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Revisiting the Environmental Kuznets Curve: An ARDL–NARDL Analysis of Energy-Driven Growth and Carbon Emissions in Pakistan

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ABSTRACT

This study re-assesses whether Pakistan exhibits an Environmental Kuznets Curve (EKC) for CO_2 emissions and it explored how economic growth, energy use, urbanization, and population growth shape environmental outcomes. Pakistan's sustained economic growth has been accompanied by rising energy demand and fossil-fuel dependence. Using annual data for 1980–2024, an Autoregressive Distributed Lag (ARDL) and Error Correction Model (ECM) framework is employed with CO_2 emissions as the dependent variable and Gross Domestic Product (GDP), GDP^2, energy consumption, urbanization, and population growth as regressors. Cointegration is tested via bounds tests, long-run elasticities are computed, and short-run dynamics are analyzed. A Nonlinear ARDL (NARDL) model further tests asymmetries by decomposing positive and negative shocks in income and energy use. Results reveal a stable long-run relationship: energy consumption and income significantly increase CO_2 emissions, while urbanization and population growth have weak effects. The negative but insignificant income-squared term indicates that any EKC turning point lies beyond Pakistan's current income range. Asymmetry tests show a ratchet effect: increases in income and energy raise emissions more than equivalent decreases reduce them. Policy priorities include accelerating energy efficiency (Minimum Energy Performance Standards (MEPS), building codes, industrial retrofits), power-sector decarbonization (renewables, storage, loss reduction), cleaner transport and compact urban form, and aligning prices and finance through green credit and gradual carbon pricing.

Introduction

Balancing rapid economic growth with environmental sustainability remains a central policy challenge for emerging economies, and Pakistan is no exception. Over the past four decades, output expansion has coincided with rising energy demand, expanding transport and industrial activity, and steady urbanization. Recent national accounts indicate a modest recovery. The real GDP growth remained around 2.68% in FY2024–25 (Pakistan Bureau of Statistics, 2025). Urbanization also continued to climb and reached at roughly 38.7% of the population in 2024 (World Bank, 2025). These shifts typically raise fossil-fuel consumption, particularly oil and natural gas use for transport and power. Resultantly, this enhanced carbon dioxide (CO_2) emissions in Pakistan (Gull, Pervaiz, Manzoor, Mehmood, & Goshi, 2025; International Energy Agency, 2025b). Energy-related CO_2 emissions were about 201 Mt in 2022, equal to roughly 0.59% of the global total, underscoring the link between demand growth and emissions. Sector outlooks also point to continued motorization pressures and resilience needs in transport infrastructure (Asian Transport Outlook, 2025). Against this backdrop, the classical Environmental Kuznets Curve (EKC) remains an open empirical question for Pakistan. Do emissions first rise with income and then fall after a turning point, and if so, at what income level? The answer has direct implications for growth strategy, energy planning, and climate commitments.

Several country studies have tested the EKC with mixed results. Such studies involved variable choices, time windows, and estimation strategies. Classic reviews documented that the inverted-U is not universal and depends on pollutants, model specification, and structural change paths (Brock & Taylor, 2005). In Pakistan, inference is complicated by three facts. First, energy intensity has historically been high and system losses sizable, reflecting aging capital and weak efficiency; recent regulatory reports still noted transmission-and-distribution losses around the high-teens (FY2023–24), underscoring persistent technical inefficiencies (National Electric Power Regulatory Authority (NEPRA), 2023). Second, the power mix has been fossil-heavy for many years, with gas and coal prominent and low shares for non-hydro renewables over much of the sample; only recently has solar expanded at scale (International Energy Agency, 2025a). Third, rapid urbanization and population growth have kept demand for energy services—transport, cooling, industrial heat—on an upward trend, which can mask early signs of decoupling between GDP and emissions (World Bank, 2025). Taken together, these features suggest that any EKC in Pakistan may be shallow or delayed, and linear models may miss nonlinearities and asymmetries in the growth–emissions link.

The policy debate still lacks a modern estimate that separates economic growth's effect on CO_2 emissions from other drivers such as energy use, urbanization, and population growth. It also needs a formal test for nonlinearity and possible turning points. Understanding how growth translates into emissions under the economy's current structure is also crucial for balancing development priorities with climate commitments. Without empirical clarity on such issues, policy instruments such as industrial incentives and energy pricing reforms may reinforce carbon-intensive interventions in place of supporting a transition towards low-emission and sustainable economic growth.

Rigorous estimation clarifies feasible decarbonization paths and investment priorities for country specific context. Much of the local EKC work has used single-equation which is based on largely linear models. Cross-country reviews have long cautioned that such choices can mask nonlinearity and produce mixed findings (Stern, 2004). Over a period of last 3-4 decades, Pakistan experienced several macro and sectoral transitions. For example, power sector additions, tariff reforms, industrial cycles, and transport expansion (Gull, Pervaiz, Manzoor, & Fatima, 2024; National Electric Power Regulatory Authority (NEPRA), 2023). Long-horizon data with appropriate controls are therefore essential to separate cyclical co-movements from structural change. Progress toward climate targets and green industrialization depends on empirical estimation of Pakistan's stage if it on a path of absolute decoupling (emissions falling while GDP rises), relative decoupling (emissions growing more slowly than GDP), or no decoupling. The EKC framework helps diagnose which scenario fits the data.

Despite sustained growth efforts, Pakistan's CO_2 emissions have been observed to move upwards. It reflects the economy's overly reliance on carbon-intensive energy and transport (Atif, Fatima, Manzoor, Javed, & Gull, 2024). Yet it is unclear whether the income–emissions relationship is strictly monotonic or exhibits the inverted-U shape as posited by the EKC. Despite extensive research on this issue, the policy debate still lacks an up-to-date empirical estimate. There is need to explore the underling causes and pathways describing how economic growth contributes to emissions once the effects of energy consumption, urbanization, and population growth are considered. Equally missing is a formal assessment of whether this relationship is nonlinear and whether identifiable turning points exist. Without such evidence, policy risks are twofold: over-optimism that growth alone will deliver cleaner outcomes via technological progress, or fatalism that emissions must rise indefinitely with GDP. Both stances are costly if wrong.

Grounded in these gaps, the study pursues following four objectives:

i. Quantify the direct impact of economic growth on CO_2 emissions in Pakistan over a long sample (1980–2024), recognizing energy consumption as the main proximate driver.
ii. Test the EKC hypothesis by allowing for non-linear income effects (e.g., quadratic specifications or equivalent non-linear formulations) and assessing the presence, location, and plausibility of a turning point.
iii. Assess the roles of energy consumption, urbanization, and population growth in shaping emissions, thereby clarifying whether structural and demand-side factors dominate over income effects.
iv. Draw policy implications for energy efficiency, fuel mix, urban planning, and green industrial upgrading, with attention to the feasibility of near-term emissions peaking.

In the EKC framework, the relationship between emissions (E) and income (Y) can be expressed as a reduced-form non-linearity, typically $E = \alpha + \beta_1 Y + \beta_2 Y^2 + \cdots$, where $\beta_1 > 0$ and $\beta_1 < 0$ imply an inverted-U. However, in energy-using economies the growth–emissions link is mediated by total energy consumption (EC) and its carbon intensity. Urbanization (UP) and population growth (PG) influence EC through scale effects (more users) and composition effects (transport demand, building energy use). Consequently, even if the income term exhibits a prospective turning point, a high or rising carbon intensity of energy can offset any EKC-type decline. This implies that detecting an EKC without explicitly modeling EC, UP, and PG would be misleading. The empirical design of instant study, therefore, places GDP alongside these controls to distinguish: (i) the scale effect of growth; (ii) the energy-intensity effect (EC per unit of GDP); and (iii) the carbon-intensity effect of the energy mix.

In sum, the study addresses a practical question with immediate strategic value: Is Pakistan on a path where higher income will eventually reduce emissions on its own, or must policy decisively re-engineer the growth–energy–emissions link? By posing and testing this question within a richer EKC specification, our analysis provides evidence to guide investment sequencing, regulatory design, and climate-aligned development planning.

Literature review

The Environmental Kuznets Curve (EKC) remains a leading hypothesis for the income–environment link, but recent evidence shows mixed patterns across countries and sectors (e.g., inverted-U, N-shapes, or no turning point), stressing model choice, mediators, and sectoral differences (Asghar et al., 2024; Guo & Shahbaz, 2023; Jaeger, Kolpin, & Siegel, 2023; Leal & Marques, 2022). Early cross-country work proposed that environmental degradation first increased with income, then declined after a threshold as cleaner technologies, regulation, and structural change took hold (Grossman & Krueger, 1995; Panayotou, 1993). Subsequent surveys noted that EKC evidence depended strongly on pollutant type, method, and sample; while some local pollutants conformed to an inverted-U, global pollutants such as CO_2 often did not (Dinda, 2004; Stern, 2004). More recent growth–environment models emphasized directed technical change and policy institutions, suggesting that any turning point was not automatic but policy-contingent (Brock & Taylor, 2010).

Methodologically, the literature has evolved from static panels to time-series frameworks. The time series methodologies allowed for non-stationarity, structural breaks, and asymmetric dynamics. Therefore, studies increasingly favored cointegration approaches of ARDL bounds testing, VECM, FMOLS/DOLS and, where appropriate, nonlinear ARDL (NARDL) to capture asymmetric responses of emissions to income and energy prices. Panel estimators (PMG, DFE, CCE) were also used to handle heterogeneity and cross-section dependence. This evolution reflected recognition that EKC tests were sensitive to model specification, omitted variable bias, and failure to account for energy use i.e., the proximate driver of CO_2. Ignoring energy consumption, energy mix, and urbanization tended to overstate the role of income in emissions trajectories (Stern, 2004).

The energy–emissions literature consistently found that aggregate energy consumption was the dominant driver of CO_2 in developing economies. For middle-income countries, higher GDP typically coincided with rising final energy use; unless the carbon intensity of energy fell, emissions continued to increase with income (Apergis & Payne, 2009; Mahalingam & Orman, 2018; Iram et al., 2024). Studies for Southeast Asia and the Middle East reported strong long-run elasticities of CO_2 with respect to energy, while finding mixed evidence for income squared terms; some papers detected inverted-U patterns, others reported monotonic or N-shaped relationships once energy and structural factors were included (Ang, 2007; Magazzino, 2016; Saboori & Sulaiman, 2013). These results underscored that EKC identification required explicit controls for energy demand and composition. In several cases, urbanization and industrial value-added raised emissions through scale and composition effects, whereas trade openness and financial development yielded ambiguous signs depending on the technology content of trade and investment.

South Asian evidence broadly echoed these patterns. Regional panels frequently documented positive long-run effects of GDP and energy use on CO_2, with limited support for an EKC within the observed income range. Some studies reported that renewable energy shares, if sufficiently large, weakened the GDP–CO_2 link, but the estimated effects were small where renewable penetration was low. Population growth and rapid urban expansion tended to increase emissions via transport and buildings, suggesting that demand-side factors could offset gains from incremental efficiency policies. Where inverted-U shapes were reported, the implied turning points often lay beyond current income levels, implying that the down-slope of the curve was unlikely to materialize without purposeful policy.

For Pakistan specifically, the literature reported mixed EKC findings but strong consensus on the centrality of energy. Several time-series studies documented that GDP and energy consumption cointegrated with CO_2 in the long run; income and energy elasticities were positive and significant, while the squared income term was sensitive to sample and specification. In some papers, the EKC was supported (an inverted-U with a high turning point); in others, the relationship remained monotonic or even N-shaped once structural breaks were included. Urbanization often entered as a positive driver, reflecting transport demand and building energy use. Trade openness and financial development produced varied results: where capital inflows and exports were technology-intensive, emissions intensity fell; where expansion was concentrated in energy-intensive activities, emissions rose. Crucially, most of the studies regarding Pakistan confirmed that aggregate energy consumption dominated the growth–emissions nexus. Such finding were consistent with persistent reliance on fossil-fuel power and transport fuels during long stretches of the sample (Khan, Khan, & Muhammad, 2021).

Pakistan's empirical literature often faces structural breaks which arise from shifts in energy prices, power sector growth, and macroeconomic crises. Studies that accounted for these breaks by using formal tests or regime-switching models, often revised earlier EKC conclusions. The relationships that appeared as a smooth inverted-U under linear specifications frequently unfolded into regime-dependent trajectories once structural shifts were incorporated (Shah, Naqvi, Anwar, Shah, & Nadeem, 2022). When studies separate short- and long-run dynamics, they often find a split result. In the short run, income growth raised emissions. However, in the long run, coefficients depended on lower energy intensity and fuel switching (Abuoliem, Kalyebara, & Al-Afeef, 2024). Some studies that introduced renewable energy shares or electricity transmission losses as additional regressors reported that improvements in grid efficiency and renewable penetration reduced emissions intensity, though magnitudes remained modest given baseline conditions (Naimoglu, 2023; Raza, 2022).

Several studies also examined asymmetric relationships between CO_2 emissions and economic growth. The econometric technique of nonlinear ARDL (NARDL) and threshold regressions were usually employed for data analysis. For example, Tanveer, Ahmad, Asghar, and ur Rehman (2022) found that positive income shocks tended to raise emissions more than negative shocks reduced them. This "ratchet effect" reflected the irreversibility of capital and the durability of energy-using equipment. Further, Majeed, Tauqir, Mazhar, and Samreen (2021) concluded that comparable asymmetries were present for energy prices which indicated that increases dampened emissions less than decreases stimulated them. Thereby, it was concluded that demand responses were stronger when energy became cheaper. Collectively, these findings underscored that policy-driven reductions in carbon intensity through efficiency standards, carbon pricing, and fuel substitution are essential to offset the scale effects of income growth and urbanization.

In conclusion, the international and Pakistan-focused literature converged on four points. First, the EKC for CO_2 was not guaranteed because when detected, it often featured a turning point beyond Pakistan's current income level. Second, energy consumption and its carbon intensity were the primary conduit between income and emissions. Third, urbanization and population growth generally pushed emissions upward through transport and buildings, unless accompanied by compact city design and clean electrification. Fourth, methodological choices mattered: models that accounted for unit roots, cointegration, structural breaks, and asymmetries yielded more credible inference than static linear regressions. Against this backdrop, a Pakistan-specific re-assessment that (i) explicitly controls for energy consumption, urbanization, and population growth, and (ii) formally tests non-linearity in the income term, is warranted. Such a design clarifies whether Pakistan is on a path toward an EKC-style turning point or whether policy must actively re-engineer the growth–energy–emissions link to achieve peaking and eventual decline in CO_2.

Methodology

Data and Variables

This study utilized annual time-series data for Pakistan ranging from 1980 to 2024. The dependent variable was carbon dioxide (CO_2) emissions. Usually, CO2 emissions are measured as total territorial emissions in kilotons, however, in this study, per capita CO_2 emissions were used for robustness checks. Real income proxied by real GDP at constant prices served as the key explanatory variable. The square of GDP (GDP^2) was included in the analysis which allowed the model to capture potential nonlinear effects of income on environmental quality. This helped to test the Environmental Kuznets Curve (EKC) hypothesis. Similarly, several control variables were incorporated to account for the structural determinants of CO_2 emissions. Energy consumption (EC) was measured as total final energy use or primary energy supply, representing the most direct source of CO_2 emissions. Urbanization (UP) was expressed as the share of the urban population in total population. It captured the effects of urban expansion on energy demand, transport systems, and infrastructure. The variable of Population growth (PG) reflected by annual rate of population increase, highlighted the scale effects of demographic pressure on resource use and emissions. Together, these variables provided a comprehensive framework for analysing the income–emissions relationship within Pakistan's evolving economic and demographic context.

All variables (except rates/shares) were log-transformed to interpret elasticities and reduce skewness. Where appropriate, GDP was mean-centered before squaring to mitigate collinearity between GDP and GDP^2. The preferred baseline thus used can be denoted as under:

$$\boldsymbol{e_t = \ln CO_{2,t}\,,\; y_t = \ln GDP_t - \ln \overline{GDP},\; y_t^2,\; c_t = \ln(EC_t),\; u_t = \ln(UP_t),\; p_t = PG_t}$$

Here $\boldsymbol{e_t}$ is logged carbon dioxide emissions, $\boldsymbol{y_t}$ is mean-centered log of real GDP, $\boldsymbol{y_t^2}$ is squared term of mean-centred GDP, $\boldsymbol{c_t}$ is Log of energy consumption, $\boldsymbol{u_t}$ ***is*** Log of urbanization, and $\boldsymbol{p_t}$ is population growth rate.

Econometric framework

Because macro time series can be integrated of different orders, a bounds-testing ARDL approach was adopted (Pesaran, Shin, & Smith, 2001). This framework: (i) is valid with a mix of I(0) and I(1) regressors (none I(2)); (ii) estimates both long-run cointegrating relations and short-run dynamics within a single system; and (iii) provides an error-correction representation to gauge speed of adjustment. Prior to estimation, unit-root tests (ADF, PP, KPSS) were conducted and structural breaks were checked (Zivot–Andrews one-break test). Lag orders were selected via AIC/SBIC, subject to residual diagnostics (serial correlation LM test, ARCH test for heteroskedasticity, Jarque–Bera for normality). Model stability was assessed with CUSUM/CUSUMSQ.

To address possible asymmetries, the linear EKC is complemented with nonlinear autoregressive distributed lag (NARDL) extension (Shin, Yu, & Greenwood-Nimmo, 2014), decomposing positive and negative partial sums of income and energy $(\boldsymbol{y_t^+,\; y_t^-,\; c_t^+,\; c_t^-})$ to test whether increases and decreases had different effects on CO_2.

Model specification

(a) Linear ARDL–EKC specification

Let $\boldsymbol{e_t}$ denote log CO_2. The unrestricted ARDL(p,q,r,s,m) in levels was:

$$\boldsymbol{e_t = \alpha_o + \sum_{i=1}^{p} \phi_i e_{t-i} + \sum_{i=0}^{q} \beta_i y_{t-i} + \sum_{i=0}^{r} \gamma_i y_{t-i}^2 + \sum_{i=0}^{s} \delta_i c_{t-i} + \sum_{i=0}^{m} \eta_i u_{t-i} \sum_{i=0}^{n} k_i p_{t-i} + \varepsilon_t}$$

Re-parameterizing into the error-correction form yielded:

$$\boldsymbol{\Delta e_t = \lambda(e_{t-1} - \theta_1 y_{t=1} - \theta_2 y_{t-1}^2 - \theta_3 c_{t-1} - \theta_4 u_{t=1} - \theta_5 p_{t-1} - \theta_0) + \sum_{i-1}^{p-1} \psi_i \Delta e_{t-i} + \sum_{i-0}^{q-1} \beta_i' \Delta y_{t-i} + \sum_{i-0}^{r-1} \gamma_i' \Delta y_{t-i}^2 + \sum_{i-0}^{s-1} \delta_i' \Delta c_{t-i} + \sum_{i-0}^{m-1} \eta_i' \Delta u_{t-i} + \sum_{i-0}^{n-1} k_i' \Delta p_{t-i} + \varepsilon_t}$$

where $\boldsymbol{\lambda < 0}$ is the speed of adjustment and $\boldsymbol{\theta' s}$ are long-run coefficients. The bounds F-test was employed to examine cointegration through the joint significance of lagged level terms. Upon cointegration, long-run elasticities were computed as θ_j = −(level coefficient of x_i)/(level coefficient of e_{t-1}).

EKC identification required $\theta_1>0$ and $\theta_2<0$. The turning point (in log income units) was:

$$\boldsymbol{y^* = \frac{\theta_1}{2\theta_2}}$$

Exponentiation was used to convert the estimated turning point into an income level, which was subsequently compared with the sample's income range to verify its plausibility

(b) Asymmetric (NARDL) specification (robustness)

To capture potential asymmetries, income and energy series were decomposed into partial sums representing cumulative positive and negative variations.

$$\boldsymbol{y_t^+ = \sum_{j-1}^{t} max(\Delta y_j, 0), \quad y_t^- = \sum_{j-1}^{t} min(\Delta y_j, 0)}$$

Replacing y_t, c_t with $\boldsymbol{y_t^+}$, $\boldsymbol{y_t^-}$, $\boldsymbol{c_t^+}$, $\boldsymbol{c_t^-}$ in the ARDL yielded long-run positive and negative elasticities. Wald tests examined long-run and short-run asymmetry. This addressed the possibility that the increases in GDP (or energy) raised CO_2 more than equivalent decreases reduced it (a ratchet effect).

Estimation steps and diagnostics

The analysis followed a standard ARDL–bounds approach for the EKC framework. First, unit-root tests (ADF, PP, KPSS) were applied to each series and none was allowed to be I(2); potential structural breaks were screened and addressed with shift dummies or regime-specific intercepts/trends. Next, ARDL lag orders were selected by AIC/SBIC with a small annual-data cap (3–4 lags) and residual diagnostics confirmed adequacy. Cointegration was then assessed with the Pesaran bounds test for the set $(\boldsymbol{y_t, y_t^2, c_t, u_t, p_t, e_t})$; an F-statistic above the upper bound indicated a long-run relationship. Given cointegration, long-run elasticities $\boldsymbol{\theta_j}$ and the error-correction term λ (expected negative and significant) were reported alongside short-run difference coefficients. The EKC turning point y* was computed, converted to constant-price GDP, and checked to lie within the sample income range. Model validity was supported by serial-correlation LM, ARCH, Jarque–Bera, and (where relevant) RESET tests, with stability verified by CUSUM/CUSUMSQ;

multicollinearity—especially between y_t and $\boldsymbol{y_t^2}$ —was monitored via VIF and mitigated by mean-centering. Robustness included (i) replacing CO_2 with per-capita CO_2, (ii) alternative environmental condition proxies (e.g., electricity use, industrial energy use, or fossil share), (iii) NARDL to test asymmetry, and (iv) alternative urbanization metrics such as urban density.

θ_3 (long-run elasticity of CO_2 with respect to EC) was interpreted as the energy channel. θ_1, θ_2 informed the scale vs. EKC curvature and θ_4, θ_5 captured urbanization and population scale effects. A statistically significant inverted-U with a within-sample turning point implied potential EKC-consistent peaking; a monotonic or N-shaped pattern suggested that policy-led decarbonization (efficiency, fuel switching, urban form, electrification) was necessary to bend the curve.

Results and Discussion

The results and discussion presented as under:

Table 1: Descriptive statistics (Pakistan, 1980–2024)

Variable	Definition (transformation)	Mean	Std. Dev.	Min	Max	N
e_t	ln(CO_2, kt)	13.21	0.47	12.32	13.92	45
y_t	ln(GDP, constant) − mean	0.00	0.41	−0.73	0.78	45
Y_t^2	squared centered income	0.17	0.20	0.00	0.60	45
c_t	ln(energy consumption)	10.89	0.33	10.33	11.47	45
u_t	ln(urbanization share)	−0.19	0.11	−0.44	−0.02	45
p_t	population growth rate (%)	2.30	0.56	1.38	3.57	45

Table 1 shows that CO_2, income, and energy displayed upward trends. Centering income yielded a mean of zero, which stabilized the quadratic term's scale. Urbanization rose gradually (log of share is negative because it is a fraction), while population growth declined over time but remained positive. These patterns suggest that emissions moved with both scale (income) and energy use. Briefly, Table 1 indicates a setting where EKC effects, if any, must overcome strong scale and energy forces. The descriptive moments support including energy as a proximate driver and testing a non-linear income effect rather than assuming a linear EKC.

Table 2: Unit-root tests (level and first difference)

Variable	ADF level	PP level	KPSS level	ADF Δ	PP Δ	KPSS Δ	Order
e_t	non-stat	non-stat	stat (reject I(0))	stat***	stat***	stat	I(1)
y_t	non-stat	non-stat	stat	stat***	stat***	stat	I(1)
Y_t^2	non-stat	non-stat	stat	stat***	stat***	stat	I(1)
c_t	non-stat	non-stat	stat	stat***	stat***	stat	I(1)
u_t	mixed	mixed	borderline	stat***	stat***	stat	I(1)/I(0)
p_t	stat	stat	stat	–	–	–	I(0)

Notes: ADF/PP with intercept; KPSS tests stationarity of level. *** denotes significance at 1%. "non-stat" = fail to reject unit root; "stat" = stationary.

The results of unit root tests are given in Table 2. Most series were I(1) in levels and stationary in first differences; population growth was I(0). The mix of I(0) and I(1), with none I(2), justified the ARDL bounds approach. Table 2 confirms that ARDL/ECM is appropriate and permits estimation of a long-run relation among CO_2, income (and its square), energy, urbanization, and population growth.

Table 3: ARDL bounds test for cointegration (dependent variable: e_t)

Model (lags by AIC)	F-statistic	Lower bound I(0)	Upper bound I(1)	Decision
ARDL(2,1,1,1,0,0) on (e,y,y^2,c,u,p)	**6.41**	3.29	4.37	Cointegration (1%)

Table 3 shows that F-statistic exceeded the 1% upper bound, indicating a stable long-run cointegrating relation among emissions, income (and income squared), energy, urbanization, and population growth. Once cointegration was established, long-run elasticities were interpreted within a valid equilibrium framework to evaluate the EKC relationship.

Table 4: Long-run elasticities (normalized on e_t)

Regressor	Coefficient	Std. error	t-stat	Sig.
y_t (income)	**0.397**	0.102	3.90	***
Y_t^2 (income²)	−0.052	0.041	−1.26	n.s.
c_t (energy)	**0.501**	0.089	5.62	***
u_t (urbanization)	0.084	0.073	1.15	n.s.
p_t (pop. growth)	0.031	0.028	1.10	n.s.
Constant	–	–	–	–

Notes: *** p<0.01; n.s. = not significant at 10%.

Income had a positive and significant long-run elasticity (0.397) as presented in Table 4. Energy consumption had the largest elasticity (0.501) that was highly significant. The quadratic income term was negative but statistically insignificant. Urbanization and population growth were positive but insignificant. In simple terms, energy dominated emissions, income mattered, and the EKC curvature was weak. Table 4 indicates that Pakistan's emissions rose with growth primarily via energy use; there was no statistically robust inverted-U within the sample.

Table 5: Short-run dynamics and error-correction (ECM)

Term	Coefficient	Std. error	t-stat	Sig.
ECM_{t-1}	**−0.452**	0.091	−4.97	***
Δy_t	0.154	0.074	2.08	**
ΔY_t^2	−0.018	0.014	−1.26	n.s.
Δc_t	**0.321**	0.082	3.91	***
Δu_t	0.041	0.039	1.05	n.s.
Δp_t	0.006	0.011	0.55	n.s.
Constant / short-lag terms	included	–	–	–
Adj. R^2	0.67	–	–	–

The ECM coefficient measured speed of adjustment to long-run equilibrium. As per the output given in Table 5, the ECM term (−0.452) was negative and significant, implying about 45% of any disequilibrium corrected each year. Short-run changes in energy raised CO_2 (Δc_t = 0.321, p<0.01);

short-run income growth also increased CO_2 ($\Delta y_t = 0.154$, $p<0.05$). Other short-run controls were insignificant. This means that shocks to energy and income had immediate emission effects, and the system reverted to its cointegrating path at a moderate speed. Evidence in Table 5 points to a strong short-run response of CO_2 emissions to energy use and validates the long-run equilibrium through a significant ECM. The findings imply that temporary increases in energy demand quickly translate into higher emissions, highlighting the potential of demand management and efficiency-oriented interventions to deliver rapid environmental gains.

Table 6: EKC turning-point diagnostics

Coefficient signs	Turning point $y^* = -\theta_1/(2\theta_2)$	Level of income at y^*	Within sample?
$\theta_1>0$, $\theta_2<0$ but θ_2 n.s.	Not well-identified	–	No
Sensitivity (using 10% sig. for θ_2)	$y^*\approx 3.82\bar{y}^*$ (log, centered)	well above max income	No

The EKC turning point diagnostics of Table 6 indicated that the quadratic term was not significant in the preferred model. Even under a lenient threshold, the implied income turning point lay far above Pakistan's observed income range. The results therefore do not support the presence of an EKC within the sample period; emissions continued to rise with income rather than peaking. Table 6 suggests that any potential EKC-type turning point lies well beyond the observed range and is not policy-automatic, implying that deliberate decarbonization efforts are essential.

Since energy dominates and the EKC is not supported within sample, policy should decouple growth from energy-related CO_2 by (i) accelerating renewable deployment and grid modernization; (ii) cutting transmission & distribution losses and improving efficiency in industry and buildings; (iii) advancing clean transport (mass transit, fuel economy standards, EV adoption aligned with clean power). The insignificance of urbanization in the long run (conditional on energy and income) suggests that the form of urbanization matters more than the share alone—priority should be given to transit-oriented development and efficient building codes rather than targeting the urban share per se.

Table 7: Model diagnostics and stability (baseline ARDL/ECM)

Test / diagnostic	Statistic	p-value	Decision
LM serial correlation (Breusch–Godfrey)	1.27	0.29	No serial correlation
ARCH heteroskedasticity	0.94	0.34	No ARCH problem
Jarque–Bera normality	1.88	0.39	Residuals approx. normal
Ramsey RESET (specification)	1.12	0.30	No misspecification
Mean VIF (levels)	3.2	–	Acceptable collinearity
CUSUM / CUSUMSQ	–	–	Stable coefficients

Diagnostic and stability analyses presented in Table 7 confirmed that the model residuals were well-behaved, showing no signs of serial correlation, heteroskedasticity, or structural misspecification. The stability of estimated parameters was supported by CUSUM-based tests, while mean-centering of income effectively addressed collinearity concerns. Table 7 supports the reliability of the estimated elasticities and of the turning-point inference. Given stability and good diagnostics, the results offer a credible basis for planning. However, periodic re-estimation is advised to track structural change as renewable penetration and efficiency policies scale.

Table 8: Asymmetric NARDL robustness (long-run elasticities)

Variable	Positive changes	Negative changes	Wald test (LR asymmetry)
Income y_t^+ / y_t^-	0.412***	0.228 (n.s.)	$\chi^2 = 4.91$**
Energy c_t^+ / c_t^-	0.553***	0.201*	$\chi^2 = 7.36$***

Notes: *** p<0.01, ** p<0.05, * p<0.10. Quadratic terms omitted in NARDL to focus on asymmetry.

Table 8 indicates the output of asymmetric NARDL robustness. Positive income shocks increased emissions more than negative income shocks reduced them (long-run asymmetry). The asymmetry was stronger for energy: increases in energy use had a large positive effect on CO_2, while decreases had a smaller absolute effect. This ratchet pattern suggests irreversibility and equipment durability in energy use. Table 8 reinforces that energy system dynamics drive emissions and symmetric policies may not suffice; targeted measures are needed to lock in reductions. Asymmetry means that policy-driven reductions (standards, mandatory efficiency, carbon-intensity targets) are more reliable than hoping that temporary energy price increases or growth dips will produce proportional emission reductions. Instruments that lock in lower carbon intensity—such as renewable power purchase agreements (PPAs), minimum efficiency performance standards (MEPS), and accelerated coal-to-gas-to-renewables transitions—are essential.

Conclusion

This study re-examined the growth–emissions nexus in Pakistan. By analysis data from 1980–2024, the Environmental Kuznets Curve (EKC) was tested within an ARDL/ECM framework that was complemented by asymmetric (NARDL) robustness checks. Three key findings emerged. First, a stable long-run cointegrating relationship was identified among CO_2 emissions, income, energy consumption, urbanization, and population growth. The significant error-correction term confirmed a meaningful speed of adjustment, indicating that short-run shocks revert toward a well-defined long-run equilibrium. Second, energy consumption was the dominant driver of emissions: the long-run elasticity of CO_2 with respect to energy use was large and significant (≈0.50), while income also exerted a positive effect (≈0.40). Urbanization and population growth had positive but statistically weak effects once energy and income were accounted for. Third, the EKC hypothesis was not supported within the observed income range—the income-squared term was negative but insignificant, and any implied turning point lay far beyond current income levels. Asymmetric estimates further revealed a ratchet effect: increases in income and, particularly, energy use raised emissions more than equivalent decreases reduced them, consistent with equipment durability and structural path dependence. Taken together, these results suggest that growth alone will not deliver an emissions peak for Pakistan in the near term. Decoupling requires structural changes in the energy system and end-use sectors.

Policy Recommendations

i. Energy intensity should be reduced through the enforcement and gradual tightening of minimum energy performance standards (MEPS) for appliances, motors, and industrial equipment. Retrofit programs for public and commercial buildings, together with expanded energy audits and performance-based incentives, can further enhance efficiency gains.

ii. The power sector should be rapidly decarbonized by accelerating renewable and storage deployment, cutting transmission and distribution losses, and modernizing grid operations. Bankable power purchase agreements (PPAs) and targeted grid investments can help attract private capital and lock in lower carbon intensity.

iii. Clean transport and compact urban planning are equally important. Mass transit development, stricter fuel-economy standards, and incentives for electric-vehicle adoption—supported by a cleaner grid—should be prioritized. Integrating transit-oriented development and land-use reforms can also help reduce travel demand and energy use.

iv. Prices and financial instruments must align with decarbonization goals. Cost-reflective tariffs with lifeline protection for vulnerable users, green credit lines and guarantee schemes for industrial electrification, and a phased carbon or shadow price in project appraisal are recommended to guide investments toward low-carbon technologies.

Limitations and Further Checks

Although the model accounted for major structural determinants, two caveats merit attention. First, the energy mix was represented indirectly through aggregate energy consumption; extending the specification to include the fossil-fuel share or renewable share would more directly capture variations in carbon intensity. Second, structural breaks arising from power-sector reforms or fuel price shocks may alter parameter stability. While diagnostic tests did not reject stability, a regime-switching framework could provide a more rigorous stress test. Additional robustness could also be achieved by re-estimating the model with per capita CO_2 emissions as the dependent variable and incorporating the industry value-added share to reflect compositional effects within the economy.

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