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The Effect of Innovation and Renewable Energy on CO_2 Emissions For Emerging Asian Countries

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Abstract: This study investigates the impact of innovation and renewable energy consumption on CO2 emissions in seven emerging Asian countries using static panel data methods. The analysis employs Pooled Ordinary Least Squares (OLS), Fixed Effect (FE), and Random Effect (RE) models to estimate the relationships, with the most appropriate model selected based on the Breusch-Pagan LM test and the Hausman test. Our findings reveal that both GDP and urbanization significantly increase CO2 emissions, while GDP squared and renewable energy consumption significantly decrease emissions, supporting the Environmental Kuznets Curve (EKC) hypothesis. Diagnostic tests indicate the presence of heteroskedasticity and first-order autocorrelation, addressed using robust standard errors. The results underscore the dual role of economic growth and technological advancement in shaping environmental outcomes, highlighting the critical importance of sustainable development policies in emerging economies.

Keywords: *CO2 emissions, innovation, renewable energy, Environmental Kuznets Curve, static panel data, emerging Asian countries.*

1. Introduction and Background

Asian economies have experienced strong economic development in recent decades with the expansion of industrialization, escalation of technology development, and an improvement in human well-being. Massive economic activities have deteriorated environmental quality with high emissions of hazardous pollutants such as CO2, NOx, and SO2. The region of Asia is becoming the primary source of greenhouse gas emissions worldwide. Asian region's proportion of global GHG emissions has increased two-fold from 22% in 1990 to 44% in 2019 (Asian Development Outlook 2023). CO2 has been widely recognized as the main source of pollution, Asian region contributing about 60% of worldwide CO2 emissions (Ritchie and Roser, 2020, revised 2024). Thus, immediate action is needed to reduce CO2 emissions from Asian countries.

Yet there is still doubt about how such rapid economic expansion would affect ecological sustainability. Scholarly discourse regards the relationship between environmental quality and economic growth as a framework for evaluating a nation's sustainability. EKC posits that economic growth and environmental pollution have an inverted U-shaped relationship. It expresses that environmental quality falls as pollution emissions rise, at the early phases of economic development, but it subsequently declines when economic growth reaches a certain threshold.

Innovation has been commonly recognized as the main factor accelerating sustainability. Innovations increase economic productivity and lessen the environmental effect of manufacturing processes by promoting technical advancement. Promoting technical innovation has become a generally acknowledged solution to address environmental issues like carbon dioxide emissions (Cheng et al., 2021) especially in emerging countries (Nazir et al., 2018). The carbon footprint connected with economic activity is often reduced by using more energy-efficient solutions that are produced by innovative technologies and processes (Menash et al., 2018). Generally, past studies have evidenced that technological innovation can help lower CO2 emissions and enhance the quality of the environment (Gerlagh, 2007; Ang, 2009; Amin, 2020; Luo et al., 2021; Khan, 2023). Still, some studies found an insignificant or positive impact of technological innovation on CO2 emissions (Cheng et al., 2019a; Cheng et al., 2019b; Rahman & Alam, 2023).

Technological innovation in environmental-related technologies improves the environment quality by increasing energy efficiency, decreasing fossil fuel energy consumption and usage of green energy (Chen & Lee, 2020; Shabir, 2023). Environment-related technology innovation is more effective than traditional technological innovation in improving the environment (Dong et al., 2022). Environmentally friendly technologies could increase production productivity (Shabir, 2023), prevent climate change, promote green economic growth, and effectively reduce CO2 emissions (Zhang et al., 2016; Dong et al., 2022). Environment-related technology innovation likely improves energy efficiency and lowers CO2 emissions. As one of the high energy consumption regions in electricity consumption governments of Asian countries face great challenges in decarbonizing the power industry without sacrificing energy security while meeting the growing electricity demand (Economist Intelligence Unit, 2022). Asian countries have taken positive energy transition and decarbonization strategies to achieve carbon neutrality such as Thailand's Renewable Portfolio Standard, Singapore's Green Plan 2030, Malaysia's Green Technology Master Plan 2017-2030 and Vietnam's Power Development Plan. Thus, there is a need to investigate the impact of renewable energy consumption on environmental degradation in Asian countries. Yet the empirical findings on the impact of renewable energy consumption on CO2 emissions were debatable, some found positive effects (Bekun et al., 2019) and some found insignificant relationships (Rahman & Vu, 2020;).

To enrich the body of current literature, this study examined the impact of technological innovation and renewable energy consumption on CO2 emissions in emerging Asian countries. There is a lack of studies in emerging Asian countries on the relationship between technological innovation and CO2 emissions. Furthermore, this paper applies the EKC hypothesis and STIRPAT model to test the impact of technological innovation and renewable energy on CO2 emissions and the validity of the EKC hypothesis by incorporating the quadratic term of per capita income in the model.

2. Literature Review

Technological Innovation and CO_2 Emissions: Kumar and Managi (2009) revealed that technological innovation reduces carbon emissions in developed nations and raises them in developing nations. Luo et al. (2021) examined the effect of technology innovation on CO2 emission in a panel of Asian countries from 2001 to 2019. Their estimated results showed that technology innovations reduce CO2 emissions and the validity of the EKC hypothesis. They recommend renewable energy sources as a primary energy source and encouraging energy-efficiency improvements to lower CO_2 emissions in Asian economies.

By applying the STIRPAT model on a panel of 13 Asian countries, He et al. (2023) examined the dynamic relationship between technology innovation, urbanization, trade openness and economic growth for the period of 1983-2019. The FMOLS analysis results support the negative relationship between technology innovation and CO2 emissions while the panel cointegration indicates a bidirectional causality relationship between these two variables. Similarly, Amin et al. (2020) findings also support that technological innovation reduces CO_2 emissions and bidirectional causality in the long run for a panel of 13 Asian countries.
Saqib et al. (2023), using the panel quantile regression method, demonstrated the significant impact of technological innovation and renewable energy on CO2 emissions in OECD countries, supporting the Environmental Kuznets Curve (ECK) hypothesis of an inverted U-shaped relationship between economic growth and CO2 emissions. Their findings also highlighted the importance of technological innovation in moderating the effects of renewable energy and economic growth.

Mehmood et al. (2023) employed cross-sectionally augmented autoregressive distributed lag (CS-ARDL) and wavelet coherence techniques to explore the relationship between CO2 emissions, energy consumption, GDP, renewable energy consumption, and technological innovations in G-7 countries from 1990 to 2020. Their results showed that while technological innovation has a negative impact on CO2 emissions in the short term, it has a positive effect in the long term. Similarly, Khan et al. (2023) confirmed the significant role of technological innovation in enhancing environmental quality across 35 Belt and Road countries.

Mensah and Salman (2019) investigated the long-run relationship between economic development and innovation and carbon emissions for a panel of 18 developed and developing economies using panel fully modified ordinary least square (FMOLS) and panel dynamic ordinary least square (DOLS). They found that innovation lowers carbon emissions in the G6 economies, yet it increases emissions in the MENA and BRICS regions. Dauda et al. (2021) argued that innovation induces the increase of CO_2 emissions in the early stages of development, but when innovation utilization or diffusion increases, CO_2 emissions start to decrease. Rahman and Alam's (2023) findings indicate technological innovation increases CO_2 emissions while renewable energy reduces CO_2 emissions in a panel of 47 Asian countries.

By applying spatial econometric analysis techniques, Chen and Lee (2020) investigated the effect of technological innovation on CO2 emissions from 1996 to 2018 across 96 countries. Their findings showed no significant effect of technological innovation in improving CO_2 emissions globally. Technological innovation is found to significantly reduce CO_2 emissions for developed and high-CO_2 emissions countries, but it leads to higher CO_2 emissions for middle-income countries. In addition, the EKC hypothesis was also confirmed in Chen and Lee's (2020) study. With a panel of 18 developed countries, Vietnu-Sackey and Acheampong's (2022) findings indicate technological innovation significantly positively impacts the CO_2 emissions for the overall sample and highly polluted countries but negatively impacts the CO_2 emissions for low-polluted countries. They also support the validity of the environment Kuznet inverted U-shaped hypothesis. Renewable energy is found to be significant in reducing CO_2 emissions for the overall sample and low-polluted countries but not for the highly polluted countries.

Several researchers have attempted to measure the extent of technological innovation by analyzing energy savings and R&D expenditures, along with their impact on carbon dioxide emissions. The relationship between patents and CO2 emissions has been extensively studied, with patent growth frequently used as an indicator of technological innovation. Studies by Álvarez-Herránz et al. (2017), Dong et al. (2020), Hashmi and Alam (2019), Wang et al. (2019), and Wurlod and Noailly (2018) have reached similar conclusions regarding the connection between energy efficiency and CO2 emissions. Additionally, other scholars have explored the dynamic relationships between research and development and CO2 emissions, considering R&D investment as a key indicator of technological innovation trends (Churchill et al., 2018; Fernández Fernández et al., 2018; Petrović & Lobanov, 2020). These findings are important as they highlight the impact of technological progress on CO2 emissions. However, the existing studies have yet to offer a comprehensive analysis of how technological innovation affects carbon emissions.

Economic Growth and CO_2 Emissions: The Environmental Kuznet Curve (EKC) framework has been considerably used to examine the relationship between environmental pollution and economic growth since it was introduced by Krueger and Grossman (1991). According to the EKC hypothesis, as income per capita increases, CO_2 emissions are also expected to increase. However, as income per capita reaches a certain threshold, increases in income per capita continue to lower CO_2 emissions. The relationship between environmental pollution and per capita income is implied by an inverted U-shaped curve. The EKC theory was confirmed by Chen and Lee (2020), Vietnu-Sackey and Acheampong (2022) developed countries, Khattak et al. (2020) for BRICS economies, and Petrovic and Lobanov (2020), and Saqib et al. (2023) for OECD countries, Chontanawat (2020) for ASEAN counties.

Renewable Energy and CO2 emissions: Zhang et al. (2023) examined the effect of renewable energy consumption and non-renewable energy on CO2 emissions in a group of Asian countries from 1975 to 2020. The panel Augmented Mean Group estimated results indicate that renewable energy is significant in reducing CO2 emissions in the long run and N-shaped of the EKC hypothesis. Using the panel quantile autoregressive distributed lag (QARDL) model, Du (2023) found a negative effect of renewable energy consumption on carbon intensity in the long run for a panel of 10 Asian countries. Anwar et al. (2021) findings also support renewable energy consumption in reducing CO_2 emissions. The analysis results of FMOLS on 15 highly renewable energy-consuming countries by Saidi and Omri (2020) revealed the significance of renewable energy in enhancing economic growth and diminishing CO2 emissions.

Rahman and Alam (2022) also support the negative impact of renewable energy on CO2 emissions for 47 Asian countries along with the validity of the EKC hypothesis. Al-Mulali et al. (2016) examined the effect of renewable energy on CO2 emission by Applying the EKC model for seven regions. Their findings indicate that renewable energy consumption improves the environment quality in Central and Eastern Europe, Western Europe, East Asia and the Pacific, South Asia, and the Americas but not significantly in the Middle East North Africa and Sub-Saharan Africa. An increase in renewable energy consumption is found likely to reduce CO2 emissions in western and eastern regions of China along with the confirmation of the EKC hypothesis while insignificant in central regions (Chen et al., 2019).

3. Research Methodology

The STRIPAT model, developed by Dietz and Rosa (1994), extends the environmental degradation framework of the IPAT model (Ehrlich & Holdren, 1971). The IPAT equation, I = PAT, expresses environmental impact through population (P), affluence (A), and technology (T). The STRIPAT equation, expressed in exponential form, is as follows:

$$I=\alpha PATe \quad (1)$$

Where b, c, and d represent the exponent terms of P, A and T, respectively, and eIs the error term. By taking the logarithmic of equation (1),

$$\ln I = \alpha+\beta \ln P + \gamma \ln A + \delta T + e \quad (2)$$

Following the work of Answer (2019) and Ojaghlou et al. (2023), this study defines I as carbon dioxide emissions (CO_2), P as urbanization (URB), A as economic growth (GDP), and T as renewable energy consumption (REN). The Environmental Kuznets Curve (EKC) hypothesis suggests an inverted U-shaped relationship between income per capita and environmental degradation, implying that as income rises, environmental degradation initially increases, but after reaching a certain income level, it starts to decline. Based on this, the empirical model in this study is expressed as:

$$\ln CO2_{it} = 0 + 1\ln GDP_{it} + \vartheta 2\ln GDP2_{it} + 3\ln PATENTRES_{it} + + 4\ln URB_{it} + 5\ln REN_{it} + _{it} \quad (3)$$

The quadratic form of per capita GDP in equation (3) indicates the application of the EKC hypothesis of an inverted U-shaped curve with the coefficient of $1 \geq 0$, and $\vartheta 2 < 0$. Furthermore, innovation (PATENTRES) is also incorporated into the model.

This study uses a balanced panel of annual data for seven emerging Asian countries from 1995 to 2020, sourced from the World Bank's World Development Indicators. The variables in equation (3) are: CO_2 emissions (in metric tons per capita), GDP per capita (constant 2015 US$), urban population (% of total population), total patent applications by residents, renewable energy consumption (% of total final energy consumption), and the KOF Globalisation Index. The subscript t refers to time, and i refers to country. Details on variable measurement and data sources are presented in Table 1.

Table 1: Variables and Data Sources

Variable	Definition	Source
CO_2	CO_2 emissions (kilo ton)	World Development Indicators, World Bank Database
GDP	GDP (constant 2015 US$)	
URB	Urban population (% of total population)	
PATENTS	Total patent applications by residents	
REN	Renewable energy consumption (% of total final energy consumption)	

This study applies static panel methods to estimate the impact of explanatory variables on CO_2 emissions. The static panel data estimation specifications include Pooled Ordinary Least Square (OLS), Fixed Effect (FE) Model and Random Effect (RE) Model. The static panel estimation equation is expressed as:

$$\ln CO2_{it} = 0 + 1\ln GDP_{it} + \vartheta 2\ln GDP2_{it} + 3\ln PATENTRES_{it} + + 4\ln URB_{it} + 5\ln REN_{it} + _{i} + _{t} + _{it}$$

Where t indicates individual-specific effects and it captures time-specific effects. In the pooled OLS model, it is treated as identically and independently distributed (i.i.d) in which i=0; t=0. The individual-specific effect is treated as constant or fixed in the FE model, whereas the RE model implies that it is drawn independently from some probability distribution.

The selection of the appropriate estimation model among the three static panel models (pooled OLS, fixed effects (FE), and random effects (RE)) is made by applying the Breusch-Pagan LM (BP-LM) test (Breusch &

Pagan, 1980) and the Hausman test (Hausman, 1978). The BP-LM test determines whether the RE model is preferable to the pooled OLS model, while the Hausman test evaluates whether the FE or RE model is more appropriate, with the null hypothesis favoring the RE model over the FE model.

The descriptive statistics of the data are presented in Table 2.

Table 2: Descriptive Statistics

	ln CO2	**ln GDP**	**ln GDP2**	**ln PATENTRES**	**ln URB**	**ln REN**
Mean	12.8437	26.9526	728.0540	7.13135	3.7350	3.0973
Standard deviation	1.4871	1.2730	70.1732	2.4552	0.3051	0.8324
Minimum	10.5346	24.9255	621.2805	3.1355	3.0986	0.6729
Maximum	16.2084	30.3132	918.8880	14.1476	4.3459	4.1725

4. Results and Discussion

A static panel data analysis has been used to assess the impact of innovation and renewable energy on environmental quality across a panel of seven developing Asian countries. Table 2 displays the estimated results for the Pooled Ordinary Least Squares (OLS), Fixed Effect, and Random Effect models. The Pooled OLS results show that the coefficients of GDP, GDP^2, and URBAN are statistically significant at the 1% level. To check for an unobserved country-specific effect, the Breusch-Pagan LM test rejects the null hypothesis, suggesting that the Random Effect model is preferable over the Pooled OLS model. Additionally, the Poolability test rejects the null hypothesis, indicating the Fixed Effect model is preferable to the Pooled OLS model. These results suggest that both Fixed and Random Effects models are appropriate, and the presence of a time effect is also confirmed. The Hausman test is then applied to determine whether Fixed Effects (FE) or Random Effects (RE) is more suitable, with the test rejecting the null hypothesis that country-specific effects are uncorrelated with the model's explanatory variables, thus favoring the FE model.

Furthermore, diagnostic checks are performed such as detecting multicollinearity, heteroskedasticity and serial correlation. The rejection of the null hypothesis of homoskedasticity indicates the presence of a heteroskedasticity problem. The serial correlation also indicates the presence of first-order autocorrelation in the data. The heteroskedasticity and serial correlation problem was addressed by performing robust standard errors (as shown in column 8 Table 2).

The results revealed that expected positive and negative signs of the coefficient for GDP and GDP2 are statistically significant at the 1% level. GDP is positively related to CO2 emissions and GDP2 is negatively related to CO2 emissions. This supports the validity of the EKC hypothesis implying an inverted U-shaped relationship between GDP and CO2 emissions. The turning point of the EKC is the long-run elasticity of CO2 emissions about GDP, $\partial lnCO2 \partial lnGDP$, Implying 1.229+E14 USD (in 2015 constant values).

The estimated results indicate that innovation has a positive statistically significant effect on CO2 emissions indicating that innovation by residents of the Asian emerging is improving the environment quality with lessening CO2 emissions. A unit increase in innovation by residents of the Asian emerging mitigates CO2 emission by 0.065%. While renewable energy consumption hurts CO2 emissions. 1% increase in renewable energy consumption, CO2 emissions reduced by 0.18% Urban population has a positive effect on CO2 emissions indicating a 1% increase in urban population will increase CO2 emissions by 0.73%.

Table 3: POLS, random effect and fixed effect estimation results with different specification models

dependent variable: (ln CO_2 emission **)**	**Pooled OLS**	**FEM**	**REM**	**Pooled OLS**	**FEM**	**REM**	**FEM robust standard errors**
	3.051***	4.111***	4.242***	4.809***	7.916***	5.879***	7.916***
	(0.429)	(0.309)	(0.452)	(0.429)	(0.394)	(0.394)	(0.694)
ln GDP	-0.050***	-0.065***	-0.059***	-0.068***	-0.122***	-0.091***	-0.122***
	(0.008)	(0.006)	(0.008)	(0.008)	(0.006)	(0.007)	(0.013)
ln GDP2	-0.001	0.066***	0.072**	0.065***	0.065***	0.169***	0.065**
	(0.025)	(0.028)	(0.028)	(0.0269)	(0.022)	(0.025)	(0.025)
ln PATENTRES	-0.440	-0.336***	-0.328***	-0.353***	-0.180***	-0.167***	-0.180**
	(0.035)	(0.049)	(0.041)	(0.036)	(0.041)	(0.037)	(0.074)
ln REN	-1.210***	0.261**	-1.045***	-0.020***	0.731***	-0.399***	0.731**
	(0.078)	(0124)	(0.089)	(0.086)	(0.102)	(0.093)	(0.269)
ln URBAN	-51.079***	-	-	-64.191***	-	-	-114.104***
	(5.778)	50.718***	54.357***	(5.801)	114.104***	78.637***	(10.677)
		(4.217)	(6.101)		(6.183)	(0.076)	
constant		70.19***			6.02***	117.36***	
F-test (year dummies)	No	Yes	Yes	No	Yes	Yes	
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes	
Year dummies					105.97***		
Poolability F				306.07***			
Breusch-Pagan LM test						98.75***	
Hausman Test					184.97***		
White Heteroskedasticity test							263.98***
Mundlak Hausman							

Notes: Values in parentheses are standard errors. ***, **, and* indicate statistical significance at 1%, 5% and 10% level, respectively.

Discussion

The validation of the inverted U-shaped EKC hypothesis has been confirmed in this study for Asian emerging countries. This is in line with studies done by (Xie et al., 2023; Kosrakis et al., 2023); and (Jiang & Khan, 2022). As emerging Asian economies are heading towards a sustainable path, rapid industrialization causes increased CO_2 emissions up to a certain point while economic expansion occurs. Emerging Asian countries highly anticipate the negative environmental impacts by implementing appropriate environmental policies to close the growth-environmental degradation gap.

Estimated results of the positive effect of technological innovation on CO_2 emissions for emerging Asian countries are consistent with findings by Jiang and Khan (2022) and Xie et al., (2023) in the short run and long run. Countries with significant CO_2 emissions should allocate more resources towards the development and implementation of innovative technologies to mitigate CO_2 emissions. Economic innovation, commonly referred to as green technology innovation, facilitates environmental conservation during the development of new products (Petak et al., 2020). Accordingly, the economy can be shifted to a more sustainable source of manufacturing and energy development through innovation.

Transitioning to a cleaner energy mix, specifically by adopting renewable energy sources and technologies, would significantly reduce CO_2 emissions. Sustained economic growth may enhance the environment by implementing energy-efficient technology, expanding the use of renewable energy sources and fostering innovation that lowers CO_2 emissions (Luo, 2021). The promotion of renewable energy not only yields environmental advantages but also contributes to the economic situation of the country. This is consistent with the findings of this study on the negative relationship between renewable energy consumption and CO_2 emissions.

In summary, innovation is a critical driver of environmental sustainability in developing Asian countries. By fostering technological advancements, improving processes, and promoting sustainable practices, innovation can significantly contribute to reducing CO2 emissions. However, to fully harness its potential, supportive policy frameworks and strategies to overcome existing barriers are essential. Continued investment in innovation, along with collaboration across sectors, will be vital for achieving sustainable development goals and improving environmental quality in the region.

5. Conclusion

This study employs static panel data analysis to assess the impact of innovation and renewable energy on environmental quality, specifically CO2 emissions, across seven developing Asian countries. The results from various econometric models—Pooled Ordinary Least Squares (OLS), Fixed Effects (FE), and Random Effects (RE)—provide valuable insights into the dynamics of economic growth and environmental sustainability. The model selection process began with the Pooled OLS approach, where significant positive coefficients for GDP and GDP^2 were observed, affirming the presence of a non-linear relationship between economic growth and CO2 emissions consistent with the Environmental Kuznets Curve (EKC) hypothesis. The Bruesch-Pagan LM test and the Poolability test reinforced the necessity to account for unobserved country-specific effects, leading to the preference for FE and

RE models. Ultimately, the Hausman test indicated that the Fixed Effects model is the most appropriate, as it effectively controls for unobserved heterogeneity correlated with the explanatory variables. Further diagnostic checks revealed issues of heteroskedasticity and first-order autocorrelation. By employing standard errors, the integrity of the estimates was preserved, allowing for more reliable interpretations of the coefficients. Importantly, innovation emerges as a critical factor for improving environmental quality. The positive and statistically significant effect of innovation on CO2 emissions—indicating a reduction of 0.065% for every unit increase—suggests that advancements in technology and processes can significantly contribute to emission reductions. This finding underscores the role of innovation as a pathway to achieve environmental sustainability, particularly in rapidly developing economies. In contrast, renewable energy consumption demonstrates a negative relationship with CO2 emissions. The finding that a 1% increase in renewable energy consumption leads to a 0.18% decrease in emissions highlights the potential of renewable sources in mitigating climate change impacts. This supports the argument for investing in and expanding renewable energy infrastructure in developing regions.

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