Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

# Digitalization, Renewable Energy Transition, and the Environmental Kuznets Curve: Evidence from a Robust Panel Analysis of GCC Economies

**Mousse Abdi Mohamoud**

mousse.abdi@ju.edu.et

jimma university

**Ibraahim Adem Aw-Cali**

jimma university

**Abdiasis Ali Mohamoud**

jimma university

**Research Article**

**Keywords:** GCC economies, Environmental Kuznets Curve (EKC), Digitalization, Renewable energy transition, STIRPAT framework, Sustainable urbanization

**Posted Date:** July 3rd, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-10105760/v1

**License:** This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

**Additional Declarations:** No competing interests reported.

# Abstract

This study investigates the nexus between digitalization, energy transition, and carbon emissions within the Environmental Kuznets Curve (EKC) framework for Gulf Cooperation Council (GCC) economies over the period 2005–2024. Integrating Ecological Modernization Theory and the STIRPAT framework, the research employs Driscoll-Kraay robust fixed-effects and Method of Moments Quantile Regression (MM-QR) to account for cross-sectional dependence and distributional heterogeneity. While energy intensity and urbanization emerge as the primary drivers of carbon intensification, with urbanization exhibiting a notably high elasticity of 2.95, internet penetration and renewable energy consumption function as critical decoupling channels. Distributional analysis via MM-QR reveals significant heterogeneity: the mitigating influence of digitalization strengthens at higher emission quantiles, whereas renewable energy is most effective in low-emission conditions. These findings imply that for GCC nations, transitioning to the descending limb of the EKC is not an automatic consequence of affluence but requires deliberate policy synchronization. Strategic implications emphasize the necessity of green urbanization, the conceptualization of digital infrastructure as environmental infrastructure, and the integration of renewable energy with smart-grid modernization. The study concludes that the "digitalization dividend" and energy diversification are indispensable instruments for structural decarbonization in hydrocarbon-dependent economies, suggesting that the downward side of the EKC must be actively constructed through policy intervention.


# 1. Introduction

Climate change has become a central constraint on contemporary development policy because the pursuit of economic expansion now occurs within a narrow global carbon budget. The Paris Agreement commits countries to hold the increase in global average temperature to well below 2°C above preindustrial levels and to pursue efforts to limit warming to 1.5°C. The 1.5°C threshold is not only a diplomatic target; it is a scientifically and ethically important benchmark because exceeding it intensifies climate-related inequality, ecological disruption, food insecurity, and heat-related health risks (Cheung et al., 2016; King & Harrington, 2018; Vicedo-Cabrera et al., 2018). Existing nationally determined contributions remain insufficient to keep global warming on a 1.5°C-consistent pathway, implying that countries must strengthen mitigation strategies while also preserving development momentum (Rogelj et al., 2016; Tanaka & O'Neill, 2018; Wigley, 2018).

The challenge is particularly acute for economies in which urbanization, rising income, expanding energy demand, trade integration, and digital transformation are unfolding simultaneously. Economic growth can improve welfare, infrastructure, and technological capacity, but it may also increase carbon dioxide emissions when growth depends on fossil-fuel-intensive production and consumption. This tension is captured by the Environmental Kuznets Curve (EKC) hypothesis, which proposes that environmental degradation initially rises with income but eventually declines after economies reach a higher stage of development and acquire cleaner technologies, stronger institutions, and less pollution-intensive industrial structures (Sohag et al., 2019; Wang et al., 2024). However, the EKC mechanism should not be

interpreted as an automatic consequence of income growth. Whether emissions eventually fall depends on the type of energy system, the quality of urban expansion, the nature of trade, and the extent to which technological progress is directed toward low-carbon transformation.

A major limitation of much EKC scholarship is that the technology channel is frequently treated as residual or secondary. Bibliometric and systematic reviews of EKC research show that the literature has historically emphasized income and energy consumption while giving less direct attention to digitalization, internet penetration, and the interaction between digital infrastructure and renewable energy deployment (Koondhar et al., 2021; Lau et al., 2025; Pincheira & Zuniga, 2021). This omission is consequential. Digital technologies can increase electricity demand through data centers, devices, and ICT infrastructure, but they can also reduce emissions by improving energy consumption, enabling smart grids, supporting renewable energy integration, improving environmental monitoring, and facilitating cleaner production systems (Axenbeck et al., 2024; Dimian et al., 2025; Santarius et al., 2020; Stermieri et al., 2024). Therefore, the environmental effect of digitalization is theoretically ambiguous and empirically dependent on context.

In the contemporary global discourse, climate change stands as the most formidable threat to sustainable development, manifesting through unprecedented shifts in weather patterns, rising sea levels, and ecological degradation (Kilinc-Ata et al., 2026; Ridwan et al., 2024). At the heart of this crisis is the surge in anthropogenic carbon dioxide ($CO_2$) emissions, which account for approximately 65% of global greenhouse gases. While the international community has committed to the Paris Agreement and Sustainable Development Goal (SDG) 13, a critical tension persists: many developing and emerging economies face a "growth-environment" paradox. These nations must prioritize economic expansion to alleviate poverty and improve welfare, yet this expansion is traditionally fueled by carbon-intensive industrialization and fossil-fuel-based energy consumption (Kilinc-Ata & Al-Fori, 2026; Voumik et al., 2023).

Despite the benefits of economic growth, the resulting increase in income often correlates with a spike in energy demand, rapid urban expansion, and the exploitation of natural resources—factors that exacerbate the carbon footprint (Ridwan et al., 2024). However, the "Fourth Industrial Revolution" offers a potential pathway out of this trade-off. The convergence of digitalization and the energy transition represents a transformative opportunity. Digital solutions, such as smart grids and ICT penetration, along with the scaling of renewable energy, are theorized to "uncouple" economic activity from environmental harm (Kilinc-Ata et al., 2026). The problem remains, however, that these enablers may have ambiguous effects; for instance, digitalization may drive efficiency while simultaneously increasing electricity demand, and trade openness may lead to either technology transfer or the relocation of "dirty" industries.

A review of the existing Environmental Kuznets Curve (EKC) literature reveals several limitations. First, traditional studies predominantly focus on the narrow nexus between GDP and energy, often neglecting the integrated role of digital transformation and financial technology (FinTech) in mitigating emissions (Kilinc-Ata & Al-Fori, 2026). Second, while recent studies have explored these variables in isolation, few

have examined the cumulative impact of digitalization, renewable energy, urbanization, oil dependence, and trade openness within a single framework. Methodologically, much of the existing research relies on mean-based estimators that overlook cross-sectional dependence and unobserved heterogeneity. This study fills these gaps by analyzing a multi-regional panel through the dual lens of Driscoll–Kraay (D-K) standard errors, to account for spatial and temporal dependencies, and Method of Moments Quantile Regression (MM-QR), which allows for an assessment of how these determinants behave across different emission intensities.

Accordingly, the central problem addressed in this study is that the six selected countries stand at a developmental crossroads. Urbanization and energy demand continue to intensify emissions pressure, yet digitalization and renewable energy offer plausible channels for structural decarbonization. The policy challenge is therefore not whether economic development should continue, but how growth can be reorganized so that productivity, urban expansion, and technological modernization occur with lower carbon intensity. This study argues that internet penetration and renewable energy should be treated as strategic decoupling variables within the EKC framework rather than as peripheral control variables.

## 2. Literature Review and Theoretical Framework

# 2.1 Environmental Kuznets Curve Hypothesis

The EKC hypothesis provides the foundational economic-environmental logic for this study. It proposes that the relationship between income and environmental degradation follows an Inverted-U shape: emissions increase during the early stages of development but decline after a turning point when higher income is associated with cleaner technologies, stronger environmental regulation, and shifts toward less pollution-intensive sectors. The first stage is dominated by scale effects, where industrial expansion, urban infrastructure, and energy-intensive production raise emissions. The second stage is driven by composition and technology effects, where structural transformation and innovation reduce the emissions intensity of output (Sohag et al., 2019; Wang et al., 2024).

Recent EKC studies have refined this framework by emphasizing that the turning point is conditional rather than automatic. In some economies, rising income may reduce emissions only when accompanied by environmental policy, renewable energy investment, industrial upgrading, and technological innovation. In others, income growth can remain carbon-intensive when production systems depend on fossil fuels and when urban growth is poorly managed. This conditional interpretation is consistent with the present study's empirical structure: GDP per capita and its square test the EKC directly, while energy consumption, urbanization, renewable energy, internet penetration, oil, and trade capture the structural channels through which income either worsens or reduces emissions. The observed positive coefficient on GDP per capita and negative coefficient on its squared term therefore support an EKC pattern, but the broader model clarifies that the emissions trajectory depends on energy and technology choices.

The EKC hypothesis posits an inverted U-shaped relationship between economic growth and environmental degradation. According to this theory, pollution levels rise during the early stages of industrialization but begin to decline once a specific income threshold is surpassed (Grossman & Krueger, 1991; Mohamad & Shaari, 2025). This transition is driven by three core mechanisms: (i) the **Scale Effect**, where increased production initially drives up emissions; (ii) the **Composition Effect**, as the economy shifts from heavy industry to service-oriented sectors; and (iii) the **Technique Effect**, where higher income levels allow for the adoption of cleaner, more efficient technologies (Schneiter & Mellon-Bedi, 2025).

## 2.2 Ecological Modernization Theory and Digital Decoupling

Ecological Modernization Theory (EMT) complements the EKC by explaining the mechanisms through which advanced technology, institutional reform, and innovation can reconcile economic development with environmental sustainability. EMT argues that environmental improvement can occur within modern economic systems when firms, governments, and societies adopt cleaner technologies, improve resource productivity, and redesign production and consumption systems around ecological efficiency (Berger et al., 2001; Pataki, 2009). Under this view, technology is not merely a by-product of growth; it is a strategic instrument for reducing the material and energy intensity of development.

Internet penetration is a key modern expression of the EMT mechanism. Greater connectivity can improve environmental performance by enabling real-time data collection, smart energy management, digital monitoring, logistics optimization, teleworking, dematerialized services, e-governance, and faster diffusion of environmental knowledge. Digital technologies also facilitate renewable energy integration through smart grids, demand-response systems, and data-driven management of distributed energy resources (Jianing et al., 2024; Santarius et al., 2020). These channels suggest that internet penetration can serve as a decoupling variable, weakening the link between economic activity and CO2 emissions.

The digitalization-environment relationship remains contested, however. ICT infrastructure requires electricity and may generate rebound effects when efficiency gains lower costs and increase consumption (Axenbeck et al., 2024; Batool et al., 2022; Stermieri et al., 2024). Evidence from Belt and Road countries also indicates that ICT can increase emissions when digital expansion is not supported by clean energy and productivity-enhancing technologies (Weili et al., 2022). The present study's results contribute to this debate by showing that internet penetration is negatively associated with emissions, with its mitigating influence becoming stronger at higher emission quantiles. This finding supports the EMT argument that digitalization can improve environmental performance, particularly by helping high-emission economies manage energy use and accelerate technological upgrading.

## 2.3 STIRPAT Framework

The STIRPAT framework provides a flexible empirical foundation for modelling environmental pressure as a function of population, affluence, and technology. Unlike the deterministic IPAT identity, STIRPAT

allows researchers to estimate elasticities and incorporate additional control variables that shape environmental outcomes. In this study, urbanization captures the population-related pressure on infrastructure, mobility, housing, and energy demand; GDP per capita represents affluence; and internet penetration and renewable energy consumption represent the technology dimension. This structure is consistent with recent environmental panel studies that use STIRPAT to evaluate the roles of urbanization, technological development, renewable energy, and economic complexity in shaping emissions and ecological footprints (Anser, 2019; Balsalobre-Lorente et al., 2025; Dutta & Hazarika, 2025; Kinnunen et al., 2024).

The advantage of combining STIRPAT with the EKC is that it prevents the analysis from reducing emissions dynamics to income alone. In the six-country context, the results show that energy consumption and urbanization are emission-increasing forces, while internet penetration, renewable energy, and trade openness exert mitigating effects. This pattern illustrates the relevance of STIRPAT: environmental degradation is a joint outcome of demographic pressure, affluence, energy intensity, and technological capacity. The model, therefore, enables a richer interpretation of the EKC by showing which structural variables support or hinder the transition from the rising to the declining side of the curve.

## 2.4 Empirical Literature

Energy consumption is one of the most persistent drivers of CO2 emissions because economic production, transport, construction, and household consumption continue to depend heavily on energy inputs. The energy-growth nexus literature shows that both renewable and non-renewable energy can support economic activity, but their environmental consequences differ substantially. Studies on Southeastern Europe and EU economies confirm strong interdependencies among energy use, growth, and emissions, emphasizing the need for integrated energy and environmental policies (Halilbegović et al., 2023; Radmehr et al., 2021). Country-specific studies similarly show that renewable and non-renewable energy can contribute to growth, but the environmental quality of that growth depends on the energy mix, institutional context, and speed of transition (Alkasasbeh et al., 2023; Leal et al., 2018; Menegaki & Ozturk, 2016; Pegkas, 2020; Shakouri & Khoshnevis Yazdi, 2017).

Several recent studies have validated the inverted U-shape. For example, Mohamad & Shaari (2025) confirmed the EKC in Japan using ARDL and NARDL models, identifying a critical income threshold beyond which emissions decline. Similarly, Kilinc-Ata & Proskuryakova (2026) supported the EKC in the MENA and Caucasus regions, highlighting the role of R&D and digitalization in reaching the turning point. Conversely, some research challenges the universal applicability of the EKC. Ridwan et al. (2024) found that in the SAARC region, higher economic growth leads to increased pollution without a clear turning point, suggesting a linear or U-shaped relationship. Voumik et al. (2023) also reported that the EKC does not hold in several popular Middle Eastern tourist destinations, where growth and emissions remain coupled.

Empirical evidence consistently shows that fossil-fuel-based energy consumption is a major culprit for environmental degradation. Ridwan et al. (2024) and Voumik et al. (2023) emphasize that the heavy

reliance on oil and gas in South Asia and the Arab Peninsula continues to drive $CO_2$ emissions upward. Studies by Mohamad & Shaari (2025) and Kilinc-Ata et al. (2026) demonstrate that investments in nuclear and renewable energy significantly lower carbon footprints. The comparative analysis of the EU and GCC shows that the EU's absolute decoupling was primarily driven by the aggressive adoption of renewables (Kilinc-Ata et al., 2026).

The impact of digitalization remains a hotbed of empirical debate. Kilinc-Ata & Proskuryakova (2026) found that internet penetration significantly mitigates emissions in MENA countries. However, Kilinc-Ata & Al-Fori (2026) noted that in low-income countries, the impact of FinTech and digital investment is often inconsistent and highly sensitive to institutional quality and model specification. Urbanization is frequently cited as a significant driver of emissions in South Asia (Ridwan et al., 2024). Regarding trade, Kilinc-Ata et al. (2026) find that in GCC countries, trade and oil dependency often offset efficiency gains, while in the EU, trade facilitates the "Pollution Halo" effect through cleaner technology imports.

Urbanization is a central demographic and spatial force in the emissions process. Urban growth can increase CO2 emissions through higher demand for electricity, transport, buildings, construction materials, and municipal services. In developing and emerging economies, rapid urbanization may intensify pollution when infrastructure expansion is energy-intensive and when urban planning does not prioritize compact design, public transport, or energy-efficient buildings. Evidence from Asian and African contexts shows that urbanization often raises pollutant emissions and energy intensity, although the magnitude of the effect depends on development stage, infrastructure quality, and policy capacity (Anochiwa et al., 2022; Dutta & Hazarika, 2025; Musah et al., 2021; Salim et al., 2019).

The findings of this study support the view that urbanization is environmentally consequential. The Driscoll-Kraay estimates show a positive and statistically significant urbanization effect, indicating that the urban transition in the six selected countries remains carbon-intensive at the mean of the emissions distribution. In the MM-QR estimates, however, urbanization is not statistically significant across quantiles, suggesting that its mean effect may be driven by country-specific urban structures or by interactions with energy consumption, income, and technological variables.

Renewable energy is widely regarded as a key channel through which economies can maintain growth while lowering emissions. It reduces dependence on fossil fuels, improves energy security, and supports long-run decarbonization. Empirical evidence across countries remains heterogeneous, however. Some studies find that renewable energy promotes growth and reduces environmental pressure, while others show limited or context-specific effects due to infrastructure constraints, intermittency challenges, policy instability, or continued dominance of fossil fuels in the total energy mix (Khah & Ahmad, 2025; Leal et al., 2018; Menegaki & Ozturk, 2016; Radmehr et al., 2021; Wang & Dong, 2021).

In the present study, renewable energy is negatively associated with emissions in the Driscoll-Kraay model, confirming its role as a mitigation variable. The MM-QR results provide a more nuanced pattern: renewable energy has a negative and statistically significant effect in the low-emission quantile but becomes statistically insignificant at the median and high quantiles. This distributional pattern suggests

that renewable energy may be more effective where emissions intensity is already relatively low, while high-emission contexts may require deeper structural changes before renewable energy can meaningfully offset carbon-intensive production and consumption.

The present findings add important evidence to this debate. Internet penetration is negative and statistically significant in the Driscoll-Kraay estimates, and the MM-QR results show that its mitigating effect strengthens as the analysis moves from lower to higher CO2 quantiles. This implies that digitalization may be particularly valuable in more emission-intensive conditions, where the potential efficiency gains from digital monitoring, smart energy systems, and resource optimization are larger.

Oil dependence remains a critical source of carbon emissions because oil is central to transport, industry, petrochemicals, and energy security. In the mean-based Driscoll-Kraay model, oil has a positive but statistically insignificant coefficient, suggesting that its average effect is weaker once energy consumption, income, urbanization, internet penetration, renewable energy, and trade are controlled for.

Trade openness has a theoretically ambiguous environmental effect. The pollution haven hypothesis suggests that trade may increase emissions by shifting dirty production to countries with weaker environmental regulations. Conversely, the technique-effect perspective argues that trade can lower emissions by facilitating access to cleaner technologies, improving productivity, and integrating economies into more efficient value chains. The present study's results support the second interpretation: trade openness is negative and significant in both the Driscoll-Kraay and MM-QR estimates, and its negative coefficient becomes slightly stronger at higher CO2 quantiles. This suggests that, in the six-country context, trade may be associated with cleaner technology diffusion, efficiency gains, or structural upgrading rather than pollution-intensive specialization.

## 3. Data and Methodology

# 3.1 Data Sources, Scope, and Variable Construction

This study uses an annual country-year panel dataset for the six Gulf Cooperation Council (GCC) economies: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. The initial dataset covers the period 2005–2024, giving a maximum possible sample of 120 country-year observations. After harmonizing the data across all variables and retaining only observations with complete information for the full empirical specification, the final estimation sample consists of 113 country-year observations. The panel is therefore near-balanced rather than fully balanced.

The dependent variable is carbon dioxide emissions per capita. Specifically, $CO_2$ emissions are measured as [production-based $CO_2$ emissions per capita, metric tons per person] obtained from Our World in Data. This clarification is important because the study focuses on per-capita emissions rather than total national emissions. GDP per capita is measured in constant 2015 US dollars and is obtained from the World Bank’s World Development Indicators. Energy use is measured as energy use per capita in kilograms of oil equivalent per capita. This variable is interpreted as per-capita energy consumption,

not energy intensity. Urbanization is measured as the urban population share of total population. Digitalization is proxied by the percentage of individuals using the internet. Renewable energy is measured as renewable energy consumption as a percentage of total final energy consumption. Oil dependence is measured by oil rents as a percentage of GDP, while trade openness is measured as the sum of exports and imports of goods and services as a percentage of GDP.

All variables are transformed into natural logarithms to reduce skewness and allow elasticity-based interpretation. Percentage variables are retained in percentage-point form before transformation unless otherwise stated. GDP per capita squared is constructed from the logarithm of GDP per capita to test the Environmental Kuznets Curve hypothesis.

No author-generated extrapolation was applied to extend unavailable series to 2024. Where the original data source reports 2024 observations as estimates or provisional values, these observations are retained but explicitly identified in the data availability table. Observations that were unavailable in the original sources were treated as missing and excluded through listwise deletion in the baseline estimation. This approach ensures that all coefficients are estimated using the same country-year information set.

Table 3.1
Variable Definitions, Measurement, Transformations, and Sources

| Variable | Definition and measurement | Transformation | Source | Expected sign |
|---|---|---|---|---|
| ln$CO_2$pc | $CO_2$ emissions per capita, measured as [production-based $CO_2$ emissions per person, metric tons per capita] | ln($CO_2$pc) | Our World in Data | Dependent variable |
| lnGDPpc | GDP per capita, constant 2015 US dollars | ln(GDPpc) | World Bank, WDI | + |
| lnGDPpc² | Squared income term used to test the EKC hypothesis | [lnGDPpc − mean(lnGDPpc)]² | Constructed by authors | − |
| lnEnergy | Energy use per capita consumption, kg of oil equivalent per capita | ln(Energy use per capita) | World Bank, WDI | + |
| lnUrban | Urban population as a percentage of total population | ln(Urban %) | World Bank, WDI | + |
| lnInternet | Individuals using the internet as a percentage of population | ln(Internet %) | World Bank, WDI | −/+ |
| lnRenew | Renewable energy consumption as a percentage of total final energy consumption | ln(Renewable %) | World Bank, WDI | − |
| lnOil | Oil rents as a percentage of GDP | ln(Oil rents %) | World Bank, WDI | +/− |
| lnTrade | Trade openness, measured as exports plus imports of goods and services as a percentage of GDP | ln(Trade %) | World Bank, WDI | +/− |

Source: Authors' compilation, 2026.

# 3.2 Empirical Model Specification

The empirical model integrates the EKC hypothesis with the STIRPAT logic. The linear income term captures the scale effect of economic expansion, while the squared income term captures the possibility that emissions decline after a sufficiently high level of income is reached. Energy consumption, urbanization, internet penetration, renewable energy, oil rents, and trade openness are included to represent structural channels through which economic activity may either intensify or reduce carbon emissions.

**Baseline EKC-STIRPAT specification**

$$\ln CO_{2i,t} = \alpha_i + \beta_1 \ln GDPpc_{i,t} + \beta_2 (\ln GDPpc_{i,t})^2 + \beta_3 \ln Energy_{i,t} + \beta_4 \ln Urban_{i,t}$$

$$+ \beta_5 \ln Internet_{i,t} + \beta_6 \ln Renew_{i,t} + \beta_7 \ln Oil_{i,t} + \beta_8 \ln Trade_{i,t} + \varepsilon_{i,t}$$

where i denotes country, t denotes year, $\alpha_i$ captures unobserved country-specific effects, and $\varepsilon_{i,t}$ is the idiosyncratic error term.

The EKC hypothesis is supported when $\beta_1$ is positive and $\beta_2$ is negative, implying that emissions rise with income at lower levels of development but decline after the estimated turning point. The turning point is computed as $\exp[-\beta_1/(2\beta_2)]$ because the income variable is specified in logarithmic form.

# 3.3 Panel Estimation Strategy and Diagnostic Tests

The analysis follows a sequential econometric strategy designed to produce reliable inference in a small multi-country panel. The estimation begins with fixed-effects (FE) and random-effects (RE) models. FE controls for time-invariant country-specific heterogeneity, while RE treats unobserved country effects as random. The Hausman specification test is then used to determine whether the country-specific effects are correlated with the regressors; rejection of the null favours the FE estimator.

**Mean-based panel estimators**

Fixed effects: $y_{i,t} = \alpha_i + X_{i,t}'\beta + \varepsilon_{i,t}$

Random effects: $y_{i,t} = \alpha + X_{i,t}'\beta + u_i + \varepsilon_{i,t}$

$X_{i,t}$ is the vector of explanatory variables: lnGDPpc, lnGDPpc2, lnEnergy, lnUrban, lnInternet, lnRenew, lnOil, and lnTrade.

Because macro-panel data may suffer from heteroskedasticity, serial correlation, and cross-sectional dependence, several post-estimation diagnostic tests are implemented. The Modified Wald test examines groupwise heteroskedasticity, the Wooldridge test evaluates first-order serial correlation, and the Pesaran, Friedman, and Frees tests assess cross-sectional dependence among the residuals. These diagnostics are essential because common shocks, oil-price movements, trade linkages, and technology diffusion can create correlated disturbances across Gulf economies.

To correct the resulting inference problem, the preferred mean-based specification is estimated using Driscoll-Kraay standard errors within the fixed-effects framework. This estimator retains the FE coefficients while producing standard errors that are robust to heteroskedasticity, autocorrelation, and general forms of cross-sectional dependence. Consequently, the Driscoll-Kraay FE model is treated as the primary mean-regression evidence.

# 3.4 Long-Run and Distributional Estimation

After estimating the robust mean model, the study tests whether the variables are connected by a long-run equilibrium relationship. Pedroni and Kao residual-based cointegration tests are applied alongside the Westerlund test, which is particularly useful in panels where cross-sectional dependence may be present. Evidence of cointegration supports the interpretation that the observed relationships are not merely short-run statistical associations but reflect persistent links between emissions, growth, energy use, digitalization, renewable energy, oil rents, urbanization, and trade openness.

Finally, the Method of Moments Quantile Regression (MM-QR) approach is used to examine distributional heterogeneity. Unlike mean regression, MM-QR evaluates whether each explanatory variable has different effects at different points of the conditional CO2-emissions distribution. This is important because the policy relevance of digitalization, renewable energy, oil dependence, or trade openness may differ between low-emission and high-emission settings.

**MM-QR representation**

$Q_y(\tau \mid X_i) = (\alpha_i + X_i'\beta) + q_\tau(\delta_i + X_i'\gamma), \tau \in \{0.25, 0.50, 0.75\}$

The 25th, 50th, and 75th quantiles represent low-, median-, and high-emission conditions, respectively.

This combined strategy improves the credibility and policy relevance of the study. Driscoll-Kraay FE estimates provide robust average effects, cointegration tests verify the long-run coherence of the model, and MM-QR reveals whether the same determinants operate differently across the emissions distribution.

# 4. Result

Table 1
Descriptive Statistics and Multicollinearity Analysis

| Variable | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|
| *lnCO2* | 3.199 | 0.307 | 2.560 | 4.117 |
| *lnGDPpc* | 10.359 | 0.439 | 9.761 | 11.309 |
| *lnGDPpc2* | 107.506 | 9.216 | 95.280 | 127.909 |
| *lnEnergy* | 9.149 | 0.342 | 8.301 | 9.973 |
| *lnUrban* | 4.496 | 0.105 | 4.274 | 4.605 |
| *lnRenew* | 0.068 | 0.156 | 0.000 | 0.832 |
| *lnInternet* | 4.206 | 0.537 | 2.039 | 4.615 |
| *lnOil* | 3.214 | 0.514 | 1.692 | 4.066 |
| *lnTrade* | 4.661 | 0.315 | 3.861 | 5.358 |
| Source: Authors, 2026 | | | | |

Table 1 provides a comprehensive overview of the distributional characteristics of the variables. The narrow standard deviation for *lnUrban* (0.105) suggests a high degree of homogeneity in the urbanization rates across the sampled economies, while the wide range in *lnInternet* (2.03 to 4.61) highlights the digital divide existing within the panel.

Source: Authors, 2026

The correlation heatmap serves as the first empirical hint of the Environmental Kuznets Curve (EKC) and the Digital-Environmental Nexus. We observe a strong positive correlation between *lnCO2*, *lnGDPpc*, and *lnEnergy*, confirming that at this stage of development, these economies remain heavily reliant on energy-intensive growth. Crucially, the preliminary negative correlation between Internet penetration/Renewable energy and *CO2* emissions provides initial support for our hypothesis: that technological modernization and energy transition act as mitigating forces against environmental degradation. The strong correlation between urbanization and energy usage suggests that the "scale effect" of urban growth is currently a primary driver of carbon footprints in these regions.

Table 2
Panel Regression Estimates and Diagnostic Results

| **Variables** | **(1) Fixed Effects** | **(2) Random Effects** | **(3) Driscoll-Kraay (FE)** |
|---|---|---|---|
| *lnGDPpc* | 3.903** | 2.539** | 3.903** |
| | (1.783) | (1.132) | (1.753) |
| *lnGDPpc2* | -0.183** | -0.111** | -0.183** |
| | (0.084) | (0.054) | (0.086) |
| *lnEnergy* | 0.784*** | 0.686*** | 0.784*** |
| | (0.079) | (0.063) | (0.082) |
| *lnUrban* | 2.947*** | 0.026 | 2.947*** |
| | (0.582) | (0.142) | (0.631) |
| *lnInternet* | -0.129*** | -0.033** | -0.129*** |
| | (0.023) | (0.016) | (0.027) |
| *lnRenew* | -0.203*** | -0.099 | -0.203** |
| | (0.061) | (0.061) | (0.083) |
| *lnOil* | 0.021 | 0.032* | 0.021 |
| | (0.021) | (0.016) | (0.036) |
| *lnTrade* | -0.099* | -0.097*** | -0.099** |
| | (0.056) | (0.026) | (0.044) |
| Constant | -36.949*** | -16.975*** | -36.949*** |
| | (9.911) | (5.785) | (11.464) |
| **Model Diagnostics** | | | |
| Observations | 113 | 113 | 113 |
| R-squared | 0.697 (Within) | 0.950 (Overall) | 0.697 (Within) |
| Hausman Test ($\chi 2$) | 29.16*** | -- | -- |
| Modified Wald Test (Het.) | 67.45*** | -- | -- |

*Note: Standard errors are reported in parentheses. Symbols ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively. Column (3) provides estimates using Driscoll-Kraay standard errors, which are robust to heteroskedasticity, serial correlation, and cross-sectional dependence. The Frees' test statistic (0.026) is compared against the Q-distribution critical values (0.14 at 10% significance).*

| Variables | (1) Fixed Effects | (2) Random Effects | (3) Driscoll-Kraay (FE) |
|---|---|---|---|
| Wooldridge Test (Serial) | 11.47** | -- | -- |
| **Cross-sectional Dep. (CD) Tests** | | | |
| Pesaran's Test | -0.795 | -- | -- |
| Frees' Test | ** | -- | -- |
| Friedman's Test | 14.70** | -- | -- |
| *Note: Standard errors are reported in parentheses. Symbols ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively. Column (3) provides estimates using Driscoll-Kraay standard errors, which are robust to heteroskedasticity, serial correlation, and cross-sectional dependence. The Frees' test statistic (0.026) is compared against the Q-distribution critical values (0.14 at 10% significance).* | | | |

Source: Authors, 2026

Table 2 presents our core findings, comparing Fixed Effects (FE) with the Driscoll-Kraay (DK) estimator. Because our diagnostic tests (Wald, Wooldridge, and Friedman) detected heteroskedasticity, autocorrelation, and cross-sectional dependence, the DK results (Model 3) represent our primary evidence.

Table 3
Marginal Effects of GDP on *CO*2 at Different Income Levels

| Income Level (*ln_gdppc*) | Marginal Effect | Std. Error | t-stat | p-value | Interpretation |
|---|---|---|---|---|---|
| **Minimum (9.76)** | + 0.315 | 0.082 | 3.84 | 0.001 | High Emission Growth |
| **Mean (10.36)** | + 0.094 | 0.041 | 2.29 | 0.034 | Slowing Emissions |
| **Turning Point (10.61)** | 0.000 | -- | -- | -- | Threshold / Peak |
| **Maximum (11.31)** | -0.255 | 0.095 | -2.68 | 0.015 | Environmental Recovery |
| Source: Authors, 2026 | | | | | |

Table 3 shows the analysis of marginal effects provides a dynamic view of the growth-pollution nexus. At the sample minimum (low-income stage), the marginal effect of GDP is positive and significant (0.315), indicating that economic expansion is coupled with heavy environmental degradation. However, as economies move toward the mean income level, this pressure diminishes to 0.094. Crucially, at the sample maximum (high-income stage), the marginal effect becomes significantly negative (-0.255). This confirms that once a country crosses the developmental threshold, further economic growth actively contributes to *CO*2 mitigation, validating the 'Greening' phase of the EKC."

Source: Authors, 2026

The visual representation of the predicted relationship between economic development and environmental quality provides a robust empirical validation of the Environmental Kuznets Curve hypothesis within the sampled panel. The resulting inverted U-shaped trajectory effectively delineates the transition of these economies through distinct developmental stages, starting with a steep ascending limb where the scale of industrial expansion dominates environmental outcomes. This initial coupling of growth and degradation reaches a definitive structural threshold at a log-income level of approximately 10.61, a turning point that possesses high internal validity as it resides squarely within the observed data range of the study. Beyond this threshold, the descending limb of the curve illustrates a significant decoupling of economic progress from carbon emissions, driven by the synergistic influence of the technique and composition effects. This transition highlights how rising affluence facilitates the integration of the green technological mitigators identified in the regression analysis, most notably internet penetration and renewable energy adoption, ultimately fostering a trajectory toward long-term environmental remediation and sustainable growth.

Table 4
Method of Moments Quantile Regression (MM-QR) MM-QR Table

| **Variables** | **Q25 (Low *CO*2)** | **Q50 (Median)** | **Q75 (High *CO*2)** |
|---|---|---|---|
| *lnGDPpc* | 2.377** (1.111) | 2.531** (1.088) | 2.662** (1.266) |
| *lnGDPpc*2 | -0.106** (0.053) | -0.111** (0.052) | -0.116** (0.060) |
| *lnEnergy* | 0.727*** (0.072) | 0.688*** (0.071) | 0.655*** (0.083) |
| *lnOil* | 0.030 (0.015)** | 0.031 (0.014)** | 0.033 (0.017)* |
| *lnInternet* | -0.016 (0.018) | -0.032* (0.018) | -0.046** (0.021) |
| *lnRenew* | -0.133* (0.078) | -0.101 (0.076) | -0.073 (0.089) |
| *lnUrban* | -0.055 (0.153) | 0.022 (0.150) | 0.088 (0.176) |
| *lnTrade* | -0.089*** (0.022) | -0.097*** (0.021) | -0.104*** (0.025) |
| Source: Authors, 2026 | | | |

Table 4 reveals that the Method of Moments Quantile Regression (MM-QR) is the "crown jewel" of this study. It allows us to see how drivers change as a country moves from low-emission (*Q*25) to high-emission (*Q*75) status.

In digitalization's Growing Power, interestingly, the mitigating effect of the Internet is insignificant at the lowest quantile but becomes increasingly negative and significant at the median (-0.032) and high-emission (-0.046) quantiles. This indicates that ICT is most effective at reducing emissions in the most polluted environments, likely through smart-grid optimization and industrial efficiency. The Persistence of the EKC; The EKC coefficients remain stable across all quantiles, proving that the income-pollution

relationship is a universal structural phenomenon, regardless of a country's specific emission level. In trade openness, trade shows a significant negative coefficient across all quantiles. This supports the "Technological Leapfrogging" theory, as these countries trade more, they import cleaner, more efficient technologies from developed nations, helping them "skip" the dirtiest stages of development.

# 5. Discussion

The estimated turning point is the central interpretive result because it identifies the income level at which the growth-emissions relationship is expected to shift from carbon intensification to carbon moderation. In EKC terms, GCC economies are not simply growing; they are approaching, crossing, or moving beyond a structural income threshold at which scale effects can begin to be offset by technology, regulation, cleaner energy systems, and a more service-oriented composition of output (Sohag et al., 2019; Wang et al., 2024). This matters because the EKC should not be read as a mechanical law. The downward side of the curve is conditional: economic growth becomes environmentally beneficial only when high income is translated into cleaner infrastructure, more efficient energy use, stronger environmental governance, and less carbon-intensive production.

Because the empirical model measures income as GDP per capita, the relevant benchmark is GDP per capita rather than total national GDP. Using the most recent World Bank 2024 GDP per capita values as a policy-positioning comparison, Qatar and the United Arab Emirates are already above the estimated threshold, while Saudi Arabia and Kuwait are relatively close but still below it. Bahrain and Oman remain further below the peak. This comparison suggests that some countries may have the income capacity to move onto the descending side of the EKC, but the statistical evidence also shows that capacity alone is insufficient. Urbanization, energy demand, and oil dependence can keep emissions high even after income rises above the threshold.

The negative and statistically significant coefficient for internet penetration provides strong evidence of a digitalization dividend. In the preferred model, a 1% increase in internet penetration is associated with approximately a 0.129% reduction in CO2 emissions, holding other factors constant. This finding is consistent with Ecological Modernization Theory, which argues that technological modernization can reduce environmental pressure by improving resource productivity and redesigning production and consumption systems around efficiency (Berger et al., 2001; Pataki, 2009). It also addresses an important gap in EKC studies, where technology is often treated as a residual rather than as an explicit decoupling mechanism (Koondhar et al., 2021; Lau et al., 2025; Pincheira & Zuniga, 2021).

The mechanisms are practical and policy-relevant. First, high-speed internet enables smart grids and demand-response systems, allowing utilities to balance electricity demand, integrate intermittent renewable power, and reduce technical losses. Second, digital platforms support remote work, teleconferencing, e-services, and online transactions, all of which can reduce commuting, office energy demand, and transport-related emissions. Third, connected logistics systems optimize routes, freight loading, inventory management, and port operations, thereby lowering fuel use in supply chains. Fourth,

internet-based environmental monitoring improves real-time measurement of air pollution, energy consumption, building performance, and industrial emissions. These channels explain why internet penetration is not merely an economic-development indicator; it is also an environmental infrastructure variable (Dimian et al., 2025; Santarius et al., 2020; Stermieri et al., 2024).

The quantile results deepen this interpretation. Internet penetration is weak at the low-emission quantile but becomes increasingly negative and statistically significant at the median and high-emission quantiles. In practical terms, the highest-emission conditions offer the largest efficiency gains from digital monitoring, smart-city platforms, industrial automation, and grid optimization. The result does not imply that digitalization is automatically green. ICT infrastructure can raise electricity demand through data centers, devices, and networks, and rebound effects may offset efficiency gains if digital expansion is powered by fossil fuels (Axenbeck et al., 2024; Batool et al., 2022). The study's negative coefficient, therefore, supports a conditional conclusion: digitalization reduces emissions when it is embedded in clean energy, efficient urban design, and active environmental governance.

Urbanization is the most striking driver in the mean-based results. The coefficient of 2.947 indicates that a 1% increase in urbanization is associated with an almost 2.95% increase in CO2 emissions, making it larger than the coefficients for energy consumption, income, and oil. This unusually high elasticity suggests that urban growth in the six GCC economies is currently more resource-intensive than sustainable. The result is plausible because GCC urbanization is characterized by high cooling demand, automobile dependence, desalination-linked water systems, large-scale construction, energy-intensive buildings, and infrastructure-led development. In this context, urbanization does not merely concentrate people; it expands the material, electricity, and transport systems that support high-carbon lifestyles.

The finding aligns with urban-environment studies showing that cities raise emissions when expansion is shaped by low-density development, private vehicle dependence, inefficient building stock, and fossil-fuel-based electricity (Anochiwa et al., 2022; Dutta & Hazarika, 2025; Musah et al., 2021; Salim et al., 2019). The GCC coefficient is especially high because urban services are energy-intensive in hot climates. Air-conditioning, district infrastructure, water desalination, road networks, malls, airports, logistics zones, and construction materials all multiply energy demand. Therefore, urbanization acts as a transmission belt between income growth and emissions: higher income increases demand for urban amenities, while current urban systems deliver those amenities through carbon-intensive infrastructure.

Taken together, the results indicate a conditional transition rather than an automatic one. The EKC confirms that higher income can eventually support environmental improvement, but the strong positive coefficients for energy consumption and urbanization show why the turning point will not be reached through GDP growth alone. Renewable energy and internet penetration are the two main decoupling variables in the model. Renewable energy directly reduces the carbon content of energy consumption, while digitalization improves the efficiency with which energy, transport, buildings and supply chains are managed. Trade openness also supports a technique effect by facilitating access to cleaner capital

goods and technologies. Oil dependence, by contrast, remains a persistent carbon pressure in the distributional results.

The most defensible scholarly interpretation is therefore that the six GCC economies are not facing a trade-off between development and decarbonization; they are facing a sequencing problem. If urban expansion and energy demand continue under existing fossil-fuel-intensive patterns, economic growth will push emissions upward even near or above the income threshold. If, however, growth is redirected through smart cities, clean electricity, digital monitoring, and low-carbon trade, the economies can move more rapidly onto the downward side of the EKC. This is why the turning point matters: it is not a passive prediction, but a policy target that must be actively achieved.

# 6. Conclusion

This study provides robust evidence that economic growth, digitalization, urbanization, and energy structure jointly shape CO2 emissions in the six GCC economies. The Driscoll-Kraay fixed-effects results support the EKC hypothesis: GDP per capita increases emissions at lower income levels, while the squared GDP term reduces emissions after an estimated turning point. Yet the conclusion is not that growth alone will clean the environment. The large positive urbanization coefficient, the strong energy-consumption effect, and the positive oil effect in the quantile results show that the current development model remains carbon-intensive. Economic growth can eventually help the environment, but only if policy intervention changes the energy, urban, and technological foundations of growth.

The central contribution of the findings is the identification of decoupling channels. Internet penetration and renewable energy significantly reduce emissions in the preferred model, while trade openness is consistently emissions-reducing across quantiles. These results imply that the transition to a lower-carbon development path is feasible, but it requires deliberate coordination. Digital infrastructure should be treated as environmental infrastructure; renewable energy should be integrated with grid modernization and storage; and urban planning should be redesigned around compact, connected, and efficient cities. The policy implication is clear: the downward side of the EKC must be built, not awaited.

# 7. Policy Implication

Since urbanization is the strongest driver of CO2 emissions in the model (2.947), the first policy priority should be green urbanization. GCC governments should shift from resource-intensive urban expansion toward smart-city systems that integrate mass transit, transit-oriented development, green buildings, district cooling, walkability, renewable-powered public infrastructure, and digital urban management. Building codes should require high energy performance, passive cooling design, rooftop solar readiness, and lifecycle carbon assessment for major construction projects. Public transport should be expanded not only as a congestion policy but as a carbon-reduction policy. Urban planning authorities should also use real-time digital dashboards to monitor electricity use, water demand, mobility patterns, air quality,

and building efficiency. In short, cities should become laboratories of decarbonization rather than engines of emissions.

The negative internet coefficient demonstrates that high-speed connectivity is both an economic and environmental asset. Governments should therefore support universal broadband, 5G/6G readiness, green data centers, digital public services, and cyber-secure environmental monitoring platforms. ICT systems should be leveraged for smart grids, demand-response pricing, renewable-energy forecasting, industrial energy audits, port and logistics optimization, intelligent transport systems, and emissions reporting. Because the MM-QR results show that internet penetration has its strongest effect in high-emission conditions, digital policy should prioritize the highest-emitting sectors and cities first. However, digitalization must be powered by clean electricity. Without renewable energy and efficiency standards for data centers, the digital dividend could be weakened by rising electricity demand.

Energy diversification is indispensable because the model shows that a 1% increase in renewable energy is associated with a 0.20% reduction in emissions, while energy consumption remains a strong positive driver of CO2. GCC economies should accelerate the shift from oil and gas dependence toward solar, wind, green hydrogen, storage, grid interconnection, and electrification of transport and industry. Renewable targets should be accompanied by fossil-fuel subsidy reform, green finance instruments, power-market regulation, and investments in transmission infrastructure. The quantile results suggest that renewable energy is most effective at lower emission levels, so high-emission conditions require complementary policies: efficiency standards, industrial decarbonization, carbon pricing or equivalent regulation, and digital energy management. The goal should not be renewable capacity alone, but a full transition from fossil-energy abundance to clean-energy competitiveness.

The policy package should be sequenced according to each country's distance from the estimated turning point. Qatar and the United Arab Emirates, already above the benchmark in current-dollar terms, should prioritize immediate absolute emissions reduction through deep efficiency standards, green public procurement, and renewable-powered digital infrastructure. Saudi Arabia and Kuwait, which are close to the threshold, should use current investment capacity to prevent a long emissions plateau by accelerating smart-city systems and clean industrial diversification. Bahrain and Oman should avoid high-carbon lock-in by placing green standards at the beginning of the urban and energy investment cycle. Across all groups, the key principle is that decarbonization must be embedded before infrastructure becomes fixed and costly to replace.

# 8. Limitations and Future Research

Although this study provides robust evidence on the relationship between digitalization, renewable energy transition, economic growth, and $CO_2$ emissions in GCC economies, several limitations should be acknowledged. First, the analysis is based on a relatively small regional panel of six GCC countries over the period 2005–2024. While this sample is appropriate for examining hydrocarbon-dependent Gulf

economies, the limited number of cross-sectional units means that the findings should be generalized with caution beyond the GCC context.

Second, the study relies on aggregate country-level indicators. Variables such as internet penetration, renewable energy consumption, urbanization, and oil rents provide useful macro-level proxies, but they do not fully capture sectoral differences in emissions behavior. For example, the environmental effect of digitalization may differ across transport, buildings, industry, logistics, and public services. Similarly, renewable energy adoption may have different impacts depending on grid integration, storage capacity, energy subsidies, and the structure of electricity generation.

Third, although the Driscoll-Kraay fixed-effects estimator corrects for heteroskedasticity, serial correlation, and cross-sectional dependence, it does not fully eliminate potential endogeneity. The relationships among income, energy use, digitalization, renewable energy, trade openness, and emissions may be jointly determined. For instance, countries with lower emissions may also be more likely to invest in renewable energy and digital infrastructure, while economic growth may simultaneously influence and be influenced by energy consumption. Therefore, the results should be interpreted as robust associations rather than strict causal effects.

Fourth, the study measures digitalization using internet penetration. This indicator captures broad digital access, but it does not measure the quality, intensity, or environmental efficiency of digital transformation. Future studies could use more detailed indicators such as broadband speed, data-center energy use, digital public services, smart-grid deployment, ICT investment, artificial intelligence adoption, or digital economy value added. These indicators would provide a more direct assessment of whether digitalization reduces emissions through efficiency gains or increases energy demand through ICT-related electricity consumption.

Fifth, renewable energy is measured as a share of total final energy consumption, which captures the broad direction of the energy transition but does not distinguish between solar, wind, green hydrogen, biomass, or other renewable sources. This is important for GCC economies because the environmental effectiveness of renewable energy depends not only on its share in the energy mix but also on storage systems, grid modernization, dispatch capacity, and the extent to which renewables replace fossil fuels rather than simply add to total energy supply.

Sixth, the study uses oil rents as a proxy for hydrocarbon dependence. While oil rents reflect the economic importance of oil, they do not directly measure domestic oil consumption, fossil-fuel combustion, or sectoral carbon intensity. Future research could incorporate more precise indicators such as oil consumption per capita, fossil-fuel electricity generation, natural gas use, fuel subsidies, or sector-specific energy consumption.

Finally, although the EKC results suggest the existence of an income-related turning point, this turning point should be interpreted cautiously. The downward side of the EKC does not imply that emissions will automatically fall as income rises. Rather, the findings suggest that income growth can support

environmental improvement only when accompanied by renewable energy expansion, green urbanization, digital efficiency, and stronger environmental governance. Future research could extend this study by using sectoral data, testing causal mechanisms through dynamic panel or instrumental-variable approaches, and examining whether digitalization and renewable energy interact jointly to accelerate decarbonization in hydrocarbon-dependent economies.

## Declarations

# Ethics approval

Not applicable. This study used secondary, publicly available country-level data and did not involve human participants, human material, animals, or personal data.

**Consent to participate**

Not applicable.

**Consent for publication**

Not applicable.

**Competing interests**

The authors declare that they have no competing interests.

# Funding

The authors received no financial support for the research, authorship, or publication of this article.

# Author Contribution

Author ContributionsMoussa Abdi Mohamoud: Conceptualization, Methodology, Data Curation, Formal Analysis, Software, Investigation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing.Ibraahim Adem Aw-Cali: Methodology, Validation, Formal Analysis, Writing – Review & Editing, Supervision.Abdiasis Ali Mohamoud: Data Curation, Literature Review, Validation, Writing – Review & Editing, Project Administration.

# Data availability

The data supporting the findings of this study are publicly available from Our World in Data and the World Bank’s World Development Indicators. The compiled dataset and analysis code can be made

available by the corresponding author upon reasonable request.

## References


1. Alkasasbeh O, Khasawneh O, Alzghoul A. The Nexus between Renewable Energy Consumption and Economic Growth: Empirical Evidence from Jordan. Int J Energy Econ Policy. 2023;13(2):194–9. https://doi.org/10.32479/ijeep.14007.
2. Anochiwa LI, Agbanike TF, Chukwu AB, Ikpe M, Otta NN. Urbanization and carbon emissions: Looking at the role of mobile phone adoption in Sub-Saharan African countries. Environ Sci Pollut Res. 2022;29(52):78526–41. https://doi.org/10.1007/s11356-022-20994-5.
3. Anser MK. Impact of energy consumption and human activities on carbon emissions in Pakistan: Application of STIRPAT model. Environ Sci Pollut Res. 2019;26(13):13453–63. https://doi.org/10.1007/s11356-019-04859-y.
4. Axenbeck J, Berner A, Kneib T. What drives the relationship between digitalization and energy demand? Exploring heterogeneity in German manufacturing firms. J Environ Manage. 2024;369:122317. https://doi.org/10.1016/j.jenvman.2024.122317.
5. Balsalobre-Lorente D, Nur T, Topaloglu EE. Examining the sustainable development process through the economic complexity, technology, urbanization, and renewable energy in D-8 countries. Qual Quant. 2025;59(5):4461–501. https://doi.org/10.1007/s11135-025-02161-3.
6. Batool Z, Ali S, Rehman A. Environmental Impact of ICT on Disaggregated Energy Consumption in China: A Threshold Regression Analysis. Sustainability. 2022;14(23):15600. https://doi.org/10.3390/su142315600.
7. Berger G, Flynn A, Hines F, Johns R. Ecological Modernization as a Basis for Environmental Policy: Current Environmental Discourse and Policy and the Implications on Environmental Supply Chain Management. Innovation: Eur J Social Sci Res. 2001;14(1):55–72. https://doi.org/10.1080/13511610125074.
8. Cheung WWL, Reygondeau G, Frölicher TL. Large benefits to marine fisheries of meeting the 1.5°C global warming target. Science. 2016;354(6319):1591–4. https://doi.org/10.1126/science.aag2331.
9. Dimian GC, Maftei M, Jablonský J, Marin E, Olaru SM. The Influence of Digitalization on Greenhouse Gas Emissions in European Union. The Analysis of Mediating Effect of Renewable Energy Consumption. J Knowl Econ. 2025;17(1):1888–928. https://doi.org/10.1007/s13132-025-02657-1.
10. Dutta UP, Hazarika N. Urbanization and carbon emissions: Panel evidence from 68 low-income and lower-middle-income countries. J Urban Affairs. 2025;47(1):269–88. https://doi.org/10.1080/07352166.2023.2174871.
11. Grossman G, Krueger A. (1991). *Environmental Impacts of a North American Free Trade Agreement* (No. W3914; p. w3914). National Bureau of Economic Research. https://doi.org/10.3386/w3914
12. Halilbegović S, Pekmez Z, Rehman A. Modeling the Nexus of Renewable and Non-Renewable Energy Consumption and Economic Progress in Southeastern Europe: A Panel Data Analysis. Sustainability.

2023;15(12):9413. https://doi.org/10.3390/su15129413.

13. Jianing P, Bai K, Solangi YA, Magazzino C, Ayaz K. Examining the role of digitalization and technological innovation in promoting sustainable natural resource exploitation. Resour Policy. 2024;92:105036. https://doi.org/10.1016/j.resourpol.2024.105036.
14. Khah AM, Ahmad M. Assessing the impact of output growth, renewable energy consumption and financial development on environmental quality: Empirical evidence from India. J Financial Economic Policy. 2025;17(5):732–57. https://doi.org/10.1108/JFEP-03-2024-0082.
15. Kilinc-Ata N, Al-Fori AM. FinTech Investment, Geopolitical-Economic Uncertainty, and CO2 Emissions in Low- and Middle-Income Countries: Evidence from Dynamic Panel Models. J Risk Financial Manage. 2026;19(5):362. https://doi.org/10.3390/jrfm19050362.
16. Kilinc-Ata N, Proskuryakova LN. Assessing the Influence of Innovation and Digitalization on Carbon Footprint Across the Middle East, North Africa, and South Caucasus Regions. Nat Resour Forum. 2026;1477–8947. https://doi.org/10.1111/1477-8947.70068.
17. Kilinc-Ata N, Xavier B, Bhat MA. Decoupling economic growth and CO2 emissions: A geopolitical comparison of the EU and GCC energy transitions. Qual Quant. 2026;60(2):7377–406. https://doi.org/10.1007/s11135-026-02572-w.
18. King AD, Harrington LJ. The Inequality of Climate Change From 1.5 to 2°C of Global Warming. Geophys Res Lett. 2018;45(10):5030–3. https://doi.org/10.1029/2018GL078430.
19. Kinnunen J, Georgescu I, Nica I. Evaluating the Environmental Phillips Curve Hypothesis in the STIRPAT Framework for Finland. Sustainability. 2024;16(11):4381. https://doi.org/10.3390/su16114381.
20. Koondhar MA, Shahbaz M, Memon KA, Ozturk I, Kong R. A visualization review analysis of the last two decades for environmental Kuznets curve EKC based on co-citation analysis theory and pathfinder network scaling algorithms. Environ Sci Pollut Res. 2021;28(13):16690–706. https://doi.org/10.1007/s11356-020-12199-5.
21. Lau L-S, Yii K-J, Ng C-F, Tan Y-L, Yiew T-H. Environmental Kuznets curve (EKC) hypothesis: A bibliometric review of the last three decades. Energy Environ. 2025;36(1):93–131. https://doi.org/10.1177/0958305X231177734.
22. Leal PH, Marques AC, Fuinhas JA. How economic growth in Australia reacts to $CO_2$ emissions, fossil fuels and renewable energy consumption. Int J Energy Sect Manage. 2018;12(4):696–713. https://doi.org/10.1108/IJESM-01-2018-0020.
23. Menegaki AN, Ozturk I. Renewable energy, rents and GDP growth in MENA countries. Energy Sources Part B: Econ Plann Policy. 2016;11(9):824–9. https://doi.org/10.1080/15567249.2014.949392.
24. Mohamad AHH, Shaari MS. The environmental Kuznets curve in Japan with nuclear energy and foreign direct investment using ARDL and NARDL models. Discover Environ. 2025;3(1):300. https://doi.org/10.1007/s44274-025-00511-4.

25. Musah M, Kong Y, Mensah IA, Antwi SK, Donkor M. The connection between urbanization and carbon emissions: A panel evidence from West Africa. Environ Dev Sustain. 2021;23(8):11525–52. https://doi.org/10.1007/s10668-020-01124-y.
26. Pataki G. Ecological modernization as a paradigm of corporate sustainability. Sustain Dev. 2009;17(2):82–91. https://doi.org/10.1002/sd.403.
27. Pegkas P. The impact of renewable and non-renewable energy consumption on economic growth: The case of Greece. Int J Sustain Energ. 2020;39(4):380–95. https://doi.org/10.1080/14786451.2019.1700261.
28. Pincheira R, Zuniga F. Environmental Kuznets curve bibliographic map: A systematic literature review. Acc Finance. 2021;61(S1):1931–56. https://doi.org/10.1111/acfi.12648.
29. Radmehr R, Henneberry SR, Shayanmehr S. Renewable Energy Consumption, CO2 Emissions, and Economic Growth Nexus: A Simultaneity Spatial Modeling Analysis of EU Countries. Struct Change Econ Dyn. 2021;57:13–27. https://doi.org/10.1016/j.strueco.2021.01.006.
30. Ridwan M, Urbee AJ, Voumik LC, Das MK, Rashid M, Esquivias MA. Investigating the environmental Kuznets curve hypothesis with urbanization, industrialization, and service sector for six South Asian Countries: Fresh evidence from Driscoll Kraay standard error. Res Globalization. 2024;8:100223. https://doi.org/10.1016/j.resglo.2024.100223.
31. Rogelj J, Den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K, Meinshausen M. Paris Agreement climate proposals need a boost to keep warming well below 2°C. Nature. 2016;534(7609):631–9. https://doi.org/10.1038/nature18307.
32. Salim R, Rafiq S, Shafiei S, Yao Y. Does urbanization increase pollutant emission and energy intensity? Evidence from some Asian developing economies. Appl Econ. 2019;51(36):4008–24. https://doi.org/10.1080/00036846.2019.1588947.
33. Santarius T, Pohl J, Lange S. Digitalization and the Decoupling Debate: Can ICT Help to Reduce Environmental Impacts While the Economy Keeps Growing? Sustainability. 2020;12(18):7496. https://doi.org/10.3390/su12187496.
34. Schneiter P, Mellon-Bedi S. The Environmental Kuznets Curve Revisited: A Spatial Panel Model with Heterogeneous Coefficients. Energy Econ. 2025;143:108237. https://doi.org/10.1016/j.eneco.2025.108237.
35. Shakouri B, Khoshnevis Yazdi S. Causality between renewable energy, energy consumption, and economic growth. Energy Sources Part B: Econ Plann Policy. 2017;12(9):838–45. https://doi.org/10.1080/15567249.2017.1312640.
36. Sohag K, Kalugina O, Samargandi N. Re-visiting environmental Kuznets curve: Role of scale, composite, and technology factors in OECD countries. Environ Sci Pollut Res. 2019;26(27):27726–37. https://doi.org/10.1007/s11356-019-05965-7.
37. Stermieri L, Kober T, McKenna R, Schmidt TJ, Panos E. The role of digital social practices and technologies in the Swiss energy transition towards net-zero carbon dioxide emissions in 2050. Energy Policy. 2024;193:114203. https://doi.org/10.1016/j.enpol.2024.114203.

38. Tanaka K, O'Neill BC. The Paris Agreement zero-emissions goal is not always consistent with the 1.5°C and 2°C temperature targets. Nat Clim Change. 2018;8(4):319–24. https://doi.org/10.1038/s41558-018-0097-x.
39. Vicedo-Cabrera AM, Guo Y, Sera F, Huber V, Schleussner C-F, Mitchell D, Tong S, Coelho MDSZS, Saldiva PHN, Lavigne E, Correa PM, Ortega NV, Kan H, Osorio S, Kyselý J, Urban A, Jaakkola JJK, Ryti NRI, Pascal M, Gasparrini A. Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios. Clim Change. 2018;150(3–4):391–402. https://doi.org/10.1007/s10584-018-2274-3.
40. Voumik LC, Md. Nafi S, Bekun FV, Haseki MI. Modeling Energy, Education, Trade, and Tourism-Induced Environmental Kuznets Curve (EKC) Hypothesis: Evidence from the Middle East. Sustainability. 2023;15(6):4919. https://doi.org/10.3390/su15064919.
41. Wang Q, Dong Z. Does financial development promote renewable energy? Evidence of G20 economies. Environ Sci Pollut Res. 2021;28(45):64461–74. https://doi.org/10.1007/s11356-021-15597-5.
42. Wang Q, Wang X, Li R, Jiang X. Reinvestigating the environmental Kuznets curve (EKC) of carbon emissions and ecological footprint in 147 countries: A matter of trade protectionism. Humanit Social Sci Commun. 2024;11(1):160. https://doi.org/10.1057/s41599-024-02639-9.
43. Weili L, Khan H, Khan I, Han L. The impact of information and communication technology, financial development, and energy consumption on carbon dioxide emission: Evidence from the Belt and Road countries. Environ Sci Pollut Res. 2022;29(19):27703–18. https://doi.org/10.1007/s11356-021-18448-5.
44. Wigley TML. The Paris warming targets: Emissions requirements and sea level consequences. Clim Change. 2018;147(1–2):31–45. https://doi.org/10.1007/s10584-017-2119-5.

# Figures

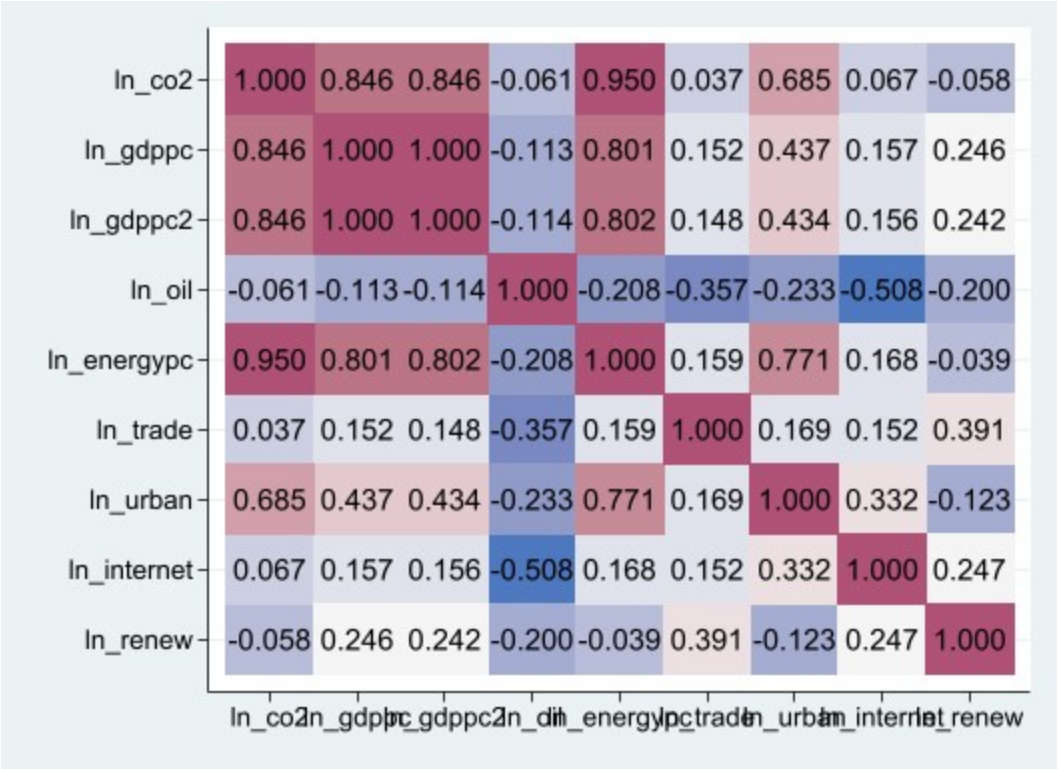



**Figure 1**

**Correlation heatmap**

Source: Authors, 2026

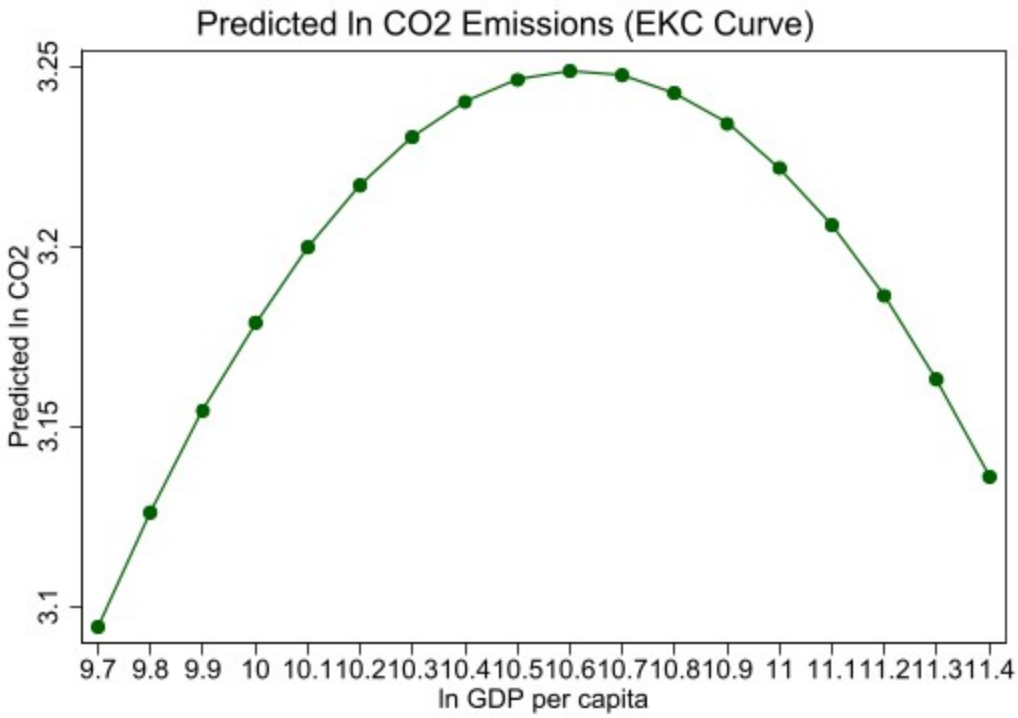



**Figure 2**

**Predicted EKC Curve: Inverted U-shaped Relationship between GDP per Capita and $CO_2$ Emissions.**

Source: Authors, 2026