CO2 Emissions and Economic Growth:

Empirical Analysis of the Environmental Kuznets Curve

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May 2023

Abstract

This research paper investigates the applicability of the Environmental Kuznets Curve (EKC) hypothesis using panel data from 183 countries between 1990 and 2019. The analysis employs a model incorporating a quadratic equation for per capita income. Methodological concerns, including simultaneous bias is addressed. Results support the existence of an EKC for both the full-sample panel and the high-income panel. The estimated tipping points, representing income levels where environmental improvement begins, for the full sample panel aligns with or below previous studies, and those for the high-income panel are higher than earlier estimates. Low- and middle-income countries, EKCs are not established in at least one of the models in each income panel, i.e. CO2 emissions are expected to continue increasing. These results implies that comprehensive strategies are needed that address both economic growth and environmental improvements, especially in low- and middle-income countries.

Keywords: Environmental Kuznets Curve, CO2 emissions, Economic Growth, Simultaneous equations

1. Introduction

Today, there is broad agreement on the close relationship between the economy and the environment. The idea of "Sustainable Development" is now well-known among people. According to *Our Common Future* (WCED, 1987), the definition of sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This is based on the idea that the environment and economic development are not “trade-offs,” and that environmental conservation and economic development can be achieved in tandem. Environmental Kuznets Curve (EKC) is one hypothesis about how economic development affects environmental pollution. This hypothesis is illustrated graphically, with per capita income on the horizontal axis and the level of environmental pollution on the vertical axis, which shows an inverted U-shaped curve where pollution initially increases as per capita income rises, reaches a certain level, and then begins to decline. The existence of an environmental Kuznets curve can be an endorsement that sustainable development is feasible. There also exists criticisms against the EKC in terms of irreversibility of environmental destruction. This paper examines whether the Environmental Kuznets Curve holds for CO2 emissions using two different models. Analysis using simultaneous equations is a unique feature of this study.

2. Literature Review

There are two pioneering research publications in EKC. *World Development Report* (1992) is particularly influential and made the hypothesis famous because it is published by World Bank. The report presents a graph showing inverse U-shape relationship between income and environmental pollution. This study tested the relationship between environmental pollution and economic development using 10 indicators of environmental degradation for 149 countries from 1960 to 1990. Three different estimating equations were used in this study: log-linear form, log-quadratic, and logarithmic cubic polynomial. The results of the analysis showed that only two air pollutants, SO_2 and SPM, satisfied the EKC hypothesis, while CO_2 increased monotonically and had no emission peaks.

The study by Grossman and Krueger (1991) is another pioneering study along with the World Bank (1992). This is a part of the National Bureau of Economic Research (NBER) working paper. They analyzed 14 environmental indicators and confirmed the existence of EKCs below the tipping point of $8,000 in many of them. However, the EKC did not exist for CO_2. The quadratic income model used in this study has been widely used in subsequent empirical studies.

There is less accumulated research on pollutants on a global scale, such as CO_2, than on other substances that have local impacts. Major studies on CO_2 are as follows. Shafic (1994) expanded World Bank's background report. This tests for 135 countries from 1960 to 1989 using three different models: Log-linear, quadratic, and cubic. The relationship between income and CO_2 is represented by log-linear so that EKC does not hold. Holts-Eakin and Selden (1995) used a quadratic model for 130 countries from 1951 to 1986. The EKC holds with an estimated turning point income of $35,428 for quadratic and $8 million for log specification. Even though the EKC hypothesis is satisfied in this result, those turning point incomes are out of the sample. This result implies that that CO_2 emissions will continue to increase within income level of the sample. Dijkgraaf and Vollebergh (2005) focused on homogeneity. They found the EKC with turning point income at $20,600. However, there is a lack of homogeneity of parameters among each country. In the research of Richmond and Kaufman (2006), the EKC hypothesis holds for all sample and OECD countries but not for non-OECD countries. In the cases of CO_2, there are coexisting cases where the hypothesis exists and cases where it does not. Also, estimation results often differ between subsamples and the full sample.

There is also criticism of the EKC hypothesis, such as by Arrow et al. (1995). Environmental pollution and natural resource uses can have irreversibility so that once the limit is exceeded, it would be impossible to reform. In addition, even though one kind of pollutant is reduced, other kinds of pollutants can be increased as a substitute.

The theoretical work on the EKC hypothesis was initiated by Lopez (1994). He proved that if producers pay the social marginal cost of pollution, then the relationship between pollution emissions and income depends on the technology available to producers and the preferences held by consumers. Thus, the amount of pollution emissions associated with an increase in income depends on the extent to which consumers are risk-averse and the elasticity of substitution between the polluting input and the general input.

Stokey (1998) derived the EKC theory applicable to stock pollutants, such as carbon dioxide. This study derives the EKC in the framework of optimal growth theory. She also introduced a theory that can be applied to stock pollutants such as carbon dioxide.

There are about four major explanations for there is the shift from increasing to decreasing pollution; changes in the structure of production and consumption, growing preferences for good environment, regulations that internalize external diseconomies, increasing returns to scale in pollution reduction activities (Andreoni and Levinson, 2001).

3. Empirical Model

In this study, I test two different empirical models. The first model is the quadratic formula for income which is used in many well-known previous studies, such as Grossman and Krueger (1991). I added population density and share of reusable energy out of total energy consumption to the model.

$$CO2_{it} = \alpha_0 + \alpha_1(lny_{it}) + \alpha_2(lny_{it})^2 + \alpha_3 D_{it} + \alpha_4 E_{it} + \epsilon_{it} \quad (1)$$

Where $CO2_{it}$ is CO2 emission, y_{it} is GDP per capita, D_{it} is population density, R_{it} is % of reusable energy in total energy consumption, and e is the stochastic error term. When α_1>0, α_2<0, it is statistically significant, and EKC holds with income at the turning point at an acceptable level. In this equation, turning point income is derived from $e^{(\alpha_1/(2\,\alpha_2))}$. Also, I expect that population density and share of reusable energy have negative correlation with CO2 emissions.

The second model is the simultaneous equations model. Coondoo and Dinda (2002) found that there are emissions to income correlations. Feedback effects of environmental degradation on income are not considered in the model (1). This model can deal with the problem of simultaneity between CO2, which is the independent variable, and GDP, which is the most important dependent variable in this study. The estimation of this model is based on the study by Youseff, Hammoudeh, and Omri (2016).

$$\ln\ CO2_{it} = \beta_0 + \beta_1(lny_{it}) + \beta_2(lny_{it})^2 + \beta_3 D_{it} + \beta_4 E_{it} + \epsilon_{it}\ (2)$$

$$\text{ln}y_{it} = \gamma_0 + \gamma_1(lnCO2_{it}) + \gamma_2(lny_{it}) + \gamma_3(lnl_{it}) + \epsilon_{it}\ (3)$$

Equation (2) is identical to (1). When β_1>0, $\beta_2$0, it is statistically significant, and EKC holds with income at the acceptable level at the turning point. Tipping point income is given from $e^{(\beta_1/(2\,\beta_2))}$. Equation (3) is an extended Cobb-Douglas production function. y_{it} denotes GDP per capita, $CO2_{it}$ denotes CO2 emission, k denotes domestic capital per capita, and l denotes labor force per capita. Considering simultaneity, $lnCO2_{it}$, lny_{it} and $(lny_{it})^2$ are classified as endogenous variables, and the other variables are considered exogenous variables. Equations (2) and (3) are estimated simultaneously by Two Stage Least Squares.

4. Data

4.1. Data Source

All data is from the World Development Index of the World Bank. This study uses per capita CO2 emission in metric tons. Per capita GDP (y) is in Purchasing Power Parity, the current international dollar. Population Density (P) is expressed in People per square km of land area. Share of reusable energy (E) is defined as the percentage of reusable energy consumption out of total final energy consumption. Per capita domestic capital (k) is gross fixed capital formation in the current US dollar. Per capita labor force (l) is measured as the labor force comprising people ages 15 and older who supply labor. Based on data availability, I use data from 1990 to 2019 for 183 countries. Further, countries are divided into four sub-samples based on income level. 54 high-income countries, 53 upper middle-income countries, 51 lower-middle-income countries, and 25 low-income countries, according to the world bank classification in 2023. The list of countries is in the appendix at the end of the paper. Descriptive statistics and correlation matrix for data are as follows. (Descriptive statistics for GDP per capita that allows comparison for each income level is also provided, as it is useful when discussing the tipping point.

Table1: Descriptive Statistics

Variable		Mean	Std. Dev.	Min	Max		Observations
CO2	overall	4.35	5.565	0	47.651	N =	5479
	between		5.444	0.034	38.541	n =	183
	within		1.209	-13.392	15.947	T-bar =	29.94
y	overall	13990.90	17503.607	284.25	163219.49	N =	5252
	between		16697.984	627.801	115547.47	n =	181
	within		6630.994	-27783.943	63445.226	T-bar =	29.017
P	overall	165.37	511.885	1.397	7965.878	N =	5477
	between		504.713	1.675	6426.343	n =	183
	within		89.71	-1713.008	1704.912	T-bar =	29.929
E	overall	33.50	30.799	0	98.34	N =	5441
	between		30.166	0	96.477	n =	183
	within		6.583	2.978	84.149	T-bar =	29.732
k	overall	0	0.003	0	0.033	N =	5477
	between		0.003	0	0.033	n =	183
	within		0	0	0.001	T-bar =	29.929
l	overall	0.42	0.087	0.208	0.755	N =	5190
	between		0.084	0.213	0.673	n =	173
	within		0.026	0.299	0.558	T-bar =	30

Table 2: Descriptive statistics of GDP per capita by Income Level

Income	Mean	Min	Max
All	13990.9	284.3	163219.5
High	32582.4	4437.2	163219.5
Uppermiddle	9914.7	579.9	33261.9
Lowermiddle	4185.3	412.4	18981.2
Low	1371.7	787.6	4813.9

Table3: Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)
(1) ln CO2	1.000				
(2) ln y	0.893*	1.000			
(3) ln ysq	0.879*	0.997*	1.000		
(4) P	0.105*	0.169*	0.180*	1.000	
(5) E	-0.832*	-0.703*	-0.681*	-0.147*	1.000

*Notes: Significance is indicated by * at 0.05 level*

4.2. Additional Tests

Before running the regressions, there are some additional tests need to be conducted. First, since this study uses panel data, problems of heteroskedasticity and autocorrelation may arise. Breusch and Pagan Lagrangian multiplier test for random effects was used for testing Heteroskedasticity. Wooldridge test for autocorrelation in panel data is conducted for testing serial correlation. As per the results shown in the table below, there are both Serial Correlation and Heteroskedasticity exist. I addressed this issue by using robust standard errors in the model.

Table4: Test results for Heteroskedasticity and Serial correlation

Heteroskedasticity	**Serial Correlation**
H0: ver(u)=0	H0: no first-order autocorrelation
chibar2(01) = 26737.02	F(1, 180) = 11.330
Prob > chibar2 = 0.0000	Prob > F = 0.0009

I also focus on the stationarity of the data since there are 30 years of data in the time-series direction. As with time series data, non-stationary variables may result in a spurious regression. Table 5 is the result of the fisher-type unit root test. For all variables except population density, the null hypothesis of the existence of unit root cannot be rejected even at the 10% significance level for at least one statistic.

Table5: Unit root test		Statistic	P-value
$ln\ CO2$	Inverse chi-squared	565.8569	0.0000
	Inverse normal	-0.1704	0.4323
	Inverse logit t	-1.2970	0.0975
	Modified inv. chi-squared	7.3877	0.0000
$ln\ y$	Inverse chi-squared	241.1531	1.0000
	Inverse normal	12.6327	1.0000
	Inverse logit t	13.1317	1.0000
	Modified inv. chi-squared	-4.4912	1.0000
$(ln\ y)^2$	Inverse chi-squared	185.5743	1.0000
	Inverse normal	15.2516	1.0000
	Inverse logit t	16.2516	1.0000
	Modified inv. chi-squared	-6.5568	1.0000
D	Inverse chi-squared	1544.9103	0.0000
	Inverse normal	-6.4748	0.0000
	Inverse logit t	-24.1887	0.0000
	Modified inv. chi-squared	43.5738	0.0000
E	Inverse chi-squared	470.9317	0.0002
	Inverse normal	3.0744	0.9989
	Inverse logit t	2.4922	0.9936
	Modified inv. chi-squared	3.8784	0.0001

Since the data is non-stationary, a cointegration test is also conducted. If data are cointegrated, that reflects the presence of long-run equilibrium in which variables converges over time, so that it is not a spurious regression. Kao test was used for the panel-cointegration test.

Table6: Kao test for cointegration

H0: No cointegration / Ha: All panels are cointegrated

	statistic	p-value
Modified Dickey–Fuller t	0.3983	0.3452
Dickey–Fuller t	-1.7291	0.0419
Augmented Dickey–Fuller t	2.4041	0.0081
Unadjusted modified Dickey–Fuller t	-3.7786	0.0001
Unadjusted Dickey–Fuller t	-4.5919	0.0000

Finally, a Hausman specification test was conducted to determine whether a random effect or a fixed effects model should be used. Since the null hypothesis that the difference in coefficients was not systematic was not rejected, a random effects model was applied.

Table 7: Hausman (1978) specification test

Variables	Coef.
Chi-square test value	-80.645
P-value	1

5. Empirical Results and Discussion

5.1. Model (1) OLS

Here, I focused primarily on the estimation results using the entire sample of 183 countries. In addition, I analyze subsamples to examine each income group's characteristics and check robustness. Following table is the result for model (1).

Table 8: Estimation result for model (1)

Variable/Income	**All**	**High**	**Uppermiddle**	**Lowermiddle**	**Low**
$\boldsymbol{ln\ y}$	1.578	1.356	1.420	1.645	-1.044
	(0.000)	(0.056)	(0.033)	(0.052)	(0.481)
$(\boldsymbol{ln\ y})^2$	-0.071	-0.062	-0.066	-0.075	0.124
	(0.001)	(0.084)	(0.070)	(0.137)	(0.288)
P	-0.000	-0.000	0.001	0.000	-0.002
	(0.303)	(0.017)	(0.003)	(0.745)	(0.111)
E	-0.023	-0.022	-0.018	-0.018	-0.026
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
_cons	-6.954	-4.942	-6.106	-7.873	1.152
	(0.000)	(0.165)	(0.049)	(0.035)	(0.802)
Tipping Point	36665.53	56133.26	46984.63	57911.23	67.33482

The result for model (1) is as seen in the above table. EKC hypothesis holds for all sample panel, high income panel, and upper-middle income panel with statistically significant estimated parameters and expected signs. The tipping point for the all sample panel is within the sample and reasonable level and is similar to previous studies. High income tipping point is relatively higher than in previous studies but within the subsample. For upper middle income, the tipping point is not within the subsample level. This result shows that many high-income and upper middle countries will face an increase in CO_2 emissions with economic growth for a while. For lower middle income, coefficients for squared GDP per capita are not significant, and that for GDP per capita is significant with a positive sign. It means that CO2 emissions keep increasing with GDP growth. For the low-income group, coefficients for both GDP per capita and squared GDP per capita are not significant, and signs are opposite from expectation. This result is consistent with previous studies that found EKC more likely to hold for higher-income panels.

With respect to population density (P), only samples for high-income and Upper middle income were significant. The value of the variable was quite small at all income levels, indicating that it did not significantly affect per capita CO2 emissions.

Coefficients for a share of reusable energy (E) are significant at 1 % level, and signs of coefficients are minus for all panels. It strongly indicates that the greater the share of renewable energy in total energy use, the lower the per capita CO2 emissions. The results support the commonly held view that the widespread use of renewable energy will reduce carbon dioxide emissions.

5.2. Model (2) Simultaneous Equations

This part uses simultaneous equations for estimation to address simultaneity in CO2 emission and GDP, which was not considered in the first model.

Coefficients for CO2 in the model (3) are significant for all panels. There is simultaneity between the global panel, the high-income panel, and the low-income panel, for which both coefficients of GDP per capita and CO2 are statistically significant. EKC holds for the full sample panel. Estimated coefficients satisfy EKC with 5 % significant level and expected sign. The tipping point for this panel is within the sample and lower than many previous studies. EKC also exists for high-income panel and low-income panel. Although tipping income for the high-income panel is within the sample, this is higher than many previous studies and one in the model (1) ($56133.26). In contrast, the tipping point for low-income panel is very low. Considering that the average of the data for low-income countries is 1300, we can say that the EKC hypothesis holds instead of monotonically decreasing. Upper and lower middle-income countries did not meet the conditions for the EKC hypothesis. Population density is significant for all panels except a panel including all countries. In each subsample, the signs of coefficients were mixed in Model 1, but in this model, they are all in the predicted negative sign. Considering the fact that some of the coefficients have changed signs between models and that the overall coefficient values are small, the impact on per capita CO2 emissions is not expected to be very large.

Table 9: Estimation result for model (2), (3)

Income levels	**All**	**High**	**Uppermiddle**	**Lowermiddle**	**low**
Model (2)					
$ln\, y$	31.122	11.073	44.086	-15.333	22.059
	(0.037)	(0.005)	(0.270)	(0.765)	(0.000)
$(ln\, y)^2$	-1.587	-0.495	-2.346	1.093	-1.468
	(0.043)	(0.011)	(0.287)	(0.717)	(0.000)
P	0.000	-0.000	-0.001	-0.001	-0.001
	(0.198)	(0.000)	(0.000)	(0.000)	(0.003)
E	0.066	-0.017	-0.010	0.009	-0.011
	(0.107)	(0.000)	(0.055)	(0.724)	(0.016)
_cons	-150.682	-58.870	-204.584	51.299	-83.422
	(0.033)	(0.004)	(0.257)	(0.813)	(0.000)
Model (3)					
ln_CO2	0.602	0.341	0.259	0.471	0.303
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$ln\, k$	0.034	0.004	-0.011	0.023	-0.027
	(0.000)	(0.509)	(0.091)	(0.001)	(0.003)
$ln\, l$	0.761	1.638	0.266	-0.078	-0.910
	(0.000)	(0.000)	(0.000)	(0.173)	(0.000)
_cons	9.639	10.734	8.908	8.495	6.493
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Table 10: Tipping point for Simultaneous Equation

Income levels	**All**	**High**	**Uppermiddle**	**Lowermiddle**	**low**
Tipping point	18150.24	72730.76	12040.04	1112.29	1832.22

The share of reusable energy turned out to be insignificant for all countries panel and lower-middle income panel. Given that the previous model met the significance level and showed the predicted sign in all panels, this variable was also influenced by the model.

The estimated results differ from the results of a previous study using subsamples by income, which found that EKCs were more likely to hold in higher-income panels and less likely to hold in lower-income ones.

To conclude the analysis results of the two models, all variables were significant in the high-income panel, and the expected sign condition was also met. In terms of whether the EKC holds or not, it was likely to satisfy the condition in the panel that included all countries and the high-income panel. In the simultaneous equation model, the fact that the EKC was also hold in the low-income country panel was an interesting result that I did not expect from previous studies.

6. Conclusion

In this study, we tested the EKC hypothesis using panel data consisting of 183 countries over the period 1990-2019. I find that there is a bidirectional relationship between economic growth and CO_2 emissions in the full-sample panel and in the high-income panel. The result obtained first confirmed the presence of EKC in the global panel and in the high-income panel both the OLS and simultaneous equation model. In addition, the tipping point was close to or lower than in the previous study for the worldwide panel and higher than in the previous study for the high-income panel. This result has important policy implications. First, just because EKC has been confirmed does not mean that policies should be pursued that only pursue economic growth. More than half of the data used in this study came from low- and middle-income countries. This means that it will take time to reach the EKC tipping point, and a worldwide trend of increasing CO2 emissions expected to be continued for a while. Second, the significant contribution of CO2 emission to lower economic growth is found in all panels. This may encourage policymakers to act proactively not only in terms of the impact of CO2 emissions on the environment but also in terms of their impact on economic growth.

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Appendix

High-Income Countries

Antigua and Barbuda	Hungary	Qatar
Australia	Iceland	Romania
Austria	Ireland	Saudi Arabia
Bahamas, The	Israel	Seychelles
Bahrain	Italy	Singapore
Barbados	Japan	Slovak Republic
Belgium	Korea, Rep.	Slovenia
Brunei Darussalam	Kuwait	Spain
Canada	Latvia	St. Kitts and Nevis
Chile	Lithuania	Sweden
Croatia	Luxembourg	Switzerland
Cyprus	Malta	Trinidad and Tobago
Czechia	Netherlands	United Arab Emirates
Denmark	New Zealand	United Kingdom
Estonia	Norway	United States
Finland	Oman	Uruguay
France	Panama	United Kingdom
Germany	Poland	United States
Greece	Portugal	Uruguay

Upper-Middle Countries

Albania	Fiji	Namibia
Argentina	Gabon	North Macedonia
Armenia	Georgia	Palau
Azerbaijan	Grenada	Paraguay
Belarus	Guatemala	Peru
Belize	Guyana	Russian Federation
Bosnia and Herzegovina	Iraq	Serbia
Botswana	Jamaica	South Africa
Brazil	Jordan	St. Lucia
Bulgaria	Kazakhstan	St. Vincent and the Grenadines
China	Libya	Suriname
Colombia	Malaysia	Thailand
Costa Rica	Maldives	Tonga
Cuba	Marshall Islands	Turkiye
Dominica	Mauritius	Turkmenistan
Dominican Republic	Mexico	Tuvalu
Ecuador	Moldova	Venezuela, RB
Equatorial Guinea	Montenegro	

Lower-middle income countries

Algeria	Haiti	Nicaragua
Angola	Honduras	Nigeria
Bangladesh	India	Pakistan
Benin	Indonesia	Papua New Guinea
Bhutan	Iran, Islamic Rep.	Philippines
Bolivia	Kenya	Samoa
Cabo Verde	Kiribati	Senegal
Cambodia	Kyrgyz Republic	Solomon Islands
Comoros	Lao PDR	Sri Lanka
Congo, Rep.	Lebanon	Tajikistan
Cameroon	Lesotho	Tanzania
Cote d'Ivoire	Mauritania	Tunisia
Djibouti	Micronesia, Fed. Sts.	Ukraine
Egypt, Arab Rep.	Mongolia	Uzbekistan
El Salvador	Morocco	Vanuatu
Eswatini	Myanmar	Vietnam
Ghana	Nepal	Zimbabwe

Low-income countries

Afghanistan	Guinea-Bissau	Sudan
Burkina Faso	Korea, Dem. People's Rep.	Togo
Burundi	Liberia	Uganda
Central African Republic	Madagascar	Yemen, Rep.
Chad	Malawi	Zambia
Congo, Dem. Rep.	Mali	
Eritrea	Mozambique	
Ethiopia	Niger	
Gambia, The	Rwanda	
Guinea	Sierra Leone	