the Supporting  
348 Information for more details). Among these units, 15GW will be located in Xinjiang and 11.5GW  
349 in Inner Mongolia. Units larger than or equal to 600MW (add up to 30.3GW) make up more than  
350 60% of this incremental capacity. Assuming most of the above units will be put into operation by  
351 2015, the total installed capacity of air-cooled coal power plants will approximately reach 155GW  
352 in 2015, accounting for 17% of the total planned capacity of coal power generation in 2015, i.e.,  
353 928GW, according to a research on the development of China's electric power industry in the 12<sup>th</sup>  
354 five-year period (2011-2015) conducted by CEC <sup>31</sup>. It is also expected that newly installed  
355 capacity of coal power generation will amount to 265GW during the 13<sup>th</sup> five-year period  
356 (2016-2020), nearly 60% of which will be located in 13 large production bases of coal mining and

357 power generation in the north and northwest China. If 70% of the new capacity in those large coal  
358 power bases adopts air-cooling system, which is a rather conservative estimation, air-cooled power  
359 plants may reach 260 GW in 2020, about 22% of China's total coal-fired power generation  
360 capacity. This would result in a greater increase in CO<sub>2</sub> emissions when compared to a scenario  
361 with wet-cooling plants.

362

363 According to China's latest water resource conservation regulation for the coal power industry  
364 promulgated in December 2013, air-cooling technology has become a mandatory technological  
365 requirement for new coal-fired thermal power plants in water-scarce regions <sup>32</sup>. The water  
366 conservation benefit of air-cooling technology has obviously received much more attention than  
367 its associated energy penalty from both energy planners in central and local government and  
368 power enterprises since its first introduction into China. Uncovering and understanding the impact  
369 of the water-carbon tradeoff described in this paper should have important policy implications  
370 mainly in three aspects.

371

372 First, it calls for a more careful evaluation of the water resources' carrying capacity and the  
373 availability of alternative non-traditional water sources for power plant cooling <sup>33</sup> in arid areas  
374 before outlining ambitious energy development plans and making large capital investments on  
375 coal-fired power plants. An increased coordination between energy administration institutions and  
376 water resources planning and management agencies is a key factor to enable such integration  
377 between energy and water policies <sup>34</sup>.

378

379 Second, as the increasing dual pressures of water scarcity in north and northwest China and the  
380 national greenhouse gas (GHG) mitigation target, identifying the magnitude of the water-carbon  
381 tradeoff embedded in the current technological choices should further motivate policy makers to  
382 pay more attention to alternative electricity supply options which bring both water conservation  
383 and carbon mitigation benefits. These options include, but are not limited to, natural gas combined  
384 cycle (NGCC), wind power, solar PV, geothermal heat pumps and nuclear power using sea water  
385 cooling to larger extent.

386

387 And third, policy makers and technologists could consider equipping new air-cooled coal power  
388 plants with carbon capture and sequestration (CCS) technology in the future <sup>35</sup>. Model-based  
389 simulation has shown that when a CO<sub>2</sub> capture system is added to an air-cooled coal power plant,  
390 the consumptive water use can be reduced by about 40% compared with typical plants using wet  
391 cooling towers <sup>36</sup>. Although the additional water use by the CO<sub>2</sub> capture system offsets a part of  
392 the water conservation effect of air-cooling technology, combining these two technologies may be  
393 a promising way to achieve both goals of mitigating carbon emission and saving water in coal  
394 power plants, although this option may only become competitive with significant regulations  
395 limiting CO<sub>2</sub> emissions. More comprehensive and system-level analysis considering capacity  
396 expansion, energy mix change and key technologies with important implications on both water use  
397 and carbon emission is needed to identify future water stress by electric power production under  
398 the policy context of carbon mitigation <sup>37,38</sup>. Such efforts may bring to the forefront policies that  
399 may support the transformation of China's electric sector towards a low-carbon and less water  
400 intensive future.

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402

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405

### 406 **Supporting Information**

407 Additional information as noted in the text. These materials are available free of charge via the  
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