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

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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 effects of air pollution control within the thermal power sector during the 2008 Beijing Olympic Games (BOG08). Using data on pollution control equipment and energy intensity, we investigate for significant differences in their levels between provinces under the regional control policy for BOG08 and other provinces. The results suggest that the energy intensity of thermal power plants improved in 2007 and 2008 in provinces designated as areas requiring coordinated air pollution control for the Olympic Games. On the other hand, we found weaker statistical evidence for treatment effects on pollution control equipment.

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 $PM_{2.5}$ is the fifth largest risk factor leading to death and is responsible for 4.2 million deaths caused by a heart disease, stroke, lung cancer, chronic lung disease, or respiratory infections. The pollution level 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 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.

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. The Beijing Olympic Committee for the Games of XXIX Olympiad (BOCOG) and the Beijing Municipal Government launched the concept of "Green Olympics" and integrated several environmental targets in the bid with accelerated deadlines. In particular, air quality improvement was of high priority in the planning for the Games. 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 one year prior to 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, suggesting that the improvement was temporary. He et al. (2016) estimate the effects of air pollution on mortality in China using exogenous variations in air quality during the BOG08. and show that monthly PM_{10} concentrations in Beijing were reduced by approximately 30%. In addition, 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 of the BOG08. Employing daily data from multiple monitoring stations, the authors find that the aggregate API fell 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 of air pollution in stationary sources, particularly in the thermal power sector.

This study investigates the pollution reduction within the thermal power sector during the BOG08. Using data on pollution control equipment and energy intensity, we investigate for significant differences in their levels between provinces under the regional control policy for BOG08 and other provinces. The results of this study suggest that installation level of pollution control equipment and energy intensity improved in Beijing and the neighboring provinces in 2007 and 2008, although the statistical evidence for the control equipment is not very strong.

This study makes three contributions to the literature. First, in contrast to previous studies that examine the impact of BOG08 on air quality improvement (Chen et al., 2013; He et al., 2015), we examine the impact of the Games on control measures for air pollution. Because the control measures are directly related to the behavior of emission sources, they can reveal the impact of various policies enforced during the period on emission. Second, this study considers two activities as control measures: installation of pollution control equipment and improvement in energy intensity. 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. 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 the 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 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. 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 of this study. We review various air pollution control policies implemented for the BOG08 in Beijing and surrounding areas. Section 3 analyzes the effect of the BOG08 on the installation of pollution control equipment. Section 4 examines the effect of BOG08 on energy intensity. Section 5 concludes.

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 the Beijing Municipal Government proposed the concept of the "Green Olympics" (UNEP 2009). Air quality, in particular, was considered 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 five objectives: reduce energy consumption growth and improve energy efficiency; close and relocate production lines in major industrial sectors; reduce emission in 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 adoption of end-of-pipe technology (installation of desulfuration, denitration, and dust removal equipment for boilers) and improvement in energy intensity (use of clean fuels to replace coal fuels; reduce industrial use of coal; and shut down of inefficient power plants, steel companies, and other petrochemical plants). 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, 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 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 to 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 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, 2007). 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 (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 strictly controlled. Furthermore, the monitoring of air pollution was reinforced during the period (Environmental Protection Bureau of Shanxi Province, 2007). By 2007, Shandong reduced SO_2 emissions by 1.82 million tons, which is a 7.12% 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 area as well, thermal power plants were 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 a large reduction of $PM_{2.5}$ can be mainly attributed to regional transportation within the area beyond Beijing.

We estimate the effects of BOG08 on air pollution controls in the thermal power sector using a sample of six provinces in the treatment area and nine provinces in the control area (Table 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 dependent variables throughout our analysis. First, we employ 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 data are adopted from the website for the data center of the Chinese Ministry of Environmental Protection. Second, we use energy intensity of the thermal power plants, which is adopted from the *Compilation of Statistics on Chinese Electric Power Industry* (China Electricity Council, respective years). In addition, we employ control variables that possibly affect the installation of control equipment and energy intensity.

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).[1] The 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, the province where 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 company that manufactured 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. 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 provincial-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

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

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.

[Table 1]

3.2 Energy intensity data

We obtained energy intensity data 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.[2] 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 energy intensity 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. Energy intensity in a coal-powered plant is generally higher than that in an oil- and gas-fired power plant.

Table 2 reports the descriptive statistics for the energy intensity data. Our sample comprises 6,265 plants in the treatment area and 7,010 plants in the control area. Average energy intensity in the treatment area is 8.9% higher than that in the control area.

[Table 2]

3.3 Control variables

The control variables for the pollution control regressions include gross regional production (GRP) per capita, pollution levy, and electricity price. Data for GRP per capita are adopted from the China Statistical Yearbook. Pollution levy data for each province are taken from the China Environment Yearbook (Editorial Committee of China Environment Yearbook, respective years). The on-grid electricity prices are from the CEIC (2015) database.

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[2] We use “gross coal consumption rate” to measure the energy intensity of each plant.

For the energy intensity regressions, we include self-use, generation, and utilization as control variables. Self-use is a variable that represents percentage of electricity used by a plant in each year. Generation is the amount of electricity generated by the plant in each year. Utilization is the plant's total operational hours in each year. All data are taken from the *Compilation of Statistics on Chinese Electric Power Industry.*

4 Effect of BOG08 on pollution control

We use a difference-in-difference (DID) model to estimate the impact of the BOG08 on air pollution controls by thermal power plants. The estimation model is represented as follows:

$$S_i = \alpha + \gamma Area_r + \lambda Time_k + \beta AreaTime_{rk} + \phi X_i + \varepsilon_i, \tag{1}$$

where S_i is 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 in each province. $Area_r$ is the dummy variable for treatment area, which takes the value of 1 for six provinces in which the MEGA policy was applied and 0 otherwise. $Time_k$ is the dummy variable for treatment period, which takes the value of 1 for the period 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.[3] $AreaTime_{rk}$ is the cross-term for $Area_r$ and $Time_k$ to capture the impact of MEGA policy on the installation level of end-of-pipe equipment.

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

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

i. China has a pollution levy system since 1979 and significantly increased the levy rates in 2003 (Lin, 2013). The benefits of pollution control are expected to increase with higher levels of pollution levy. This provides stronger incentives for the thermal power sector to install end-of-pipe equipment. The pollution levy of SO_2 emissions increased several times from 0.21 RMB/kg in 2002 to 1.26 RMB/kg in 2007 (JES, 2007; OECD, 2007). Second, GRP_i indicates the GRP per capita in province i and captures the level of economic development in each province. We assume that the share of boilers with control equipment is higher in developed provinces. Third, $Price_i$ represents the on-grid electricity price in province i. In July 2003, a market-based pricing system was introduced in the thermal power sector. We assume that a higher on-grid tariff is associated with a greater capacity share of end-of-pipe equipment owing to higher profit.

As of 2013, among 1,835 China's independent power producer, approximately 74% of thermal power boilers installed desulfuration equipment and 22% had denitration equipment (Chinese Ministry of Environmental Protection, 2015).[4] Figure 2 illustrates the trends of desulfuration equipment installation in the thermal power sector. The Chinese government initiated efforts to reduce SO_2 emission much before the preparation period of the Beijing Olympic Games. The central government reinforced a policy to control SO_2 discharge from the thermal power sector in the Tenth (2001–2005) and Eleventh Five-Year Plan (2006–2010) periods. In the Tenth Five-Year Plan period, a total of 75 power plants (165.85 MW) installed desulfurization equipment. Following this period, a larger-scale desulfurization plan[5] was issued in Eleventh Five-Year Plan period. The plan defines targets for desulfurization at the provincial 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.

The capacity share for desulfurization equipment in the treatment area was higher than

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[4] Note that our calculation of the share of boilers that installed control equipment is based on the capacity of boilers and does not coincide with these figures.

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

that in the control area till 2009, but decreased following 2010. The SO_2 emissions control policy in China began during the Tenth 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 the 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 of SO_2 emissions, the government began controlling NO_x emissions from the thermal power sector in the Eleventh Five-Year Plan (2006–2010) and seriously implemented controls in the Twelfth Five-Year Plan period (2011–2015). Figure 3 presents the trends in the 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]

The results of the simple DID model are presented in Table 3. Columns (1) and (2) list the results for desulfurization equipment and columns (3) and (4) present those for denitration equipment. The models in columns (2) and (4) are estimated with control variables. The cross-term $AreaTime_{rk}$ are statistically insignificant in both desulfurization and denitration models. This suggests no significant impact by the BOG08 on the level of end-of-pipe control.

[Table 3]

Next, we estimate a fixed-effects model to explore the panel structure of the data (15 provinces for 10 years). The dummy variables for provinces and year are included in the model: Dum_pro_i denotes the province dummy and Dum_year_j is the year dummy that uses 2006 ($j = -1$) as the base year.

$$S_{it} = \alpha + \beta AreaTime_{rk} + \sum_{i=2}^{15} \xi_i Dum\_pro_i + \sum_{j=-4}^{5} \eta_j Dum\_year_j (t = m+j) + \phi X_{it} + \upsilon_i + \varepsilon_{it}, \quad (2)$$

where υ_i is an unobservable individual effect and ε_{it} is idiosyncratic errors. Table 4 reports the results for the fixed-effects model. The coefficients of $AreaTime_{rk}$ are positive and statistically significant at 10% in the models for desulfurization equipment without control variables; however, they are insignificant in models with control variables. As for the models for denitration equipment, the coefficients of $AreaTime_{rk}$ are positive and statistically significant at 10% without control variables and at 5% with control variables.[6]

[Table 4]

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

$$\begin{aligned} S_{it} = & \alpha + \sum_{j=-4}^{5} \beta_j AreaDum\_year_{rt} (t = m + j) + \sum_{i=2}^{15} \xi_i Dum\_pro_i \\ & + \sum_{j=-4}^{5} \eta_j Dum\_year_t (t = m + j) + \upsilon_i + \varepsilon_{it}, \end{aligned} \quad (3)$$

where the excluded time category is 2006 ($j = -1$) such that the effects are measured relative to the year prior to the implementation of the MEGA policy. Figure 4 shows the treatment area effect on desulfurization equipment installation for each year. The installation effects of desulfurization equipment are negative but statistically insignificant during 2007–2008. The result suggests that the installation of desulfurization equipment in the treatment area

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[6] When using a random effects model, the coefficient of $AreaTime_{rk}$ is positive but statistically insignificant. The chi-square statistics of Hausman test is negative, suggesting that the test is invalid for these models. Considering the small sample size, here, we report the results for fixed effects model.

does not significantly differ from that in the control area in these periods compared to 2006. In addition, the figure shows that the impact is negative and statistically significant after 2010. This suggests that, after the BOG08 period, the numbers of installations of control equipment increased in the control area compared to the treatment area.

[Figure 4]

Figure 5 reports the estimation results for denitration equipment for each year. In particular, the effects on denitration equipment in each year are statistically insignificant, suggesting that the treatment area effect in each year is not significantly different from that in 2006.

[Figure 5]

To further compare the treatment effects by provinces, we use a multiple-region fixed-effects DID model. $Dum\_AreaproTime_{ik}$ is the cross-term for $Dum\_Areapro_i$ and $Time_k$, where $Dum\_Areapro_i$ is a dummy variable for each province in the treatment area and Beijing ($i = 1$) is used as a base category. It captures the difference in the installation level of end-of-pipe equipment in each province of treatment area during the BOG08 by the coefficient β_i for the ith province.

$$\begin{aligned} S_{it} =& \alpha + \sum_{i=2}^{6} \beta_i Dum\_AreaproTime_{ik} + \sum_{i=2}^{6} \xi_i Dum\_pro_i \\ &+ \sum_{j=-4}^{5} \eta_j Dum\_year_j (t = m + j) + \upsilon_i + \varepsilon_{it}. \end{aligned} \tag{4}$$

Figure 6 summarizes the results. We find that the effects of the BOG08 on desulfurization equipment are statistically significant only in Tianjin. The installation level of desulfurization equipment in Tianjin is 37% lower than that in Beijing in both 2007 and 2008. The coefficients for other provinces are statistically insignificant, suggesting that the installation level of desulfurization equipment in other provinces does not significantly different from that in Beijing.

[Figure 6]

Figure 7 presents the results for the multiple-region fixed-effects DID model for denitration equipment installation. Compared to Beijing, the effects of the BOG08 are negative and statistically significant in other provinces. The installation level of denitration equipment in Beijing is 30% higher than that in other provinces under the MEGA policy during the BOG08 period. In other words, the positive installation effect for denitration equipment might be due to the early introduction of the equipment in Beijing, not the MEGA policy,.

[Figure 7]

In sum, our results suggest that the BOG08 promote the installation of pollution equipment, although the statistical evidence is weak. The treatment effect during the BOG08 is not significant in the simple DID model, but it is significant in some of the fixed effects models. Following the Olympic Games period, the capacity share of desulfurization equipment in the treatment area becomes lower than that in the control area. The result for the multiple-period fixed-effects DID model indicates that effects of a MEGA policy no longer exist after the Olympic Games period. Furthermore, the BOG08 effect on denitration might be attributed to the early introduction of equipment in Beijing, not the regional control policy for the Games. The installation of denitration has been promoted at the national level since the Twelfth Five-Year Plan (2011–2015), which is 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 Beijing Olympic Games period (2007–2008), where most of the thermal power boilers (958 boilers) did so during 2011–2013.

5 Effect of BOG08 on energy intensity

First, we estimate the effects of the BOG08 on energy intensity using the following simple DID model:

$$EI_i = \alpha + \gamma Area_r + \lambda Time_k + \beta AreaTime_{rk} + \phi X_i + \varepsilon_i, \tag{5}$$

where dependent variable EI_i denotes energy intensity in thermal power plant i and measures the amount of energy (in coal equivalent) used to generate one kWh of electricity. Higher energy intensity generally means lower energy efficiency of a power plant. The average energy intensity in our data is 428 gce/kWh in the treatment area, and 392 gce/kWh in the control area. $Area_r$ is a dummy variable that represents plants located in provinces under the MEGA policy. Our sample comprises of 1,246 thermal power plants (approximately 27.28% of all thermal power plants in China) in the treatment area and 1,865 thermal power plants (approximately 40.83% of all thermal power plants in China) in the control area. The dummy variable $Time_k$ takes the value of 1 if the period is 2007 or 2008, and 0 otherwise. $AreaTime_{rk}$ indicates the cross-term of $Area_r$ and $Time_k$. X_i represents the control variables that include $Self\_use_i$, $Generation_i$, and $Utilization_i$. $Self\_use_i$ indicates the rate of self-consumption of electricity in power plant i. A higher number for $Self\_use_i$ means reduction of the electricity transmitted to grid.[7] The reduction in self-consumption improves the net unit heat. $Generation_i$ is the electricity generation of power plant i. In our sample, 40% of the thermal power plants have generation capacity greater than 300 GWh.[8] $Utilization_i$ represents the annual utilization hours in plant i. Longer utilization time means greater electricity generation. The average annual utilization hour in the treatment area is 4,848 hours, which is slightly lower than that in the control area (5,045 hours).

We also estimate the models with panel data settings, as follows:

$$EI_{it} = \alpha + \gamma Area_r + \lambda Time_k + \beta AreaTime_{rk} + \phi X_{it} + \upsilon_i + \varepsilon_{it}, \tag{6}$$

assuming that counterfactual outcomes in the absence of treatment are independent of treat-

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[7] The self consumption of electricity includes a feed-water system, cooling water system, pollution control system, combustion air and fuel gas, fuel handing, and other loads.

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

ment, and conditional on an unobservable individual effect υ_i and covariates X_{it}. The Hausman test rejected the null hypothesis that the individual-level effects are adequately modeled by a fixed effects model (p-value=0.466). 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.

Figure 8 shows changes in energy intensity during the study period. The energy intensity level in both areas is steadily decreasing, and although the level in the treatment area is always higher than that in the control area.[9] The figure shows that energy intensity in the treatment area sharply declined in 2007 and was close to that in the control area. In Beijing, several large thermal power plants and 16,000 boilers located in the central area of Beijing 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). This variety of policies in MEGA policy areas could have been effective in reducing energy intensity during the BOG08 period.

[Figure 8]

Table 5 reports the results for pooled ordinary least squares in columns (1) and (2) and those for the random effects models in columns (3) and (4). Models in columns (2) and (4)

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[9] Several national-level polices have contributed to the steady decrease of energy intensity. 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 terms of the thermal power sector, the plan targeted the decrease of the energy consumption index (ECI) 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 by adopting advanced technologies during the Eleventh 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 Eleventh Five-Year Plan (National Development and Reform Commission, 2006). A total of 132 thermal power plant can be found in 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 Eleventh Five-Year Plan (Ke et al., 2012).

are estimated with control variables. $Area_r$ is positive and statistically significant, which means that the energy intensity in the treatment area is significantly higher than that in the control area. $Time_k$ is negative and statistically significant, which suggests that energy intensity is significantly improved during the BOG08 period. The cross-term $AreaTime_{rk}$ is negative and statistically significant in the random effects models, suggesting that energy intensity in the treatment area improved during the BOG08 period.

[Table 5]

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

$$\begin{aligned} EI_{it} =& \alpha + \gamma Area_r + \sum_{j=-4}^{5} \beta_j AreaDum\_year_{rt}(t=m+j) + \sum_{j=-4}^{5} \eta_j Dum\_year_t(t=m+j) \\ &+ \upsilon_i + \varepsilon_{it}, \end{aligned} \tag{7}$$

where $AreaDum\_year_{rt}$ are the cross-terms of $Area_r$ and Dum_year_t. 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 9 shows the effects of the BOG08 on energy intensity in each year. Compared to the base year (2006), the effect is negative and statistically significant in 2007, 2008, and 2009. Energy intensity in the treatment area shows a declining trend since 2006, with a decrease of 32.52 gce/kWh, 30.28 gce/kWh, and 20.09 gce/kWh in 2007, 2008, and 2009, respectively. From this, it can be interpreted that the effect of the BOG08 on the improvement of energy intensity was maintained for three years. The reductions are 7.5%, 7%, 4.6% of the average energy intensity in the treatment area. These are sizable numbers compared to the estimate presented in Chan et al. (2017), who show that electricity restructuring led to a 1.4% improvement in China's energy efficiency.

[Figure 9]

To evaluate the effects of the BOG08 on energy intensity in each province, we use a multiple-region random-effects DID model as follows:

$$\begin{aligned} EI_{it} =& \alpha + \gamma Time_k + \sum_{i=2}^{6} \beta_i Dum\_AreaproTime_{ik} + \sum_{i=2}^{6} \eta Dum\_pro_i \\ &+ \upsilon_i + \varepsilon_{it}. \end{aligned} \tag{8}$$

Figure 10 summarizes the effects of the 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 does not differ by the provinces involved.

[Figure 10]

The improvement of energy intensity can be attributed to several factors. First, the use of cleaner coal is relatively easier measure to reduce energy intensity. Although the difference by the provinces are not statistically significant (Figure 10), a large improvement of energy intensity in Shanxi compared to that in Beijing suggest that there is a higher impact of the MEGA policy in the coal rich province. Second, the closure of small thermal power plants directly affects energy intensity by reducing operation of boilers with lower efficiency. Figure 11 compares the Kernel density for generation capacity of power plants in the treatment area between 2006 and 2008. It shows that the density of smaller power plants are higher in 2006. While the total number of power plants in operation does not change during the study period, there is a shift in the distribution of generation capacity.

[Figure 11]

The results can be summarized as follows. First, energy intensity significantly reduced in the treatment area during the BOG08 period. Under the stringent policy, thermal power plants began using cleaner fuel and made other efforts to reduce coal consumption. These efforts might contribute to the improvement of energy intensity in the treatment area with heavily polluting thermal power plants. Second, the effects of the BOG08 on the energy intensity of thermal power sector were sustained until 2008. This finding is in line with Chen et al.'s (2013) result that the effect of the BOG08 on air pollution reduction dissipated one year after the Games.

6 Robustness checks

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

Table 6 reports the estimation results. The numbers presented are the effects of the MEGA policy on the installation of desulfurization equipment and denitration equipment and energy intensity during the BOG08 period. The estimated coefficients for desulfurization equipment are statistically insignificant at all conventional significance levels. The coefficients for denitration equipment are statistically significant in columns (3) and (4); however, they are insignificant in columns (5) and (6). The coefficients for energy intensity are negative and statistically significant in all alternative models, except in column (6), where the effect is not statistically significant. In summary, the estimation results indicate that the main results are robust to alternative definitions of the control area and treatment period.

[Table 6]

7 Conclusions

This study examined the impacts of the BOG08 on pollution control in the China's thermal power sector. Our results indicate that the energy intensity of thermal power plants improved in 2007 and 2008 in provinces designated as areas requiring a coordinated air pollution control policy for the Olympic Games. On the other hand, evidence of such a treatment effect is weak for the effect on pollution control equipment.

The reason for the slightly contrasting results might be attributed to differences in characteristics between end-of-pipe controls and improvement in energy intensity. Typically, the end-of-pipe control strategy entails considerable amount of investment and requires considerable fixed costs. The 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 sufficient financial resources. Hammar and Löfgren (2010) investigate drivers for investments in end-of-pipe solutions and clean technologies and find that the expenditures for environmental R&D played an important role in the former type of investment, while energy price is important for the latter.

Our results complement those of Chen et al. (2013) and He et al. (2016), who present a significant but temporal effect of the BOG08 on air quality improvement. Our findings suggest that energy intensity improved during the studied period in the treatment area. Because the improvement in energy intensity has persistent effects over the long term, the observed change in the thermal power plants has significant policy implications in contrast to the temporal effects caused by reduced traffic volume (Chen, 2013). Although we could not examine the impact of the improvements in energy intensity on reduced air pollution in the area, it is reasonable to expect that there is a considerable linkage between them. To sustain good air quality even after the Beijing Olympic period, policies with a long-term impact 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
$Share\_sulfur_i$	%	60	55.4	0.315	90	53.2	0.365
$Share\_nitrogen_i$	%	60	17.3	0.279	90	10.6	0.174
$Time_k$	Dummy	60	0.200	0.403	90	0.200	0.402
GRP_i	10,000 RMB	60	40.65	22.75	90	24.75	14.22
$Levy_i$	Billion RMB	60	0.744	0.583	90	0.529	0.434
$Price_i$	RMB	60	0.585	0.088	90	0.628	0.083

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

Table 2: Descriptive statistics for energy intensity

		Treatment Area			Control Area		
		6 provinces			9 provinces		
	Unit	N	Mean	SD	N	Mean	SD
EI_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: Our sample includes unbalanced panel data from 2003 to 2012. There are 1,206 thermal power plants in Beijing and its surrounding regions.

Table 3: Simple DID results for pollution control equipment

	(1)	(2)	(3)	(4)
S_i	$Share\_sulfur_i$	$Share\_sulfur_i$	$Share\_nitrogen_i$	$Share\_nitrogen_i$
$Time_k$	-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)
$AreaTime_{rk}$	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_w^2	0.008	0.346	0.055	0.491

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

Table 4: Fixed effects DID results for pollution control equipment

S_{it}	(1) $Share\_sulfur_i$	(2) $Share\_sulfur_i$	(3) $Share\_nitrogen_i$	(4) $Share\_nitrogen_i$
$AreaTime_{rk}$	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)
Year dummy	Yes	Yes	Yes	Yes
Province dummy	Yes	Yes	Yes	Yes
N	150	150	150	150
R_w^2	0.902	0.906	0.804	0.833

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

Table 5: Simple and random effects DID results in energy intensity

EI_i	(1) POLS	(2) POLS	(3) RE	(4) RE
$Area_r$	37.54***	16.65***	52.71***	39.97***
	(5.330)	(5.211)	(13.27)	(13.21)
$Time_k$	-9.621**	-10.05**	36.50***	33.08***
	(4.813)	(4.226)	(5.107)	(4.475)
$AreaTime_{rk}$	-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)
Year dummy	No	No	Yes	Yes
Province dummy	No	No	Yes	Yes
N	13,274	12,936	13,274	12,936
R^2	0.006	0.094		
R_b^2			0.043	0.074

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

Table 6: BOG08 effects: alternative definition of control

	(1) Baseline	(2) Baseline	(3) All Provinces	(4) All Provinces	(5) 2008	(6) 2008
Desulfurization	0.098*	0.077	0.038	0.030	0.063	0.051
	(0.050)	(0.055)	(0.048)	(0.057)	(0.054)	(0.055)
N	150	150	310	310	150	150
R_w^2	0.902	0.906	0.752	0.779	0.899	0.905
Denitration	0.078*	0.115**	0.167*	0.132**	0.074	0.091
	(0.046)	(0.049)	(0.098)	(0.064)	(0.065)	(0.065)
N	150	150	310	310	150	150
R_w^2	0.804	0.833	0.558	0.710	0.802	0.826
Energy intensity	-20.27***	-15.85**	-18.62***	-11.75*	-16.71**	-9.701
	(6.873)	(6.792)	(6.432)	(6.776)	(7.772)	(7.189)
N	13,274	12,936	18,935	18,424	13,274	12,936
R_b^2	0.043	0.074	0.055	0.120	0.043	0.074

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. Control variables are used in column (2), (4), and (6). The year dummy variables and province dummy variables are used in the analysis of energy intensity.

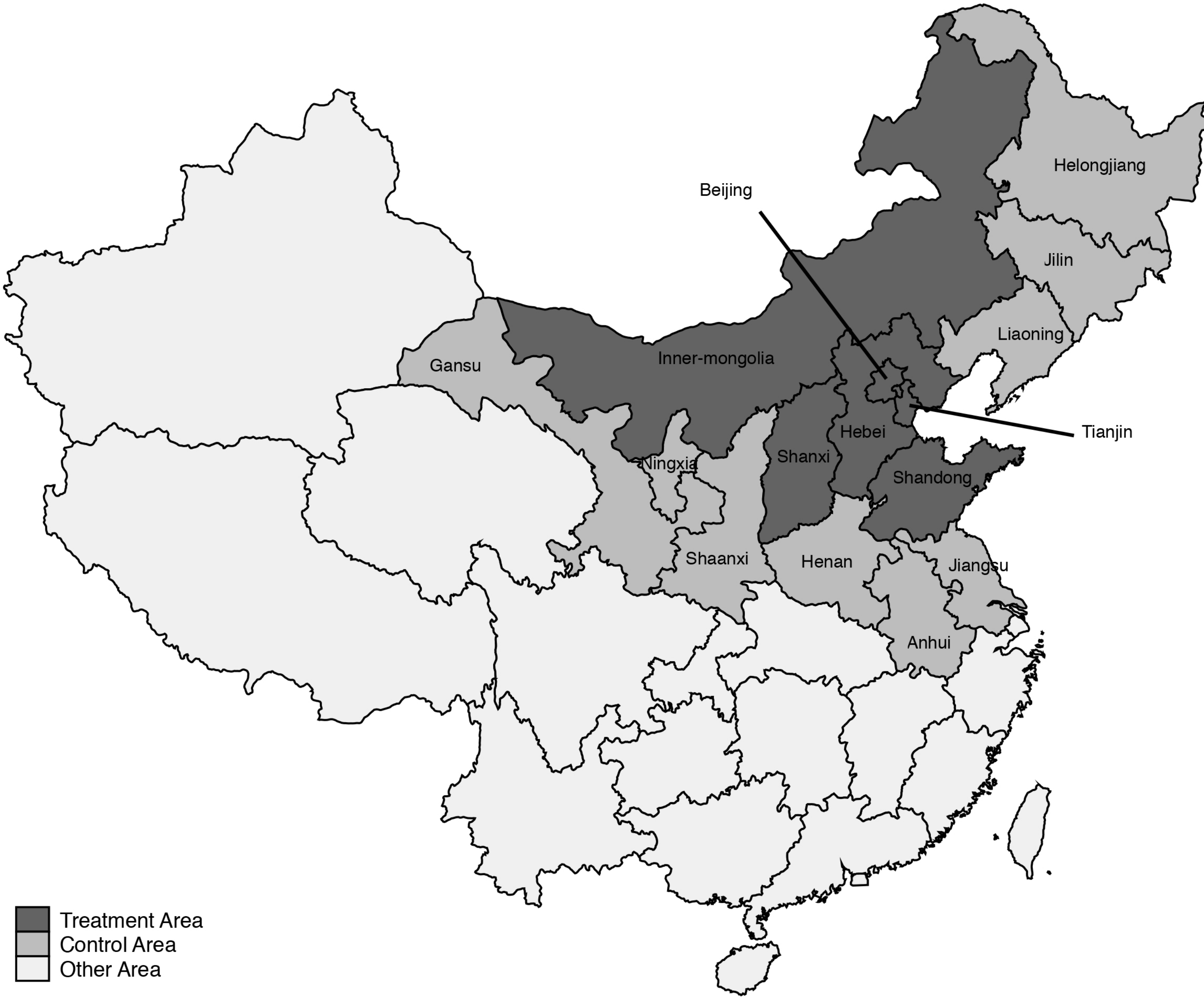


Figure 1: Treatment area and control area

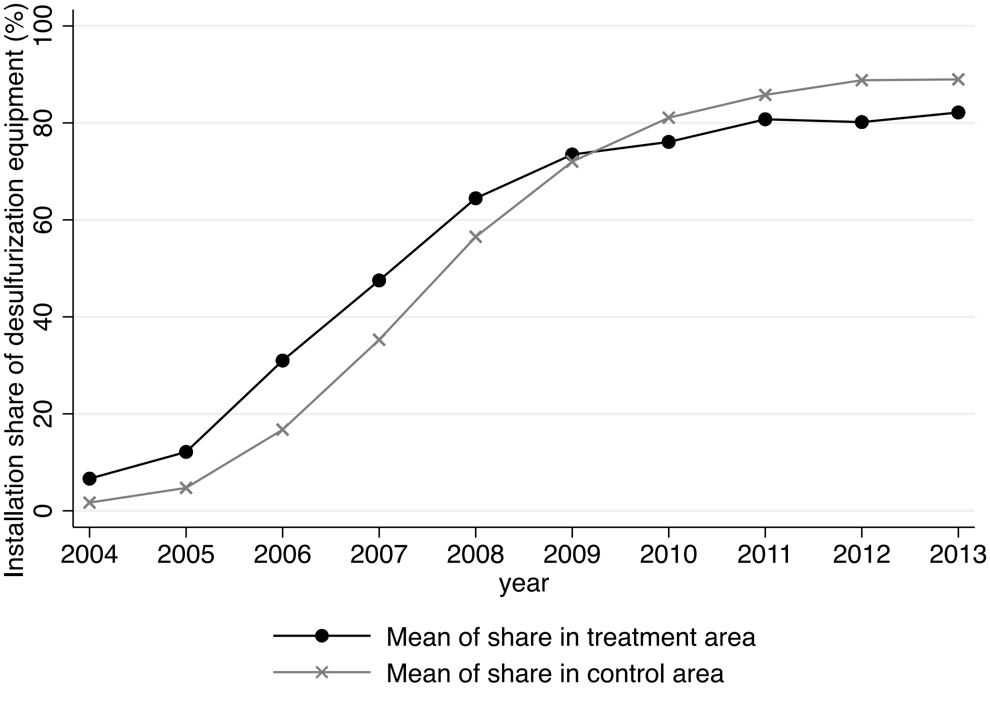


Figure 2: Share of desulfurization equipment

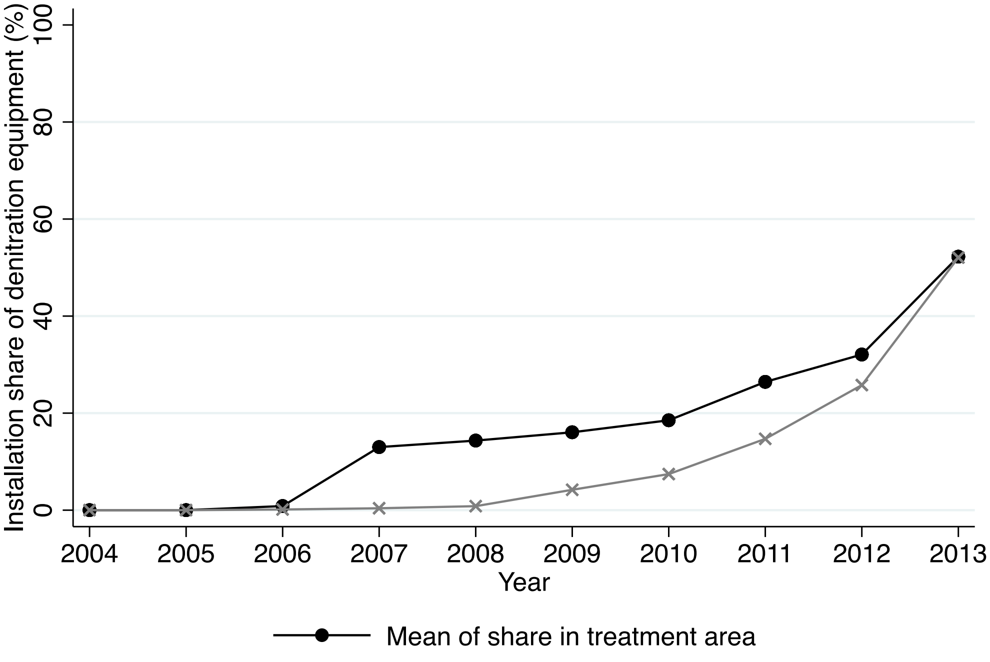
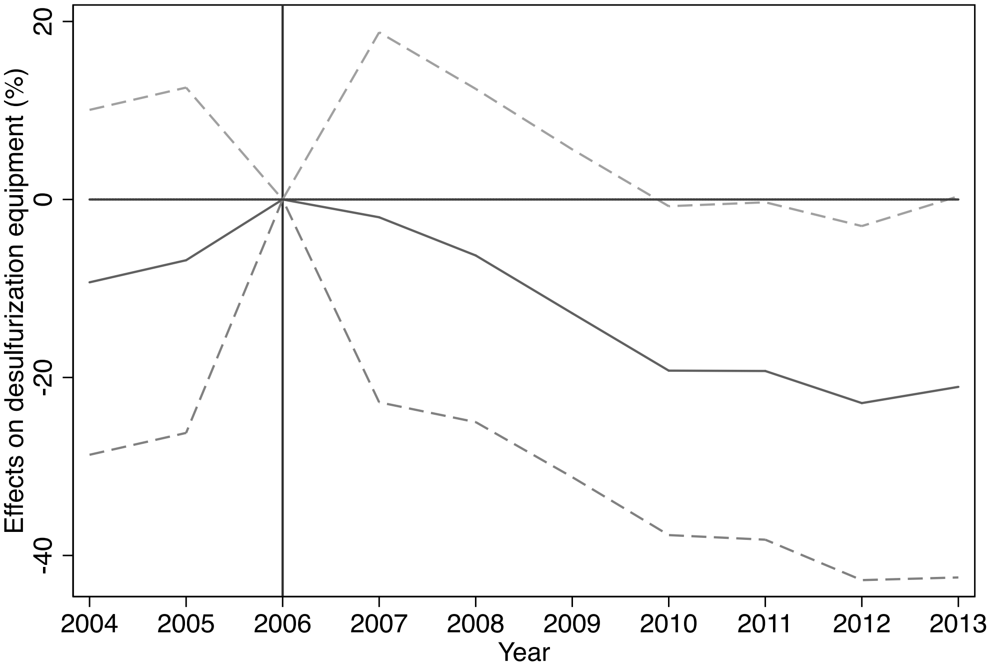
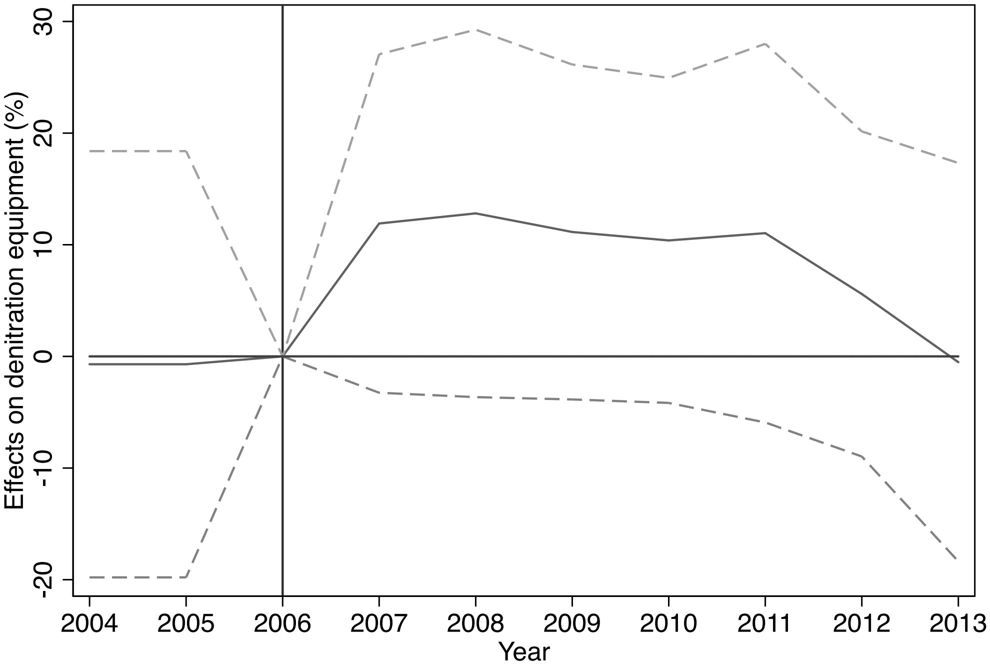


Figure 3: Share of denitration equipment



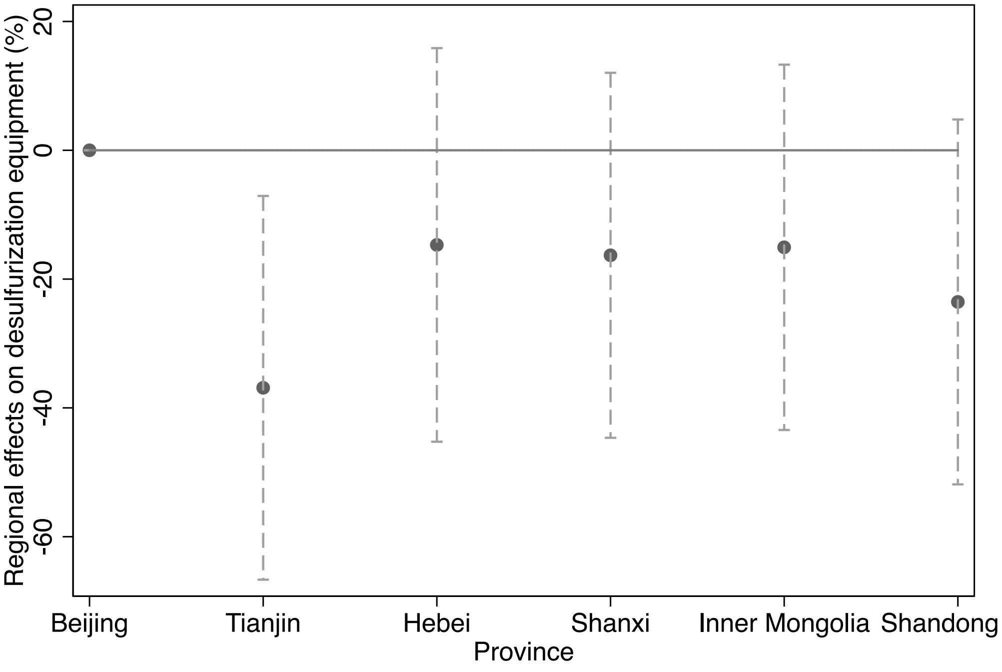
Note: Dashed lines indicate 90% confidence intervals.

Figure 4: Multiple-period model for desulfurization equipment



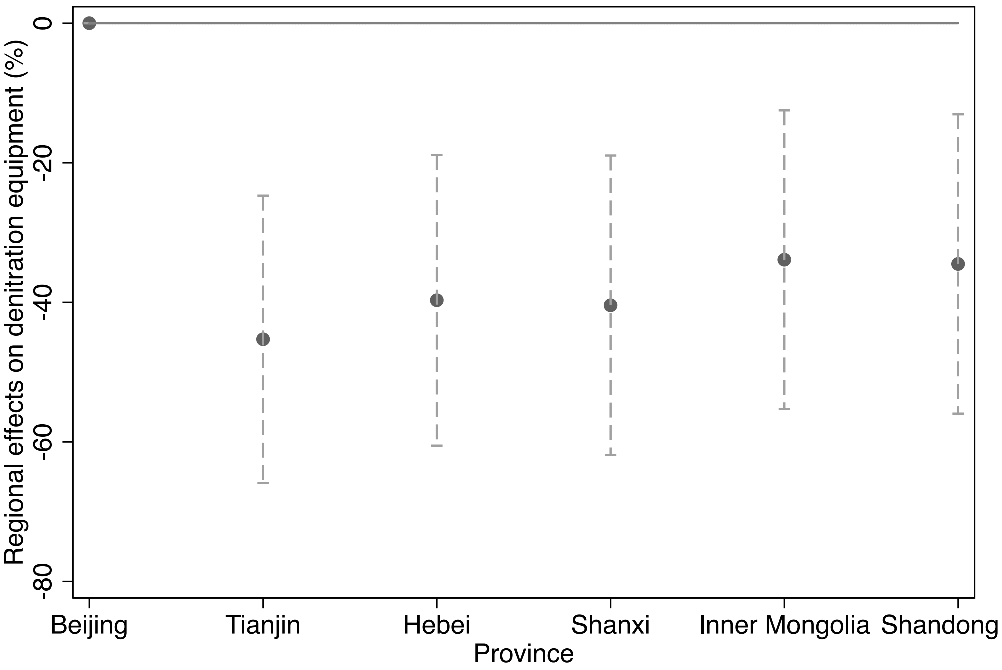
Note: Dashed lines indicate 90% confidence intervals.

Figure 5: Multiple-period model for denitration equipment



Note: Dashed lines indicate 90% confidence intervals.

Figure 6: Multiple-region model for desulfurization equipment



Note: Dashed lines indicate 90% confidence intervals.

Figure 7: Multiple-region model for denitration equipment

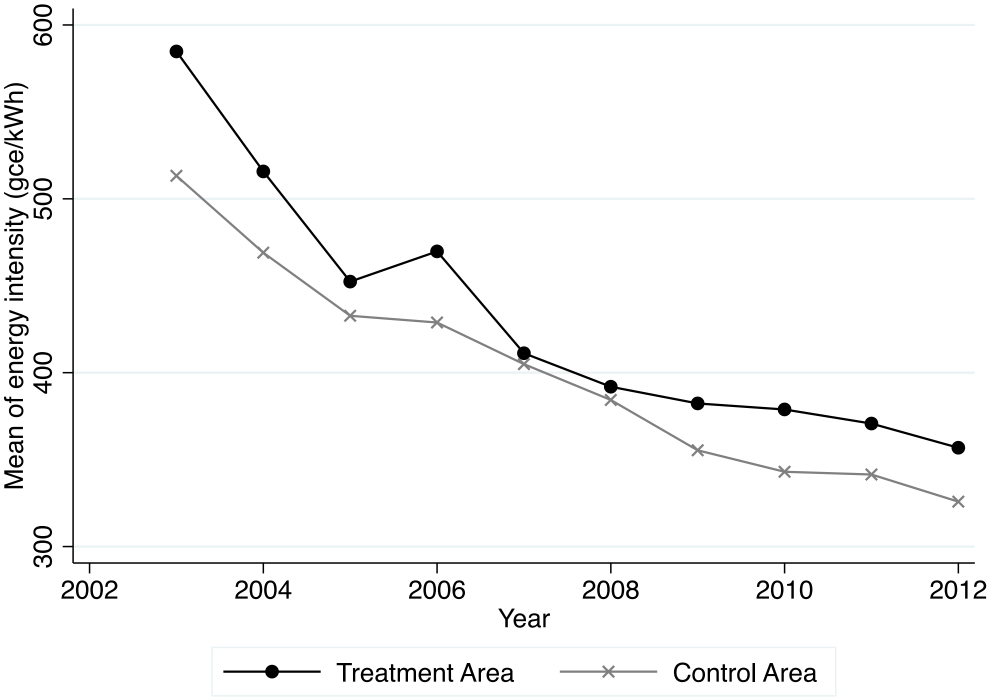
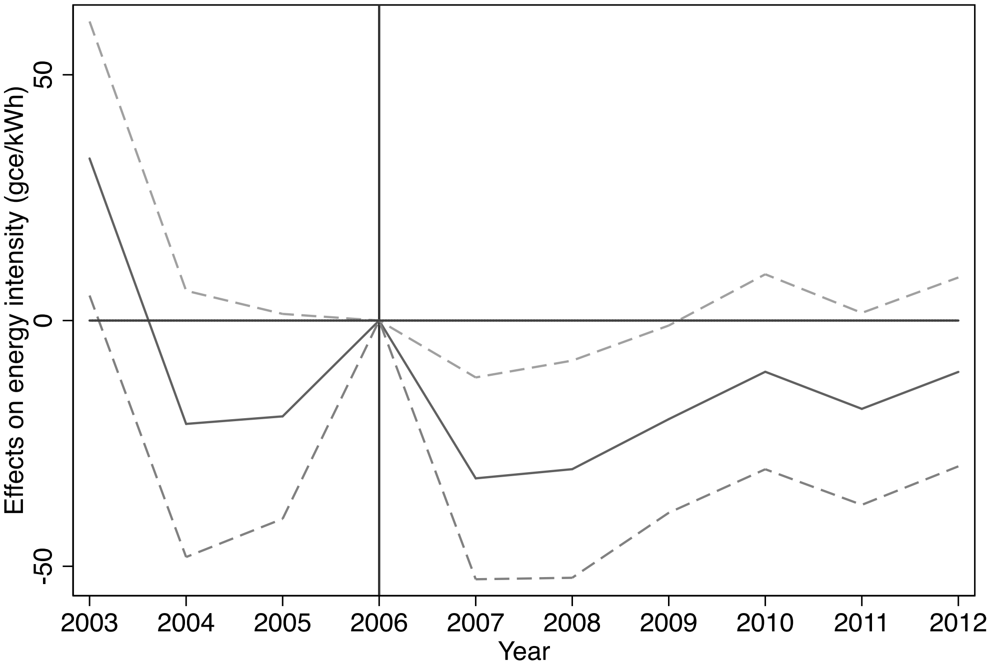
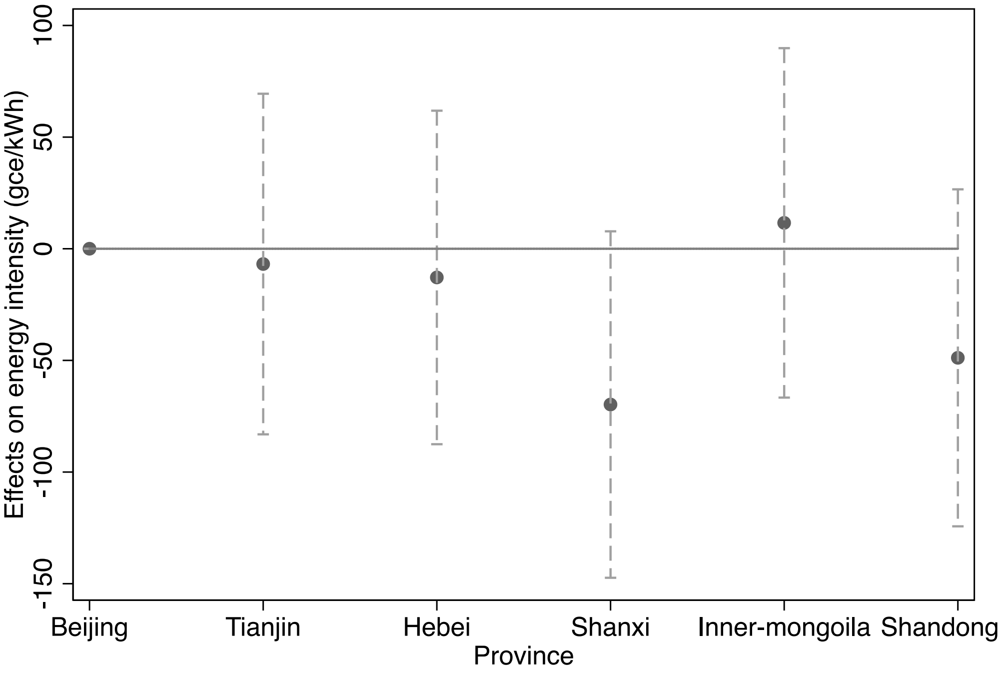


Figure 8: Energy intensity



Note: Dashed lines indicate 90% confidence intervals.

Figure 9: Multiple-period model for energy intensity



Note: Dashed lines indicate 90% confidence intervals.

Figure 10: Multiple-region model for energy intensity

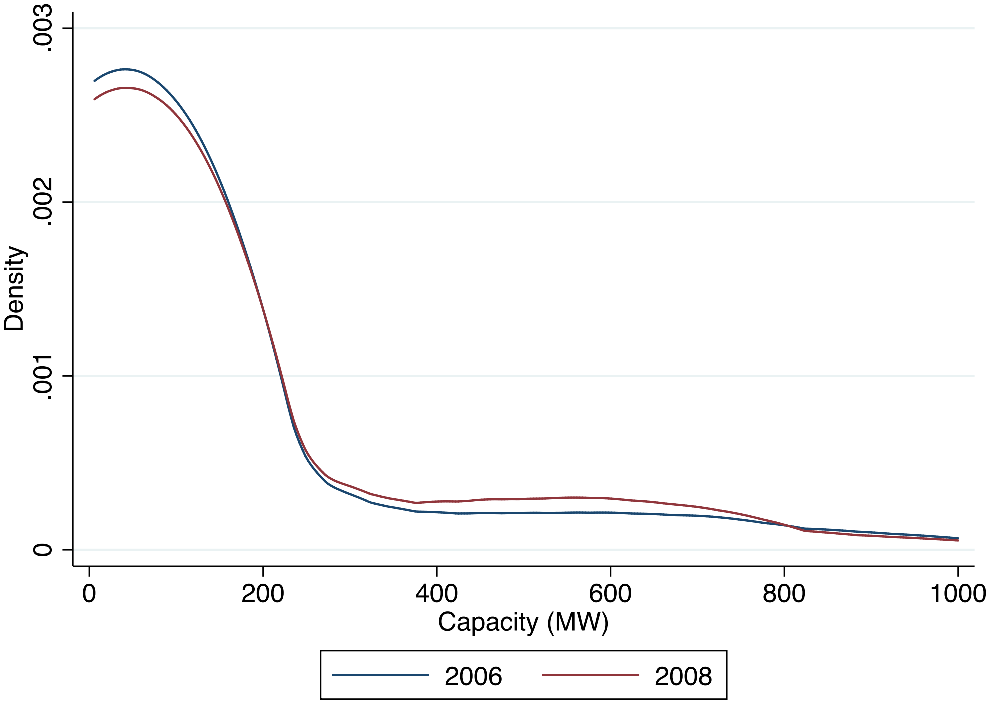


Figure 11: Multiple-region model for energy intensity