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Three Essays on Air Pollution Control Policy in China

（中国の大気汚染政策に関する三つの研究）

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Teng Ma

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Chapter 1

Introduction

China has the largest thermal power sector in the world, which consumes vast amounts of fossil fuel, and is ranked first in terms of air pollution emissions. In 2014, the discharge of SO_2, NO_x, and dust pollutants in the thermal power sector were 6.2, 7.13, and 4.27 million ton (ESY, 2014) respectively. These air pollutions may cause environmental damage and are linked to a number of adverse effects on the human respiratory system.

To control air pollution in the thermal power sector, the government issued The Environmental Protection Law of the People's Republic of China on December 26, 1989. Since then, various emission standards have been issued. Under GB13223-91, for example, the Chinese government designated a national standard for pollution emissions from this sector. A variety of other environmental policies have also been implemented to control the discharge of air pollution from this sector. For example, the Chinese Ministry of Environmental Protection announced policies to install control equipment for pollution abatement, and the National Energy Administration issued policies to improve energy efficiency and reduce energy consumption. The Chinese government strengthened its efforts to control SO_2 emissions during the 11th Five-year Plan period (2006–2010), and began serious efforts to reduce NO_x emission in the 12th Five-year Plan period (2011–2015). Due to the successful implementation of these policies, the total amount of SO_2 and NO_x emissions have been decreasing in recent years.

The thesis studies the effectiveness of policies in reducing energy consumption and emissions from the thermal power sector. Chapter 2 investigates the impact of policy measures on reducing SO_2 emissions during the period of the 11th Five-Year Plan of China (2006–2010). By using a provincial-level panel data set, this chapter finds that the 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. In addition, results of the panel threshold models show that the level of economic development in each province might influence the effectiveness of pollution control technology.

Chapter 3 investigates the choices of denitration technology in this thermal power sector. Using a multinominal logit model of the choices among 1,135 boilers in thermal power plants operating in China in 2013, the chapter analyzes how the choices were influenced by government policies, the stringency of national standards, and subsidies for using specific technology. The results are as follows. First, China's 12th Five-year Plan might make it more attractive for power plants to choose the cheapest denitration technology among the three options examined in this study. Second, technology choices differed significantly by region before the 12th Five-year Plan period. These regional differences have disappeared recently, perhaps due to the economic development across all regions of China. Third, electricity price subsidies offered to plants that use denitration equipment might affect their technology choice. These results suggest that plants might choose the cheapest technology available, in order to lower investment costs.

Chapter 4 investigates the effect of air pollution control in the thermal power sector during the 2008 Beijing Olympic Games (BOG08). By using data on pollution control equipment and energy intensity, we assess if there are significant differences in the levels of these measures related to pollution when comparing the provinces under the regional control policy for BOG08 with the other provinces. Our results indicate that energy intensity of thermal power plants improved in 2007 and 2008 in provinces designated as areas that required a coordinated air pollution control policy for the Olympic Games. On the other hand, such treatment effects during BOG08 are almost negligible for pollution control equipment.

Chapter 2

Policies for Controlling SO_2 emissions and its effects

2.1 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 20 years has been to reduce

[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.

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 began to decrease in 2006 (Figure 2.1). 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).

[Figure 2.1]

There are some ex-ante evaluation of air pollution control 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 command-and-control 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]

This chapter examines how policy measures might have played a role in reducing SO_2 emissions in Chinese provinces between 2006 and 2010. the chapter focuses 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. the chapter also controls 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, the chapter examines the effect of economic development on the effectiveness of the installation of FGD equipment, by using a panel threshold model.

The contribution of this chapter can be summarized as follows. Firstly, the chapter investigates 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, the chapter investigates the role of policies for small-scale power plants. The government issued requirements to close small, inefficient electric power generating units and

[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.

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, the chapter investigate how the level of economic development might influence the effectiveness of pollution control technology. Our results suggest that there is a threshold of GRP per capita, beyond that the effectiveness of FGD installation significantly higher. More stringent monitoring and enforcement activity might play a role behind the observation.

The remainder of the paper structured as follows. In Section 2.2, I explain the Chinese policy for controlling SO_2 during the 11th Five-Year Plan period. Section 2.3 introduces the empirical model and data. The empirical results are presented in Section 2.4. Section 2.5 employs a threshold model and investigates possible structural breaks in terms of the installation of FGD equipment. Section 2.6 concludes.

2.2 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 higher level of political agenda. 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 for the quantitative assessment. 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.

[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.

Economic incentives were also strengthened. The level of 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).

While our focus is on the above-mentioned policies implemented during the 11th five-year plan, there is an important precedent as a measure for controlling SO_2 emissions in China: that 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 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).

2.3 Empirical strategy and data

2.3.1 Empirical model

In this chapter, total SO_2 emissions at province i in year t ($Emission_{it}$) are regressed on two policies examined herein as well as on other variables as follows:

$$Emission_{it} = \alpha + \beta Policies_{it} + \gamma X_{it} + \zeta_i + \delta_t + \epsilon_{it}, \tag{2.1}$$

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

$Policies_{it}$ summarizes the installation of FGD equipment (FGD_{it}) and closure of small coal-fired power plants ($Closure_i$). 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. $Closure_i$ 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 is closed during the period, we assume that all closures occurred in 2006, the starting year of the policy. This means that $Closure_i$ 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 average fuel efficiency improves by technological advancement, it reduces SO_2 emissions as long as total production remains the same. Therefore, I can expect a negative relation between fuel efficiency and SO_2 emissions. We calculate $\mathit{Efficiency}_{it}$, 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.

2.3.2 Data

Table 2.1 presents the descriptive statistics. We use data for 31 provinces from 2005 to 2010,[5] to investigate the impact of the 11th five-year plan from 2006 to 2010. Our data set includes annual province-level information 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, 2005–2010; 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, 2005–2010; SEPA and NDRC, 2007).

This chapter uses the total SO_2 emissions from CEY. According to CESY, coal accounted

[5] For some lagged variables, we use data from 2004.

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 sourced from CESY. Due 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 information on TCZ policy from Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution.

[Table 2.1]

2.4 Empirical results

Firstly, we estimate a linear fixed effects model, assuming the province effects v_i are unobserved. Table 2.2 presents the estimation results for the fixed effects models.[6] The dependent variable is total SO_2 emissions at province i in year t ($Emission_{it}$). We include time dummy variables for models shown in column (2) and (4). The results in general suggest that the cumulative installation of FGD equipment and closure of small power plants are negatively related to total emissions at a statistically significant level. For example, it is suggested that an increase in the 10,000-ton capacity of FGD equipment leads to a reduction

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

of 6,700−7,800 ton of SO_2. Also, the closure of coal-fired power plants with a capacity of 10 MW might lead to a reduction of roughly 120 tons of total SO_2 emissions.

[Table 2.2]

The coefficient of fuel efficiency is negative and statistically significant at 10% in the model in column (4). Since higher fuel efficiency means lower SO_2 emissions per energy production, this is theoretically reasonable.

The variables $Content_i$ and TCZ_i are not included in above models because these are time-invariant. Therefore, to estimate the impact of these variables, we use a hybrid method developed by Mundlak (1978), namely the correlated random effects model. Let assume $\zeta_i = \phi + \eta\overline{Policies}_i + \xi_i$ in the equation (1) and represent the estimation model as follows:

$$Emission_{it} = \alpha + \beta Policies_{it} + \gamma X_i + \phi + \eta\overline{Policies}_i + \xi_i + \delta_t + \epsilon_{it}, \tag{2.2}$$

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

$$\overline{Emission}_i = (\alpha + \phi) + \beta\overline{Policies}_i + \gamma X_i + \eta\overline{Policies}_i + \xi_i + \delta_t + \bar{\epsilon}_i, \tag{2.3}$$

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

$$\begin{aligned} Emission_{it} - \overline{Emission}_i =& \beta(Policies_{it} - \overline{Policies}_i) + (\epsilon_{it} - \bar{\epsilon}_i) \\ \Rightarrow \ddot{Emission}_{it} =& \beta\ddot{Policies}_{it} + \ddot{\epsilon}_{it}, \end{aligned} \tag{2.4}$$

By summation, we obtain:

$$\begin{aligned} \overline{Emission}_i + \ddot{Emission}_{it} =& (\alpha + \phi) + \beta\ddot{Policies}_{it} + \beta\overline{Policies}_i \\ & + \gamma X_i + \eta\overline{Policies}_i + \xi_i + \delta_t + \bar{\epsilon}_i + \ddot{\epsilon}_{it}, \end{aligned} \tag{2.5}$$

Finally, we obtain the following expression:

$$Emission_{it} = (\alpha + \phi) + \beta \ddot{Policies}_{it} + (\beta + \eta)\overline{Policies}_i + \gamma X_i + \xi_i + \delta_t + \epsilon_{it}, \tag{2.6}$$

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

[Table 2.3]

The estimation result with the hybrid model are presented in Table 2.3. With regard to the coefficient of FGD_{it} and $Closure_i$, 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.[7] 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 SO_2 emissions are higher in the TCZ, although in a statistically insignificant manner in every model. One reason might be that 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 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 6,700−7,800 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

[7]Shanxi, Shaanxi, Inner Mongolia and Henan produced 62.1% of coal in 2012.

of SO_2 in coal-fired power plants was utilized in 2007. Our estimation results therefore suggest that FGD equipment was not properly operated although the level 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 120 tons of SO_2 emissions when we use the coefficient from the model that include year dummy variables. Based on this estimates, 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.[8] Hence, the emissions from these new units with larger capacity might offset some of the reductions of the closure policy.

2.5 Panel threshold estimators

Several scholars have pointed out that the the significant 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.

Based upon these findings, this section investigate if the performance of pollution abatement technology depends on the level of economic development in each region. Specifically, we use GRP as a measure of economic development and assume that the effectiveness of

[8] 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.

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. If 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. In fact, official statistics on environmental monitoring in China suggest that monitoring expenditures per monitoring station increases dramatically when GRP per capita in a province is above 20,000 RMB (Figure 2.2).

[Figure 2.2]

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 applied to investigate 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 $GRP_{i,t-1}$ as the threshold variable. In general, the threshold variable should be predetermined and stationary, therefore we use $GRP_{i,t-1}$ as the threshold variable:

$$\begin{aligned} Emission_{it} =& \alpha + \beta_1 FGD_{it} I(\theta_1 \leq GRP_{i,t-1} < \theta_2) \\ & + \beta_2 FGD_{it} I(GRP_{i,t-1} \geq \theta_2) + \gamma X_{it} + \zeta_i + \delta_t + \epsilon_{it}, \end{aligned} \tag{2.7}$$

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 higher than β_1, since a higher level of economic development would lead to the better enforcement of environmental regulations. Figure 2.3 shows the scatter plot between $GRP_{i,t-1}$ and FGD_{it}.

In our estimation, data for Beijing, Tianjin, Shanghai and Guizhou are excluded as outliers.

[Figure 2.3]

The estimation results are presented in Table 2.4. The coefficients of $FGD_{it}(\theta_1 \leq GRP_{i,t-1} < \theta_2)$ and $FGD_{it}(GRP_{i,t-1} \geq \theta_2)$ are statistically significant in all models.[9] In all of the columns, we find that the threshold estimator is 20.63. The result means that the effectiveness of the installtion of FGD equipment differs for provinces whose per capita GRP is below or above 20,630 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 20,630 RMB in a province. The effectiveness of the same FGD capacity is a $9,200$-ton reduction in total SO_2 emissions when GRP per capita is more than 20,630 RMB.

In 2005, only four provinces were above the threshold value and there were large disparities between those provinces whose prior year of GRP was the highest and lowest (Figure 2.4). The lowest and the highest GRP per capita was about 4,200 RMB and 43,800 RMB, respectively. Indeed, because of the rapid economic development in China at that time, 11 provinces were above the threshold in 2010 and 20 were below. Further, between 2008 and 2009, average GRP per capita in China rose above the threshold. Higher income level can lead to higher monitoring and enforcement, thereby increasing the effectiveness of the installation of FGD equipment.

[Table 2.4]

[Figure 2.4]

[9] 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.

2.6 Conclusion and policy implications

This chapter 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 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 6,700−7,800 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 120 tons of total SO_2 discharge. 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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Table 2.1: Descriptive statistics

Variable	Unit	N	Mean	SD	Min	Max
$Emission_{it}$	10,000 t	186	77.01	47.45	0.200	200.3
FGD_{it}	10,000 t	186	6.615	9.812	0.000	50.09
$Closure_{i}$	10 MW	186	138.09	167.46	0.000	899.9
$Levy_{i,t-1}$	10 million RMB	186	42.73	39.80	0.374	252.9
$Efficiency_{it}$	%	180	0.205	0.043	0.071	0.380
GRP_{it}	1,000 RMB	186	21.12	13.43	5.135	65.78
$Content_{i}$	%	186	0.846	0.146	0.515	0.940
TCZ_{i}	Dummy	186	0.452	0.499	0.000	1.000

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

Table 2.2: Estimation results: Fixed effects model

	(1)	(2)	(3)	(4)
FGD_{it}	-0.783***	-0.674***	-0.729***	-0.663***
	(0.072)	(0.092)	(0.085)	(0.093)
$Closure_i$	-0.005**	-0.012**	-0.004	-0.012**
	(0.002)	(0.006)	(0.002)	(0.005)
$Levy_{i,t-1}$			-0.002	-0.010
			(0.025)	(0.029)
$Efficiency_{it}$			-15.93*	-15.11*
			(8.435)	(7.965)
GRP_{it}			-0.131	-0.116
			(0.147)	(0.259)
$Constant$	85.67***	84.97***	91.24***	90.07***
	(0.623)	(0.684)	(2.664)	(4.083)
Year dummies	No	Yes	No	Yes
N	180	180	180	180
R^2_w	0.820	0.840	0.828	0.844

Note: $***$, $**$, and $*$ denote statistical significance at the 1%, 5%, and 10% levels, respectively. Models in columns (2) and (4) include the year dummy variables for 2006 to 2010. Standard errors are clustered by province and written in parentheses.

Table 2.3: Estimation results: Hybrid model

	(1)	(2)	(3)	(4)
$dFGD_{it}$	-0.783***	-0.674***	-0.728***	-0.662***
	(0.073)	(0.093)	(0.087)	(0.095)
$dClosure_i$	-0.005**	-0.013**	-0.004	-0.012**
	(0.002)	(0.006)	(0.003)	(0.005)
$dLevy_{i,t-1}$			-0.002	-0.011
			(0.026)	(0.030)
$dEfficiency_{it}$			-15.82*	-14.98*
			(8.608)	(8.132)
$dGRP_{it}$			-0.132	-0.117
			(0.150)	(0.265)
$mFGD_{it}$	4.176***	4.197***	2.618***	2.630***
	(0.759)	(0.766)	(0.692)	(0.703)
$mClosure_i$	0.059	0.060	0.066**	0.067**
	(0.042)	(0.043)	(0.029)	(0.029)
$mLevy_{i,t-1}$			0.432**	0.432**
			(0.203)	(0.206)
$mEfficiency_{it}$			-296.3*	-296.0
			(179.4)	(182.0)
$mGRP_{it}$			-0.288	-0.288
			(0.366)	(0.369)
$Content_i$			-46.46	-46.46
			(34.78)	(35.28)
TCZ_i			6.348	6.354
			(9.420)	(9.550)
$Constant$	34.64***	33.63***	133.7***	131.9***
	(7.760)	(8.258)	(32.67)	(33.56)
Year dummies	No	Yes	No	Yes
N	180	180	180	180
R^2_w	0.820	0.840	0.828	0.844

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. Models in columns (2) and (4) include the year dummy variables for 2006 to 2010. Standard errors are clustered by province and written in parentheses.

Table 2.4: Results of the threshold effects (cleaned sample)

	(1)	(2)	(3)	(4)
$FGD_{it}(\theta_1 \leq GRP_{it} < \theta_2)$	-0.686***	-0.609***	-0.654***	-0.593***
	(0.053)	(0.068)	(0.082)	(0.081)
$FGD_{it}(GRP_{it} \geq \theta_2)$	-1.020***	-0.907***	-0.970***	-0.921***
	(0.123)	(0.151)	(0.181)	(0.219)
$Closure_i$	-0.003*	-0.008**	-0.002	-0.008*
	(0.001)	(0.004)	(0.002)	(0.004)
$Levy_{i,t-1}$			-0.004	-0.011
			(0.021)	(0.024)
$Efficiency_{it}$			-15.67	-14.49*
			(9.267)	(7.644)
GRP_{it}			-0.077	0.093
			(0.185)	(0.439)
$Constant$	89.51***	89.10***	93.85***	91.04***
	(0.500)	(0.700)	(2.954)	(5.278)
Year dummies	No	Yes	No	Yes
N	156	156	156	156
R^2_w	0.860	0.872	0.863	0.875
Threshold number	1	1	1	1
Threshold value	20.63	20.63	20.63	20.63
Threshold effect test	0.010	0.007	0.027	0.083

Note: $***$, $**$, and $*$ denote statistical significance at the 1%, 5%, and 10% levels, respectively. Models in columns (2) and (4) include the year dummy variables for 2006 to 2010. Robust standard errors are written in parentheses. The threshold effect test is displayed by a F statistic. We used 156 samples, because the samples of Beijing, Tianjin, Shanghai, Chongqing was removed as outliers. Double threshold models were not statistically significant.

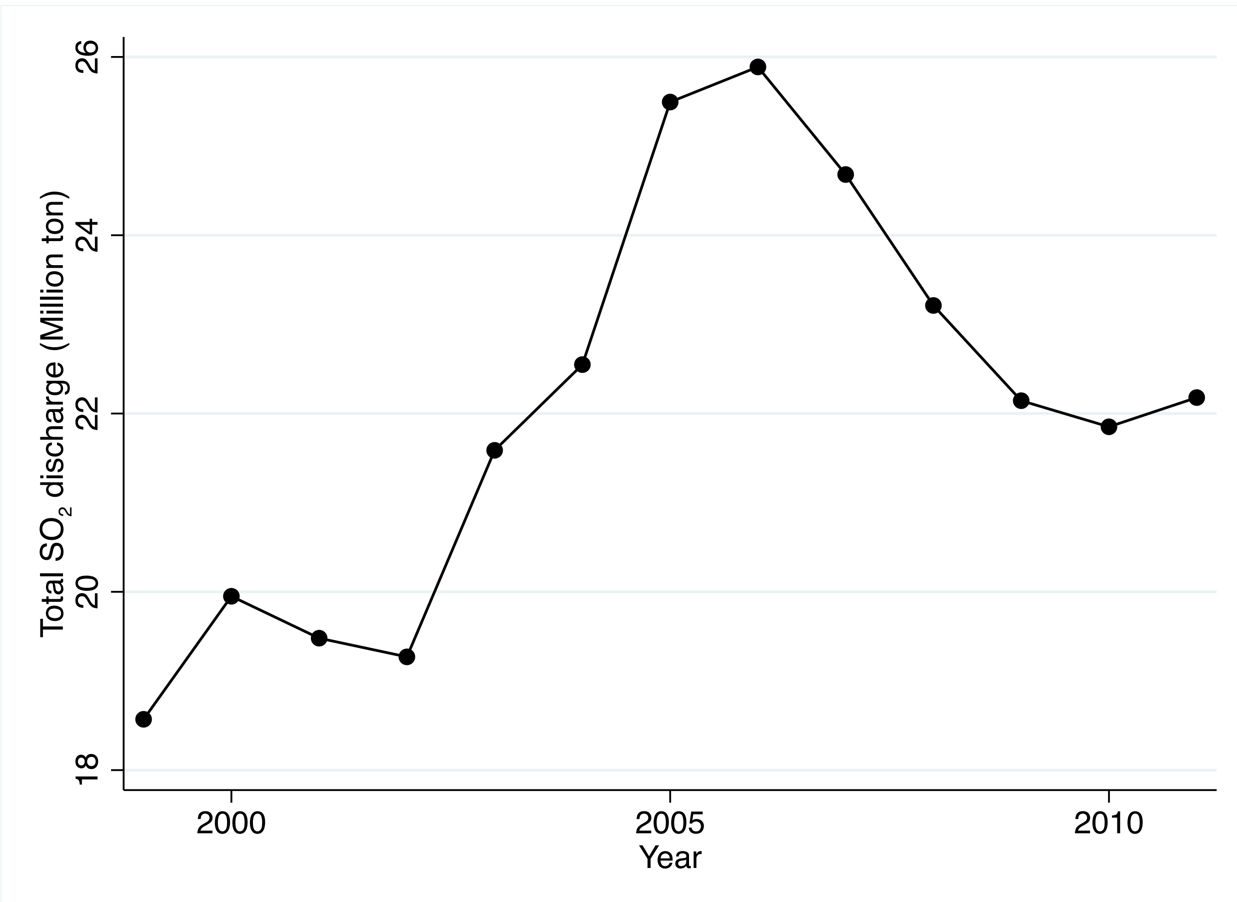

Figure 2.1: Trend of SO_2 emissions in China (millions of tons)

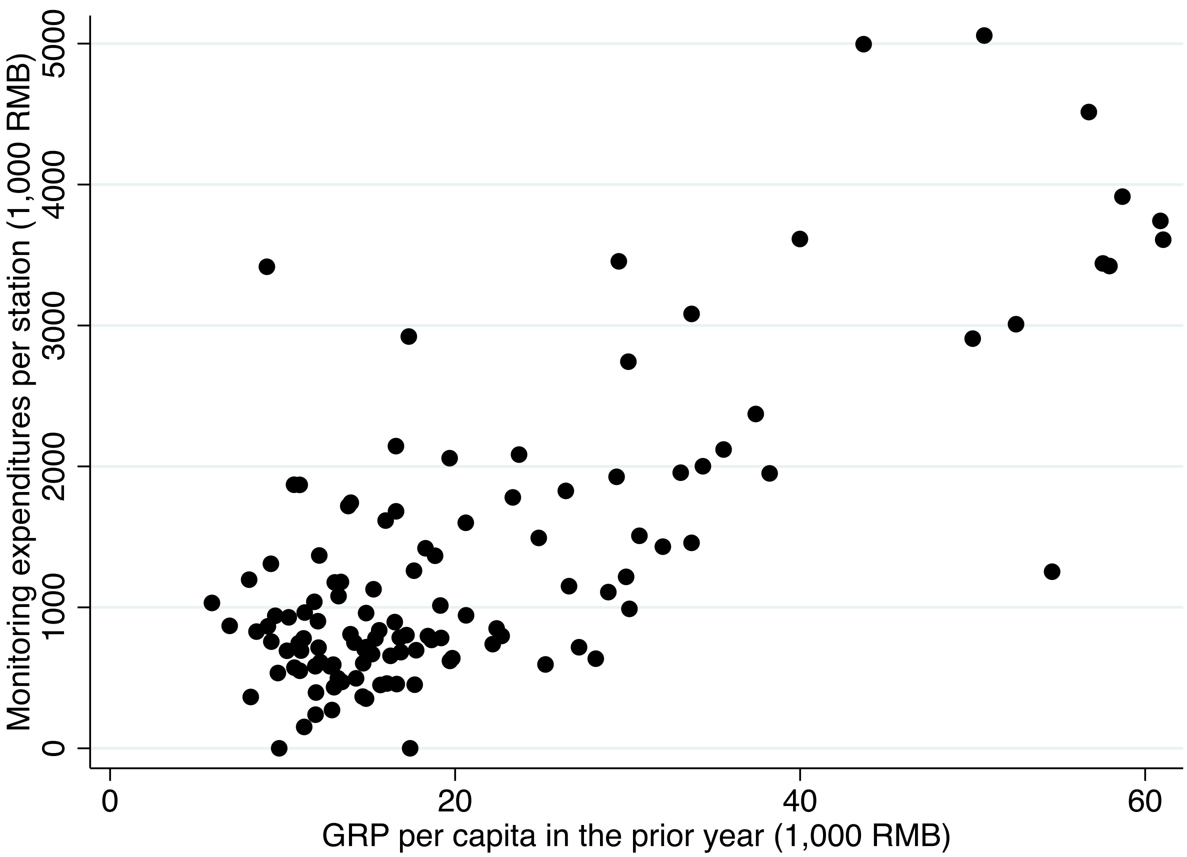

Figure 2.2: GRP and monitoring expenditures

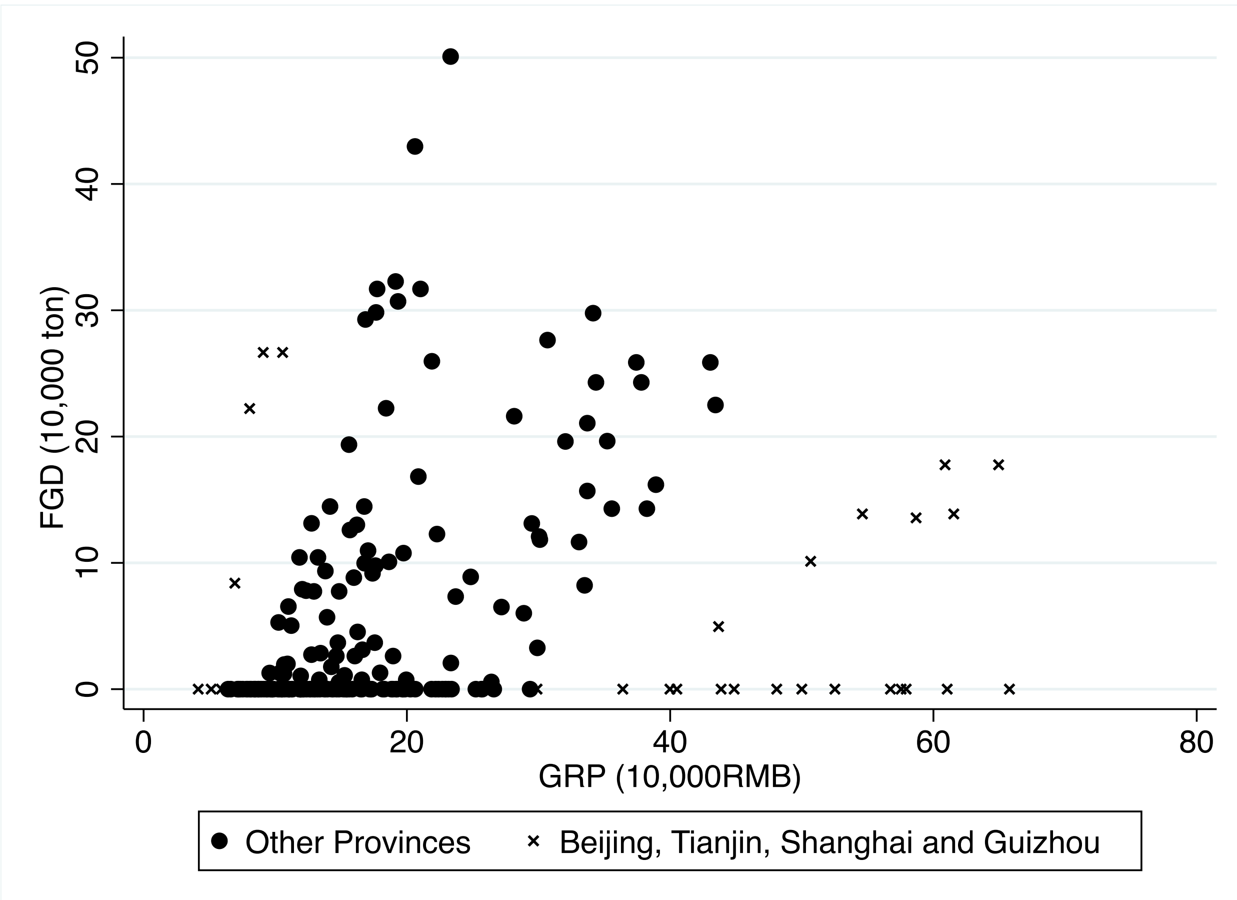

Figure 2.3: GRP and FGD capacity

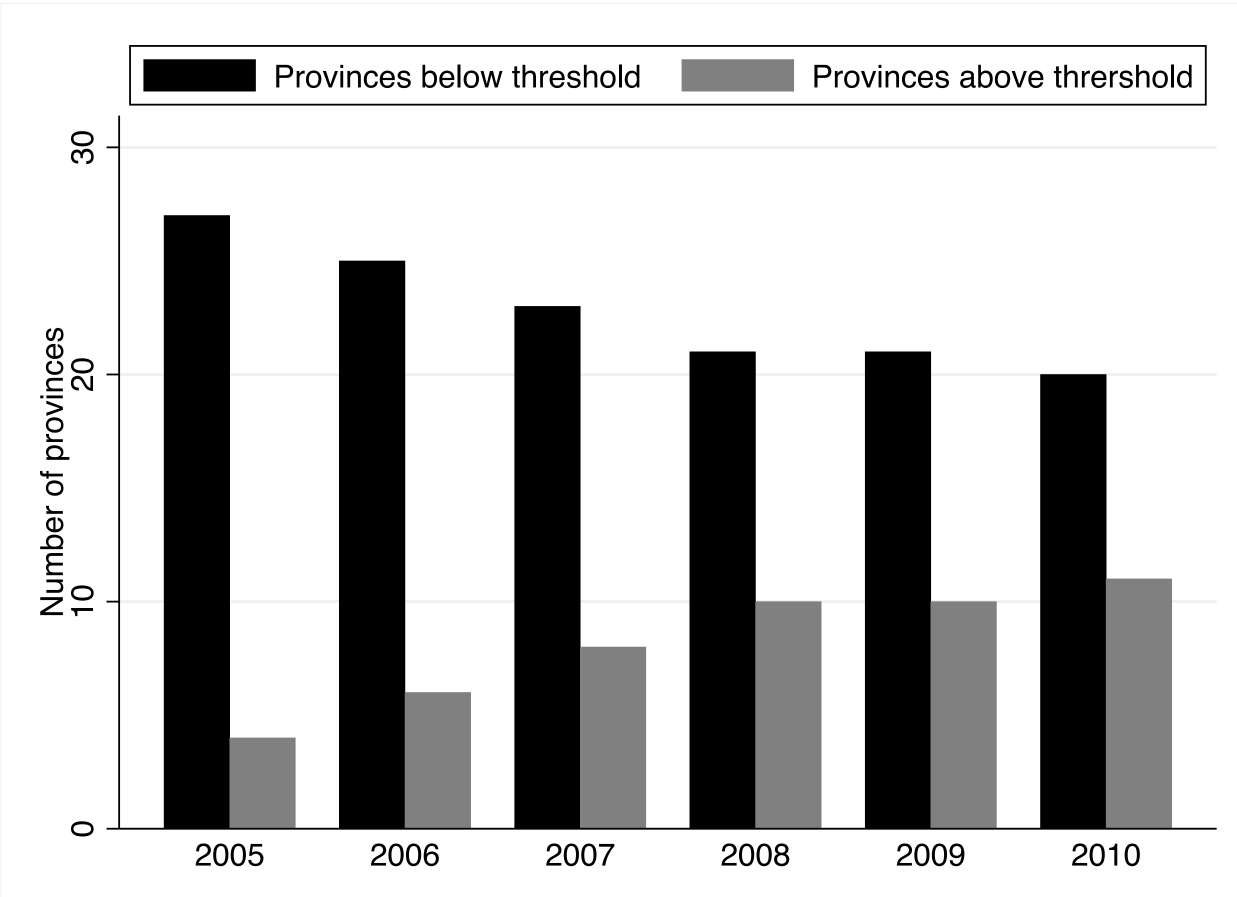

Figure 2.4: Number of provinces below and above the threshold value

Chapter 3

Policies for Controlling NO_x Emissions and the denitration technology choice

3.1 Introduction

A large proportion of air pollution in China stems from coal combustion: coal was the source of 90% of all sulfur dioxide (SO_2) emissions and 67% of nitrogen oxides (NO_x) emissions in 2005 (Liang et al., 2011). Although total SO_2 emissions from the industrial sector decreased from 22.37 million tons in 2006 to 18.35 million tons in 2013, total NO_x emissions increased from 11.36 million tons to 15.45 million tons during the same period (China State Statistical Bureau, 2007, 2014). NO_x emissions contribute to the formation of fine particles (PM10/PM2.5) that inflict significant damage to the health of Chinese citizens (Chen et al., 2015).

The regulation of NO_x emissions in China has lagged behind that of SO_2 emissions. Between 2005 and 2010, the share of thermal power plants that installed desulfurization equipment increased from 14% to 86%. As a result, total SO_2 emissions decreased 14.29%

during the same period. In contrast, the Chinese government shifted its focus to the regulation of NO_x, starting with the 12th Five-year Plan initiated in 2011. This plan announced, for the first time, a concrete target for reducing nitrogen oxide emissions: a 10% reduction in NO_x emissions from the 2010 levels by 2015 (State Council of the People's Republic of China, 2011a).

Several policies were implemented to control NO_x emissions during the 12th Five-year Plan (2011–2015). The *12th Five-year Plan on Environmental Protection* insists that all newly built power generation units and existing units whose capacities exceed 300 MW be coupled with denitration equipment (State Council of the People's Republic of China, 2011a). The new NO_x emission standards were released in July 2011 and took effect in January 2012. Furthermore, the government issued the *12th Five-year Plan for the Prevention and Control of Air Pollution in Key Regions* (Key Regions Plan) in October 2012 (Chinese Ministry of Environmental Protection, 2012). It sets higher emissions reduction targets in specific regions designated according to the type and level of air pollutants experienced there. The government also offered subsidies to thermal power plants that used denitration equipment. As a result, the use of technology for controlling NO_x began to proliferate. As of 2013, 1,238 pieces of denitration equipment had been installed on 7,515 boilers in 3,102 power plants in China.[1] By 2013, NO_x emissions from the thermal power sector had decreased 1.2 million tons (or by 11%) from the 2012 volume (Chinese Ministry of Environmental Protection, 2014a).

Several engineering studies have investigated the role of technological options for controlling NO_x emissions in the thermal power sector in China. Xiong et al. (2016) investigated the emission inventory of coal-fired power plants in Shandong and projected future emissions under three scenarios. Under the assumption that the penetration of selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) technology would increase

[1]The number is the total of utility power plants and non-utility power plants. The latter consists of power plants managed by industrial sectors for their own energy consumption. There were 1,853 utility power plants and 1,249 non-utility power plants in China in 2013. They have 4,825 and 2,690 boilers, respectively. Among them, 1,076 utility boilers and 162 non-utility boilers had installed denitration equipment in 2013.

from 10% and 2% in 2012 to 95% and 5% in 2030, respectively, they predict that NO_x emissions will decrease by 80.63% relative to the 2012 baseline. Zhao et al. (2008) evaluate the cost-effectiveness of various coal-power technologies and estimate the differences in capital costs and overall cost of electricity. The net plant efficiency for the integrated gasification combined cycle (IGCC) technology is 45%, and NO_x emissions are minimized by using IGCC among all the technological options. However, the cost per unit of electricity generated while using IGCC is 30% to 40% higher than the option using SNCR technology, even when charges related to pollutant emissions are included. While these studies suggest that the technology adoption will play a key role in reducing NO_x emissions in China, details on the actual adoption process and its driving force have not been analyzed.

On the other hand, economic studies of the technology choices for controlling NO_x have focused on cases in developed countries. For example, Popp (2010) investigates links between knowledge stock and the adoption of NO_x control technology in US coal-fired power plants. His results suggest that an increased level of knowledge stock—measured by patent count—increases the adoption rates of combustion modification techniques and post-combustion treatments. Examining the impact of Swedish emission regulations, Sterner and Turnheim (2009) considered the process of technological change in relation to NO_x abatement from large stationary sources. They regressed the plant emission intensities of NO_x on various explanatory variables, including specific technological options. Their results suggest that the most significant and sizeable reduction was attained by using SCR, followed by that attained using SNCR. Bonilla et al. (2015) studied how the use of various NO_x abatement technologies has diffused under the Swedish system of refunded emission payments by analyzing the determinants of the time to adoption. Their results revealed an economy of scale: the greater the capacity of the boiler, the more likely it is that post-combustion technologies will be adopted. Their results also suggest that stringent standards increase the regulatory costs of NO_x emissions and motivate firms to invest in more than one NO_x-reducing technology. They attribute no explanatory power to the predicted decrease in net charge liabilities or to most of the other covariates across the subsamples in Sweden.

This chapter focuses on the choices of NO_x control technology in the thermal power sector in China, where air pollution is a major issue under conditions of rapid economic growth. We analyze how technological choices have been influenced by government policies, the stringency of national standards, and subsidies for using specific technologies. We focus on the available post-combustion technologies, as the removal efficiency of NO_x through post-combustion technology is higher than that through the pre-combustion or combustion process. We find that SNCR adoption increased after 2010 and identify a clear distinction in regional distribution between the pre- and post- 2010 periods concerning the adoption of SCR technology. We also investigate how subsidies for operating denitration equipment affected SCR adoption and find that subsidies somewhat discouraged it, perhaps because SCR is more expensive than the other technological options.

In Section 3.2, we provide background information and develop our hypothesis. We also introduce the denitration technology, national standards, and various policies relevant to the NO_x emitted by thermal power sector in China. Section 3.3 explains the chapter's empirical strategy and data. Section 3.4 presents the chapter's empirical results, and Section 3.5 concludes the paper.

3.2 Background, and Hypothesis Development

3.2.1 Technological Options for Post-combustion Control

The abatement of NO_x emissions occurs by way of three different processes: pre-combustion control, combustion modification, and post-combustion capture (Skalska et al., 2010; Cheng and Bi, 2014). Pre-combustion control involves fuel purification, used to reduce the nitrogen content of the fuel. Combustion modification refers to technology improvements in the boiler design, which can reduce NO_x formation during the combustion processes. Post-combustion technologies are end-of-pipe solutions that reduce NO_x in the flue gases following the combustion stage. Post-combustion technologies can remove up to 90% of NO_x (Guo et al., 2012), while that of pre-combustion control and combustion modification control can reduce NO_x by only less than 50% (Radojevic, 1998). Therefore, the adoption of post-combustion technology is important for making any significant reductions in NO_x emissions.

The SCR and SNCR technology are representative post-combustion processes. SCR technology is usually applied to thermal power plants with capacities greater than 200 MW and that work at a temperature in the range of 300 to 400 °C (Cofala and Syri, 1998). While the denitration efficiency of SCR is high (i.e., up to 80−90%), one problem is that catalyst pollutes the environment (Zhou et al., 2012). The ammonia used in the catalytic process can corrode the equipment, produce ash pollution, and damage the environment. SNCR is another technology used to control NO_x emissions from coal-fired power plants. Since it does not require any catalyst, the denitration process produces no pollution. It incurs a lower investment cost and can be applied to any size of unit. On the other hand, it requires a high working temperature (i.e., 870−1100 °C), and its rate of denitration efficiency is usually lower than 40% (Liang et al., 2011).

Table 3.1 summarizes the characteristics of these two technologies. SCR requires catalyst, while SNCR does not, and there is a pressure loss with SCR but not with SNCR. The removal efficiency of SCR is as high as 80%, while that of SNCR is 40% at most. The construction cost of SCR is higher than that of SNCR. SCR produces ammonium hydrogen sulfate, while SNCR does not (Zhou et al., 2012). In addition to the SCR and SNCR technologies, a hybrid of these two technologies, SNCR−SCR, is used in Chinese thermal power plants (Liang et al., 2011). It is more environmentally friendly and cost-effective than SCR and is more denitration-efficient than SNCR. SCR and SNCR technologies were initially installed in the early 2000s, while the first SNCR−SCR technology was installed in 2006 (Chinese Ministry of Environmental Protection, 2014b). As we will see in a later section, a large proportion of these technologies were installed after 2010.

[Table 3.1]

3.2.2 National Emission Standards

Table 3.2 summarizes the national standards for NO_x control in China. National emissions standards for NO_x from thermal power plants were introduced and updated in 1997, 2003, and 2012. These are included in direct regulations of various air pollutants from the power generation sector, named GB13223-1996, GB13223-2003, and GB13223-2011. These GBs are implemented on the basis of the Air Pollution Prevention and Control Law.

[Table 3.2]

GB13223-1996 included the first national standard for controlling NO_x emissions from the thermal power sector. It requires that effluent concentrations be less than 650 mg/m^3. The regulation applies only to boilers with a maximum continuous rating greater than 1,000 t/h and that began operating after January 1997. GB13223-1996 was updated to GB13223-2003 in 2003; the emissions standard in this GB varied according to the year in which the plant was built. The first category contains plants that started operations before the end of 1996; the second category includes plants that started operations between January 1997 and December 2003; and the third category includes plants that started operations after January 2004. For plants in the first category, the most stringent standard was 1,100 mg/m^3. For the second and third categories, the values were 650 mg/m^3 and 450 mg/m^3, respectively. More stringent standards were applied to newer plants. Subsequently, GB13223-2011 was introduced in 2012. The most stringent standard is 450 mg/m^3 and applies to plants that were in operation until 2012; it is 100 mg/m^3 for those that started operations after 2012.

It is reasonable to expect that more stringent standards would encourage firms to employ denitration technology that features higher removal efficiency. On the other hand, firms might not control their emissions, even under tighter standards, due to insufficient monitoring and enforcement. In such a case, regulation via stringent standards might not be effective in inducing firms to invest in better emissions control equipment.

3.2.3 Policy Instruments under Five-year Plans

The Chinese government mentioned NO_x control as a policy agenda for the first time in the 11th Five-year Plan (2006–2010). The government announced that it would control the growth trend of NO_x emissions and reduce the power sector's NO_x emissions intensity by 2010. The government also announced that it would control the total NO_x discharge by 2020. However, the plan did not specify any concrete target during that period (Chinese Ministry of Environmental Protection, 2012).

The subsequent 12th Five-year Plan (2011–2015) introduced a concrete target for NO_x emissions for the first time in the history of Chinese environmental policy. Based on the *12th Five-year Plan on Environmental Protection* in December 2011, it announced a 10% reduction in NO_x emissions by 2015 from 2010 levels (State Council of the People's Republic of China, 2011a). The emissions target for each province in China was also announced (State Council of the People's Republic of China, 2011b). The targets exceed 15% in the eastern regions such as the Yangtze River Delta area, the Beijing–Tianjing–Tangshan area, and the Pearl River Delta area (see Table 3.3), and are approximately 10% in the inland areas. Areas such as Hainan and Qinghai were allowed to increase their emissions, suggesting that differences in economic development levels were considered when these targets were set (Xing, 2012).

In October 2012, the *12th Five-year Plan for the Prevention and Control of Air Pollution in Key Regions* (Key Regions Plan) was issued to promote the enforcement of air pollution control in specific regions. The 2015 reduction target for NO_x emissions in key regions was 13%, and that for the NO_x concentration was 7%, both from 2010 levels. Furthermore, the Key Regions Plan defines Key Control Areas with regards to different types of air pollution, where even stricter pollution control measures were implemented. Concerning NO_x control, 44 cities in the central region of Liaoning, around of Wuhan, Changsha–Zhuzhou–Xiangtan, Chengdu–Chongqing, and the urban area of Western Taiwan Straits were designated as Key Control Areas (Chinese Ministry of Environmental Protection, 2012). We can expect that the reduction target of each province and the designation of the Key Control Areas impacted firms' choices of NO_x control technology during this period.

[Table 3.3]

Regarding the means of controlling NO_x emissions, the 12th Five-year Plan insists that all newly built power generation units and large existing units ($\geq$ 300 MW) be equipped with flue gas denitrification equipment (Zhao et al., 2013). The Key Regions Plan announced that thermal power generating units larger than 200 MW that had been operating for fewer than 20 years should have denitration equipment installed, and it required that the removal efficiency of that equipment be greater than 85%. Moreover, the government would strengthen its monitoring of installed equipment to ensure its stable operation. To offer an incentive for operating control equipment, in November 2011, the Chinese National Development and Reform Commission introduced a subsidy via higher on-grid electricity prices for coal-fired power plants that were using NO_x emissions control equipment. The policy was first implemented in 14 pilot provinces selected from China's 31. The subsidy level was 0.008 RMB/kWh in addition to the baseline electricity price. In the first half of 2012, NO_x emissions declined by 0.24% from the previous year. Denitration efficiency was 40.3%, a 16.1% increase over the previous year. In January 2013, the application for a subsidy was extended nationwide, although the subsidy level remained unchanged from the 2011 level (Chinese National Development and Reform Commission, 2013). These policy instruments might influence the adoption of particular technologies, as plants might choose cheaper and less-effective technologies if monitoring and enforcement instruments are not strong.

3.3 Empirical Strategy and Data

3.3.1 Empirical Model

We focus on the choices of technologies used to control NO_x within China's thermal power sector. We assume that these choices are affected by the policies, subsidies, and economic characteristics of each region. We also assume that there are three options (j = 1, 2, 3) for control technology (i.e., SCR = 1, SNCR = 2, SNCR−SCR = 3). The expected profit that the ith boiler (i =1,...,n) derives from the jth option can be expressed as V_{ij}. The expected profit function is written as:

$$V_{ij} = \beta_{j1}P_i + \beta_{j2}S_i + \beta_{j3}O_i + \beta_{j4}E_i + \epsilon_{ij} = Z_{ij} + \epsilon_{ij}, \tag{3.1}$$

where P represents the policies applied when the boiler is transformed, S represents the standards applied to the emissions from the thermal power plant, O denotes boiler-specific characteristics, and E represents regional economic characteristics. We use a multinomial logit model to analyze plants' choices among the three technologies.

A plant will choose the technological option m if and only if it brings the highest economic return among all the available choices. In other words, the probability that plant i will choose alternative m is

$$\begin{aligned} Pr(Y_i = m) &= Pr(V_{im} > V_{ij}) \quad for\ all\ j = 1, 2, 3,\ j \neq m \\ &\Longrightarrow Pr(Z_{im} + \epsilon_{im}) > Pr(Z_{ij} + \epsilon_{ij}) \\ &\Longrightarrow Pr(Z_{im} - Z_{ij}) > Pr(\epsilon_{ij} - \epsilon_{im}) \quad for\ all\ j = 1, 2, 3,\ j \neq m. \end{aligned} \tag{3.2}$$

Based on McFadden (1973), the error terms ϵ_{ij} are assumed to be independently and identically distributed with Weibull distribution $F(\epsilon_{ij}) = exp[exp(-\epsilon_{ij})]$; then,

$$Pr(Y_i = m) = \frac{exp(Z_{im})}{exp(Z_{i1}) + exp(Z_{i2}) + exp(Z_{i3})}, \tag{3.3}$$

$$Pr(Y_i = k) = \frac{exp(Z_{ik})}{exp(Z_{i1}) + exp(Z_{i2}) + exp(Z_{i3})}. \tag{3.4}$$

From equations (3) and (4), the logarithm of the ratio of the probability of outcome $j = m$ to that of outcome $j = k$ is

$$log\left(\frac{Pr(Y_i = m)}{Pr(Y_i = k)}\right) = (\beta_{m1} - \beta_{k1})P_i + (\beta_{m2} - \beta_{k2})S_i + (\beta_{m3} - \beta_{k3})O_i + (\beta_{m4} - \beta_{k4})E_i, \tag{3.5}$$

P_i includes policies for controlling NO_x emissions. In our analysis, there are five explanatory variables for policies. *12th FYP* is a dummy variable denoting whether a boiler was transformed during the 12th Five-year Plan. *NO_x Control Area* is a dummy variable denoting whether a boiler was built in the NO_x control area designated under the Key Regions Plan.[2] This dummy variable takes the value of one if a boiler was operating in a NO_x control area and transformed after 2012. *Subsidy 2011* and *Subsidy 2013* are dummy variables for subsidy policies for boilers operating denitration equipment implemented in November 2011 in 14 specific provinces and January 2013 nationwide, respectively. *Subsidy 2011* takes the value of one if the boiler operates in 14 pilot provinces and was transformed in 2011 or 2012. *Subsidy 2013* takes value of one if the boiler was transformed in 2013. *Provincial Target* represents the reduction target for NO_x until 2015 in each province; it is denoted by a percentage reduction from 2010 emissions in each province. Since the provincial target is announced in 2011, the variable takes zero for all boilers that installed the control equipment before that year.

S_i is the stringency of emissions standards for NO_x emitted by the thermal power sector.

[2]These are 44 cities and areas that belong to the central region of Liaoning, around Wuhan, and in each of Changsha–Zhuzhou–Xiangtan, Chengdu–Chongqing, and the urban area of Western Taiwan Straits.

This is represented by the *Emission Standard* variable, which uses the values applied to each boiler under GB13223-1996, GB13223-2003, and GB13223-2011. For example, we set the value of *Emission Standard* equal to 1,100 if a boiler started operations before 1996 and transformed before 2010 because the GB applied to this boiler when it installed control equipment was GB13223-2003, and, under this GB, the emissions standard applied to this boiler was 1,100 mg/m^3. Likewise, we set the emissions standard level equal to 650 if operations started between 1997 and 2003 and the transformation took place earlier than 2010. Similarly, the value equals 450 if the boiler started operations earlier than 2003 and transformed after 2011 or if its first operation year was between 2004 and 2011. We set the value equal to 100 if the first year of operation was after 2012.

O_i summarizes the individual characteristics of boilers. *Capacity* is a variable reflecting boiler capacity. *Installation Age* measures the years that passed between when the boiler started operations and when NO_x control equipment was installed. *Selfbuilt* is a dummy variable that takes the value of one if the plant installed control equipment that it had manufactured; if the plant installed control equipment manufactured by other companies, the value is zero.

E_i summarizes the economic characteristics of each province. We use four variables: gross regional products (GRP), value-added in the manufacturing sector, utilization of the thermal power sector, and share of thermal power to total capacity. *GRP* represents the real GRP in each province, and *Industrial Value-added* is the real value added of the manufacturing sector in each province. *Utilization* represents the utilization of thermal power capacity in each province; we calculate this variable by dividing the generated electricity by the capacity of thermal power plants in each province. *Share of Thermal Power* measures the capacity share of the thermal power sector; it is calculated by dividing the capacity of thermal power generation by the total capacity of the electricity sector in each province.

3.3.2 Data

We use boiler-level data from the *Denitration Equipment List of National Coal-Fired Boilers*, which is accessible from the website of the data center of the Chinese Ministry of Environmental Protection (http://datacenter.mep.gov.cn). The list contains information on 1,135 utility and non-utility boilers that have installed denitration equipment and are operating in China as of 2013. Since the Chinese Ministry of Environmental Protection (2014a) reports that there are 1,238 pieces of denitration equipment in thermal power plants in China as of 2013, it captures 92% of equipment operating at that moment. We collect information on the name of the plant, the generation capacity, the year in which it started operations, the year in which it adopted denitration equipment, the construction company that installed the equipment, the type of denitration technology chosen, and the province in which each boiler is operating. Unfortunately, the database does not contain information on the boilers without denitration equipment, restricting our analysis to the technology choices of those that installed them. Figure 3.1 presents the cumulative number of boilers with denitration equipment in our dataset and compares it with the total number of boilers with capacity larger than 6MW from 2001 to 2013. It is clear that our dataset captures only a fraction of boilers operating in China.[3]

Descriptive statistics are shown in Table 3.4. On average, the boilers in our sample had a capacity of 381 MW and were 6.78 years old when denitration equipment was installed. Figure 3.2 shows the number of boilers that started operation in each year. In the sample, 81.59% of the boilers were built after 2000. There was a significant increase in the number of boilers after 2003, as the Chinese economy started to grow rapidly after China joined the World Trade Organization in 2000. Many boilers in our dataset had denitration equipment installed after 2007 (see Figure 3.3). Although the earliest installation took place in 2001, only nine boilers featured denitration equipment until 2006. The number of boilers with the

[3] In 3.4.4, we analyze the decision to install denitration equipment by looking at the installation situation of 1,083 boilers operating in 2012.

NO_x control equipment exceeded 100 after 2011; among these, 84% of the boilers installed control equipment during the 12th Five-year Plan period.

[Table 3.4]

[Figure 3.1]

[Figure 3.2]

[Figure 3.3]

Among the 1,135 boilers in our dataset, 894 (79%) installed SCR technology, 209 (18%) installed SNCR technology, and 32 (3%) installed SNCR−SCR technology. Various factors potentially affect these choices. Figure 3.4 is a box chart indicating the distribution of the boiler size for the three technology choices. It suggests that SCR technologies are chosen by larger boilers while SNCR are installed on smaller units. The age of the boiler also matters for technology choice. Figure 3.5 shows that SNCR−SCR is installed on old boilers, while SCR is installed on new units.

Of the total, 275 boilers (24%) installed denitration equipment in the year they began operations.[4] It is very likely that these boilers are equipped with NO_x control technology when they are constructed. Interestingly, many boilers that installed equipment in the first year of their operation choose SCR and SNCR technology, but none installed SNCR−SCR. This can be also confirmed by Figure 3.6, which shows the relationship between the year the boilers began operating and the year they installed their NO_x control equipment. The upper parts of these figures include frontier lines indicating boilers that installed equipment in the year they began operating. While there are dots on the frontier lines in the SCR and SNCR panel, there are no dots on the line in the SNCR−SCR panel. The dots in the SNCR panel are concentrated on the right, indicating that most of the boilers installed SNCR technology after 2010.

[4] In Appendix A, we investigate the characteristics of these boilers that installed the denitration equipment in the first year of their operation.

[Figure 3.4]

[Figure 3.5]

[Figure 3.6]

3.4 Empirical Results

3.4.1 Baseline analysis

We use a multinomial logit model to investigate the factors affecting plants' choices among the three denitration technologies. The results are shown in Table 3.5. Since we take SNCR technology as the base technology, the coefficients in the models show the effect of various factors on the choice of SCR or SNCR–SCR technology over SNCR technology. As noted earlier, SNCR has the lowest investment cost but also the lowest denitration efficiency. To avoid correlation with the dummy variable for the 12th Five-year Plan period (*12th FYP*), we exclude variables concerning the subsidy policy (i.e., *Subsidy 2011* and *Subsidy 2013*) in these estimations.

[Table 3.5]

Column (1) in Table 3.5 shows how various policies influence each plant's choices of technology. We also estimate models with control variables (*GRP* and *Industrial Value-added*); the results are in columns (2) and (3). The coefficient of *12th FYP* has a negative sign and is statistically significant for the choice of SCR over SNCR. On the other hand, the coefficient of *NO_x Control Area* variable has a positive sign and is statistically significant for SCR technology (columns (1)–(3)). While SNCR technology (the cheapest technology) was preferred during the 12th Five-year Plan period over SCR technology (the most expensive technology), this is not the case for the plants located in the NO_x control areas. In columns (4) to (6) of Table 3.5, we use *Targeted Plant in 12th FYP*, rather than *12th FYP*. The variable is a dummy denoting plants targeted in the 12th Five-year Plan; taking the value of one when a boilers is larger than 300 MW and transformed during the 12th Five-year Plan, and zero otherwise. The coefficient of this variable is statistically insignificant for the choice of SCR over SNCR, suggesting that there is no difference among these technologies in terms of firm preference.

Regarding boiler characteristics, *Capacity* is both positive and statistically significant, in line with our expectation that plants with larger boilers tend to choose SCR or SNCR–SCR over SNCR technology. *Installation Age* is positive and statistically significant for SCR technology, suggesting that the plants with older boilers tend to choose SCR technology. The dummy variable for the self-built denitration equipment (*Selfbuilt*) is negative and statistically significant for the choice of SNCR–SCR. *Emission Standard* is negative and statistically significant for the choice of SCR over SNCR technology; since a lower-value for this variable means stricter regulation, it is reasonable to derive a negative coefficient for the choice of a more efficient technology option.

Therefore, we find a negative and statistically significant results for the dummy variable of the 12th Five-year Plan concerning the more expensive technological choices. On the other hand, the effect is statistically insignificant when we use the *Targeted Plant in 12th FYP*; this difference suggests that plants with boilers larger than 300 MW are indifferent about which technologies to choose to control NO_x. Furthermore, two policies might have promoted the choice of SCR technologies during the 12th Five-year Plan period. The positive coefficient of the *NO_x Control Area* dummy can be interpreted to mean that plants in NO_x control areas tend to choose more expensive technology to control NO_x and thus fulfill the stringent requirements under the policy. The statistically significant coefficient of *Emission Standard* also suggests that SCR technology was chosen under more stringent emission regulations.

As an additional analysis, we create the dummy variable *Targeted Plant in Key Regions* to denote the installation of denitration equipment in thermal power generating units that are larger than 200 MW, had operated for fewer than 20 years by 2013, and operated in key regions. The results are shown in Table 3.6. The coefficient of the variable is negative but statistically insignificant for both SCR and SNCR–SCR technologies, suggesting that the boilers targeted in the Key Regions Plan did not strictly comply with the requirement immediately.

[Table 3.6]

Regarding boiler capacity, plants with larger-sized boilers might obey the policy by choosing a higher-efficiency technology because doing so is economically reasonable for them. This is also suggested by the positive and significant coefficient of the *Capacity* variable for choosing SCR and SNCR–SCR than SNCR technology. To investigate whether the effect of the targeted policy might differ according to boiler size, we use different boiler sizes (i.e., 300–800 MW instead of 200 MW) to create the *Targeted Plant in Key Regions* variable. The results are presented in Table 3.7. *Targeted Plant in Key Regions* is positive and statistically significant when the boiler is larger than 600 MW, suggesting that, under this policy, boilers operating for fewer than 20 years will choose SCR technology when the boiler is larger than 600 MW. Thus, the requirement stipulated in the Key Regions Plan might affect the choice of plants with larger boilers but not that of plants with smaller ones.

[Table 3.7]

3.4.2 Comparisons before and after 2010

This subsection examines changes in plants' choices of technology before and after the 12th Five-year Plan. We conduct separate estimations for subsamples based on the timing of their installation of control equipment in boilers (i.e., before or after 2010). We also investigate differences among the eastern, central, and western regions of China by including dummy variables (*East* and *West*) and using the central region as a base category. Income is the highest in the eastern region, and the western region lags behind in terms of economic development. Some studies have pointed out that the regional differences among Chinese provinces affect their energy consumption and environmental policies (Song et al., 2013; Xu and Lin, 2016).

[Table 3.8]

The estimation results are presented in Table 3.8. *East* and *West* are positive and statistically significant until 2010; during the 12th Five-year Plan period, however, they were not significant for the choice of SCR technology. These results suggest that regional differences do not play a significant role in the plants' choice of SCR technology after 2010.

Capacity is also positive and statistically significant after 2010 but is statistically insignificant for choices of SNCR–SCR until 2010. *Installation Age* is positive and statistically significant after 2010 for SCR but negative and statistically significant for the period until 2010 for the choice of SNCR−SCR. Plants with newer boilers prefer SNCR−SCR technology before 2010, and those with older boilers prefer SCR technology after 2010.

The stringency of emission standards (*Emission Standard*) is statistically insignificant for SCR and is positive and statistically significant for SNCR–SCR technology until 2010; after 2010, however, it is negative and statistically significant for both SCR and SNCR–SCR technologies. Since the lower value of *Emission Standard* points to a stricter emission regulation, the negative sign means that the technology is chosen when the regulation is tighter. The result suggests that plants under a stricter regulation prefer SCR and SNCR–SCR technologies over SNCR technology after 2010. Until 2010, however, the effects of emissions standards had no impact on the choice of technology.

The results discussed above can be summarized as follows. First, until 2010, SCR technology was chosen more readily by plants in the eastern and western regions than by plants in the central region. This can be explained by the regional differences in capital investment in the early 2000s. Since the western region was less developed than the other two regions, huge investments were made in this region under the Western Development Program. Because of this, plants in the western region were more able to purchase expensive pollution control equipment than those in the central region were. After 2010, as the economy in the central region caught up, these regional differences might have become insignificant. Second, the results suggest that plants under stricter emission standards will choose SCR and SNCR–SCR technologies during the 12th Five-year Plan period. A more stringent standard might play a role in plants' preference for efficient technology during this period.

3.4.3 Subsidy policy

This subsection discusses the effect of subsidy policies during the period of the 12th Five-year Plan. The subsidy is offered to plants whose boilers are fitted with denitration equipment and takes the form of a premium on the electricity prices. We use the dummy variables *Subsidy 2011* and *Subsidy 2013* to express two kinds of subsidies. *Subsidy 2011* refers to the 14 provinces taking part in this subsidy's pilot program, initiated in November 2011. *Subsidy 2013* takes the value of one if the installation of control equipment took place after January 2013, when the subsidy was extended nationwide.

[Table 3.9]

The results in Table 3.9 show that *Subsidy 2011* is negative and statistically significant for choosing SCR and SNCR–SCR technology over SNCR technology. This suggests that the subsidy policy offered in the 14 pilot provinces might have promoted investment in cheaper technology. On the other hand, the coefficient for *Subsidy 2013* is statistically insignificant in most of the estimations. When the subsidy was extended nationwide, it did not affect the plants' choice of technology. After January 2012, stringent emission standards were implemented, which might have promoted the choice of technologies that were highly efficient at removing emissions; this effect might have been strong enough to offset the impact of the subsidy (i.e., to choose a cheaper technology).

3.4.4 Analysis of the installation status in 2012

All boilers in our dataset had installed denitration equipment by 2013. In this subsection, we investigate the decision to install pollution control equipment by looking at the installation status as of 2012. In our dataset, the 538 boilers (50% of 1,083 boilers operating in 2012) installed denitration equipment in 2013 did not have denitration equipment in 2012. Therefore, we can use a logit model to investigate the factors affecting the installtion decision as of 2012 by regarding these 538 boilers as being without denitration equipment.[5] We define *Installation2012* as a dummy variable reflecting the installation status of denitration equipment as of 2012. It takes the value of one if the boiler had denitration equipment installed by 2012 and zero otherwise. We estimate the following model:[6]

$$logit(Pr(Installation2012_i)) = \beta_1 P_i + \beta_2 O_i + \beta_3 E_i, \quad (3.6)$$

[Table 3.10]

The estimation results are shown in Table 3.10. The number of observation is reduced to 1,083, since 52 boilers that started their operation in 2013 are excluded in this analysis. *Provincial Target 2012* is positive and statistically significant in all models, while *NO_x Control Area* is mostly not statistically significant. These results suggest that provincial (rather than national) policy is more effective in promoting control equipment. *Capacity* and *First Operation Year* is positive and statistically significant, suggesting that larger sized boilers and newer boilers tend to introduce denitration technologies. *Utilization* and *Share of Thermal Power* are not statistically significant. In other words, the results can be interpreted to

[5] There remains the issue of sample selection, since all the 1,083 boilers in this analysis had installed control equipment by the end of 2013. As of 2013, there were 7,515 boilers in China, including non-utility power plants (Chinese Ministry of Environmental Protection, 2014a).

[6] Some variables used in the technology choice model are not included or are modified in the logit model because of difference in assumptions. We cannot include *Targeted Plant in 12th FYP* or *12th FYP*, since these variables perfectly predicts the installation status. We include *Provincial Target 2012* to represents the reduction target for NO_x until 2015 in each province as of 2012. Moreover, as we assumed that the 538 boilers are without equipment, the variable *Selfbuilt* and *Emission Standard* are not used. We used the variable *First Operation Year* instead of *Installation age*. *First Operation Year* represents the year that the boiler started their operation.

mean that boilers that are smaller, older, and are in provinces with lower emissions reduction targets tend not to have the NO_x control equipment installed.

3.5 Conclusion

This chapter investigated the choices of denitration technology in the Chinese thermal power sector. Considering the choices made by 1,135 boilers operating in China in 2013, we derived the following results. First, the 12th Five-year Plan might encourage plants to choose SNCR technology, the cheapest of the three denitration technological options. We consider that, under the 12th Five-year Plan, strict policy enforcement was implemented, and plants chose the technology that would satisfy the emission target at the cheapest cost. The results suggest that the plants have some flexibility in choosing a preferred technology even though command-and-control policies constitute major instruments of Chinese environmental policy. As Liu et al. (2013) point out, the affordability of energy costs is an important driver of their energy management strategies for Chinese companies.

Second, prior to the $12th$ Five-year Plan period, regional differences had significant effects on technology choices; these later disappeared, perhaps due to the economic development that occurred across all regions of China. On the other hand, the effect of emission standards was statistically significant only during the 12th Five-year Plan period. The implementation of emission standards after 2011 is thought to be ever more stringent.

Finally, the subsidy of electricity prices for plants with denitration equipment might have affected their technology choice. Unfortunately, since the subsidy does not depend on the technology option chosen, plants might choose the cheapest technology to lower their investment costs. As many studies have pointed out, an incautious subsidy policy may lead to overcapacity, overinvestment, and fierce competition in the power sector (Shen and Luo, 2015; Zhang et al., 2016).

Chinese policy for controlling SO_2 has advanced in the 11th Five-year Plan period

(Schreifels et al., 2012; Ma and Takeuchi, 2016). Control of NO_x began in earnest during the 12th Five-year Plan period. Our results suggest that incentives to save investment costs and receive subsidies might influence the choice of technology: therefore, the sophistication of the design of economic instruments could play a role in China's development of effective and efficient environmental policy.

While this chapter focused on the technology choice of boilers that installed NO_x control equipment, it is important to note that it does not capture the decision making for the large portion of boilers that have not installed the equipment. We attempted to consider this decision in subsection 4.4, but it is not free from the sample selection bias, and the result should be interpreted with caution. Further chapter is necessary to understand the full picture of NO_x control strategy in the Chinese thermal power sector.

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Appendix A

To examine the difference between boilers with equipment installed from the beginning and boilers with it installed after years of operation, we use the following logit model:

$$logit(Pr(AgeZero_i)) = \beta_1 P_i + \beta_2 S_i + \beta_3 O_i + \beta_4 E_i, \tag{3.7}$$

where *AgeZero* is a dummy variable that takes value of one when the boiler has NO_x control equipment installed at the start of operations and zero otherwise. The model also includes dummy variables *SCR* and *SNCR−SCR* to indicate the use of these technologies. By looking at the coefficient of these variables, we can investigate the characteristics of boilers with control equipment installed in the first year.

[Table 3.11]

The estimation results are summarized in Table 3.11. *Capacity* and *First Operation Year* are positive and statistically significant in all models, suggesting that larger and recent boilers tend to have denitration equipment installed in the first year. *SCR* is positive and statistically significant in all models, meaning that SCR technology tends to be installed in the first year, relative to SNCR technology. On the other hand, *SNCR−SCR* is not statistically significant. *12th FYP*, *NO_x Control Area* and *Provincial Target* are all negative and statistically significant. These results might be interpreted to mean that these policies for NO_x control promote the installation of control equipment on boilers that did not have equipment in their first year of operation.

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Table 3.1: Comparison of SCR and SNCR technology

	SCR	SNCR
Catalyst	Yes (30% of investment)	No
Pressure loss	Yes	No
Size	Large	Small
Reduction process	Outside of the boiler	Inside of the boiler
Efficiency	80%	$25 - 40\%$
Cost of construction	High	Low
Side effect	Produce NH_4HSO_4	–

Table 3.2: Emission standards for NO_x in China

	Classification based on first year of operation		
	I	II	III
GB13223-1996	N.S.	N.S.	$650 mg/m^3$
	(Before $Aug.1, 1992$)	($Aug.1, 1992$–$Dec.31, 1996$)	(After $Jan.1, 1997$)
GB13223-2003	$1100 mg/m^3$	$650 mg/m^3$	$450 mg/m^3$
	(Before $Dec.31, 1996$)	($Jan.1, 1997$–$Dec.31, 2003$)	(After $Jan.1, 2004$)
GB13223-2011	$450 mg/m^3$	$100 mg/m^3$	
	(Before $Dec.31, 2011$)	(After $Jan.1, 2012$)	

Note: The values indicate the most stringent standards applied for boilers that started operations in each period (as shown in the bracket). N.S.: not specified. GB 13223-1996 standards are applied only to cases of 1000t/h or more.

Table 3.3: NO_x target in 12th Five-year Plan for each province

Province	Emissions in 2010	Target	
		Target in 2015	Change from 2010 (%)
Beijing	19.8	17.4	-12.3
Tianjin	34	28.8	-15.2
Hebei	171.3	147.5	-13.9
Shanxi	124.1	106.9	-13.9
Inner Mongolia	131.4	123.8	-5.8
Liaoning	102	88	-13.7
Jilin	58.2	54.2	-6.9
Heilongjiang	75.3	73	-3.1
Shanghai	44.3	36.5	-17.5
Jiangsu	147.2	121.4	-17.5
Zhejiang	85.3	69.9	-18
Anhui	90.9	82	-9.8
Fujian	44.8	40.9	-8.6
Jiangxi	58.2	54.2	-6.9
Shandong	174	146	-16.1
Henan	159	135.6	-14.7
Hubei	63.1	58.6	-7.2
Hunan	60.4	55	-9
Guangdong	132.3	109.9	-16.9
Guangxi	45.1	41.1	-8.8
Hainan	8	9.8	22.3
Chongqing	38.2	35.6	-6.9
Sichuan	62	57.7	-6.9
Guizhou	49.3	44.5	-9.8
Yunnan	52	49	-5.8
Xizang	3.8	3.8	0
Shannxi	76.6	69	-9.9
Gansu	42	40.7	-3.1
Qinghai	11.6	13.4	15.3
Ningxia	41.8	39.8	-4.9
Xinjiang	67.6	67.6	0
Total	2,273.6	2,021.6	-11.1

Source: Xing (2012).
Note: The unit is in $10,000t$; the total emissions target is $20,462kt$. The difference in the total emissions target in this table is used by the Chinese government for reduction of NO_x emissions trading.

Table 3.4: Descriptive statistics

	N	Mean	Std.Dev.	Min	Max
12th FYP (*dummy*)	1,135	0.843	0.364	0	1
Targeted Plant in 12th FYP (*dummy*)	1,135	0.082	0.275	0	1
NO_x Control Area (*dummy*)	1,135	0.033	0.178	0	1
Subsidy 2011[a](*dummy*)	1,135	0.186	0.389	0	1
Subsidy 2013 (*dummy*)	1,135	0.520	0.500	0	1
Selfbuilt (*dummy*)	1,135	0.025	0.155	0	1
Provincial Target (%)	1,135	0.108	0.067	-0.223	0.180
Capacity (GW)	1,135	0.381	0.256	0.003	1.03
Installation Age[b](*year*)	1,135	6.782	7.247	0	52
Emission Standard ($1,000\ mg/m^3$)	1,135	0.434	0.158	0.1	1.1
Utilization ($1,000\ h$)	1,135	4.956	1.821	3.295	46.44
Share of Thermal Power (%)	1,135	0.787	0.159	0.137	0.999
GRP (*trillion RMB*)	1,135	22.22	13.64	1.299	47.98
Industrial Value-added (*trillion RMB*)	1,135	11.41	7.807	0.463	27.46

Note: Data regarding the Key Control Area and provincial targets were obtained from the Chinese Ministry of Environmental Protection (2012) and Xing (2012). GRP and the value-added of the manufacturing sector were obtained from the China Statistical Yearbook (China State Statistical Bureau, 2002-2014). Province-level capacity and generation data were obtained from the CEIC database (CEIC, 2015).

[a] The 14 pilot provinces that implemented trial subsidies on electricity price starting in November 2011 were: Beijing, Tianjin, Hebei, Shanxi, Shandong, Shanghai, Zhejiang, Jiangsu, Fujian, Guangdong, Hainan, Sichuan, Gansu, and Ningxia. The dummy variable *Subsidy 2011* takes the value of one if the control equipment was installed after November 2011 and it is located in one of these 14 provinces.

[b] Installation Age refers to the number of years that passed between the first operation of the boiler and the installation of denitration equipment.

Table 3.5: Targeted plant in key regions

	(1)	(2)	(3)
SCR			
Targeted Plant in Key Regions	-0.297	-0.353	-0.343
	(0.516)	(0.524)	(0.523)
NO_x Control Area	1.746*	1.797*	1.754
	(1.054)	(1.082)	(1.080)
Provincial Target	-0.054**	-0.062***	-0.062***
	(0.025)	(0.023)	(0.024)
Capacity	16.37***	17.08***	17.00***
	(1.354)	(1.559)	(1.546)
Installation Age	0.072***	0.071***	0.072***
	(0.019)	(0.019)	(0.019)
Selfbuilt	-0.429	-0.438	-0.415
	(0.409)	(0.410)	(0.413)
Emission Standard	-1.543	-1.768*	-1.767*
	(1.047)	(0.977)	(0.979)
Utilization	0.949***	0.933***	0.930***
	(0.361)	(0.345)	(0.347)
Share of Thermal Power	0.098	-0.210	-0.082
	(0.997)	(1.005)	(0.997)
GRP		0.016	
		(0.012)	
Industrial Value-added			0.025
			(0.020)
Constant	-6.152***	-6.152***	-6.152***
	(1.545)	(1.522)	(1.525)
SNCR	(Baseline)		
SNCR-SCR			
Targeted Plant in Key Regions	-1.304	-1.473	-1.442
	(0.981)	(1.028)	(1.032)
NO_x Control Area	-7.828***	-7.778***	-8.083***
	(1.425)	(1.464)	(1.475)
Provincial Target	-0.013	-0.044	-0.038
	(0.051)	(0.043)	(0.043)
Capacity	8.302***	9.780***	9.533***
	(2.245)	(2.376)	(2.388)
Installation Age	0.027	0.028	0.027
	(0.031)	(0.031)	(0.031)
Selfbuilt	-12.81***	-13.06***	-13.24***
	(0.453)	(0.453)	(0.452)
Emission Standard	2.114	1.502	1.601
	(2.022)	(1.924)	(1.942)
Utilization	1.103***	1.074***	1.077***
	(0.365)	(0.348)	(0.350)
Share of Thermal Power	6.751***	6.211***	6.604***
	(2.040)	(2.064)	(2.070)
GRP		0.040**	
		(0.019)	
Industrial Value-added			0.059*
			(0.034)
Constant	-14.97***	-15.08***	-15.21***
	(2.772)	(2.832)	(2.872)
N	1135	1135	1135
$Pseudo\ R_2$	0.537	0.540	0.539

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

Table 3.6: Baseline results

	(1)	(2)	(3)	(4)	(5)	(6)
SCR						
12th FYP	-1.822**	-1.698**	-1.738**			
	(0.776)	(0.813)	(0.825)			
Targeted Plant in 12th FYP				-0.258	-0.392	-0.379
				(0.735)	(0.732)	(0.731)
Provincial Target	0.019	0.012	0.014	-0.057**	-0.067***	-0.066***
	(0.040)	(0.042)	(0.043)	(0.025)	(0.024)	(0.025)
NO_x Control Area	1.835*	1.846*	1.831*	1.645	1.674	1.632
	(1.060)	(1.079)	(1.072)	(1.060)	(1.091)	(1.089)
Capacity	17.21***	17.45***	17.35***	16.16***	16.87***	16.79***
	(1.358)	(1.479)	(1.457)	(1.178)	(1.370)	(1.353)
Installation Age	0.080***	0.079***	0.079***	0.072***	0.072***	0.072***
	(0.021)	(0.021)	(0.021)	(0.019)	(0.019)	(0.019)
Selfbuilt	-0.013	-0.039	-0.024	-0.402	-0.405	-0.383
	(0.468)	(0.471)	(0.471)	(0.396)	(0.394)	(0.398)
Emission Standard	-2.713**	-2.714**	-2.712**	-1.671	-1.955*	-1.947*
	(1.123)	(1.131)	(1.138)	(1.177)	(1.081)	(1.083)
Utilization	0.903***	0.899***	0.899***	0.918**	0.897**	0.896**
	(0.348)	(0.342)	(0.345)	(0.365)	(0.349)	(0.351)
Share of Thermal Power	-0.799	-0.904	-0.828	0.133	-0.154	-0.026
	(1.015)	(1.035)	(1.023)	(0.988)	(1.002)	(0.994)
GRP		0.007			0.017	
		(0.013)			(0.012)	
Industrial Value-added			0.007			0.026
			(0.022)			(0.020)
Constant	-4.242**	-4.364**	-4.324**	-5.917***	-5.876***	-5.886***
	(1.766)	(1.782)	(1.805)	(1.446)	(1.415)	(1.419)
SNCR	(Baseline)					
SNCR-SCR						
12th FYP	-5.244*	-4.612*	-4.886*			
	(2.705)	(2.683)	(2.732)			
Targeted Plant in 12th FYP				-12.28***	-14.18***	-12.49***
				(0.918)	(0.908)	(0.911)
Provincial Target	0.239	0.194	0.214	-0.031	-0.062	-0.056
	(0.167)	(0.166)	(0.169)	(0.047)	(0.042)	(0.042)
NO_x Control Area	-7.239***	-7.583***	-8.559***	-9.418***	-10.99***	-9.405***
	(1.578)	(1.566)	(1.578)	(1.233)	(1.250)	(1.261)
Capacity	9.166***	9.540***	9.366***	7.486***	8.833***	8.605***
	(2.167)	(2.203)	(2.210)	(2.027)	(2.105)	(2.111)
Installation Age	0.030	0.029	0.030	0.023	0.024	0.024
	(0.033)	(0.033)	(0.033)	(0.032)	(0.032)	(0.032)
Selfbuilt	-11.90***	-12.64***	-13.46***	-13.65***	-15.33***	-13.64***
	(0.597)	(0.602)	(0.603)	(0.457)	(0.460)	(0.458)
Emission Standard	0.404	0.350	0.386	1.666	1.018	1.125
	(2.034)	(1.996)	(2.013)	(2.209)	(2.128)	(2.144)
Utilization	1.046***	1.037***	1.040***	1.065***	1.033***	1.037***
	(0.351)	(0.345)	(0.348)	(0.368)	(0.352)	(0.354)
Share of Thermal Power	5.808**	5.577**	5.759**	6.645***	6.112***	6.470***
	(2.279)	(2.256)	(2.272)	(2.034)	(2.081)	(2.070)
GRP		0.017			0.038**	
		(0.018)			(0.018)	
Industrial Value-added			0.016			0.055*
			(0.031)			(0.031)
Constant	-12.30***	-12.51***	-12.46***	-14.15***	-14.15***	-14.27***
	(2.952)	(2.961)	(3.001)	(2.719)	(2.774)	(2.788)
N	1135	1135	1135	1135	1135	1135
$Pseudo\ R_2$	0.543	0.544	0.544	0.536	0.539	0.538

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

Table 3.7: Comparisons by capacity

	(1) 200MW	(2) 300MW	(3) 400MW	(4) 500MW	(5) 600MW	(6) 700MW	(7) 800MW
SCR							
Targeted Plant in Key Regions	-0.297	-0.267	-0.267	-0.267	-0.267	6.609***	3.494***
	(0.516)	(0.592)	(0.592)	(0.592)	(0.592)	(0.952)	(1.160)
Provincial Target	-0.054**	-0.054**	-0.054**	-0.054**	-0.054**	-0.055**	-0.055**
	(0.025)	(0.026)	(0.026)	(0.026)	(0.026)	(0.024)	(0.024)
NO_x Control Area	1.746*	1.747	1.747	1.747	1.747	1.680	1.680
	(1.054)	(1.069)	(1.069)	(1.069)	(1.069)	(1.051)	(1.051)
Capacity	16.37***	16.28***	16.28***	16.28***	16.28***	16.10***	16.10***
	(1.354)	(1.344)	(1.344)	(1.344)	(1.344)	(1.149)	(1.149)
Installation Age	0.072***	0.072***	0.072***	0.072***	0.072***	0.072***	0.072***
	(0.019)	(0.019)	(0.019)	(0.019)	(0.019)	(0.019)	(0.019)
Selfbuilt	-0.429	-0.424	-0.424	-0.424	-0.424	-0.410	-0.410
	(0.409)	(0.405)	(0.405)	(0.405)	(0.405)	(0.400)	(0.400)
Emission Standard	-1.543	-1.509	-1.509	-1.509	-1.509	-1.554	-1.554
	(1.047)	(1.050)	(1.050)	(1.050)	(1.050)	(1.045)	(1.045)
Utilization	0.949***	0.929**	0.929**	0.929**	0.929**	0.919**	0.919**
	(0.361)	(0.363)	(0.363)	(0.363)	(0.363)	(0.366)	(0.366)
Share of Thermal Power	0.098	0.099	0.099	0.099	0.099	0.095	0.095
	(0.997)	(0.994)	(0.994)	(0.994)	(0.994)	(0.981)	(0.981)
Constant	-6.152***	-6.054***	-6.054***	-6.054***	-6.054***	-5.967***	-5.967***
	(1.545)	(1.524)	(1.524)	(1.524)	(1.524)	(1.504)	(1.504)
SNCR	(Baseline)						
SNCR-SCR							
Targeted Plant in Key Regions	-1.304	-15.392***	-15.392***	-15.392***	-15.392***	-4.249***	-6.056***
	(0.981)	(0.664)	(0.664)	(0.664)	(0.664)	(1.440)	(1.642)
Provincial Target	-0.013	-0.005	-0.005	-0.005	-0.005	-0.023	-0.023
	(0.051)	(0.050)	(0.050)	(0.050)	(0.050)	(0.046)	(0.046)
NO_x Control Area	-7.828***	-9.063***	-9.063***	-9.063***	-9.063***	-11.143***	-10.398***
	(1.425)	(1.560)	(1.560)	(1.560)	(1.560)	(1.214)	(1.214)
Capacity	8.302***	8.678***	8.678***	8.678***	8.678***	7.379***	7.378***
	(2.245)	(2.155)	(2.155)	(2.155)	(2.155)	(2.065)	(2.064)
Installation Age	0.027	0.027	0.027	0.027	0.027	0.020	0.020
	(0.031)	(0.031)	(0.031)	(0.031)	(0.031)	(0.032)	(0.032)
Selfbuilt	-12.81***	-15.54***	-15.54***	-15.54***	-15.54***	-15.32***	-14.58***
	(0.453)	(0.451)	(0.451)	(0.451)	(0.451)	(0.456)	(0.456)
Emission Standard	2.114	2.278	2.278	2.278	2.278	2.152	2.152
	(2.022)	(2.027)	(2.027)	(2.027)	(2.027)	(2.042)	(2.042)
Utilization	1.103***	1.084***	1.084***	1.084***	1.084***	1.072***	1.072***
	(0.365)	(0.367)	(0.367)	(0.367)	(0.367)	(0.369)	(0.369)
Share of Thermal Power	6.751***	6.746***	6.746***	6.746***	6.746***	6.749***	6.751***
	(2.040)	(2.032)	(2.032)	(2.032)	(2.032)	(2.085)	(2.085)
Constant	-14.97***	-15.10***	-15.10***	-15.10***	-15.10***	-14.61***	-14.61***
	(2.772)	(2.735)	(2.735)	(2.735)	(2.735)	(2.705)	(2.705)
N	1135	1135	1135	1135	1135	1135	1135
$Pseudo\ R_2$	0.537	0.541	0.541	0.541	0.541	0.535	0.535

Note: The dummy variables of *Targeted Plant in Key Regions* in columns (2)–(7) denotes the capacities of 300–800MW, as shown, have operated for fewer than 20 years as of year 2013, and operated in key regions. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.8: Comparisons before and after 2010

	(1) Until 2010	(2) After 2010	(3) Until 2010	(4) After 2010	(5) Until 2010	(6) After 2010
SCR						
East	2.517*	0.417	4.346***	0.200	4.409***	0.214
	(1.438)	(0.394)	(1.277)	(0.411)	(1.301)	(0.418)
West	16.413***	1.043	15.04***	1.085	15.89***	1.099
	(1.114)	(0.874)	(1.149)	(0.875)	(1.153)	(0.876)
Capacity	21.19**	17.23***	16.91*	17.49***	16.54*	17.508***
	(9.132)	(1.281)	(9.354)	(1.345)	(9.058)	(1.358)
Installation Age	0.016	0.103***	-0.004	0.101***	-0.009	0.101***
	(0.038)	(0.021)	(0.046)	(0.022)	(0.047)	(0.022)
Selfbuilt	9.937***	-0.195	10.469***	-0.227	11.444***	-0.214
	(3.676)	(0.449)	(3.718)	(0.451)	(3.647)	(0.453)
Emission Standard	-0.979	-3.149**	0.285	-3.158**	0.478	-3.133**
	(2.661)	(1.490)	(2.548)	(1.494)	(2.527)	(1.492)
Utilization	1.254**	0.538	-0.011	0.505	-0.035	0.480
	(0.553)	(0.429)	(0.072)	(0.420)	(0.057)	(0.427)
Share of Thermal Power	-4.109*	0.260	-2.990	0.011	-3.305	0.139
	(2.466)	(1.218)	(2.824)	(1.299)	(2.927)	(1.273)
GRP			-0.078	0.015		
			(0.051)	(0.017)		
Industrial Value-added					-0.135	0.025
					(0.085)	(0.029)
Constant	-6.424*	-5.195***	-0.769	-5.081***	-0.586	-5.038**
	(3.419)	(1.986)	(4.281)	(1.950)	(4.171)	(1.965)
SNCR	(Baseline)					
SNCR-SCR						
East	17.06***	16.04***	17.83***	14.61***	18.66***	14.63***
	(1.587)	(0.508)	(1.417)	(0.777)	(1.423)	(0.819)
West	15.23***	16.52***	13.53***	16.28***	14.43***	16.37***
	(0.936)	(1.505)	(0.981)	(1.568)	(0.971)	(1.578)
Capacity	15.25	8.341***	10.054	9.279***	9.822	9.288***
	(9.298)	(2.518)	(9.706)	(2.498)	(9.468)	(2.478)
Installation Age	-0.130**	0.075*	-0.167**	0.069	-0.180**	0.067
	(0.052)	(0.041)	(0.067)	(0.043)	(0.071)	(0.043)
Selfbuilt	10.230***	-15.116***	10.729***	-15.010***	11.720***	-14.874***
	(3.542)	(0.662)	(3.558)	(0.694)	(3.499)	(0.699)
Emission Standard	7.275**	-5.179**	9.621**	-5.041**	10.006**	-5.058**
	(3.383)	(2.197)	(3.883)	(2.295)	(3.910)	(2.287)
Utilization	1.416**	1.119*	0.152	1.075	0.115	0.952
	(0.564)	(0.648)	(0.126)	(0.704)	(0.116)	(0.690)
Share of Thermal Power	4.432	10.045***	5.507	7.751**	4.869	8.490***
	(4.698)	(3.067)	(5.168)	(3.266)	(5.202)	(3.133)
GRP			-0.138**	0.054*		
			(0.062)	(0.029)		
Industrial Value-added					-0.246**	0.096*
					(0.104)	(0.056)
Constant	-34.03***	-31.47***	-26.58***	-29.87***	-27.08***	-29.756***
	(5.775)	(3.776)	(6.642)	(3.560)	(6.622)	(3.507)
N	178	957	178	957	178	957
$Pseudo\ R_2$	0.489	0.577	0.526	0.580	0.535	0.580

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

Table 3.9: The effects of subsidy on technological choice

	(1)	(2)	(3)
SCR			
Subsidy 2011	-0.990**	-0.971*	-0.971*
	(0.501)	(0.505)	(0.504)
Subsidy 2013	-0.571	-0.582	-0.573
	(0.468)	(0.472)	(0.473)
Provincial Target	0.017	0.0072	0.008
	(0.039)	(0.043)	(0.044)
Capacity	16.76***	16.99***	16.97***
	(1.290)	(1.375)	(1.374)
Installation Age	0.101***	0.0992***	0.0992***
	(0.024)	(0.025)	(0.025)
Selfbuilt	0.035	-0.007	0.005
	(0.484)	(0.490)	(0.490)
Emission Standard	-3.223**	-3.190**	-3.183**
	(1.575)	(1.622)	(1.623)
Utilization	0.795*	0.765*	0.753*
	(0.412)	(0.410)	(0.416)
Share of Thermal Power	-0.851	-1.021	-0.934
	(1.039)	(1.074)	(1.064)
GRP		0.009	
		(0.016)	
Industrial Value-added			0.0146
			(0.029)
Constant	-4.675**	-4.522**	-4.505**
	(2.005)	(2.000)	(2.011)
SNCR	(Baseline)		
SNCR-SCR			
Subsidy 2011	-1.710*	-1.720**	-1.722**
	(0.885)	(0.870)	(0.867)
Subsidy 2013	-1.106	-1.242	-1.232
	(0.815)	(0.811)	(0.812)
Provincial Target	0.305*	0.119	0.116
	(0.177)	(0.179)	(0.182)
Capacity	8.180***	8.578***	8.514***
	(2.625)	(2.531)	(2.521)
Installation Age	0.073	0.069	0.067
	(0.045)	(0.045)	(0.046)
Selfbuilt	-10.81***	-13.12***	-13.08***
	(0.800)	(0.770)	(0.767)
Emission Standard	-6.084***	-5.697***	-5.695***
	(2.139)	(2.182)	(2.198)
Utilization	2.372***	2.129***	2.049***
	(0.627)	(0.583)	(0.568)
Share of Thermal Power	5.168*	3.951	4.660
	(3.122)	(2.915)	(3.038)
GRP		0.051*	
		(0.026)	
Industrial Value-added			0.086*
			(0.050)
Constant	-21.21***	-17.64***	-17.59***
	(5.988)	(4.726)	(4.555)
N	957	957	957
$Pseudo\ R_2$	0.574	0.577	0.576

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

Table 3.10: Installation status on 2012: logit models

Dependent variable: Installation2012	(1)	(2)	(3)	(4)	(5)	(6)
Provincial Target 2012	0.038***	0.081***	0.074***	0.038***	0.080***	0.072***
	(0.014)	(0.024)	(0.023)	(0.014)	(0.024)	(0.023)
NO_x Control Area				-0.560*	-0.516	-0.505
				(0.328)	(0.327)	(0.328)
Capacity	0.648***	0.574**	0.603**	0.692***	0.615**	0.643**
	(0.249)	(0.250)	(0.250)	(0.251)	(0.252)	(0.251)
Operation Year	0.041***	0.039***	0.039***	0.040***	0.039***	0.039***
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Utilization	0.007	0.010	0.009	0.002	0.005	0.004
	(0.028)	(0.027)	(0.027)	(0.028)	(0.027)	(0.027)
Share of Thermal Power	0.224	0.178	0.115	-0.028	-0.051	-0.107
	(0.418)	(0.446)	(0.447)	(0.440)	(0.466)	(0.466)
GDP		-0.025***			-0.024***	
		(0.007)			(0.007)	
Industrial Value-added			-0.036***			-0.035***
			(0.012)			(0.012)
Constant	-82.79***	-79.42***	-79.30***	-81.49***	-78.25***	-78.19***
	(26.44)	(25.63)	(25.57)	(26.25)	(25.45)	(25.41)
N	1083	1083	1083	1083	1083	1083
$Pseudo\ R_2$	0.027	0.036	0.033	0.029	0.038	0.035

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

Table 3.11: The characteristics of technology choices in new boilers

	(1)	(2)	(3)	(4)
SCR				
AgeZero	0.424	0.173	0.634	0.436
	(0.440)	(0.448)	(0.462)	(0.436)
Provincial Target	-0.046*	0.003	-0.050*	-0.041
	(0.026)	(0.045)	(0.027)	(0.026)
Capacity	16.63***	17.22***	16.83***	16.94***
	(1.273)	(1.413)	(1.343)	(1.345)
Operation Time	-0.081***	-0.082***	-0.084***	-0.081***
	(0.022)	(0.022)	(0.022)	(0.022)
Selfbuilt	-0.293	-0.059	-0.254	-0.286
	(0.426)	(0.479)	(0.414)	(0.423)
Emission Standard	-2.093*	-2.857**	-2.424**	-1.625
	(1.084)	(1.255)	(1.129)	(1.074)
Utilization	0.928***	0.925***	0.922***	0.868**
	(0.353)	(0.349)	(0.348)	(0.343)
capacity_share	-0.824	-1.290	-0.732	-0.058
	(0.955)	(1.026)	(0.976)	(0.953)
GDP	0.014	0.009	0.016	0.016
	(0.012)	(0.013)	(0.012)	(0.012)
12th FYP		-1.221		
		(0.844)		
Targeted Plant in 12th FYP			-0.950	
			(0.779)	
NO_x Control Area				2.614**
				(1.218)
Constant	157.0***	161.2***	164.1***	155.9***
	(44.05)	(45.02)	(44.33)	(44.84)
SNCR	Baseline			
SNCR-SCR				
AgeZero	-0.674	-1.314	-0.274	-0.672
	(0.974)	(1.077)	(1.000)	(0.970)
Provincial Target	-0.079	0.193	-0.081*	-0.073
	(0.048)	(0.169)	(0.048)	(0.048)
Capacity	8.657***	9.749***	8.850***	8.934***
	(2.069)	(2.118)	(2.087)	(2.122)
Operation Time	-0.035	-0.034	-0.039	-0.035
	(0.034)	(0.035)	(0.034)	(0.034)
Selfbuilt	-13.672***	-12.674***	-13.734***	-15.552***
	(0.464)	(0.614)	(0.466)	(0.466)
Emission Standard	0.427	-0.981	0.058	0.709
	(1.989)	(2.018)	(2.053)	(2.007)
Utilization	1.099***	1.086***	1.085***	1.029***
	(0.358)	(0.353)	(0.353)	(0.348)
Share of Thermal Power	6.603***	5.844**	6.488***	6.897***
	(2.444)	(2.580)	(2.425)	(2.480)
GDP	0.038**	0.015	0.039**	0.038**
	(0.018)	(0.018)	(0.018)	(0.018)
12th FYP		-5.156*		
		(2.886)		
Targeted Plant in 12th FYP			-12.51***	
			(1.278)	
NO_x Control Area				-10.381***
				(1.264)
Constant	56.08	56.56	64.40	56.39
	(69.28)	(71.58)	(70.06)	(69.84)
N	1135	1135	1135	1135
$Pseudo\ R_2$	0.539	0.544	0.540	0.544

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

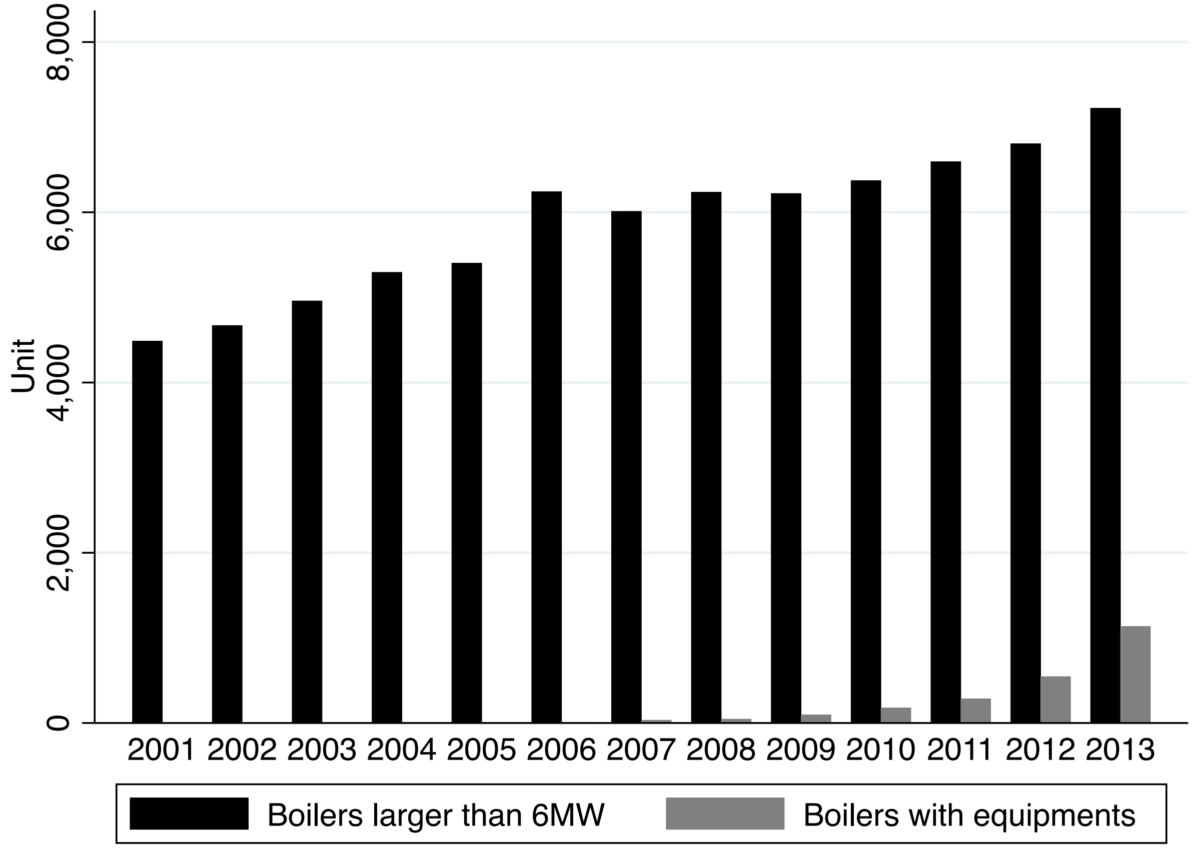

Figure 3.1: Total number of boilers and boilers with NO_x control equipment: 2001–2013
Note: Total number of boilers is taken from respective years' edition of China Electric Power Yearbook. Since the historical data is available only for boilers with capacity larger than 6MW, it does not coincide with numbers mentioned in Section 1.

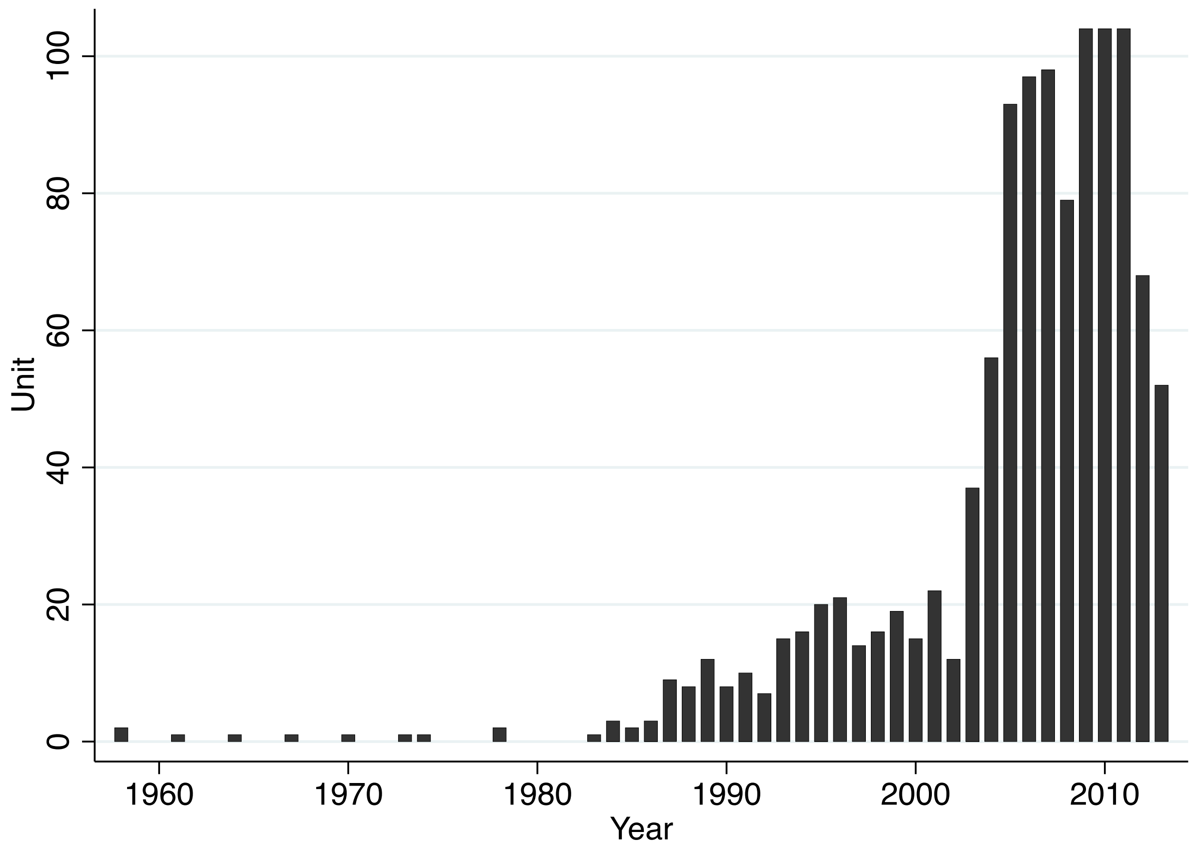

Figure 3.2: Number of boilers starting operations: 1950s–2010s

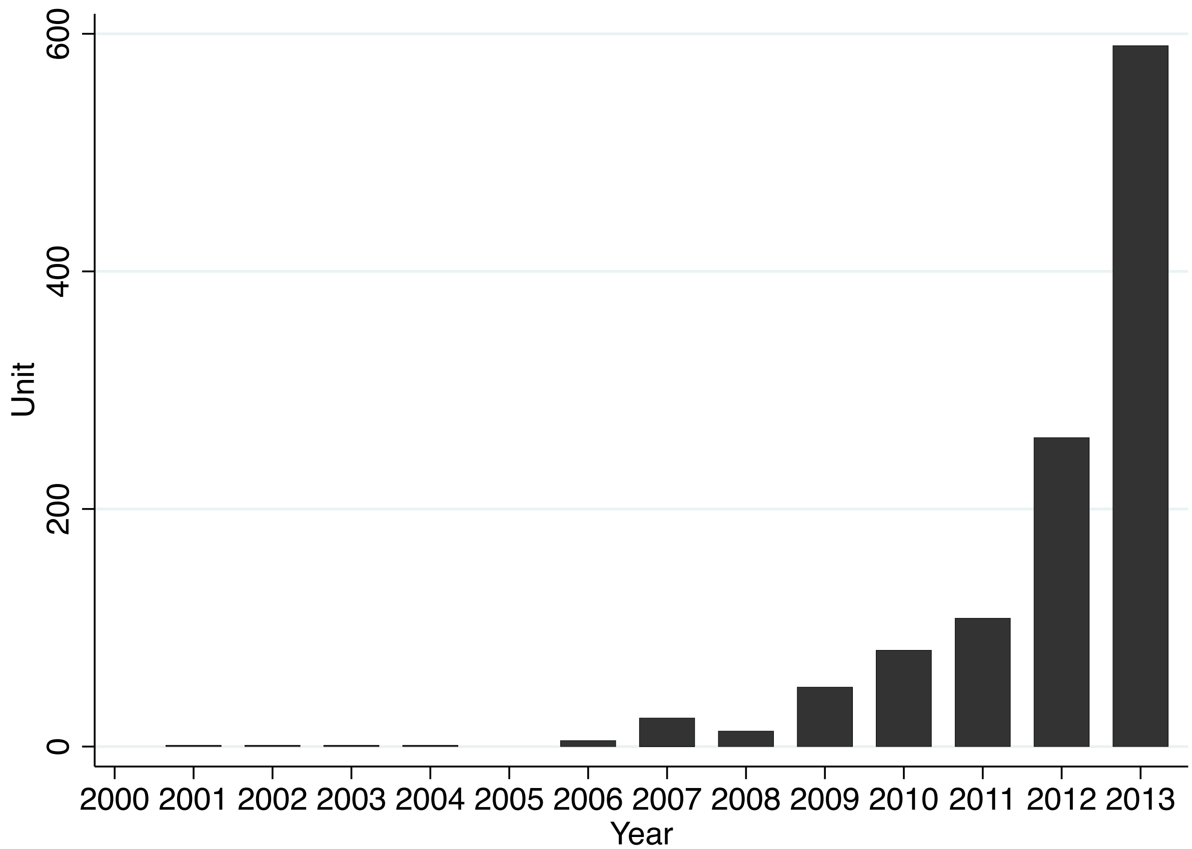

Figure 3.3: Number of boilers installed NO_x control equipment: 2000–2013

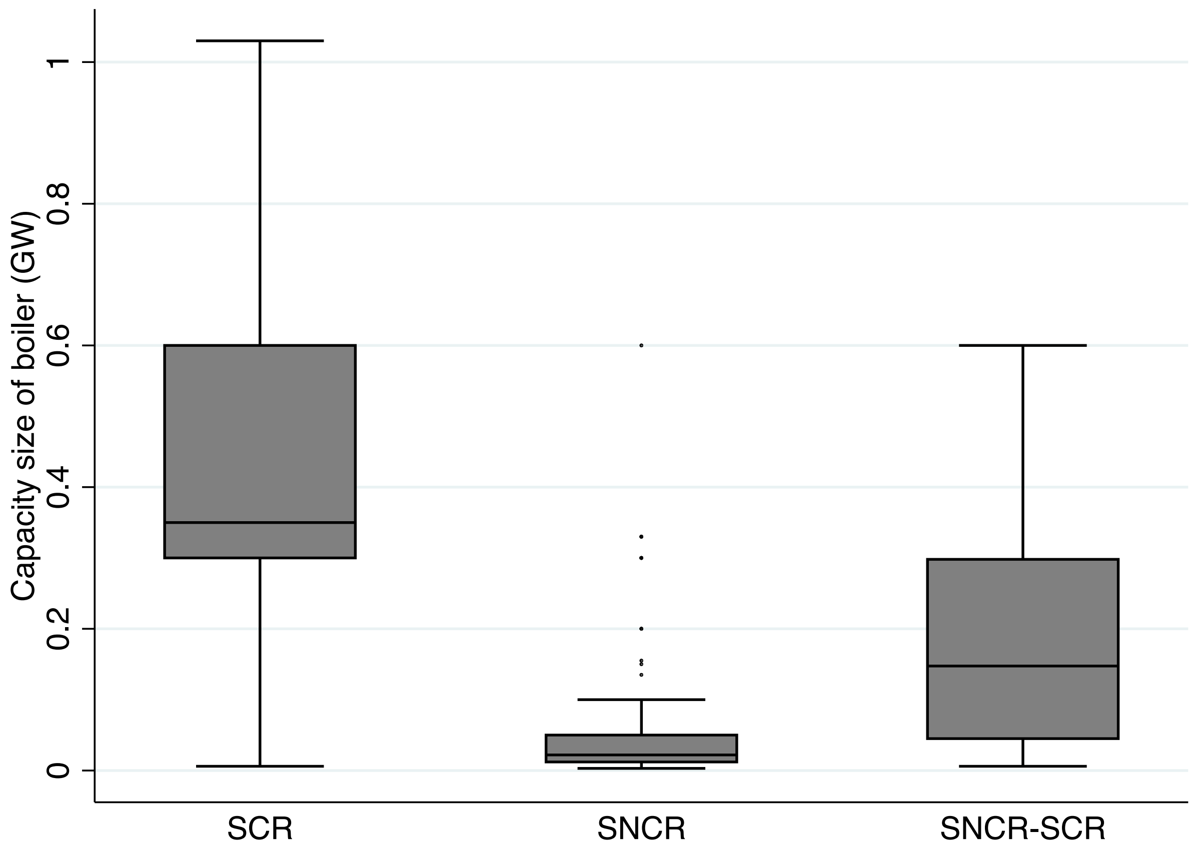

Figure 3.4: Distribution of boiler capacity for each technology

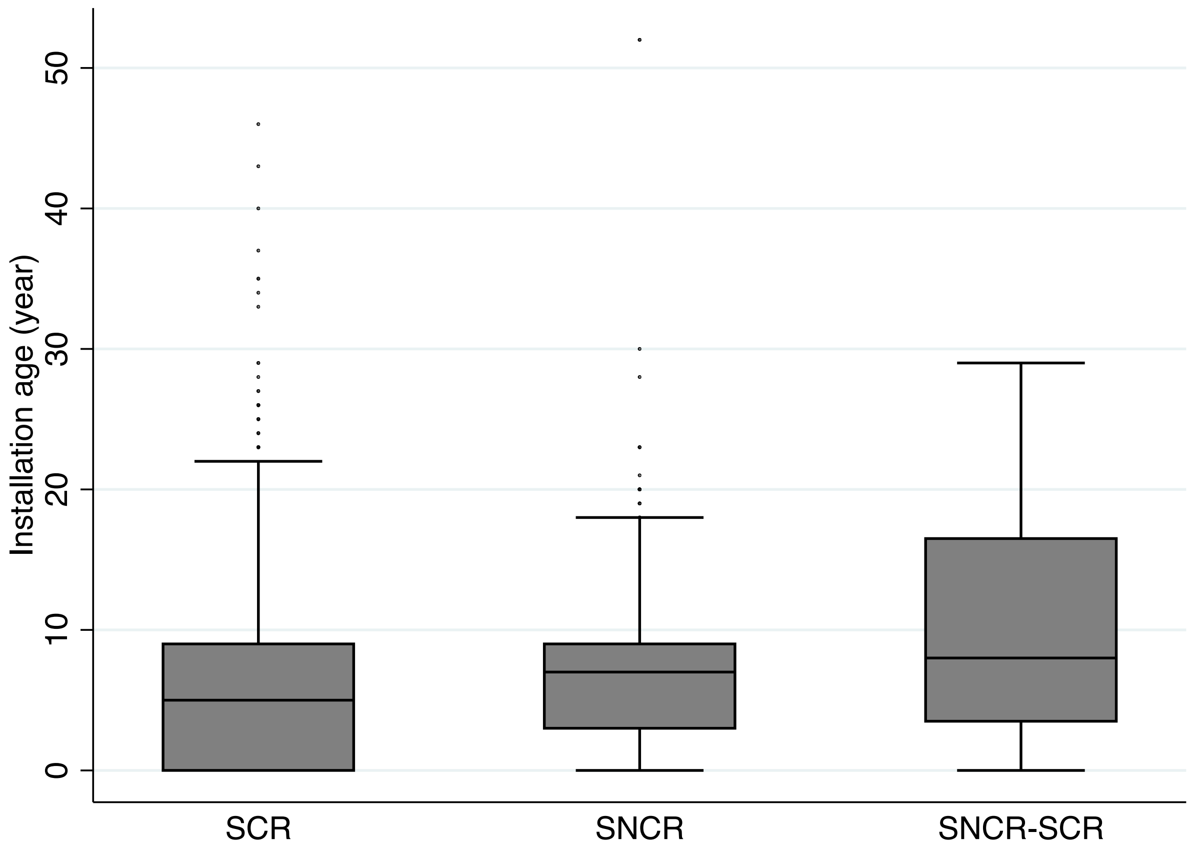

Figure 3.5: Distribution of installation age for each technology

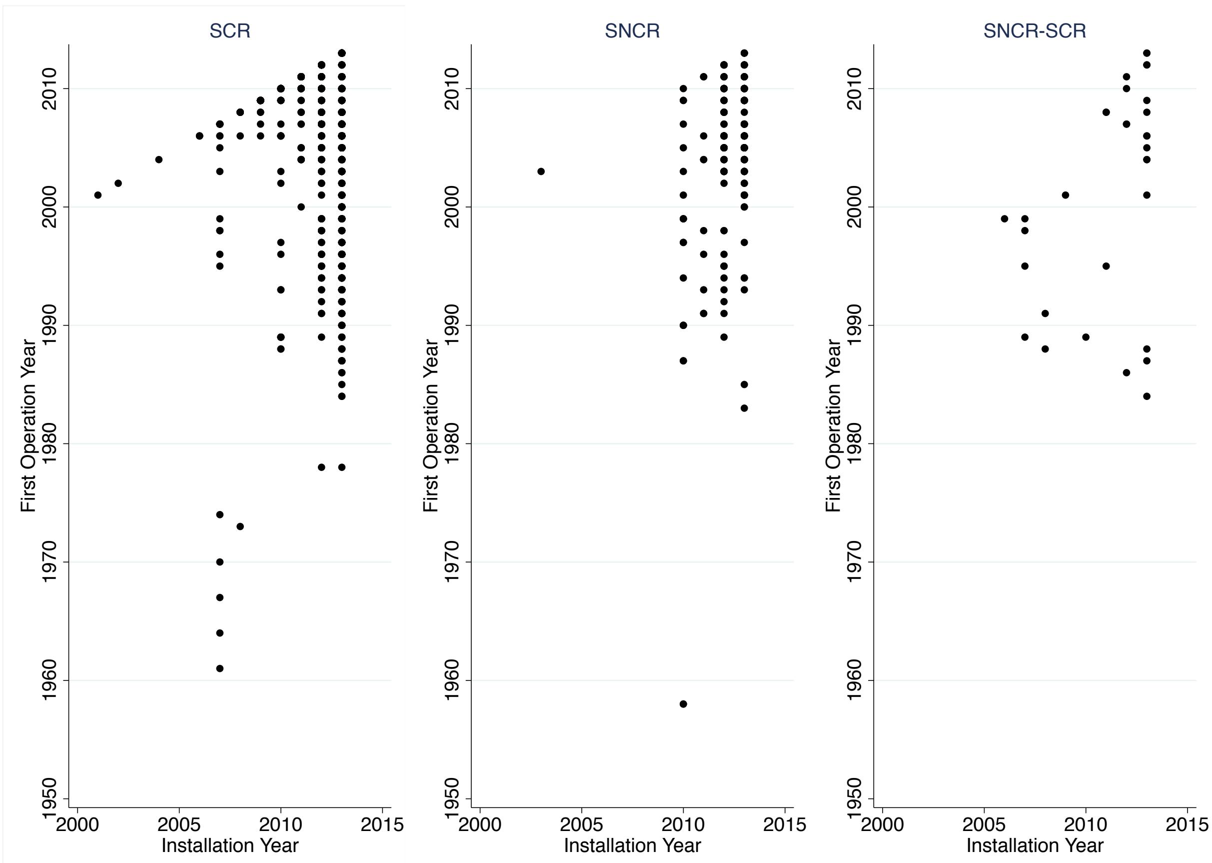

Figure 3.6: First operation year and installation year

Chapter 4

The effect of Beijing Olympic Games on air pollution control in thermal power sector

4.1 Introduction

Air pollution is an important global risk factor for disease. The Health Effects Institute (2017) reports that exposure to $PM_{2.5}$ is the 5^{th} biggest risk factor for death and is responsible for 4.2 million deaths from heart disease and stroke, lung cancer, chronic lung disease, and respiratory infections. The level of pollution is particularly serious in Asian countries: 86% of the most extreme concentrations (above $75\mu g/m^3$) are experienced by populations in China, India, Pakistan, and Bangladesh. Although stringent environmental policies are necessary to reduce harmful health risks in these countries, it is often difficult to enforce effective regulations owing to rapid economic growth and population increases.

In this study, we examine the effect of the 2008 Beijing Olympic Games (BOG08) on air pollution control in Beijing and neighboring provinces. As a big event that attracts international attentions, the Olympic Games offer a great opportunity for a country to promote ambitious policy for environmental improvement. The Beijing Olympic Committee for the Games of XXIX Olympiad (BOCOG) and the Beijing Municipal Government launched the "Green Olympics" concept and integrated several environmental targets into the bid with accelerated deadlines. In particular, air quality improvement was a top priority in planning for the Games. The actions for air pollution control reduced the Air Pollution Index (API) in Beijing by 24.9% during the Games, compared with that of 1 year before any Olympic-motivated actions (Chen et al., 2013).

Several studies have investigated the impact of air quality control during the BOG08. Chen et al. (2013) use officially reported API from 2000 to 2009 and show that policy measures improved the API of Beijing during and shortly after the Games. In addition, the authors find that most of the improvement in air quality dissipated 1 year after the Games, suggesting that the improvement was temporary. He et al. (2016) estimate the effect of air pollution on mortality in China, by using exogenous variations in air quality during the BOG08. The results show that monthly PM_{10} concentrations in Beijing were reduced by approximately 30%. Moreover, the authors find that a 10% reduction in PM_{10} concentrations is associated with an 8% decrease in the overall mortality rate. Viard and Fu (2015) evaluate the pollution and labor supply reductions from driving restrictions, including the period during the BOG08. Based on daily data from multiple monitoring stations, the authors find that the aggregate API falls 18% during the odd–even policy that restricts cars to being driven only every other day. However, these studies do not fully address how the reduction of air pollution was attained in stationary sources, particularly in the thermal power industry.

This study investigates how pollution reduction is attained in the thermal power industry during the BOG08. By using data on pollution control equipment and energy intensity, we examine if there are significant differences in the levels of these measures related to pollution between the provinces under the regional control policy for the BOG08 and the other provinces. The results of this study suggest that the installation level of pollution control equipment, as well as energy intensity, improved in Beijing and the neighboring provinces in 2007 and 2008.

This study makes three contributions. First, in contrast to previous studies that examine the impact of BOG08 on air quality improvement, this study examines the impact of the Games on control measures of air pollution. Because the control measures are directly related to the behavior of emission sources, these measures can reveal how emission reduction is realized as various policies were enforced during the period. Second, this study considers two activities as control measures: installation of pollution control equipment and energy intensity. Both are important measures that determine emissions from thermal power plants, as the former relates to end-of-pipe control and the latter to cleaner production processes. Third, this study focuses on pollution control in the thermal power industry. Nevertheless, this industry is a major contributor to air pollution. Wang et al. (2010) analyze pollution emission reductions during the BOG08 and find that in the pre-Games period, power plants were the largest contributors to SO_2 emissions, which accounted for 11% of total SO_2 emissions in Beijing.

The rest of this paper is organized as follows. Section 4.2 explains the background of study. We introduce a variety of air pollution control policies implemented for BOG08 in a regional control area. Section 4.3 reports the analysis on the effect of BOG08 on installation of pollution control equipment. Section 4.4 presents the analysis on the effect of BOG08 on energy intensity. Section 5 concludes.

4.2 Background

In order to bid for China's Olympic Games, the BOCOG was established in December 2001 (UNEP 2009). The "Green Olympics" concept was launched by the BOCOG and the Beijing Municipal Government to promote the environmental sustainability of the BOG08. Air quality was a particular concern, because of the direct impact of poor air on the health and performance of the athletes. The measures taken to clear the sky for the Games fall into the following five areas: reducing energy consumption growth and improving energy efficiency; closure and relocation of production lines in major industrial industries; emission reduction in the transportation industry; control of dust from construction; and other special short-term measures.

The reduction of air pollution from the thermal power industry includes using clean fuels to replace coal fuels; reducing industrial use of coal; shutting down inefficient power plants, steel companies, and other petrochemical plants; installation of desulfuration, denitration, and dust removal equipment for boilers; and promoting the retirement of old boilers. Beijing's effort to reduce air pollutants in the thermal power industry for the BOG08 began as early as late 2002 (Chen et al., 2013). In 2003 and 2004, Beijing reduced its industrial use of coal by 10 million tons and shut down coal-fired generators at the Capital Steel Company and Beijing Coking Plant. Between 2005 and 2006, desulfuration, denitration, and dust removal facilities are constructed at the Beijing Thermal Power Plant and the power plant of Capital Steel. In addition, Beijing renovated 100% of its boilers for clean fuel in five districts, and 50% in three other districts by late 2006.

As Streets et al. (2007) suggest, neighboring provinces and municipalities, such as Hebei, Shandong, and Tianjin, significantly contribute to air pollution in Beijing. Recognizing this point of view, the State Council of China issued "Measures to Ensure Good Air Quality in the 29th Beijing Olympics and Paralympics (MEGA)" policy in October 2007. This is a wider regional control policy for six provinces, including Beijing and the neighboring provinces of Tianjin, Hebei, Shandong, Shanxi, and Inner Mongolia (He et al., 2016). Beijing and these neighboring provinces and cities were required to retire outdated production facilities in power plants and to install desulfurization facilities. The Chinese Ministry of Environmental Protection coordinated the governments of these provinces and cities to improve air quality through cooperation (Chinese Ministry of Environmental Protection, 2012).

Tianjin government required all thermal power plants to install desulfurization equipment before June 2008 (People's Daily, 2008). Furthermore, the government asked coal boiler to adopt clean coal (Government of Tianjin, 2008). In Hebei, a closure list was compiled for small thermal power plants, which were required to close in 2007. In Shijiazhuang, all coal-fired boilers in Tangshan, Langfang, Baoding (the key regions designated by Hebei government) were required to install desulfurization and dust removal equipment if the capacity of a boiler was larger than 4 tons. Moreover, all boilers for electricity generation in the key region were ordered to use clean coal (Government of Hebei, 2007). Shanxi Province is one of the biggest electricity producers in China. The Shanxi Provincial Government requested a part of thermal power plants to install desulfurization equipment during the pre-Olympic Games (i.e., from November 2007 to July 2008). In addition, during the Olympic Games, the SO_2 and NO_x discharges in thermal power plants were controlled. Shandong reduced SO_2 emissions by 1.82 million tons in 2007, which is a reduction of 7.12% from the emission level in 2006. Thermal power plants that failed to achieve the SO_2 standards were required to shut down during the BOG08 (Government of Shandong, 2008). Furthermore, the monitoring of air pollution was reinforced during the period (Environmental Protection Bureau of Shanxi, 2007). In Inner Mongolia, the Provincial Government set regional controls, including for Huhhot, Baotou, Chifeng, Xilingol, and Ulanqab. Thermal power plants were required to install desulfurization and denitration equipment or even to close from January 1, 2007 to September 20, 2008 (Government of Inner Mongolia, 2007). These policy measures in neighboring provinces were important for reducing air pollution in Beijing. Xu et al. (2016) analyze the impact of air pollution controls in the North China Plain during the BOG08 and find that a large reduction of $PM_{2.5}$ was mainly due to regional transportation within the area beyond Beijing.

In order to estimate the effects of BOG08 on air pollution controls in the thermal power industry, we set *Treatment Area* as the provinces under the MEGA policy: Beijing, Tianjin, Hebei, Shandong, Shanxi, and Inner Mongolia. In addition, we set nine provinces neighboring the *Treatment Area* as the *Control Area*: Heilongjiang, Jilin, Liaoning, Gansu, Ningxia, Shaanxi, Henan, Anhui, and Jiangsu. The areas are shown in Figure 4.1.

[Figure 4.1]

4.3 Data

We use two primary data sets for dependent variables throughout our analysis. First, we use installation of pollution control equipment in the thermal power industry. There are two types of pollution control equipment examined: a desulfurization system for removing sulfur and a denitration system for removing nitrogen oxides. Both data types are taken from the website of the data center of the Chinese Ministry of Environmental Protection. Second, we use energy intensity of the thermal power industry. Energy intensity is calculated from the *Compilation of Statistics on Chinese Electric Power Industry* (China Electricity Council, respective years). In addition, we use control variables that might affect installation of control equipment and energy intensity. Table 4.1 provides summary statistics for the main variables.

4.3.1 Pollution control data

Data on pollution control equipment come from *the List of Pollution Control Equipment of Coal-Fired Boilers* by the data center of the Chinese Ministry of Environmental Protection (2014a, 2014b, 2015).[1] The list contains information of 4,659 coal-fired boilers that have installed desulfurization equipment and 1,135 coal-fired boilers that have installed denitration equipment. It includes name of each boiler, the province where the boiler is located, the year when the boiler started operation, the capacity of the boiler, the type of technology of desulfurization and denitration, the year when the equipment was installed, and the name of the company that manufactured pollution control equipment. We use information of the year when the equipment was installed and aggregate the capacity of the boiler that installed

[1]http://datacenter.mep.gov.cn

equipment by province for each year from 2003 to 2012. By dividing this number by the total capacity of boilers that are operating in each province in each year, taken from the China Energy Statistical Yearbook, we construct provincial-level panel data of the share of boilers that installed pollution control equipment among all boilers. Table 4.1 provides summary statistics of the pollution control data. During the study period, the share of boilers with pollution control equipment is 54.1% for desulfurization equipment and 13.3% for denitration equipment. Because the implementation of policy to control SO_2 started earlier than that to control NO_x, the average share of boilers with desulfurization equipment is higher than that of boilers with denitration equipment.

[Table 4.1]

4.3.2 Energy intensity data

Energy intensity data come from *Compilation of Statistics on Chinese Electric Power Industry* by the China Electricity Council. It contains plant-level information of thermal power plants in China. We calculate the energy intensity of 4,568 thermal power plants from 2003 to 2012 by dividing total coal consumption of each plant by total electricity generated by each plant. The mean value of energy intensity of all thermal power plants in China is 409 grams per kWh, regardless whether it the plant generates electricity as its main purpose or is in other industries, such as steel and chemicals. Approximately 92% of thermal power plants are coal fired power plant. Energy intensity in a coal-powered plant is usually higher than in an oil and gas-fired power plant.

4.3.3 Control variables

The pollution control regressions include gross regional production (GRP) per capita, pollution levy, and electricity price as control variables. GRP per capita is taken from the China Statistical Yearbook. Pollution levy data in each province are taken from the China

Environment Yearbook (Editorial Committee of China Environment Yearbook, respective years). The on-grid electricity prices are taken from the CEIC database (CEIC, 2015).

For the energy intensity regressions, we include self-use, generation, and utilization. Self-use is a variable that represents percentage of electricity used by the plant in each year. Generation is the amount of electricity generated by the plant in each year. Utilization is hours that the plant is in operation in each year. All of these data are taken from *Chinese power industry statistics compilation*.

4.4 Effect of BOG08 on pollution control

We use a difference-in-differences (DID) model to estimate the impact of BOG08 on air pollution controls by thermal power plants. Because the MEGA policy was issued in October 2007 and the Games finished on September 17, 2008, we define the period dummy variable of BOG08 from 2007 to 2008. The estimation model is represented as follows:

$$S_i = \alpha + \gamma Area_r + \lambda Time_t + \beta AreaTime_{rt} + \phi X_i + \epsilon_i, \quad (4.1)$$

where S_i represents the installation share of desulfurization ($Share\_sulfur_i$) or denitration ($Share\_nitrogen_i$) equipment by generation capacity in province i. The share is calculated by dividing the total capacity of boilers that installed end-of-pipe equipment by the total capacity of thermal power boilers. $Area_r$ is a regional dummy variable. It takes the value of 1 for six provinces in which the MEGA policy was designated, and 0 otherwise. $Time_t$ is a period dummy variable. It takes the value of 1 for the period from 2007 to 2008, and 0 otherwise. $AreaTime_{rt}$ is the cross-term of $Area_r$ and $Time_t$ to capture the impact of regional control policy on installation level of end-of-pipe equipment.

In addition, we include several control variables (X_i) in the model, not only to control for confounding trends but also to reduce the variance of ϵ_i. We use three control variables in the model. First, $Levy_i$ represents the pollution levy for total pollutants discharged in province

i. China has applied a pollution levy system to control industrial emissions since 2003. The benefits of pollution control are expected to increase with higher levels of pollution levy. It provides stronger incentives for the thermal power industry to install end-of-pipe equipment. The pollution levy of SO_2 emissions increased from 0.42 RMB/kg in 2004 to 1.26 RMB/kg in 2007 (JES, 2007; OECD, 2007). Second, GRP_i indicates the GRP per capita in province i. It shows the level of economic development in each province. We consider that the share of boilers with control equipment is higher in developed provinces. Third, $Price_i$ represent the on-grid electricity price in province i. After $Stipulation\ of\ Electrical\ Law$ was issued in 1996, power plants were allowed to earn reasonable profits from electricity tariffs. From July 2003, a market-based pricing system was introduced in the thermal power industry. In consideration of average social costs in each province, provincial-specific benchmark on-grid tariffs were applied in power generation. The benchmark on-grid tariffs reflect the difference in social development, economic development, and energy supply across provinces. From 2006, under China's energy conservation and environmental protection policies, on-grid tariffs have been used to provide incentives for power producers to phase-out small-sized, low-efficiency, and high-polluting coal-fired generation units (Ma, 2011). We assume that a higher on-grid tariff is associated with a higher capacity share of end-of-pipe equipment because of the efficiency effect.

[Figure 4.2]

Figure 4.2 shows the trends in installation of end-of-pipe equipment in the thermal power industry. The capacity share of desulfurization equipment in $Treatment\ Area$ is higher than that in $Control\ Area$ until 2009 (the year after of the Beijing Olympic Games), but after 2010, becomes lower. The SO_2 emissions control policy in China started during the $10th$ Five-Year Plan period (2001–2005). Until the end of 2007, 17 GW of thermal power boilers cumulatively installed desulfurization equipment in $Treatment\ Area$. We hypothesize that, even though the SO_2 emissions control policies started earlier than preparations started for BOG08, the installation level of desulfurization equipment accelerated because of the demand for cleaner air during the BOG08 period in *Treatment Area* than *Control Area*.

[Figure 4.3]

In contrast to the regulation of SO_2 emissions, the government began to control NO_x emissions in the thermal power industry from the $11th$ Five-Year Plan (2006–2010) and seriously implemented controls from the $12th$ Five-Year Plan period (2011–2015). Figure 4.3 presents the trends in installation of end-of-pipe equipment in the thermal power industry. The capacity share of installed denitration equipment in *Treatment Area* is higher than that in *Control Area* from 2007 to 2013.

The results of the simple DID model are presented in Table 4.2. Columns (1) and (2) show the results for desulfurization equipment; columns (3) and (4) show the results for denitration equipment. Control variables are included in the models shown in columns (2) and (4). The cross-term $AreaTime_{rt}$ is statistically insignificant in both models for desulfurization and denitration. This suggests there is no significant impact by BOG08 on the level of end-of-pipe control.[2]

[Table 4.2]

In the simple DID model shown above, the serial correlation cannot be dealt with. Province- and year-specific random effects might cause a clustering problem that affects statistical inference. Therefore, we also analyze the model in a panel data setting. To consider the small sample size, we use the least square dummy variable method to estimate the fixed effects. All regional dummy variables and time dummy variables are included in the model: Dum_pro_i represents the province dummy and Dum_year_j is the year dummy.

$$S_{it} = \alpha + \beta AreaTime_{rt} + \sum_{i=1}^{14} \xi_i Dum\_pro_i + \sum_{j=1}^{9} \eta_j Dum\_year_j + \phi X_{it} + \upsilon_i + \epsilon_{it}, \qquad (4.2)$$

[2]As a robustness check, we estimate a model setting all other provinces as a control area. The result is similar to our main analysis and $AreaTime_{rt}$ is statistically insignificant.

Table 4.3 reports the results of the fixed-effects model. The coefficients of $AreaTime_{rt}$ are positive and statistically significant in models for desulfurization equipment when the control variables are not included, but they are insignificant in models with the control variables. The coefficients of $AreaTime_{rt}$ are positive and statistically significant in all models for denitration equipment. [3]

[Table 4.3]

In order to investigate the effects of regional control policy in each year further, we use a multiple-period fixed-effects DID model. We introduce $AreaDum\_year_{rj}$, which are interaction terms between $Area_r$ and Dum_year_j. The coefficient of $AreaDum\_year_{rj}$ demonstrates the effects of regional control policy on installed end-of-pipe equipment by each year.

$$\begin{aligned} S_{it} =& \alpha + \sum_{j=1}^{9} \beta_j AreaDum\_year_{rj} + \sum_{i=1}^{14} \xi_i Dum\_pro_i \\ &+ \sum_{j=1}^{9} \eta_j Dum\_year_j + \upsilon_i + \epsilon_{it}, \end{aligned} \tag{4.3}$$

Figure 4.4 shows the treatment area effect of installed desulfurization equipment for each year. We use 2006 as the baseline year of this model. The installation effects of desulfurization equipment are negative but statistically insignificant during 2007–2008 (the period defined as the MEGA policy in this study). The result suggests that installation of desulfurization equipment in $Treatment\ Area$ is not significantly different from that in $Control\ Area$ in these periods. In addition, the figure shows that the impact becomes negative and statistically significant after 2010. This suggests that, after the BOG08 period, there is more installation of control equipment in $Control\ Area$ than in $Treatment\ Area$.

[Figure 4.4]

[3] A similar result is obtained by a robustness check by a model setting all other provinces as a control area.

Figure 4.5 reports the result for denitration equipment for each year. The effects on denitration equipment are statistically insignificant in each year. This suggests that the treatment area effect in each year is not significantly different from that in 2006.

[Figure 4.5]

To break down the treatment effects for each province further, we use a multiple-region fixed-effects DID model. $Dum\_AreaproTime_{it}$ is the cross-term of $Dum\_Areapro_i$ and $Time_t$, where $Dum\_Areapro_i$ is a dummy variable for each province in $Treatment\ Area$, using Beijing as a base category. It captures the difference in installation level of end-of-pipe equipment in each province of $Treatment\ Area$ during the BOG08. β_i is the coefficient on the ith province.

$$\begin{aligned} S_{it} =& \alpha + \sum_{i=1}^{5} \beta_i Dum\_AreaproTime_{it} + \sum_{i=1}^{14} \xi_i Dum\_pro_i \\ &+ \sum_{j=1}^{9} \eta_j Dum\_year_j + \upsilon_i + \epsilon_{it}, \end{aligned} \tag{4.4}$$

Figure 4.6 shows the results of the estimation. The effects of BOG08 on desulfurization equipment is statistically significant only in Tianjin. The installation level of desulfurization equipment in Tianjin is 37% lower than in Beijing in 2007 and 2008. The coefficients for other provinces are statistically insignificant, which suggests that the installation level of desulfurization equipment in other provinces is not significantly different from that in Beijing.[4]

[Figure 4.6]

Figure 4.7 shows the regional effects of installed denitration equipment. Compare to Beijing, the effects of BOG08 on installation of denitration equipment are negative and statistically significant in other provinces. The installation level of denitration equipment in

[4] If we set $Time_t$ as 2008, the desulfurization levels in Hebei, Shanxi, and Inner Mongolia are higher than that in Beijing, and the results are statistically insignificant.

Beijing is 30% higher than other provinces under MEGA policy during the BOG08 period. Therefore, the positive installation effect for denitration equipment might not be due to the MEGA policy, but due to the early introduction of these equipment in Beijing.

[Figure 4.7]

In summary, our results suggest that BOG08 does not significantly promote the installation of pollution equipment. The treatment effect during the BOG08 is not significant in all models, except for denitration equipment. Furthermore, the BOG08 effect on denitration might not be due to the regional control policy for the Games, but to early introduction of equipment in Beijing. One reason might be that the installation of desulfurization equipment has been promoted as national policy from the $10th$ Five-Year Plan period (2001–2005), the period before the BOG08, and the installation of denitration has been promoted from the $12th$ Five-Year Plan period (2011–2015), the period after the BOG08. Among 1135 thermal power boilers examined in this study, 37 thermal power boilers installed denitration equipment during the Beijing Olympic Games period (2007–2008) and 958 thermal power boilers were installed during 2011–2013.

4.5 Effect of BOG08 on energy intensity

By using a simple DID model, we estimate the effects of BOG08 on energy intensity.

$$EI_i = \alpha + \gamma Area_r + \lambda Time_t + \beta AreaTime_{rt} + \phi X_i + \epsilon_i, \tag{4.5}$$

The dependent variable EI_i represents the energy intensity in thermal power plant i. It measures how much coal is required to generate one kWh of electricity. Higher energy intensity means lower energy efficiency of the power plant. The average energy intensity in our data is 428 g/kwh in $Treatment\ Area$, and 392 g/kwh in $Control\ Area$.[5] $Area_r$ is a

[5]Chinese energy intensity has been improving year by year. In order to control energy intensity, "China

regional dummy variable that represents plants located in provinces under the MEGA policy. In our sample, there were 1,246 thermal power plants (approximately 27.28% of all thermal power plants in China) in $Treatment\ Area$ and 1,865 thermal power plants (approximately 40.83% of all thermal power plants in China) in $Control\ Area$. We set a dummy variable $Time_t$, which takes the value of 1 if the period is between 2007 and 2008, and 0 otherwise. $AreaTime_{rt}$ indicates the cross-term of $Area_r$ and $Time_t$.

X_i represents the control variables. $Self\_use_i$ indicates the auxiliary power consumption rate in power plant i. A higher number for $Self\_use_i$ means a reduction of the electricity transmitted to grid.[6] Reduction of auxiliary power use improves the net unit heat.[7] $Generation_i$ is the electricity generation of power plant i. Among our sample, 40% of thermal power plants have generation capacity larger than 300 GWh.[8] $Utilization_i$ represents the annual utilization hours in plant i. Longer utilization time means more electricity generation. The average annual utilization hour in $Treatment\ Area$ is 4,848 hours, which is slightly lower than $Control\ Area$ (5,045 hours).

In addition, we analyze the results with panel data settings. We assume that counterfactual outcomes in the absence of treatment are independent of treatment, and conditional on an individual υ_i and covariates X_{it}. Furthermore, we use a random-effects model, because the sample size is large enough. Under large N and fixed T asymptotics, any kind of serial dependence is allowed in the observables and unobservables.

$$EI_{it} = \alpha + \gamma Area_r + \lambda Time_t + \beta AreaTime_{rt} + \phi X_{it} + \epsilon_{it}, \qquad (4.6)$$

Medium and Long Term Energy Conservation Plan" was issued by the National Development and Reform Commission in November 2004 (Ke et al., 2012). Regarding the thermal power industry, the plan set a target for the Energy Consumption Index (ECI) per unit in the power supply industry to decrease from 392 gce/kwh in 2000 to 320 gce/kwh in 2020.

[6] The auxiliary power use includes a feed-water system, cooling water system, pollution control system, combustion air and fuel gas, fuel handing, and other loads.

[7] The relationship between net heat rate and auxiliary power use can be written as follows: $HR_{net} = \frac{HR_{cycle}}{\eta_B(1-\frac{P_{ss}}{P_G})}$. HR_{cycle} is turbine cycle heat rate, η_B indicates the plants efficiency, and $(1-\frac{P_{ss}}{P_G})$ represents auxiliary power use.

[8] In China, a plant with generation capacity larger than 300 GWh is defined as a large power plant.

[Figure 4.8]

Figure 4.8 shows the change in energy intensity during the study period. The energy intensity level in both areas is steadily decreasing while that in *Treatment Area* is always higher than that in *Control Area*. The figure shows that energy intensity in *Treatment Area* dropped sharply in 2007 and came very close to that in *Control Area*. In Beijing, several large thermal power plants and 16,000 boilers located in the central area of Beijing were requested to change to cleaner fuels during the BOG08 period (Beijing Daily, 2008). Tianjin government requested all coal-fired boilers to use low-sulfur coal based on the following environmental standard for air pollution emissions: DB12/151-2003. The Hebei Government asked all coal-fired boilers in Shijiazhuang, Tangshan, Langfang, and Baoding to use clean coal (Government of Hebei, 2007).

[Table 4.4]

Table 4.5 reports the results of pooled ordinary least squares in columns (1) and (2) and random-effects models in columns (3) and (4). Columns (2) and (4) show the results with control variables. $Area_r$ is positive and statistically significant, which means that the energy intensity in *Treatment Area* is significantly higher than that in *Control Area*. $Time_t$ is negative and statistically significant, which suggests that energy intensity is significantly improved during the BOG08 period. The cross-term $AreaTime_{rt}$ is negative and statistically significant in the random-effects models, suggesting that energy intensity in *Treatment Area* improved during the BOG08 period.[9]

[Table 4.5]

Next, we use a multiple-period random-effects DID model to estimate the year effects.

$$\begin{aligned} EI_{it} =& \alpha + \gamma Area_r + \sum_{j=1}^{9} \beta_j AreaDum\_year_{rj} + \sum_{j=1}^{9} \eta_j Dum\_year_j \\ & + \upsilon_i + \epsilon_{it}, \end{aligned} \tag{4.7}$$

[9] We obtain similar results for the model with a broader definition of *Control Area*.

$AreaDum\_year_{rj}$ are the cross-terms of $Area_r$ and Dum_year_j. These variables capture the effects of the MEGA policy on energy intensity in each year. β_j is the coefficient on the jth lead or lag.

[Figure 4.9]

Figure 4.9 shows the effects of BOG08 on energy intensity in each year. Compared with 2006, the effect is positive and statistically significant in 2007, 2008, and 2009. Energy intensity in $Treatment\ Area$ is reduced to 32.52 g/kWh, 30.28g/kWh, and 20.09 g/kWh in 2007, 2008, and 2009, respectively. This can be interpreted as follows: the effect of BOG08 on the improvement of energy intensity lasted for 3 years.

In order to evaluate the effects of BOG08 on energy intensity in each province, we use a multiple-region random-effects DID model.

$$\begin{aligned} EI_{it} = & \alpha + \gamma Time_t + \sum_{i=1}^{5} \beta_i Dum\_AreaproTime_{it} + \sum_{i=1}^{14} \eta Dum\_pro_i \\ & + \upsilon_i + \epsilon_{it}, \end{aligned} \tag{4.8}$$

Figure 4.10 shows the effects of BOG08 on energy intensity in each province under the MEGA policy. The results show that, compared to Beijing, the reduction of energy intensity in the other five provinces are statistically insignificant during the BOG08 period. This suggests that the impact of the MEGA policy was not different among the provinces involved.

[Figure 4.10]

The abovementioned results can be summarized as follows. First, the energy intensity in $Treatment\ Area$ is higher than that in $Control\ Area$. The results suggest that the energy intensity of thermal power plants operating in provinces under $Treatment\ Area$ are higher than that in other provinces. This might be because provinces in $Treatment\ Area$ are heavily polluted. Hebei is a heavily polluted province in the southern area of Beijing and many cities with poor air quality are located there. Shandong is an important manufacturing province and ranked as a province with the third highest GDP in China. Shanxi is the most important coal-producing province and many coal-fired power plants operate in this region. Second, energy intensity significantly reduced in $Treatment\ Area$ during the BOG08 period. Under the stringent policy, thermal power plants changed their fuel to cleaner fuel and made other efforts to reduce coal consumption. Third, the effects of the BOG08 on cleaner production processes was sustained until 2008. This is in line with Li et al. (2015), who find that in the post-Olympic Games period (2009–2012), emission intensity declined by 147% and reduced overall emissions as much as 24% in Beijing.

4.6 Conclusions

This study has examined the impacts of the BOG08 on pollution control in the Chinese thermal power industry. Our results indicate that the energy intensity of thermal power plants improved in 2007 and 2008 in provinces designated as areas requiring coordinated air pollution control policy for the Olympic Games. On the other hand, such a treatment effect during the BOG08 is almost negligible for pollution control equipment.

As approaches to reducing pollution, control equipment and improvement in energy intensity have similar but somewhat different characteristics. Typically, the end-of-pipe control strategy entails a huge amount of investment and requires considerable fixed costs. Reduction of energy intensity, such as using cleaner fuel or reducing waste heat, is relatively cheaper and affordable even for power plants that do not have enough financial resources.

Our results complement those of Chen et al. (2013) and He et al. (2016), who find a significant but temporal effect of the BOG08 on air quality improvement. The findings of our study suggest that energy intensity reduced during the period in the treatment area. This was because, in many cases, the improvement of energy intensity has persistent effects over the long term, and the change in thermal power plants might be in contrast to the temporal effects caused by reduction of traffic volume. Furthermore, the improvement of energy intensity reasonably contributed to the improvement of air pollution in the area although we did not address this topic in this study. To sustain good air quality even after the Beijing Olympic period, policy that has impacts over a longer time horizon plays an important role.

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Table 4.1: Descriptive statistics for pollution control equipment

VARIABLES	Unit	N	Mean	SD	Min	Max
$Share\_sulfur_i$	%	150	0.541	0.345	0	1.069
$Share\_nitrogen_i$	%	150	0.133	0.224	0	0.960
$Area_r$	Dummy	150	0.400	0.492	0	1
$Time_t$	Dummy	150	0.200	0.401	0	1
GRP_i	10,000 RMB	150	31.11	19.66	6.418	96.61
$Levy_i$	Billion RMB	150	0.615	0.508	0.0251	2.633
$Price_i$	RMB	150	0.611	0.087	0.366	0.881

[a] The unbalanced data are from 2003 to 2012. There are 1,206 thermal power plants served in around Beijing and surrounding region.

Table 4.2: The simple DID results for installation of end-of-pipe equipment

	(1)	(2)	(3)	(4)
S_i	$Share\_sulfur_i$	$Share\_sulfur_i$	$Share\_nitrogen_i$	$Share\_nitrogen_i$
$Time_t$	-0.091	-0.021	-0.124***	-0.061***
	(0.068)	(0.068)	(0.022)	(0.018)
$Area_r$	0.003	-0.215***	0.052	-0.079**
	(0.068)	(0.058)	(0.045)	(0.034)
$AreaTime_{rt}$	0.098	0.063	0.078	0.086
	(0.097)	(0.094)	(0.098)	(0.077)
GRP_i		0.010***		0.008***
		(0.001)		(0.001)
$Levy_i$		0.219***		-0.057*
		(0.043)		(0.030)
$Price_i$		-0.429		-0.225
		(0.266)		(0.139)
Constant	0.550***	0.442**	0.130***	0.083
	(0.047)	(0.178)	(0.022)	(0.086)
N	150	150	150	150
R^2	0.008	0.346	0.055	0.491

Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Note: The robust option is used on all of the models. Control variables are used in columns (2) and (4).

Table 4.3: The fixed effects DID results in installed end-of-pipe equipment

	(1)	(2)	(3)	(4)
S_{it}	$Share\_sulfur_i$	$Share\_sulfur_i$	$Share\_nitrogen_i$	$Share\_nitrogen_i$
$AreaTime_{rt}$	0.098*	0.077	0.078*	0.115**
	(0.050)	(0.055)	(0.046)	(0.049)
GRP_{it}		-0.005*		0.005**
		(0.002)		(0.002)
$Levy_{it}$		0.067		-0.199***
		(0.049)		(0.070)
$Price_{it}$		-0.227		0.167
		(0.144)		(0.127)
Constant	-0.045	0.333	0.438***	0.051
	(0.104)	(0.211)	(0.118)	(0.221)
N	150	150	150	150
R^2	0.902	0.906	0.804	0.833

Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Note: The robust option is used on all of the models. Control variables are used in columns (2) and (4). Year dummy variables and province dummy variables are usually used.

Table 4.4: Descriptive statistics for energy intensity

VARIABLES	Unit	N	Mean	SD	Min	Max
EI_i	g/kwh	13,274	409.4	247.8	6	17,494
$Area_r$	Dummy	13,275	0.472	0.499	0	1
$Time_t$	Dummy	13,275	0.218	0.413	0	1
$Utilization_i$	h	13,275	4,888	1,953	2	8,760
$Self\_use_{it}$	%	12,939	9.091	5.016	0	85
$Generation_{it}$	GWh	13,273	1,254	2,554	0.0200	66,536

[a] The unbalanced data are from 2003 to 2012. There are 1,206 thermal power plants served in around Beijing and surrounding regions. [b] The minimum value of $Utilization_i$ equals 0 because the sets are backup plants.

Table 4.5: Simple and random-effects DID results in energy intensity

	(1)	(2)	(3)	(4)
EI_i	POLS	POLS	RE	RE
$Area_r$	37.54***	16.65***	52.71***	39.97***
	(5.330)	(5.211)	(13.27)	(13.21)
$Time_t$	-9.621**	-10.05**	36.50***	33.08***
	(4.813)	(4.226)	(5.107)	(4.475)
$AreaTime_{rt}$	-11.06	-1.522	-20.27***	-15.85**
	(8.490)	(7.989)	(6.873)	(6.792)
$Self\_use_i$		12.66***		5.309***
		(0.797)		(0.863)
$Generation_i$		-0.011***		-0.002**
		(0.001)		(0.001)
$Utilization_i$		0.001		-0.0001
		(0.002)		(0.002)
Constant	394.9***	296.2***	352.5***	314.7***
	(2.579)	(11.69)	(5.237)	(11.83)
N	13,274	12,936	13,274	12,936
R^2	0.006	0.094		
R_b^2			0.043	0.074

Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Note: The robust option is used on all of the models. Control variables are used in columns (2) and (4). Year dummy variables and province dummy variables are used in random-effects models.

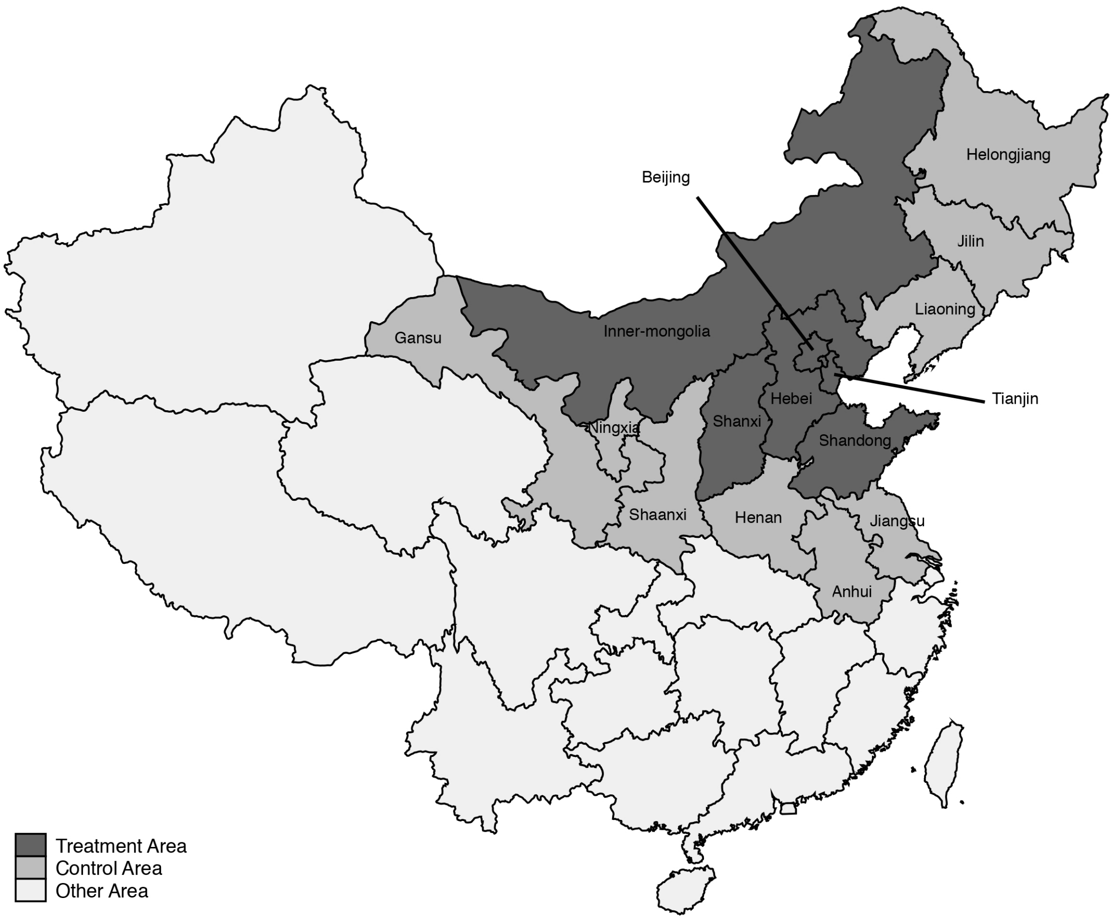


Figure 4.1: The set of *Treatment Area* and *Control Area*

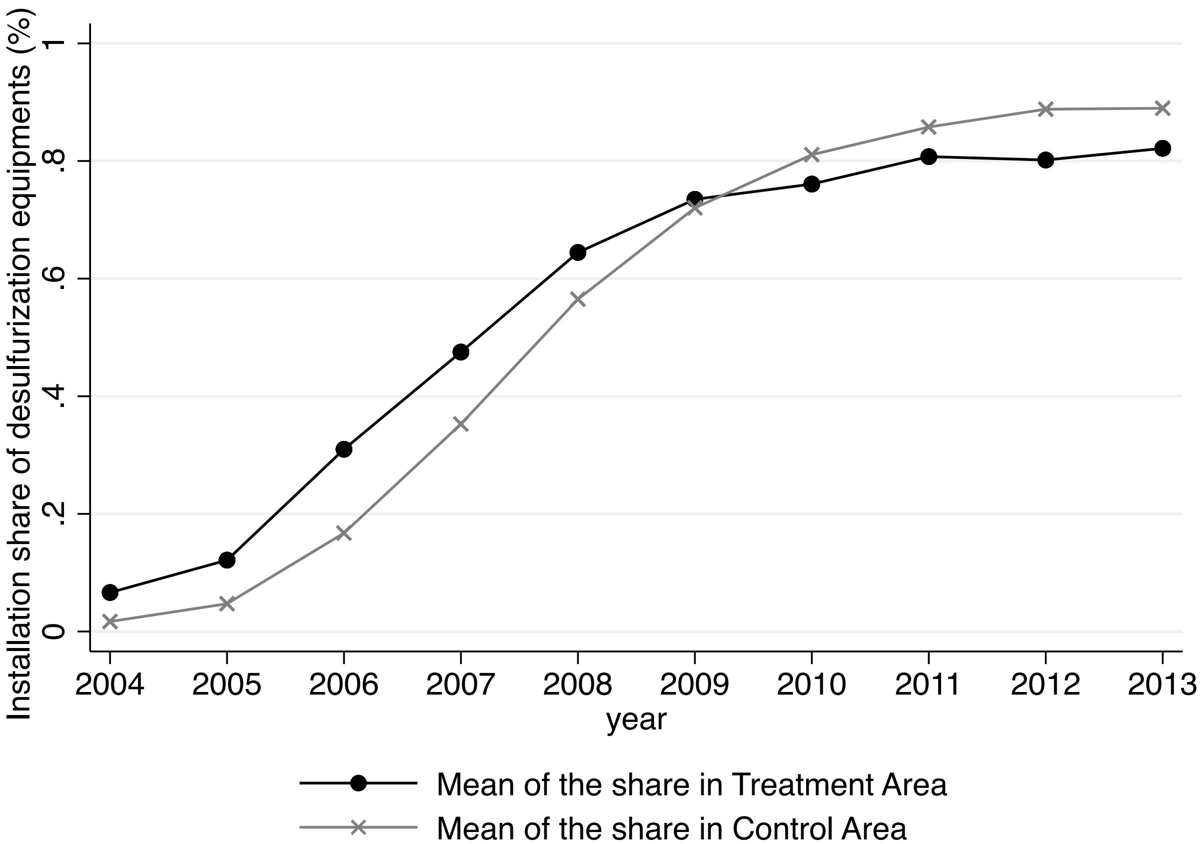


Figure 4.2: The share of desulfurization equipment in thermal power sector which in *Treatment Area*

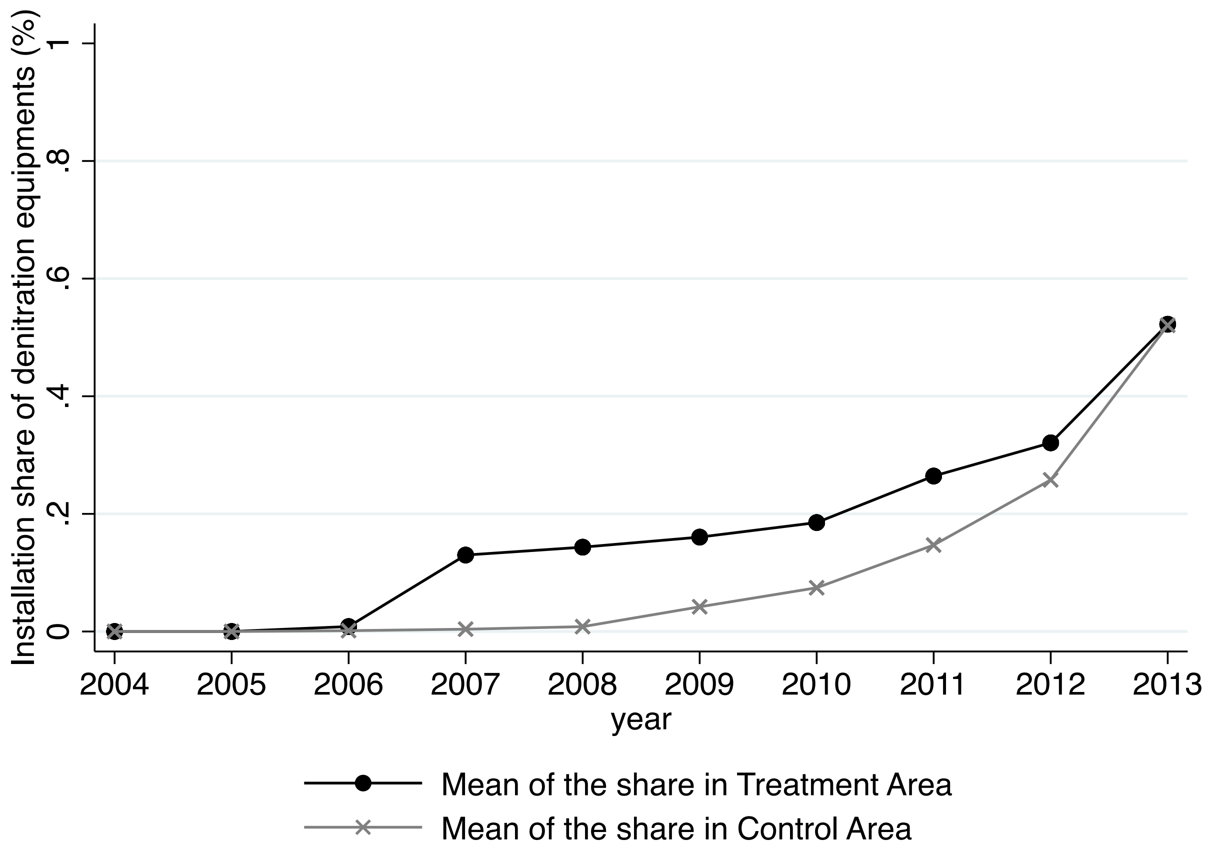


Figure 4.3: The share of denitration equipment in the thermal power industry in *Treatment Area*

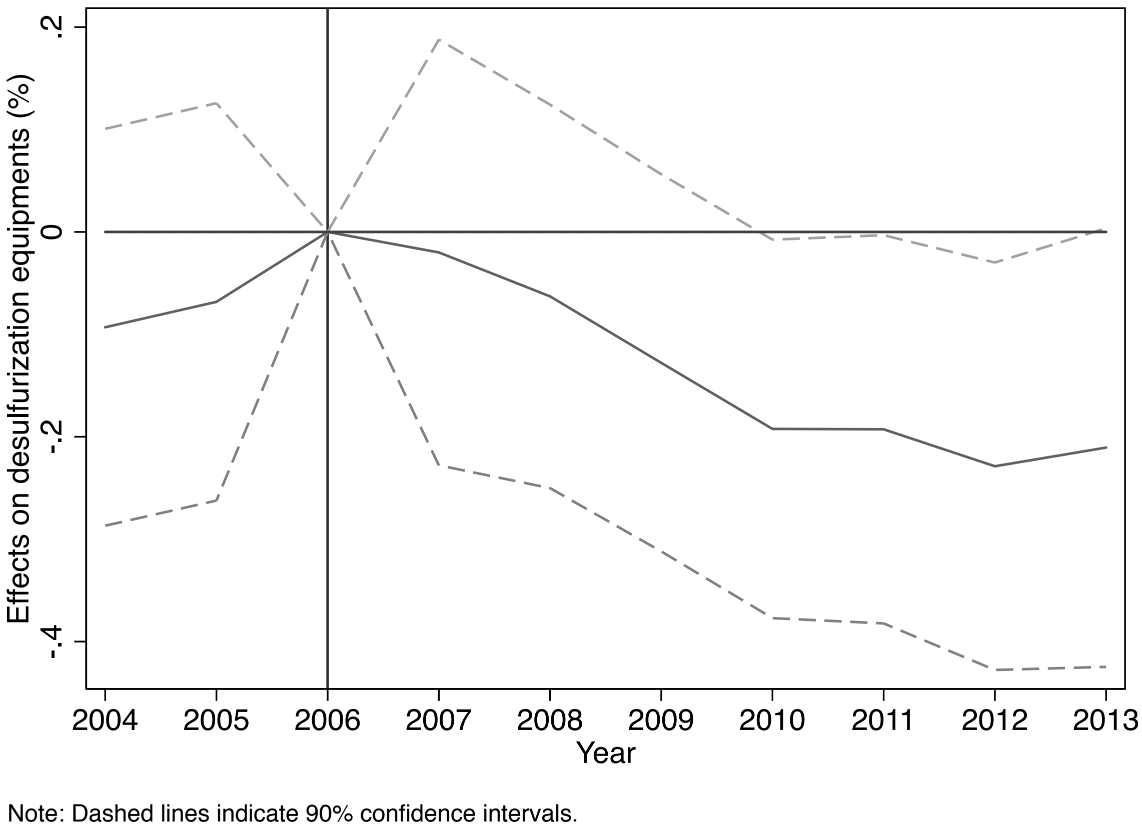
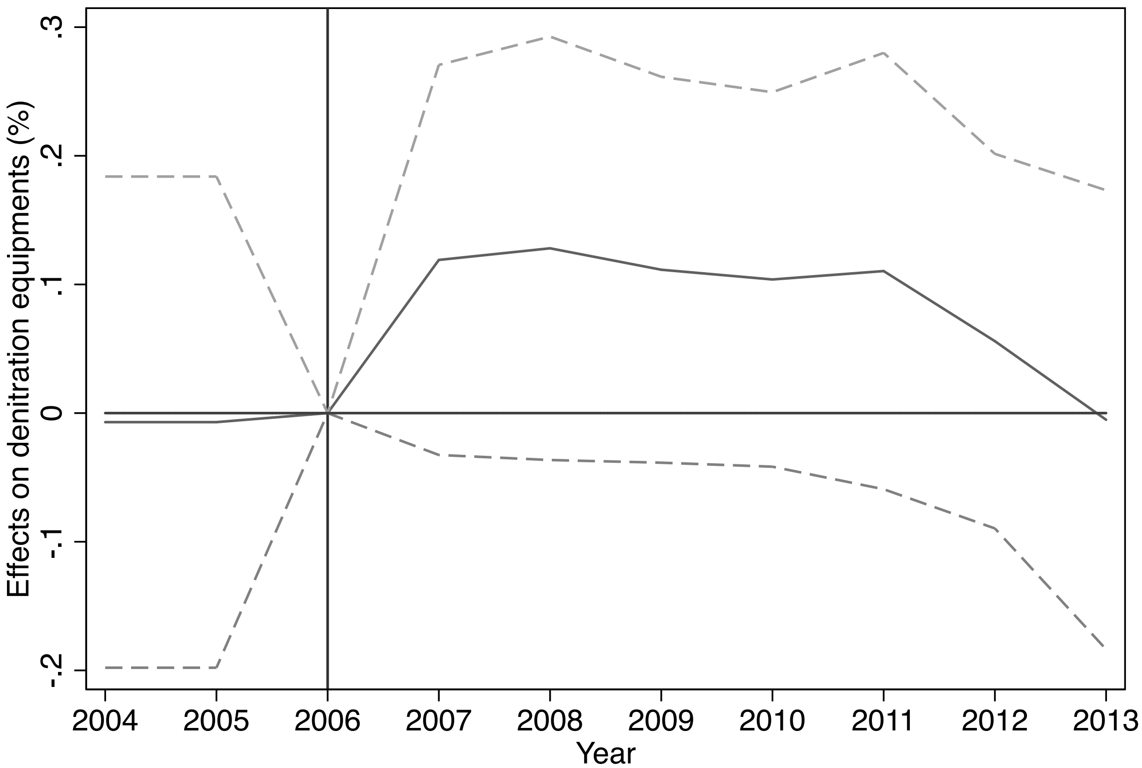
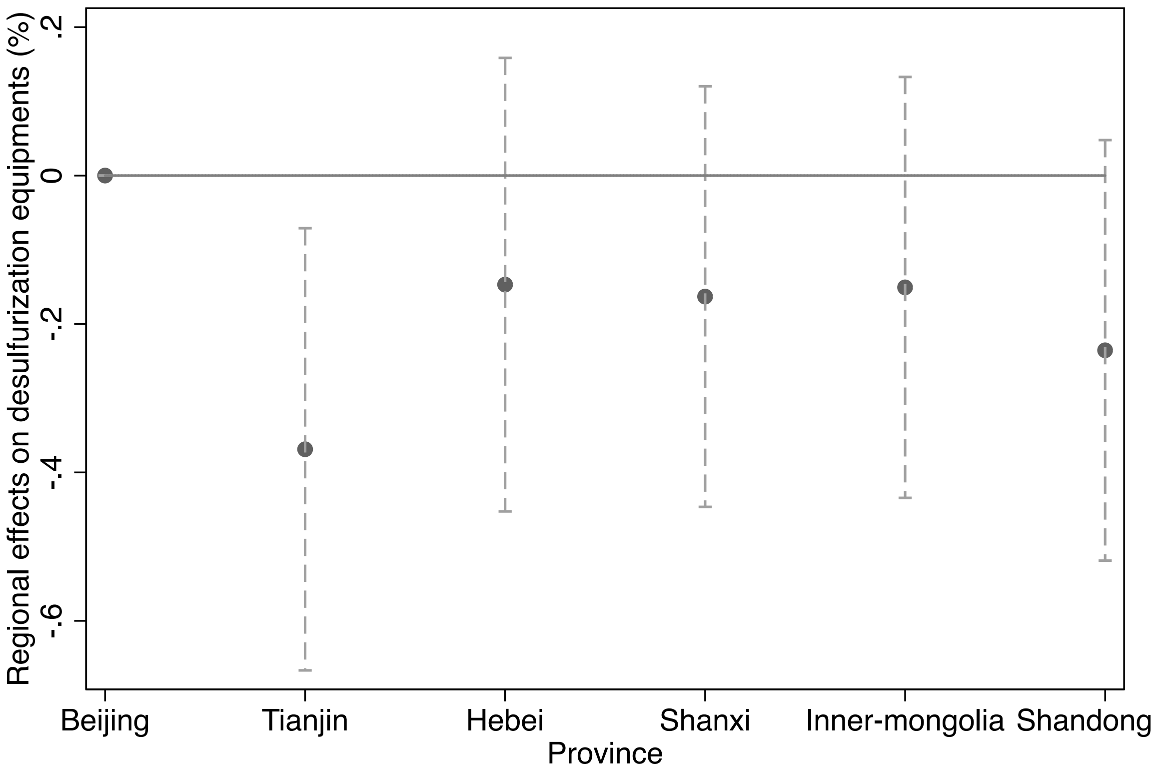


Figure 4.4: Result of installed desulfurization equipment effects of multiple-period model



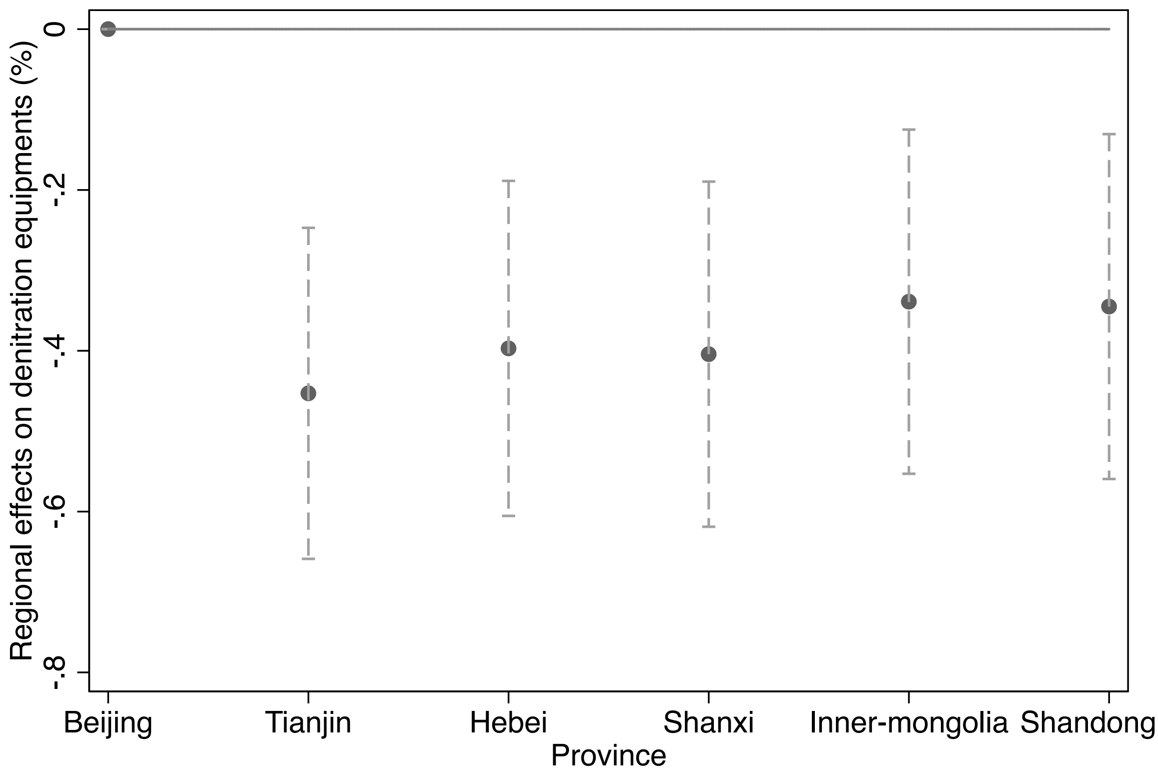
Note: Dashed lines indicate 90% confidence intervals.

Figure 4.5: Result of installed denitration equipment effects of multiple-period model



Note: Dashed lines indicate 90% confidence intervals.

Figure 4.6: Result of installed desulfurization equipment effects of multiple-region model



Note: Dashed lines indicate 90% confidence intervals.

Figure 4.7: Result of installed denitration equipment effects of multiple-region model

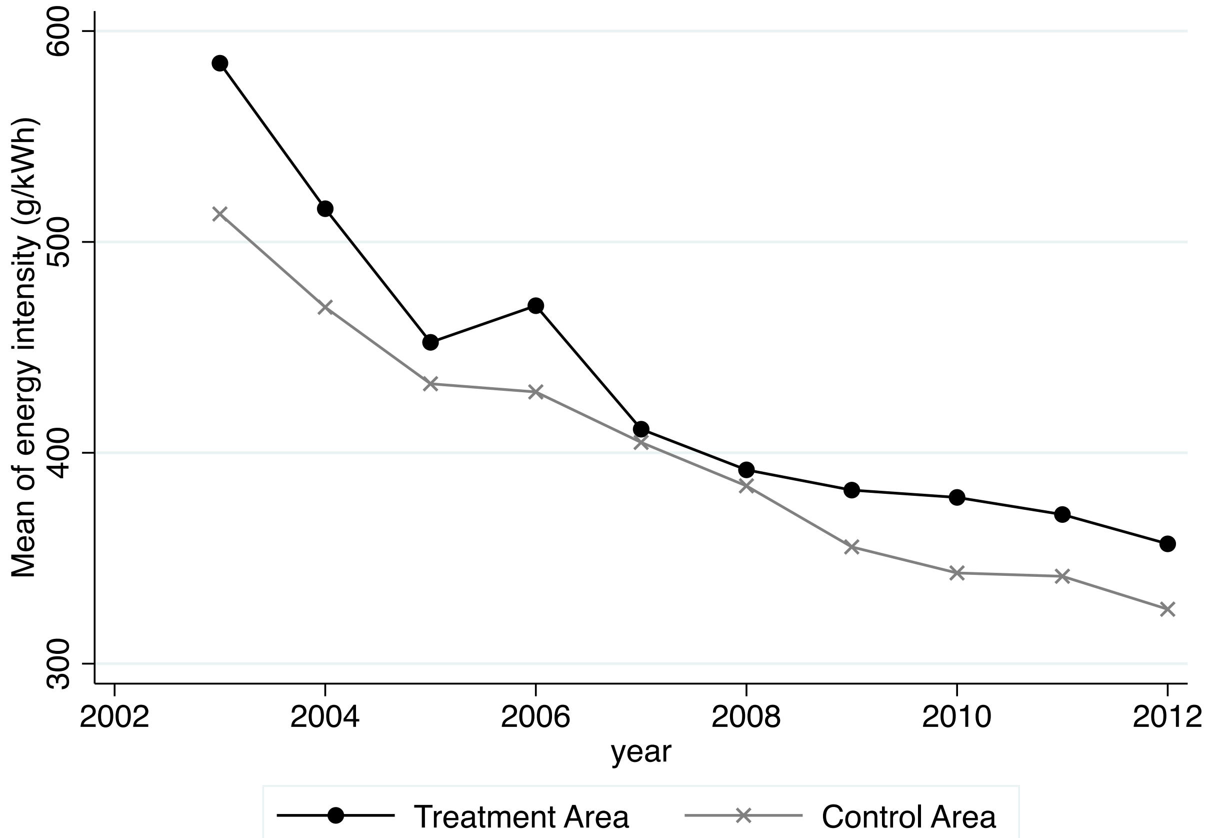
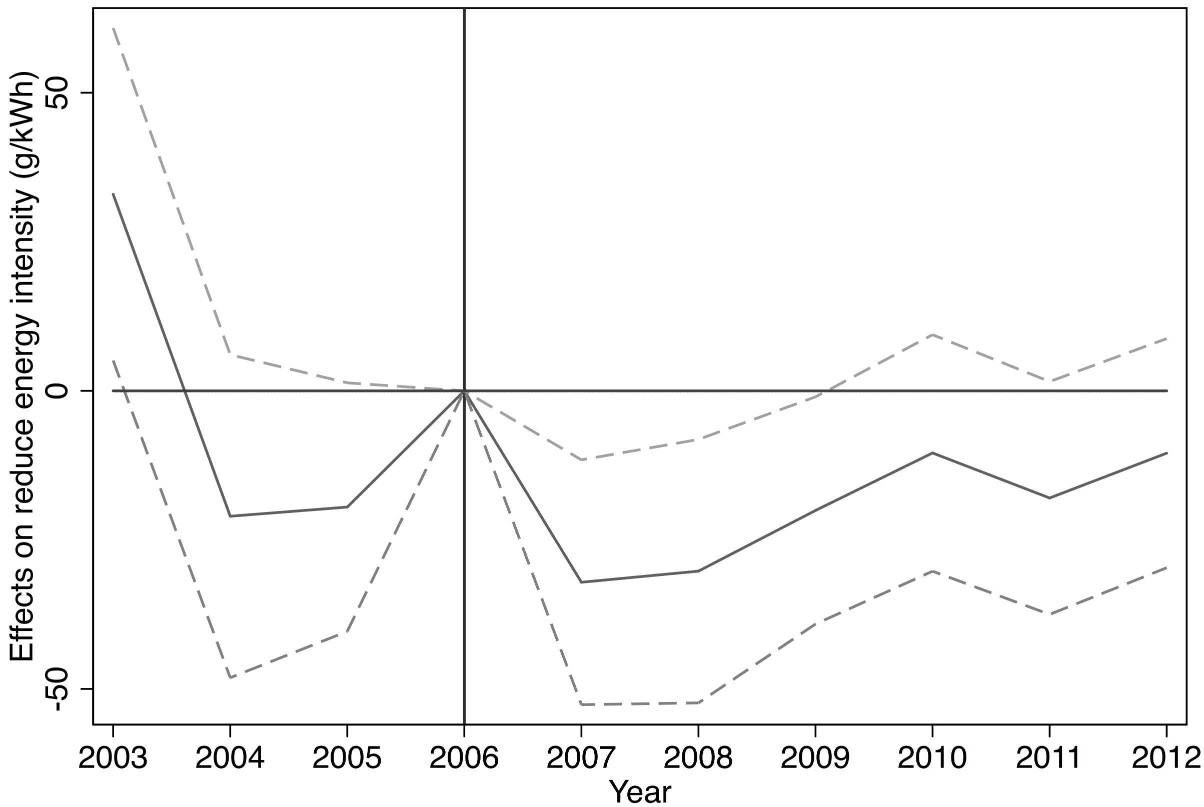


Figure 4.8: Trend of energy intensity decreasing



Note: Dashed lines indicate 90% confidence intervals.

Figure 4.9: Result of reduced energy intensity effects in each year

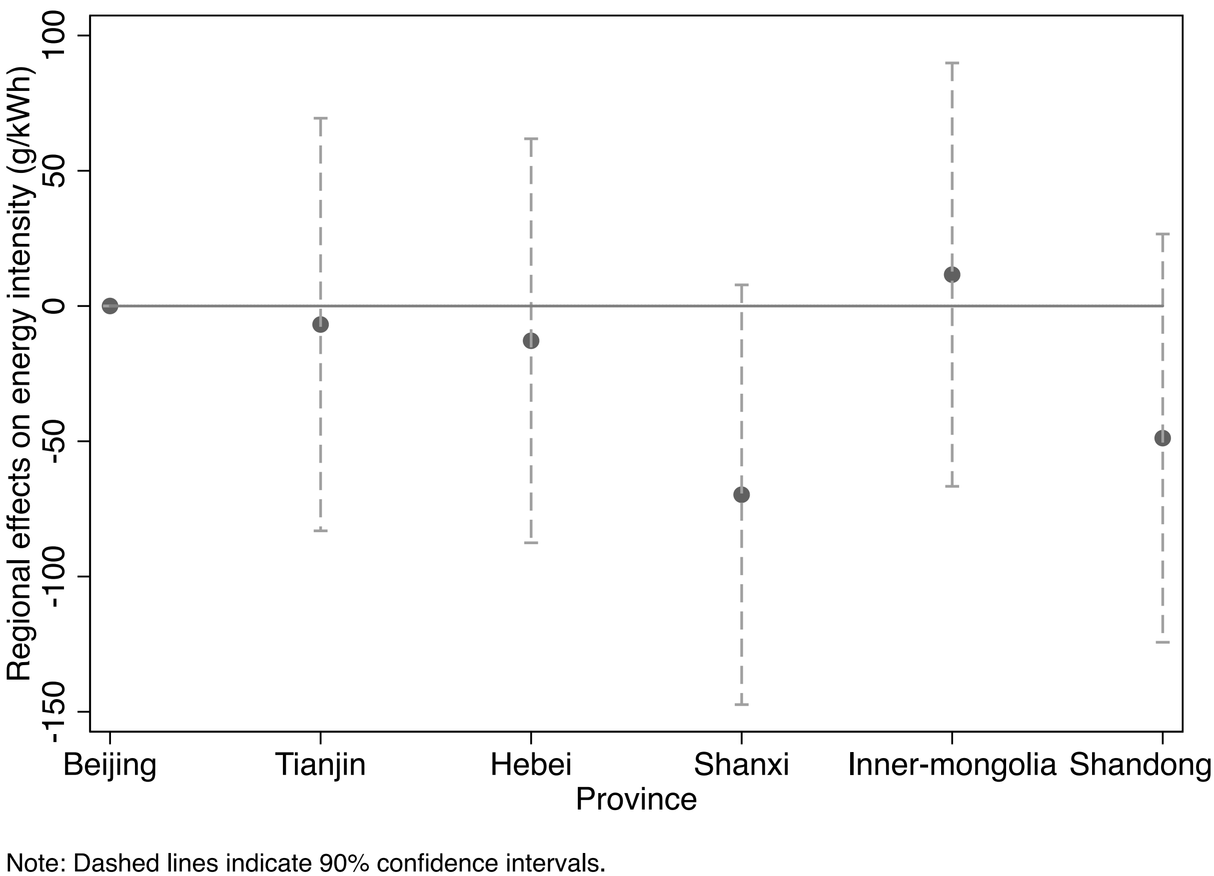


Figure 4.10: Result of reduced energy intensity effects in each province

Chapter 5

Conlusions

This thesis examined policies that control various air pollutants in the Chinese thermal power sector. We investigate the effectiveness of air pollution control from three points of view: enforcement of commend and control policies; technology choice for pollution control; and the impact of the Beijing Olympic Games on air pollution control.

First, in order to reduce emissions of air pollutants, the policies for installing control equipment and closure of small coal-fired power plants were effective. On the other hand, the effectiveness of FGD equipments differs across the country. Because of improved monitoring and enforcement by environmental departments, the gap regarding the effectiveness of FGD equipment among provinces will converge as income levels increase.

Second, the results of this thesis suggest that the power plants have some flexibility in choosing a preferred technology to reduce NO_x emissions. Therefore, it is possible that plants choose the cheapest technology to lower their investment costs, since the subsidy does not depend on the technology option chosen.

Lastly, BOG08 might have had the effect of improving the energy intensity of the thermal power sector. Energy saving actions, such as using cleaner fuel, and strengthening management of coal-use, are relatively cheaper and affordable, even for power plants. Such improvement of energy intensity might have an impact on better air quality over a longer term than those attained by the temporal restriction of traffic volume.