Beyond Income: Energy Intensity, Industrialization and the CO_2 Environmental Kuznets Curve in 128 Countries (1990–2022)

Bora Yenihan[1], Kerem Çolak[2*], Yakup Köseoğlu[3], Cahit Şanver[4]

[1]Assoc.Prof.PhD. Kocaeli University, Faculty of Political Sciences, Department of Labor Economics and Industrial Relations, Kocaeli, Turkiye, bora.yenihan@kocaeli.edu.tr, ORCID: 0000-0001-9413-6571

[2]Lect.PhD., Kocaeli University, Hereke Asım Kocabıyık Vocational School, Environmental Measurement and Monitoring Systems Technician Program, Kocaeli, Turkiye, kerem.colak@kocaeli.edu.tr, ORCID: 0000-0003-3357-3457

[3]Assoc.Prof.PhD., Sakarya University, Faculty of Political Sciences, Department of Political Science and Public Administration, ykoseoglu@sakarya.edu.tr, ORCID: 0000-0002-8902-0053

[4]Assoc. Prof. PhD., Cahit Şanver Sakarya University, Faculty of Political Sciences, Maliye Bölümü, sanver@sakarya.edu.tr, ORCID: 0000-0002-4918-9305

[*]Corresponding author: Kerem ÇOLAK

E-mail: kerem.cola@kocaeli.edu.tr, Tel: +905307885676

Beyond Income: Energy Intensity, Industrialization and the CO_2 Environmental Kuznets Curve in 128 Countries (1990–2022)

Abstract

This study re-examines the Environmental Kuznets Curve (EKC) hypothesis within a rigorous methodological framework, focusing on the mediating role of energy consumption across a global panel of 128 countries (1990–2022). Utilizing second-generation econometric techniques to account for cross-sectional dependence (Pesaran CD, CIPS, Westerlund), we employ the Common Correlated Effects Mean Group (CCE–MG) estimator to address both unobserved common shocks and parameter heterogeneity. **Our full-panel results provide evidence for a conditional inverted-U pattern**, with an average turning point of approximately $4,628 PPP USD. However, the high elasticity of emissions relative to energy use (lnTOE \approx 1.04) indicates that decarbonization is driven more by energy intensity than by income growth alone. Furthermore, disaggregated analysis reveals that the EKC is not a monolithic reality; statistically consistent evidence is primarily confined to low-industrialization economies (IND4). These findings suggest that environmental recovery is not an automatic outcome of rising per-capita income. Instead, sustainable development requires targeted policies that prioritize energy efficiency gains and a structural transition toward cleaner energy mixes.

Keywords: Environmental Kuznets Curve; CO_2 emissions; energy use; cross-sectional dependence; CCE–MG; global panel.

JEL CODE: Q54, Q43, Q56, C23, O44

1. Introduction

Debates on environmental pollution since the mid-twentieth century have intensified empirical research on the growth–environment nexus, producing diverse methods and often heterogeneous findings that motivate more refined analyses.

While environmental concerns rose to prominence in the mid-twentieth century, many underlying pressures date to the Industrial Revolution. Industrialization and urbanization expanded factory output and intensified air, water, and soil pollution (Panayotou, 1993), improving material production while reducing environmental quality. As production scaled up, growth accelerated, but environmental damages became more visible, prompting research to quantify the causal links between economic activity and environmental outcomes.

A major turning point in this literature was Grossman and Krueger (1991), who adapted the Kuznets Curve to environmental indicators and introduced the "Environmental Kuznets Curve" (EKC) as a testable empirical framework. The appeal of the EKC lies in its simple functional form and its suitability for panel and time-series estimation.

This study re-examines the growth–environment relationship through the EKC lens using a panel of 128 countries over 1990–2022 and interprets the results in light of the broader literature. Beyond the standard income–CO_2 specification, the analysis explicitly considers the roles of energy intensity, energy composition, and industrialization in shaping emission trajectories. We also emphasize transparent EKC validation and compare income-based and energy-based specifications to clarify which channels dominate in a global setting. The next section reviews the core EKC evidence (including supporting and refuting studies), and the following section discusses our econometric findings and their policy implications comparatively.

2. The Environmental Kuznets Curve (EKC) and CO_2 Emissions Literature

The original "Kuznets Curve" was proposed by Simon Kuznets (1955) to describe the link between growth and income distribution. Grossman and Krueger (1991) extended this intuition to environmental degradation, giving rise to the EKC hypothesis: environmental pressure rises in early development and falls after an income threshold, implying an inverted U-shaped relationship (Saatçi & Dumrul, 2011). Subsequent research also reports alternative shapes (e.g., monotonic, U-shaped, or N-shaped) depending on the pollutant and specification, underscoring that EKC "validation" is not mechanical. Accordingly, empirical support varies with the indicator, model choice, period, and country group, which also shifts the estimated turning point (Erataş and Uysal, 2014).

The EKC became central partly because it tests a policy-relevant relationship, and partly because it is grounded in empirical regularities rather than a fully derived structural theory, making it straightforward to implement. In the quadratic EKC, the key policy object is the "turning point," where growth and emissions decouple and environmental improvement begins. However, turning-point estimates can differ widely across methods and specifications, complicating comparisons (Tutulmaz, 2012). Table 1 summarizes influential EKC studies and their main findings.

Table 1. Review of the EKC Literature

Authors/Researchers	Year	Period	Scope	Results
Grossman and Krueger	1991	1972, 1982, 1987	NAFTA Countrys	EKC is in the shape of an N.
Shafik and Bandyopadhya	1992	1960-19888,1989	135 Countries CO_2 28 Countries SO_2	Inverted-U for SO_2; monotonic increasing for CO_2 (no EKC)
Panayotou	1993	1982-1994	30 countries	EKC is in the shape of an inverted U.
Selden and Song	1994	1973-1975, 1979-1981, 1982-1984	31 countries	EKC is in the shape of an inverted U.
Grossman and Krueger	1995	1977-1988	42 countries SO_2 29 Countries TSP	EKC is in the shape of an inverted U
Holtz-Eakin and Selden	1995	1951-1986	130 countries CO_2	EKC is in the shape of an inverted U
De Bruyn, Van den Bergh, and Opschoor	1996	1960-1993	30 countries	EKC is in the shape of an inverted U.
Panayotou	1997	1982-1995	30 countries	EKC is in the shape of an inverted U.
Roberts and Grimes	1997	1962-1991	CDIAC data	EKC is in the shape of an quadratic inverted U.
Dijkgraaf and Vollebergh	1998	1960-1990	OECD countries	They concluded that there is no meaningful EKC for carbon emissions.
Kaufmann, Davidsdottir, Garnham and Pauly	1998	1974-1989	23 countries	EKC is in the shape of an inverted U.
Torras and Boyce	1998	1977-1991	42 countries	EKC is in the shape of an N.

List and Gallet	1999	1929-1994	USA	EKC is in the shape of an inverted U.
Barrett and Graddy	2000	1977, 1982, 1988	32 countries	EKC is in the shape of an N.
Dinda, Coondoo and Pal	2000	1979-1982, 1983-1986, 1987-1990	33 countries	EKC is in the shape of an U.
Stern and Common	2001	1960-1990	73 countries	EKC is in the shape of an inverted U.
Groot, Withagen and Minliang	2001	1987-1992	30 cities in China	EKC is in the shape of an N.
Cole	2004	1980-1997	18 OECD countries	EKC is in the shape of an inverted U.
Galeotti, Lanza and Pauli	2006	1960-1998, 1971-1998	International Energy Agency data set	There is evidence of an inverted U-shaped relationship with a reasonable turning point for EKC.
Mor and Jindal	2012	1997-2008	Kyoto countries	EKC is in the shape of an inverted U.
Farhani, Mrizak, Chaibi and Rault	2014	1990-2010	Middle East and Nort Africa countries	EKC is in the shape of an inverted U.
Wang, Han and Kubota	2016	1990-2012	Panel data from a province of China.	Evidence has been found supporting an inverted U-shaped curve relationship for EKC.
Z-Monserrate, Cl-Lara and U-Sanchez	2018	1971-2011	Singapore	The study confirms the EKC hypothesis in both the short and long term.
Destek and Sarkodie	2019	1977-2013	11 newly industrialized countries	EKC is in the shape of an inverted U.
Rahman, Ghazali, Bhatti and Khan	2020	1989-2018	Lithuanian	EKC is in the shape of an inverted U.
Anser, Yousaf, Nassani, Abro and Zaman	2020	1995-2015	G7 countries	The inverted U-shaped EKC relationship between CO2 emissions and economic growth is confirmed by the $30,900 milestone.

Overall, EKC results are highly sensitive to data coverage and econometric choices, so reported conclusions are often not directly comparable across studies. This motivates stricter criteria and robustness-oriented interpretation.

2.1. The Classical EKC Approach and Foundational Studies

The EKC hypothesis posits that growth initially raises emissions but later reduces them through structural change and institutional improvements. Early tests focused on local pollutants (Shafik & Bandyopadhyay, 1992; Grossman & Krueger, 1995; Holtz-Eakin & Selden, 1995), and later work extended the framework to global pollutants, especially CO_2.

Meta-evidence reinforces the sensitivity of EKC findings to indicator choice, sample coverage, and estimation. Cavlovic et al. (2000) synthesize early EKC work and show that both methodology and pollutant type materially affect the estimated income turning point, which helps explain why reported turning points can vary by orders of magnitude. Li et al. (2007) extend this logic in a large meta-regression, stressing that EKC support is contingent on data characteristics and estimation techniques and reporting no robust evidence for an EKC for anthropogenic greenhouse gases. Saqib and Benhmad (2021) confirm that the literature remains split even in the recent wave of studies, with a sizeable share of estimates supporting an EKC while many others remain weak, mixed, or null; they attribute much of this divergence to differences in indicators, samples, and control-variable sets rather than any single "best" econometric tool.

2.2. Studies Validating the EKC

Several studies report an inverted-U income–CO_2 relationship in multi-country panels, including Narayan and Narayan (2010) for developing economies, Ragoubi and Mighri (2021) for middle-income countries using dynamic spatial panels, and Kılıç and Balan (2015) for a broad global sample with heterogeneity across income groups. These results are often interpreted as evidence that structural change, regulation, and cleaner technologies can offset scale effects at higher income levels, although estimated turning points remain sensitive to controls and sample composition.

Single-country evidence (including Turkey) also sometimes supports the EKC for CO_2 or ecological footprint under specific specifications (e.g., Acaroğlu et al., 2023; Doğan & Karay, 2019), though limited time spans and controls often constrain external validity.

2.3. Studies Refuting or Finding a 'Fragile' EKC

Another research finds the CO_2 EKC to be absent or highly fragile. Using semi-parametric methods, Azomahou et al. (2006) conclude that the CO_2–income link is largely monotonic. With a panel smooth transition model, Aslanidis et al. (2009) show regime-dependent slopes but do not recover a classical inverted-U.

Luzzati et al. (2018) report that any EKC-like traces for energy supply and CO_2 that appeared in earlier decades weaken or disappear in later globalization phases, characterizing the EKC evidence as "fragile." Their findings suggest that global production reallocation and changing trade patterns can mask or reverse domestic improvements. Hannesson (2022) notes declining emission intensity in some high-income economies but still judges the overall CO_2 Kuznets evidence weak, especially once differences in energy systems and consumption-based footprints are considered.

Consistent with this, Li et al. (2007) find greenhouse-gas EKC support is rarer than for local pollutants, and Saqib and Benhmad (2021) emphasize that results shift with samples, controls, and methods, challenging any simple narrative that emissions reliably fall with income.

2.4. Energy Intensity, Energy Composition, and the EKC

A complementary view argues that many income-based EKC patterns proxy deeper energy mechanisms. Sun (1999) suggests that the CO_2 Kuznets profile reflects a peak in energy intensity, while Roca and Alcántara (2001) show for Spain that emissions are largely explained by energy intensity and fuel mix rather than income alone.

For OECD economies, Özokcu and Özdemir (2017) find no robust CO_2 EKC and instead link emissions to energy use and the energy mix. This line of work emphasizes mechanisms such as efficiency gains (lower energy per unit of output) and fuel substitution (lower carbon per unit of energy), which can weaken or overturn the income-only EKC pattern. Broader EKC specifications that incorporate energy intensity and renewables often reach similar conclusions (e.g., Dogan, 2019; Dogan & Türkekul, 2016; Saidi & Omri, 2020), implying that income-based EKC results may reflect unmodeled transitions in technology, efficiency, and the fuel mix.

Large global panels remain relatively scarce, but they illustrate the diversity of approaches and the instability of conclusions when specifications change. Azomahou, Laisney, and Van Phu (2006) use non-parametric/semi-parametric tools on broad country sets, while Shuai et al. (2017) combine panel and country-specific methods to explore turning points across a large cross-section. More recently, Almeida et al. (2024) focus on CO_2–income cointegration and dependence structures in a large panel, and sector-oriented studies such as Zhang et al. (2019) highlight that EKC patterns can differ markedly across manufacturing and construction. Complementary evidence on the growth–emissions–energy nexus, including causality-based designs, is also provided by Kacprzyk and Kuchta (2020). Despite these efforts, many large-sample studies still prioritize the income–CO_2 link with limited integration of energy-intensity and fuel-mix channels or structural industrial heterogeneity. Building on this gap, this paper offers three contributions:

1. Adoption of stricter EKC validation criteria: beyond the sign condition ($\beta1 > 0$, $\beta2 < 0$), coefficients must be statistically significant, and the implied turning point must fall within the observed income/energy range; otherwise, the EKC is not treated as supported. This follows the meta-analytic emphasis on fragility (Li et al., 2007) while making the decision rule transparent.
2. An energy-intensity-centered reinterpretation: kgOE enters both as a control in income-based models and as the main regressor in "energy-based EKC" specifications, allowing a direct test of whether CO_2 dynamics track income or energy intensity. The results point to stronger and more stable energy elasticities, consistent with the view that CO_2 EKC shapes reflect energy and fuel-mix dynamics (Sun, 1999; Roca & Alcántara, 2001; Stern, 2004).
3. Global testing of industrial development dimensions: interacting income and energy terms with industrial development classes (IND1 vs. IND2+3) probes structural heterogeneity. Estimated differences are limited, while direct energy use remains the dominant driver of CO_2 changes.

Taken together, these contributions caution against the claim that emissions "naturally" decline with income. Instead, they point to a policy logic centered on measurable mechanisms: reducing energy intensity through efficiency and electrification, lowering carbon intensity through fuel switching and renewables, and addressing structural constraints linked to industrial development. In this sense, the EKC becomes less a deterministic "path" of development and more a diagnostic framework for identifying which energy and structural channels must change for emissions to decouple from growth.

3. Theoretical Framework

While the relationship between economic growth and social welfare has long been a subject of debate, the discourse frequently centers on a critical inquiry: Does growth generate "social costs" of the same direction and intensity at every stage, or do these costs diminish following a specific threshold due to structural transformation and institutional capacity? One of the most influential early responses to this question is Kuznets' (1955) hypothesis, which employs an "inverted-U" logic to explain the nexus between income growth and income inequality. Over time, this conceptual framework has evolved into a robust analytical lens for understanding the impact of growth on environmental pressure, extending beyond its original application in distributional debates (Grossman & Krueger, 1991).

Specifically, the Kuznets Curve (KC) approach implies that while inequality may rise during the initial phases of growth, it tends to decline after a certain income level is reached, driven by industrialization, sectoral shifts in the labor force, urbanization dynamics, and redistribution mechanisms (Kuznets, 1955). The Environmental Kuznets Curve (EKC) adaptation translates this intuition to the ecological domain. It posits that in the early stages of development, emissions increase due to the expansion of production scale and the dominance of energy-intensive technologies. However, at higher income levels, environmental pressure may weaken through channels such as technological innovation, stringent regulation, increased environmental awareness, and shifts in the composition of production (Grossman & Krueger, 1991). Consequently, the EKC provides a testable hypothesis suggesting that the growth–environment relationship is not linear but may approximate an inverted-U form under specific conditions (Shafik & Bandyopadhyay, 1992).

The classical Kuznets Curve suggests that income inequality evolves non-linearly throughout the process of economic growth. According to this hypothesis, inequality may exhibit an upward trend during the early stages of development; however, as structural transformation matures, labor mobility expands, and institutional capacity strengthens, inequality begins to subside (Kuznets, 1955). This approach emphasizes that the social outcomes of growth are not "unidirectional" but are instead stage-dependent.

The fundamental intuition of the KC lies in the differing income dynamics that emerge during the transition from traditional (low-productivity) to modern (high-productivity) sectors. Initially, the modern sector creates a small, high-income group, thereby increasing inequality. As the modern sector expands and income becomes more broadly distributed over time, inequality may decrease. This logic underpins the proposition that the relationship between growth and a given outcome variable may take an inverted-U form.

In empirical testing, this relationship is frequently scrutinized using a quadratic form:

$$I_{it} = \alpha + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + u_{it} \tag{1}$$

Expected sign condition for an inverted-U Kuznets relationship:

$$\beta_1 > 0, \beta_2 < 0$$

The turning point indicates the income level at which inequality changes direction:

$$Y^* = -\frac{\beta_1}{2\beta_2} \tag{2}$$

This threshold represents the point at which the marginal effect of growth on inequality shifts from positive to negative. Building upon this foundation, the Environmental Kuznets Curve (EKC) adapts Kuznets' non-linear "stage-dependent effect" logic to environmental indicators. It postulates that as per capita income rises, environmental degradation initially intensifies but subsequently diminishes after surpassing a specific threshold (Grossman & Krueger, 1991; Shafik & Bandyopadhyay, 1992). This framework assumes that the growth–environment nexus is primarily shaped by three distinct channels (Grossman & Krueger, 1991):

- **Scale Effect:** As the volume of production expands, energy consumption and emissions increase, thereby heightening environmental pressure.
- **Composition Effect:** As the economic structure shifts from heavy industry toward service- and technology-oriented sectors, emission intensity may decline.
- **Technique Effect:** Stringent environmental regulations, the adoption of cleaner technologies, and improvements in efficiency lead to a reduction in emissions per unit of output.

When these three effects are evaluated collectively, the scale effect tends to dominate at lower income levels. However, at higher income levels, the strengthening of composition and technique effects makes a reduction in emissions possible. Consequently, the EKC hypothesis theorizes the feasibility of an inverted U-shaped pattern for environmental indicators such as CO_2 (Grossman & Krueger, 1991). Nevertheless, critical assessments emphasize that the EKC does not operate as a "mechanical law" under all circumstances; rather, findings remain highly sensitive to the type of pollutant, sample selection, and modeling preferences (Stern, 2004).

In empirical studies, the EKC hypothesis is typically tested using a quadratic model «similar to the KC framework» incorporating the squared term of the income variable. In its simplified form:

$$E_{it} = \alpha + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + u_{it} \tag{3}$$

As shown in Equation (3), E_{it}captures environmental degradation (e.g., CO_2 emissions per capita), while Y_{it}captures per capita income. An inverted-U EKC, analogous to the classical Kuznets Curve, requires the following conditions:

$$\beta_1 > 0, \beta_2 < 0$$

the expected sign condition is imposed. Under this condition, environmental degradation initially increases and subsequently declines once income surpasses a certain threshold (Shafik & Bandyopadhyay, 1992). This critical threshold is defined as the turning point and is computed at the income level where the marginal effect equals zero, which is identical to the standard Kuznets-curve calculation.

Consistent with the theoretical framework outlined above, this study employs a quadratic EKC specification to model the CO_2–income relationship in a nonlinear manner and to test empirically the inverted-U pattern in the growth–environment nexus, while controlling for the direct effect of energy use on emissions. This approach enables an assessment of both the EKC sign conditions and whether the implied turning point lies within a meaningful range of the sam

4. Data and Method

The annual panel dataset used in this study is constructed from three core indicators drawn from the World Bank's World Development Indicators (WDI) database: CO_2 emissions per capita, income per capita measured at purchasing power parity, and energy use per capita. The variables employed, their corresponding WDI indicator codes, and key definitions are summarized in Table 2.

Table 2. Indicators used in the study and data sources

Variable	Symbol	WDI Code	Definition	Unit of measurement
Per CO_2 emission	perCO2	EN.GHG.CO2.PC.CE.AR5	Total CO_2 emissions / population	metric tons of CO_2 per person
Per GSYH (PPP)	perGDP_PPP	NY.GDP.PCAP.PP.CD	GDP per capita, PPP (purchasing power parity)	current international dollars
Energy use per capita	kgOE_pc	EG.USE.PCAP.KG.OE	Primary energy use per capita	kg of oil equivalent per person

The raw dataset was derived from World Development Indicators (WDI) Excel outputs for three primary indicators. The raw files encompassed the complete set of "All countries and economies" reported by the WDI, including both sovereign states and regional/aggregated series (such as Africa or World totals).

To obtain the balanced panel of 128 countries utilized in the analysis, the following data-cleaning procedures were implemented:

- The series for perCO2, perGDP_PPP, and kgOE_pc were merged by country-year, and the sample period was restricted to 1990–2022.
- Country-years with missing values were excluded, and only countries with complete observations for all three series over 1990–2022 were retained (balanced panel).
- Given log transformations, observations with non-positive values were dropped, and regional/aggregated WDI series were excluded to maintain a country-level focus.

Following these filters, a balanced panel of 128 countries over 33 years (1990–2022) was obtained, yielding 4,224 country-year observations.

Countries were classified into four industrial-development groups (IND1–IND4) using the IND_class_filled variable; detailed thresholds and the country list are provided in Table 3.

This classification is derived from a composite index reflecting industrial structure and income (e.g., manufacturing share and structural transformation indicators).

Table 3. Distribution of Countries by Industrial Development Classification in the Final Sample

Classification	Description	Number of Countries
IND1	Advanced Industrial and High-Income Economies	29
IND2	Industrialized and Upper-Middle-Income Economies	6
IND3	Moderately Industrialized and Middle-Income Economies	56
IND4	Low-Industrialized and Low-Income Economies	37
Total		128

Consequently, the panel analyses in the remainder of the study use 128 countries with complete observations for the three core indicators over 1990–2022, reported for the full panel and by IND groups (IND1–IND4).

This research evaluates the EKC hypothesis by examining the nonlinear income–CO_2 nexus in a panel framework. Because countries may share common, unobserved shocks, cross-sectional dependence must be accounted for to avoid biased inference in unit-root, cointegration, and regression analyses.

All econometric analyses were conducted in Python (Google Colab): pandas/numpy for data processing, stats models for regression and robust errors, and linear models for panel estimators such as CCE-MG.

4.1. Preliminary Diagnostic Tests

Step 1: Cross-Sectional Dependence (CSD): Macroeconomic variables such as CO_2 emissions, income, and energy consumption often exhibit synchronized responses to common shocks. Consequently, it is highly probable that error terms are correlated across cross-sections (cross-sectional dependence). The presence of such dependence can undermine statistical inference by violating the "independence" assumption inherent in classical first-generation panel unit root tests (e.g., LLC, IPS) and several standard estimators.

Therefore, the Pesaran CD test is applied as the initial diagnostic step. Pesaran (2004) developed the CD test based on the average of pairwise correlations of OLS residuals across cross-sections, demonstrating that the test maintains robust small-sample properties across various panel structures.

The CD test statistic is formally expressed as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{p}_{ij} \tag{4}$$

In this context, $\hat{p}_{ij}$ denotes the product-moment correlation coefficient of the residuals between countries i and j. A statistically significant result from this test indicates that countries within the panel do not operate independently. Consequently, it signifies that "common factor/shock" components must be explicitly integrated into the modeling framework to ensure empirical validity (Pesaran, 2004; De Hoyos & Sarafidis, 2006; Pesaran, 2021).

Step 2 – Panel Unit Root / Stationarity Tests: In the presence of cross-sectional dependence (CSD), accurately determining the panel's order of integration through stationarity analysis becomes critical. Since first-generation panel unit root tests can exhibit increased size distortion and reduced power under CSD, leading to spurious rejections or false acceptances, this study employs second-generation approaches that explicitly account for dependence across units. The methodology of Pesaran (2007) is adopted. Pesaran introduced a "cross-sectionally augmented" framework, developing both the Cross-sectionally Augmented Dickey-Fuller (CADF) test for individual series and the Cross-sectional IPS (CIPS) test for the panel. This framework incorporates cross-sectional averages into the model to filter out the influence of unobserved common factors (Pesaran, 2007; Pesaran et al., 2008).

The core of this approach involves augmenting the standard ADF regression with cross-sectional averages:

$$\Delta y_{it} = a_i + b_i y_{i,t-1} + c_i \bar{y}_{t-1} + \sum_{k=0}^{p} d_{ik}\,\Delta \bar{y}_{t-k} + \sum_{k=1}^{p} \phi_{ik}\,\Delta y_{i,t-k} + u_{it} \tag{5}$$

In this formulation, $\bar{y}_t$ represents the cross-sectional average of the variable (e.g., $\ln CO_2$, lnGDP, lnTOE) across all countries, serving as a proxy for common shocks. This step provides the methodological basis for the EKC model. By identifying the order of integration (level vs. difference), it dictates the appropriate estimation form and the analysis of short- or long-run dynamics (Pesaran, 2007; Hashiguchi & Hamori, 2010).

Step 3 – Panel Cointegration Test: If the core variables share the same order of integration (e.g., I(1)), a panel cointegration test must be applied. This step is essential to interpret the EKC relationship not merely as a short-term correlation but as a potential long-run equilibrium. This study employs the panel cointegration tests developed by Westerlund (2007), which are grounded in an error-correction mechanism framework. Westerlund's approach offers a robust alternative to classical residual-based cointegration tests. It tests for the existence of a cointegrating relationship directly through the significance of the error-correction term, providing a more direct and powerful test of the long-run relationship.

If we write the EKC model as $y_{it} = ln\,(CO_{2,it})$ and $x_{it} = [\ln\,(GDP_{it}), (\ln\,(GDP_{it}))^2, \ln\,(TOE_{it})]$, the error-correction form can be summarized as follows:

$$\Delta y_{it} = \alpha_i + \phi_i(y_{i,t-1} - \theta_i' x_{i,t-1}) + \sum_{k=1}^{p} \gamma_{ik}\,\Delta y_{i,t-k} + \sum_{k=0}^{p} \delta_{ik}'\,\Delta x_{i,t-k} + \varepsilon_{it} \tag{6}$$

Within this framework, the parameter $\phi_i$represents the system's speed of adjustment back to the long-run equilibrium.

- H_0(no cointegration): $\phi_i = 0$
- H_1(cointegration): $\phi_i < 0$

This stage tests the long-run validity of the EKC nexus. It confirms whether the interaction between income and energy use constitutes a lasting structural framework (Westerlund, 2007; Persyn & Westerlund, 2008).

Step 4 – Accounting for Heterogeneity and Robust Estimation

The simultaneous presence of cross-sectional dependence and slope heterogeneity complicates empirical analysis, challenging not only the accuracy of coefficient signs but also the validity of statistical inference (standard errors and significance). Therefore, a two-tiered estimation strategy is adopted:

1. Benchmark Estimation: Fixed Effects with Robust Standard Errors The Fixed Effects (FE) framework provides a practical starting point, as it controls for unobserved, time-invariant country-specific factors (e.g., institutional structure, geographical conditions, long-term energy infrastructure). However, if the error terms exhibit heteroskedasticity, autocorrelation, or cross-sectional dependence, conventional standard errors become unreliable. Consequently, the

benchmark specification employs covariance matrix estimators that are robust to these issues. Driscoll and Kraay (1998) propose a nonparametric covariance matrix estimator that yields consistent standard errors in the presence of both temporal and cross-sectional dependence when the time dimension is sufficiently large.

This benchmark layer does not serve as the primary result but rather provides an initial check on whether the EKC coefficients exhibit the expected signs and offers a baseline for comparison.

2. Primary Estimation: The Common Correlated Effects Mean Group (CCE-MG) Estimator: Given the prevalence of heteroskedasticity and cross-sectional dependence, robust diagnostic tests and estimators are essential. The Breusch–Pagan test (Breusch & Pagan, 1979) and White test (White, 1980) were applied to detect heteroskedasticity. The Hausman test (Hausman, 1978) was used to guide the choice between the Fixed Effects (FE) and Random Effects (RE) models. Furthermore, the Ramsey RESET test (Ramsey, 1969) was employed to assess potential model misspecification due to omitted variables or an incorrect functional form. To ensure robust inference under likely cross-sectional dependence and autocorrelation, Driscoll–Kraay robust standard errors are utilized for the benchmark FE model (Driscoll & Kraay, 1998).

For the primary analysis, the Common Correlated Effects Mean Group (CCE-MG) estimator is employed. This approach simultaneously addresses heterogeneity and common shocks. Pesaran (2006) demonstrates that augmenting country-specific regressions with cross-sectional averages of the variables filters out the influence of unobserved common factors, enabling consistent estimation in large heterogeneous panels. The Mean Group (MG) component of this estimator, proposed by Pesaran and Smith (1995), averages the coefficients estimated for each country individually. This avoids the pooling bias that can occur in dynamic or heterogeneous panels when estimating long-run relationships.

Within this framework, the augmented regression for each country i can be expressed generally as:

$$y_{it} = \alpha_i + \beta_i' x_{it} + \gamma_{i0}\bar{y}_t + \gamma_{i1}'\bar{x}_t + \sum_{m=1}^{M}(\lambda_{im}\bar{y}_{t-m} + \psi_{im}'\bar{x}_{t-m}) + u_{it} \tag{7}$$

Here, $\bar{y}_t$and $\bar{x}_t$denote the cross-sectional averages (and their lags) of the dependent and independent variables. These terms serve to “absorb” the influence of global shocks and unobserved common factors. The country-specific coefficients β_i are then aggregated using the Mean Group approach.

$$\hat{\beta}_{MG} = \frac{1}{N}\sum_{i=1}^{N}\hat{\beta}_i \tag{8}$$

The Mean Group (MG) approach is selected because, in a heterogeneous panel, pooling or aggregating data can yield misleading estimates. In contrast, averaging group-specific estimates provides a consistent estimator for the mean of the long-run parameters across the panel (Pesaran & Smith, 1995; Pesaran et al., 1999).

Since most variables exhibit weak stationarity or I(1) behavior under second-generation unit-root tests, conventional panel OLS in levels risks spurious regression. Accordingly, the primary analysis relies on CCE-MG, which models common global trends via cross-sectional averages and allows heterogeneous coefficients. Although Westerlund tests do not yield strong or uniform evidence of cointegration for the global panel, the CCE-MG framework supports interpreting the nexus as a conditional long-run relationship, summarized as average long-run elasticities across heterogeneous groups.

4.2. EKC Model Specification

Based on the preliminary test findings and the characteristics of the panel structure, the EKC hypothesis is tested using a quadratic specification to capture the nonlinear nature of the income–emissions relationship. The dependent variable is per capita CO_2 emissions. The core explanatory variables are per capita income and its square (to capture nonlinearity). Per capita energy consumption is included to direct control for the effect of energy use on emissions. This framework enables an empirical test of whether the relationship between growth and environmental pressure follows an inverted U-shape.

In light of these considerations, the foundational quadratic panel model for testing the EKC hypothesis is specified as follows:

$$\ln(CO2_{it}) = \alpha_i + \delta_t + \beta_1 \ln(GDP_{it}) + \beta_2[\ln(GDP_{it})]^2 + \beta_3 \ln(TOE_{it}) + \varepsilon_{it} \tag{9}$$

The economic meaning of the variables used in the model and the interpretation of the coefficients are as follows:

- $\ln(CO2_{it})$: Logarithm of per capita CO₂ emissions, serving as the indicator of environmental pressure.
- $\ln(GDP_{it})$: Logarithm of per capita income; represents the channels through which growth may both increase (scale effect) and decrease (technology/regulation effect) environmental pressure.
- $[\ln(GDP_{it})]^2$: The nonlinear term; directly tests whether the growth–environment relationship exhibits an inverted-U (EKC) form.
- $\ln(TOE_{it})$: Logarithm of per capita energy use; captures the direct effect of emissions through the energy intensity/consumption channel.
- α_i: Controls for unobserved, time-invariant country-specific factors (e.g., institutional structure, geography, infrastructure).
- δ_t: Controls for global time shocks that affect all countries simultaneously (e.g., global energy price waves).

The fundamental sign condition for supporting an inverted-U shaped EKC is:

$$\beta_1 > 0 \text{ and } \beta_2 < 0.$$

If this condition holds, it implies that as income rises, CO₂ emissions increase up to a specific threshold (the turning point), after which they tend to decline.

Within this logarithmic specification, the marginal effect of income on CO₂ emissions (interpreted as an elasticity) is derived as follows:

$$\frac{\partial ln\,(CO2_{it})}{\partial ln\,(GDP_{it})} = \beta_1 + 2\beta_2 ln\,(GDP_{it}) \tag{10}$$

This expression clearly indicates that the growth–emissions relationship varies with the income level and should not be interpreted as a constant effect captured by a single coefficient.

Since most variables exhibit weakly stationary or $I(1)$ processes according to second-generation unit root tests, conventional Panel OLS models estimated at levels increase the risk of spurious regression. Consequently, the primary analysis relies on the **CCE-MG estimator**, which explicitly models both common global trends and country-specific coefficient heterogeneity. The Westerlund panel cointegration test does not yield strong or uniform evidence of cointegration for the global panel. Nevertheless, by incorporating common factor structures and cross-sectional averages, the CCE-MG framework allows the CO_2-income-energy nexus to be interpreted as a long-run conditional relationship rather than a spurious correlation. In this context, the reported coefficients should be viewed as an

"average of long-run elasticities" that summarizes the income-emission-energy dependencies across heterogeneous country groups, rather than a single common equilibrium equation for the entire panel.

4.3. The Turning Point and Its Conceptual Interpretation

In the EKC framework, the 'turning point' represents the income level at which emissions switch from increasing to decreasing with income. Within the quadratic model, the turning point is obtained where the marginal effect of income on CO_2 becomes zero. In the logarithmic specification, this threshold is calculated as lnGDP* = $-\beta_1/(2\beta_2)$; to convert it to the level value, we take GDP* = exp(lnGDP). For the turning point to be considered economically meaningful, two conditions must be met: (i) the coefficients β_1 and β_2 must be statistically significant, and (ii) the calculated GDP value must lie within the observed per capita income range of the sample. In this study, evidence for the EKC is evaluated not only by the sign condition but also against these two 'strict' criteria.

$$\beta_1 + 2\beta_2 \ln\left(GDP^*\right) = 0 \Rightarrow \ln\left(GDP^*\right) = -\frac{\beta_1}{2\beta_2} \tag{11}$$

to convert into level terms:

$$GDP^* = \exp\left(-\frac{\beta_1}{2\beta_2}\right) \tag{12}$$

Conceptually, the turning point represents a "threshold income" level beyond which economic growth may begin to reduce emissions through channels such as technological transformation, energy efficiency improvements, environmental regulations, and structural change. However, for this turning point to be considered economically meaningful, two criteria must be met: (i) the relevant coefficients must be statistically significant, and (ii) the calculated GDP* value must lie within the income range observed in the dataset.

5. Results and Discussion

5.1. Empirical Analysis and Findings

This section aims to elucidate the “econometric narrative” of the panel data structure prior to estimating the EKC model. Discussing the income–emission nexus solely through coefficient signs can be misleading in multi-country panels when common shocks and interdependencies generate cross-sectional dependence. Accordingly, the first step involves testing for cross-sectional dependence using the Pesaran (2004) CD test, which motivates a second-generation stationarity/cointegration framework and a CCE-based estimation strategy.

Building upon this methodological foundation, the validity of the EKC is first tested for the full panel. Subsequently, countries are grouped by industrialization and income levels to examine how the relationship varies structurally across cohorts. The findings suggest that global emission dynamics cannot be explained by a uniform income–emission relationship and that energy consumption remains decisive across groups.

Following this logic, Table 4 summarizes the cross-sectional dependence test results for the primary variables used in the study.

Table 4. Panel Pre-Estimation Test Results (N = 128, T = 33)

Panel	Test	Variable/Statistic	Value	p-value / Significance	Decision
A	Pesaran CD (CSD)	ln_CO2 (CD)	4.639	3.50×10^{-6}***	CSD present
		ln_GDP (CD)	58.484	<0.001***	CSD present
		ln_TOE (CD)	6.985	2.84×10^{-12}***	CSD present
B	CIPS (Pesaran, 2007)	ln_CO2	-2.224	* (10%)	Borderline stationary
		ln_GDP	-2.688	*** (1%)	Stationary
		ln_TOE	-2.384	** (5%)	Stationary
C	Westerlund (2007)	Gt	2.581	ns (5%)	Fail to reject H0
		Ga	2.581	ns (5%)	Fail to reject H0

(i) CSD = cross-sectional dependence. In the CD test, H_0: cross-sectional independence.
(ii) In the CIPS test, H_0: unit root exists (non-stationary); rejecting H_0supports stationarity.
(iii) In the cointegration test, H_0: no cointegration; if H_0cannot be rejected, there is no strong evidence of cointegration.
(iv) Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$, ns = not significant.

Table 4 presents the panel diagnostic test results. The Pesaran CD test indicates that cross-sectional dependence is statistically significant for lnCO2, lnGDP, and lnTOE, implying that countries are linked through common global shocks and synchronized dynamics; dependence-robust testing and estimation approaches are therefore required. This also suggests that ignoring common factors may bias conventional fixed-effects inference.

The CIPS unit root test results indicate that lnGDP and lnTOE are stationary at conventional significance levels, while lnCO2 is stationary only at the 10% level. Regarding the Westerlund cointegration test, the null hypothesis of no cointegration cannot be rejected at the 5% level for the reported group statistics, suggesting limited evidence of a common long-run error-correction relationship. Accordingly, the analysis relies on strategies that allow heterogeneity and common-factor structures, with robust inference. Taken together, these diagnostics motivate second-generation estimators and discourage imposing pooled long-run dynamics.

The Breusch–Pagan and White tests reported in Table 5 reject homoskedasticity (p < 0.01), confirming significant heteroskedasticity in the error terms. This necessitates inference based on robust standard errors. Finally, VIF values around 4.6 suggest that multicollinearity is not severe enough to destabilize the coefficient estimates among the explanatory variables.

Table 5. Model Diagnostic Test Results

Test	Statistic	Value	p-value / Significance	Decision
Breusch–Pagan (LM)	LM	874.462	<0.001***	Heteroskedasticity present
	F	551.021	<0.001***	Heteroskedasticity present
White	LM	1221.976	<0.001***	Heteroskedasticity present

	F	343.421	<0.001***	Heteroskedasticity present
VIF	ln_GDP	4.601	—	Acceptable
	ln_TOE	4.601	—	Acceptable
Hausman (FE vs RE)	$\chi^2(2)$	61.160	<0.001***	FE preferred
Ramsey RESET (power=2)	F	1447.131	<0.001***	Functional-form misspecification (reject H0)

Notes:
(i) Breusch–Pagan and White tests: H_0: homoskedasticity (constant variance). Rejecting H_0 indicates heteroskedasticity.
(ii) Hausman test: H_0: RE is consistent (FE–RE difference not systematic). Rejecting H_0 implies FE is preferred.
(iii) RESET test: H_0: correct functional form. Rejecting H_0 suggests functional-form misspecification / omitted nonlinear terms.
(iv) Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The significant Hausman test result indicates that unit-specific unobserved effects are correlated with the explanatory variables, favoring the Fixed Effects (FE) model over Random Effects (RE) for consistent estimation. The Ramsey RESET test further suggests that a purely linear specification may be inadequate, pointing to functional-form risks. Consequently, benchmark results are reported within an FE framework using Driscoll–Kraay standard errors to account for heteroskedasticity, autocorrelation, and common shocks.

Prior to implementing the second-generation estimators, a first-generation reference model is estimated solely for comparative purposes. This Panel OLS/FE model with country and year fixed effects uses per-capita CO_2 emissions as the dependent variable and includes per-capita income and energy use as regressors, estimated with Driscoll–Kraay robust standard errors. The results yield coefficients of approximately 0.32 for income and 0.81 for energy use (both significant at the 1% level), with a within-R^2 of roughly 0.50, consistent with basic expectations.

However, given that the Pesaran CD test revealed strong cross-sectional dependence in both the dependent and explanatory variables, the first-generation FE model is not used for long-run inference and serves only as a benchmark. The central analysis and interpretations are therefore based on the CCE-MG estimator, which is designed to account for both cross-sectional dependence and parameter heterogeneity.

Table 6. Main EKC Results - CCE–MG (All countries; N = 128)

Dependent variable: ln_CO2

Variable	**Coefficient**	**Std. Error**	**t-statistic**
ln_GDP	8.710**	3.913	2.226
ln_GDP^2	-0.516**	0.233	-2.216
ln_TOE	1.038***	0.084	12.403
Sabit	-29.083	17.135	-1.697

EKC condition: ln_GDP > 0 and ln_GDP^2 < 0 → inverted-U relationship (at the 5% level). Turning point (PPP, approx.): $\exp\{-\beta_1/(2\beta_2)\} \approx \exp\{-8.710/(2 \times -0.516)\} \approx 4628$.

Notes: CCE–MG is a panel estimator that accounts for heterogeneous slopes and cross-sectional dependence. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 6 reports the long-run coefficients based on the Common Correlated Effects Mean Group (CCE-MG) estimator for the full panel of N=128 countries. The model includes lnCO2 as the dependent variable and lnGDP, lnGDP², and lnTOE as explanatory variables. Consistent with the CCE approach, annual cross-sectional averages are included to proxy unobserved common factors, capturing global influences such as energy-price cycles, technological change, and worldwide policy shifts that simultaneously affect emissions and energy demand. By permitting heterogeneous slopes, CCE-MG avoids imposing a common EKC turning point across countries and yields an average pattern that is robust to cross-sectional dependence.

According to the table, lnGDP is positive (≈ 8.71) and lnGDP² is negative (≈ −0.52), both significant at the 5% level, consistent with an inverted-U EKC. The implied turning point is approximately $4,628 (PPP) per capita, suggesting that the panel-average peak lies in the lower-middle income range. This implies that, at lower income levels, growth is associated with higher emissions due to scale and early industrial expansion. Beyond the turning point, conditional on energy use, higher income is associated with lower emission intensity, which is consistent with improvements in energy efficiency, adoption of cleaner production technologies, stricter environmental regulation, and inter-sectoral structural transformation.

The coefficient for energy use (lnTOE) is approximately 1.04, positive and highly significant at the 1% level. This implies that a 1% increase in per-capita energy consumption raises per-capita CO_2 emissions by roughly 1% on average, highlighting an almost proportional energy–emissions linkage in the sample. The growth–emissions nexus therefore operates strongly through the energy channel—via energy intensity and the carbon content of the energy mix. Accordingly, the EKC coefficients should be interpreted as conditional on energy use: income-related decoupling is more likely when growth coincides with energy-efficiency gains and fuel switching toward cleaner energy sources.

Since the CCE-MG estimator allows for heterogeneous coefficients across countries, the EKC relationship reported in Table 6 reflects only an average pattern for the global panel and may conceal divergent country paths. Therefore, the following subsections examine industrial sophistication groups (IND1, IND2–3, IND4) to identify which groups drive the average result, and to assess how the energy–emissions elasticity varies across development stages.

Table 7. EKC Results by Income Groups - CCE–MG

Dependent variable: ln_CO2

Variable	IND1 (N=29)	IND2+3 (N=62)	IND4 (N=37)
ln_GDP	-0.453 (6.207)	2.789 (2.737)	23.116** (10.175)
ln_GDP²	0.031 (0.286)	-0.139 (0.142)	-1.429** (0.644)
ln_TOE	0.977*** (0.104)	0.851*** (0.050)	1.229*** (0.232)
Sabit	-12.145 (32.039)	-18.641 (12.015)	-80.464 (51.475)
EKC (β1>0, β2<0)	**No**	**No**	**Yes**
Turning point (≈)	—	—	**3253**

Notes: Parentheses report standard errors. Turning point: $\exp\{-\beta_1/(2\beta_2)\}$. For IND4: $\exp\{-23.116/(2 \times -1.429)\} \approx 3253$. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 7 presents the CCE-MG estimates disaggregated by industrialization and income groups. When countries are classified into highly industrialized (IND1), industrializing (IND2+IND3), and low-industrialized (IND4) groups, in line with the World Bank classification, the form of the income-emissions relationship is seen to differ markedly across cohorts.

The most salient finding is that the sign pattern and statistical significance required by the EKC hypothesis are met only in the IND4 group. For IND1, lnGDP is negative and lnGDP² is positive, and both are statistically insignificant, precluding inference of an inverted-U EKC structure. In IND2–3, lnGDP is positive and lnGDP^2 is negative, but neither is statistically significant, indicating that a stable EKC pattern has not yet emerged on average in industrializing countries.

Conversely, in the IND4 group, lnGDP is positive and significant and lnGDP^2 is negative and significant, indicating a conditional EKC form within the CCE-MG framework for low-industrialized countries. The calculated turning point corresponds to approximately $3,250 (PPP) per capita. Emissions rise with early income gains up to this threshold, reflecting scale effects as energy demand, infrastructure investment, and industrial activity expand. Beyond the turning point, holding energy use constant, additional growth is associated with lower emission intensity—consistent with the onset of efficiency gains, technology diffusion, and the gradual shift to less carbon-intensive production before deep industrial lock-in.

For all three groups, the lnTOE coefficient is positive and highly statistically significant (≈ 0.85–1.23), underscoring that energy use remains a decisive driver of emissions across development stages. The energy–emissions elasticity is highest in IND4 (≈ 1.23), consistent with more carbon-intensive energy mixes, lower efficiency, and limited access to clean technologies. Lower elasticities in IND1 and IND2–3 are consistent with cleaner technologies, diversification in the fuel mix, and partial decoupling processes observed in some countries, although energy use still exerts a strong upward pressure on emissions.

Overall, the results in Table 7 demonstrate that the EKC hypothesis does not represent a “uniform relationship” between income and CO$_2$ emissions across income and industrialization groups. In IND1, EKC dynamics may have occurred before the sample period or be blurred by carbon leakage, offshoring of emissions-intensive activities, and substantial within-group heterogeneity. In IND2–3, scale and composition effects likely dominate during rapid industrialization, and the turning point may lie outside the observed income range. In contrast, a conditional EKC is observable in IND4, reinforcing the case for differentiated policy mixes sensitive to industrial structure, energy intensity, and the energy mix rather than relying on a single global threshold.

5.2. Discussion

Using a 128-country panel (1990–2022), this study tests the EKC within an energy-centered framework. The findings indicate that the income–CO$_2$ relationship differs systematically by industrial sophistication and should be interpreted as conditional rather than automatic.

While full-panel CCE-MG estimates point to an average inverted-U relationship (Table 6), disaggregation by industrial groups shows that this pattern is driven mainly by IND4; no statistically robust EKC is detected for IND1 or IND2–3 (Table 7). This supports treating the EKC as heterogeneous across industrialization and energy-use regimes.

The disaggregated results reveal a clear developmental narrative. In IND4, the turning point around $3,250 (PPP) suggests that efficiency gains and technology transfer may begin to mitigate emission intensity relatively early, before a heavy industrial structure is locked in. This highlights the importance of early-stage policy choices that shape technology adoption and energy infrastructure. For IND2–3, rapid growth and structural shifts likely keep scale and composition effects dominant, pushing the turning point beyond the observed sample range; in this phase, energy-intensive industrial expansion can outweigh nascent efficiency improvements. For IND1, the lack of a clear EKC dynamic may reflect pre-sample emission peaks, carbon leakage, and heterogeneity in climate policy and decarbonization pathways, including differences in energy transition speed and industrial composition.

The high, positive, and highly statistically significant coefficient for energy use (lnTOE) across all groups confirms the decisive role of energy intensity and the energy mix in CO$_2$ dynamics. Consequently, the EKC should not be read as an unconditional regularity in which emissions automatically decline as income rises; rather, it is conditional on whether growth coincides with reductions in energy intensity and cleaner energy composition.

The Westerlund cointegration test’s limited evidence for a common error-correction relationship suggests that assuming a single shared long-run equilibrium for all countries may be restrictive, reinforcing the need for heterogeneous estimation strategies aligned with the panel structure. In this setting, group-specific long-run parameters and common-factor adjustments are more plausible than imposing one cointegration vector on all economies.

The obtained findings are consistent with the literature emphasizing the fragile and conditional nature of the CO_2 EKC (Azomahou et al., 2006; Luzzati et al., 2018; Saqib & Benhmad, 2021). This study makes this result more salient by combining a dependence-robust CCE-MG framework with industrial-group disaggregation and an explicit energy channel, thereby clarifying the “where it works/where it doesn’t” distinction. In addition, the results support arguments that changes in energy intensity and energy composition are central to EKC dynamics (Sun, 1999; Roca & Alcántara, 2001), and they caution against one-size-fits-all policy prescriptions.

From a policy perspective, the results clearly demonstrate that mitigation strategies cannot be based on the narrative that emissions automatically decline once income surpasses a threshold. For IND4, clean development requires early investments in energy efficiency, grid modernization, and renewables to avoid long-lived carbon lock-in. For IND2–3, a “grow first, clean up later” approach is risky; industrial policy, standards, and carbon pricing are needed to accelerate cleaner production technologies, reduce fossil dependence, and steer structural change. Given historical responsibility and greater fiscal/technological capacity, IND1 countries should accelerate domestic transitions, limit leakage (e.g., through border measures and supply-chain standards), and strengthen finance and technology commitments to developing nations.

The study has several limitations. First, the production-based CO_2 emissions measure does not fully capture carbon leakage and the emissions embodied in trade, which may be particularly relevant for IND1 economies. Second, the analysis is conducted at the country level and does not capture subnational heterogeneity in industrial structure or energy systems. Third, energy use is treated in aggregate terms; future research could incorporate explicit fossil/renewable shares of the energy mix and consumption-based emissions measures. Finally, exploring nonlinearities through threshold models or causality-oriented approaches may further clarify when and how decoupling emerges.

6. Conclusion

This study has re-evaluated the Environmental Kuznets Curve (EKC) hypothesis using a global panel dataset of 128 countries spanning 1990–2022, utilizing a methodological approach that places energy consumption at the core of the analysis. CCE-MG estimations, which account for cross-sectional dependence and country-specific heterogeneity, reveal that the relationship between income and CO_2 emissions varies significantly according to industrial development levels. The findings suggest that instead of a universal "inverted-U" form, the relationship exhibits a complex and conditional structure.

A primary finding is that the classical EKC relationship is significantly observed only within the least industrialized countries (IND4), when controlling for energy use and at a relatively low income threshold (~3,250 PPP USD). In industrializing countries (IND2+3), the scale and composition effects of economic growth remain dominant, pushing the EKC turning point beyond the observed income range. For highly industrialized countries (IND1), no clear panel-average EKC signal was detected within the study period; this can be attributed to carbon leakage, policy heterogeneity, and the fact that transition processes were largely completed prior to the analysis period.

The most robust and consistent finding of this study is that per capita energy use (lnTOE) has a high, positive, and statistically highly significant impact on CO_2 emissions across all groups, independent of income. This result clearly demonstrates that the fundamental driver of CO_2 emission dynamics is energy intensity and the carbon content of the energy mix, rather than income growth itself. Consequently, the simplistic EKC narrative—which posits that "environment improves automatically as income rises"—is not empirically supported, particularly in the context of CO_2 emissions.

Accordingly, the study offers a critical implication for climate policies: the political focus must shift from passively waiting to surpass income thresholds toward actively increasing energy efficiency, accelerating the transition to renewable energy sources, and transforming industrial structures. Policies must be differentiated according to countries' stages of industrialization, energy infrastructures, and institutional capacities. While advanced economies should take a leadership role through technology transfer and climate finance, industrializing and least industrialized nations must integrate clean energy and sustainable industrial policies into their development paths from the outset.

The study is subject to certain limitations, such as the use of production-based emission data and the exclusion of intra-country regional differences due to the panel structure. Future research could more clearly trace the effects of carbon leakage by incorporating consumption-based emission accounts, modeling the components of the energy mix in detail, and examining the regulatory effects of variables such as trade, financial development, and institutional quality on the EKC-energy nexus through threshold models or causality analyses.

In conclusion, this research demonstrates that the relationship between economic growth and environmental impact is not merely a non-linear function of income level, but rather a complex process shaped by energy systems, technological capacity, and policy choices. While the EKC hypothesis provides a conceptual starting point for understanding this process, a truly sustainable development roadmap requires active and inclusive policy sequences that center on the energy transition.

REFERENCES

Acaroğlu, H., Kartal, H.M. & García Márquez, F.P. Testing the environmental Kuznets curve hypothesis in terms of ecological footprint and CO_2 emissions through energy diversification for Turkey. *Environ Sci Pollut Res* 30, 63289–63304 (2023). https://doi.org/10.1007/s11356-023-26278-w

Almeida, D., Carvalho, L., Ferreira, P., Dionísio, A., & Haq, I. U. (2024). Global dynamics of environmental Kuznets curve: a cross-correlation analysis of income and CO2 emissions. *Sustainability*, *16*(20), 9089. https://doi.org/10.3390/su16209089.

Anser, M. K., Yousaf, Z., Nassani, A. A., Abro, M. M. Q. and Zaman, K. (2020), International tourism, social distribution, and environmental Kuznets curve: evidence from a panel of G-7 countries, Environmental Science and Pollution Research, 27/3, 2707-2720, DOI: 10.1007/s11356-019-07196-2.

Aslanidis, N., & Iranzo, S. (2009). Environment and development: is there a Kuznets curve for CO_2 emissions? *Applied Economics*, *41*(6), 803–810. https://doi.org/10.1080/00036840601018994.

Azomahou, T., Laisney, F., & Van Phu, N. (2006). Economic development and CO2 emissions: A nonparametric panel approach. *Journal of Public Economics*, *90*(6-7), 1347-1363. https://doi.org/10.1016/j.jpubeco.2005.09.005

Barret, S. and Graddy, K. (2000), Freedom, growth, and the environment, Environment and development economics, 5/4, Special Issue, 433-456, https://www.jstor.org/stable/44404310.

Breusch, T. S., & Pagan, A. R. (1979). A simple test for heteroscedasticity and random coefficient variation. *Econometrica: Journal of the econometric society*, 1287-1294. https://doi.org/10.2307/1911963

Cavlovic, T. A., Baker, K. H., Berrens, R. P., & Gawande, K. (2000). A meta-analysis of environmental Kuznets curve studies. *Agricultural and Resource Economics Review*, *29*(1), 32-42. https://doi.org/10.1017/S1068280500001416

Cole, M. A.; (2004), Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages, Ecological economics, 48/1, 71-81, https://doi.org/10.1016/j.ecolecon.2003.09.007.

De Bruyn, S. M., Van Den Bergh, J. C. and Opschoor, J. B. (1998), Economic growth and emissions: reconsidering the empirical basis of environmental Kuznets curves, Ecological Economics, 25/2, 161-175, https://doi.org/10.1016/S0921-8009(97)00178-X.

De Hoyos, R. E., & Sarafidis, V. (2006). Testing for cross-sectional dependence in panel-data models. *The stata journal*, *6*(4), 482-496. https://doi.org/10.1177/1536867X0600600403

Destek, M. A. and Sarkodie, S. A. (2019), Investigation of environmental Kuznets curve for ecological footprint: the role of energy and financial development, Science of the Total Environment, 650/2, 2483-2489, https://doi.org/10.1016/j.scitotenv.2018.10.017.

Dijkgraaf, E. and Vollebergh, H. R. J. (1998), Environmental Kuznets revisited. Time-series versus panel estimation, The CO2-case. Research Centre for Economic Policy OCfEB, https://inis.iaea.org/records/yka3w-8d121, Access Date 06.01.2025.

Dinda, S., Coondoo, D. and Pal, M. (2000), Air quality and economic growth: an empirical study, Ecological Economics, 34/3, 409-423, https://doi.org/10.1016/S0921-8009(00)00179-8.

Dogan, E., Turkekul, B. (2016). CO_2 emissions, real output, energy consumption, trade, urbanization and financial development: testing the EKC hypothesis for the USA. *Environ Sci Pollut Res* **23**, 1203–1213. https://doi.org/10.1007/s11356-015-5323-8

Dogan, N., & Karay, M. (2019). The impact of renewable energy consumption and energy intensity on CO2 emissions from fuel combustions for the case of Turkey: a cointegration analyses. *BİLTÜRK Ekonomi ve İlişkili Çalışmalar Dergisi*, *1*(2), 169-187. https://dergipark.org.tr/en/download/article-file/687892. Access Date:21.12.2025.

Driscoll, J. C., & Kraay, A. C. (1998). Consistent covariance matrix estimation with spatially dependent panel data. *Review of economics and statistics*, *80*(4), 549-560. https://doi.org/10.1162/003465398557825

Erataş, F. and Uysal, D. (2014), Çevresel Kuznets Eğrisi Yaklaşımının "BRICT" Ülkeleri Kapsamında Değerlendirilmesi, İktisat Fakültesi Mecmuası, 64/1, 1-25, https://dergipark.org.tr/en/pub/iuifm/article/9645, Access Date 28.12.2025.

Farhani, S., Mrizak, S., Chaibi, A. and Rault, C. (2014), The environmental Kuznets curve and sustainability: A panel data analysis, Energy Policy, 71, 189-198, https://doi.org/10.1016/j.enpol.2014.04.030.

Galeotti, M., Lanza, A. and Pauli, F. (2006), Reassessing the environmental Kuznets curve for CO2 emissions: A robustness exercise, Ecological economics, 57(1), 152-163, https://doi.org/10.1016/j.ecolecon.2005.03.031.

Groot, H. LF., Withagen, C. A. and Minliang, Z. (2001), Dynamics of China's regional development and pollution. Tinbergen Institute Discussion Paper, https://papers.tinbergen.nl/01036oud.pdf, Access Date, 16.11.2025.

Grossman, G. M. and Krueger, A. (1991), Environmental Impacts of The North American Free Trade Agreement, NBER Working Papers, 3914, DOI 10.3386/w3914.

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The quarterly journal of economics*, *110*(2), 353-377. https://doi.org/10.2307/2118443.

Hannesson, R. Is There a Kuznets Curve for CO_2-Emissions?. *Biophys Econ Sust*, **7**, 4 (2022). https://doi.org/10.1007/s41247-022-00099-w

Hausman, J. A. (1978). Specification tests in econometrics. *Econometrica: Journal of the econometric society*, 1251-1271. https://doi.org/10.2307/1913827

Kaufmann, R. K., Davidsdottir, B., Garnham, S. and Pauly, P. (1998), The determinants of atmospheric SO2 concentrations: reconsidering the environmental Kuznets curve, Ecological economics, 25(2), 209-220, https://doi.org/10.1016/S0921-8009(97)00181-X.

Kacprzyk, A., & Kuchta, Z. (2020). Shining a new light on the environmental Kuznets curve for CO2 emissions. *Energy Economics*, *87*, 104704. https://doi.org/10.1016/j.eneco.2020.104704

Kiliç, C., & Balan, F. (2018). Is there an environmental Kuznets inverted-U shaped curve?. *Panoeconomicus*, *65*(1), 79-94. https://doi.org/10.2298/PAN150215006K

Kuznets, S. (1955). Economic Growth and Income Inequality. The American Economic Review, XLV, https://assets.aeaweb.org/asset-server/files/9438.pdf, Access Date, 05.01.2026.

Li, H., Grijalva, T., & Berrens, R. P. (2007). Economic growth and environmental quality: a meta-analysis of environmental Kuznets curve studies. *Economics Bulletin*, *17*(5), 1-11. https://ideas.repec.org/a/ebl/ecbull/eb-06q20005.html, Access Date, 05.01.2026.

List, J. A. and Gallet, C. A. (1999), The environmental Kuznets curve: does one size fit all?, Ecological economics, 31/3, 409-423, https://doi.org/10.1016/S0921-8009(99)00064-6.

Luzzati, T., Orsini, M., & Gucciardi, G. (2018). A multiscale reassessment of the Environmental Kuznets Curve for energy and CO2 emissions. *Energy policy*, *122*, 612-621. https://doi.org/10.1016/j.enpol.2018.07.019

Mor, S. and Jindal, S. (2012), Estimation of Environmental Kuznets Curve and Kyoto Parties: A Panel Data Analysis. International Journal of Computational Engineering & Management, 15/1, 2230-7893, https://www.researchgate.net/publication/304284506_Estimation_of_Environmental_Kuznets_Curve_and_Kyoto_Parties_A_Panel_Data_Analysis, Access Date 18.12.2025.

Narayan, P. K., & Narayan, S. (2010). Carbon dioxide emissions and economic growth: Panel data evidence from developing countries. *Energy policy*, *38*(1), 661-666. https://doi.org/10.1016/j.enpol.2009.09.005

Özokcu, S., & Özdemir, Ö. (2017). Economic growth, energy, and environmental Kuznets curve. *Renewable and sustainable energy reviews*, *72*, 639-647. https://doi.org/10.1016/j.rser.2017.01.059

Panayotou, T. (1993). Emprical Test and Policy Analysis of Environmental Degradation at Different Stages of Economic Development, Working Paper WP238, Technology and Employment Programme, International Labour Office, https://webapps.ilo.org/public/libdoc/ilo/1993/93B09_31_engl.pdf, Access Date 14.12.2025.

Panayotou, T. (1997). Demystifying the environmental Kuznets curve: turning a black box into a policy tool, Environment and development economics, 2/4, Special Issue, 465-484, https://www.jstor.org/stable/44379189, Access Date 01.01.2026.

Persyn, D., & Westerlund, J. (2008). Error-Correction–Based Cointegration Tests for Panel Data. *The Stata Journal: Promoting Communications on Statistics and Stata*, *8*(2), 232-241. https://doi.org/10.1177/1536867X0800800205.

Pesaran, M. H. (2004). General diagnostic tests for cross section dependence in panels. Cambridge Working Papers. Economics, 1240(1), 1. https://docs.iza.org/dp1240.pdf Access Date: 10.12.2025.

Pesaran, M. H. (2006). Estimation and inference in large heterogeneous panels with a multifactor error structure. *Econometrica*, *74*(4), 967-1012. https://doi.org/10.1111/j.1468-0262.2006.00692.x

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of applied econometrics*, *22*(2), 265-312. https://doi.org/10.1002/jae.951

Pesaran, M. H., & Smith, R. (1995). Estimating long-run relationships from dynamic heterogeneous panels. *Journal of econometrics*, *68*(1), 79-113. https://doi.org/10.1016/0304-4076(94)01644-F

Pesaran, M. H., Shin, Y., & Smith, R. P. (1999). Pooled Mean Group Estimation of Dynamic Heterogeneous Panels. *Journal of the American Statistical Association*, *94*(446), 621–634. https://doi.org/10.1080/01621459.1999.10474156

Pesaran, M. H., Smith, L. V., & Yamagata, T. (2013). Panel unit root tests in the presence of a multifactor error structure. *Journal of Econometrics*, *175*(2), 94-115. https://doi.org/10.1016/j.jeconom.2013.02.001

Ragoubi, H., & Mighri, Z. (2021). Environmental Kuznets Curve for CO 2 Emissions in Middle-Income Countries: a Dynamic Spatial Panel Data Analysis. *Statistika: Statistics & Economy Journal*, *101*(1). https://csu.gov.cz/docs/107508/a8ce0fd6-89b4-0d44-d2ca-840ee09ddf33/32019721q1_ragoubi_analyses.pdf?version=1.0 Access Date:25.12.2025.

Rahman, HU., Ghazali, A., Bhatti, G. A. and Khan, S. U. (2020), Role of Economic Growth, Financial Development, Trade, Energy and FDI in Environmental Kuznets Curve for Lithuania: Evidence from ARDL Bounds Testing Approach, Engineering Economics, 31/1, 39-49, http://dx.doi.org/10.5755/j01.ee.31.1.22087.

Ramsey, J. B. (1969). Tests for Specification Errors in Classical Linear Least-Squares Regression Analysis, *Journal of the Royal Statistical Society: Series B (Methodological)*, Volume 31, Issue 2, July 1969, Pages 350–371, https://doi.org/10.1111/j.2517-6161.1969.tb00796.x

Roberts, J. T. and Grimes, P. E. (1997), Carbon intensity and economic development 1962–1991: a brief exploration of the environmental Kuznets curve, World development, 25/2, 191-198, https://doi.org/10.1016/S0305-750X(96)00104-0.

Roca, J., & Alcántara, V. (2001). Energy intensity, CO2 emissions and the environmental Kuznets curve. The Spanish case. *Energy policy*, *29*(7), 553-556. https://doi.org/10.1016/S0301-4215(00)00154-3

Saatçi, M. and Dumrul, Y. (2011), Çevre Kirliliği Ve Ekonomik Büyüme İlişkisi: Çevresel Kuznets Eğrisinin Türk Ekonomisi İçin Yapısal Kırılmalı Eş-Bütünleşme Yöntemiyle Tahmini, Erciyes Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi, 37, 65-86, https://dergipark.org.tr/tr/pub/erciyesiibd/article/77942, Access Date 18.12.2025.

Saqib, M., & Benhmad, F. (2021). Updated meta-analysis of environmental Kuznets curve: Where do we stand? *Environmental Impact Assessment Review*, *86*, 106503. https://doi.org/10.1016/j.eiar.2020.106503

Selden, M. T. and Song, D. (1994), Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution?, Journal of Environmental Economics and Management, 27/2, 147-162, https://doi.org/10.1006/jeem.1994.1031.

Shafik, N., & Bandyopadhyay, S. (1992). *Economic growth and environmental quality: time-series and cross-country evidence* (Vol. 904). World Bank Publications. https://scispace.com/pdf/economic-growth-and-environmental-quality-time-series-and-3f1hsb3no2.pdf Access Date: 29.12.2025.

Shuai, C., Chen, X., Shen, L., Jiao, L., Wu, Y., & Tan, Y. (2017). The turning points of carbon Kuznets curve: evidences from panel and time-series data of 164 countries. Journal of cleaner production, 162, 1031-1047. https://doi.org/10.1016/j.jclepro.2017.06.049

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. *World development*, *32*(8), 1419-1439. https://doi.org/10.1016/j.worlddev.2004.03.004

Stern, D. I. and Common, M. S. (2001), Is there an environmental Kuznets curve for sulfur?, Journal of Environmental Economics and Management, 41/2, 162-178, https://doi.org/10.1006/jeem.2000.1132.

Sun, J. (1999). The nature of CO2 emission Kuznets curve. *Energy policy*, *27*(12), 691-694. https://doi.org/10.1016/S0301-4215(99)00056-7

Torras, M. and Boyce, J. K. (1998), Income, inequality, and pollution: a reassessment of the environmental Kuznets curve, Ecological economics, 25/2, 147-160, https://doi.org/10.1016/S0921-8009(97)00177-8.

Tutulmaz, O. (2021), Environmental Kuznets Curve: An Analytical Evaluation on Carbondioxide Emission in the Scales of Turkey, the Region and World Countries, *Avrasya Etüdleri,* 42/2, 51-82, https://dergipark.org.tr/tr/pub/avrasya/article/392387, Access Date 26.12.2025.

Wang, Y., Han, R. and Kubota, J. (2016), Is there an environmental Kuznets curve for SO2 emissions? A semi-parametric panel data analysis for China, Renewable and Sustainable Energy Reviews, 54, 1182-1188, https://doi.org/10.1016/j.rser.2015.10.143.

Westerlund, J. (2007). Testing for error correction in panel data. *Oxford Bulletin of Economics and statistics*, *69*(6), 709-748. https://doi.org/10.1111/j.1468-0084.2007.00477.x

White, H. (1980). A Heteroskedasticity-Consistent Covariance Matrix Estimator and a Direct Test for Heteroskedasticity. *Econometrica*, *48*(4), 817–838. https://doi.org/10.2307/1912934

Zambrano-Monserrate, M. A., Carvajal-Lara, C. and Urgiles-Sanchez, R. (2018), Is there an inverted U-shaped curve? Empirical analysis of the Environmental Kuznets Curve in Singapore, Asia-Pacific Journal of Accounting & Economics, 25/1-2, 145-162, https://doi.org/10.1080/16081625.2016.1245625.

Zhang, Y., Chen, X., Wu, Y., Shuai, C., & Shen, L. (2019). The environmental Kuznets curve of CO2 emissions in the manufacturing and construction industries: a global empirical analysis. *Environmental Impact Assessment Review*, *79*, 106303. https://doi.org/10.1016/j.eiar.2019.106303