The Impact of China's Acid Rain and Sulfur Dioxide Control Zones Policy on Industrial Sulfur Dioxide Emissions: A Panel Analysis

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Abstract: In order to control sulfur dioxide (SO_2) emissions, the Chinese government in 1998 implemented the Acid Rain and Sulfur Dioxide Emission Control Zones policy (known as the Two Control Zone or TCZ policy). In a panel analysis of the impact of the TCZ policy on China's industrial SO_2 emissions, two-way fixed-effects models show that it did not significantly reduce either per capita SO_2 emissions or SO_2 intensity in China. The study also reveals that instead of the traditional inverted U-shaped Environmental Kuznets Curve, the relationship between income growth and sulfur pollution in China favors an N-shaped pattern. The empirical results indicate that the TCZ policy has not had a consistent, long-term impact on sulfur pollution control. This is in accord with previous studies and the actual situation in the two control zones. This paper presents two policy recommendations for improving the mitigation of SO_2 pollution in China.

Keywords: sulfur dioxide, acid rain, two control zones, China, air pollution

INTRODUCTION

China's blistering economic growth has resulted in a rapid increase in energy consumption over the last two decades. In 2009, coal still represented more than 70 percent of China's total energy supply, and even the most optimistic alternative policy scenario from the International Energy Agency (IEA) showed that coal would still be used to meet more than 60 percent of China's total energy demand in 2030 (Cao,

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Manuscript received June 10, 2011; out for review June 16, 2011; review completed August 5, 2011; accepted August 8, 2011.

The Korean Journal of Policy Studies, Vol. 26, No. 2 (2011), pp. 77-100.

Garbaccio, & Ho, 2009). In China, coal-fired power plants have been recognized as the main source of industrial SO_2 emissions. As illustrated in graph 1 in appendix 1, total SO_2 emissions in China climbed rapidly in the last two decades, and China became the biggest emitter in 2005 with total SO_2 emissions of 21 million tons.

In 1998, the Chinese government promulgated the Two Control Zone (TCZ) package of policies, resulting in the establishment of acid rain and sulfur dioxide control zones. The "two control zones" cover 1.09 million square kilometers, comprising 175 cities and districts in 27 provinces, which account for about 11.4 percent of China's territory (Xue, Chai, Duan, Chen, & Li, 2002). The policy package includes the following provisions (Li & Gao, 2002):

1. Any new coal mine with a sulfur content greater than 3.0 percent will be shut down; output of existing coal mines with a sulfur content greater than 3.0 percent will be limited.
2. The construction of new thermal power plants will not be approved in large and medium-size cities or their suburbs; for newly built or rebuilt thermal power plants, if the sulfur content in burning coal exceeds 1.0 percent, desulfurization facilities must be installed.

Since provinces in the two control zones received and executed the same package of polices at almost the same time, this paper will focus on the TCZ policy as a whole and its overall impact on China's industrial SO_2 emissions.

LITERATURE REVIEW

Previous research on China's TCZ policy can be divided into two categories. The first, on mainstream SO_2 control policies, traces the origins of the TCZ policy and studies the challenges and opportunities for implementing control policies within the two control zones. For example, Hao, Wang, Liu, and He (2000) reviewed the design of the two control zones and elaborated that the key control strategies were formulated on the basis of a life-cycle assessment of coal consumption. In addition, this paper indicated that due to the foreseeable huge increase in electricity consumption, driven by China's rapid economic growth, control of SO_2 emissions would become an extremely tough task in the two control zones. Hence, it might be necessary to develop clean coal technologies to ensure the abatement of SO_2 emissions in China.

Another study, conducted by Xue et al. (2002), summarized the designation and control strategies of the two control zones. Based on a review of socioeconomic and environmental conditions, the paper suggested follow-up actions for controlling SO_2

emissions in the two zones, especially by increasing the emissions charge and installing desulfurization facilities for power plants.

A great many studies of this type have argued that the TCZ policy initially played a positive role in controlling SO_2 emissions but that its positive impact gradually weakened. Li and Gao (2002) pointed out that although the TCZ policy has resulted in short-term success in mitigating acid deposition problems, it would not necessarily ensure that the SO_2 emissions are steadily abated in the long run. They also argued that the TCZ policy could be considered a sound approach for avoiding a drastic rise in control costs but that additional policy tools are needed in order to enforce these measures. A similar argument was presented by Gao, Yin, Ai, and Huang (2009), who reviewed the development and implementation of SO_2 control policies in China between 1996 and 2006. They found that although the TCZ policy contributed to achieving the SO_2 emission control goal made by the 9th Five-Year Plan (1996-2000), the reduction in SO_2 emissions failed to continue during the 10th Five-Year Plan (2001-2005).

The TCZ policy has also been addressed by a second type of literature, on SO_2 policy optimization, which has evaluated command-and-control policies and market instruments based on cost and benefit analyses and tried to identify cost-effective policies for abating SO_2 emissions in China. For instance, Cao et al. (2009) used a dynamic computable general equilibrium model to examine the costs and benefits of the implementation of two major policies in the two control zones—the small power plant shutdown, and fluidized gas desulfurization installation for key power plants. This study concluded that both policies imposed costs on the Chinese economy but that the costs were modest in comparison to the reductions in damages to human health and ecosystems.

Cofala et al. (2004) adopted the RAINS-Asia[1] integrated assessment model for acidification in Asia to study the optimization routine that can be used to identify cost-effective emissions control strategies for abating SO_2 concentrations and sulfur deposition in Asia. However, this study only briefly reviewed the TCZ policy. The second type of literature also includes some studies of the tradable permit mechanism for controlling SO_2 emissions in China, which usually offer only a short and simple discussion on the TCZ policy.

The first type of literature often draws conclusions based on descriptive studies and

1. RAINS (Regional Air Pollution Information and Simulation)-Asia Model was developed and applied for integrated assessment of future SO2 emissions in Asia. The model offers an opportunity to assess sulfur deposition and ecosystems protection levels resulting from different energy pathways and different emission control strategies. (Foell et. al, 1995)

simple statistical trend analyses, while the second type of literature pays little attention to the TCZ policy. Unlike the earlier research, this paper will focus only on the TCZ policy, instead of studying overall SO_2 abatement policies or selecting the optimal SO_2 control policy for China. It will apply a panel analysis to assess the impact of the TCZ policy on industrial SO_2 emissions in China.

DATA SOURCE

This paper uses Chinese province-level panel data from 1991 to 2007 to evaluate the effect of the TCZ policy on China's industrial SO_2 emissions. Chongqing Province lacks six years of data because it did not become an administrative district until it was separated from Sichuan Province in 1997. In order to maintain consistency and avoid omitting data, this paper merges the data from Chongqing Province into the data from Sichuan Province between 1997 and 2007, considering these two provinces as one for the whole time frame. Data statistics are presented in tables 1 and 2 in appendix 1.

METHODOLOGY

It is clear that the impressive development of the Chinese economy has exerted huge pressures on its environmental capacity. It is supposed that per capita income growth in line with economic development in China should increase the demand for better environmental quality. This kind of relation between economic development and environmental quality has been addressed in a large body of literature. The Environmental Kuznets Curve (EKC),[2] which indicates an inverted U-shaped curve for the income-inequality relationship, was popularized as a hypothesis analogous to the income-pollution relationship.

Almost all EKC studies (Stern & Common, 2001) that are based on cross-country datasets support the inverted U-shaped relation between SO_2 pollution and per capita income, which implies that, with economic growth, pollution should increase at first and then diminish once per capita income has attained a determined level. However, the EKC relationship does not automatically come from the increase in per capita income itself, but from exogenous public actions. Under the EKC hypothesis, the growth of per capita income could lead to an increase in environmental consciousness in a society, which could spur government to adopt environmental regulations, thereby

2. Dinda (2004) gives an overview of the EKC literature and background history.

diminishing pollution.

Thus, in order to assess the specific impact of the TCZ policy on industrial SO_2 emissions, empirical variables must be added to the EKC model in order to control for the Chinese government's overall regulation of SO_2 emissions. The standard empirical model of EKC for SO_2 emissions uses SO_2 per capita (SO_2PC) as the dependent variable; the independent variables include GDP per capita (GDPPC), quadratic term of GDP per capita (GDPPC_sq), and population density (pop_density).

The traditional inverted U-shaped EKC hypothesis has often been accepted by cross-country studies, which have predominated in the EKC literature. In recent years, however, an N-shaped EKC relationship, which implies an increase in pollution levels after an initial decrease, has been increasingly reported for some pollution indicators in country- and location-specific studies. For example, Mazzaniti, Montini, and Zoboli (2007) studied the delinking trends of emission-related indicators in Italy at both sectoral and provincial levels. This study found mixed evidence supporting the EKC hypothesis. Some of the pollutants confirmed the inverted U-shaped EKC hypothesis, while others produced N-shaped curves. A case study by Diao, Zeng, Tam, and Tam (2009) showed a weak N-shaped relationship between industrial solid waste and GDP per capita in Jiaxing of Zhejiang Province, China. Llorca and Meunie (2009) also found an N-shaped relationship between per capita income growth and per capita SO_2 emissions in China. Therefore, this paper will introduce a cubic term of GDP per capita to capture a possible N-shaped pattern in the China-specific EKC. The baseline model is as follows:

Baseline Model I

$$SO_2PC_{it} = \beta_0 + \beta_1 GDPPC_{it} + \beta_2 GDPPC_{it}^2 + \beta_3 GDPPC_{it}^3 + \beta_4 pop\_density_{it}$$
$$+ \beta_5 thermal\_electricity_{it} + \beta_6 Treatment\_98_{it} + \sum_{1991}^{t} \delta time_t + \alpha_i + \mu_{it}$$

On the right-hand side of Model I, a treatment dummy was introduced to capture the specific impact of the TCZ policy on SO_2 emissions. The treatment dummy is set equal to 1 after the year 1998 for provinces in the two control zones, and equal to 0 before 1998 for all provinces. All data are taken from the China Statistical Year Book (1990-2008), so it is reasonable to assume that they are consistently measured over time.

The three variables GDPPC, GDPPC_sq, and pop_density, are empirical independent variables for the EKC hypothesis. GDPPC is used as an index to indicate economic growth or regional production for each province in China. Since China's economic activities, such as industrial production, consume large amounts of energy provided by coal, it is probable that higher GDP would lead to increased SO_2 emissions. Models used here include population density (pop_density) as well, because a higher population density tends to intensify the negative impact of sulfur pollution. Hence, a densely populated province should have fewer pollution problems than a province that has the same income level but a lower population density. So we should expect to see a negative coefficient on this variable.

Apart from these empirical EKC variables, thermal-power-produced electricity (thermal_electricity) is also included in baseline model I, because thermal power plants are the main contributors to China's industrial SO_2 emissions. For instance, coal is used to generate 80 percent of China's electricity, and in 2009, 49 percent of coal in China was consumed by electricity production. In this sense, thermal_electricity should gain a positive coefficient, indicating a positive correlation between SO_2 per capita emission and thermal-power-produced electricity.

Besides SO_2 emission per capita, SO_2 emissions per GDP (SO_2GDP) can also be a valuable indicator of the effectiveness of the TCZ policy. It measures how many tons of SO_2 emissions are generated per unit of GDP, thereby showing the SO_2 intensity in China. The SO_2 intensity can be considered as an indicator of the impact of sulfur-related economic activities on the environment. In addition to baseline model I, a study on SO_2 intensity will also be conducted as follows:

Baseline Model II

$$SO_2PGDP_{it} = \beta_0 + \beta_1 GDPPC_{it} + \beta_2 pop\_density_{it} + \beta_3 thermal\_electricity_{it} + \beta_4 Treatment\_98_{it} + \sum_{1991}^{t} \delta time_t + \alpha_i + \mu_{it}$$

There is no empirical evidence that improved SO_2 intensity is expressed in the classic inverted U shape against per capita income. Therefore, model II excludes the quadratic and cubic terms of GDP per capita, leaving only GDPPC, pop_density and thermal_electricity as basic control variables.

Before finalizing the two models, we must first look carefully at the potential for reverse causality. This paper provides a specific test for the endogeneity problem in the section entitled Robustness Checks. The test results imply that reverse causality is indeed a concern in this model. In order to solve this problem, both models assign each observation its own time trend by using an interaction term between id[3] and time to

3. The variable of id is created to represent individuals of the sample used by the two-way fixed-effects models in this paper.

control the different rate of change in SO_2 emissions between the treatment and control groups. After accounting for reverse causality problems, the two baseline models are as follows:

Model I with Time Trend

$$SO_2PC_{it} = \beta_0 + \beta_1 GDPPC_{it} + \beta_2 GDPPC_{it}^2 + \beta_3 GDPPC_{it}^3 + \beta_4 pop\_density_{it} + \beta_5 thermal\_electricity_{it} + \beta_6 Treatment\_98_{it} + \sum_{1991}^{t} \delta(id*time)_{it} + \alpha_i + \mu_{it}$$

Model II with Time Trend

$$SO_2PGDP_{it} = \beta_0 + \beta_1 GDPPC_{it} + \beta_2 pop\_density_{it} + \beta_3 thermal\_electricity_{it} + \beta_4 Treatment\_98_{it} + \sum_{1991}^{t} \delta(id*time)_{it} + \alpha_i + \mu_{it}$$

Since observations are collected at the province level over time, there may be many unobserved factors that could influence SO_2 emissions. Problems arise when these factors are also correlated with the decision to implement the TCZ policy. If we use random-effects or pooled-OLS methods, we must assume that there is no correlation between SO_2 per capita and unobservable provincial variation. However, because each province has its own unique features and characteristics, it is difficult to defend this assumption. Hence, the safest way to address these factors is to remove them with a fixed-effects analysis. Tables 3 and 4 in appendix 2 present the results of Hausman tests for both models I and II. Because the tests indicate that we reject the null hypothesis, we can say that fixed-effects regression—rather than random-effects regression—is the preferred method.

EMPIRICAL RESULTS

Model I

Before running the baseline model, a simple two-way fixed-effects model without time dummies was conducted. Table 5 in appendix 3 shows that the TCZ policy has not had a significant effect on per capita SO_2 emissions. After adding time dummies to knock down the overall time trend of SO_2 emissions, the coefficient of the treatment variable for Model I became significant (table 6 in appendix 3) at the 10 percent level. However, the sign of the coefficient on the policy dummy is positive, which indicates that SO_2 emissions per capita of provinces in the two control zones actually increased, compared to the emissions of provinces outside the zones. Moreover, after making an adjustment for time trends within each unit, as table 7 in appendix 3 illustrates, the treatment variable is not significant at either the 5 percent or 10 percent level in Model I. Interestingly, the negative GDPPC quadratic term and positive GDDPC cubic term indicate that there is an N-shaped pattern for the relationship between income growth and industrial SO_2 emissions in China (see graph 2 in appendix 3).

Model II

Table 8 in appendix 4 gives the regression outcome for the baseline model without time dummies, which suggests that the reduction in industrial SO_2 emissions in the control zones is 24.15 kg more per 10,000 yuan (around US$1,500) than in provinces outside of the control zones. After applying the time dummy in the model, the marginal effect of the treatment dummy remained highly significant, but the scale of coefficient was reduced from 24.15 kg per 10,000 yuan to 15.39 kg per 10,000 yuan (see table 9 in appendix 4).

The fixed-effects model with time adjustment for each unit gave a significant coefficient for SO_2 intensity (see table 10 in appendix 4), which indicates that rather than a reduction in SO_2 intensity, the TCZ policy resulted in an average increase in SO_2 emissions by 12.72 kg per 10,000 yuan in the two control zones. The fixed-effects result also shows that growth in GDP per capita will increase SO_2 intensity with an average growth rate of 10.62 kg per 10,000 yuan. Similarly, the regression result implies that each increase in thermal-power-generated electricity by 100 million kWh will increase SO_2 intensity by 0.04 kg per 10,000 yuan.

ROBUSTNESS CHECK

Endogeneity

It is important to point out that the TCZ policy is not a random trial and that those provinces with high SO_2 emissions and serious acid rain problems would have been likely policy targets. If reverse causality is an issue, one would expect the rate of change of per capita SO_2 and SO_2 intensity between the treatment group and the control group to be different before and after the implementation of TCZ policy.

In order to test this assumption, the dataset was collapsed by group and year, and pre-treatment T-tests were conducted for the means of change of both SO_2PC and SO_2PGDP variables between the control group and treatment group. In appendix 5, tables 11 and 12 demonstrate that there is no significant difference between control group and treatment group before policy implementation for either per capita SO_2 or SO_2 intensity. However, the T-tests have only weak power due to the low degrees of freedom. As shown in the two tables, the means of change of per capita SO_2 and SO_2 intensity in the treatment group are almost three times that of the mean of change in the control group. Graphs 3 and 4 also provide visual evidence that, before the implementation of the TCZ policy, per capita SO_2 started at a higher level with a faster growth rate in the treatment group, while SO_2 intensity started at a higher level with a faster reduction rate in the treatment group than in the control group.

Additionally, by applying a Probit model, we can discover the common features among observations in the treatment group. Regression outcomes shown in table 13 demonstrate that all independent variables are key factors in determining which provinces are included in the TCZ policy. In other words, provinces within the control zones are characterized by high existing SO_2 pollution, high GDP per capita, and high population density.

These characteristics exactly reflect the selection criteria identified by the *Plan on Identifying the Acid Rain Control Zone and Sulfur Dioxide Pollution Control Zone*, issued by the State Environmental Protection Administration in 1996. In this plan, selection criteria for areas to be included in the acid rain control zone were (1) current pH level of precipitation less than 4.5, (2) sulfur deposition exceeding critical loads, and (3) presence of a large amount of SO_2 emissions. Criteria for inclusion in the SO_2 pollution control zone were (1) recent annual average concentrations of SO_2 exceeding level II of the national standard, (2) daily average concentration of SO_2 exceeding level III of the national standard, and (3) presence of a large amount of SO_2 emissions. (For detailed information on national ambient air quality standards, please refer to table 14 in appendix 5.) Thus the policy specifically targeted areas that received more SO_2 emissions and acid rain. As a result, the policy analysis seems to be affected by selection bias, leading to a reverse causality problem. The third item in each set of selection criteria is very vague, without a quantity specified for what constitutes "a large amount" of SO_2 emissions. Thus, some scholars have cast doubts on the effectiveness of the TCZ policy, and some have even argued that the control standards were just used to prioritize SO_2 control efforts that would divert extra resources and attention to those cities and regions.

Autocorrelation

Another problem that must be considered is autocorrelation in the error term for both model I and model II. Autocorrelation, if it exists, would not result in "wrong" answers for coefficient estimates, but would magnify the standard error and generate an incorrect confidence interval. After running a regression of the residuals of both SO_2PC and SO_2PGDP on their lags, this study found that there are three lags with a significant impact on the SO_2PC's and SO_2GDP's residuals (see tables 15 and 16 in appendix 5). To correct this, Newey-West standard errors were applied to account for the autocorrelation (table 17). As stated earlier, the estimates of the treatment dummy are still not significant in model I. Although the coefficient of the treatment dummy becomes negative, the estimation is not statistically significant.

CONCLUSION AND POLICY IMPLICATIONS

One interesting finding of this empirical study is that there is an N-shaped relationship, rather than the traditional inverted U-shaped EKC, between per capita income and per capita SO_2 emissions in China. Sulfur pollution starts to decline after reaching a threshold of 17,529 yuan, and begins to increase again after per capita income increases to a second threshold of 54,430 yuan.[4] One possible explanation of the N-shaped pattern is that the delinking of sulfur pollution from income growth is only temporary in the two control zones. The SO_2 emissions in the zones were initially reduced by the package of policies. After a while, however, its effectiveness faded away, and continuous economic growth began to worsen sulfur pollution again. This interpretation is accord with earlier studies (in the first category of literature described above), which argued that SO_2 control policies in China can become weaker and less effective in the long run.

In addition, the regression results of models I and II indicate that the TCZ policy has no significant impact on sulfur pollution in the control zones, for provinces in the zones experience declining trends neither for SO_2 emission per capita nor for SO_2 intensity at the average level, compared to provinces that are not included in the zones.

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4. This result is obtained from the cubic polynomial function derivative, and the two thresholds can be obtained from the following equations:

$$\tau_1 = \frac{-2\beta_2 - \sqrt{4(\beta_2)^2 - 12\beta_1\beta_3}}{6\beta_3}, \quad \tau_2 = \frac{-2\beta_2 - \sqrt{4(\beta_2)^2 - 12\beta_1\beta_3}}{6\beta_3}$$

These results are in accord with the actual situation for the past two decades. In fact, Chinese environmental reports have stated that the TCZ policy did not fundamentally prevent the growth of SO_2 pollution in China, especially from 2000 to 2005.

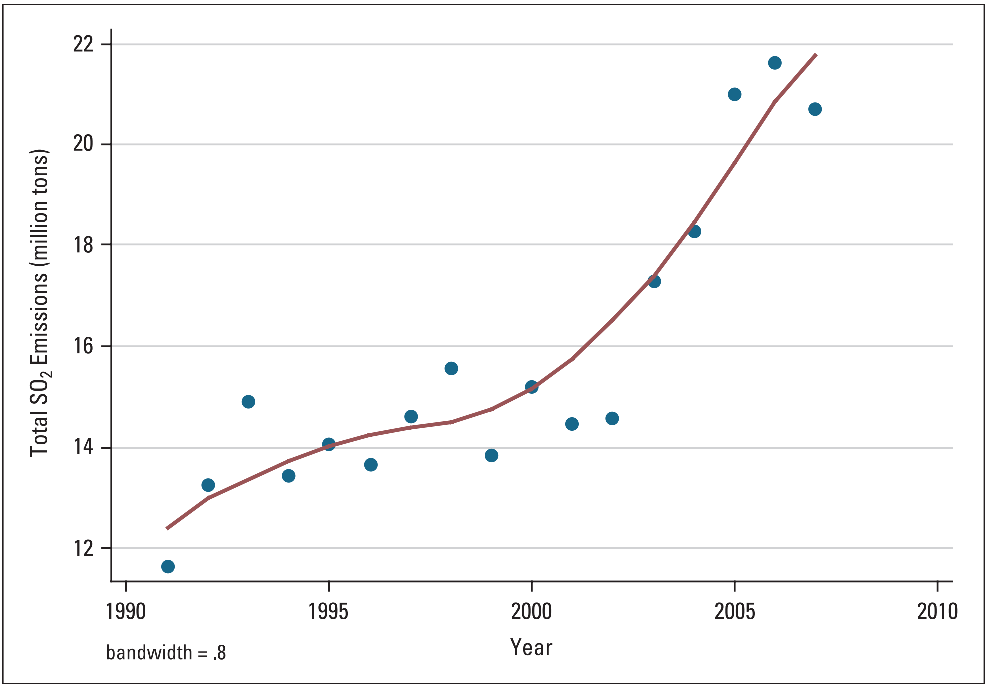
According to government reports on environmental policy, specific requirements of the TCZ policy did not come into practice until after 2000. The main reason is that energy efficiency was seriously underfunded, and the Chinese government emphasized economic growth over improving energy efficiency and environmental protection (Gao et al, 2009). In China, an electricity shortage emerged in 2002 and worsened in 2004. In the summer of 2004, 24 provinces experienced a brownout, which caused widespread disruption of industrial production and huge economic losses. Because of power shortages, the plan to shut down small coal-fired power units was not carried out. On the contrary, some small units that had been shut down resumed operation, and many new small coal-fired power units were built in a short period of time. As a result, SO_2 emissions from coal-fired power plants increased by 70 percent, from 6.54 million tons in 2001 to 11.12 million tons in 2005(SEPA 2002, 2006). Rather than dropping in 2000-2005 by 10 percent (to 18 million tons) as planned, by 2005 national SO_2 emissions had actually risen to 21 million tons, almost 17 percent above the goal. (Gao et. al 2009)

The temporary effectiveness and eventual failure of the TCZ policy imply that two key components need to be strengthened for the further development of sulfur pollution control policies. First, the government should adopt cost-effective policies that ensure long-term sulfur pollution control because they reduce implementation costs and therefore create more incentives for stakeholders to implement the policies. Second, in line with the implementation of an SO_2 control policy, China has to reduce its high reliance on coal for electricity generation and develop a cleaner energy mix. The significantly positive correlation between thermal-power-produced electricity and SO_2 intensity estimated by model II reflects the fact that China's electricity production relies heavily on coal, which is the main source of SO_2 emission.

Shealy and Dorian (2010) predicted that the energy demand will at least double in China between 2005 and 2030, and coal consumption in particular will hit 5 billion tons in 2025, even if the economy sustains only a moderate 6.5 percent average GDP growth rate. Therefore, it is urgent for China to diversify energy resources and exploit renewable resources like wind energy to guarantee a stable electricity supply without worsening sulfur pollution.

APPENDIX 1: SO_2 POLLUTION

Graph 1. Total Chinese SO_2 Emissions 1991-2007



APPENDIX 2: METHODOLOGY AND DATA DESCRIPTION

Table 1. Variable Descriptions

Dependent variable	Description	Unit
SO_2 per capita (SO2PC)	China's industrial SO2 emissions per person, calculated as total SO2 emissions divided by total population	kg/person
SO_2 per GDP (SO2PGDP)	China's industrial SO2 emissions per GDP, calculated as total SO2 emissions divided by total GDP	kg/10,000 yuan
GDP per capita (GDPPC)	China's GDP per person, calculated as total GDP divided by total population	10,000 yuan/person
GDP per capita squared (GDPPC_sq)	Quadratic term of GDP per capita	$(10{,}000\ \text{yuan/person})^2$
GDP per capita cubed (GDPPC_cube)	Cubic term of GDP per capita	$(10{,}000\ \text{yuan/person})^3$
Population density (pop_density)	Number of people per square kilometer	person/km^2
Thermal production of electricity (thermal_electricity)	Thermal production of electricity	100 million kWh
Treatment (treatment_98)	Dummy variable of "two control zone" policy	

Table 2. Variable Statistics

Variable	#	Mean	Std dev.	Min	Max
SO2PC	510	13.82916	9.573403	0	60.25645
SO2PGDP	510	27.48502	32.51312	0	343.3522
GDPPC	510	0.9211395	0.9186862	0.0874088	6.560199
GDPPC_sq	510	1.690828	4.255604	0.0076403	43.03621
GDPPC_cube	510	5.136292	22.29954	0.0006678	282.3261
Pop_density	510	365.104	461.2879	3.88647	2,996.774
Thermal_electricity	507	418.3202	423.7342	0.01	2691.43
Treatment_98	510	0.4509804	.4980798	0	1

= number of observations.

Table 3. Hausman Test for Model I

	Coefficients		(b-B) Difference	sqrt(diag(v_b_v_B)) S.E.
	(b) fe	(B) .		
GDPPC	8.518388	8.535229	-.0168411	.1140979
GDPPC_square	-2.973362	-3.150601	.1772388	.0471168
GDPPC_cube	.299272	.2887529	.0105191	.
thermal_el~y	.0045431	.004945	-.000402	.0002976
pop_density	-.0190064	-.0020105	-.0169959	.0060387
treatment_98	-.8830301	-1.133698	.2506676	.1467039

b = consistent under Ho and Ha; Obtained from xtreg
B = inconsistent under Ha, efficient under Ho; obtained from xtreg
Test: Ho: difference in coefficients not systematic
chi2(6) = (b-B)'[v_b_v_B)^(-1)](b-B)
= -11.23 chi2<0 ==> model fitted on these data fails to meet the asymptotic assumptions of the Hausman test;
see suest for a generalized test

Table 4. Hausman Test for Model II

	Coefficients		(b-B) Difference	sqrt(diag(v_b_v_B)) S.E.
	(b) fe	(B) .		
GDPPC	-7.035875	-4.666058	-2.369817	1.945515
thermal_el~y	-.0077276	-.0089265	.0011989	.0026758
pop_density	.0607377	.0043656	.0563721	.0243351
treatment_98	-24.14697	-21.98025	-2.166713	.

b = consistent under Ho and Ha; Obtained from xtreg
B = inconsistent under Ha, efficient under Ho; obtained from xtreg
Test: Ho: difference in coefficients not systematic
chi2(4) = (b-B)'[v_b_v_B)^(-1)](b-B)
= -553.44 chi2<0 ==> model fitted on these data fails to meet the asymptotic assumptions of the Hausman test;
see suest for a generalized test

APPENDIX 3: EMPIRICAL RESULTS FOR MODEL I

Table 5. Two-Way Fixed-Effects Regression of Baseline Model I without Time Dummies

Independent variable	Dependent variable: SO2PC	
GDPPC	8.518***	(1.560)
GDPPC_sq	-2.973***	(0.637)
GDPPC_cube	0.299***	(0.076)
Thermal_electricity	0.00454***	(0.00123)
Pop_density	-0.0190***	(0.00676)
Treatment_98	-0.883	(0.670)
Constant	15.02***	(2.455)
Observations	507	
Number of id	30	
R-squared	0.230	
RMSE	4.634	

Standard errors are given in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1

Table 6. Two-Way Fixed-Effects Regression of Baseline Model I with Time Dummies

Independent variable	Dependent variable: SO2PC	
GDPPC	12.09***	(3.408)
GDPPC_sq	-4.346***	(1.052)
GDPPC_cube	0.410***	(0.108)
Thermal_electricity	0.00265**	(0.00125)
Pop_density	-0.008	(0.00697)
Treatment_98	1.841*	(0.990)
Constant	11.09***	(2.553)
Observations	507	
Number of id	0.307	
R-squared	30.000	
RMSE	4.472	

Standard errors are given in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1

Graph 2. N-Shaped EKC Hypothesis for the Income to SO2 Pollution Relation in China

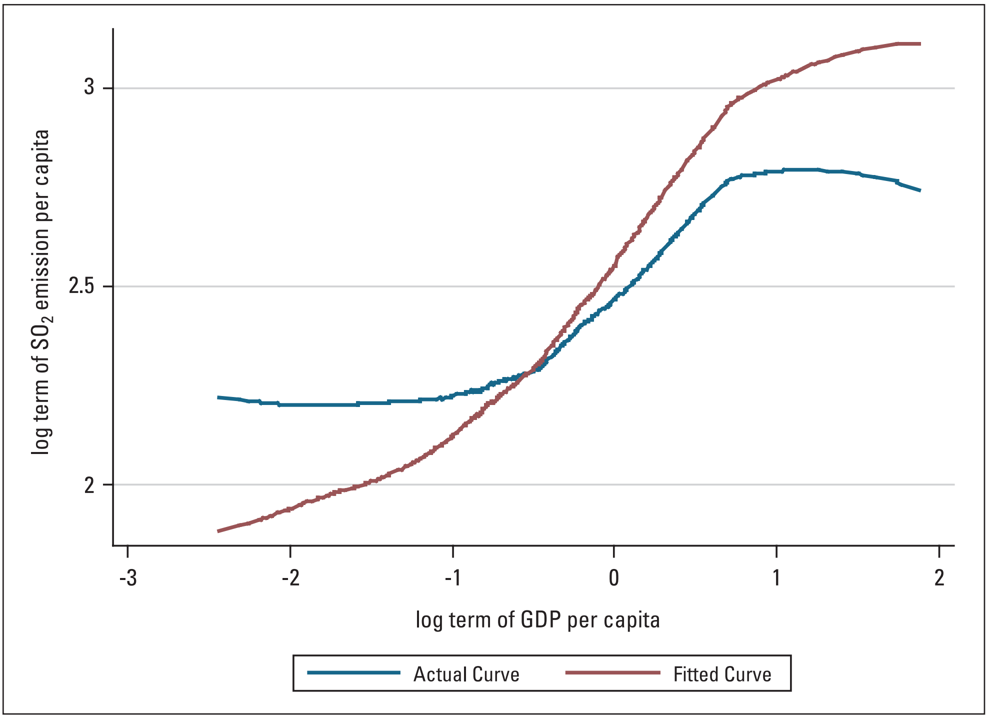


Table 7. Two-Way Fixed-Effects Adjusted Regression of Model I with id*time Term

Independent variable	Dependent variable: SO2PC	
GDPPC	21.66***	(3.697)
GDPPC_sq	-4.411***	(1.043)
GDPPC_cube	0.346***	(0.105)
Thermal_electricity	0.000897	(0.00248)
Pop_density	0.009	(0.01720)
Treatment_98	0.67	(0.963)
Constant	7.2	(11.780)
Observations	507	
Number of id	30	
R-squared	–	
RMSE	4.05	

Standard errors are given in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

APPENDIX 4: EMPIRICAL RESULTS FOR MODEL II

Table 8. Two-Way Fixed-Effects Regression of Baseline Model II without Time Dummies

Independent variable	Dependent variable: SO2PGDP	
GDPPC	-7.036**	(2.901)
Thermal_electricity	-0.00773	(0.005)
Pop_density	0.0607**	(0.026)
Treatment_98	-24.15***	(2.699)
Constant	26.02***	(8.601)
Observations	507	
Number of id	30	
R-squared	0.311	
RMSE	21	

Standard errors are given in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1

Table 9. Two-Way Fixed-Effects Regression of Baseline Model II with Time Dummies

Independent variable	Dependent variable: SO2PGDP	
GDPPC	8.228**	(3.447)
Thermal_electricity	-0.0061	(0.005)
Pop_density	-0.00289	(0.025)
Treatment_98	-15.39***	(4.009)
Constant	65.27***	(8.707)
Observations	507	
Number of id	0.518	
R-squared	30.000	
RMSE	18	

Standard errors are given in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1

Table 10. Two-Way Fixed-Effects Adjusted Regression of Model II with id*time Term

Independent variable	Dependent variable: SO2PGDP	
GDPPC	10.62**	(4.799)
Thermal_electricity	0.0365***	(0.009)
Pop_density	-0.0156	(0.059)
Treatment_98	12.72***	(3.628)
Constant	40.160	(37.550)
Observations	507	
Number of id	30.000	
R-squared		
RMSE	16	

Standard errors are given in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

APPENDIX 5: ROBUSTNESS CHECKS

T-Test: Pre-Treatment Comparison of Mean of Change between Control Group and Treatment Group

Table 11. Pre-Treatment T-Test for Change of SO2 per Capita between Control Group and Treatment Group

Two-sample t-test with equal variances						
Group	obs	Mean	Std. Err.	Std. Dev.	[95% Conf. Interval]	
0	7	.1480796	1.85819	4.916309	-4.398748	4.694907
1	7	.4418322	.4684325	1.239356	-.7043808	1.588045
combined	14	.2949559	.9214734	3.447838	-1.695766	2.285678
diff		-.2937525	1.916325		-4.469065	3.88156

diff = mean(0) - mean(1) t = -0.1533
Ho: diff = 0 degrees of freedom = 12

Ha: diff < 0 Ha: diff ! = 0 Ha: diff > 0
Pr(T < t) = 0.4404 Pr(|t| > |t|) = 0.8807 Pr(T > t) = 0.5596

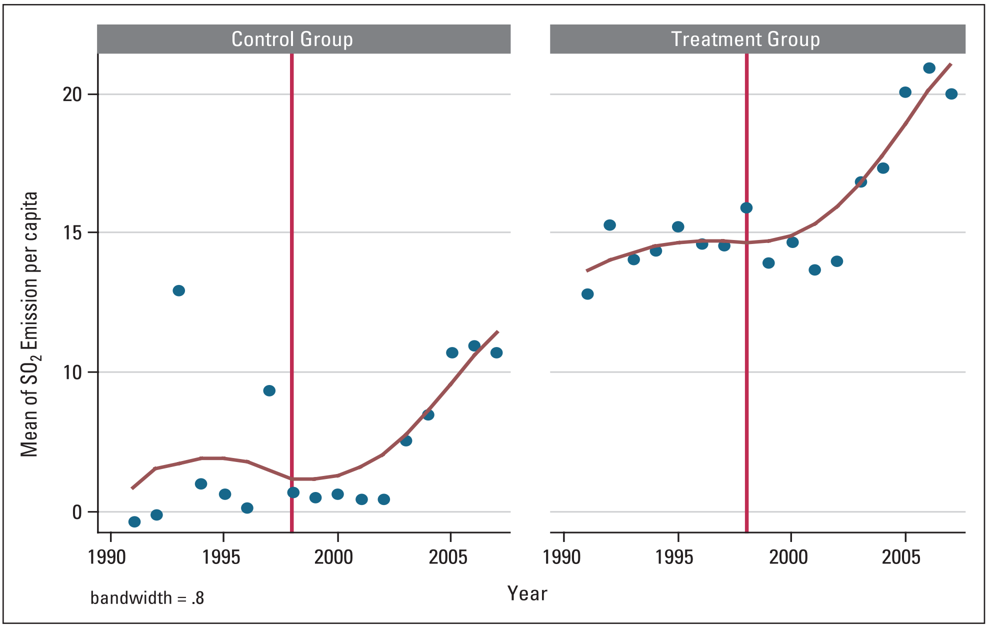
Table 12. Pre-Treatment T-Test for Change of SO2 per GDP between Control Group and Treatment Group

Two-sample t-test with equal variances						
Group	obs	Mean	Std. Err.	Std. Dev.	[95% Conf. Interval]	
0	7	-2.905581	6.05293	16.01455	-17.71657	11.9054
1	7	-6.623227	3.392511	8.975741	-14.9244	1.677949
combined	14	-4.764404	3.37293	12.62035	-12.05118	2.522367
diff		3.717646	6.938811		-11.40072	18.83602

diff = mean(0) - mean(1) t = 0.5358
Ho: diff = 0 degrees of freedom = 12

Ha: diff < 0 Ha: diff ! = 0 Ha: diff > 0
Pr(T < t) = 0.6990 Pr(|t| > |t|) = 0.6019 Pr(T > t) = 0.3010

Graph 3. Mean of SO2 per Capita in Control Group and Treatment Group, 1991-2007



Graph 4. Mean of SO2 Intensity in Control Group and Treatment Group, 1991-2007

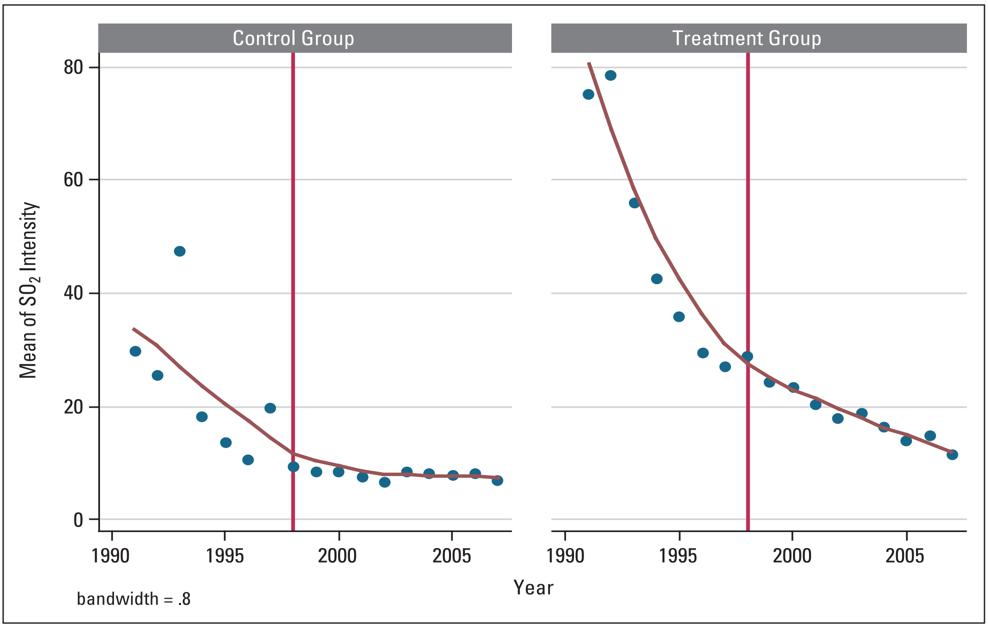


Table 13. Probit Model for Treatment Dummy Variable

Independent variable	Dependent variable: treatment_98	
GDPPC	0.330***	(0.116)
Thermal_electricity	0.000957***	(0.000)
Pop_density	-0.000616***	(0.000)
SO2PC	0.0800***	(0.01340)
SO2PGDP	-0.0236***	(0.00492)
Constant	-1.058***	(0.15700)
Observations	507	
Number of id		
R-squared		

Standard errors are given in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1

Table 14. National Standards for SO2 Concentration in China

Time unit	Concentration limit (μg/m3)		
	Level I	Level II	Level III
Annual average	0.02	0.06	0.10
Daily average	0.05	0.15	0.25
Hourly average	0.15	0.50	0.70

Source: State Administration of Environmental Protection of China, 1996.

Table 15. Test of Autocorrelation for Model I

Independent variable	Dependent variable: residual of SO2PC	
Residual_lag1	0.746***	(0.0448)
Residual_lag2	0.157***	(0.0401)
Residual_lag3	0.0934***	(0.0349)
Residual_lag4	0.0126	(0.0338)
Constant	0.0112	(0.153)
Observations	377	
R-squared	0.907	
RMSE	2.974	

Standard errors are given in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1

Table 16. Test of Autocorrelation for Model II

Independent variable	Dependent variable: residual of SO2PGDP	
Residual_lag1	0.700***	(0.0398)
Residual_lag2	0.110***	(0.0301)
Residual_lag3	0.0486**	(0.0202)
Residual_lag4	0.0245	(0.0193)
Constant	0.0309	(0.350)
Observations	377	
R-squared	0.896	
RMSE	6.7930	

Standard errors are given in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1

Table 17. Two Models with Newey-West Standard Errors, Time Dummies Not Reported

Independent variable	Dependent variable: SO2PC	Dependent variable: SO2PGDP
GDPPC	-85.57*** (12.940)	-13.68*** (2.761)
GDPPC_sq	29.48*** (5.541)	N/A
GDPPC_cube	-2.902*** (0.625)	N/A
Thermal_electricity	0.00814** (0.003)	0.0000918 (0.004)
Pop_density	0.000312 (0.004)	0.00401 (0.00377)
Treatment_98	2.187 (2.997)	-5.773 (3.897)
Constant	67.08*** (8.029)	41.39*** (4.912)
Observations	507	507

Standard errors are given in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1

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