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Empirical Analysis on Determinants of Air Pollution in China

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ABSTRACT : The rapid economic growth has brought tremendous pressure on the environment and caused severe air pollution in China. This study empirically examines causes of air pollution in China. Panel-corrected standard errors procedure (PCSE) was used to analyze major determinants of increasing or reducing emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_X) in 30 Chinese provinces. The estimation results show that SO_2 emission is mitigated as per capita regional GDP increases, but the relation between emission of NO_X and per capita regional GDP is found to have an inverse N-shaped curve, which implies that emission of NO_X is ultimately expected to decline with economic growth. As for increasing factors of air pollutants, electricity consumption is a significant common source of SO_2 and NO_X emissions. Moreover, the results show that increment of coal consumption significantly affects emission of SO_2 while increase of natural gas consumption reduce emission of SO_2. On the other side, investment in energy industry, and investment on treatment of waste gases are determinants of mitigating emissions of SO_2, but have no impact on NO_X. Consumption of diesel, truck ratio and number of vehicles increase emission of NO_X. Meanwhile, higher precipitation rate is a common determinant of mitigating emissions of SO_2 and NO_X. Policy implications are suggested in the conclusion.

Keywords : Determinants, Air pollution in China, Emission of SO_2 and NO_X, PCSE procedure

JEL Classification : Q2

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중국의 대기오염 배출 결정요인에 대한 경험적 분석

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요 약 : 중국의 급속한 경제성장은 환경에 커다란 부하를 초래하였고, 이를 통해 대기오염 문제도 심각해졌다. 본 연구는 중국의 대기오염 원인을 경험적으로 분석하였다. 표준오차 패널수정 추정기법(PCSE)을 이용하여 중국의 30개 성을 대상으로 아황산가스 및 질소산화물의 배출요인을 분석하였다. 아황산가스의 경우 일인당 실질소득이 증가할수록 배출 수준이 감소하고, 질소산화물은 일인당 실질소득과 역N자형의 관계에 있는 것으로 분석되었다. 소득 이외의 배출요인으로 우선 전기소비량은 아황산가스나 질소산화물을 증가시키는 요인이었고, 석탄소비량은 아황산가스 배출을 증가시키는 반면에 천연가스 소비량은 아황산가스 배출을 감소시키는 요인으로 나타났다. 한편 에너지 산업에 대한 투자와 폐가스 처리에 대한 투자는 아황산가스 배출을 감소시키는 결정요인이지만 질소산화물 배출에 영향을 미치지 않는 것으로 나타났다. 한편 디젤 소비량, 트럭 비율 및 차량 수는 질소산화물 배출을 증가시키는 것으로 나타났다. 강수량의 증가도 아황산가스와 질소산화물의 배출을 감소시킨 요인이었다. 끝으로 본 연구의 정책적 시사점과 향후 연구방향을 제시하였다.

주제어 : 결정요인, 중국의 대기오염, 아황산가스 및 질소산화물 배출, PCSE 추정법

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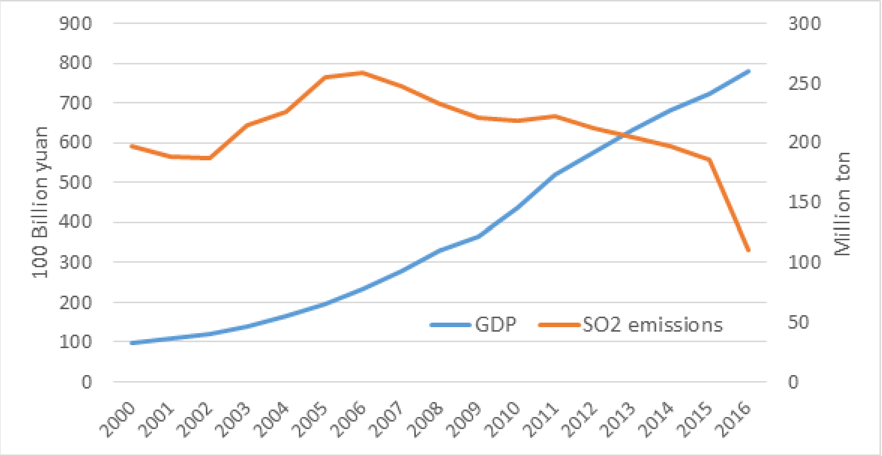
Ⅰ. Introduction

Since the economic reform in 1978, China experienced a substantial economic growth. According to the United Nations, per capita real GDP of China increased from USD 227 in 1978 to USD 8,109 in 2015. China’s relative contribution to global economic growth has exceeded 30%, and it has become second largest economy in the world, the largest trader of commodities, and the largest holder of foreign exchange reserves. Meanwhile, with a dramatic economic growth, China’s energy demand has also increased sharply. Wu et al. (2019) argued that 70% of the energy consumed in China came from coal due to its abundance but combustion of coal resulted in significant environmental pollution. Emissions of various air pollutants have caused adverse effects on human health and the ecosystem, and could lead to an acid rain problem and respiratory diseases (Venners et al., 2003; Wei et al., 2014; Song et al., 2016).

According to the Chinese Statistical Yearbook, China was the largest Sulfur dioxide (SO_2) emitter in the world in 2006. In response to such an enormous increase in SO_2 emissions, Chinese government began to implement the “total emission control on SO_2” policy in order to reduce intensity of SO_2 emission on the per currency of GDP by 10% as a national target (Jin et al., 2016). As a result, this policy was effective, so China’s SO_2 emissions have fallen continuously from 25.88 million tons in 2006 to 8.75 million tons, even if China still remained the second largest polluter of SO_2 in the world as of 2017 (China Statistical Yearbook, 2018).

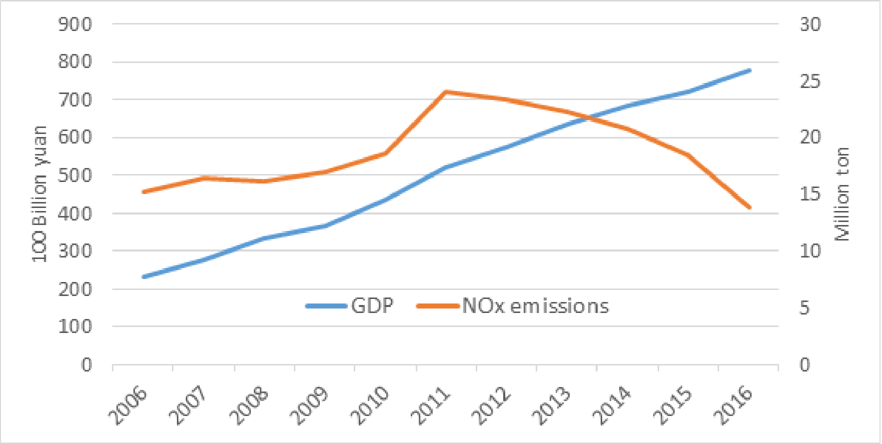
On the other side, with the improvement of Chinese people’s living standards, their demands for vehicles have been significantly increased over time. The enormous growth of transportation sector in China has led to the tremendous increase of demand for petroleum. In consequence, nitrogen oxides (NO_X) emissions have been one of the major environmental problem in China. Figures 1 and 2 show the trend of SO_2 and NO_X emissions respectively.

〈Figure 1〉 Annual GDP and SO_2 Emissions in China from 2000–2016 (unit: tons)



Source: China Statistical Yearbook (http://data.stats.gov.cn/english/publish.htm?sort=1)

〈Figure 2〉 Annual GDP and NO_X Emissions in China from 2006–2016 (unit: tons)



Source: China Statistical Yearbook (http://data.stats.gov.cn/english/publish.htm?sort=1)

The objective of this study is to examine which factors affect SO_2 and NO_X emissions by using a panel econometric approach on 30 Chinese provinces. Economic development is known as one of the major determinants that affect environmental pollution. According to the Environment Kuznets Curve (EKC) hypothesis, proposed by Grossman and

Krueger in 1991, relationship between the national income and environmental pollution can be represented by an inverted-U shaped curve. Grossman and Krueger (1991) suggested that some air pollutants such as SO_2, dark matter, and suspended particles increase with per capita GDP in the early stage of economic development, but gradually decrease beyond some level of GDP, so-called an income turning point.

Undoubtedly, environmental pollution depends not only on the national income level, but also on the other factors such as technological innovation, industrial structure, citizen's awareness on environmental pollution, and government effort to reduce the environmental pollution. Therefore, the EKC – related studies has employed several common factors such as energy consumption, urbanization, investment, and international trade openness (see, e.g., Torras and Boyce, 1998; Farzin and Bond, 2006; Jalil and Mahmud, 2009; Qu and Zhang, 2011; Wang et. al., 2011).

This study also employs consumption of energy sources such as electricity, coal, oil, natural gas and diesel. Furthermore, as road transport has considerable impacts on NO_X emissions, this study considers the total number of vehicles and track ration, and assumes that both these factors would increase NO_X emissions. Several empirical studies on the EKC also indicated that weather conditions such as precipitation rate, temperature, humidity, wind speed, or direction of wind also affect air quality (Zhang et al., 2015; Manju et al., 2018; Kayes et al., 2019). This study accounts average annual precipitation rate as a weather variable, but the other climate variables such as temperature, wind speed, or direction of wind are not used as they were not significant in explaining variability in the emissions of air pollutants. Lastly, we examine if the investment in the treatment of waste gas and investment in energy industry have been effective in mitigating the air pollution.

This paper is organized as follows. In the next section, we review previous studies that are associated with empirical analysis for exploring determinants of air pollution in China. Section 3 describes the panel data, explanatory variables, and model specification, and Section 4 presents outcomes of the panel econometric analysis. Section 5 includes summary of this study and policy implications.

II. Literature review

The environmental Kuznets curve (EKC) represents the relationship between economic development and environmental pollution levels. Grossman and Krueger (1991) was the first economists who empirically found that the relationship between environmental degradation and economic growth followed an inverted U-shaped curve. The inverted U-shaped curve between environmental pollution and economic growth is known as the EKC. During the following decades, hundreds of studies have empirically explored the relationship between economic growth and environmental pollution but with no conclusive results. Grossman and Krueger (1991) argued that The inversed-U shaped relationship between the economic growth or per capita income and environmental pollution can be explained by three channels:

a) *Scale effect:* in the early stages of economic growth, with a given level of technology, increase in the output production requires increase in the inputs, specifically, greater use of fossil fuels that lead to increase in environmental pollution levels.
b) *Composition effect:* The economic stage transforms from a developing economy, with pollution-intensive production processes, to more developed one, with less polluting production pattern. In other words, composition effect represents the transition from pollution intensive- industrial sectors to less intensive- service sector. Such structural transformation might have a positive impact on the environment. However, in the case of transformation from agricultural economy to industrial one, composition effect might have an adverse impact on the environment.
c) *Technical effect:* as a country becomes richer, environmental awareness and the demand for environmental regulation increases. This may lead to the substitution of obsolete and dirty technologies to cleaner ones, thereby improve the quality of environment.

Although China's economy has been growing astonishingly relative to the other developing countries, China's environmental pollution has been worsened severely as well. In this context, numerous studies investigated the existence of EKC in China. Brajer et al. (2011) summarized results of the EKC-relevant studies for China until 2009, and showed large divergences in the conclusions about the test of EKC hypothesis for China. However, Brajer et al. (2011) also conclude that the relationships between income and pollution indicators such as SO_2, total suspended particles (TSP) and Nitrogen oxide (NO_2) in most cases have cubic form. Alvarez-Herranz et al. (2017) tried to explain the occurrence of N-shaped relationship between income and pollution. N-shaped relationship implies that in the initial economic development stage, environmental pollution increases with income but decreases after reaching threshold income level when the economy is industrialized. After all, environmental pollution rises again as the economy is stabilized, which shows an N-shaped curve. Alvarez-Herranz et al. (2017) suggested that increase in pollution at the last stage of N-shaped relationship occurs due to *technical obsolescence effect:* as the economy moves along the decreasing part of N-shaped curve, environmental pollution reduction technologies become outdated, and economic growth increases environmental pollution. In order to reduce/eliminate that *technical obsolescence effect* Alvarez-Herranz et al. (2017) argue that R&D investment in energy efficiency and renewable energy technologies should be expanded in the developed countries.

There are numerous studies which analyzed the EKC hypothesis in China for SO_2 emissions by using different time period, various regional levels such as national, provincial, or city levels, and applying different econometric approaches. For instance, Yang et al (2015) used data for seven air pollutants (including SO_2) in 29 Chinese provinces from 1995 to 2010, and conducted Extreme Bound Analysis (EBA), which shows that emissions more often reveal a positive linear relationship with income. In contrast, Yaguchi et al. (2007), by employing a panel data for 29 provinces for the time period of 1985 and 1999, showed that linear and quadratic terms of China's GDP had no significant impacts on SO_2 emissions. Wang et al. (2016) showed that the relationship between economic growth and SO_2 emissions supported inverse U-shaped curve for provincial panel of China spanning the period 1990–2012. However, more recent studies on the EKC hypothesis for SO_2 and solid waste in China showed that the relationship between China's economic growth and emissions did not follow the inverted U shaped curve, but the inverted N shaped relationship (Zhao et al., 2019).

There is a scarcity of papers that test EKC hypothesis for NO_X emissions, probably due to data restriction. one of such study is Wang et al. (2019), who investigated the impacts of energy consumption and socioeconomic context on NO_X emission across provincial regions in China. As Wang et al. (2019) used only linear term for GDP, they found that economic growth positively affects NO_X emission in China. Similarly, Zheng et al. (2020) considered only linear term of GDP in NO_X, SO_2, and PM2.5 (fine particles with a diameter of 2.5 μm or less). The results indicated that economic development has a significant reduction effect on SO_2 pollution as well as an aggravation effect on PM2.5 pollution, but it was statistically insignificant in NO_X emission equation. This shows that China's SO_2 and NO_X emission is not only affected by economic growth, but also by different factors such as energy consumption, industrial structure, and policy implementation.

As shown in Table 1, apart from GDP, the previous studies used trade variables, population variables, energy intensity, total energy consumption, research and development (R&D) and foreign direct investment (FDI) as determinants of environmental pollution. This study tries to find the appropriate determinants of SO_2 and NO_X emissions in China. Specifically, as the main source of SO_2 emissions is accounted combustion of fossil fuels, we included three main energy sources coal, petroleum (gasoline and diesel, separately), and natural gas consumption. In addition to these energy variables, we also considered electricity consumption, as Klimont et al. (2013) argued that the electricity sector accounts about 64%, followed by industry sector with 28% of all SO_2 emissions in 2005. Instead of analyzing the impact of FDI on SO_2, we used investment on the treatment of waste gas (*Treatment*) which represented the direct spending in reduction of

〈Table 1〉 Summary of SO_2 and NO_X emissions in China

Study	Period	Methodology	Pollutant	Explanatory variables	EKC type
Yang et al., (2015)	1995-2010	Extreme Bound Analysis	total CO_2 emission, total SO_2 emission, industrial dust, industrial waste gas, industrial smoke, industrial SO_2, Industrial waste water	Real GDP, the percentage of the secondary sector in GDP, the percentage of exports in GDP, the percentage of imports in GDP, the ratio of entry of FDI over GDP, the population density and the percentage of domestic trade in GDP	Mostly linear
Yaguchi et al. (2007)	1985-1999	First-difference ordinary least square (OLS) and the fixed effect model	total CO_2 emission, total SO_2 emission	Real GDP	Positive (CO_2), no relation (SO_2)
Wang et al. (2016)	1990-2012	Parametric and semi-parametric panel fixed effects	Total SO_2 emission	Total population, energy intensity, GDP per capita, percentage of the urban population in the total population	Inversed-U shaped
Zhao et al. (2019)	1999-2017	Panel data fixed effects, spatial Durbin model (SDM)	industrial sulfur dioxide, industrial solid waste, industrial waste water discharge (per capita)	Real GDP per capita, total energy consumption per capita, Loans and deposits/GRP, Loans/deposits, % of secondary sector value added in total GRP, Real FDI, Number of patents granted per 10,000 people, % of industrial pollution-elimination investment in the GRP	Inversed-N shaped
Wang et al. (2019)	2005-2015	Exploratory Spatial Data Analysis, Ordinary Least Squares	NO_X generation from energy consumption	Population size, Urban density, Per capita GDP, FDI, The proportion of tertiary industry, Energy intensity, Thermal power generation, Natural gas consumption ratio.	Positive
Zheng et al. (2020)	2006-2016	Panel threshold model	NO_X per capita emissions, SO_2 per capita emissions, PM2.5 annual average concentration	Industrial added value as a percentage of GDP, Per capita GDP, Total imports and exports as a percentage of GDP, The proportion of urban population to the total population, Energy per capita consumption, R&D personnel as a percentage of the total population, Agriculture, forestry, animal husbandry, fishery and extractive industries account for the proportion of total fixed assets investment in the whole society	Positive

pollution, and Investment in Energy Industry (*Energy investment*). Finally, several previous studies argued that higher precipitation rate (*Rain*) might have positive impact on air quality, so we also included this variable in the SO_2 equation. However, in our data set precipitation rate available only from 2004 that considerably reduce the number of observations, therefore, we estimated this model separately. According to the Zhao et al. (2013), the distribution of NO_X emissions between power, industry, and transportation sectors was 28%, 27%, and 25% respectively. Thus, main explanatory variables in this study include electricity consumption and variables that represented transport sector such as number of vehicles, diesel consumption and track ratio. In addition to above mentioned variables, NO_X emission equation also includes *Rain, Energy investment* and *Treatment* variables. To the best of our knowledge, the previous literature did not use such proxies for transport sector (NO_X emission equation), particular types of investment (*Energy investment* and *Treatment*) and fossil fuel mix (coal, oil and natural gas) for SO_2 emissions.

III. Data and Model specification

We collected unbalanced panel data for 30 provinces in China from 2000 to 2016. As for the air pollutants, SO_X and NO_X emission levels are used in metric tons from China Environmental Statistics Yearbook. Data on per capita regional GDP in RMB (renminbi) is the official currency of the People's Republic of China) was collected from China Regional Statistical Yearbook. By using consumer price indices, we converted the nominal regional GDP into real regional GDP (base year=1998). Regarding the energy consumption-related variables, coal, gasoline, natural gas, diesel, and electricity consumption are used, and the data also comes from China Regional Statistical Yearbook. In order to improve the environmental quality, and mitigate air pollution, China has increased public investment on the treatment of waste gas pollution and investment in energy sector. We included these variables, obtained from China Regional Statistical Yearbook, in order to assess the effectiveness of such environmental investment. Another factor that affects air pollution is associated with road transport, so the total number of vehicles and ratio of trucks to total number of vehicles are used to evaluate the contribution of transport on air pollution. Data for the number of vehicles and trucks are collected from China Regional Statistical Yearbook. The last factor that we considered is average precipitation rate to reflect relation between climate condition and air pollution, which was obtained from Chinese meteorological data network. Although there are other climate factors such as temperature, wind speed, or wind direction, they were not considered in the estimation because estimates of them were insignificant or wrong signal. Table 2 provides definitions, units, available period, data source, and summary statistics for all variables.

A primary econometric model on the relationship between pollution (*Poll*), per capita GDP (*GDP*) and a vector of other explanatory variables (*X*) has the following form[1]:

$$\mathrm{Ln}\, Poll_{i,t} = \beta_0 + \beta_1 \mathrm{Ln}\, GDP + \beta_2 \mathrm{Ln}\, GDP^2 + \beta_3 \mathrm{Ln}\, GDP^3 + \gamma_x X_{i,t} + \epsilon_{i,t} \qquad (1)$$

In this equation (1), subscript *i* represents 30 provinces in China, *t* is year, β_0 is a constant, $\beta_{1,}$ β_2 and β_3 are coefficients of the linear, quadratic and cubic terms of regional GDP per capita in real term, respectively. γ_x is a vector of coefficients of the other explanatory variables, and $\epsilon_{i,t}$ is an error terms.

As a panel data includes both time and province dimension, it may suffer from serial correlation and heteroskedasticity problems. If these problems are detected before the estimation process, the OLS estimator would not be efficient or unbiased. One of the approaches that can deal with such problems is a Feasible Generalized Least Squares (FGLS) proposed by Parks (1967). However, the FGLS estimator cannot be estimated when the number of time periods, T, is less than the number of panels, N, because the

1) The equation has a ln-ln form as each variable has a different unit, so we can remove scaling effects due to the differences in units of variables in the equation.

associated error variance-covariance matrix cannot be inverted (Beck and Katz, 1995). As the panel data includes 30 Chinese provinces and cover only 16 years period, we cannot use the FGLS estimator. To address this problem, Beck and Katz (1995) proposed a modification of the full GLS-Parks estimator which is called Panel-Corrected Standard Errors (PCSE). By using Monte Carlo experiments, Moundigbaye (2018) concluded that the PCSE estimator should be best for testing hypothesis in all situations. Therefore, we apply the PCSE technique to estimate coefficients of the equation (1).

〈Table 2〉 Descriptive statistics

Variable	*Units*	*Obs*	*Mean*	*Min*	*Max*	*Period*
SO_2 emissions	ton	510	701599.2	16957.63	2002000	2000-2016
NO_X emissions	ton	330	624285.1	40000	1801000	2006-2016
Real regional GDP	RMB per person	510	23277.54	2795.22	84328.13	2000-2016
Electricity consumption	100million kWh	510	1189.95	38.37	5610.13	2000-2016
Coal consumption	10000 ton	506	10684.03	191.63	40939.2	2000-2016
Oil consumption	10000 ton	463	1381.805	0.01	10203.42	2000-2016
Natural gas consumption	100 million m^3	510	32.45	0	181.57	2000-2016
Diesel consumption	10000 ton	507	435.51	11.22	1814.34	2000-2016
Number of vehicles	10000 units	510	241.34	8.28	1723.34	2000-2016
Track ratio	%	510	27.28	4.31	56.00	2000-2016
Energy investment	100 million RMB	510	551.89	9.35	2998.27	2000-2016
Treatment investment	10000 RMB	480	99162.12	140	1281351	2000-2016
Precipitation rate	millimeter	386	933.57	113.53	2377.01	2004-2016

IV. Estimation results

As discussed earlier, the PCSE procedure was applied to analyze the impact of real per capita GDP and other related variables on environmental pollution in 30 Chinese provinces. Before we apply the PCSE procedure, we used a test of modified Wald statistics to examine a group wise-heteroscedasticity (Greene, 2000) under the null hypothesis of homoscedasticity, and for serial correlation in the idiosyncratic errors (Wooldridge, 2002) with null hypothesis of no first-order autocorrelation. As the test results are shown in Tables 3 and 4, significance of statistics in all tests indicates the rejection of null hypothesis which implies that the data suffer from heteroscedasticity and first-order autocorrelation. Therefore, the PCSE procedure is used to handle heteroscedasticity and first-order autocorrelation.

Table 3 summarizes the estimation results of equation (1) for the four different model specifications with SO_2 emissions as a dependent variable. The specification SO2_1, SO2_2 and SO2_3 use linear, quadratic and cubic forms of per capita GDP and the other common variables respectively. Then, the AIC and BIC criteria show that model SO2_1 is better specified relative to the other two specifications. The SO2_4 model extends SO2_1 model with average annual precipitation rate (LnRain). Previous studies indicate that higher precipitation rate significantly reduces emissions of SO_X and NO_X. Concerning the other explanatory variables in the SO_2 equation, electricity, coal, oil and natural gas consumptions are included as most of SO_2 emissions come from the generation of electricity and combustion of fossil fuels that contain sulfur.

In addition to energy-related variables, we also consider such variables related to the government efforts to reduce environmental pollution. Specifically, investment in the treatment of waste gas, as well as its square term, in order to assess the effectiveness of such environmental improvement efforts by the government. In addition to *Treatment* investment this paper considers investment in energy industry.

Notably, the linear term for per capita GDP is statistically significant with negative signs in the model SO2_1 and SO2_4. Signs of estimated GDP coefficients for quadratic and cubic terms in the model SO2_2 and SO2_3 represent inverted-U shaped and N-shaped relations between per capita GDP and SO_X emissions respectively, but these coefficients are not statistically significant. Moreover, in terms of the AIC and BIC criteria, the SO2_1 model is better-specified compared to the SO2_2 and SO2_3 models, as it has the lowest AIC and BIC criteria. Since all variables are transformed into a natural logarithm, the estimated linear coefficients are corresponded to the income elasticities for the SO_X emissions. Thus, an increase of the per capita GDP by 1% will reduce SO_2 emissions by 0.55-0.58%. Although reduction of SO_2 emissions with income growth might not be persuasive at first, but this result can be explained by *Technical effect.* In 2004 National Development and Reform Commission (NDRC) implemented a mandatory policy that any new coal plants larger than 600 MW or with a coal consumption rate of less than 286 grams (g)/kWh should have PM removal and flue gas desulfurization (FGD) systems installed. Moreover, in 2007, China launched a “Large Substituting Small” program for every new and existing coal plants of more than 135 MW needed FGD systems.[2] Thus, increase in income has led to higher environmental awareness and higher demand for clean air in accordance with the stringent environmental regulation on SO_2 emissions.

Next, the estimated parameters of electricity and coal consumption in all models are positive and statistically significant at 1%. An increase of electricity consumption by 1% will increase SO_2 emissions by 0.3%, while the elasticity for coal consumption is much higher (0.77), as electricity could be produced from different sources, while coal is the most pollution-intensive fossil fuel. However, the estimated parameters for consumption of oil and natural gas are found to be negative, but coefficients for oil consumption do not statistically differ from zero even at 10% level. Over the past three decades, approximately two-thirds of China’s primary energy consumption has come from coal, which is the most polluting fossil fuel. According to the U.S. Energy Information Administration, one million British thermal units (Btu) of energy from coal produce 228.6 pounds of carbon dioxide, while the same amount of energy from oil and natural gas produces only 161.3 and 117 pounds respectively. Thus, substitution of energy input from coal to natural gas might have positive impact on reduction of SO_2 emissions.[3] Currently, China makes efforts in substitution of coal with less polluting fuels such as petroleum,

2) ttps://www.powermag.com/how-china-is-on-the-leading-edge-of-environmental-technologies/
3) https://www.eia.gov/tools/faqs/faq.php?id=73&t=11

〈Table 3〉 The PCSE estimates for SO_2 emissions

Variable	*SO2_1*	*SO2_2*	*SO2_3*	*SO2_4*
LnGDP	-0.550***	0.228	14.627	-0.578***
	(0.040)	(0.754)	(12.997)	(0.043)
LnGDP2		-0.039	-1.504	
		(0.038)	(1.321)	
LnGDP3			0.049	
			(0.045)	
LnCoal consumption	0.775***	0.771***	0.775***	0.736***
	(0.048)	(0.048)	(0.048)	(0.048)
LnOil consumption	-0.011	-0.011	-0.010	-0.005
	(0.012)	(0.012)	(0.012)	(0.013)
LnGas consumption	-0.023*	-0.023*	-0.024*	-0.050**
	(0.013)	(0.013)	(0.013)	(0.022)
LnElectricity consumption	0.292***	0.298***	0.296***	0.349***
	(0.051)	(0.051)	(0.051)	(0.060)
LnTreatment	0.671***	0.674***	0.662***	0.595***
	(0.167)	(0.171)	(0.169)	(0.169)
LnTreatment2	-0.032***	-0.032***	-0.032***	-0.028***
	(0.008)	(0.008)	(0.008)	(0.008)
lnEnergy investment	-0.068*	-0.081**	-0.081**	-0.092**
	(0.039)	(0.040)	(0.040)	(0.045)
LnRain				-0.122***
				(0.036)
Constant	6.806***	3.001	-43.980	8.370***
	(0.958)	(3.721)	(42.467)	(0.990)
N. of obs.	429	429	429	352
R - square	0.836	0.8364	0.8368	0.8592
AIC	279.55	281.42	281.93	167.1
BIC	323.52	329.38	333.88	208.79
Homescedasticity	2739***	2934***	2957***	4565***
No autocorrelation	153.48***	208.28***	225.1***	145.55***

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parentheses.

natural gas, nuclear, or renewable energy. Furthermore, the estimates for the linear and quadratic terms of the investment in the treatment of waste gas show the inverse U-shaped relation, as the linear and the quadratic terms of the *LnTreatment* variable are statistically significant at 1% level with positive and negative signs respectively. It implies that low anti-pollution investment is deficient to mitigate the SO_2 emissions, but above a threshold level (about RMB 350 million) of the investment in the treatment of waste gas, that is quite below the mean (above RMB 990 million), the SO_2 emissions begin to decrease.

Finally, the model SO2_4 considers the average annual precipitation rate (*LnRain*) in addition to the above-mentioned variables. The reason why we do not include *LnRain* variable in previous models is data restriction. As shown in Table 3, when we include the *LnRain* variable, the number of observations falls from 429 to 352. By the way, the inclusion of *LnRain* does not change the estimation results from the SO2_1 model in overall. Meanwhile, the increase in precipitation rate by 1 % reduces SO_2 emissions by 0.12%.

Table 4 shows the estimation results for NO_X emissions. As was discussed above, energy and transport sectors contribute to Chinese NO_X emissions by 28% and 25% respectively. Thus, road transport as well as electricity variables are included as explanatory variables in the NO_X equations. More specifically, the number of vehicles, truck ratio and diesel consumption are used as the proxies for emission sources of road transportation. It is expected that all these variables will contribute to NO_X emissions as increase in the number of vehicles will raise the number of emitters and trucks are usually more pollution-intensive than passenger transport. We also expect that diesel consumption will increase NO_X emissions because it is known that diesel vehicles emit around 30% more NO_X than petroleum cars (Nieuwenhuis and McNabola, 2017). In addition to road transport variables, we consider average precipitation rate, investment in the treatment of waste gas and investment in energy industry as similar to the SO_2 equations.

In parallel to the SO_2 emission models, we consider linear, quadratic and cubic terms for the per capita GDP. In contrast to the SO_2 models, the lowest values of AIC and BIC criteria were for the model specification with the cubic term for the income variable. Based on the signs of the linear, quadratic, and cubic terms of the income variables, the relationship between the GDP and NO_X emissions follows an inverse N-shaped curve. The income turning points are calculated as 8,189 RMB/person and 33,183 RMB/person. In other words, NO_X emissions decrease with income until the per capita GDP reaches 6,069 RMB/person, while increase for 8,189~33,183 RMB/person, but decrease above 33,183 RMB/person. However, in 2006 (starting year in NO_X analysis), only per capita GDP of Guizhou province was below this threshold. Notice that in the model specification with the quadratic term for the income variable, the EKC hypothesis is approved, and the NO_X emissions increase until the per capita GDP reaches about 26,743 RMB/person, but decrease after that threshold level. Notably, in 2016 (final year off estimation), only 14 among 30 provinces had their GDP levels above 33,183 RMB/person, so in most provinces, NO_X emissions increased with income level. Regarding the marginal effect of per capita GDP on NO_X emissions, 1% increase in the per capita GDP leads to 0.23% increase in NO_X emissions.[4)]

The estimated coefficients for electricity and diesel consumption as well as the number of vehicles and truck ratio are statistically significant and positive as expected. Specifically, the increase in electricity and diesel consumption by 1% increase NO_X emissions by 0.42% and 0.46% respectively. Meanwhile the increase in the number of vehicles and truck ratio contribute to NO_X emissions in China by 0.114 and 0.03 percent respectively. However, investment in the treatment of waste gas and investment in Energy industry (except model *NOX_1*) do not affect NO_X emissions significantly, probably because such activities are targeting on the flue gas desulfurization (FGD) systems, which reduce SO_2 emissions.

4) We derived partial differentiation of NO_X emissions with regard to per capita GDP in the equation (1), plugging the estimated parameters for per capita GDP and the mean value of the natural log of per capita GDP (RMB21,631).

〈Table 4〉 The PCSE estimates for NO_X emissions

	NOX_1	*NOX_2*	*NOX_3*
LnGDP	0.029	4.047***	-49.008*
	(0.064)	(1.202)	(26.028)
LnGDP2		-0.199***	5.073**
		(0.059)	(2.565)
LnGDP3			-0.174**
			(0.084)
LnElectricity consumption	0.416***	0.439***	0.421***
	(0.066)	(0.066)	(0.065)
LnDiesel consumption	0.490***	0.468***	0.464***
	(0.056)	(0.056)	(0.055)
LnVehicles	0.097	0.093	0.114*
	(0.063)	(0.061)	(0.060)
Truck ratio	0.031***	0.029***	0.030***
	(0.006)	(0.006)	(0.006)
LnEnergy investment	0.106***	0.059	0.042
	(0.040)	(0.040)	(0.039)
LnTreatment	-0.081	-0.035	-0.028
	(0.102)	(0.098)	(0.099)
LnTreatment2	0.004	0.003	0.002
	(0.005)	(0.005)	(0.005)
LnRain	-0.201***	-0.207***	-0.222***
	(0.035)	(0.034)	(0.034)
Constant	6.767***	-13.464**	164.249*
	(0.935)	(6.135)	(87.953)
Number of observations	326	326	326
R-square	0.8449	0.8523	0.8553
AIC	163.98	150.16	145.41
BIC	205.64	195.61	194.64
Homescedasticity	236***	229.6***	236.4***
No autocorrelation	6.47**	8.44***	7.39***
Turning point(s)		26743.68	8189.07 33183.06

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parentheses.

Zhao et al. (2013) mentioned that the emissions of NO_X from energy sector are decreasing from 2004 due to national-wide NO_X combustion technologies. Similar decreasing trend of NO_X emissions has been observed in transport sector from 2001 because of introduction of emissions standards for new vehicles. However, NO_X emissions from the industrial sector have increased constantly, which could be attributed to rapid development of industry in China.

V. Conclusion

This study explores the relationship between per capita GDP and air pollution (SO_2 and NO_X) by using a PCSE procedure, and identifies other determinants that might have positive or negative impacts on the air pollution in 30 Chinese provinces. Estimation results show that per capita GDP has a negative, linear relation with SO_2 emissions, which implies that the increment of per capita GDP leads to reduction of the SO_2 emissions through more stringent environmental regulation and investment on clean technology. However, the estimation results show an inverted-N shaped relationship between per capita GDP and NO_X emissions. According to the estimated turning points, most of the Chinese provinces are still in increasing side of this inverted-N shaped curve. Moreover, we found that electricity consumption raises both SO_2 and NO_X emissions significantly. Also, consumptions of coal and diesel are included as explanatory variables to analyze if these energy sources significantly affect air pollution. The results show that increase in the coal consumption leads to increase of SO_2 emissions, while natural gas consumption reduces SO_2 emissions as it is a relatively cleaner fuel to the coal. Those results suggest that China should make efforts to reduce the share of coal consumption and replace it by clean fuels such as natural gas. Although the Chinese government has listed switch from coal to gas as a key part of China's sustainable energy system transformation strategy (Zhang and Paltsev, 2016), some provinces canceled 'coal to gas' initiative due to natural gas shortages and high cost (Jin et al., 2016).

In terms of relevant government policy, our analysis reveals that the implementation of air pollution prevention and control law also helps pollution reduction. Hopefully, market-oriented policies such as China's Environmental Protection Tax that was implemented on January 1, 2018 might be more effective in mitigating air pollution. The estimation results also show that investment on the waste gas treatment facilities and energy industry can reduce SO_2 emissions effectively. However, such investments do not affect significantly reduction of NO_X emissions. As one of the main sources of NO_X emissions is a road transport, policies such as restriction in the number of private cars, increase in petroleum tax, promotion of bio-fuels (ex: bio-ethanol, bio-diesel, or bio-gas) and electric vehicles would reduce NO_X emissions more effectively.

As for policy implications of this study, factors that contribute to increasing air pollution (especially particulate matters) in China such as electricity, coal, and diesel consumptions would be controlled more effectively by the collaboration with neighboring countries such as Korea, Japan, and southern Asian countries. Korea and Japan can provide accumulated experiences in transition from fossil fuels to renewable ones, for example. Also, it is important to remove subsidies to fossil fuel consumption and reflect changes in fuel costs as energy prices are regulated by the Chinese government. Next, in order to reduce NO_X emissions Chinese government should put more focus on the promotion of public transportation and investment on flue gas denitrification technoligies. Most public transportation in Korea is fueled by LNG (Liquefied Natural Gases), and Seoul metropolitan region prohibits entrance of diesel vehicles that exceeds a threshold level in terms of air pollution. In this regard, Chinese government would need to support switch from fossil fuels to LNG in the public transportation.

Finally this paper remains with further research. First of all, this study should be extended to examine if the air pollution in China affects significantly air quality in Korea, and what kind of pollutants are major pollution sources in the transboundary pollution if it does. In addition, we attempted to examine the impact of renewable energy production on mitigation of SO_X and NO_X, but data was not available for Chinese provincial levels.

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