Supporting Information

for

A comparative advantage strategy for rapid pollution mitigation in China

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Containing:

9 pages

3 figures

1. Data

❖ Data for the SO_2 mitigation case

This article employs two major categories of data in the analysis. The first one is publically available. Since 2008, China's Ministry of Environmental Protection has been annually publishing information on every single SO_2 scrubber in coal-fired power plants that went online by the end of the previous year. The dataset is updated annually, adding previously missing SO_2 scrubbers. In the 2008 dataset, it reported 712 sets of SO_2 scrubbers with a total capacity of 266,000 MW. In the following updates, the two figures were 1,010 sets and 363,000 MW in 2009, 1,264 sets and 461,000 MW in 2010, 2,119 sets and 578,000 MW in 2011, and 4,473 sets and 670,000 MW in 2012 *(1)*. If units smaller than 100 MW are excluded, China had 619,600 MW of SO_2 scrubbers by the end of 2011 *(1)*. The later versions include many small SO_2 scrubbers that were missing in the earlier versions. For data on the capital costs of SO_2 scrubbers, this article relies on two sources. From February to August 2006, China's Association of Environmental Protection Industries surveyed SO_2 scrubber projects in operation or under construction at the end of 2005 *(2)*. 113 projects (223 coal-fired power units) with a total capacity of 83,850 MW applied limestone-gypsum wet scrubber technology – which is used in 80% of China's SO_2 scrubbers *(1)* – and had cost information available. Data on projects using other technologies are much less continuous to provide longitudinal insights. They had already been or were expected to be in operation over the period from 2002 to 2008. Their expected time in operation could partly reflect when the contracts were signed and accordingly the then market situation. Furthermore, the author's interviews provided an independent source to cross-check the survey data and also to shed light on their more recent changes. Data for the United States came from the U.S. Energy Information Administration *(3)*.

Another key data source is the author's field interviews that spanned the four years from 2009 to 2012. A stratified sampling method was utilized to select sites for interviews. Three major categories of stakeholders are critical to ensure that the research questions are properly approached, including coal-fired power plants that install SO_2 scrubbers, SO_2 scrubber companies as suppliers, and government regulators.

Coal-fired power plants were selected according to their features with maximized variety and potential variance to enhance their representativeness of China's entire fleet. Ten coal-fired power plants in mainland China were visited: seven in four rich, coastal provinces, and three in two poorer, inland ones. They had a total of 23 SO_2 scrubbers

with their unit capacity covering all major scales: < 100 MW; 100 ~ 200 MW; 200 ~ 300 MW; 300 ~ 600 MW; and > 600 MW. Five SO_2 scrubbers went online on or before 2002, another 15 on or before 2007, and three in 2008. The widespread completion years will facilitate the analysis on the decisions to install and operate SO_2 scrubbers. Nine SO_2 scrubber companies were suppliers to these SO_2 scrubbers, applying four SO_2 scrubbing technologies with the limestone-gypsum wet type dominating. Thirteen SO_2 scrubbers went online together or earlier than one year after the online date of their corresponding coal-fired power units. The other ten were retrofits. In order to minimize potential sampling bias, seven different channels were utilized to introduce the author to visit the power plants and none of them were environmental regulators. In addition, interviews were also conducted at Hong Kong's only two coal-fired power plants that had their SO_2 scrubbers built by China's domestic companies. Unlike mainland China, Hong Kong has a well-established rule of law and good environmental regulation. From contracting to completion, the projects took roughly twice the amount of time that was normal in mainland China. The SO_2 scrubbers were much more expensive and of better quality than those which were installed at the same time in mainland China.

SO_2 scrubber companies were selected in the three categories. China has five large state-owned power corporations at the national level, four having major SO_2 scrubber companies, and two were selected for interview. In the available SO_2 scrubbers at the end of 2011 with unit scales not smaller than 100 MW, the two companies had market shares of 11.9% and 3.3%, respectively. Another smaller company owned by one of the five power corporations was also visited and its market share was 0.4%. The special relationship with their parent corporations put them in relatively advantageous positions in market competition. Eight companies that have no association with power corporations were selected. Their market shares ranged from 0.7% to 6.0%, being 22.8% in total. In addition, two foreign companies and their Chinese representative offices as technology licensors were also interviewed to provide an external perspective.

China's environmental regulators were selected for interviews based on their various roles in regulating SO_2 scrubbers. Three interviews were conducted on environmental regulators at the national and provincial levels. One visit was made to a regional data center to receive real-time data from continuous emission monitoring systems (CEMSs). Six interviews were conducted in the power regulators and the environmental departments within power corporations. Compared to engineers and managers in coal-fired power plants and SO_2 scrubber companies, environmental regulators were much more cautious when being interviewed.

- **Data for the wind energy development case**

Other than publically available data from various sources, this research emphasizes field work to get first-hand and indepth insights. Wind companies were selected to cover both wind turbine manufacturers and component suppliers. Interviews were mainly conducted in two exhibitions to take the advantage of many related companies in one location. The first one was the China Wind Energy Exhibition held in Shanghai, China from April 26 to 28, 2012. The second one was the Guangzhou Wind Energy Exhibition held in Guangzhou, China from August 21 to 23, 2012. In total, 37 interviews were conducted on 34 companies or agencies. Seven companies were wind turbine manufacturers. Their market shares in the Chinese market in 2011 were ranked to be first, third, fourth, fifth, ninth, thirteenth and sixteenth with a combined share of 55.5%, or 9,792 MW *(4)*. Two of these manufacturers exported 198 MW of wind turbines in 2011, and were responsible for 90% of China's total export *(4)*. Twenty-three companies were suppliers of blades, generators, gearboxes, control systems (hardware and software), flanges, and other items. Two manufacturers and one component supplier of small wind turbines were also interviewed. One agency was for evaluating the performance of wind turbines.

One wind turbine manufacturer was interviewed in Portugal in June 2012. It is one of the largest ten companies in the world by market share, installing 2,846 MW (7.2%) of wind turbines in 2010 and heavily focusing on the European market *(5)*. The factory in Portugal is one of its manufacturing bases. The interview provides information on the market situation in developed countries.

One wind farm in eastern Inner Mongolia was visited in August 2012. It has a rich wind resource and is recognized by the Chinese government as a suitable location for the building of a large-scale wind energy base *(6)*. Although the day of visit was windy, many wind turbines were not revolving. In addition to the quality reason, another reason was due to the inadequate capacity of local electric grid to absorb intermittent wind energy.

2. Model

A decision-maker can make a certain amount of effort to work for pollution mitigation. He or she has two choices, either to deploy more pollution control facilities or to enhance the operational performance of the existing stock. The goal is to maximize the impacts of his or her efforts on pollution mitigation at every step.

Applying research findings from the article, after a certain amount of pollution control facilities have been deployed, the net political resistance against the deployment of one more facility and against the enhancement of operational performance by 1% could be roughly taken as unchanged with the level of deployment. So does the monitoring, reporting and verification (MRV) costs on policy enforcers.

Accordingly, a given amount of effort could either raise the deployment rate by α (in the two cases of SO_2 scrubbers and wind turbines, the unit is MW) or the performance of existing facilities by $\beta\%$ (in the SO_2 scrubber case, the unit is percentage points of SO_2 removal rates, and in the wind turbine case, the unit is percentage points of a year when wind turbines are working normally for generating electricity). The initially deployed facilities have a total capacity of A and the initial performance is $B\%$. Then the initial pollution mitigation effect of the facilities is roughly proportional to $A \times B\%$. The performance has a technical upper limit, $B^*\%$.

The option of devoting the efforts to the deployment could raise the pollution mitigation effect to $(A+\alpha)\times B\%$ and the other option to work on the operation would have an effect of $A\times(B\%+\beta\%)$. If there is no constraint, a rational decision-maker, in order to maximize the impact of his or her efforts, will choose the first option when $(A+\alpha)\times B\% > A\times(B\%+\beta\%)$, or when $\frac{A+\alpha}{A} > \frac{B\%+\beta\%}{B\%}$ or $\frac{\alpha}{A} > \frac{\beta\%}{B\%}$. The second option will be taken when $\frac{\alpha}{A} < \frac{\beta\%}{B\%}$ and the two options are no different when $\frac{\alpha}{A} = \frac{\beta\%}{B\%}$. With the progress on the deployment and operation, the choice could change. This is the comparative advantage strategy as examined in this article.

If adding one constraint that the choice should prioritize policy enforcement, the progress should be first made to improve the operation. Only when $B\%$ has reached $B^*\%$, more facilities are allowed to be deployed. This could be taken as a rule-of-law strategy.

One more constraint could be added to describe the situation on the supply side. The comparative advantage strategy lowers the technological barriers of market entry to facilitate the rapid establishment of large enough supply capacity, while the rule-of-law strategy corresponds to higher market entry barriers and discounted supply capacity. To simplify the model, this article assumes that the supply capacity in the rule-of-law strategy is η% less than that in the comparative advantage strategy. Then in the rule-of-law strategy, the same amount of efforts could only raise the deployment rate by $\alpha \times (1-\eta\%)$.

The SO_2 scrubber case is simulated here to exemplify the usefulness of this very simple model. Here are the assumptions of the above parameters:

A_0: the initial capacity of SO_2 scrubbers, 7,000 MW, equivalent to the level in 2000 *(1)*;

B_0%: the initial SO_2 removal rate in coal-fired power plants with SO_2 scrubbers, 31.3%, equivalent to the level in Jiangsu province in 2006 *(7)*;

$B^*\%$: 79%, the highest SO_2 removal rate China achieved in 2010 (Figure 1);

$\frac{\alpha}{\beta\%}$: $\frac{4,500 \text{ MW}}{1\%}$, or the required effort from decision-makers is the same to deploy 4,500 MW of SO_2 scrubbers and to increase the SO_2 removal rate of the existing stock by 1%. The number is assumed to fit China's actual data; and

η%: 50%, assumed to indicate the impacts of higher market entry barriers in the rule-of-law strategy.

As illustrated in Figure S2, the projection with the comparative advantage strategy fits well with China's SO_2 mitigation path in coal-fired power plants with SO_2 scrubbers. If considering no constraint from the supply side, the rule-of-law strategy mainly differs from the comparative advantage strategy at the early stage of progress (Figure S3). However, if considering the potential supply constraints due to higher market entry barriers in the rule-of-law strategy, the pollution mitigation would proceed at a much slower pace (Figure S3).

References:

(1) Ministry of Environmental Protection, *The list of China's SO_2 scrubbers in coal-fired power plants*; Beijing, China, 2008-2012.

(2) Xu, F.; Yi, B.; Zhuang, D.; Yang, M.; Yan, J.; Yan, Z., *Survey report on the construction and operation of SO_2 scrubbers at coal power plants in the 10th Five-Year Plan*; Beijing, China, 2006.

(3) EIA, *Electric Power Annual 2010-2011*; U.S. Department of Energy: 2012-2013.

(4) China Wind Energy Association, Statistics on China's Wind Turbine Installation. **2006-2012**.

(5) Li, J.; Cai, F.; Tang, W.; Xie, H.; Gao, H.; Ma, L.; Chang, Y.; Dong, L., *China Wind Power Outlook 2011*. China Environmental Science Press: Beijing, China, 2011.

(6) McElroy, M. B.; Lu, X.; Nielsen, C. P.; Wang, Y. X., Potential for Wind-Generated Electricity in China. *Science* **2009,** *325* (5946), 1378-1380.

(7) Xu, Y., Improvements in the operation of SO_2 scrubbers in China's coal power plants. *Environmental Science & Technology* **2011,** *45* (2), 380–385.

(8) EIA, *Electric Generator Report data (Form EIA-860)*; U.S. Department of Energy: 2007-2011.

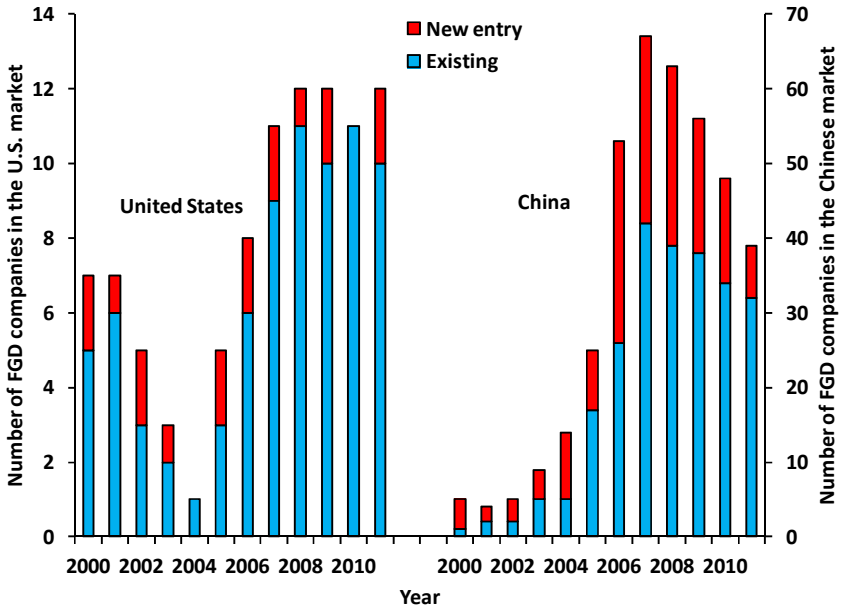

Figure S1. Companies in the Chinese and U.S. markets installing 100-MW-scale or greater SO_2 scrubbers *(1, 8)* ("Existing": companies have been in the market in the past. "New entry": companies entering the market for the first time. The U.S. numbers use the left axis and the Chinese numbers use the right axis.)

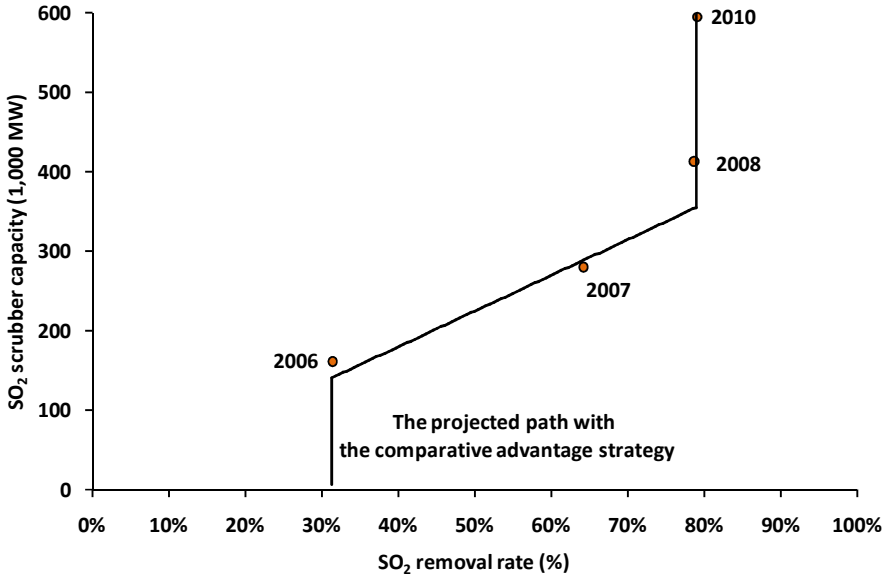

Figure S2. Model projection of the SO_2 mitigation path in China's coal-fired power plants with the comparative advantage strategy (the dots refer to actual data)

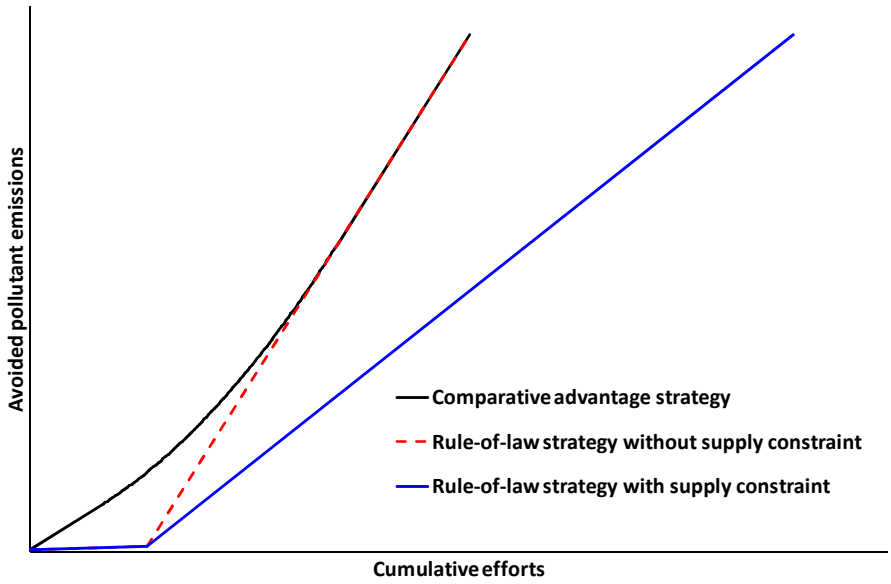

Figure S3. Illustration of model results comparing the comparative advantage strategy and the rule-of-law strategy