Energy Consumption, CO2 Emissions and Economic Growth: A Comparative Analysis in Guangdong, China

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Abstract: Carbon dioxide (CO2) is the chief greenhouse gas causing global warming, and the relationship between this gas and economic development is a major subject of research. This study uses panel data and models for coastal cities in Guangdong province, China, from 2005 to 2017, as well as the robustness results obtained using Driscoll-Kraay standard errors. The study finds that an inverted U-shaped relationship exists between income and emissions in the Pearl River Delta region; the expected income per capita at the inflection point on the U curve is between US$24,920 and 27,860, and the expected per capita CO2 emissions at the inflection point are projected to be approximately 13 tons annually. However, the EKC hypothesis is not verified in the non-Pearl River Delta area. Population agglomeration is found to benefit the reduction in per capita CO2 emissions, and a population scale effect exists; however, the emissions reduction effect of population agglomeration in the non-Pearl River Delta area is greater than that in the Pearl River Delta region. This study also provides relevant policy recommendations and suggestions for future research.

1 INTRODUCTION

Climate change has become a major global issue, and excessive greenhouse gas emissions pose a threat and disaster to the survival of life on Earth. Carbon dioxide (CO2) is the chief greenhouse gas causing global warming and currently accounts for approximately 75% of the earth's greenhouse effect (Sirag, 2018). While CO2 emissions are tightly linked with fossil fuel consumption, fossil fuels are an important factor driving the rapid economic development of numerous countries and areas. The relationship between environmental quality and economic development can be represented by what is known as the environmental Kuznets curve (EKC), which has become a major topic of research.

The Kuznets curve was first proposed by the economist Simon Kuznets in 1955 while researching per capita income and the fairness of income distribution (Kuznets, 1955). Afterwards, during the early 1990s, many scholars innovatively applied the Kuznets curve in the field of environmental quality and proposed that the relationship between per capita income and environmental quality took the form of an inverted U-shaped curve (Grossman, 1995). While numerous empirical studies have supported the EKC hypothesis (Diao, 2009), other scholars have reached different conclusions and believe that there is no empirical support for EKC (Sanchez, 2016). Some studies have reached different conclusions concerning the shape of the EKC curve due to differences in regional characteristics (Churchill, 2018) or differences in the pollutants studied (Kaika, 2013). As a result, doubts still exist concerning the relationship between CO2 emissions and income that form the basis of the EKC hypothesis, and further efforts must be made to verify the hypothesis employing representative geographical areas and methods.

This study takes CO2 emissions per capita as an indicator of environmental degradation to analyze and compare the EKC of the Pearl River Delta region with other areas in Guangdong province, during the period from 2005 to 2017.

2 METHODS

2.1 Data Sources and Variables

This study employs balanced panel data from 21 cities in Guangdong province from 2005 to 2017 as

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a sample and obtains GDP per capita and population density data from the Guangdong Statistical Yearbook for various years. This paper takes 2005 as the base year for GDP per capita, corrected for inflation, and converts all amounts into US dollars from the average annual exchange rates. The cities' energy consumptions are calculated from each city's energy intensity and GDP, and CO2 emissions are estimated by the energy and economic data. The definitions of the variables involved are shown in Table 1.

Table 2 provides a statistical description of the panel sample data. The sample consists of balanced panel data with a period of 13 years. The Pearl River Delta region includes Guangzhou, Shenzhen, Huizhou, Dongguan, Foshan, Zhaoqing, Zhuhai, Zhongshan, and Jiangmen, and the overall sample size is 117. This study classifies the remaining areas of Guangdong province, including the eastern region, western region, and mountain areas, as the non-Pearl River Delta area. This area includes 12 cities and has an overall sample size of 156. From this table, the CO2 emissions per capita, GDP per capita, and population density of the Pearl River Delta region are 2, 3, and 2.77 times greater than the corresponding figures for the non-Pearl River Delta area, respectively. This outcome indicates that significant differences exist between these two areas. The standard deviations of the research variables are relatively small, which indicates that the fluctuations in values of the variables around the mean values are relatively small; this also shows that the data are stable and suitable for further study.

Table 1: Summary of variable definitions.

Name of variable	Abbreviation	Description	Units	Source
CO2 emissions per capita	CO2pc	Average per capita CO2 emissions	Tons/person	Estimated from energy consumption, GDP, and population data from the Guangdong Statistical Yearbook
Income level	GDPpc	GDP per capita	US$10,000/person	Guangdong Statistical Yearbook for various years
Population density	Popuden	Permanent population/area	1,000 persons/km2	Guangdong Statistical Yearbook for various years

Table 2: Descriptive statistics of variables.

Region	Pearl River Delta			Non-Pearl River Delta		
Variable	CO2pc	GDPpc	Popuden	CO2pc	GDPpc	Popuden
Mean	9.336	0.975	1.729	4.694	0.32	0.624
St.d	2.912	0.509	1.53	2.216	0.146	0.618
Min	2.762	0.145	0.247	1.029	0.091	0.154
Max	13.972	2.122	6.272	10.899	0.675	2.55
Size	117	117	117	156	156	156

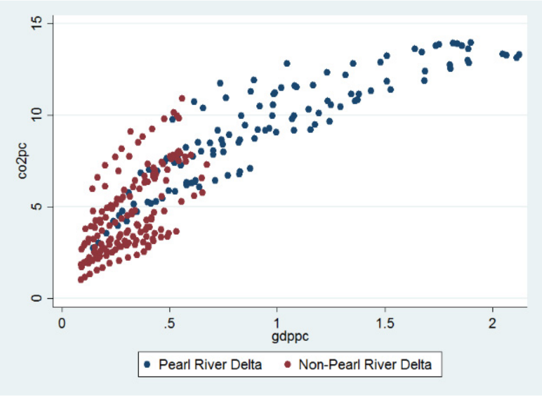

Figure 1: Scatter diagram of the GDP and CO2 emissions per capita.

Figure1 shows the results of the quadratic curve fitting for GDP per capita and CO2 emissions per capita in the Pearl River Delta and the non-Pearl River Delta area. From this figure, the Pearl River Delta region has a significantly higher income level than that in the non-Pearl River Delta area, and CO2 emissions per capita display a slowing trend as the income level increases. This very likely indicates that the EKC inflection point has been reached, while emissions per capita in the non-Pearl River Delta area continue to increase rapidly.

2.2 Model Design

Equations used to test EKC models include quadratic term equations and cubic term equations, and linear equations are usually used for model testing in the case of countries or areas that are not fully industrialized. A quadratic polynomial model is a very versatile means of assessing the form of an EKC curve. To observe whether an inverted U-shaped curve is present, and whether environmental degradation continues as income increases, this study uses per capita income as a quadratic term in model testing. The equation used to test the EKC model in this study is as follows:

$$\mathrm{Y}_{it} = \alpha_i + \beta_1 X_{it} + \beta_2 {X_{it}}^2 + \beta_3 Z_{it} + \varepsilon_{i,t} \quad (1)$$

Here, Y is the variable expressing the degree of environmental degradation; X is the income level (GDP per capita); Z consists of other explanatory variables; $\varepsilon_{i,t}$ is an error term; i indicates different entities; and t expresses time. The coefficients in front of X and its quadratic term determine the form of the curve. Accordingly, the following situations can be used to judge whether the EKC hypothesis is correct:

If β_1>0 and β_2=0, then X and Y have a monotonically increasing relationship.

If β_1<0 and β_2=0, then X and Y have a monotonically decreasing relationship.

If β_1>0 and β_2>0, then X and Y have a U-shaped relationship

If β_1>0 and β_2<0, then X and Y have an inverted U-shaped relationship.

All of these different curve shapes have different implications. A monotonically decreasing curve indicates that environmental quality improves as income increases, while a monotonically increasing curve indicates that environmental quality deteriorates as income increases. A U-shaped curve indicates that while environmental quality improves as income increases, it begins to deteriorate after reaching a certain point. When an inverted U-shaped curve is present, this outcome indicates that environmental quality first deteriorates steadily with rising income but begins to improve with rising income after reaching an inflection point.

The explained variable in this model is CO2 emissions per capita, and the explanatory variables are GDP per capita and its quadratic term. Model 1.1 is used to determine whether the EKC hypothesis is applicable to the study area. Degree of population agglomeration is subsequently added to model 1.1 as an explanatory variable, yielding model 1.2. This study also establishes models 2.1 and 2.2 for the non-Pearl River Delta area during the same period and adopts a fixed effects model and the random effects model to compare the results of other models. These models' equations are as follows:

$$\mathrm{CO2pc}_{it} = \alpha_i + \beta_1 GDPpc_{it} + \beta_2 {GDPpc_{it}}^2 + \varepsilon_{i,t} \quad (2)$$

$$\mathrm{CO2pc}_{it} = \alpha_i + \beta_1 GDPpc_{it} + \beta_2 {GDPpc_{it}}^2 + \beta_3 Populden_{it} + \varepsilon_{i,t} \quad (3)$$

Here, the subscript $\mathrm{i} = 1, \cdots, \mathrm{n}$ indicates cross-sectional units, and the subscript $\mathrm{t} = 1, \cdots, \mathrm{T}$ indicates time.

While many factors influence CO2 emissions per capita, this study adopts per capita income and degree of urban population agglomeration as the two chief research variables. One of the chief difficulties affecting analysis is model selection because the choice of model has a large effect on the analysis. Apart from the ordinary least squares method (OLS), the fixed effects and random effects models are used to analyze the panel data. An F-test is used to determine the importance of individual effects and compares a mixed OLS model with the fixed effects model. In addition, the Lagrange multiplier (LM) test is used to compare the OLS regression model with the random effects model. Finally, the Hausman test is used to confirm whether to use a random effects model or a fixed effects model. Cameron and Trivedi suggested that the sigmamore option is the best in Stata for the Hausman test because this option indicates that the two covariance matrices are based on an estimation variance by the same effective estimator (Cameron, 2010). These tests indicate that model 1.1, model 1.2, and model 2.2 are fixed effects models, while model 2.1 is a random effects model. Diagnostic testing is performed on all models. The Pesaran cross-sectional dependence test (Pesaran CD) is employed to determine whether the residual is relevant across different cities (Pesaran, 2004). The revised Wald test is used to determine the models' heteroscedasticity. The Wooldridge test is used to test the serial correlation of the panel data. According to Hoechle, if models are heterogeneous, autocorrelated, and cross-regionally dependent, the Driscoll-Kraay standard errors method should be used (Hoechle, 2007).

3 RESULTS

From the F statistic of model 1.1 in Table 3, the results of the F-test are significant for a fixed effects model (F (2, 106) = 441.819, p-value = 0.000). Model fitting reveals that a regression estimate using the CO2 emissions per capita function can explain up to 89% of the variation in CO2 emissions per capita (R-squared = 0.848). The fixed effects modeling results also reveal that the coefficients of all variables are significant to a level of 1%. Furthermore, model 1.1 verifies the existence of an inverted U-shaped curve. After the population density variable is added, this study finds that the fixed effects model is also applicable to model 1.2. Based on the results of testing for heteroscedasticity, autocorrelation, and panel dependence, this study employs the Driscoll-Kraay standard errors method to overcome and minimize these problems. The results of the fixed effects estimation and Driscoll-Kraay standard errors estimation are shown in Table 3. From the F statistic of model 1.2, the results of the F-test are significant for a fixed effects model (F (3, 105) = 313.032, p-value = 0.000). Similarly, the model estimation results indicate that the data and model have a good fit, and the model can explain 62.7% of the variation in per capita CO2 emissions (R-squared = 0.627). The coefficients of all variables are significant in a fixed effects model. For population density, each increase in population density by 1,000 persons per square kilometer could reduce per capita CO2 emissions by 0.734 tons.

4 DISCUSSION

This study consequently discovers that a significant inverse correlation exists between population density and CO2 emissions per capita. Furthermore, the inverted U-shaped curve in the Pearl River Delta region is also confirmed by this model. From the results of the fixed effects model estimation employing models 1.1 and 1.2 and Driscoll-Kraay standard errors estimation in the table, the monomial coefficient of GDP per capita is significantly positive, while the second-order coefficient is significantly negative. Model 1.1 indicates that per capita income at the inflection point is US$24,920 while CO2 emissions per capita at the inflection point are 12.922 tons, with a 95% confidence interval of 12.178 to 13.667 tons.

Table 3: Panel regression results for the pearl river delta region.

	Model 1.1 FE		Model 1.2 FE	
	Square FE	Driscoll- Kraay Standard Errors	Square FE	Driscoll- Kraay Standard Errors
GDPpc	6.983***	6.983***	7.020***	7.020***
	(-14.65)	(-15.59)	(-15.12)	(-18.84)
$GDPpc^2$	-1.401***	-1.401***	-1.260***	-1.260***
	(-7.09)	(-7.35)	(-6.31)	(-8.10)
Popuden			-0.734**	-0.734***
			(-2.61)	(-6.60)
_cons	4.220***	4.220***	5.282***	5.282***
	(-17)	(-19.33)	(-11.17)	(-16.78)
Observations	117	117	117	117
Cities	9	9	9	9
F-test or Wald chi2	441.819	415.713	313.032	606.414
R-square/ R-square within	0.848	0.893	0.627	0.899
EKC Holds	Yes	Yes	Yes	Yes
Turning points (real 2005 US$)	2.492	2.492	2.786	2.786

Note: ***, **, and * indicate 1%, 5%, and 10% levels of significance.

Table 4: Panel regression results for the non-pearl river delta region.

	Model 2.1 RE		Model 2.2 FE	
	Square RE	Driscoll- Kraay Standard Errors	Square FE	Driscoll- Kraay Standard Errors
GDPpc	9.654***	9.654***	10.808***	10.808***
	(-8.44)	(-5.6)	(-9.68)	(-7.87)
$GDPpc^2$	-2.721	-2.721	-3.538**	-3.538
	(-1.64)	(-1.04)	(-2.24)	(-1.69)
Popuden			-5.811***	-5.811***
			(-4.20)	(-3.39)
_cons	1.939***	1.939**	5.295***	5.295***
	(-3.58)	(-2.38)	(-6.49)	(-5.48)
Observations	156	156	156	156
Cities	12	12	12	12
F-test or Wald chi2	921.321	394.165	347.441	165.244
R-squared	0.396	0.396	0.881	0.881
EKC Holds	No	No	Yes	No
Turning points (real 2005 US$)	-	-	1.527	-

Note: ***, **, and * indicate 1%, 5%, and 10% levels of significance.

The results of the LM test, the F test, and the Hausman test reveal that while model 2.1 for the non-Pearl River Delta area should be treated as a random effects model, model 2.2 for the Pearl River Delta region should be treated as a fixed effects model. Similarly, after confirming the heteroscedasticity, autocorrelation, and panel dependence of these models, this study employs the Driscoll-Kraay standard errors method to overcome these problems. Table 4 displays the random effects results for model 2.1 and the fixed effects results for model 2.2. However, although the quadratic term for GDP per capita in the fixed effects results for model 2.2 is significant (as indicated by two asterisks), after employing the Driscoll-Kraay standard errors to overcome the problems of heteroscedasticity, autocorrelation, and panel dependence, this term is not significant, which is consistent with expectations. Based on the F test and the Wald chi-squared values of the two models, this study finds that these two models are significant, and there are significant inverse correlations between increasing population density and CO2 emissions per capita. In the non-Pearl River Delta area, each increase in population density by 1,000 persons per square kilometer could reduce per capita CO2 emissions by 5.8 tons. However, an inverted U-shaped curve is not verified for the non-Pearl River Delta area. According to the standard errors estimation results for models 2.1 and 2.2, the first-order coefficient of GDP per capita is significantly positive, but the second-order coefficient is not significant.

5 CONCLUSIONS

An inverted U-shaped relationship exists between income and environmental degradation in the Pearl River Delta region. This study finds that an income per capita between US$24,920 and 27,860 is expected at the EKC inflection point for the Pearl River Delta region. Although economic growth could cause pollution in the short run, it could reduce emissions and pollution in the long term. However, reductions in environmental degradation may not spontaneously appear as per capita income increases, and attention should be paid to the specific mechanisms by which this positive effect occurs. An inverted U-shaped relationship does not exist in the non-Pearl River Delta area, but a significant positive correlation exists between income and environmental degradation. The reason for this difference between the Pearl River Delta region and the non-Pearl River Delta area lies in the relatively high level of urbanization and industrialization of the Pearl River Delta region; even some cities in the Pearl River Delta region have already reached the middle or late stage of urbanization and industrialization. However, most areas in the non-Pearl River Delta area are still in the initial stage of rapid urbanization and industrialization, and these processes will continue in the future. Finally, we find that population agglomeration can facilitate a reduction in the per capita CO2 emissions in the Pearl River Delta and the non-Pearl River Delta area. The population agglomeration brings a population scale effect and can significantly reduce the level of carbon dioxide emissions.

Although the article has made some significant findings, it still has certain limitations. Besides CO2 emissions, other pollutants such as sulfur dioxide, methane and so on, could be also used to measure environmental degradation. Furthermore, CO2 emissions data cannot be obtained directly, so the carbon emissions data estimated by the energy and economic data in this paper are not completely accurate, so more precise data should be obtained through more advanced tools and methods in the future.

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