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Cleaning up the air for the 2008 Beijing Olympic Games: Empirical study on China's thermal power sector*

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Abstract

This study examines the impact of the 2008 Beijing Olympic Games (BOG08) on pollution control strategies in the thermal power sector. We focus on two pollution control strategies: the installation of pollution control equipment and improvement in energy efficiency. By using a difference-in-differences methodology, we investigate if there is a significant difference in the installation of pollution control equipment between provinces under the regional control policy for the BOG08 and other provinces. Furthermore, by using matching methods, we explore the differences in the energy efficiency between power plants in provinces targeted by the policy and those in other provinces. The results suggest that there are no statistically significant effects of the BOG08 on pollution control equipment. On the other hand, energy efficiency measured by the coal consumption per unit of electricity generation by thermal power plants improved in 2007 and 2008 in provinces designated as areas requiring coordinated air pollution control for the Olympic Games. These results are consistent with the hypothesis that faster and cheaper responses played a larger role in pollution reduction in BOG08.

Keywords: Air pollution; China; Beijing Olympic Games; Thermal power sector

JEL Classification Codes: Q52, L51, L94

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1 Introduction

Air pollution is a global risk factor for various diseases. According to the Health Effects Institute (2017), exposure to PM2.5 is the fifth largest risk factor leading to death and is responsible for 4.2 million deaths worldwide caused by a heart disease, stroke, lung cancer, chronic lung disease, or respiratory infections.[1] The pollution level is particularly serious in Asian countries: 86% of the most extreme concentrations (above 75μg/m^3) are experienced by populations in China, India, Pakistan, and Bangladesh (Health Effects Institute, 2017). Although stringent environmental policies are needed to reduce harmful health risks in these countries, it is often difficult to enforce effective regulations because of rapid economic growth and population increases.[2]

In this study, we examine the effect of the 2008 Beijing Olympic Games (BOG08) on air pollution control in Beijing and neighboring provinces. As an event attracting international attentions, the Olympic Games serve as an opportunity for a country to promote an ambitious policy for environmental improvement. In the planning for the Games, the Beijing Olympic Committee for the Games of the XXIX Olympiad (BOCOG) and Beijing Municipal Government launched the concept of the "Green Olympics" and integrated several environmental targets into the bid with accelerated deadlines. In particular, air quality improvement was of high priority. The resultant air pollution control reduced the air pollution index (API) in Beijing by 24.9% during the Games compared with the index value reported a 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 values for 2000–2009 and show that policy measures improved the Beijing's API during and shortly after the Games. In addition, they find that most of the improvement in air quality dissipated one year after the Games,

[1] Ambient air pollution is the fourth leading risk factor for disability-adjusted life years (DALYs) in China (Yang et al., 2013).

[2] Ebenstein et al. (2017) estimate that compliance to China's Class I standards for PM10 would save 3.7 billion life-years.

suggesting that the improvement was temporary. He et al. (2016) estimate the effects of air pollution on mortality in China by using exogenous variations in air quality during the BOG08 and show that monthly PM10 concentrations in Beijing reduced by approximately 30%. In addition, the authors find that a 10% reduction in PM10 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 during the period of the BOG08. By employing daily data from multiple monitoring stations, the authors find that the aggregate API fell by 18% during the implementation of the odd–even policy, which restricted cars to being driven only every other day. However, these studies do not fully address the reduction in air pollution in stationary sources, particularly in the thermal power sector.

This study investigates pollution control strategies within the thermal power sector during the BOG08. By using data on pollution control equipment and energy efficiency, we investigate for significant differences in their levels between provinces under the regional control policy for the BOG08 and other provinces. A difference-in-differences (DID) strategy is used for the province-level analysis of pollution control equipment and propensity score matching (PSM) is applied to the plant-level analysis of energy efficiency. The results of this study suggest that energy efficiency improved in the targeted area in 2007 and 2008, while the impact of the BOG08 on the installation level of pollution control equipment was not statistically significant.

This study makes three contributions to the literature. First, in contrast to previous studies that examine the impact of the BOG08 on air quality improvement (Chen et al., 2013; He et al., 2015), we examine the impact of the Games on measures to control air pollution. Because the control measures are directly related to the behavior of emissions sources, they can reveal the impact of various policies enforced during the period on emissions more in detail. Second, this study considers two activities as control measures: the installation of pollution control equipment and improvement in energy efficiency. Both are important measures determining emissions from thermal power plants, where the former relates to end-of-pipe control and the latter to cleaner production processes.[3] Typically, installing pollution control equipment requires significant investment, while using cleaner fuel or reducing waste heat can improve energy efficiency relatively faster and cheaper. Thus, we can hypothesize that energy efficiency improvements are more effective under time and budget constraints. Comparing the Olympic effect on these two measures, we can identify the stage of pollution reduction that played a more important role in reducing air pollution in Beijing. Finally, this study focuses on pollution control in the thermal power sector, a major contributor to air pollution. Wang et al. (2010) analyze pollution emissions reductions during the BOG08 and estimate that in the pre-Games period, the thermal power sector was one of the largest contributors to SO_2 emissions, which accounted for 11% of total SO_2 emissions in Beijing.[4] Thus, this study complements previous studies that focus on other sectors (Viard and Fu, 2015; Sun et al, 2014) and can help understand air quality control during the Olympic Games in a rapidly growing economy.

The remainder of this paper is organized as follows. Section 2 presents the background to this study. We review the various air pollution control policies implemented for the BOG08 in Beijing and surrounding areas. Section 3 describes the data used in the analyses. Section 4 analyzes the effect of the BOG08 on the installation of pollution control equipment. Section 5 examines the effect of the BOG08 on energy efficiency measured by coal consumption per unit of electricity generation. Section 6 contains the robustness analyses. Finally, Section 7 concludes.

[3] Fuel switching to low-sulfur coal is one of the important compliance channels, although detailed data on its use are not available. Stoerk (2017) shows that low-sulfur coal plays a role in SO_2 abatement in China.

[4] There are variations in the estimates of the power sector's contribution to total SO_2 emissions. For example, Lu et al. (2010) estimate that the share of the power sector in total SO_2 emissions in Beijing was 30% in 2007.

2 Background

The BOCOG was established in December 2001 to bid for China's Olympic Games. To promote the environmental sustainability of the BOG08, the BOCOG and Beijing Municipal Government proposed the concept of the "Green Olympics" (UNEP, 2009). Air quality, in particular, was considered to be a concern because of the direct impact of poor air on the health and performance of athletes. The measures taken to reduce air pollution for the Games can be classified under the following six objectives: reduce energy consumption growth and improve energy efficiency; reduce the emissions produced for a given amount of electricity; close and relocate production lines in major industrial sectors; reduce emissions in the transportation sector; control dust from construction; and other special short-term measures.

Reduced air pollution from the thermal power sector was achieved through various options, which can be classified into the adoption of end-of-pipe technology (installation of desulfurization, denitration, and dust removal equipment for boilers) and improvement in energy efficiency (reduction in coal consumption per unit of electricity generation). Beijing's effort to reduce air pollutants in the thermal power sector for the BOG08 began in late 2002 (Chen et al., 2013). In 2003 and 2004, the city 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, desulfurization, denitration, and dust removal facilities were constructed at the Beijing Thermal Power Plant and the power plant at Capital Steel. Further, Beijing renovated 100% of its boilers for clean fuel in five districts and an additional 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. Acknowledging this viewpoint, in October 2007, the State Council of China issued *Measures to Ensure Good Air Quality in the 29th Beijing Olympics and Paralympics* (MEGA policy), which 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 install desulfurization facilities. The Chinese Ministry of Environmental Protection coordinated with the governments of these provinces and cities to improve air quality through cooperation (Chinese Ministry of Environmental Protection, 2012).

Provinces and cities included under the MEGA policy made various attempts to reduce air pollution. For instance, Tianjin's municipal government required all thermal power plants to install desulfurization equipment by June 2008 (People's Daily, 2008). Furthermore, all coal-fired boilers were asked to adopt clean coal (Tianjin Municipal Government, 2008). In Hebei Province, a list was compiled of small thermal power plants that were required to shut down in 2007. In Shijiazhuang, all coal-fired boilers with a capacity of more than four tons in Tangshan, Langfang, and Baoding, which are key regions designated by the Hebei Provincial Government, were required to install desulfurization and dust removal equipment. In addition, all boilers for electricity generation in the key regions were ordered to use clean coal (Hebei Provincial Government, 2008). Shanxi Province is a major coal producer and the largest electricity provider in China. Shanxi's provincial government requested several thermal power plants to install desulfurization equipment during the pre-Olympic Games period (i.e., from November 2007 to July 2008). In addition, during the Olympic Games, the SO_2 and NO_x discharges from thermal power plants were strictly controlled. Furthermore, the monitoring of air pollution was reinforced during the period (Environmental Protection Bureau of Shanxi Province, 2007). By 2007, Shandong had reduced SO_2 emissions by 1.8 million tons, a 7% reduction compared with the emission level in 2006. Thermal power plants that failed to achieve the SO_2 standards in the province were required to shut down during the BOG08 (Shandong Provincial Government, 2008). In Inner Mongolia, the provincial government implemented a regional control policy for Huhhot, Baotou, Chifeng, Xilingol, and Ulanqab. In these areas, thermal power plants were also required to install desulfurization and denitration equipment or shut down from January 1, 2007, to September 20, 2008 (the Government of Inner Mongolia Autonomous Region, 2007). These policy measures in neighboring provinces were crucial to 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 the large reduction in PM2.5 can be mainly attributed to regional transportation within the area beyond Beijing.

We estimate the effects of the BOG08 on measures for air pollution controls in the thermal power sector by using a sample of six provinces in the treatment area and nine provinces in the control area (Figure 1). The treatment area includes provinces under the MEGA policy: Beijing, Tianjin, Hebei, Shandong, Shanxi, and Inner Mongolia. The control area comprises provinces neighboring the treatment area: Heilongjiang, Jilin, Liaoning, Gansu, Ningxia, Shaanxi, Henan, Anhui, and Jiangsu.

[Figure 1]

3 Data

We use two primary datasets for the dependent variables throughout our analysis. First, we employ the installation of pollution control equipment in the thermal power sector. We examine two types of pollution control equipment: a desulfurization system to remove sulfur and a denitration system to remove nitrogen oxides. Both datasets are taken from the data center of the Chinese Ministry of Environmental Protection. We aggregate the data at province level and use it in the analysis in Section 4. Second, we use coal consumption per unit of electricity generation by the thermal power plants, taken from the *Compilation of Statistics on Chinese Electric Power Industry* (China Electricity Council, respective years). These plant-level data are used for the analysis in Section 5.

3.1 Pollution control data

Data on pollution control equipment are obtained from *the List of Pollution Control Equipment of Coal-Fired Boilers* published by the data center at the Chinese Ministry of Environmental Protection (2014a, 2014b, 2015).[5] This list contains information on 4,659 coal-fired boilers that have installed desulfurization equipment and 1,135 coal-fired boilers with denitration equipment. More specifically, it includes the name of each boiler, province in which the boiler is located, year in which the boiler began operation, boiler capacity, type of desulfurization and denitration technology, year of equipment installation, and name of the company that manufactured the pollution control equipment. We use the year of equipment installation and aggregate the capacity of boilers with installed equipment by province for each year from 2003 to 2012. By dividing this number by the total capacity of boilers operating in each province per year, for which data are taken from the China Energy Statistical Yearbook, we construct province-level panel data for the share of boilers that installed pollution control equipment among all boilers.

Table 1 provides the summary statistics of the pollution control data. During the study period, the average share of boilers with pollution control equipment is 55.4% in the treatment area and 53.2% in the control area for desulfurization equipment and 17.3% in the treatment area and 10.6% in the control area for denitration equipment. Because the policy for SO_2 control was implemented before that for NO_x control, the average share of boilers with desulfurization equipment is higher than that of boilers with denitration equipment.[6]

[Table 1]

[5]See http://datacenter.mep.gov.cn.

[6]The installation of control equipment does not necessarily mean that they are actually in operation. For example, Xu et al. (2009) note that China's State Environmental Protection Administration announced that fewer than 40% of SO_2 scrubbers are working reliably and continuously.

3.2 Energy efficiency data

We obtained data on coal consumption per unit of electricity generation for 4,568 thermal power plants between 2003 and 2012 from the *Compilation of Statistics on Chinese Electric Power Industry* published by the China Electricity Council.[7] Our sample includes plants whose main purpose is to generate electricity and those in other industries such as steel and chemicals. The mean value of coal consumption per unit of electricity generation for all thermal power plants in China is 409 grams of coal equivalent (gce) per kWh. Approximately 92% of thermal power plants in our sample are coal-fired.

Table 2 reports the descriptive statistics for the energy efficiency data. Our sample comprises 6,265 plants in the treatment area and 7,010 plants in the control area. Average coal consumption per unit of electricity generation in the treatment area is 8.9% higher than that in the control area.

[Table 2]

4 Effects of the BOG08 on pollution control

We use a DID methodology to estimate the impact of the BOG08 on the installation of equipment for air pollution controls by thermal power plants. The estimation model is represented as follows:

$$Share_{rt} = \beta(Area_r \times Time_t) + \gamma_r + \delta_t + \varepsilon_{rt}, \tag{1}$$

where $Share_{rt}$ is the installation share of desulfurization ($Share\_sulfur_{rt}$) or denitration ($Share\_nitrogen_{rt}$) equipment by generation capacity in province r. This share is calculated by dividing the total capacity of boilers that installed end-of-pipe equipment by the total capacity of thermal power boilers in each province. $Area_r \times Time_t$ is the cross-term for $Area_r$

[7] We use the "gross coal consumption rate" to measure the energy efficiency of each plant.

and $Time_t$ to capture the impact of the MEGA policy on the installation level of end-of-pipe equipment. $Area_r$ is the dummy variable for the treatment area, which takes the value of 1 for the six provinces in which the MEGA policy was applied and 0 otherwise. $Time_t$ is the dummy variable for the treatment period, which takes the value of 1 for 2007–2008 and 0 otherwise. Because the MEGA policy was issued in October 2007 and the Games were completed on September 17, 2008, we define the treatment period as 2007–2008.[8] γ_r is the province-specific effects that control for any unobserved heterogeneity across provinces. δ_t is the year fixed effects that control for any external event that is common to all provinces. ε_{rt} is an error term.

A key assumption for the DID approach is that, in the absence of treatment, the average outcomes of the treatment group and comparison group would follow parallel paths over time. In our case, we assume that if there were no policy intervention, the installation share of pollution control equipments would have evolved similarly between the treatment and control provinces. As we show later in this section, we indirectly test this assumption by analyzing the common pretreatment trend and find that the evidence supports this assumption. In addition, in Section 6, we confirm the robustness of the baseline results by estimating models with an alternative definition of the control area and treatment period.

As of 2013, among China's 1,835 independent power producers, approximately 74% of thermal power boilers had installed desulfurization equipment and 22% had denitration equipment (Chinese Ministry of Environmental Protection, 2015).[9] Figure 2 illustrates the trends of desulfurization equipment installation in the thermal power sector. The Chinese government initiated efforts to reduce SO_2 emissions long before the preparation period of the BOG08. Indeed, it reinforced a policy to control SO_2 discharges from the thermal power sector in the 10th (2001–2005) and 11th Five-Year Plan (2006–2010) periods. In the 10th

[8]As noted in the previous section, preparation for the BOG08 began in late 2002. Thus, our definition of the treatment period is narrow to capture the total effect of the policies for the BOG08 implemented in the preparation period.

[9]Our calculation of the share of boilers that had installed control equipment is based on the capacity of boilers and does not coincide with these figures.

Five-Year Plan period, 75 power plants (165.85 MW) installed desulfurization equipment. Following this period, a larger-scale desulfurization plan[10] was issued in the 11th Five-Year Plan period. This plan defines targets for desulfurization at the province level to reduce SO_2. That is, 248 power plants (126.19 GW) were ordered to install desulfurization equipment and 679 power plants (51.48 GW) were instructed to shut down within the period (SEPA and NDRC, 2007).

The capacity share for desulfurization equipment in the treatment area was higher than that in the control area untill 2009, but it became lower after 2010. The SO_2 emissions control policy in China began 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 the treatment area. We hypothesize that although the SO_2 emissions control policies were implemented before the BOG08 preparation period, the installation of desulfurization equipment accelerated because of greater demand for cleaner air during the BOG08 period in the treatment area than in the control area.

[Figure 2]

In contrast to the regulation on SO_2 emissions, the government began controlling NO_x emissions from the thermal power sector in the 11th Five-Year Plan (2006–2010) and seriously implemented controls in the 12th Five-Year Plan period (2011–2015). Figure 3 presents the trends of denitration equipment installation in the thermal power sector. The capacity share of installed denitration equipment in the treatment area is higher than that in the control area from 2007 to 2013.

[Figure 3]

Table 3 reports the baseline results from estimating equation (1). Standards errors are clustered at the province level. The coefficients of $Area_r \times Time_t$ are not statistically significant in the models for desulfurization equipment and denitration equipment. This finding

[10] In 2007, the State Environmental Protection Administration and National Development and Reform Commission issued the *National Acid Rain and SO_2 Pollution Control in the 11th Five-Year Plan.*

suggests that the BOG08 are not effective to promote the installation of pollution control equipment in the treatment provinces. The table also reports the results of the alternative specification that divides the treatment area into Beijing and the surrounding provinces (Tianjin, Hebei, Shandong, Shanxi, and Inner Mongolia). The results suggest that the effect of the BOG08 is statistically significant only in the Beijing area.

[Table 3]

To further investigate the effects of a regional control policy on subsequent dynamics, we use a flexible form of the DID model. We introduce $Area \times \delta_{rt}$, which are the interaction terms between $Area_r$ and δ_t. The coefficient of $Area \times \delta_{rt}$ demonstrates the effects of a regional control policy on the installation of end-of-pipe equipment in each year:

$$Share_{rt} = \sum_{j=-3}^{6} \beta_j (Area_r \times \delta_t) + \gamma_r + \delta_t + \varepsilon_{rt}, \tag{2}$$

where the excluded time category is 2006 ($j = -1$) such that the effects are measured relative to the year before the implementation of the MEGA policy. Figure 4 plots the point estimates of the interaction coefficients β_j over time.[11] These coefficients in the pre-policy period are not statistically significant, supporting the assumption of common pre-trends for the DID methodology. The effects of the BOG08 on desulfurization equipment, however, are also not statistically significant. This result suggests that the installation of desulfurization equipment in the treatment area does not significantly differ from that in the control area in these periods compared with 2006. In addition, the figure shows that the interaction coefficients are negative and statistically significant after 2010. This finding suggests that after the BOG08 period, installations of control equipment increased in the control area compared with the treatment area.

[Figure 4]

[11] Estimation results of flexible DID models are reported in Table A1 in the Appendix.

Figure 5 reports the estimation results for denitration equipment in each year. It plots the point estimates of the interaction coefficients β_j over time. Although the point estimates of the interaction coefficients are positive from 2007 to 2012, these are not statistically significant, suggesting that the treatment area effect in each year is not significantly different from that in 2006.

[Figure 5]

In summary, our results does not suggest that the BOG08 promote the installation of pollution control equipment. The treatment effect during the BOG08 is not significant in the baseline DID estimation. The results for the flexible DID model also support this findings, indicating that the installation of pollution control equipment in the provinces under the MEGA policy does not differ from that in the control provinces during and after the Olympic Games period. Indeed, the effect on desulfurization is negative and statistically significant during 2010 to 2012, suggesting that the installation of desulfurization equipment in the control area becomes greater than that in the treatment area after 2010. While the BOG08 effect on pollution control equipment is positive and statistically significant in Beijing, this might be attributed to the early introduction of equipment in the city rather than the regional control policy for the Games.

One reason for the difficulty in detecting the BOG08 effect might be the timing of the national promotion of installing pollution control equipment. The installation of desulfurization equipment was promoted at the national level during the 11th Five-Year Plan period (2006–2010) which included the BOG08. In 2007, the National Acid Rain and SO_2 Pollution Control program was issued (SEPA and NDRC, 2007). This 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 desulfurization equipment at coal-fired power plants and listed 679 small power plants targeted for closure to remove more than 50 GW of electricity generation capacity. On the contrary, the installation of denitration was promoted at the national level in the 12th Five-Year Plan period (2011–2015), namely the period after the BOG08. Of the 1,135 thermal power boilers examined in this study, only 37 thermal power boilers installed denitration equipment during the Games period (2007–2008); by contrast, most (958 boilers) did so during 2011–2013.

5 Effects of the BOG08 on energy efficiency

In this section, we investigate the effects of the BOG08 on the energy efficiency of thermal power plants. Considering the possibility of selection bias, we employ PSM and then use the DID model to estimate the treatment effects. In our context, selection bias matters if the characteristics of the power plants in treatment area are systematically different from those in the control groups.

To estimate the propensity score, we use three covariates that explain the probability of power plants operating in the treatment area: $Utilization_{it}$, $Self\_use_{it}$, and $Generation_{it}$. $Utilization_{it}$ represents the total operational hours of the power plant i in year t. A longer utilization time means more electricity can be generated by power plants with the same installed capacity. The annual average utilization hour of power plants in the treatment area is 5,549 hours, slightly lower than that in the control area (5,647 hours). $Self\_use_{it}$ indicates the auxiliary power consumption rate of power plant i in year t. A higher auxiliary power consumption rate represents a lower available amount of on-grid electricity.[12] A reduction in auxiliary power use will improve the energy efficiency. $Generation_{it}$ is the electricity generation of power plant i in year t. Average electricity generation is higher in the treatment area than in the control area before matching. To apply matching methodologies, we only adopt thermal power plants that had started their operations before 2003 in our analysis. To check the robustness of the PSM result, we also use the Mahalanobis distance matching (MDM) method. Table 4 shows the balancing test results of the PSM and MDM, suggesting

[12]Auxiliary power use includes the feed-water system, cooling water system, pollution control system, combustion air and fuel gas, fuel handing, and other loads.

that the difference in the three covariates between the treatment and control groups is considerably reduced after matching.

[Table 4]

We estimate the effects of the BOG08 on energy efficiency by using the following DID model:

$$EE_{it} = \beta(Area_i \times Time_t) + \eta_i + \delta_t + \varepsilon_{it}, \tag{3}$$

where the dependent variable EE_{it} denotes coal consumption per unit of electricity generation by thermal power plant i in year t measured by the amount of energy (in coal equivalent) used to generate one kWh of electricity. A higher number means lower energy efficiency. $Area_i \times Time_t$ indicates the cross-term of $Area_i$ and $Time_t$. $Area_i$ is the dummy variable that takes the value of 1 if power plant i is located in a province under the MEGA policy. The dummy variable $Time_t$ takes the value of 1 if the period is 2007 or 2008 and 0 otherwise. η_i is the power plant-specific effects that control for any unobserved heterogeneity across power plants. δ_t is the year fixed effects that control for any external event common to all power plants. ε_{it} is an error term.

Figure 6 shows the changes in energy efficiency during the study period. Coal consumption per unit of electricity generation is steadily decreasing in the treatment and control areas, while that in the treatment area is higher than that in the control area.[13] However, by

[13] Several national policies have contributed to the steady improvement in energy efficiency. For example, in November 2004, the National Development and Reform Commission issued the China Medium and Long Term Energy Conservation Plan (Ke et al., 2012). In the thermal power sector, the plan targeted a decrease in the energy consumption index per unit in the power supply sector from 392 gce/kWh in 2000 to 320 gce/kWh in 2020. In addition, under the Coal-fired Industrial Boiler Retrofit Projects, an additional 5% of coal use was reduced for coal-fired boilers. Furthermore, the central government planned to reduce 25 million tons of coal by using high quality coal and adopting advanced technologies during the 11th Five-Year Plan period (National Development and Reform Commission, 2006). In 2006, China's central government launched the Top-1000 Enterprises Project, which aimed to improve the industrial energy efficiency of the largest energy users in China's industrial sector. The project includes 1,008 enterprises with a minimum annual energy consumption of 180,000 tce and set a 100 million tce energy-saving target during the 11th Five-Year Plan period (National Development and Reform Commission, 2006). A total of 132 thermal power plant can be found on the list (40 thermal plants are observed in the treatment area and 51 thermal plants in the control area). The target was achieved by the end of the 11th Five-Year Plan period (Ke et al., 2012).

2007, energy efficiency in the treatment area had greatly improved. The figure shows that coal consumption per unit of electricity generation in the treatment area sharply dropped in 2007 and became close to that in the control area. In Beijing, several large thermal power plants in the central area were requested to use cleaner fuels during the BOG08 period (Beijing Daily, 2008). Following the environmental standard DB12/151-2003, Tianjin's municipal government requested all coal-fired boilers use low-sulfur coal. The Hebei Provincial Government asked all coal-fired boilers in Shijiazhuang, Tangshan, Langfang, and Baoding to use clean coal (Hebei Provincial Government, 2007). These regulations operated by regional governments under the MEGA policy could have lead to the improvement in energy efficiency during the BOG08 period.

[Figure 6]

Table 5 reports the baseline results based on PSM in columns (1) and (2) and the results based on MDM in columns (3) and (4). Estimation results without matching are shown in Table A2 in Appendix. The models in columns (2) and (4) are estimated by using data on coal-fired power plants only. The coefficients of $Area_r \times Time_t$ is negative and statistically significant in all models, suggesting that the energy efficiency of power plants in the treatment area improved during the BOG08 period.

[Table 5]

To investigate the heterogeneity of the treatment effect in Beijing and the other surrounding provinces, we divide the treatment area into Beijing and the surrounding provinces (Tianjin, Hebei, Shandong, Shanxi, and Inner Mongolia) and include their interaction with the treatment period dummy in the estimation models. Table 6 presents the estimation results. The coefficient of the surrounding provinces ($Surrounding_i \times Time_t$) is negative and statistically significant in all of the models, while the coefficient of Beijing ($Beijing_i \times Time_t$) is not statistically significant. This result suggests that energy efficiency greatly improved in the surrounding areas during the BOG08 period.

[Table 6]

To further investigate the effects of a regional control policy on subsequent dynamics, we use a flexible form of the DID model:

$$EE_{it} = \sum_{j=-3}^{6} \beta_j (Area_r \times \delta_t) + \eta_i + \delta_t + \varepsilon_{it}, \tag{4}$$

where the excluded time category is 2006 ($j = -1$) such that the effects are measured relative to the year before the implementation of the MEGA policy. The coefficients of the interaction term capture the effects of the MEGA policy on energy efficiency in each year during the study period. β_j is the coefficient of the jth lead or lag.

Figure 7 plots the point estimates of the interaction coefficients β_j over time. Compared with the baseline year, the energy efficiency improved from 2007 to 2009. Coal consumption per unit of electricity generation by thermal power plants in the treatment area is declining since 2006, with a decrease of 30.28 gce/kWh, 33.26 gce/kWh, and 33.97 gce/kWh in 2007, 2008, and 2009, respectively. The results suggest that the effect of the BOG08 on the improvement in energy efficiency lasted for three years. Compared with 2006, the energy efficiency improved by 6.5%, 7.1%, and 7.3% in the treatment group. These are sizable numbers compared with the estimate presented by Chan et al. (2017), who show that electricity restructuring led to a 1.4% improvement in China's energy efficiency.

[Figure 7]

The improvement in energy efficiency might be attributed to several factors. First, an improvement in energy efficiency is generally easier for less efficient power plants. From the analysis that divides the sample into Beijing and the surrounding provinces, we find that the effect of the MEGA policy is significant in the latter. Because surrounding provinces contain coal-rich provinces such as Shanxi and Shandong, power plants in these locations use larger amounts of coal compared with other provinces. For the power plants in surrounding areas, using cleaner coal or reducing waste heat offers faster and cheaper energy efficiency improvements. In addition, as Figure 6 shows, energy efficiency in Beijing improved steadily before the treatment period in this study. These reasons explain why we find differences between Beijing and the surrounding area. Second, the closure of small thermal power plants might affect energy intensity by reducing the operations of boilers with lower efficiency. However, this reasoning is not supported by Figure 8 that compares the Epanechnikov kernel density for the generation capacity of power plants in the treatment area between 2006 and 2008. This shows that the distribution of the generation capacity of power plants is similar between these two periods.

[Figure 8]

The results of this study can be summarized as follows. Firstly, energy efficiency significantly improves in the treatment area during the BOG08 period. By contrast, the effect of the BOG08 is not confirmed for the installation of pollution control equipment. Secondly, the effects of the BOG08 on the energy efficiency of thermal power plants only sustained until 2009. This finding is in line with the result of Chen et al. (2013) that the effect of the BOG08 on air pollution reduction dissipated one year after the Games.

6 Robustness checks

To assess the robustness of the main findings, we conduct estimations by using an alternative definition of the control area and treatment period. First, we extend the control area from the nine provinces neighboring the treatment area to all provinces in China other than the treatment area. We also estimated the model by using 2008 as the treatment period instead of 2007 and 2008.

Table 7 presents the results of robustness checks. The numbers reported are the effects of the MEGA policy on various outcome measures with the alternative control area (columns (3) and (4)) and the alternative treatment period (columns (5) and (6)). Compared to the models in columns (1), (3), and (5), the models in columns (2), (4), and (6) contains additional control variables. Panel A corresponds to models using all MEGA policy area as the treatment group, while Panel B shows models using Beijing and the surrounding area as the treatment groups.

Regarding the treatment effect on pollution control equipment, they are not statistically significant in Panel A. While positive and statistically significant results are found in Beijing in Panel B, the coefficients for the surrounding area are not statistically significant. In contrast, the effects of MEGA policy on energy efficiency are mostly negative and statistically significant in Panel A and in the surrounding area in Panel B. In summary, the estimation results indicate that the main results are mostly robust to alternative definitions of the control area and treatment period.

[Table 7]

7 Conclusions

This study examined the impacts of the BOG08 on measures for pollution control in China's thermal power sector. Our results indicate that coal consumption per unit of electricity generation by thermal power plants decreased in 2007 and 2008 in provinces designated as areas requiring a coordinated air pollution control policy for the Olympic Games. On the contrary, evidence of such a treatment effect is not confirmed for the effect on pollution control equipment. The result of this study is in line with the previous literature. For example, Stoerk (2017) investigates the effects of SO_2 control targets during the 11th Five-Year Plan period (2006–2010) and finds that compliance relied less on the installation of desulfurization equipment and that the main driver for reducing emissions was the shutdown of small inefficient power plants.

The contrasting results between pollution control equipments and energy efficiency might be attributed to differences in the characteristics of end-of-pipe controls and improvement in energy efficiency. Typically, the end-of-pipe control strategy entails a large amount of investment and requires considerable fixed costs. Reducing coal consumption per unit of electricity generation such as by using cleaner coal or reducing waste heat is faster and cheaper, even for power plants that lack sufficient financial resources. Hammar and Löfgren (2010) investigate the drivers of investments in end-of-pipe solutions and clean technologies and find that environmental R&D plays an important role in the former type of investment, while energy price is important for the latter.

The results of this study complement the findings of Chen et al. (2013) and He et al. (2016) that present a significant but temporal effect of the BOG08 on air quality improvement. Our findings suggest that energy efficiency improved during the studied period in the treatment area but that the effect did not last long. Although we could not examine the impact of improvements in energy efficiency on reduced air pollution in the area, it is reasonable to expect a considerable linkage between them. To sustain good air quality for better health outcomes even after the Beijing Olympic Games period, policies that ensure such long-term impacts are crucial.

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Table 1: Descriptive statistics for pollution control equipment

		Treatment Area			Control Area		
		6 provinces			9 provinces		
	Unit	N	Mean	SD	N	Mean	SD
$Share\_sulfur_{rt}$	%	60	55.4	0.315	90	53.2	0.365
$Share\_nitrogen_{rt}$	%	60	17.3	0.279	90	10.6	0.174
$Time_t$	Dummy	60	0.200	0.403	90	0.200	0.402

Note: The data are province-level balanced panel data from 2004 to 2013.

Table 2: Descriptive statistics for energy efficiency

		Treatment Area 6 provinces			Control Area 9 provinces		
	Unit	N	Mean	SD	N	Mean	SD
EE_i	gce/kWh	6,264	427.9	302.3	7,010	392.8	184.5
$Time_k$	Dummy	6,265	0.219	0.413	7,010	0.218	0.413
$Utilization_i$	h	6,265	4,836	1,987	7,010	4,936	1,921
$Self\_use_i$	%	6,077	9.892	4.948	6,862	8.382	4.968
$Generation_i$	GWh	6,265	1,271	2,872	7,008	1,239	2,232

Note: The data are plant-level unbalanced panel data from 2003 to 2012.

Table 3: Fixed effects DID results for pollution control equipment

	(1)	(2)	(3)	(4)
	$Share\_sulfur_{it}$	$Share\_nitrogen_{it}$	$Share\_sulfur_{it}$	$Share\_nitrogen_{it}$
$Area_r \times Time_t$	0.098	0.078		
	(0.064)	(0.070)		
	[0.08]	[0.32]		
$Beijing_r \times Time_t$			0.275***	0.401***
			(0.040)	(0.140)
			[0.04]	[0.00]
$Surrounding_r \times Time_t$			0.062	-0.014
			(0.058)	(0.026)
			[0.20]	[0.72]
Constant	-0.044	0.438***	-0.081*	0.373***
	(0.026)	(0.0435)	(0.028)	(0.032)
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
N	150	150	150	150
R^2	0.902	0.804	0.905	0.831

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Heteroskedasticity-robust standard errors clustered at the province level are shown in parentheses. Wild bootstrap p-values clustered at the province level are shown in square brackets.

Table 4: Balancing test results

Panel A: Nearest-neighbor propensity score matching (PSM)

	Unmatched/	Mean				t-test	
	Matched	Treatment	Control	%bias	%bias reduction	t-value	p-value
$Utilization_{it}$	U	5,549	5,647	-5.6		-0.61	0.541
	M	5,549	5,456	5.3	6.2	0.61	0.541
$Self\_use_{it}$	U	9.837	8.789	23.7		2.57	0.010
	M	9.837	9.643	4.4	81.5	0.47	0.642
$Generation_{it}$	U	1,289	894.4	18.8		2.05	0.041
	M	1,289	1236	2.6	86.4	0.25	0.800

Panel B: Mahalanobis distance matching (MDM)

	Unmatched/	Mean				t-test	
	Matched	Treatment	Control	%bias	%bias reduction	t-value	p-value
$Utilization_{it}$	U	5,549	5,647	-5.6		-0.61	0.541
	M	5,549	5,536	0.7	87.3	0.09	0.929
$Self\_use_{it}$	U	9.837	8.789	23.7		2.57	0.010
	M	9.837	9.416	9.5	59.9	1.04	0.298
$Generation_{it}$	U	1,289	894.4	18.8		2.05	0.041
	M	1,289	1,144	6.9	63.3	0.70	0.486

Table 5: Fixed-effects DID results for energy efficiency

EE_{it}	(1) PSM	(2) PSM	(3) MDM	(4) MDM
$Area_r \times Time_t$	-18.30*	-17.52*	-18.36**	-17.58**
	(10.12)	(10.24)	(10.12)	(10.23)
Constant	907.5***	906.8***	907.4***	906.6***
	(9.715)	(9.707)	(9.699)	(9.690)
$Yeardummy$	Yes	Yes	Yes	Yes
$Plantdummy$	Yes	Yes	Yes	Yes
$Sample$	All thermal	Coal power only	All thermal	Coal power only
$Reduction$	-4.251%	-4.064%	-4.265%	-4.077%
N	4,033	3,927	4,040	3,934
R^2	0.605	0.604	0.605	0.604

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors clustered at the plant level are in parentheses. Economic magnitude for the effects of energy efficiency improvement shown in *Reduction*.

Table 6: Fixed-effects DID results in energy efficiency (Beijing and surrounding area)

EE_{it}	(1) PSM	(2) PSM	(3) MDM	(4) MDM
$Beijing_r \times Time_t$	71.94	95.63	71.88	95.57
	(59.07)	(73.93)	(59.07)	(73.93)
$Surrounding_r \times Time_t$	-22.04**	-21.20**	-22.10**	-21.26**
	(10.10)	(10.13)	(10.09)	(10.12)
Constant	889.5***	884.2***	889.4***	884.0***
	(13.84)	(16.15)	(13.83)	(16.14)
$YearFE$	Yes	Yes	Yes	Yes
$PlantFE$	Yes	Yes	Yes	Yes
$Sample$	All thermal	Coal power only	All thermal	Coal power only
$Reduction$ $(Surrounding)$	-5.068%	-4.885%	-4.875%	-5.093%
N	4,033	3,927	4,040	3,934
R^2	0.606	0.605	0.606	0.605

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors clustered at the plant level are in parentheses. Economic magnitude for the effects of the energy efficiency improvement shown in *Reduction*.

Table 7: BOG08 effects: alternative definition of control

	(1) Baseline	(2) Baseline	(3) All Provinces	(4) All Provinces	(5) 2008	(6) 2008
Panel A: MEGA policy area						
Desulfurization						
$Area_r \times Time_t$	0.098	0.077	0.052	0.033	0.063	0.051
	(0.065)	(0.055)	(0.054)	(0.054)	(0.058)	(0.054)
	[0.08]	[0.08]	[0.28]	[0.48]	[0.20]	[0.20]
N	150	150	310	310	150	150
R^2	0.902	0.906	0.902	0.906	0.899	0.905
Denitration						
$Area_r \times Time_t$	0.078	0.115	0.112	0.151	0.075	0.091
	(0.070)	(0.090)	(0.095)	(0.102)	(0.070)	(0.077)
	[0.32]	[0.16]	[0.48]	[0.20]	[0.36]	[0.28]
N	150	150	310	310	150	150
R^2	0.804	0.833	0.731	0.769	0.802	0.826
Energy efficiency						
$Area_r \times Time_t$	-18.30*	-14.94	-22.15**	-18.09*	-15.98	-14.88
	(10.12)	(9.962)	(10.07)	(10.07)	(11.97)	(11.88)
N	4,033	4,031	5,644	5,639	4,033	3,925
R^2	0.605	0.614	0.625	0.633	0.604	0.612
Panel B: Beijing and the surrounding area						
Desulfurization						
$Beijing_r \times Time_t$	0.275***	0.277***	0.137**	0.251***	0.059	0.061
	(0.040)	(0.040)	(0.056)	(0.042)	(0.045)	(0.048)
	[0.04]	[0.00]	[0.00]	[0.00]	[0.20]	[0.20]
$Surrounding_r \times Time_t$	0.062	0.033	0.012	-0.025	0.064	0.049
	(0.058)	(0.060)	(0.048)	(0.063)	(0.060)	(0.059)
	[0.20]	[0.68]	[1.00]	[0.760]	[0.28]	[0.28]
N	150	150	310	310	150	150
R^2	0.905	0.911	0.753	0.782	0.899	0.905
Denitration						
$Beijing_r \times Time_t$	0.401***	0.394***	0.770***	0.556***	0.400***	0.390***
	(0.014)	(0.014)	(0.019)	(0.123)	(0.012)	(0.014)
	[0.00]	[0.00]	[0.00]	[0.24]	[0.00]	[0.00]
$Surrounding_r \times Time_t$	0.014	0.055	0.011	0.026	0.009	0.030
	(0.026)	(0.046)	(0.027)	(0.033)	(0.023)	(0.032)
	[0.72]	[0.32]	[0.76]	[0.48]	[0.76]	[0.36]
N	150	150	310	310	150	150
R^2	0.831	0.853	0.634	0.745	0.817	0.839
Energy Efficiency						
$Beijing_r \times Time_t$	71.94	66.55	68.65	64.06	67.25	9.28
	(59.07)	(56.08)	(59.17)	(56.27)	(49.57)	(57.33)
$Surrounding_r \times Time_t$	-22.04**	-18.35*	-25.91**	-21.52**	-19.47	-18.02
	(10.10)	(9.952)	(10.03)	(10.03)	(12.14)	(12.02)
N	4,033	4,031	5,644	5,639	4,033	3,925
R^2	0.606	0.614	0.626	0.634	0.605	0.612

Note: Robust standard errors are in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The numbers denote the coefficient of the interaction term between the treatment area and treatment period. In columns (3) and (4), the control area includes all provinces in China except the treatment area. In columns (5) and (6), the treatment period is defined as 2008 instead of 2007 and 2008. The control variables are used in columns (2), (4), and (6). The control variables for the pollution control regressions include gross regional production (GRP) per capita, pollution levy, and electricity price, whereas for the energy efficiency regressions include self-use, generation, and utilization. The year fixed-effects and province fixed-effects are included in all models. Wild bootstrap p-values clustered at the province level are shown in square brackets. PSM is used for the analysis of energy efficiency.

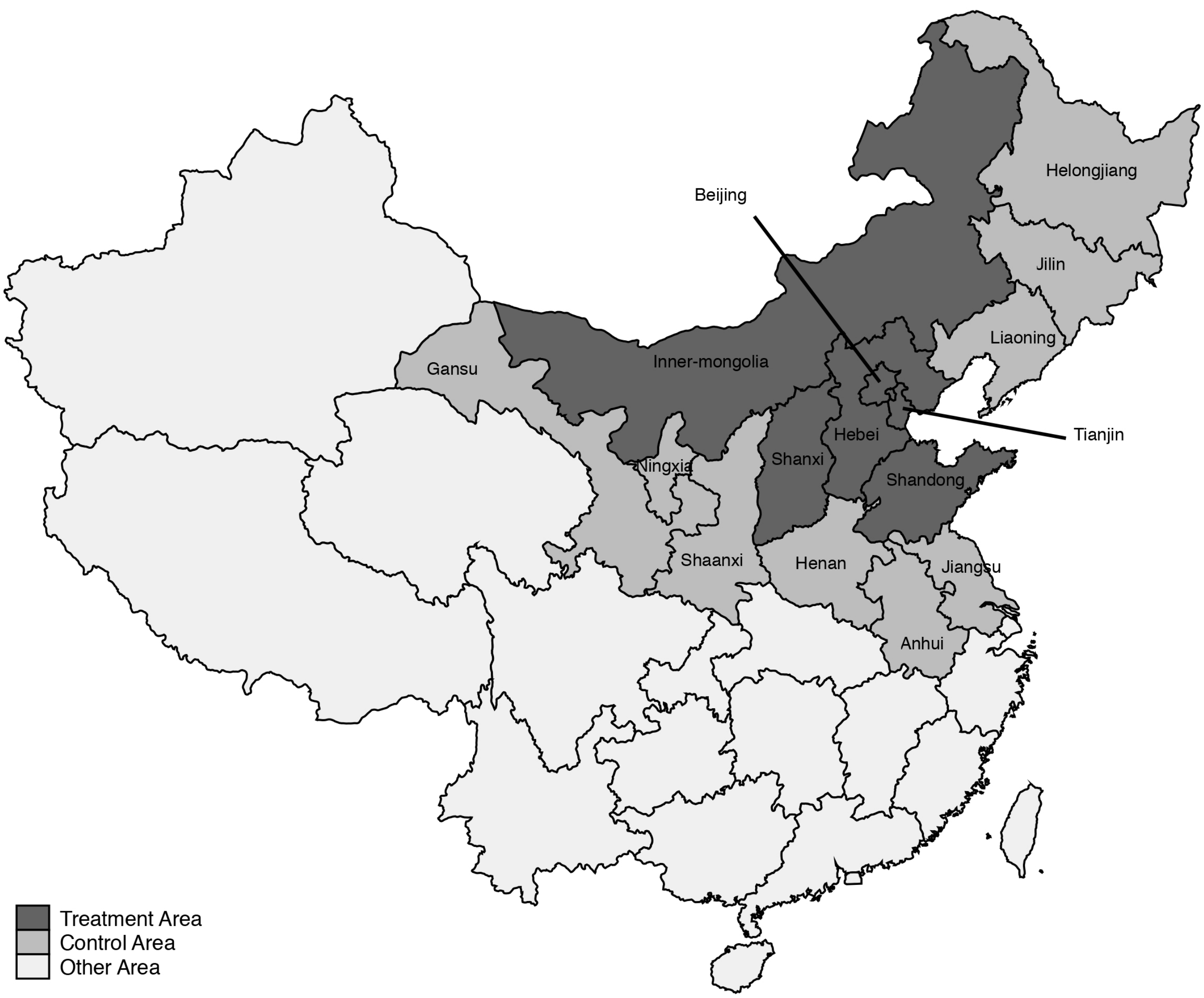


Figure 1: Treatment area and control area

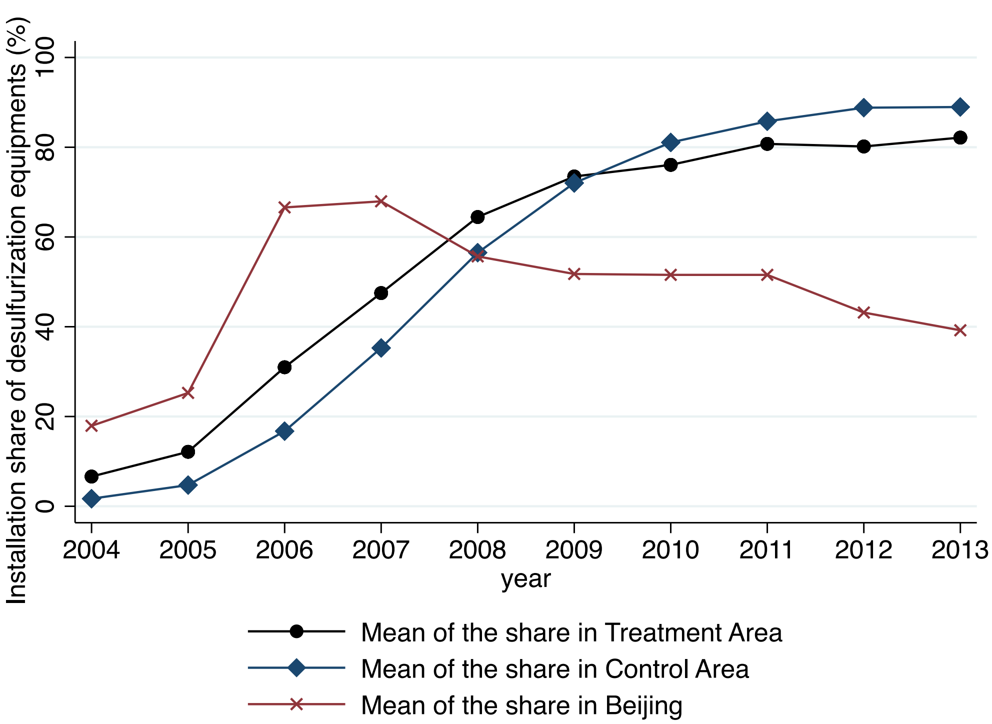


Figure 2: Share of desulfurization equipment

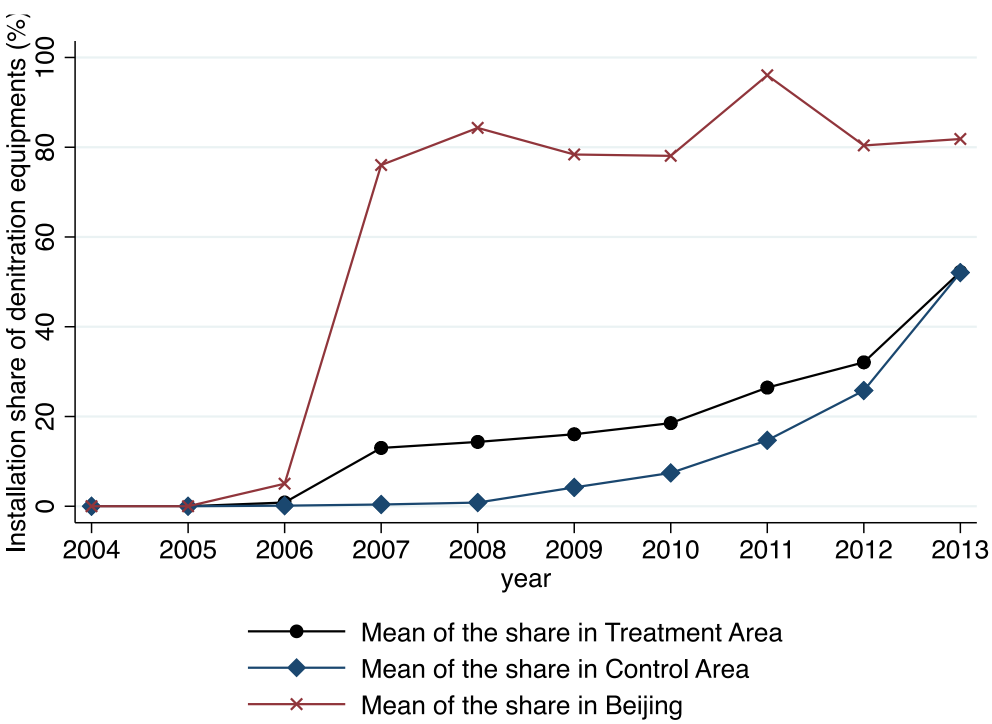
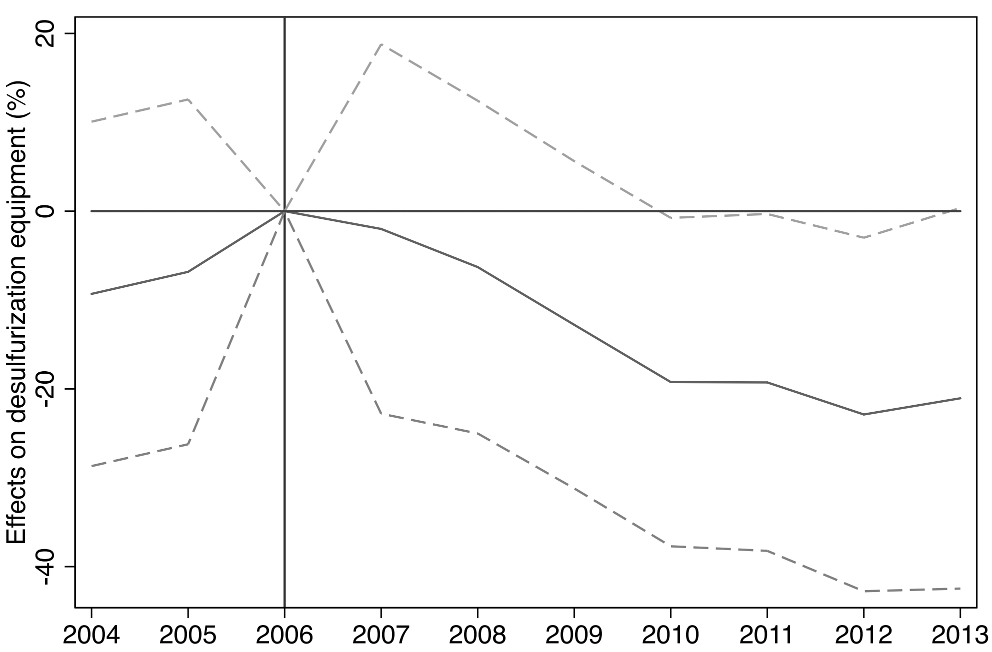
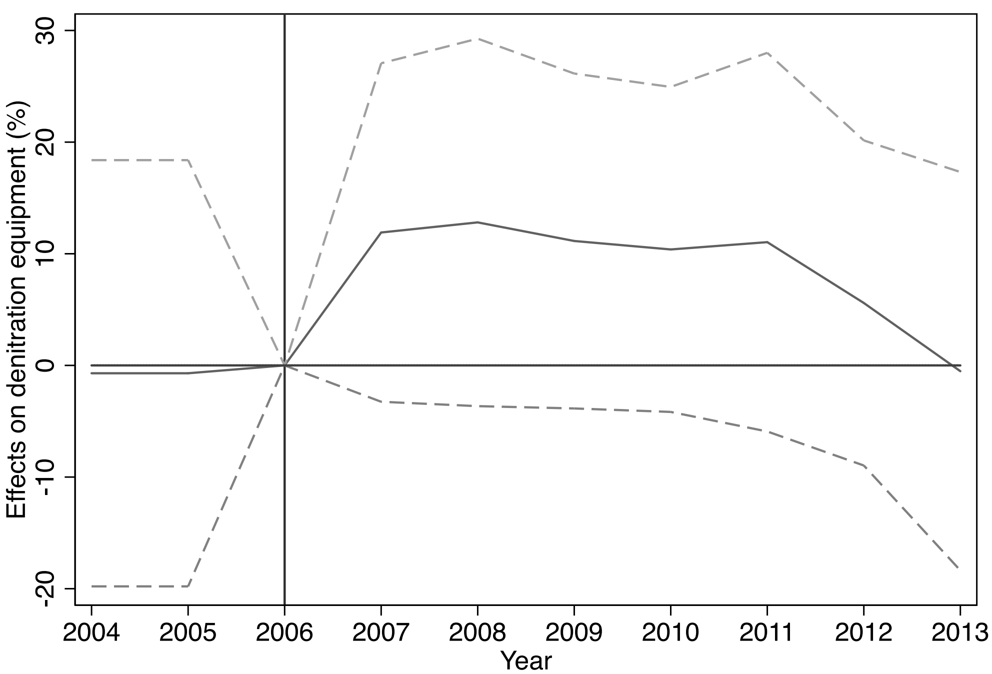


Figure 3: Share of denitration equipment



Note: Dashed lines indicate 90% confidence intervals.

Figure 4: Flexible DID model for desulfurization equipment



Note: Dashed lines indicate 90% confidence intervals.

Figure 5: Flexible DID model for denitration equipment

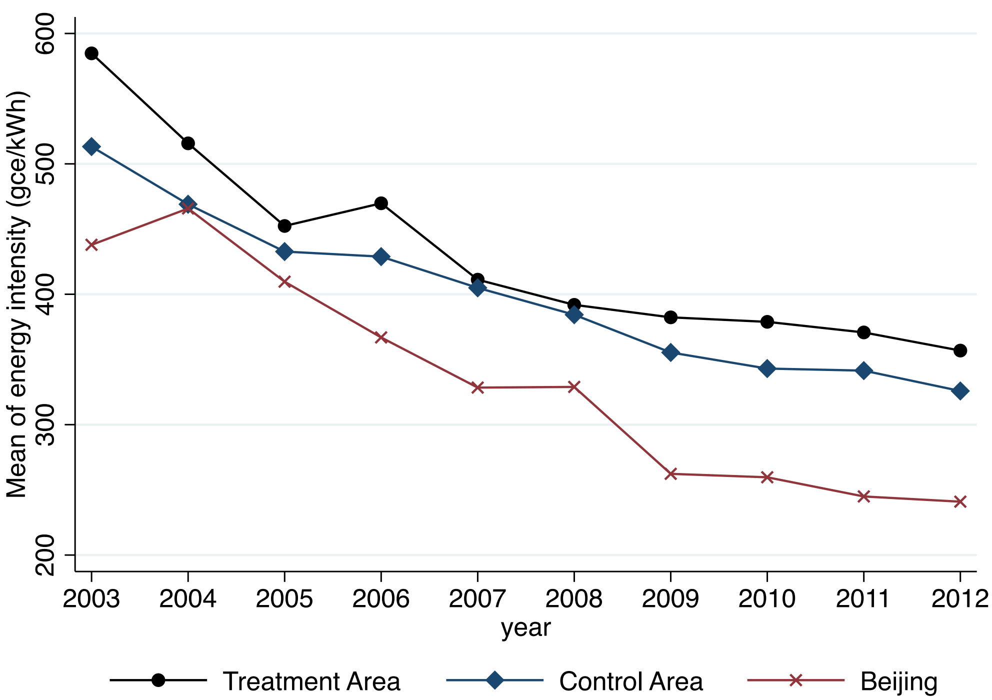
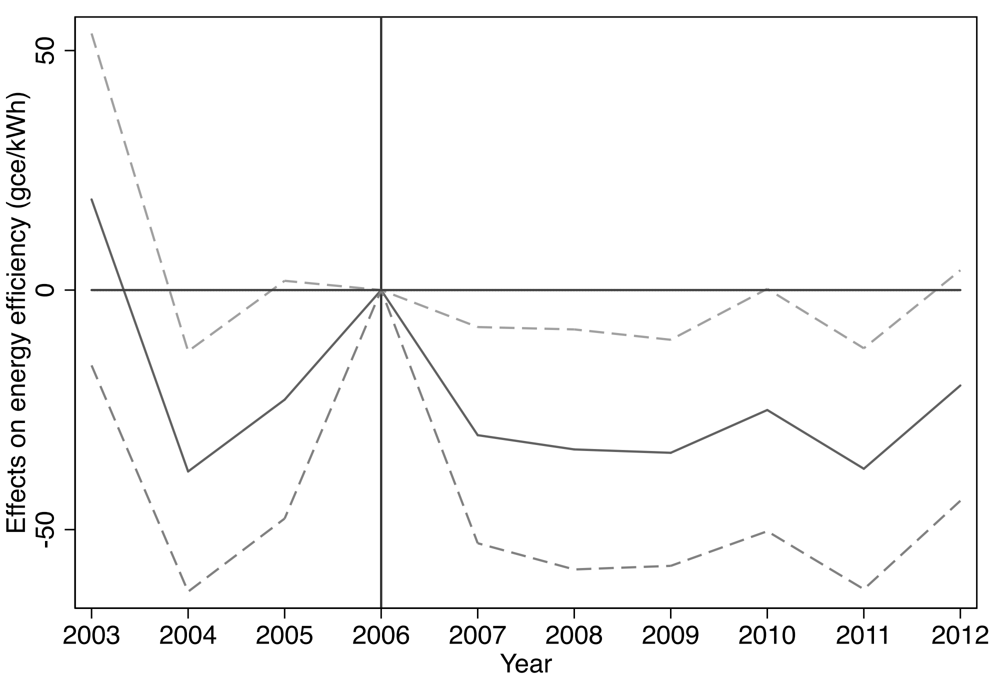


Figure 6: Energy efficiency



Note: Dashed lines indicate 90% confidence intervals.

Figure 7: Flexible DID model for energy efficiency

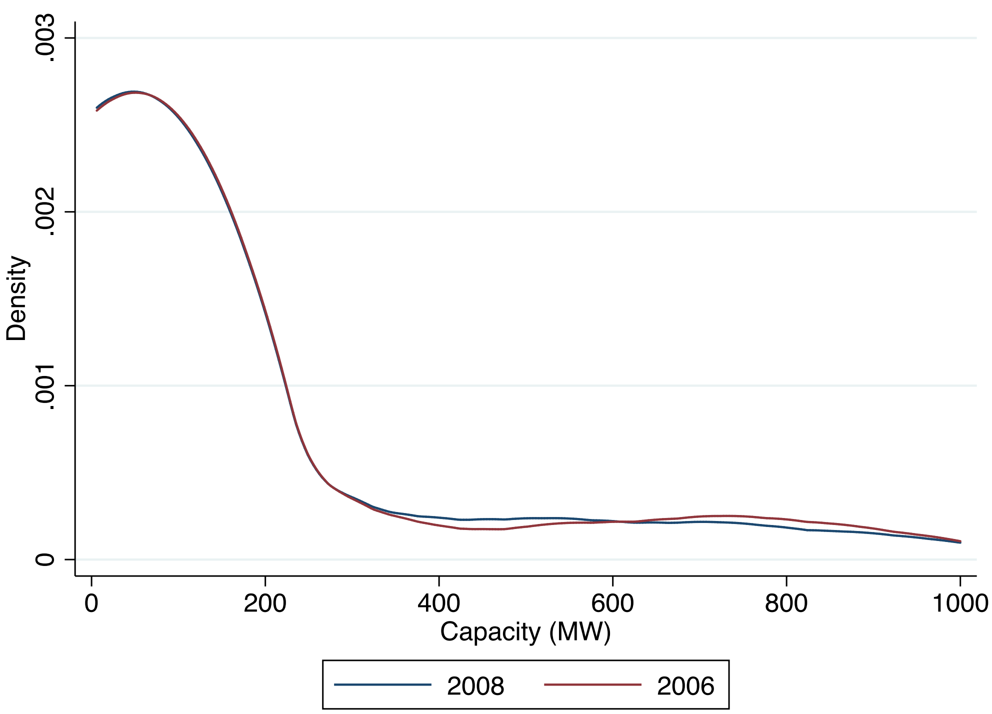


Figure 8: Capacity of power plants in 2006 and 2008

Appendix

Table A1: The results of flexible DID models

	(1) Desulfization	(2) Denitration	(3) Energy Efficiency
$Area_r \times 2004$			32.97*
			(17.00)
$Area_r \times 2004$	-0.093	-0.007	-21.03
	(0.118)	(0.116)	(16.52)
$Area_r \times 2005$	-0.068	-0.007	-19.50
	(0.118)	(0.116)	(12.71)
$Area_r \times 2007$	-0.020	0.119	-32.11**
	(0.127)	(0.0924)	(12.52)
$Area_r \times 2008$	-0.063	0.128	-30.24**
	(0.114)	(0.100)	(13.47)
$Area_r \times 2009$	-0.128	0.111	-20.06*
	(0.112)	(0.0915)	(11.62)
$Area_r \times 2010$	-0.192*	0.104	-10.42
	(0.113)	(0.089)	(12.09)
$Area_r \times 2011$	-0.193*	0.110	-17.97
	(0.116)	(0.103)	(11.91)
$Area_r \times 2012$	-0.229*	0.056	-10.46
	(0.121)	(0.089)	(11.71)
$Area_r \times 2013$	-0.211	-0.005	
	(0.131)	(0.109)	
Constant	0.226	0.415***	427.3
	(0.147)	(0.132)	(6.311)
N	150	150	13,559
R^2	0.911	0.815	0.04

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors clustered at the plant level are in parentheses. The robust option is used on all of the models. Fixed-effects method is selected in column (1) and (2), random-effects method is selected in column (3) based on Hausman text. Year dummy variables are both used in all of the models, and province dummy variables are used in column (1) and (2).

Table A2: The results of energy efficiency without matching

EE_{it}	(1)	(2)	(3)	(4)
$Area_r$	52.71***	52.13***	50.13***	49.55***
	(13.27)	(13.68)	(13.27)	(13.63)
$Time_t$	-125.1***	-125.2***	-124.1***	-124.4***
	(8.291)	(8.392)	(8.229)	(8.347)
$Area_r \times Time_t$	-20.27***	-19.71***	-19.02***	-18.89***
	(6.873)	(7.017)	(6.859)	(7.006)
$Self\_use_{it}$			0.365	0.348
			(0.344)	(0.328)
$Generation_{it}$			-0.003***	-0.002***
			(0.001)	(0.001)
$Utilization_{it}$			-0.001	-0.002
			(0.002)	(0.002)
Constant	514.0***	515.3***	519.8***	524.2***
	(8.095)	(8.273)	(13.27)	(13.54)
$Year\ dummy$	Yes	Yes	Yes	Yes
$Sample$	All thermal	Coal power only	All thermal	Coal power only
$Reduction$	4.70%	4.56%	4.41%	4.37%
N	13,274	12,809	12,936	12,489
R_b^2	0.043	0.044	0.048	0.050

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors clustered at the plant level are in parentheses. The robust option is used on all of the models. Control variables are used in columns (3) and (4). Random-effects method is selected in all of the model, since the results of Hausman text > 0.05. Year dummy variables and province dummy variables are used in random-effects models.