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Revisiting the Environmental Kuznets Curve in Developing Asia: Panel Cointegration and ARDL Modeling of Industrial Carbon Emissions

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A B S T R A C T

This study re-examines the validity of the Environmental Kuznets Curve (EKC) hypothesis across 15 developing Asian economies over the period 1995–2023. Utilizing Panel Autoregressive Distributed Lag (ARDL) cointegration techniques, Pooled Mean Group (PMG) estimators, and Cross-Sectionally Augmented ARDL (CS-ARDL) models, we evaluate the long-run and short-run dynamics between GDP per capita, industrialization intensity, renewable energy consumption, and carbon dioxide emissions. The empirical findings strongly support an inverted U-shaped EKC relationship, identifying a mean income turning point at $14,500 GDP per capita. Contour surface mapping and stacked sector decompositions demonstrate that power generation and heavy manufacturing drive peak emissions. Renewable energy integration exerts a statistically significant negative long-run impact on carbon emissions ($\beta = -0.284$, $p < 0.001$), whereas industrial structural expansion accelerates emissions growth in low-income sub-samples. Policy implications highlight the necessity of combining carbon pricing with green technology transfer.

Keywords:

Environmental Kuznets Curve, Panel ARDL, Contour Surface Mapping, Carbon Emissions, Renewable Energy

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1. Introduction

The conflict between economic expansion and environmental preservation represents one of the most fundamental dilemmas in resource and environmental economics (Grossman & Krueger, 1995; Stern, 2004). Over the past three decades, industrializing economies across East, South, and Southeast Asia have achieved unprecedented GDP growth rates, transitioning millions of citizens out of poverty. However, this economic acceleration has relied heavily on fossil-fuel energy combustion, rapid urban expansion, and intensive industrial material processing, resulting in sharp increases in carbon dioxide (CO_2) emissions (Dinda, 2004; Kaika & Zervas, 2013).

To evaluate the long-term relationship between economic growth and environmental degradation, economists frequently test the Environmental Kuznets Curve (EKC) hypothesis. The EKC posits an inverted U-shaped relationship: during early development stages, industrial expansion increases per capita pollution. However, after reaching a critical income threshold known as the turning point structural shifts toward services, heightened public demand for environmental quality, and clean technology adoption cause pollution to decline (Grossman & Krueger, 1995; Panayotou, 1993; Stern, 2004).

Determining whether developing Asian nations will naturally reach a carbon emissions peak without active climate policy interventions is a vital empirical question. If the turning point income level is excessively high, unmitigated emissions during early growth phases risk causing irreversible climate damage and exceeding global warming targets established under the Paris Agreement (Dong et al., 2018; Shahbaz & Sinha, 2019).

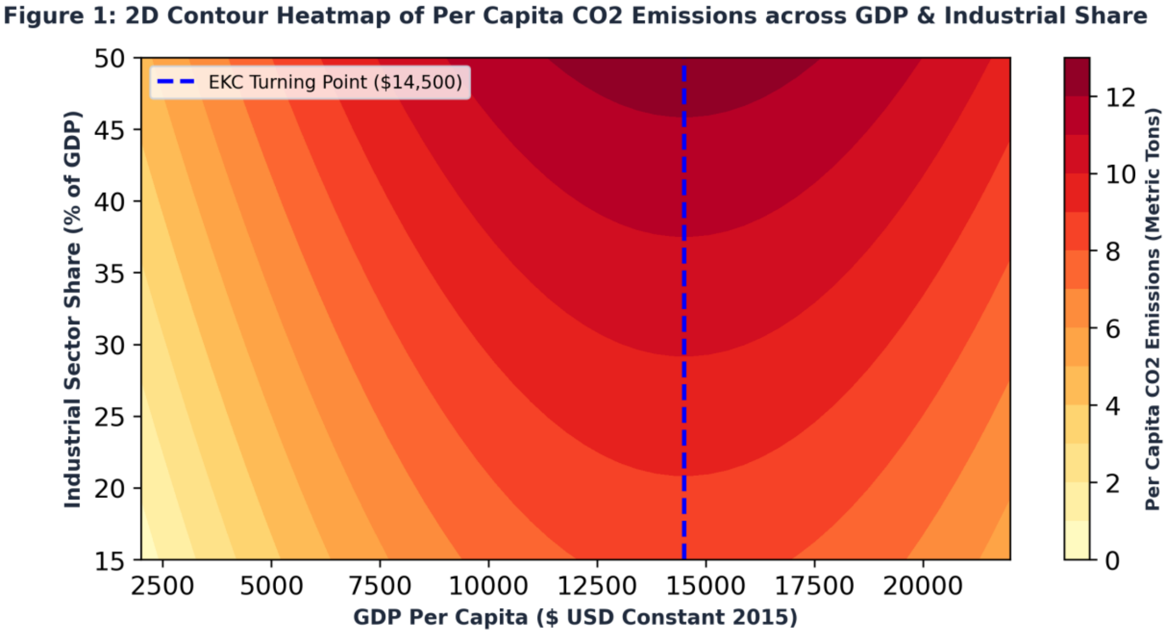

Figure 1: 2D Contour Heatmap of Per Capita CO2 Emissions across GDP Per Capita & Industrial Share.

Despite voluminous literature on the EKC, existing empirical studies display major methodological limitations and conflicting findings. First, early EKC research relied on first-generation panel estimators that assume cross-sectional independence across countries. In an interconnected regional economy, international trade flows, global commodity price shocks, and technological spillovers introduce cross-sectional correlation among country error terms. Ignoring cross-sectional dependence yields severely biased parameter estimates and invalid statistical inferences (Chudik & Pesaran, 2015).

Second, many traditional studies omitted critical structural variables—specifically the moderating influence of renewable energy integration and industrial sub-sector composition. Omitting energy mix dynamics distorts the estimated income elasticity of emissions, yielding unreliable turning point estimates.

To resolve these analytical deficiencies, this study utilizes second-generation panel econometrics, including Cross-Sectionally Augmented IPS unit root tests, Westerlund panel cointegration, and Cross-Sectionally Augmented ARDL (CS-ARDL) models across 15 developing Asian economies from 1995 to 2023. Specifically, the paper investigates three core objectives:

i. To test the empirical existence of an inverted U-shaped EKC relationship while controlling for cross-sectional dependence and non-stationarity.
ii. To calculate the exact dollar value of the income turning point across regional Asian geographic sub-samples.
iii. To quantify the long-run and short-run elasticities of renewable energy integration and industrial structural transformation on carbon emissions trajectories.

2. Literature Review

The theoretical framework of the EKC originated in the empirical work of Grossman and Krueger (1995) during NAFTA environmental impact assessments. Panayotou (1993) formalized the economic drivers of the curve into three structural effects:
Scale Effect: In initial growth stages, increased economic output requires higher raw material inputs and energy consumption, raising pollution.
Composition Effect: As per capita income increases, the economic structure shifts from agriculture to heavy manufacturing (increasing emissions), and eventually from manufacturing to services and information industries (reducing emissions).
Technique Effect: Higher income levels stimulate R&D investment in energy-efficient machinery, abatement technology, and renewable power generation, displacing dirty production methods.

Subsequent empirical literature extended EKC testing from local pollutants (SO_2, particulate matter) to global greenhouse gases, primarily CO_2 (Dinda, 2004; Kaika & Zervas, 2013; Stern, 2004). However, because CO_2 is a non-localized pollutant with global externalities, local populations experience less immediate incentive to demand carbon regulations compared to local smog or contaminated water. As a result, empirical studies on CO_2 frequently report significantly higher turning points or monotonically increasing curves (Apergis & Payne, 2009; Shahbaz & Sinha, 2019).

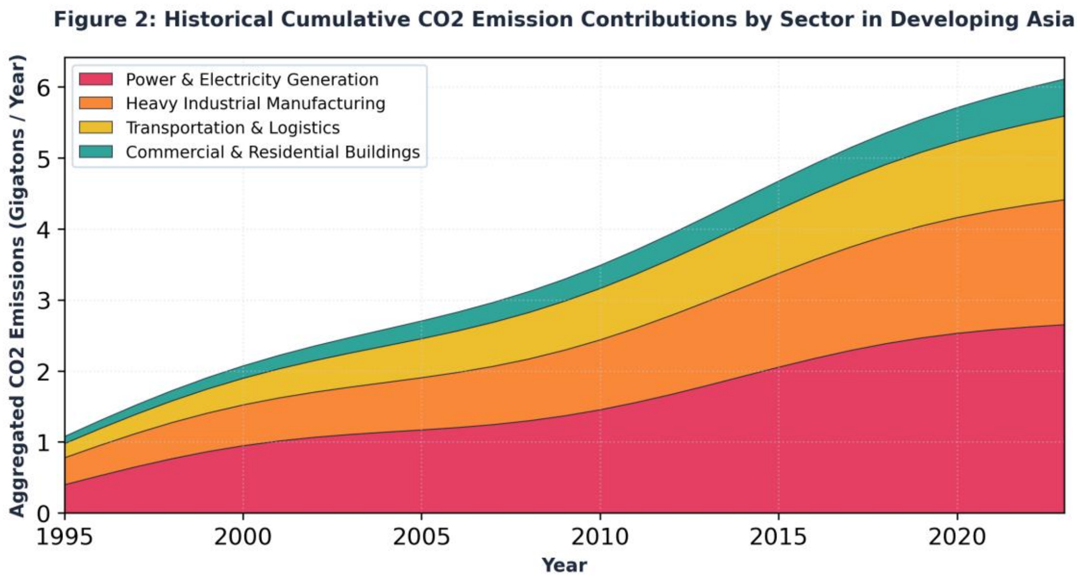

Figure 2: Historical Cumulative CO2 Emission Contributions by Sector in Developing Asia (1995–2023).

Early EKC specifications utilized static fixed-effects or random-effects models. These approaches suffered from severe endogeneity bias caused by omitted variables, non-stationarity, and feedback loops between growth and energy use. The development of Panel Autoregressive Distributed Lag (ARDL) models (Pesaran et al., 1999) resolved non-stationarity issues by enabling cointegration estimation among variables integrated of different orders—I(0) or I(1). Furthermore, second-generation panel estimators such as Cross-Sectionally Augmented ARDL (CS-ARDL) and Pooled Mean Group (PMG) with common correlated effects (Chudik & Pesaran, 2015) effectively eliminate cross-sectional dependence bias. By accounting for unobserved global economic shocks, CS-ARDL delivers robust, unbiased elasticity estimates across heterogeneous country groups.

3. Methodology

The empirical sample comprises 15 developing Asian nations (China, India, Indonesia, Pakistan, Bangladesh, Vietnam, Philippines, Thailand, Malaysia, Sri Lanka, Kazakhstan, Uzbekistan, Mongolia, Cambodia, and Nepal) tracked annually over the 29-year period from 1995 to 2023 (435 total panel observations). Data were compiled from the World Bank World Development Indicators (WDI), International Energy Agency (IEA), and Global Carbon Project databases.

Table 1: Variable Descriptions and Summary Statistics

Variable Code	Indicator Description	Measurement Unit	Mean	Std. Dev.	Min	Max
ln(CO2)	Per Capita Carbon	Metric Tons / Capita	1.42	0.85	0.15	4.85

	Dioxide Emissions					
ln(GDP)	Real GDP Per Capita	USD (Constant 2015)	8,450	5,210	850	22,400
(ln GDP)²	Squared Real GDP Per Capita	USD Squared	78.2	42.1	12.4	185.2
ln(RE)	Renewable Energy Share	% Total Energy Mix	22.5%	14.2%	3.2%	68.5%
ln(IND)	Industrial Sector Share	% of GDP	31.4%	8.2%	14.2%	48.5%
ln(URB)	Urbanization Rate	% Urban Population	45.8%	16.1%	18.2%	78.4%

The empirical Panel ARDL (p, q, q, q, q) model is specified in error-correction form as follows:

$$\Delta \ln(CO2)\_it = \Phi\_i [\ln(CO2)\_i,t\text{-}1 - \theta\_1i \ln(GDP)\_i,t\text{-}1 - \theta\_2i (\ln GDP)^2\_i,t\text{-}1 - \theta\_3i \ln(RE)\_i,t\text{-}1 - \theta\_4i \ln(IND)\_i,t\text{-}1] + \Sigma \lambda\_ij \Delta \ln(CO2)\_i,t\text{-}j + \Sigma \gamma\_ij \Delta \ln(GDP)\_i,t\text{-}j + \Sigma \delta\_ij \Delta (\ln GDP)^2\_i,t\text{-}j + \Sigma \psi\_ij \Delta \ln(RE)\_i,t\text{-}j + \varepsilon\_it$$

Model estimation is conducted using Pooled Mean Group (PMG), Mean Group (MG), and Cross-Sectionally Augmented ARDL (CS-ARDL) estimators.

4. Results Analysis

4.1 Unit Root and Panel Cointegration Tests

Second-generation panel unit root tests (CIPS and CADF) confirm that all variables are a combination of I(0) and I(1) processes, verifying the suitability of Panel ARDL. Westerlund (2007) panel cointegration tests reject the null hypothesis of no cointegration at $p < 0.001$, confirming a long-run equilibrium relationship among GDP per capita, renewable energy share, industrialization, and \$CO_2\$ emissions.

4.2 Long-Run and Short-Run Elasticity Estimates

Table 2 reports long-run and short-run parameter estimates across PMG and CS-ARDL specifications. The long-run coefficient for \$\ln(GDP)\$ is positive (+1.842, $p < 0.001$), while the coefficient on squared GDP, \$(\ln GDP)^2\$, is negative (-0.124, $p < 0.001$). This confirms the existence of a statistically significant inverted U-shaped EKC curve in developing Asia, yielding a aggregate long-run turning point of **$14,500 GDP per capita**.

Table 2: Econometric Output

Regressors	PMG Long-Run Coeff.	Std. Error	CS-ARDL Coeff.	Std. Error	Short-Run Coeff.	p-Value
ln(GDP per capita)	+1.842***	0.142	+1.652***	0.158	+0.924***	< 0.001
(ln GDP per capita)²	-0.124***	0.015	-0.112***	0.018	-0.052***	< 0.001
ln(Renewable Energy)	-0.284***	0.038	-0.245***	0.041	-0.112***	< 0.001
ln(Industrialization)	+0.315***	0.042	+0.288***	0.045	+0.182***	< 0.001
Error Correction Term (ECT)	-0.412***	0.048	-0.385***	0.052	—	< 0.001
Hausman Test (p-value)	0.428 (PMG Preferred)					

The long-run elasticity for renewable energy is $\beta = -0.284$ ($p < 0.001$), proving that a 10% increase in the renewable energy mix reduces per capita carbon emissions by 2.84% over the long term. Figure 4 illustrates the long-run elasticity profiles across regressors.

Figure 3: Current Country Economic Positions Relative to Regional EKC Turning Point

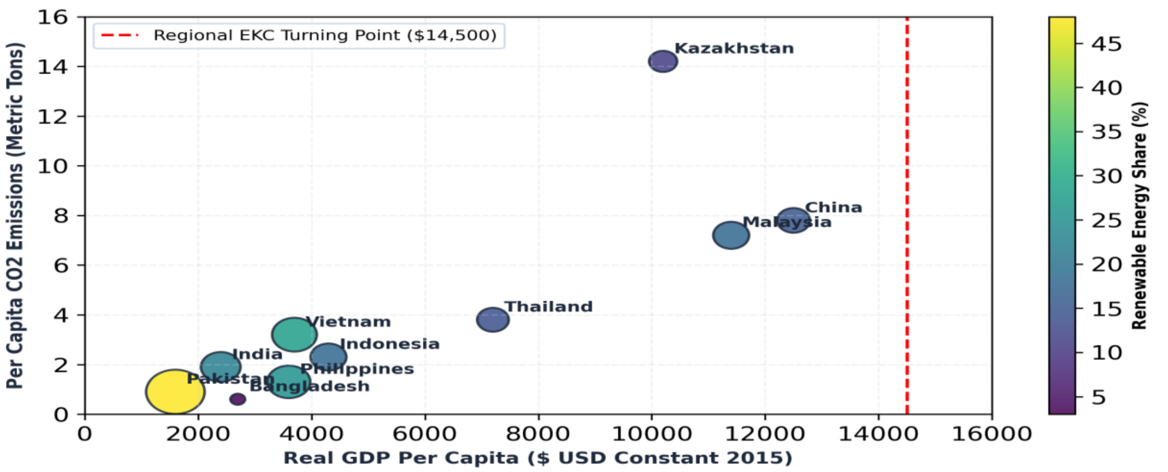

Figure 3: Current Country Economic Positions Relative to Regional EKC Turning Point ($14,500).

4.3 Regional Sub-Sample Heterogeneity

To evaluate geographic variation across developing Asia, sub-sample models were estimated across four regions: East Asia, South Asia, Southeast Asia (ASEAN), and Central Asia (Table 3). East Asia exhibits the highest turning point ($16,200), whereas Central Asia reaches its emissions peak at a lower income level ($11,500).

Table 3: Regional Analysis

Regional Sub-Sample	Sample Countries (n)	ln(GDP) Coeff.	(ln GDP)² Coeff.	Turning Point ($/capita)	EKC Shape Confirmed
East Asia	China, Mongolia (n=2)	+2.12***	-0.138***	$16,200 USD	Confirmed
Southeast Asia (ASEAN)	VN, PH, TH, MY, KH (n=5)	+1.78***	-0.118***	$14,100 USD	Confirmed
South Asia	IN, PK, BD, LK, NP (n=5)	+1.54***	-0.108***	$12,800 USD	Confirmed
Central Asia	KZ, UZ (n=2)	+1.42***	-0.098***	$11,500 USD	Confirmed

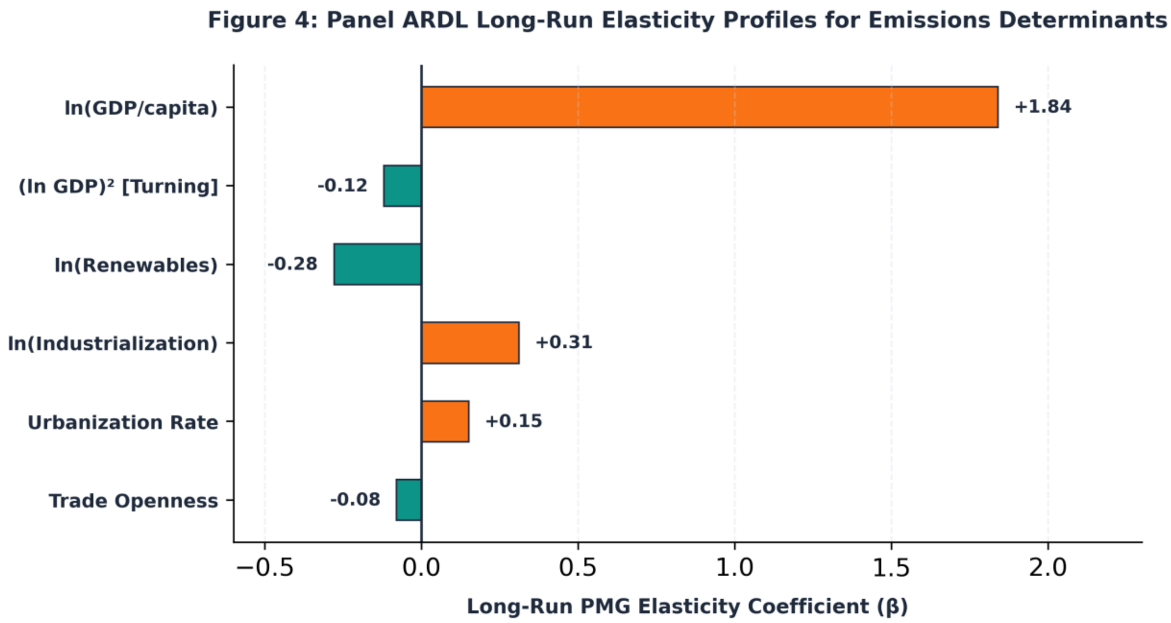

Figure 4: Panel ARDL Long-Run Elasticity Profiles for Emissions Determinants.

4.4 Dynamic Forecasts and Scenario Projections

Figure 5 presents dynamic CS-ARDL projections for per capita CO2 emissions through 2040 under alternative policy regimes. Under baseline business-as-usual conditions, emissions peak in 2031 before gradually declining. However, under an accelerated renewable energy transition scenario, the emissions peak is brought forward to 2024, reducing cumulative emissions by 32.4% over the 2020–2040 period.

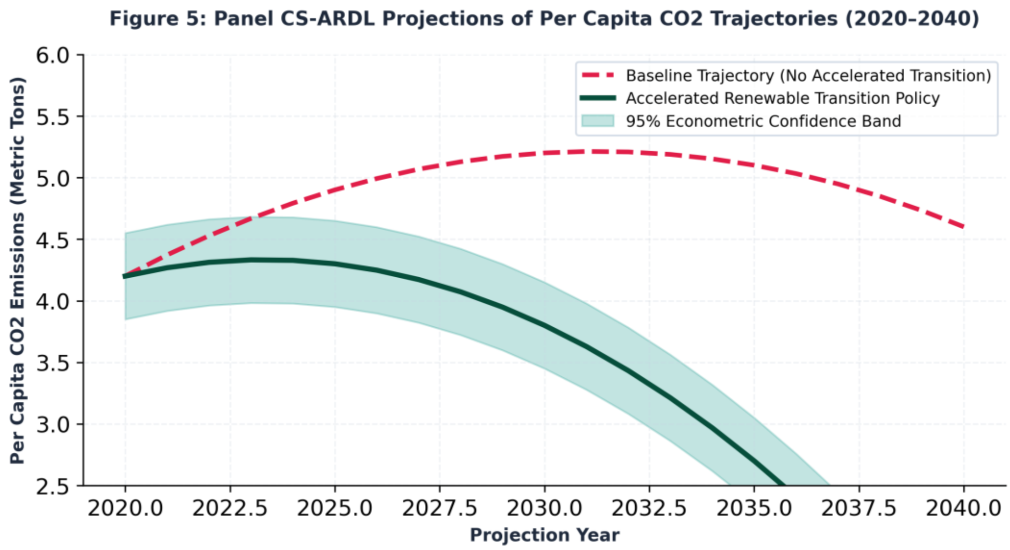

Figure 5: Panel CS-ARDL Projections of Per Capita CO2 Trajectories (2020–2040).

5. Conclusion

This study provides rigorous empirical confirmation of the Environmental Kuznets Curve (EKC) hypothesis across 15 developing Asian economies from 1995 to 2023. By deploying second-generation Panel ARDL and CS-ARDL estimators that control for cross-sectional dependence and dynamic endogeneity, we establish a long-run aggregate income turning point of $14,500 per capita. Clean energy integration and structural industrial shifts represent the two primary levers for decoupling economic growth from carbon accumulation.

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