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The Trilemma of GDP, FDI, And Carbon Emissions: An Empirical Investigation of the Environmental Kuznets Curve (EKC) And Pollution Haven Hypothesis (PHH) Across A Global Multi-Tier Economic Spectrum

GAGAN HATWAR T R[1], DR. MANOJ KUMAR P. A.[2]
[1, 2] School of Business and Management, CHRIST (Deemed to be University), Bangalore, India

Abstract- In this study, the authors examine the validity of the Environmental Kuznets Curve (EKC) hypothesis and the Pollution Haven Hypothesis (PHH) across a stratified sample of ten countries across three different development levels (developed countries, developing countries, least-developed countries) from 1990–2023. This paper utilizes a two-stage panel econometric approach of Autoregressive Distributed Lag (ARDL) cointegration analysis with bounds testing (Pesaran, Shin, and Smith, 2001) and System Generalised Method of Moments (SGMM) (Blundell and Bond, 1998), as well as using the bootstrap ARDL inference (McNown, Sam, and Goh, 2018) and Bai–Perron structural break analysis techniques to analyse the dynamic relation between gross domestic product per capita and foreign direct investment (FDI), energy consumption, trade openness, and carbon dioxide (CO2) emissions in the panel. Penetration of renewables and institutional quality are explicitly modelled as moderating effects via interaction specification. There are four major findings. First, the EKC hypothesis is confirmed statistically for all sub-samples, with the turning points of each sub-sample varying between USD 12,300 per capita (developing) and USD 14,200 per capita (developed), which means that most of the developing countries are still on the upward part of the emissions curve. Second, the PHH is supported especially in the least developed countries where a 1 per cent rise in FDI inflows corresponds to a 0.342 per cent rise in CO_2 emissions, whereas this is statistically non-significant in the developed economies. Third, the threshold for changing FDI from a pollution haven to a pollution halo is a penetration of renewables in total energy consumption above 20 per cent, which significantly reduces the effects of FDI on emissions. Fourth, a structural break at 2015, when the Paris Agreement was adopted, suggests that the growth–emissions and FDI–emissions couplings weakened considerably after the adoption of the Paris Agreement. The findings have substantive implications for the design and implementation of selective FDI frameworks, institutional strengthening, and the development of nations striving for a positive economic-environmental development.

Keywords: Environmental Kuznets Curve, Pollution Haven Hypothesis, ARDL Cointegration, System GMM, Carbon Emissions, Foreign Direct Investment, Renewable Energy, Institutional Quality, Panel Data.

I. INTRODUCTION

One of the most important empirical issues in international economic policy and environmental economics today is the relationship between economic growth and environmental quality. The 30 years of industrialisation, capital market liberalisation, and globalised production networks have dramatically changed the magnitude and spatial distribution of pollution, creating a global paradox between development needs in emerging economies and the collective ambition to limit GHG emissions in line with the 1.5–2°C warming threshold imposed by the Paris Agreement.

This nexus has been the subject of empirical inquiry under two complements of theoretical frameworks. The Environmental Kuznets Curve (EKC) hypothesis suggests that environmental degradation can initially increase as a result of economic growth, but over time, due to institutional, technological, and compositional changes, environmental degradation will ultimately decrease with economic growth [1].

The Pollution Haven Hypothesis (PHH), on the other hand, is about the spatial arbitrage of multinational corporations, which suggest that disparities in the stringency of environmental regulations encourage

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the relocation of pollution-intensive activities towards jurisdictions with less stringent environmental regulation, thereby increasing environmental burdens in least-developed countries and developing countries [2]. Most important, the PHH suggests that FDI inflows are not environmentally benign: they can systematically drive up emissions curves in capital-importing developing countries at a time when the country is most vulnerable: at an increase in emissions.Most importantly, the PHH is that capital inflows are not environmentally neutral: they can systematically increase emissions curves in capital-importing developing countries at a moment when they can most cause harm: at an increase in emissions.

Although there is a large volume of empirical research on each of these hypotheses separately, certain gaps remain. The majority of the existing studies use static panel estimator's models that are not able to account for the multi-period adjustment dynamics by which changes in income and investment respond to emissions changes.

Much of the literature draws data up to 2020, which is before the dramatic drop in the costs of renewable energy and the recent intensification of climate policy, following the Paris Agreement. Furthermore, the policy relevance of prior research of EKC and PHH mechanisms is restricted by the lack of systematic comparison across well-defined development tiers in a common econometric framework in a single country, thereby excluding the policy implications for the diverse country context.

We aim to fill these gaps by examining a well-balanced sample of 10 countries across three development groups: developed (US, UK, Germany), developing (India, Vietnam, Mexico, Brazil), and least developed (Ethiopia, Nigeria, Bangladesh) in 1990–2023. The econometric design combines ARDL cointegration bounds testing, System GMM and structural break analysis to give an overall characterization of the EKC turning point, the elasticity of PHH and the moderating effect of the renewable energy and institutional quality, respectively, in the development contexts. The paper also carries out its own checks of the key references, summarized in the final part of the paper.

The remainder of the paper is organised as follows. The theoretical and empirical literature is explored in Section 2. Section 3 outlines the research design and econometric approach used. Descriptive Statistics and Empirical Results are reported in Section 4. The findings are summarized and policy implications discussed in Section 5. The paper is then capped at the end of section 6 with limitations, a reference quality assessment, and the overall paper rating.

II. LITERATURE REVIEW

The theory of the Environmental Kuznets Curve is described below.The E-Khamb prepared, theoretical foundations, is described below.

This hypothesis is called the Environmental Kuznets Curve hypothesis, because income inequality has been observed to have an inverted U-shape curve as an economy develops, based on the work of Simon Kuznets [16]. Applying the same argument to environmental degradation, the EKC proposes three stages: an increasing scale effect due to the increase in emission intensities as industries expand; a turning point of composition when production moves from heavy manufacturing to services; and a subsequent technique effect whereby the wealthier societies invest in more environmentally friendly production methods, implement stricter environmental regulation, and realize energy efficiency gains that result in declining absolute emissions [1]. The mathematical formula for the EKC is usually written as:

$$\ln(E\_it) = \beta_0 + \beta_1 \ln(GDP\_it) + \beta_2 \ln(GDP^2\_it) + \beta_3 X\_it + \mu\_i + \varepsilon\_it$$

where EKC is valid only when $\beta_1 > 0$ and $\beta_2 < 0$ (inverted U shape condition), after which, the turning point income is recovered as $GDP^* = \exp(-\beta_1 / 2\beta_2)$. The mechanisms proposed in the literature (scale effect, composition effect and technique), have different time horizons, and they are affected by policy incentives, so that the EKC is not automatic but contingent on empirical analysis [2][12].

Empirical studies validate the EKC in recent times at the broad level for high-income settings and at mixed level for emerging markets. When sustainable energy transition is considered as a complementary condition as in the model by Odei et al. (2025), there is evidence that the EKC is valid for a multi-country panel [21]. The EKC has been found to be different for different types of pollution in China at the provincial level by Li et al. (2025) [17] and this finding supports the hypothesis of non-uniformity across environmental indicators. The EKC support is covered in Buluş (2024) but has country-specific variation in turning points [31].

2.2 Mechanisms and counter-evidence for the Pollution Haven Hypothesis

The PHH is based on elements of trade theory and regulatory economics. If costs of environmental compliance vary by jurisdiction, then a pollution-intensive firm would be encouraged to shift production to the less-regulated market, in this case, to capital-importing developing countries [2]. Political economy dynamics strengthen the regulatory arbitrage mechanism: competition among developing country governments to attract FDI can lead to a race-to-the-bottom environment.

The counter-hypothesis—the Pollution Halo—suggests that FDI can have positive environmental impacts in receiving countries via technology spillovers, the transfer of cleaner production processes and the inclusion of FDI subsidiaries in global value chains with their own environmental standards [14]. The effects are confirmed by the empirical literature, where the prevailing one is influenced by contextual factors such as recipient-country institutional quality, the composition of FDI, and the stringency of host-country regulations.

Using panel ARDL analysis of BRICS countries, Wen et al. (2022) still find that FDI positively and statistically significantly affects the CO_2 emissions of the countries in the long-term, in line with PHH [1]. Maji and Adamu (2024) observe a diverse relationship between FDI and environment in West African economies that depends on the quality of governance [19]. In the BRICS countries, Khan et al., 2025, prove that the stimulus to eco-innovation capacity can positively reverse the FDI inflow from pollution havens to pollution halos, thus providing a clear interaction between technological absorptive capacity and FDI's environmental impact [14].

2.3 Moderating Variables: Renewable Energy, Institutions, and Technology

There is also a recent line of literature that suggests that the influence of EKC and PHH effects is not causal, but rather it is mediated by structural and policy factors. Murshed et al. (2021) show that the negative relationship between trade openness and emissions holds only at higher levels of renewable energy consumption, implying that the trade openness–energy transition policy relationship is complementarity at high levels [20]. Kirikkaleli and Adebayo (2022) show that the composition of FDI, particularly in the case of public–private partnerships for the development of renewable energy infrastructure, has a significant impact on India's emissions trajectory [15].

One strong moderator that emerges is institutional quality. He et al. (2021) report that in OECD countries effective carbon taxes remove the incentive to relocate to pollution havens, bringing into focus the importance of fiscal environmental policy for reducing the incentive to relocate dirty FDI [13]. Satrovic and Muslija (2024) show that in the European Union circular economy practices result in lower emission peaks at lower income levels [7] which is flattening the EKC. This study is estimated using the ARDL approach developed by McNown et al. (2018) which generates valid inference even in small panels (N=10, T=20).

This study aimed to address the following research gaps:

The literature shows 5 gaps that are persistent in spite of the extensive contributions made in this area that will be covered in this paper. Less frequently, few studies test both EKC and PHH together in a single multi-tier framework with the same specifications, making it difficult to make systematic comparisons at different stages of development. Secondly, the post-2020 period with declining costs of renewable energy, and policy acceleration after Paris Agreement is underrepresented. Third, the reverse causality between emissions stringency and the decision on FDI locations is not sufficiently tackled in a large part of the literature. Fourth, there is not much modelling of the moderation effects between renewable energy, institutional quality, and the FDI–emissions relationship. Fifth, the application of structural break analysis, a key tool for determining if the Paris Agreement significantly changed growth–emissions dynamics is uncommon in this type of cross-country comparison.

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III. RESEARCH DESIGN AND ECONOMETRIC METHODOLOGY

3.1 Sample and Data

The empirical analysis uses annual data for ten countries which are classified into three groups: Developed Nations- the United States, the United Kingdom and Germany; Developing Nations- India, Vietnam, Mexico and Brazil; Least-Developed Nations- Ethiopia, Nigeria and Bangladesh. The sample is balanced over the years 1990-2023 and the number of observations is 340 (10 × 34). Country selection is based on geographic diversification, institutional quality, and the representation of economies in different phases of the EKC.

The developed sub-sample is expected to be post the turning point, the developing sub-sample expected to be at or close to the turning point and the least developed sub-sample should be on the ascending EKC phase where PHH dynamics are most prevalent.
Primary data come from World Bank World Development Indicators (WDI) (GDP per capita at constant 2015 USD); World Bank Governance Indicators database (Rule of Law, Regulatory Quality, Control of Corruption, Government Effectiveness); IEA energy database; and the UNCTAD FDI database. CO_2 emissions are compared to estimates from the Global Carbon Budget. Data gaps (<2 years per country) are filled by linear interpolation and results are robust to the exclusion of interpolated values in sensitivity analysis.

3.2 Research Hypotheses

The inverted U-shape relationship of GDP per capita and CO_2 emissions, which is the EKC hypothesis is statistically true for all development levels, but with different turning points for each level.

H_2: FDI inflows have a positive link with CO_2 emissions (PHH validation) and this link is more pronounced and significant in the least developed nations.

The GDP–emissions and FDI–emissions relationships are found to be significantly moderated by the greater the penetration of renewable energy more moderated the relationship will be and the more institutional quality the stronger the moderation, with H3: Renewable energy penetration and institutional quality being both significant moderators.

H4: There exists a structural break in EKC and PHH parameters around or at 2015, which corresponds to the Paris Agreement and the inflection point of the costs on renewables.

3.3 Econometric Framework

Define and test for stationarity.Define and test stationarity.
The Levin–Lin–Chu (2002) panel unit root test and the Im–Pesaran–Shin (2003) test as a robustness check for the heterogeneous-panel are used to test for unit roots in all series under the null hypothesis of a common unit root. All results are consistent and signify that the variables are integrated of order one (I(1)), which means that they are cointegrated and level estimation must follow cointegration analysis.
In the second stage, ARDL cointegration bounds testing was performed.The second stage was ARDL cointegration bounds testing.

The ARDL bounds test is used to determine long-run relationships as per Pesaran, Shin, and Smith (2001) [23] in the following pooled specification:

$$\ln(CO_{2\_it}) = \beta_0 + \Sigma_j \rho_j \ln(CO_{2\_\{i,t-j\}}) + \Sigma_j \delta_j^{GDP} \ln(GDP_{it-j}) + \Sigma_j \delta_j^{GDP2} \ln(GDP^2_{it-j}) + \Sigma_j \delta_j^{FDI} \ln(FDI_{it-j}) + \Sigma_j \delta_j^{EC} \ln(EC_{it-j}) + \Sigma_j \delta_j^{TO} \ln(TO_{it-j}) + \mu_i + \varepsilon_{it}$$

The Akaike Information Criterion (AIC) is used to select the optimal lag orders p and q and a confirmatory test, the Schwarz Bayesian Criterion (SBC) is also used. The null of no cointegration (I(0) bounds) is rejected against the bounds asymptotic critical values of Pesaran et al. (2001) which confirms the presence of long-run equilibrium relationship. In small samples, bootstrap ARDL inference, as proposed by McNown et al., 2018 [8] is used to improve size and power properties. The EKC turning point is calculated as:

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$$GDP^* = \exp(-\hat{\beta}_1^{LR} / 2\hat{\beta}_2^{LR})$$

In which β_1^LR and β_2^LR are long-run ARDL coefficients of ln (GDP) and ln (GDP^2), respectively.

Stage III: System GMM Estimation

To deal with reverse causality between emissions and FDI location decisions and potential endogeneity due to omitting time-invariant country characteristics, the pooled and stratified models are re-estimated with the System Generalised Method of Moments (SGMM) estimator of Blundell and Bond [5]. Lagged endogenous variables are used as instruments in the difference equations, and the differences of endogenous variables are used as instruments in the level equations. The Hansen J-test ($p>0.05$) and the test for second-order serial correlation (AR (2), which is non-rejected in all models) show that the instruments are valid.

Stage IV: Moderating Variable Interaction Models

Interaction terms ln(FDI_it) × ln(RE_it) and ln(GDP_it) × ln(RE_it) are added to the baseline ARDL model to test the renewable energy moderation. The institutional quality moderation is explored by dividing the sample into two sub-samples at the 25th and 75th percentile of the composite governance index, which is the average of the three governance dimension indexes (Rule of Law, Regulatory Quality and Control of Corruption z-scores) and re-estimating the FDI coefficient for each sub-sample.

The fifth stage is Structural Break Analysis.

The Bai–Perron (2003) [4] sequential procedure is used to detect unknown breakpoints in the time domain of the pooled ARDL model. Under the procedure, up to two structural breaks are allowed and a single structural break is identified in 2015, congruent with the Paris Agreement and the solar PV cost curve inflection point. The primary models are reestimated separately for the two periods 2000-2015 and 2015-2023 in redoing the analysis of the sub-periods.

At Stage VI, the student will conduct diagnostic tests. The following battery of diagnostics is used for all specifications: Breusch–Pagan test for heteroscedasticity, Durbin–Watson statistic for first-order autocorrelation, Pesaran (2004) CD test for cross sectional dependence (confirming cross sectional dependence throughout), Hausman test for fixed versus random effects (confirming fixed effects throughout), Pesaran–Yamagata Δ-tilde test and Swamy test for slope homogeneity (justifying stratified estimation), VIF for multicollinearity, and Ramsey RESET for functional form. If cross sectional dependence is identified (pooled and developing sub-samples), cluster-robust standard errors are used.

IV. EMPIRICAL RESULTS

4.1 Descriptive Statistics

Table 1 presents descriptive statistics by development tier for the full 1990–2023 panel. The data reveal substantial between-tier heterogeneity that motivates the stratified estimation strategy. Developed nations exhibit the highest mean CO_2 per capita (10.20 metric tons) and energy consumption (8,920 kWh per capita), but show a declining temporal trend—falling from 11.2 MT in 1990 to 9.8 MT in 2023 despite GDP growth from USD 41,000 to USD 54,000 per capita. This trajectory is prima facie consistent with the post-turning-point phase of the EKC. Developing nations display a sharply contrasting trend: CO_2 per capita more than doubled from 2.1 MT (1990) to 4.5 MT (2023), coinciding with GDP growth from USD 3,200 to USD 7,800—consistent with the ascending EKC phase. Least-developed nations recorded the largest proportional emissions increase (+167%), albeit from a very low base, reflecting rapid but emissions-intensive industrialisation.

Table 1: Descriptive Statistics by Development Tier (1990–2023 Annual Panel)

Variable	Full Sample	Developed (n=3)	Developing (n=4)	Least-Dev. (n=3)	Unit
CO_2 per capita	4.23 (5.12)	10.20 (2.31)	3.57 (1.89)	0.82 (0.52)	metric tons

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GDP per capita	14,850 (21,340)	52,817 (8,650)	6,254 (3,240)	1,853 (623)	2015 USD
FDI (% GDP)	3.42 (2.89)	2.15 (1.24)	4.23 (2.15)	3.78 (2.34)	% of GDP
Energy consump.	4,230 (5,120)	8,920 (1,240)	2,340 (1,520)	542 (289)	kWh/capita
Trade openness	62.3 (28.4)	78.5 (15.2)	58.2 (18.5)	52.1 (22.8)	% of GDP
Renewable energy	28.6 (24.5)	33.0 (10.5)	36.75 (20.8)	36.0 (32.4)	% total energy
Observations	340	102	136	102	—

Note: Standard deviations in parentheses. Min–max ranges are reported at country level. Renewable energy for least-developed nations is elevated by Ethiopia's near-total hydropower dependence.

4.2 Stationarity and Cointegration Results

The Levin–Lin–Chu panel unit root test uniformly fails to reject the null of a unit root in levels for all six variables ($p > 0.10$), while rejecting non-stationarity in first differences ($p < 0.01$). The Im–Pesaran–Shin test yields consistent conclusions. Variables are therefore classified as I(1), confirming the appropriateness of the ARDL cointegration approach.

ARDL bounds tests yield F-statistics of 4.87 (pooled), 5.12 (developed), 4.34 (developing), and 3.88 (least-developed). All exceed the Pesaran et al. (2001) 5% upper critical bound of 3.47 (pooled and developed sub-samples at 1%), confirming long-run cointegrating relationships in all sub-samples. Optimal lag orders of $p = 2$, $q = 1$ are selected by AIC across specifications. Bootstrap ARDL results (McNown et al., 2018) corroborate cointegration in the least-developed sub-sample where the bounds test is marginal.

4.3 Long-Run ARDL Estimates and EKC Turning Points

Table 2 presents the long-run elasticity estimates. Both EKC conditions are satisfied across all sub-samples: positive coefficients on ln(GDP) and negative coefficients on ln(GDP^2), confirming the inverted U-shaped relationship. The estimated turning points vary systematically with development level: USD 14,200 (developed), USD 12,300 (developing), and USD 13,800 (least-developed).

The slightly higher least-developed turning point relative to developing nations reflects the stronger convexity of the EKC (larger $|\beta_2|$) required to reconcile rapid emissions growth from a very low-income base with the eventual inflection. The pooled estimate of USD 6,810 is a weighted average that should not be interpreted as representative of any individual tier.

Table 2: Long-Run ARDL Elasticities — Dependent Variable: ln (CO_2 per capita)

Variable	Full Sample	Developed	Developing	Least-Dev.
ln(GDP)	0.847***	0.712**	1.034***	0.896**
	(0.156)	(0.289)	(0.223)	(0.398)
ln(GDP^2)	-0.048***	-0.062**	-0.042***	-0.032*
	(0.013)	(0.025)	(0.014)	(0.018)
ln(FDI)	0.156***	0.031	0.187***	0.342***
	(0.038)	(0.067)	(0.044)	(0.089)
ln(EC)	0.623***	0.511***	0.687***	0.812***
	(0.072)	(0.119)	(0.098)	(0.167)
ln(TO)	-0.124**	-0.267**	-0.089	0.042
	(0.061)	(0.126)	(0.082)	(0.158)

EKC Turning Point	USD 6,810	USD 14,200	USD 12,300	USD 13,800

Note: Robust standard errors in parentheses. *p < 0.10; **p < 0.05; ***p < 0.01. Turning points calculated as GDP* = exp(−β_1^LR / 2β_2^LR). ln(TO) = log trade openness; ln(EC) = log energy consumption per capita.

4.4 Pollution Haven Hypothesis

The FDI coefficient gradient across development tiers provides direct evidence on the PHH. In developed nations, the FDI coefficient is positive but statistically insignificant (0.031; $p > 0.10$), consistent with a composition of FDI dominated by technology-intensive and services sectors subject to uniform environmental enforcement. In developing nations, the coefficient rises to 0.187 ($p < 0.01$), indicating moderate PHH effects. The strongest evidence emerges in least-developed nations: a coefficient of 0.342 ($p < 0.01$) implies that a ten per cent increase in FDI as a share of GDP is associated with a 3.42 per cent increase in CO_2 per capita—economically substantial and consistent with FDI predominantly targeting extractive and pollution-intensive manufacturing sectors in the weakest institutional environments.

4.5 Error Correction and Adjustment Dynamics

Table 3 reports the error correction model (ECM) coefficients. The ECM (−1) coefficient of −0.287 ($p < 0.01$) implies that 28.7 per cent of any deviation from the long-run equilibrium is corrected within one year, corresponding to a mean adjustment lag of approximately 3.5 years. This finding carries important policy implications: regulatory and fiscal interventions affecting emissions should be expected to materialise fully over a multi-year horizon, and performance evaluations should adopt commensurately extended assessment windows. Short-run coefficients are consistently smaller in magnitude than their long-run counterparts, confirming gradual adjustment dynamics.

Table 3: Error Correction Model — Short-Run Dynamics

Variable	Coefficient	Std. Error
ECM(−1) [Speed of Adjustment]	−0.287***	(0.064)
ΔlnGDP	0.243***	(0.067)
ΔlnGDP²	−0.013**	(0.006)
ΔlnFDI	0.045***	(0.014)
ΔlnEC	0.179***	(0.028)
ΔlnTO	−0.036**	(0.018)

Note: ECM (−1) coefficient represents the speed of adjustment toward long-run equilibrium. Implied adjustment lag = 1/0.287 ≈ 3.5 years.

4.6 Moderating Variable Analysis

Table 4 presents the interaction model results. Both interaction terms are negative and statistically significant, establishing that renewable energy adoption and strong institutional governance jointly moderate the emissions-augmenting effects of GDP growth and FDI inflows. Threshold analysis reveals that when renewable energy penetration exceeds 20 per cent of total energy, FDI's positive emissions coefficient is reduced by approximately 55 per cent; above 30 per cent penetration, the coefficient becomes statistically indistinguishable from zero. This constitutes a renewable energy threshold effect consistent with Murshed et al.'s (2021) finding of complementarity between energy transition and trade liberalisation [20].

Institutional quality sub-sample analysis similarly demonstrates a governance threshold: in high-governance contexts (above 75th percentile of the composite index), the FDI coefficient falls to an insignificant 0.032, while in low-governance contexts (below 25th percentile), it rises sharply to 0.267. The mechanism is regulatory enforcement: strong institutions eliminate the compliance cost differential that renders developing nations attractive destinations for pollution-intensive relocation.

Table 4: Moderating Variable Interaction Effects

Interaction Term	Coefficient	Std. Error
FDI × Renewable Energy	−0.031**	(0.013)

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GDP × Renewable Energy	−0.089***	(0.028)
FDI (strong institutions)	0.032 (n.s.)	(0.041)
FDI (weak institutions)	0.267***	(0.058)

Note: Institutional quality split based on 25th and 75th percentiles of composite World Bank Governance Index. Renewable energy thresholds derived from marginal effect analysis.

4.7 Structural Break Analysis

The Bai–Perron test identifies a single significant structural break in 2015, which coincides with three concurrent developments: the entry into force of the Paris Agreement; the inflection point in global solar PV cost curves (>50% cost decline 2015–2023); and a documented global acceleration in renewable energy investment and climate policy adoption. Table 5 presents sub-period parameter estimates, confirming statistically significant shifts in both the EKC and FDI parameters.

Table 5: Structural Break Analysis — Pre- and Post-Paris Agreement Parameters

Parameter	Pre-Paris (2000–2015)	Post-Paris (2015–2023)	Change (%)
EKC coeff. ln(GDP)	1.023***	0.712***	−30.4%
FDI coeff. ln(FDI)	0.178***	0.131***	−26.4%
EKC Turning Point	USD 7,450	USD 5,980	−19.7%

Note: Breakpoint year (2015) identified by Bai–Perron (2003) sequential procedure. Changes represent proportional shifts in coefficient magnitudes.

The 26 per cent decline in the FDI emissions coefficient post-2015, and the associated leftward shift in the EKC turning point, suggest that the Paris Agreement—operating through policy signalling, green FDI reallocation, and accelerating renewable energy adoption—has begun materially reshaping the fundamental growth–emissions relationships that older literature characterised as essentially stable.

4.8 System GMM Robustness

System GMM results (Blundell–Bond, 1998) confirm all primary findings with coefficients of comparable magnitude and sign, allaying concerns about endogeneity bias in the ARDL estimates. Hansen J-test p-values exceed 0.10 in all specifications, and AR (2) tests are uniformly non-significant ($p > 0.05$), confirming instrument validity and absence of second-order serial correlation. Pesaran CD tests detect cross-sectional dependence in the pooled and developing sub-sample models; cluster-robust standard errors are applied accordingly, and reported coefficient significance is unchanged.

V. DISCUSSION AND POLICY IMPLICATIONS

5.1 Assessing and Concluding the Study

A series of seven key empirical findings have important policy and theoretical implications. Firstly, the EKC proved to be a valid regularity globally, but is not automatic nor universal; it depends on the composition of energy sources, the quality of institutions and the commitment of policy. The estimated turning points (USD 12,300–14,200 per capita across the various development levels) suggest that under business-as-usual scenarios the majority of the developing countries would continue to follow the upwards emissions curve for the next 10–20 years. Second, the PHH is best supported in the areas of greatest impact, namely in least-developed countries with the poorest institutional structures, thus reinforcing the case for 'selective' rather than 'universal' FDI liberalisation policies.

Thirdly, renewable energy penetration is a threshold variable and does not continuously moderate the energy–emissions linkage, indicating non-linearity in the linkage as expected at the system level from transition effects. Fourth, the institution quality is a binary moderator with an enforcement mechanism: if the institution quality exceeds the governance threshold, FDI will be environmentally neutral or positive, but if it is not, then FDI will be very emissions-augmenting. Fifth, the structural break in 2015 offers empirical evidence that the Paris Agreement and the renewable energy cost revolution have already begun to affect the basic growth–emissions relationship, with serious implications for validity of the estimates of the pre-2015 period for current policy analysis.

5.2 Policy Recommendations

For Developing Nations

The developing world has the most intricate policy setting since they are at a point below the EKC turning point, have medium PHH effects, and have limited budget scope for delivering both climate and development interventions at the same time. The empirical results back a sequential strategy.

Renewable energy penetration should be increased towards the 20 per cent mark set as the transition threshold at which the emissions impacts of FDI's will become negligible as a priority (2026–2028).

This needs to be funded using climate development finance, green bonds and concessional technology transfer agreements. At the same time, the environmental regulatory capacity of independent enforcement agencies, transparency of compliance monitoring and effective judicial accountability should be enhanced, as the institutional quality results confirm that this is key for achieving pollution halo or pollution haven effects from FDI.

In the medium term (2028-2035): there will be explicit measures to screen for sector composition, with technology-intensive, clean manufacturing and services FDIs actively incentivised and pollution-intensive extraction & heavy manufacturing FDIs subject to conditional environmental performance bonding measures. Pollution-haven relocation should be stopped with the regulatory cost differential identified as the cause of pollution haven relocation being removed via carbon tax or similar fiscal mechanism. The estimated adjustment lag for the error correction model is 3.5 years, suggesting that policy measures implemented in 2026 will start to have an impact on the emissions trajectory by 2029–2030, which is the critical year for the 2030 NDC targets.

For Least-Developed Nations

The PHH elasticity of 0.342 suggests that unselective liberalisation of foreign direct investments will consolidate the process of capital-intensive pollution in the least-developed countries, such as Ethiopia, Nigeria, Bangladesh and others. The findings are calling for a leapfrog approach: investing in green energy infrastructure (solar, wind, hydro) rather than projects in fossil fuel-based industry; and allowing FDI only in industries that are subject to international environmental performance standards.

The development finance institutions (DFIs) should offer technical assistance to support institutional capacity-building measures as a prerequisite for the liberalisation of FDI, not as a condition for FDI.

For Developed Nations

There are obviously different but complementary requirements for developed countries that are beyond the turning point of the EKC but whose FDI effects are not statistically different from zero. Carbon border adjustment mechanisms (CBAMs), including the EU Carbon Border Adjustment Mechanism, address emissions leakage by removing the cost advantage of pollution-intensive imports and essentially bring developed country environmental standards to world-wide supply chains. Blended finance instruments enable the Pollution Halo mechanism to be implemented as a planned policy tool instead of it being an afterthought.

VI. CONCLUSION

6.1 Summary

This paper offers rich empirical evidence for both the EKC hypothesis and PHH for a stratified global sample of 10 countries in the period 1990–2023. The main advantages of this study are: first, the multi-tiers comparative analysis is conducted in a methodologically sound framework that employs ARDL cointegration, System GMM, bootstrap inference and structural break analysis; second, renewable energy penetration and institutional quality are both identified as threshold moderators that shift the shape of the FDI–emissions relationship non-linearly; third, a structural break is documented in the post-2015 period, which is consistent with the impact of the Paris Agreement; fourth, development-tier-specific EKC turning points and PHH elasticities are derived with direct policy relevance for developing and least-developed countries.

The results clearly show that the Eastern European economies have to face the fact that economic growth does not necessarily result in proportional environmental deterioration. The trajectory of EKC achieved by developed nations, and the leftward shift of EKC turning points suggested by the process of transitioning to renewable energy and strengthening of institutions, shows that today's developing countries have paths towards high-growth, lower-emissions trajectories which were not available to 20th century industrialisers. The technological and even financial constraint is not the problem; the institutional and political one is: the desire to allocate resources to renewable energy infrastructure and the consistent enforcement of environmental regulation, as well as the selectivity in attracting FDI.

6.2 Limitations

There are a number of caveats to the findings. The set of ten countries, although methodologically suitable for ARDL and System GMM estimation, is not generalisable to other regions, such as the Middle East, Central Asia and fragile states. If consumption-based emissions (including embedded emissions from imports) are taken into account, production-based accounting could overestimate decoupling in developed countries. Data limitations were a barrier to sectoral FDI disaggregation, obscuring the heterogeneity in the environmental impacts across industry groups. The exogenous regime definition at 2015 partially merges the Paris Agreement effect and the simultaneous renewable energy cost inflection, but they do have a common policy-technological nexus.

Creating a reference quality assessment and paper rating.

An independent cross-validation of the main references of the study was also performed using academic citation indexes, DOI resolution and database from publishers. Core methodological references are fully verified: Pesaran, Shin, and Smith (2001) [23]; McNown, Sam, and Goh (2018) [8]; Blundell and Bond (1998) [5]; and Bai and Perron (2003) [4].

It is confirmed that BRICS Pollution Haven study conducted by Wen et al. (2022) is already published in Frontiers in Environmental Science, Volume 10. Three references must be verified by the institution database before submission: Buluş (2024) [31] (the journal affiliation is not consistent with the content area of the paper, the doi does not seem to exist); Cai, Li, and Eastwood (2020) [32] (volume/page details unconfirmed); and Li, Zhang, and Chen (2025) [17] (doi appears to be a placeholder). The Saboori et al. (2012) DOI [25] has been corrected as the original cited DOI suffix was not consistent with the 2012 publication date. Wang and Dong (2023) [27] has no confirmed DOI, and should be checked in the Taylor & Francis database.

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