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Controlling SO_2 emissions in China: A panel data analysis of the 11th Five-Year Plan

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Abstract

We investigate the impact of policy measures to reduce SO_2 emissions during 11th Five-Year Plan of China (2006–2010). By using a provincial-level panel data set, we find that installation of the flue-gas desulfurization equipment and closure of small coal-fired power plants contributed to a statistically significant reduction in SO_2 emissions. While estimation results suggest that these two policy measures played an important role in reducing SO_2 emissions in China during this period, the size of the estimated coefficients shows that the effects might have been weaker than those predicted by ex-ante cost-benefit analysis.

Keywords: SO_2; Air pollution; Panel data; China; 11th Five-Year Plan.

JEL Classification Numbers: L94, P28, Q53, Q56.

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1 Introduction

More than 20 million tons of SO_2 were emitted in China in 2011, three times higher than that in the United States in the same year (National Bureau of Statistics of China, 2012).[1] SO_2 is a major source of atmospheric haze and acid deposition, and it has been linked to a number of adverse effects on the human respiratory system (Nielsen and Ho, 2007; World Bank., 1997; Venners et al., 2003). World Bank (2007) estimates that the cost of air pollution in China was 157.3 billion RMB in 2003, or 1.16% of GDP[2]. The largest contributor of SO_2 emissions in China is coal-fired power generation. Chinese thermal power sector discharges 40% of total SO_2 while supplying more than 80% of electricity (Department of Energy Statistics, National Bureau of Statistics of China, 2012). Among the electricity produced by thermal power plant, 87% is produced by coal.

One challenge for the Chinese government over the past 30 years has been to reduce SO_2 discharges. A limit on total national emissions of SO_2 was first introduced in the 9th Five-Year Plan (1996–2000) (JES 2007). The emissions target in 2000 of 27.1 million tons was easily achieved, with total SO_2 emissions accounting for 22 million tons. In the following 10th Five-Years Plan, the total emissions control target was set as a 10% reduction from 2000 emission levels by 2005. However, actual emissions in 2005 increased by 27.8% from that in 2000 against a backdrop of rapid economic growth with the average GDP growth rate of 9.5%. Following this experience, the 11th Five-Year Plan (2006–2010) implemented more ambitious policies to reduce SO_2 emissions. Total SO_2 emissions as well as industrial SO_2 emissions began to decrease in 2006 (Figure 1). Between 2006 and 2010, total SO_2 emissions declined by more than 14%, despite the economy growing annually by more than 10% on average. Hence, in terms of total SO_2 emissions, the official statistics suggests that China has passed the turning point of the environmental Kuznets curve (Grossman and Krueger, 1995).

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[1] According to OECD (2015), there were 5.85 million tons of sulfur oxides emissions in the United States in 2011.

[2] As of January 2003, 1 US dollar was 8.28 RMB.

[Figure 1]

Several studies have investigated air pollution in China during the 11th Five-Year Plan period. JES (2007) provides a cost-benefit analysis of China's energy saving and SO_2 control policies during this period, concluding that the abatement of SO_2 emissions of the 11th Five-Year Plan will lead to significant improvements in air quality in Chinese cities. The estimation results show that the benefit-cost ratio is more than 5 to 1. Indeed, quantifiable benefits reach 4.7 billion US dollars compared with costs of only 950 million US dollars. Cao et al. (2009) extend JES (2007) by using a CGE model of the Chinese economy. Their simulation results show that the overall impacts of the 11th Five-Year Plan's SO_2 reduction policies is a 0.48% increase in GDP in 2010 above the baseline. They find that the productivity improvement generated by the closure of small-unit coal-fired power plants offsets the decline in GDP resulting from the installation of the flue-gas desulfurization (FGD) equipment. While these studies suggest that these regulations might have been effective for reducing SO_2 emissions in China, no study has thus far conducted a thorough ex-post evaluation of the policy measures taken during this period.[3]

Based on the foregoing, this study examines how policy measures might have played a role in reducing SO_2 emissions in Chinese provinces between 2006 and 2010. We focus on the policies promulgated in National Acid Rain and SO_2 Pollution Control in 11th Five-Year Plan and discuss how they contributed to control emissions from coal-fired power plants in each province. Special attention is paid to the effect of two policies: the installation of FGD equipment and closure of small coal-fired power plants. We also control for the impact of other policies introduced before the period (e.g., pollution levy and Two Control Zones (TCZ) policy), regional variation in sulfur content in the coal used in coal-fired power plants, and improvement in energy efficiency for the power generation sector that has occurred during the period. In addition, we examine the effect of economic development on the effectiveness

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[3] The 2008 Olympic Games in Beijing might have been a driving force behind the strict regulation introduced in the 11th Five-Year Plan. Chen et al. (2013) evaluate the impact of policy measures on improving air quality to prepare for the Olympic Games.

of the installation of FGD equipment, by using a panel threshold model.

The contribution of this study can be summarized as follows. Firstly, we investigate the impact of SO_2 control policies on the coal-fired power sector in China's 11th Five-Year Plan. Although several studies have evaluated the pollution control in the same period (JES, 2007; Cao et al., 2009), econometric analyses are scarce. Since the SO_2 emissions started to decrease during this period, empirical analysis of the role of policy instruments has significant implications for understanding the mechanism behind the turning point of the environmental Kuznets curve. Secondly, we empirically examine the extent to which a technological intervention for pollution control is effective. Since our dataset on the installation of control equipment contains information of the reduction capacity, we can examine whether the installation of FGD equipment successfully led to actual reductions. Thirdly, we investigate the role of policies for small-scale power plants. The government issued requirements to close small, inefficient electric power generating units and replace them with larger, more efficient plants. This policy improves energy efficiency as well as reduces SO_2 emissions, and thus might be effective as an efficient command-and-control policy instrument. Fourthly, we show that the level of economic development might influence the effectiveness of pollution control technology. Our results suggest that as the Chinese economy develops, more stringent monitoring and enforcement activity can be expected.

The remainder of the paper structured as follows. In Section 2, we explain the Chinese policy for controlling SO_2 during the 11th Five-Year Plan period. Section 3 introduces the empirical model and data. The empirical results are presented in Section 4. Section 5 employs a threshold model and investigates possible structural breaks in terms of the installation of FGD equipment. Section 6 concludes.

2 Chinese policies for controlling SO_2 emissions

As mentioned in the Introduction, China's 11th Five-Year Plan included two major policies to control SO_2 emissions: the installation of FGD equipment and closure of small power plants. In 2007, the National Acid Rain and SO_2 Pollution Control program was issued (SEPA and NDRC, 2007; Cao et al., 2009). The plan specified emissions targets for 2010 for each province that ranged from a reduction of 25.9% from the 2005 level for Shanghai to simply maintaining the 2005 levels in Hainan and other provinces. It also included schedules for installing 167 GW of new FGD equipment at coal-fired power plants and listed 679 small power plants targeted for closure in order to remove more than 50 GW of electricity generation capacity.

According to JES (2007), the expected net reduction in SO_2 emissions was 5.4 million tons from the installation of FGD equipment and 2.1 million tons from the closure policy. The annualized benefits were estimated to be 35.4 billion RMB. The annualized cost estimate for the FGD equipment was 7.15 billion RMB and that of the closure policy was assumed to be zero. Since these small power plants are inefficient and highly pollution-intensive, the effectiveness of closure policy is expected to be high.

Many power plants installed FGD equipment during this period (Schreifels et al., 2012). The percentage of coal-fired power plants that had FGD rose from 14% in 2005 to 86% by the end of 2010. However, the operation and performance of FGD equipment was insufficient. Field inspections in early 2007 by the State Environmental Protection Agency (SEPA), which was replaced by the Ministry of Environmental Protection in 2008, revealed that less than 40% of the installed FGD equipment was running continuously and reliably (Xu, 2009). High operation costs might have been the main reason for this inactiveness.

Despite these limitations, SO_2 emissions in 2010 declined by 14% from 2005 levels, exceeding the reduction target of 10%. Schreifels et al. (2012) point out that several factors contributed to this reversal from the environmental policies in the 10th and 11th Five-Year Plans. Firstly, the reduction target was taken more seriously in the political process. The goal of a 10% reduction was included in the Outline of the National 11th Five-Year Plan on Economic and Social Development issued by the the National People's Congress, whereas the previous goal was only listed in the National 10th Five-Year Plan for Environmental Protection issued by SEPA. Secondly, the attainment of these environmental goals was linked to the performance evaluation of local leaders.[4] Indeed, the energy conservation target (energy consumption per unit of GDP) accounted for 40 points out of the 100 points available. Thirdly, the monitoring and enforcement of environmental policy was strengthened. In 2006, SEPA established six regional supervision centers to supervise local governments and environmental protection bureaus in order to prevent inadequate activities (Moore, 2011). It also established two new departments to oversee the implementation and enforcement of SO_2 emission targets.

Economic incentives were also strengthened. The pollution levy for SO_2 rose from 0.42 RMB/kg in 2004 to 1.26 RMB/kg in 2007 (OECD, 2007; JES, 2007). Further, the green pricing program for electricity from FGD-equipped power plants was revised to focus on FGD operation and performance. Since 2003, the Chinese government has applied an electricity price premium for the electricity sector to encourage coal-fired power plant to install the FGD equipment. In 2007, it even started to provide an incentive of 15 RMB/kWh for power plants operating FGD equipment for 90% or more of total electricity generated, a penalty of 15 RMB/kWh for plants operating FGDs between 80% and 90% of total generation, and a penalty of 75 RMB/kWh for plants operating FGDs less than 80% of the time (Cao et al., 2009).

Another important measure for controlling SO_2 emissions in China is the TCZ policy implemented in 1998. The objective of this policy is to reduce SO_2 emissions in cities and areas with particularly high air pollution. Cities exceeding specific standards were designated as either acid rain or SO_2 pollution control zones, based on their records in past years. The

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[4] Zheng et al. (2014) investigates how proxies for greenness is included in promotion evaluation. Their results suggest that facility expenditure variable is highly significant while air quality measures is less significant. It supports the claim that the promotion criteria emphasize input-based performance rather than output such as level of air quality.

area covers 175 cities across 27 provinces in China, and it accounted for around 60% of SO_2 emissions in 1995 (Hao et al., 2001). The three main policy measures embodied in the TCZ policy were closing the biggest polluters, reducing the sulfur-content of coal, and burning cleaner coal-burning. While SO_2 emissions in the power sector increased by 1.5 times from 2000 to 2005 (Zhao et al, 2008), Hering and Poncet (2014) find that the TCZ policy might have been effective for reducing SO_2 emissions. Other studies have also pointed out the effectiveness of the measures in the TCZ policy (He et al., 2002; Xu et al., 2004).

3 Empirical strategy and data

3.1 Empirical model

In this study, SO_2 emissions are regressed on two policies examined herein as well as on other variables as follows:

$$Emission_{it} = \alpha + \beta Policies_{it} + \gamma X_{it} + \zeta_i + \delta_t + \epsilon_{it}, \tag{1}$$

where ζ_i and δ_t are the province-specific effects and year-specific effects, respectively.

$Emission_{it}$ is total SO_2 emissions in province i in year t. In some of the estimation models, we use SO_2 emissions from the process of fuel burning in the industrial sector in province i in year t as an explained variable ($EmissionInd_{it}$).

$Policies_{it}$ summarizes the installation of FGD equipment (FGD_{it}) and closure of small coal-fired power plants ($Closure_{it}$). FGD_{it} is the cumulative amount of planned reduction in SO_2 emissions owing to the installation of FGD equipment in province i in year t. SEPA planned to install FGD equipment that can reduce 4.4 million tons of SO_2 in 31 provinces from 2006 to 2010. $Closure_{it}$ represents the closure of small coal-fired power plants to reduce SO_2 emissions in province i, measured in terms of electricity generation capacity. Small plants have low fuel efficiency, and it is economically unreasonable to install expensive equipment in them. Indeed, units smaller than 300 MW consume 25% of total coal fuel in the electricity sector, but emit 54% of total SO_2 emissions (Chen et al., 2014). Since we cannot identify when each plant actually closed during the period, we assume that all closures occurred in 2006, the starting year of the policy. This means that $Closure_{it}$ takes the same value in all periods after 2006.

X_{it} summarizes the control variables of five factors: pollution levy, fuel efficiency, gross regional product (GRP) per capita, sulfur content in coal, and TCZ policy. The pollution levy was among the earliest policy instruments adopted to address SO_2 emissions from industrial sources. We assume that the total pollution levy paid to the government in a province in the prior year ($Levy_{i,t-1}$) influences SO_2 emissions. Fuel efficiency ($Efficiency_{it}$) is also related to SO_2 emissions. When old and small plants close, average fuel efficiency improves, thereby reducing SO_2 emissions as long as total production remains the same. Therefore, we can expect a negative relation between fuel efficiency and SO_2 emissions. We calculate $Efficiency_{it}$, fuel efficiency in province i in year t, by dividing total electricity production by total coal consumption in each province. GRP per capita (GRP_{it}) represents the level of economic development in each province. We assume that developed regions have higher SO_2 emissions than others. $Content_i$ represents the percentage of average sulfur content in coal in province i, which is used in coal-fired power plants. SO_2 emissions are strongly related to the quality of coal used in each province. Coal with a high sulfur content is widely used in provinces in the southeast of China, whereas that with relatively lower sulfur content is used in northeast China. The weighted average of sulfur content in all provinces is about 1.10% (Fridley et al., 2013). World Bank (2003) estimates that low-sulfur coal increases firms' total operating costs, as it is 40–50% more expensive than high-sulfur coal. To control for the effect of the TCZ policy on SO_2 emissions, we add a dummy variable TCZ_i into our models. TCZ_i takes a value of 1 when the province has a city that is under the TCZ policy and 0 otherwise.

3.2 Data

Table 1 presents the descriptive statistics. We collect data for 31 provinces from 2004 to 2010. Our data set includes annual province-level information from 2004 to 2010 collected from the China Energy Statistical Yearbook (CESY), China Environment Yearbook (CEY), China Energy Databook (CED), China Statistical Yearbook on the Environment (CSYE), China Statistical Yearbook (CSY), and National Acid Rain and SO_2 Pollution Control in the 11th Five-Year Plan (Department of Energy Statistics, National Bureau of Statistics of China, 2004–2010; Editorial Committee of China Environment Yearbook, 2004–2010; Fridley et al., 2013; National Bureau of Statistics and Ministry of Environmental Protection, 2004–2010; National Bureau of Statistics of China, 2004–2010; SEPA and NDRC, 2007).

This study uses total SO_2 emissions and SO_2 emissions from the process of fuel burning in the industrial sectors in each province from CEY. According to CESY, coal accounted for over 80% of the primary energy supply in China in 2010 (Department of Energy Statistics, National Bureau of Statistics of China, 2011). The planned reduction through the installation of FGD equipment and capacity reduction through the closure policy in each provinces are taken from SEPA and NDRC (2007). Data for the pollution levy in each province are taken from CEY for the corresponding year. In all major sources, the pollution levy of SO_2 emissions increased from 0.42 RMB/kg in 2004 to 1.26 RMB/kg in 2007 (OECD, 2007; JES, 2007). GRP per capita is taken from CSY. The generating capacity of thermal plants and coal consumption of coal-fired power plant in each province are derived from CESY. Owing to data availability, we use the generating capacity of all thermal power plants instead of that of coal-fired power plants. In 2012, approximately 66% of installed capacity for power generation was at coal-fired power plants (Zhang, 2014). The sulfur content level of coal is measured at the regional level: North, Northeast, East, South Central, Southwest, and Northwest. We calculate the market share of coal that has a sulfur content lower than 3% in each region (Fridley et al., 2013). Finally, we take the TCZ policy from Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution.

[Table 1]

4 Empirical results

Firstly, we estimate a linear fixed effects model, assuming the province effects v_i are unobserved. Table 2 presents the estimation results for the fixed effects models.[5] The sulfur content and TCZ variables are not included in these models because these are time-invariant and thus they were removed from the time-demeaned equation. The results suggest that the cumulative installation of FGD equipment and closure of small power plants are negatively related to total emissions and industrial emissions at a statistically significant level.

[Table 2]

The coefficient of fuel efficiency is negative and statistically significant at 10% in the model in column (3). Since higher fuel efficiency means lower SO_2 emissions per energy production, this is theoretically reasonable. In the estimation models for industrial sector emissions, the coefficient of the pollution levy is negative but not statistically significant.

Since $Content_i$ and TCZ_i are time-invariant, they can not be included in the fixed effects model. Therefore, to estimate the impact of these variables, we use a hybrid method instead (Mundlak, 1978), namely the correlated random effects model. Let be $\zeta_i = \phi + \eta \overline{Policies}_i + \xi_i$. We present the estimation model in question as follows:

$$Emission_{it} = \alpha + \beta Policies_{it} + \gamma X_i + \phi + \eta \overline{Policies}_i + \xi_i + \delta_t + \epsilon_{it}, \tag{2}$$

By averaging across t, we obtain a cross-sectional equation:

$$\overline{Emission}_i = (\alpha + \phi) + \beta \overline{Policies}_i + \gamma X_i + \eta \overline{Policies}_i + \xi_i + \delta_t + \bar{\epsilon}_i, \tag{3}$$

By subtracting (4) from (3), we have:

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[5] The Hausman test rejected the use of the random effects model.

$$\begin{aligned} Emission_{it} - \overline{Emission}_i =& \beta(Policies_{it} - \overline{Policies}_i) + (\epsilon_{it} - \bar{\epsilon}_i) \\ \Rightarrow \ddot{Emission}_{it} =& \beta \ddot{Policies}_{it} + \ddot{\epsilon}_{it} \end{aligned} \tag{4}$$

By summation, we obtain:

$$\begin{aligned} \overline{Emission}_i + \ddot{Emission}_{it} =& (\alpha + \phi) + \beta \ddot{Policies}_{it} + \beta \overline{Policies}_i \\ & + \gamma X_i + \eta \overline{Policies}_i + \xi_i + \delta_t + \bar{\epsilon}_i + \ddot{\epsilon}_{it} \end{aligned} \tag{5}$$

Finally, we obtain the following expression:

$$Emission_{it} = (\alpha + \phi) + \beta \ddot{Policies}_{it} + (\beta + \eta)\overline{Policies}_i + \gamma X_i + \xi_i + \delta_t + \epsilon_{it} \tag{6}$$

If $\beta + \eta = \beta$, it is a random effects model. If $\beta + \eta \neq \beta$, it is a fixed effects model.

[Table 3]

The estimation result with the hybrid model are presented in Table 3. With regard to the coefficient of FGD_{it} and $Closure_{it}$, we obtain a similar result to that in fixed effects model, that is they are negatively correlated with SO_2 emissions in a statistically significant way in most models.

The coefficient of $Content_i$ is not statistically significant, perhaps because coal-fired power plants do not use local coal. In China, coal production is concentrated in several provinces (Shanxi, Shaanxi, Inner Mongolia and Henan produced 62.1% of coal in 2012). Moreover, imported coal has increasingly been used for thermal power plants in recent years. Indeed, the use of imported coal increased 10-fold from 9.82 million tons in 2008 to 101 million tons in 2012 (Wang and Ducruet, 2014).

Total and industrial SO_2 emissions are higher in the TCZ, although in a statistically insignificant manner in every model. Here, new coal-fired power plants have typically been constructed outside the TCZ in recent years. Further, regional structure of Chinese SO_2

emissions might be gradually changing, since SO_2 controls have been expanded to the national level (SEPA and NDRC, 2007).

The results of our model thus suggest that the policy to install FGD equipment helped reduce total and industrial SO_2 emissions from 2006 to 2010. The estimated coefficient can be interpreted as that a $10,000$-ton increase in the control capacity of FGD equipment is associated with a 5,700−6,600-ton reductions in SO_2 discharge. The actual reduction might have been smaller than the installed capacity because some installed FGD equipment was not properly operated. According to Xu (2009), less than 40% of the available capacity for the reduction of SO_2 in coal-fired power plants was utilized in 2007. Our estimation results therefore suggest that the utilization of installed FGD equipment might have been better than that reported.

Our results also suggest that the closure of small coal-fired power plants might have helped reduce SO_2. The size of the estimated coefficient can be interpreted as that the closure of coal-fired power plants with a capacity of 10 MW can reduce roughly 130 tons of total SO_2 emissions, or 150 tons of SO_2 emissions from the industrial sector. From this result, we can expect that the closure of 50 GW small coal-fired power plants can reduce 0.6 million tons of SO_2. This is considerably smaller than the assumption of JES (2007) that the closure of 50 GW small coal-fired power plants can reduce 2.1 million tons of SO_2. When smaller power plants are closed, they are typically replaced with larger and more efficient power generation units.[6] Hence, the emissions from these new units with larger capacity might offset some of the reductions of the closure policy.

5 Panel threshold estimators

This section extends the analysis presented in the previous section by considering a factor that might influence the effectiveness of the installation of FGD equipment. Several scholars

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[6] According to Li (2011), the guideline issued by the government in 2007 required that the capacity of new coal-fired power units should be larger than 300MW and that in major grids should be larger than 600 MW.

have pointed out that the the large difference in economic development among Chinese regions should be considered when analyzing environmental policy in China. For example, Song et al. (2013) use data envelopment analysis and find that environmental efficiency is higher in affluent regions and lower in poor regions. Xu and Lin (2016) also find that energy efficiency improvement has greater potential to mitigate $PM_{2.5}$ emissions in the central and western regions than those in the eastern region because of the lower technology levels.

Therefore, we investigate if the performance of pollution abatement technology depends on the level of economic development. Specifically, we use GRP to measure of economic development and ensure that the effectiveness of the installation of FGD equipment is significantly different between provinces above and below a certain GRP threshold. Our hypothesis is that the coefficient of FGD indicates the utilization of installed capacity, which decreases because of insufficient monitoring and enforcement by the regulator. Further, when there is a large disparity in enforcement activity between a rich province and a poor province, the coefficient of FGD might be higher in the former province than in the latter.

To find the threshold between SO_2 emissions and the installed ability of FGD equipment in coal-fired power sector, we use a non-dynamic panels with individual-specific fixed effects (Hansen, 1999). This technique has been used to analyze the relationship between pollution and income (Aslanidis and Xepapadeas, 2006), the relationship between energy consumption and economic growth (Huang et al., 2008), and the impact of exports on energy intensity (Zheng et al., 2011). We treat FGD_{it} as the regime-dependent variable and GRP_{it} as the threshold variable:

$$\begin{aligned} Emission_{it} = &\alpha + \beta_1 FGD_{it} I(\theta_1 \leq GRP_{it} < \theta_2) \\ &+ \beta_2 FGD_{it} I(GRP_{it} \geq \theta_2) + \gamma X_{it} + \zeta_i + \delta_t + \epsilon_{it}, \end{aligned} \tag{7}$$

In this model, β_1 captures the effectiveness of FGD for provinces below the threshold and β_2 captures that for provinces above the thresholds. We expect that β_2 is lower than

β_1, since a higher level of economic development would lead to the better enforcement of environmental regulations. Figure 2 shows the scatter plot between GRP_{it} and FGD_{it}. In our estimation, data for Beijing, Tianjin, Shanghai and Guizhou are excluded as outliers.

[Figure 2]

The estimation results are presented in Table 4. The coefficients of $FGD_{it}(\theta_1 \leq GRP_{it} < \theta_2)$ and $FGD_{it}(GRP_{it} \geq \theta_2)$ are statistically significant in all models.[7] In columns (1) and (3), we find that the threshold estimator is 23.34. The result means that the effectiveness of the installtion of FGD equipment differs for provinces whose per capita GRP is below or above 23,000 RMB. The estimated coefficients also suggest that a $10,000$-ton increase in FGD capacity is associated with a $6,000$-ton reduction in total SO_2 emissions when GRP per capita is less than 23,000 RMB in a province. The effectiveness of the same FGD capacity is a $9,300$-ton reduction in total SO_2 emissions when GRP per capita is more than 23,000 RMB.

In 2005, only six provinces were above the threshold value, namely Beijing, Tianjin, Shanghai, Jiangsu, Zhejang, and Guangdong (Figure 3), and there were large disparities between those provinces whose GRP was the highest and lowest. The lowest and the highest GRP per capita was about 5,000 RMB and 48,000 RMB, respectively. Indeed, because of the rapid economic development in China at that time, 12 provinces were above the threshold in 2010 and 19 were below. Further, between 2008 and 2009, average GRP per capita in China rose above the threshold. Higher GRP per capita leads to higher monitoring and enforcement, thereby increasing the effectiveness of the installation of FGD equipment.

[Figure 2]

[Table 4]

[Figure 3]

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[7] The threshold effect test shows that the threshold is not significant for the models of emissions from the industrial sector. The LR test statistics also reject the existence of two thresholds for the models of total emissions.

6 Conclusion

This study investigated the impact of policies for controlling SO_2 emissions in the 11th Five-Year Plan period, using a provincial-level panel dataset in China. First, the results of our model suggest that the policy to install FGD equipment might have reduced total and industrial SO_2 emissions from 2006 to 2010. The estimated coefficient can be interpreted as that an increase in the $10,000$-ton capacity of FGD equipment is associated with a $6,000$-ton reduction in SO_2 discharge. Second, the closure of small coal-fired power plants might have helped reduce SO_2 emissions, too. The size of the estimated coefficient suggests that the closure of coal-fired power plants with a capacity of 10 MW can reduce roughly 130 tons of total SO_2 discharge, or 150 tons of SO_2 from the industrial sector. These results suggest that the two policy measures examined herein played a significant role in reducing SO_2 emissions in China during that period, although the size of the estimated coefficients shows that the effects might have been weaker than those predicted by ex-ante cost-benefit analysis.

I addition, we used a non-dynamic panel threshold effects model and found significant differences in the effectiveness of the installation of FGD equipment between provinces above and below a GRP per capita threshold. As the Chinese economy develops, the gap between provinces will converge, leading to better monitoring and enforcement by the environmental departments in each provinces. As of 2010, FGD equipment has already been installed in 86% of coal-fired power plants in China. The next Five-Year Plan, should aim to emphasize controlling pollution by monitoring and enforcing the use and operation of this installed equipment.

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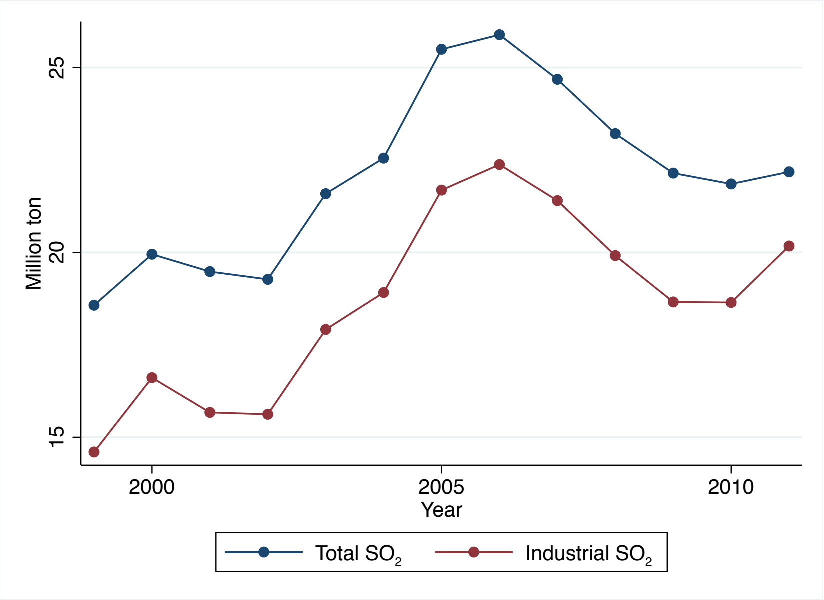

Figure 1: Trend of SO_2 emissions in China (millions of tons)

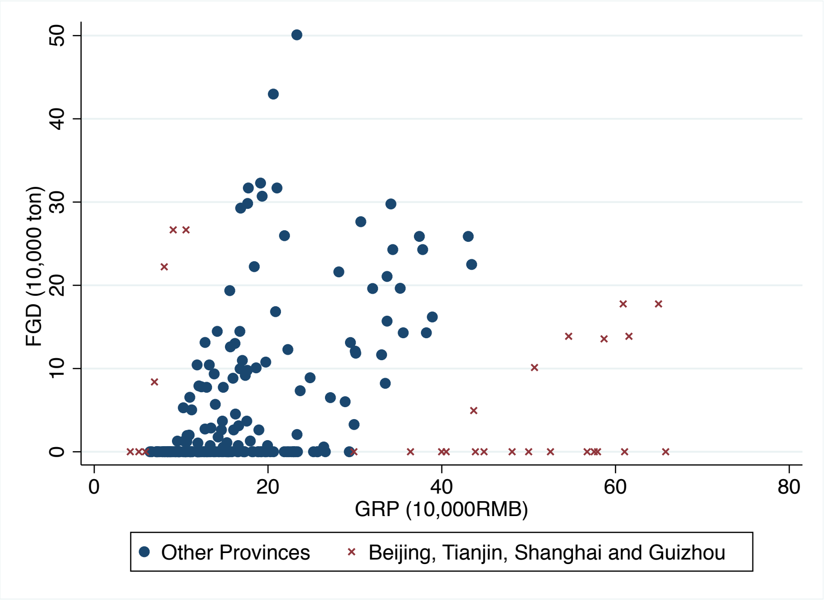

Figure 2: GRP and FGD capacity

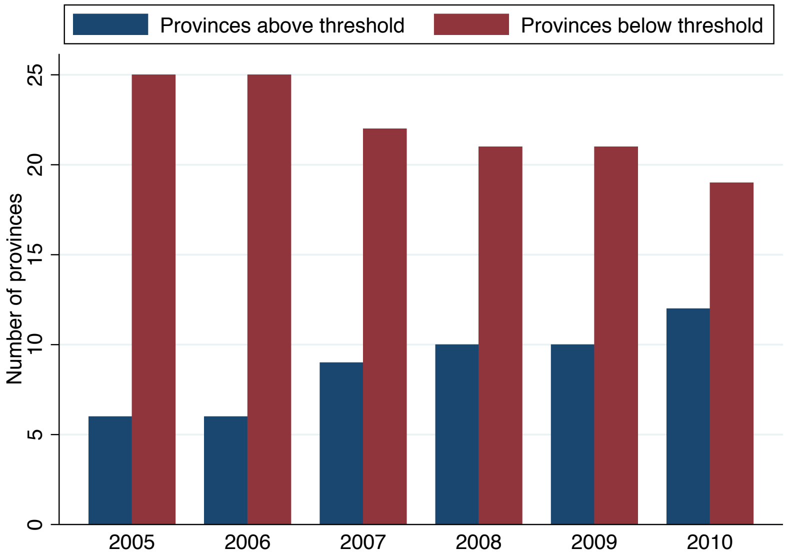

Figure 3: Number of provinces below and above the threshold value

Table 1: Descriptive statistics

Variable	Unit	N	Mean	SD	Min	Max
$Emission_{it}$	10,000 t	217	75.78	46.88	0.10	200.3
$EmissionInd_{it}$	10,000 t	217	58.13	36.53	0.041	156.6
FGD_{it}	10,000 t	217	5.670	9.370	0.000	50.09
$Closure_{it}$	10 MW	217	118.4	162.4	0.000	899.9
$Levy_{i,t-1}$	10 million RMB	186	42.73	39.80	0.374	252.9
$Efficiency_{it}$	%	217	0.200	0.040	0.070	0.380
GRP_{it}	1,000 RMB	217	20.04	13.18	4.150	65.78
$Content_{i}$	%	217	0.850	0.150	0.520	0.940
TCZ_{i}	Dummy	217	0.450	0.500	0.000	1.000

Note: Levy and per capita GRP are adjusted to 2004 value by using the CPI.

Table 2: Estimation results: Fixed effects model

	(1)	(2)	(3)	(4)
Dependent variable	$Emission_{it}$	$EmissionInd_{it}$	$Emission_{it}$	$EmissionInd_{it}$
FGD_{it}	-0.674***	-0.567***	-0.663***	-0.578***
	(0.092)	(0.104)	(0.093)	(0.108)
$Closure_{it}$	-0.013**	-0.015***	-0.012**	-0.014***
	(0.006)	(0.004)	(0.005)	(0.004)
$Levy_{i,t-1}$			-0.010	0.016
			(0.029)	(0.028)
$Efficiency_{it}$			-15.11*	9.954
			(7.965)	(8.999)
GRP_{it}			-0.116	-0.123
			(0.259)	(0.264)
$Constant$	84.97***	65.11***	91.66***	66.97***
	(0.684)	(1.073)	(6.762)	(7.761)
N	180	180	180	180
R^2_w	0.840	0.641	0.844	0.644

Note: $***$, $**$, and $*$ denote statistical significance at the 1%, 5%, and 10% levels, respectively. All models include the year dummy variables from 2005 to 2010. Standard errors are clustered by province and written in parentheses.

Table 3: Estimation results: Hybrid model

	(1)	(2)	(3)	(4)
Dependent variable	$Emission_{it}$	$EmissionInd_{it}$	$Emission_{it}$	$EmissionInd_{it}$
$dFGD_{it}$	-0.674***	-0.566***	-0.662***	-0.575***
	(0.093)	(0.104)	(0.095)	(0.111)
$dClosure_{it}$	-0.013**	-0.015***	-0.012**	-0.014***
	(0.006)	(0.004)	(0.005)	(0.004)
$dLevy_{i,t-1}$			-0.011	0.014
			(0.029)	(0.028)
$dEfficiency_{it}$			-14.98*	10.11
			(8.132)	(9.174)
$dGRP_{it}$			-0.117	-0.130
			(0.265)	(0.272)
$mFGD_{it}$	4.197***	2.680***	2.630***	1.604**
	(0.766)	(0.617)	(0.703)	(0.630)
$mClosure_{it}$	0.0596	0.0743**	0.0667**	0.073**
	(0.043)	(0.033)	(0.029)	(0.036)
$mLevy_{i,t-1}$			0.432**	0.298
			(0.206)	(0.199)
$mEfficiency_{it}$			-296.0	-62.54
			(182.0)	(211.3)
$mGRP_{it}$			-0.288	-0.481
			(0.369)	(0.447)
$Content_i$			-46.46	-5.297
			(35.28)	(27.25)
TCZ_i			6.354	5.034
			(9.550)	(7.505)
$Constant$	0	0	131.9***	50.63
	(.)	(.)	(33.56)	(36.21)
N	180	180	180	180
R^2_w	0.840	0.641	0.844	0.644

Note: All variables starting with a small d indicate the deviations from the mean value and all variables starting with a small m indicate the average among periods. $***$, $**$, and $*$ denote statistical significance at the 1%, 5%, and 10% levels, respectively. All models include the year dummy variables from 2005 to 2010. Standard errors are clustered by province and written in parentheses.

Table 4: Results of the threshold effects (cleaned sample)

	(1)	(2)	(3)	(4)
Dependent variable	$Emission_{it}$	$EmissionInd_{it}$	$Emission_{it}$	$EmissionInd_{it}$
$FGD_{it}(\theta_1 \leq GRP_{it} < \theta_2)$	-0.605***	-0.486***	-0.587***	-0.484***
	(0.067)	(0.123)	(0.081)	(0.142)
$FGD_{it}(GRP_{it} \geq \theta_2)$	-0.914***	-0.783***	-0.929***	-0.862***
	(0.150)	(0.120)	(0.218)	(0.131)
$Closure_{it}$	-0.008**	-0.010**	-0.008**	-0.010**
	(0.004)	(0.004)	(0.004)	(0.004)
$Levy_{i,t-1}$			-0.014	-0.002
			(0.025)	(0.025)
$Efficiency_{it}$			-14.14*	9.945
			(7.339)	(9.888)
GRP_{it}			0.107	0.306
			(0.442)	(0.393)
$Constant$	88.95***	70.72***	89.91***	61.68***
	(1.478)	(1.706)	(9.214)	(9.451)
N	156	156	156	156
R^2_w	0.874	0.711	0.876	0.715
Threshold number	1	1	1	1
Threshold value	23.34	23.70	23.34	23.70
Threshold test	0.010	0.173	0.063	0.227

Note: $***$, $**$, and $*$ denote statistical significance at the 1%, 5%, and 10% levels, respectively. All models include the year dummy variables from 2005 to 2010. Robust standard errors are written in parentheses.