Environmental Regulation and SO_2 Emission: Evidence from the SO_2 Scrubber Subsidy in China [1]

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Very Preliminary

Abstract

This paper attempts to evaluate the effect of the SO_2 scrubber subsidy on pollution emission by exploiting a natural experiment in China's environmental policies in 2004. Using a city level panel dataset from 2001 to 2010, we find that the SO_2 scrubber subsidy stimulates the installation and operation of sulfur dioxide scrubbers in power plants and significantly reduces SO_2 emission. This finding is robust to a set of alternative specifications, and we rule out several alternative interpretations. We also show that the effect of the policy is particularly pronounced for cities with a higher geographical concentration of power plants and a higher share of state ownership in the power plants in the region. Our empirical results highlight the importance of incentive compatibility in making environmental regulation work.

Keywords: Sulfur Dioxide Emission; Subsidy, Environmental Protection, China

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1. Introduction

China has become the largest contributor of SO_2 emission in the world. It emitted 21.176 million tons of SO_2 in 2012, which accounted for over 30 percent of the global SO_2 emissions while its contribution to the global GDP was about 12 percent in that year. In contrast, the United States created 22 percent of global GDP with a 9 percent share of SO_2 emission. The deteriorating air quality in China caused serious economic and social consequences, such as high incidence of chronic respiratory disease, reduction in life expectancy, and loss of human capital.

The Chinese government has started to combat SO_2 emission since early 1990s, but its main approach was to rely on administrative command and control. Due to its high implementation costs, this regulatory approach turned to be ineffective. In 2004, the Chinese government introduced the SO_2 scrubber subsidy for coal-fired power plants. According to this policy, newly-established plants which deploy the SO_2 scrubber are eligible for a price subsidy of 1.5 cents RMB per kilowatt-hour. The subsidy plan was extended to cover all power plants, both new and existing, in 2007. In contrast with the early command-and-control approach, the SO_2 scrubber subsidy creates an incentive for power plants to install and operate the SO_2 scrubber voluntarily in order to get the subsidy payment. To what extent this subsidy policy will impact SO_2 emissions of power plants remains an empirical question.

Using a city level panel dataset from 2001 to 2010, this paper attempts to evaluate the effect of the SO2 scrubber subsidy on pollution emission. We find that the SO2 scrubber subsidy stimulates the installation and operation of sulfur dioxide scrubbers in power plants and significantly reduces SO2 emission. Our estimates show that a city with one more power plant in 2000 will exhibit an increase of 0.787 percentage points in desulfurization ratio after the policy was in place in 2004. This finding is robust to a set of alternative specifications, and we rule out several alternative interpretations. We also show that the effect of the policy is larger for cities with a higher geographical concentration of power plants and a higher share of state ownership in power plants.

Our empirical results highlight the importance of incentive compatibility in making environmental regulation work. The SO_2 scrubber subsidies belong to a broader category of market-based environmental policy instruments which rely on market signals to encourage behaviors in pollution control.[2] A conventional approach is so-called “command-and-control” regulations which set uniform standards for all firms and allow little flexibility in achieving regulatory goals. One type of the conventional approach is restrictions on entry of pollution-intensive firms or limitations on car use. Several studies examine the effect of driving restrictions on pollution in developing countries (Carrillo et al., 2013; Lucas, 2008; Viard and Fu, 2014). Davis (2008) finds out that the driving restriction in Mexico city led people to buy more cars to circumvent the restrictions, causing more pollution. Viard and Fu (2014) identify a positive effect in China’s context. Another type of command-and-control regulations is to shut down or re-allocate polluting firms, which is quite popular in China. Chen et al. (2013) show a significant yet temporary effect on improving air quality in Beijing 2008 Olympic Game when Beijing shut down certain polluting firms and reallocated some others outside Beijing. These studies indicate that the command-and-control approach could be very costly and its impact on pollution control is hard to sustain.

There is a growing literature examining the effect of market-based instruments on achieving regulatory goals (Barter, 2005; Greenstone and Gallagher, 2008; Perason and Smith, 1998; Schennach, 2000). However, very few studies touch upon the effect of market-based instruments in China where the command-and-control has been a dominant approach to dealing with environmental issues. This paper attempts to fill up

[2] See Stavins (2003) for an extensive literature review on market-based instruments in environmental regulation.

the void in the literature.

The rest of the paper is arranged in the following. Section 2 presents the institutional background on China's power industry and the enactment of the SO_2 scrubber subsidies in 2004. Section3 describes the data and shows the summary statistics. Section 4 specifies the baseline econometric specification and reports the baseline regressions results. Several robustness checks are done in section 5. Section 6 looks into the evidence on the heterogeneous treatment effects of the subsidy policy. Section 7 concludes.

2. Institutional Background

In China, coal accounts for two thirds of the primary energy consumption and is the major source of SO_2 emission. Nearly half of SO_2 emissions come from the power-generating industry. According to China's official data, China installed SO_2 scrubbers in 422,000-megawatt (MV) coal fired plants, and the share of the cola-fired power capacity with SO_2 scrubbers increased from 10% to 71% during 2006 and 2009.[3]

The Chinese government has started to combat SO_2emission since early 1990s, but the main approach in 1990s and early 2000 was to rely on administrative command and control. As early as 1992, the Chinese government asked the coal power plants to take efforts to desulfurize, but installing desulfurization equipment was too costly for the power plants to comply with this directive. In 1998 the State Council issued a regulatory policy of setting up two areas controlling acid rains and SO_2 respectively. According to this policy, an area of 1090 thousand kilometers surrounding cities are specified to limit the deployment of high sulfur coal, prohibit establishment of new coal fired power plants, and regulate over-quota pollution emissions. As China entered an

[3] For the details, see Annual Statistical Report on the Environment in China, Ministry of Environmental Protection, Beijing, China, 2010, and Annual Report of National Power Generation, China Electricity Council, Beijing, China, 2006-2010.

era of high-growth since 2000, this two-area control policy turned to be ineffective. The SO_2 emissions over the country increased over 5 percent from 2000 to 2005 while the original goal was to reduce the size of SO_2 emissions during the same period. The coal power plants have to pay fines for their noncompliance, but the SO_2 effluent discharge fee was too low to deter offenders. For a long time the fee was $0.029/kg in most provinces, and it increased to $0.092/kg in 2005, which was still too low compared with the much higher operation and maintenance costs (Xu, 2011).

Against the backdrop that the command-and-control approach failed to motivate a voluntary compliance of coal power plants with the state's regulation, the Chinese government introduced the SO_2 scrubber subsidy for coal-fired power plants in 2004. According to this policy, new coal power plants which deploy SO_2 scrubbers are eligible for receiving a price premium of 0.0015 RMB per kilowatt-hour or $2.2 per megawatt hour. The price premium for SO_2 scrubbers was extended to cover all power plants, both new and retrofitted ones, in June 2006. The price premium itself was not strong enough to invite voluntary compliance of coal power plants. The price premium plus the effluent discharge fee were only a little higher than the operation and maintenance costs of installing SO_2 scrubbers (Xu, 2011). Realizing this, the Chinese government evoked a harsh penalty measure accompanied with the price premium plan. A coal power plant was required to fulfill a 100 percent of desulfurization, otherwise it would face penalties, depending on the situations, if being caught. If the operation rate of SO_2 scrubbers is above 90 percent, it needs to return the price premium for electricity when SO_2 scrubbers are not in operation. If the operation rate is between 80 and 90 percent, the price premium for electricity in case of nonoperation will be returned and the penalty of $2.05/MWh will be imposed. And if the operation rate is below 80 percent, the penalty will be increased to $11.0/MWh besides the return of the price premium for the electricity without SO_2 scrubber operation. For state-owned power plants, their managers are subject to additional punishment for cheating and noncompliance: they may be removed from their posts if the nonoperation of SO_2 scrubbers is being caught. In order to ensure the data accuracy for SO_2 scrubber deployment, the government requested every coal power plant to establish online connection with provincial continuous emission monitoring systems (CEMSs). In contrast with the early command-and-control approach, the SO_2 scrubber subsidy creates an incentive for power plants to install and operate the SO_2 scrubber voluntarily in order to get the subsidy payment. Up to the end of 2012, China installed and operated SO_2 scrubbers in 710,000 MW coal power plants and the operation rate of SO_2 scrubbers increased from less than 60 percent to over 95 percent in 2012.

3. Data and Descriptive Statistics

We collect the data on city-level SO_2 emissions from China Environment Yearbook which annually releases SO_2 emissions for 113 prefectural cities in China. These 113 cities are the most important contributors of pollution emissions in China, and regularly and closely monitored by the Ministry of Environmental Protection. The yearbook contains information on city-level SO_2 emissions (i.e., the SO_2 content directly emitted without any treatment), the amount of desulfurization, the capacity of the desulfurization equipment measured by the maximum of desulfurization at the given time, and the operation and maintenance costs of SO_2 scrubbers. We will use these pieces of information to construct the dependent variables for our empirical analysis.

The other important source of data comes from China Annual Survey on Industrial Firms above the Scale including all state-owned enterprises and the above-the-scale,[4] non-state enterprises in the industrial sector. Based on the firm-level information on the coal-fired power plants, we calculate the number and value-added of coal fired power plants at the city-level as two alternative measures for the intensity of coal power plants

[4] The cut-off scale is 500 million RMB annual sales.

in cities. In the similar way, we also calculate the intensity of the city-level hydro-power plants and steel plants. In our subsequent robustness analysis, we will use these plants as control groups since their production has nothing to do with SO_2 emissions but may be affected by other regulatory changes in environmental protection.

We match SO_2 emission data with the intensity of coal-fired power plants at the city level and end up with 1089 complete observations. For the purpose of our analysis, we focus on the time frame from 2001 to 2010. Table 1 presents summary statistics for the key variables used in our analysis.

We divide the whole sample into treatment and control groups based on whether the city had any coal power plants in 2000. If it did have, it belongs to the treatment group and otherwise it belongs to the control group. The reason why we choose the year 2000 as a cut-off is simply because the distribution and output of coal power plants was predetermined when the SO_2 scrubber subsidy was introduced in 2004.[5] Using the predetermined intensity of coal power plants helps lessen the concerns over the endogenous response of coal power plants in establishing new plants or increasing production to the policy change.

The validity of DID estimation requires that the treatment and control groups have a parallel trend in outcome variables before the treatment. Since we do not have a clear cut between treatment and control groups, We define the cities with a number of power plants in the 75th percentile of the whole sample in 2000 as treatment group and the cities with a number of power plants in the 25th percentile as control group.

Figure 1 plots the time trend of the rate of desulfurization for the treatment and control groups. The rate of desulfurization is defined as the amount of desulfurization

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[5] We also try other cut-off years such as 2001, 2002, and 2003, and the basic results remain similar. We will present the results on the contemporaneous intensity of coal power plants in section 5.

divided by the sum of SO_2 emissions and desulfurization. Figure 1 clearly shows such a parallel trend in desulfurization rates between these two groups of cities in 2001-2003 before the subsidy for SO_2 scrubbers was introduced. Since 2004, a sharp divergence has appeared between these two groups and cities in the treatment group have experienced a significant and increased improvement in reducing SO_2 emissions compared to those in the control group.

Although it only presents preliminary evidence for the positive effect of the subsidy for the SO_2 emission reduction, Figure 1 offers a good test of the validity for our DID identification strategy which requires the control group to serve as a good counterfactual for the treatment group.

4. Empirical Analysis of the Effect of the Subsidy for SO_2 Scrubbers

In this section, we examine the effects of the subsidy for SO_2 scrubbers on desulfurization, SO_2 emissions, and the incentives for coal power plants to operate SO_2 scrubbers. We will estimate the following model with OLS:

$$y_{it} = \alpha + \beta Density\_2000_i * After2003 + X_{it}\gamma + \delta_i + u_t + \varepsilon_{it} \qquad (1)$$

where y_{it} denotes the rate of desulfurization in city i at year t which equals the size of desulfurization divided by SO_2 emissions in the city. $Density\_2000_i$ denotes the density of power plants in city i in 2000. We choose two proxies for this density variable: one is the number of coal power plants in the city, and the other is the sales of the electricity generated by all power plants in the city. After2003 is a dummy variable indicating whether the year t is after 2003. The coefficient β on the interaction term between $Density\_2000_i$ and After2003 is supposed to capture the causal effect of the subsidy for SO_2 scrubbers on the behavior of power plants in reducing SO_2 emissions. This specification is a typical difference-in-differences design. A vector of controls for the characteristics of cities which may affect the performance in SO_2 emissions are denoted by X_{it}, such as per capita GDP, and the share of the manufacturing industry in the city

GDP. The city and year dummies are also controlled in the regressions. To deal with the heterogeneity of observations across cities, we use robust standard errors.

Table 3 report OLS regression results using the specification of equation (1). We look at three outcome variables: ratio of desulfurization, amount of desulfurization (log) and SO_2 emissions (log). We report two sets of results based on two density measures: the number of power plants and production of power plants. If we use the number of power plants as the density measure, we find that a higher density in 2000 is significantly associated with a higher ratio of desulfurization after the subsidy for SO_2 scrubbers was implemented in 2004. More specifically, a city with one more power plant in 2000 will exhibit an increase of 0.787 percentage points in desulfurization ratio after 2003. In all three model specifications, the treatment effect is positive and significant at the 1 percent level.

When we use production of power plants in 2000 as the density measure, the results look very similar. The estimates for β are all positive and their magnitudes are fairly close to those using the first measure, with 1 percent or 5 percent level of significance. Overall we find significant effects of the city-level density of power plants in 2000 on the behavior of power plants in desulfurization rates after 2003. We interpret these significant effects as strong evidence for the effectiveness of the subsidies for SO_2 scrubbers.

We have already shown a parallel trend between the treatment and control groups before the policy was enacted. We can also test this parallel trend in a more formal way: we keep observations from 2001 to 2003, assume that there were a treatment in 2002, and re-estimate equation (1). In this case, the variable "After2003" is replaced by the one "After2001". If the control group provides a good counterfactual benchmark for the treatment group, the estimated coefficient β should be statistically insignificant. Table 3 reports results for such a placebo test. We find that neither of the estimated coefficients on the interaction term is significant regardless of which density measures to choose. This test further confirms the comparability between treatment and control groups before the treatment.

As mentioned in the previous section, the SO_2 scrubber subsidies were targeted at those newly established power plants when they were enacted in 2004 and then expanded to all existing power plants in 2007. The gradual expansion of the SO_2 scrubber subsidies provides us an opportunity to identify the differential effects of the subsidy policy over time. Table 4 reports the results for the differential effects over time. The only difference between Table 3 and Table 4 is that in the latter case the density measure of power plants is interacted with each possible year dummy. Three key findings emerge from Table 4. First, with a complete set of controls, there is no significant treatment effect in years of 2002 and 2003 (the year 2001 is the base year for comparison) when the subsides for SO_2 scrubbers were not in place, which confirms the parallel trend between treatment and control groups in the pre-treatment period in Figure 1. The parallel pattern is robust to different sets of controls and two density measures. Second, Columns (3) and (6) indicate that the positive effects of the subsidy policy on SO_2 reduction have showed up since 2004, and gradually turned larger over time, and peaked in 2007. This empirical finding is highly consistent with the timing and expected effects of the SO_2 scrubber subsidies taking effect in 2004 for newly established power plants and then becoming applicable for all existing power plants in 2007. Third, the positive effects of subsidies stopped increasing over time after 2007, as one might expect, but declined instead. If using the number of power plants as the density measure, we can find that the estimated coefficients on the interaction terms are still economically and statistically significant after 2007, and decrease over time. But if using the production of power plants as the density measure, the post-2007 coefficients on the interaction terms are no longer significant. These results suggest that subsides for SO_2 scrubbers exhibited decreasing returns in terms of incentivizing the efforts in reducing SO_2 emissions.

Although Tables 3-5 present strong evidence indicative of the effect of the SO_2 scrubber subsidies on the reductions in SO_2 emissions, these effects are only the reduced-form ones in nature. So far it remains unclear how these subsidies exerted impact on the efforts of power plants in installing and operating equipment for desulfurization. If we believe that the subsides do have produced significant and positive effects, they should have similar effects on the installation and operation of desulfurization equipment.

Fortunately we have information on the city-level desulfurization capacity and operating costs. Desulfurization capacity is defined as the maximum weight of desulfurization per hour, which measures the level of the capital stock accumulated through installing desulfurization equipment in the past. Operating costs are the firms' expenditures on operating desulfurization facilities. Even if desulfurization facilities are successfully installed, the operating costs would be zero if firms do not operate them. So these two variables, desulfurization capacity and operating costs, offer us the ideal proxies for the incentives and efforts of the firms to reduce SO_2 emissions. To some extent, operating costs serve as a better measure of the incentives to reduce SO_2 emissions than desulfurization capacity since firms may install desulfurization facilities in order to meet the regulatory requirements from the government but do not put them in operation.

Table 5 report the regression results on the effect of the SO_2 scrubber subsidies on the city-level aggregate desulfurization capacity and operating costs.[6] The dependent variables are the logarithm of desulfurization capacity and operating costs respectively. We again use the number of power plants and production of power plants as two

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[6] There are missing values on desulfurization capacity and operating costs for some cities.

alternative density measures. The specification is same as equation (1). When we use the first density measure, Columns (1) and (2) show that the effect of the subsidies on the installation of desulfurization capacity is very insignificant, but their effect on operation costs are highly significant both statistically and economically. For cities with one more power plant in 2000, the implementation of the SO_2 scrubber subsidies since 2004 leads to an approximately 2.9 percent increase in operating costs.

The insignificant effect on facility installation is not surprising. It is possible that many power plants installed desulfurization facilities even before the implementation of the subsidies for SO_2 scrubbers as a response to the government regulation, but these facilities were mostly idle when the incentives were absent. When the subsidies were introduced, those power plants had incentives to utilize the existing capacity for desulfurization to be eligible for subsidies. This is why we do not see any significant increase in capacity but significant increases in operating costs.

Using the production of power plants as the density measure offers a somewhat different picture. The results in columns (3) and (4) show positive and significant effects of subsidies on both capacity and operating costs. And these effects are economically large: a city with an additional billion Yuan of sales in 2000 will increase equipment installation and operating costs by 7.3 percent and 6.4 percent after the implementation of the subsidies.

The results reported in Table 5 are important in that they present consistent evidence on the mechanisms by which the subsidies influence the incentives and behavior of power plants in decreasing pollution emission, and hence help increase our confidence on the casual effect of the subsidies identified in Table 2. They suggest that the SO_2 scrubber subsidies provide the polluting power plants positive incentives to install and operate desulfurization facilities and reduce SO_2 emissions. While different density measures employed in Table 5 do not produce the consistent results on the effect on capacity building, we argue that even the insignificant effects on capacity installation are not necessarily against our argument and thus justifiable. More importantly, for the reasons described above, we should put more weight on the significant results on operating costs which are highly consistent between two density measures.

5. Robustness Checks

In this section, we will do several robustness checks to further establish the causal relationship between the SO_2 scrubber subsidies and reductions in SO_2 emissions.

5.1 The Impacts of Other Contemporary Environmental Policies

In the eleventh five-year plan (2005-2010), the Chinese central government made an unprecedented commitment to reduce energy consumption of GDP by 20 percent and SO_2 emissions by 10 percent. To ensure that these ambitious goals be achieved, the Chinese government has issued a set of environmental policies since 2004, such as stricter standards on pollution emissions, enhanced monitoring on critical polluting sources, increasing fees levied on pollution, and downsizing and even shutting down pollution-intensive plants. The SO_2 scrubber subsidies we focus on in this paper are only among these joint efforts to reduce pollution emissions and save energy utilization. The implementation of so many environmental policies together with SO_2 scrubber subsidies raises concerns about the confounding influences of these contemporary polices on identifying the causal linkage between SO_2 scrubber subsidies and SO_2 emissions.

In order to isolate the impact of SO_2 scrubber subsidies on SO_2 emissions from the impacts of other environmental policies, we include the intensities of steel production and hydro-electricity generation in the regressions. The inclusion of steel production intensity is helpful here because the steel industry has been a big consumer of coal as well as a large contributor of pollution in China and various environmental policies enacted since 2004 should more or less affect the polluting behavior of steel plants. Furthermore, unlike the cola-fired power industry, the steel price is not subject to government control and fully determined by the market, so the steel industry does not enjoy policy benefits granted by the SO_2 scrubber subsidies. The hydro-electricity industry does not emit SO_2 and is not eligible for the SO_2 scrubber subsidies, but controlling the effects of hydro-electricity generation on SO_2 emissions helps us capture the confounding influences created by the power industry specific factors, such as fluctuations in market demand for electricity which affects SO_2 emissions.

Table 6 reports the results with inclusion of densities of steel plants and hydro-electricity generating plants interacted with the dummy "After2003". The estimated coefficient on the treatment effect is positive and significant in all three specifications. But for the interaction terms for steel plants and hydro-electricity plants, their coefficients are insignificant when a full set of controls are included. This result lends further support for our maintained hypothesis on the effect of the SO_2 scrubber subsidies.

5.2 Newly Built and Existing Power Plants

The SO_2 scrubber subsidies were targeted at those newly established power plants when they were enacted in 2004 and then expanded to all existing power plants in 2007. This policy design implies that if the SO_2 scrubber subsidies do have an effect on SO_2 emissions, we would expect that an increase in the number of new power plants since 2004 would have positive and significant effect, and for the number of existing power plants, the policy effect should be larger in the period 2007-2010 than in the period 2004-2006.

In order to avoid the endogeneity of new power plants in response to the subsidy policy, we use the average increase of power plants in each city during 2001-2003 to proxy for the increase of new power plants in that city since 2004, which is denoted as

"New" in Table 7. We additionally create two time dummies, "Year04-06" which denotes the indicator for years of 2004, 2005 and 2006, and "Year07-10" which is defined in a similar way.

Table 7 shows that the new power plants established since 2004 contributed most to reductions in SO_2 emissions. For the existing power plants which are proxied by the number of power plants in 2000, the policy effect is larger for the time period 2007-2010 than the period 2004-2006, which is consistent with the changes in subsidy policies. All these results are robust to the inclusion of additional controls in the regressions.

5.3 The Policy Impacts on Smoke and Dust Emissions

The power plants emit not just sulfur dioxide, but also other pollutants, such as smoke and dust. Many environmental policies tend to be effective in reducing emission of various pollutants. For instance, the Chinese government encouraged power plants to employ clean energy, which will reduce emissions in smoke, dust as well as sulfur dioxide. The shutdown of high-polluting plants due to the stricter environmental regulation has the similar effects in reducing emissions in multiple pollutants.

The unique feature of the SO_2 scrubbers is to reduce SO_2 emissions only and has little effect on smoke and dust emissions if the structure of the energy use is fixed. This fact motivates us to look into the effect of SO_2 scrubber subsidies on smoke and dust emissions. If the significant effects we observed from Table 2 are really driven by the subsidy policy, we would not see a similar effect on smoke and dust emissions. We repeat the regressions in Table 2 but replace the dependent variable to be smoke and dust removal rates respectively. The results are reported in Table 8. We find that the treatment effect on smoke removal rate is significantly negative, regardless of model specifications, but the effect on dust removal rate in negligible in both magnitude and statistical significance. In other words, the SO_2 scrubber subsidies enacted since 2004 made smoke emissions even go up significantly, but had no impacts on dust emissions. A potential interpretation about the negative effect of the subsidy policy on smoke emissions is that power plants may be induced by the subsidy police to use low-sulfur coal which leads to more smoke emission.

5.4 Other Robustness Checks

In previous analyses, we use the density of power plants in 2000 to avoid the endogenous reaction of power plants to the subsidy policy. As a robustness check, we employ contemporaneous density of power plants in each city to interact with the "After2003" dummy. Regression results, which are reported in Table 9, show a positive and significant effect on reducing SO_2 emissions.

Table 10 reports the results using the amount of desulfurization and SO_2 emissions as dependent variables. It is clear that a higher density of power plants in 2000 is associated with larger amount of desulfurization and less SO_2 emission after the subsidy policy was in place. This result is similar regardless of which density measure to be used.

6. The Heterogeneous Effects of the SO_2 Scrubber Subsidy

In this section, we will examine the heterogeneous impacts of the subsidy policy on SO_2 emissions. We consider the heterogeneity of the treatment effect in two dimensions: industrial concentration and ownership structure.

The industrial concentration affects the impact of the subsidy policy on polluting behavior because the regulatory costs typically increase with the number of regulated power plants in a city. We speculate that if power plants are more concentrated in a city, the impact of the subsidy policy will be greater. In order to examine the validity of this hypothesis, we introduce a triple interaction term between the intensity of power plants in 2000, the after-2004 dummy, and the concentration of power plants in the city which varies over time. The concentration of power plants is measured by the market share of the top three power plants in the city. Table 9 reports the regression results. Different model specifications yield a similar and robust result: a higher degree of concentration of power plants leads to a larger effect on reducing SO_2 emissions.

The state ownership may affect the incentives of power plants in response to the subsidy policies in two ways. On the one hand, compared with private firms, state-owned enterprises (SOEs) face additional punishment if they fail to comply with the regulatory polices: the managers may be removed from their executive positions due to their incompliance (Xu, 2011). The potential political consequences of incompliance should make the SOEs more responsive to the environmental regulation than private firms. On the other hand, SOEs care less about profits than non-SOEs due to the soft-budget constraints of the SOEs, which implies that all else being equal, SOEs will be less responsive to economic incentives offered by the subsidy policy than non-SOEs. So the net effect of firm ownership on the impact of the subsidy policy is ambiguous, and awaits an empirical analysis.

Table 12 looks at how state ownership affects the policy impact on reducing SO_2 emissions. We first calculate the share of state-owned power plants in a city, and then interact this share with the treatment dummy (i.e. the interaction term between the intensity of power plants in 2000 and the after-2004 dummy). The regression results show that when we have a complete control of covariates and city and year fixed effects, the triple interaction term has a positive and significant coefficient. This means that a higher share of SOEs leads to a larger impact of the SO_2 scrubber subsidy on constraining polluting behaviors. This also implies that the political incentives of SOE managers may dominate the negative effect of the soft-budget constraint in response to the subsidy policy.

7. Concluding Remarks

China's long-term economic growth has been challenged by the deteriorating environments. The extremely high dependence of the Chinese economy on coal burning caused SO_2 emissions to be the most serious source of pollution. The Chinese government has taken numerous actions to reduce SO_2 emissions, but for a long time the dominant approach has been the so-called command-and-control regulation. Since 2004, China has introduced the SO_2 scrubber subsidies to encourage power plants to make desulfurization efforts, which provides a unique opportunity to evaluate the effects of the market-based instrument in China's context.

Using a city level panel dataset from 2001 to 2010, we find that the SO2 scrubber subsidy stimulates the installation and operation of sulfur dioxide scrubbers in power plants and significantly reduces SO2 emission. This finding is robust to a set of alternative specifications, and we rule out several alternative interpretations. We also show that the effect of the policy is particularly pronounced for cities with a higher geographical concentration of power plants and a higher share of the state ownership in the power plants in the region. Our empirical results, which highlight the importance of incentive compatibility in making environmental regulation work, have important policy implications for rethinking China's environmental regulation.

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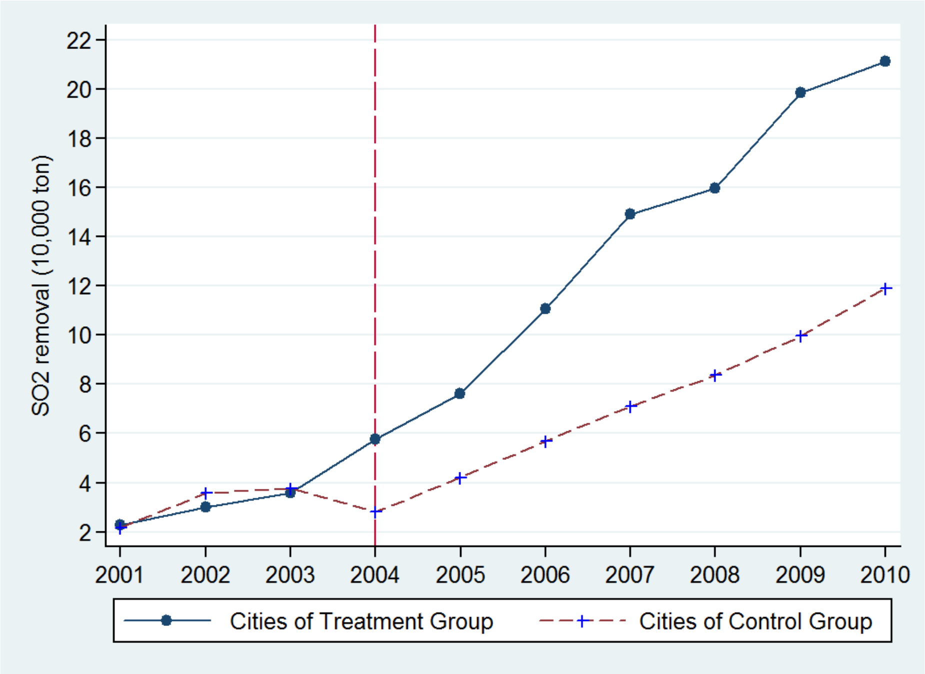

Figure 1 Desulfurization Rates over Time between Treatment and Control Groups

Table 1 Summary Statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
SO2 emission (ton)	1089	90824.10	77111.05	103.00	711537
SO2 removal (ton)	1089	76716.14	129913.75	0.00	1.27e+06
SO2 removal ratio (%)	1089	32.61	22.43	0.00	93.75
GDP (billion Yuan)	1089	145.28	180.19	3.71	1716.6
Industrial share of GDP	1089	0.45	0.12	0.06	0.95
GDP per capita (Yuan)	1089	26339.26	18824.46	3520.00	121387
Number of power plants	1089	5.61	4.88	0.00	27
Production of power plants (billion Yuan)	1089	1.48	1.55	0.00	8.68

Table 2 The Effects of Sulfur Dioxide Subsidy on Desulfurization

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent Variable: SO_2 removal rate					
Measure of density	Number of power plants			Production of power plants		
Density*After2003	0.987***	0.985***	0.787***	0.744**	0.733**	0.756***
	(0.178)	(0.148)	(0.153)	(0.318)	(0.287)	(0.273)
City FE	Y	Y	Y	Y	Y	Y
Year FE		Y	Y		Y	Y
Control Variables			Y			Y
Obs.	1089	1089	1089	1089	1089	1089
R-squared	0.566	0.744	0.750	0.558	0.737	0.743

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Table 3 The Placebo Test for the Subsample from 2001 to 2003

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent Variable: SO_2 removal rate					
Measure of density	Number of power plants			Production of power plants		
Density*After2001	0.172	0.173	0.068	0.234	0.234	0.116
	(0.177)	(0.174)	(0.169)	(0.293)	(0.287)	(0.242)
City FE	Y	Y	Y	Y	Y	Y
Year FE		Y	Y		Y	Y
Control Variables			Y			Y
Obs.	322	322	322	322	322	322
R-squared	0.900	0.906	0.908	0.900	0.906	0.908

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Table 4 The Effects of Sulfur Dioxide Subsidy over Time

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent Variable: SO_2 removal rate					
Density Measures	Number of power plants			Production of power plants		
Density*2002	0.390*	0.107	0.079	0.245*	-0.046	-0.047
	(0.227)	(0.319)	(0.319)	(0.126)	(0.592)	(0.561)
Density*2003	0.395*	0.250	0.272	0.230*	0.323	0.333
	(0.215)	(0.302)	(0.302)	(0.118)	(0.558)	(0.530)
Density*2004	0.707***	0.818***	0.787***	0.281**	0.402	0.424
	(0.217)	(0.298)	(0.300)	(0.117)	(0.536)	(0.506)
Density*2005	1.043***	0.888***	0.799***	0.511***	0.519	0.566
	(0.212)	(0.281)	(0.287)	(0.120)	(0.515)	(0.495)
Density*2006	1.812***	1.324***	1.211***	0.958***	1.095*	1.155*
	(0.203)	(0.284)	(0.291)	(0.120)	(0.622)	(0.604)
Density*2007	2.567***	1.410***	1.231***	1.485***	1.329*	1.371**
	(0.209)	(0.315)	(0.321)	(0.125)	(0.680)	(0.668)
Density*2008	3.025***	1.067***	0.784**	1.866***	0.451	0.466
	(0.235)	(0.308)	(0.318)	(0.128)	(0.698)	(0.673)
Density*2009	3.644***	1.174***	0.824**	2.307***	0.894	0.900
	(0.250)	(0.351)	(0.366)	(0.133)	(0.748)	(0.701)
Density*2010	4.044***	1.051***	0.605*	2.641***	1.093	1.089
	(0.305)	(0.334)	(0.343)	(0.134)	(0.767)	(0.733)
City FE	Y	Y	Y	Y	Y	Y
Year FE		Y	Y		Y	Y
Control Variables			Y			Y
Obs.	1089	1089	1089	1089	1089	1089
R-squared	0.651	0.745	0.751	0.728	0.738	0.745

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Table 5 The Mechanisms of Sulfur Dioxide Subsidy's Effect on Desulfurization

	(1)	(2)	(3)	(4)
Dependent Variable	Ln(capacity)	Ln(cost)	Ln(capacity)	Ln(cost)
Measure of density	Number of power plants		Production of power plants	
Density*After2003	-0.009	0.029***	0.073**	0.064***
	(0.018)	(0.008)	(0.032)	(0.022)
Year FE	Y	Y	Y	Y
City FE	Y	Y	Y	Y
Control Variables	Y	Y	Y	Y
Obs.	1068	1086	1068	1086
R-squared	0.845	0.760	0.845	0.759

Note: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Robust standard errors in parentheses.

Table 6 Compared with Iron & Steel and Hydro Power Industry

	(1)	(2)	(3)
	Dependent Variable: SO_2 removal rate		
Density*After2003	0.905***	0.905***	0.734***
	(0.188)	(0.154)	(0.159)
Steel_den*After2003	0.048	0.048*	0.035
	(0.035)	(0.024)	(0.024)
Hydro_den*After2003	0.036	0.051	0.084
	(0.161)	(0.127)	(0.129)
City FE	Y	Y	Y
Year FE		Y	Y
Control Variables			Y
Obs.	1089	1089	1089
R-squared	0.566	0.744	0.750

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Table 7 Newly-Built vs. Existing Power Plants

	(1)	(2)	(3)
	Dependent Variable: SO_2 removal rate		
New*After2003	17.091***	17.073***	17.075***
	(5.395)	(5.343)	(5.269)
Density*Year04-06	0.764***	0.768***	0.694***
	(0.174)	(0.160)	(0.157)
Density*Year07-10	0.934***	0.932***	0.714***
	(0.179)	(0.170)	(0.173)
City FE	Y	Y	Y
Year FE		Y	Y
Control Variables			Y
Obs.	1089	1089	1089
R-squared	0.566	0.744	0.750

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Table 8 Smoke and Dust as Alternative Dependent Variables

	(1)	(2)	(3)
A	Dependent Variable: Smoke removal rate		
Density*After2003	-0.215***	-0.216***	-0.159**
	(0.062)	(0.062)	(0.064)
Obs.	1084	1084	1084
R-squared	0.688	0.715	0.718
B	Dependent Variable: Dust removal rate		
Density*After2003	-0.000	-0.000	0.002
	(0.001)	(0.001)	(0.001)
Obs.	1076	1076	1076
R-squared	0.589	0.612	0.618
City FE	Y	Y	Y
Year FE		Y	Y
Control Variables			Y

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Table 9 Dynamic Number of Power Plant as the Density Measure

	(1)	(2)	(3)
	Dependent Variable: SO_2 removal rate		
Density*After2003	1.170***	1.144***	0.979***
	(0.166)	(0.136)	(0.143)
City FE	Y	Y	Y
Year FE		Y	Y
Control Variables			Y
Obs.	980	980	980
R square	0.616	0.747	0.749

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Table 10 Desulfurization and SO2 Emission as the Dependent Variables

	(1)	(2)	(3)	(4)
Dependent Variable	Ln(SO2 removal)	Ln(SO2 emission)	Ln(SO2 removal)	Ln(SO2 emission)
Measure of density	Number of power plants		Production of power plants	
Density*After2003	0.037***	-0.008**	0.037*	-0.012*
	(0.010)	(0.003)	(0.022)	(0.007)
Year FE	Y	Y	Y	Y
City FE	Y	Y	Y	Y
Control Variables	Y	Y	Y	Y
Obs.	1089	1089	1089	1089
R-squared	0.835	0.938	0.834	0.938

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Table 11 Heterogeneous Effects: Industrial Structure

	(1)	(2)	(3)
	Dependent Variable:SO_2 removal rate		
Density*After2003*Concentration	2.417***	2.513***	2.360***
	(0.898)	(0.808)	(0.790)
Density*After2003	-0.681	-0.601	-0.651
	(0.570)	(0.526)	(0.501)
Density*Concentration	-5.053***	-2.980***	-3.010***
	(0.994)	(0.875)	(0.853)
After*Concentration	-5.620	-5.013	0.938
	(4.338)	(4.121)	(4.348)
Density	0.906	0.498	0.694
	(0.679)	(0.611)	(0.576)
Concentration	6.811	5.239	2.976
	(5.176)	(4.816)	(4.828)
City FE	Y	Y	Y
Year FE		Y	Y
Control Variables			Y
Obs.	980	980	980
R-squared	0.622	0.747	0.752

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Table 12 Heterogeneous Effects: Ownership Structure

	(1)	(2)	(3)
	Dependent Variable: SO_2 removal rate		
Density*After2003*SOE	0.502	1.763**	1.709*
	(1.010)	(0.878)	(0.877)
Density*After2003	0.677***	0.578**	0.460**
	(0.243)	(0.225)	(0.221)
Density*SOE	-2.993***	-2.172***	-1.969**
	(0.895)	(0.800)	(0.803)
After2003*SOE	-18.270***	-11.185**	-10.314**
	(5.318)	(4.824)	(4.875)
Density	-1.507***	-0.819***	-0.721**
	(0.314)	(0.301)	(0.294)
SOE	11.460***	11.232***	9.884**
	(4.429)	(4.075)	(4.164)
City FE	Y	Y	Y
Year FE		Y	Y
Control Variables			Y
Obs.	980	980	980
R-squared	0.638	0.747	0.750

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.