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Research Article

Multiple pathways to a low-carbon future: Examining evidence from the BRICS+

Stephen Asare Abankwah[a] and Samuel Osei Afriyie [b*]

[a] Department of Economics, University of Ghana, Legon, Post Office Box LG 25, Accra, Ghana

[b] Department of Economics, University of Insubria, , Via Monte Generoso 71, Varese, Italy

Abstract. This study examines the structural and distributional drivers of energy transition in BRICS+ economies (Brazil, Russia, India, China and South Africa, Egypt, Ethiopia, Iran, UAE and Indonesia) over the period 1996-2023. We address the critical gap in understanding how economic and environmental factors differentially influence energy transition across varying levels of transition intensity. To account for cross-sectional dependence and endogeneity, we employ a smoothed common correlated effects instrumental variable quantile regression (CCE-IV QR) model, which robustly handles multiple endogenous regressors and unobserved global shocks. Our findings reveal that the drivers of transition are fundamentally stage dependent. The results reveal significant heterogeneity: CO_2 emissions negatively impact energy transition, particularly at lower quantiles, while GDP exhibits a positive association at median and lower quantiles but becomes insignificant at higher levels. Ecological footprint positively influences transition, whereas political stability and technological adoption yield mixed results, with the latter displaying a weakly significant positive impact. Robustness checks, including alternative specifications and subsample analyses, confirm the stability of these findings. These results necessitate a tiered policy framework. Particularly, early-transition economies should break fossil fuel lock-in through fiscal diversification and subsidy reallocation. Mid-transition economies should focus on reforming incumbent energy monopolies and financing decarbonization in hard-to-abate sectors. Advanced-transition economies need to overcome institutional fragmentation by creating cross-sectoral governance to direct investment toward grid modernization and systemic resilience. The methodological innovation of combining CCE with IV quantile regression further enhances the robustness of the analysis, addressing key econometric challenges in energy transition research.

Keywords: Energy transition analysis, CO_2 emissions policies, instrumental variables, common correlated effects, quantile regression

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1. Introduction

The global transition towards a low-carbon future has emerged as one of the critical pathways for countries to revolutionize existing energy systems, restructure economies towards sustainable economic development, and contribute to reducing global warming levels to 1.5^0 C (IEA, 2023). Although these outcomes reflect long-term transformations across economies, they resonate with myriad short-to medium-term implications, including recurrent cost changes to different energy technologies, changes to global energy market dynamics, and shifts in investment away from fossil fuels to renewable energy resources (Gerasimchuk *et al.*, 2019).

Energy transition, defined as the shift from non-renewable to renewable energy sources (Edenhofer *et al.*, 2012), is influenced by a complex interplay of economic, technological, and policy factors. Existing literature highlights the role of GDP growth, energy prices, and environmental regulations in shaping this transition (Cherp *et al.*, 2011; Michailidis et al., 2025). However, these studies often assume homogeneous effects across countries and quantiles, overlooking the potential for nonlinear relationships. For instance, the impact of CO_2 emissions on renewable energy adoption may vary depending on a country's existing energy infrastructure or policy framework. Similarly, the effect of GDP growth could diminish as economies reach higher levels of development, a hypothesis supported by recent work on energy system transitions (Staffell *et al.*, 2019). This study builds on these insights by examining how these relationships differ across the conditional distribution of energy transition intensity— the speed and magnitude at which clean energy systems replace fossil fuels.

The hypothesis driving this research posits that energy transition in BRICS+ countries is shaped by a combination of economic incentives and environmental pressures, with effects that vary across quantiles. Drawing from the theoretical framework of Taghizadeh-Hesary & Rasoulinezhad (2020) we extend prior work by incorporating variables such as ecological footprint, inflation, real oil price, and control variables such as population growth, political stability, and technological adoption which are factors increasingly recognized for their relevance in shaping energy policy outcomes. We employ a smoothed Common Correlated Effects Instrumental Variable Quantile Regression (CCE-IV QR) model. This approach which accounts for the endogeneity, cross-sectional dependence, and parameter heterogeneity often overlooked in prior research. By

* Corresponding author
Email: soseiafriyie@uninsubria.it (S. Osei Afriyie)

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focusing on BRICS+ countries, the study provides insights into the energy transition dynamics of economies that are both major contributors to global emissions and key players in the renewable energy sector.

The remainder of this paper is organized as follows. Section 2 reviews the existing literature. Section 3 discusses the theoretical model used in the study, explores the methodology, and outlines the data description and model specifications. Section 4 presents a detailed analysis of the results obtained. Finally, Section 5 concludes the paper, summarizing the main findings of the study.

2. Literature Review

The study of energy transition has evolved significantly in recent years, with a growing emphasis on understanding the complex interplay between economic development, environmental sustainability, and policy interventions (Ergun & Rivas, 2023; Lau *et al.*, 2023; Zambrano-Monserrate, 2024). Early work in this field primarily focused on aggregate trends in renewable energy adoption, often employing traditional linear regression models that assumed homogeneous effects across countries and time periods (Timmons *et al.,* 2014). While these studies provided valuable insights into the broad determinants of energy transition, they largely overlooked the potential for heterogeneous effects across different stages of development or levels of energy system maturity.

Recent advances in econometric methods have enabled researchers to explore these nuances more rigorously. For instance, the application of quantile regression techniques has revealed that the relationship between economic growth and renewable energy consumption varies significantly across the conditional distribution of energy transition intensity. This finding challenges the conventional wisdom that GDP growth uniformly promotes renewable energy adoption, suggesting instead that the effect may diminish or even reverse at higher quantiles of energy transition. Similarly, studies employing panel data methods have highlighted the importance of accounting for cross-sectional dependence, particularly in regions like BRICS+ where countries are subject to common global shocks such as oil price fluctuations or climate policy shifts (Chovancová *et al.*, 2024).

The role of environmental factors in driving energy transition has also received considerable attention. A robust body of literature demonstrates that CO_2 emissions exert a negative influence on renewable energy adoption, as countries facing higher environmental costs are more likely to prioritize clean energy alternatives (Li *et al.*, 2022). However, the magnitude of this effect appears to vary depending on institutional and technological contexts (Karasmanaki *et al.,* 2025). For example, nations with strong environmental governance frameworks or advanced renewable energy technologies may exhibit a more pronounced response to emissions pressures compared to those with weaker institutions or limited technological capacity (Aziz *et al.,* 2020). This heterogeneity underscores the need for quantile-specific analyses that can capture differential responses across the energy transition spectrum.

While a significant body of literature, including this study, focuses on the macroeconomic and environmental determinants of energy transitions, a parallel strand of research emphasizes the micro-level governance and financing mechanisms that enable specific sustainable projects. For example, Rehman *et al.* (2018) examined the application of the Public-Private Partnership model to develop sustainable irrigation infrastructure in Pakistan. Their work underscores that successful decarbonization and resource efficiency often depend on tailored institutional arrangements that can mobilize investment and manage local implementation challenges. This study complements such micro-level analyses by providing a macro-quantitative perspective on the stage-dependent drivers that shape the broader environment in which these individual projects and policies must operate.

Methodological innovations have played a pivotal role in advancing this field. The development of common correlated effects (CCE) estimators has addressed longstanding challenges associated with cross-sectional dependence in panel data, enabling more reliable inference in the presence of unobserved global factors (Azhgaliyeva *et al.*, 2020). Similarly, instrumental variable (IV) techniques have been increasingly employed to mitigate endogeneity concerns, particularly in studies examining the causal effects of policy interventions on energy transition outcomes (Smith & Urpelainen, 2014). Recent work has further combined these approaches with quantile regression methods, yielding insights into how the impacts of key determinants vary across different segments of the energy transition distribution (Ojekemi *et al.*, 2023).

Despite these advances, several gaps remain in literature. First, most existing studies focus on developed economies or broad global samples, paying limited attention to the unique circumstances of emerging economies like those in the BRICS+ bloc. This oversight is particularly problematic given that these nations account for a substantial share of global energy consumption and emissions, yet face distinct challenges in transitioning their energy systems (Sachan & SenGupta, 2025). Second, while some studies have employed quantile regression techniques, few have integrated these methods with CCE and IV approaches to simultaneously address heterogeneity, cross-sectional dependence, and endogeneity. This methodological shortcoming may lead to biased or inefficient estimates, potentially obscuring important nuances in the energy transition process.

Moreover, newer studies have employed the Machado and Santos Silva (2019) Method of Moments Quantile Regression (MM-QR) approach (Adebayo *et al.,* 2024; Afshan *et al.*, 2022). While this approach presents an elegant estimation technique, it is more restrictive in its assumptions as it relies on a specific location-scale model which can lead to inconsistent estimates when mis-specified. More importantly, the MM-QR approach does not satisfactorily accommodate multiple endogenous regressors which limit their suitability in contexts where simultaneity bias and reverse causality are theoretically and empirically plausible. Given the methodological gaps with these approaches, smoothed (CCE) instrumental variables (IV) quantile regression framework is considered a suitable approach in analyzing the energy transition dynamics in the new BRICS block as it could address cross-sectional dependencies and unobserved common factors using instrumental variables to correct for simultaneity bias.

The political economy of energy transition has emerged as another critical area of inquiry. Research has shown that political stability and institutional quality can significantly influence the pace and direction of renewable energy adoption, with more stable and transparent governance systems generally associated with faster transitions (Urpelainen et al., 2018). However, these relationships may be nonlinear, as excessive bureaucratic hurdles or rent-seeking behavior in otherwise stable political environments can sometimes hinder progress. Technological factors, including innovation capacity and infrastructure readiness, have also been identified as key determinants of energy transition success, though their impacts appear to vary depending on a country's stage of development and existing energy mix (Solarin *et al*., 2022).

Compared to existing studies that often treat energy transition as a uniform process, our research highlights the substantial heterogeneity in how economic and environmental factors influence renewable energy adoption across BRICS+ countries. While prior work has identified general patterns in the relationship between GDP growth and energy transition (Hlongwane *et al*., 2025), our analysis reveals that this relationship is contingent on a country's position in the energy transition distribution. Similarly, whereas previous research has established the negative impact of CO_2 emissions on renewable energy adoption in broad terms (Özkan & Destek, 2025), we show that this effect is particularly pronounced at lower quantiles of energy transition distribution. These findings underscore the value of moving beyond average effects to examine how determinants operate differently across the conditional distribution, providing policymakers with more precise guidance for intervention design.

3. Methodology

This section is divided into two parts. The first part discusses the theoretical model of the study while the second part details the data and variables used as well as the empirical model and strategy of the study.

3.1 Theoretical Model

Our core theoretical model focuses on the economic incentives that influence energy transition decisions for the two primary actors in the energy system (profit maximizing firms and utility-maximizing households). This approach, based on the work of Taghizadeh-Hesary & Rasoulinezhad (2020), provides a clear, testable hypothesis about how prices, costs, and income influence the choice between renewable and non-renewable energy. Based on the theoretical model, the variables include electricity tariff, price of final industry products, exchange rate, environmental costs, and GDP of the economy (see supplementary file for derivation of the theoretical model).

3.2 Data and Variables of the Study

This study uses an annual panel dataset from 1996–2023. We adopt this period due to data availability and also to ensure we do not overstretch our approach in addressing data missingness among variables which may inadvertently bias results. The data were obtained from multiple sources including the World Bank's World Development Indicators (WDI), the Global Footprint Network (GFN), Cugat and Manera (2024) technology adoption index data and the Energy Institute Statistical Review. Due to the recent expansion of BRICS (now referred to as BRICS+), which includes five additional countries, the study focuses on data from full members of the bloc as of January 2025: Brazil, Russia, India, China, South Africa, Egypt, Ethiopia, Iran, UAE and Indonesia.

This expanded sample is deliberately chosen for three complementary reasons. First, it captures the full heterogeneity of energy transition stages ranging from Ethiopia's low-carbon but energy-poor economy to the hydrocarbon-rich petrostates of Iran and the UAE which is essential for our quantile-based approach. Second, the new members introduce critical variation in fossil fuel dependence, institutional quality, and climate vulnerability, strengthening the empirical identification of transition drivers. Third, analyzing the enlarged bloc reflects the emerging geopolitical and economic reality of a coalition that now represents nearly half the world's population and a dominant share of global fossil fuel reserves.

Based on the theoretical model, this study posits that energy transition defined as the ratio of renewable energy consumption to non-renewable energy consumption is the dependent variable. Similarly, the independent variables include exchange rate, GDP, real oil prices (used as a proxy for energy prices), and CO_2 emissions. The study incorporates control variables such as population growth rate, political stability, ecological footprint, and technological adoption (see Table 1). To ensure consistency and comparability, all macroeconomic data were extracted from WDI.

Given that our data is unbalanced, we employed linear interpolation, based on the structure of variables to fill missing values. Interpolation was selected because it preserves the temporal structure of the data and minimizes disruptions to underlying trends (Knutsen, 2012). This method is particularly suited for variables which exhibit gradual and continuous changes over time.

3.3 Econometric Model Specification

Based on the variables for the study and the theoretical foundation underpinning their selection, the multivariate econometric specification can be written as:

$$\boldsymbol{et_{it} = \gamma + \delta co2_{it} + \varphi ex_{it} + \rho gdp_{it} + \sigma infl_{it} + \alpha r\_oil\_px_{it} + \vartheta \sum controls_{it} + \varepsilon_{it}} \quad (1)$$

We adopted a log-transform of the model due to the non-normality of the data. The log-transform of the model is expressed in Eq.1 as follows:

Table 1
Definition of Variables

Variables	Log Transform	Definition	Database
Energy transition (et)	let	$\frac{\%\textbf{Renewable energy cons.}}{\%\textbf{Fossil fuel energy cons.}}$	WDI
CO_2 Emissions (co2)	lco2	Metric tons per capita	WDI
Population growth (pop)	lpop	Annual percentage growth rate of population	WDI
Exchange rate (ex)	lex	Official exchange rate (LCU per US$, period average)	WDI
GDP	lgdp	GDP percapita	WDI
Inflation rate (infl)	linfl	Consumer prices (annual %)	WDI
Ecological footprint (eco_fp)	leco_fp	Global Footprint Network	GFN
Political Stability (pol_stab)	lpol_stab	estimates	WDI
Real Oil Price (r_oil_px)	lr_oil_px	Adjusted Brent crude ($/bbl)	EISR
Technology adoption (tech)	ltech	Technology adoption index	(Cugat and Manera, 2024)

$$let_{it} = \gamma + \delta lco2_{it} + \varphi lex_{it} + \rho lgdp_{it} + \sigma linfl_{it} + \alpha lr\_oil\_px_{it} + \vartheta \sum controls_{it} + \varepsilon_{it} \quad (2)$$

Where γ is the intercept term, φ, ρ, σ, α, ϑ are the slope coefficients and ε is the error term. Additionally, i represents the cross-section of countries and t represents the time period.

3.3.1 Smoothed (common correlated effects) Instrumental Variable Quantile Regression Model

Introduced by Koenker and Bassett (1978), the traditional quantile regression model estimates the effects of a given set of covariates at the conditional quantiles of the dependent variable (Fitzenberger and Wilke, 2015). Canay (2011) argues that the ability to account for unobserved heterogeneity and the varying effects of covariates is one of the many powerful features of the quantile regression model.

However, the traditional quantile regression model has several limitations. First, it assumes exogeneity of regressors, an assumption rarely tenable in observational panel data where simultaneity, endogeneity, omitted variable bias, and measurement errors are common. Second, the standard QR model does not account for cross-sectional dependence. Ignoring such dependencies can lead to inconsistent estimates and invalid inference. Third, inference in panel QR models is inherently difficult due to the non-smoothness of the objective function. Bootstrap methods are usually an alternative, but they are computationally intensive and sensitive to tuning parameters, especially when individual fixed effects are present (Fitzenberger & Wilke, 2015)

Due to these multilayered problems, we adopt the smoothed instrumental variables quantile regression approach proposed by Kaplan & Sun (2017) and adjust the model with common correlated effects following Harding & Lamarche (2014). Notably, our choice of the smoothed CCE IV-QR model stems from at least three main reasons. Firstly, theory suggests that some of our key regressors are endogenously determined. Secondly, considering the shared exposure of BRICS+ economies to global shocks such as geopolitical tensions and multilateral agreements, cross-sectional dependence is a likely concern. Without accounting for this, we are likely to obtain imprecise and biased estimates. We utilize cross-sectional averages of both the dependent and explanatory variables following an adjustment of Pesaran (2006) model. Lastly, standard IV-QR approaches, often rely on local linear or check function approximations, which make theme computationally unstable, and inference likely unreliable when there are multiple endogenous regressors (Kaplan & Sun, 2017).

In specifying our robust model, we first let y_{it} represent the energy transition index for country i at time t, defined as the ratio of renewable to non-renewable energy consumption. The baseline quantile regression model takes the form:

$$Q_{y_{it}}(\tau|X_{it}) = \alpha(\tau) + X_{it'}\beta(\tau) + \epsilon_{it}(\tau) \quad (3)$$

where $Q_{y_{it}}(\tau|X_{it})$ denotes the τ-th conditional quantile of y_{it}, X_{it} is a vector of covariates including CO_2 emissions, GDP, and control variables, and $\beta(\tau)$ captures quantile-specific coefficients. The error term $\epsilon_{it}(\tau)$ satisfies $P(\epsilon_{it}(\tau) \leq 0|X_{it}) = \tau$.

To account for endogeneity, we introduce instrumental variables Z_{it} that satisfy the relevance and exogeneity conditions. The first-stage regression for endogenous variable x_{it}^k is specified as:

$$x_{it}^k = \gamma_0 + Z_{it'}\gamma_1 + W_{it'}\gamma_2 + \nu_{it} \quad (4)$$

where W_{it} contains exogenous covariates and ν_{it} is the error term. The predicted values $\hat{x}_{it}^k$ from Equation 2 replace endogenous regressors in Equation 1.

The CCE extension augments the model with cross-sectional averages of dependent and independent variables to control unobserved common factors:

$$Q_{y_{it}}(\tau|\cdot) = \alpha(\tau) + X_{it'}\beta(\tau) + \bar{y}_{t'}\delta_1(\tau) + \bar{X}_{t'}\delta_2(\tau) + \epsilon_{it}(\tau) \quad (5)$$

where $\bar{y}_t$ and $\bar{X}_t$ are cross-sectional averages at time t. The smoothing kernel $K_h(\cdot)$ with bandwidth h ensures continuity in the quantile process:

$$\hat{\beta}(\tau) = \operatorname*{argmin}_{\beta} \sum_{i=1}^{N} \sum_{t=1}^{T} \rho_\tau (y_{it} - X_{it'}\beta) K_h(F_n(y_{it}) - \tau) \quad (6)$$

where $\rho_\tau(u) = u(\tau - I(u < 0))$ is the check function and $F_n(\cdot)$ denotes the empirical distribution function.

3.3.1 Identification Strategy

The identification of causal effects relies on three key assumptions:

1. Instrument Relevance: The matrix $E[Z_{it}X_{it}]$ has full column rank, ensuring instruments strongly predict endogenous variables. This is verified through first-stage F-statistics exceeding the Stock-Yogo critical values.
2. Exclusion Restriction: Instruments affect the energy transition index only through the endogenous variables, formalized as $\boldsymbol{E[Z_{it}\epsilon_{it}(\tau)] = 0}$. We use lagged values of endogenous regressors to satisfy this condition.
3. Common Correlated Effects: The factor structure of errors $\boldsymbol{\epsilon_{it}(\tau) = \lambda_{i'}F_t + e_{it}}$ is adequately captured by cross-sectional averages, where $\boldsymbol{F_t}$ represents unobserved common factors and $\boldsymbol{\lambda_i}$ denotes factor loadings. Due to model parsimony, we do not include averages from all variables into the model.

The smoothed quantile approach transforms the discrete optimization problem into a continuous one through kernel weighting:

$$\hat{\beta}(\tau) = \operatorname*{argmin}_{\beta} \sum_{i=1}^{N} \sum_{t=1}^{T} w_{it}(\tau) \rho_\tau (y_{it} - X_{it'}\beta) \quad (7)$$

with weights $w_{it}(\tau) = K_h(\hat{u}_{it}(\tau))$ derived from preliminary quantile regression residuals $\hat{u}_{it}(\tau)$.

4. Empirical Results

This section presents descriptive statistics, diagnostic tests, empirical findings and a thorough discussion of results.

4.1 Descriptive Statistics

Table 2 presents the descriptive statistics for the variables and the pairwise correlation matrix. The variables exhibit significant non-normality, as evidenced by positive

Table 2
Descriptive Statistics

Variables	Obs	Mean	Std. Dev.	Min	Max	Skew.	Kurt.
et	223	2.158	6.303	.001	29.699	3.174	11.595
ex	280	2857.706	7687.789	1.005	42000	3.599	16.817
co2	280	6.561	7.16	.053	31.141	1.622	4.971
pop	280	1.66	2.09	-.475	18.128	4.825	33.508
r_oil_px	280	2210000	7480000	-60300	65036304	5.064	33.66
gdp	280	8885.281	13813.073	245.505	62334.41	2.597	8.464
infl	278	9.338	10.781	-16.267	85.746	2.928	17.37
pol_stab	250	-.663	.705	-2.184	.995	.441	2.931
eco_fp	280	7.350e+08	1.100e+09	28919608	5.178e+09	2.625	9.404
tech	250	33.689	10.097	16.689	62.045	.675	2.591

Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) et	1.000									
(2) ex	-0.111	1.000								
(3) co2	-0.294	-0.051	1.000							
(4) pop	0.168	-0.071	0.358	1.000						
(5) r_oil_px	-0.093	0.547	-0.119	-0.076	1.000					
(6) gdp	-0.186	-0.123	0.907	0.529	-0.106	1.000				
(7) infl	-0.034	0.371	-0.089	-0.021	-0.019	-0.178	1.000			
(8) pol_stab	-0.314	-0.268	0.669	0.285	-0.045	0.751	-0.471	1.000		
(9) eco_fp	-0.187	-0.139	-0.048	-0.294	-0.085	-0.127	-0.210	0.033	1.000	
(10) tech	-0.272	0.351	-0.180	-0.132	0.308	-0.066	-0.059	0.006	-0.081	1.000

skewness and high kurtosis for all series. The nature of the distribution supports the use of a framework that is robust to these deviations. The correlation matrix reveals meaningful associations that align with theoretical expectations. Energy transition shows a negative correlation with CO_2 emissions (–0.294), GDP (–0.186), and political stability (–0.314). The weak negative association between energy transition and exchange rate (–0.111) or oil price (–0.093) reflects exposure to external macroeconomic shocks influencing renewable investment costs.

4.1.1 Cross-Sectional Dependence Test

A critical preliminary step in our empirical strategy was to test the assumption of cross-sectional independence, which is foundational to many standard panel estimators. This assumption is particularly untenable in our context, as the countries in our sample are embedded in a globally integrated economic system. Shared exposures to global climate policy frameworks, global fossil fuel price shocks, and global financial cycles create strong channels for cross-sectional dependence. Ignoring these interconnections risks biased inference and unreliable policy conclusions, as unobserved common factors can induce spurious correlations. In performing this essential diagnostic, we employed the Breusch-Pagan (1980) Lagrange Multiplier (LM) test, a robust choice for our data structure where T > N (see Table 3). The results displayed an LM statistic of 228.64 ($p < 0.001$), leading to a rejection of the null hypothesis of cross-sectional independence.

4.1.2 Panel Unit Root Test

Following the conclusions drawn from the cross-sectional dependence test, a panel unit root test was necessary to assess the suitability of the model for estimation (Tugcu, 2018). This crucial diagnostic test identifies the presence of stationarity or non-stationarity in both covariates and dependent variables. Second-generation panel unit root test, the cross-sectionally augmented lm-Pesaran-Shin (CIPS) second-generation panel unit root estimator was employed to determine the stationarity of the variables (Pesaran, 2007). The results presented in Table A5 indicate that the test without trend and test with trend both display all variables except energy transition (let), CO_2 emissions, population growth and ecological footprint and technology as stationary at levels. Based on the p-values of these variables, we could not reject the null hypothesis of no unit root at 1% significance level. However, when expressed as first difference, all variables exhibit stationarity,

Table 3.
Breusch-Pagan LM Test of Independence

Cross-Sectional Dependence	Statistic	p-value
Model	228.64***	0.000

*** p<0.01, ** p<0.05, * p<0.10

Table 4.
Cointegration Test Results

	Statistic	P-value
Pedroni Cointegration Test		
Modified Phillips-Perron *t*	2.551***	0.005
Phillips-Perron *t*	-3.363***	0.000
Augmented Dickey-Fuller *t*	-3.400***	0.000
Kao test		
Modified Dickey-Fuller *t*	2.397***	0.000
Dickey-Fuller *t*	3.544***	0.000
Augmented Dickey-Fuller *t*	2.522***	0.000
Unadjusted modified Dickey-Fuller *t*	3.863***	0.000
Unadjusted Dickey-Fuller *t*	5.759***	0.000
Westerlund test		
Variance ratio	2.989***	0.001

*** $p<0.01$, ** $p<0.05$, * $p<0.10$

with and without a trend term implying that the data series are integrated of mixed order *I(0) and I(1).*

4.1.4 Panel Cointegration Test

Establishing a long-run equilibrium relationship among the variables is a prerequisite for meaningful policy inference, as it ensures that the estimated relationships are not spurious. To this end, we conducted a comprehensive battery of cointegration tests, the results of which are presented in Table 4. We primarily rely on the Pedroni (2004) test, which is particularly suited to our context as it allows for heterogeneous intercepts and trend coefficients across panels, consistent with our finding of slope heterogeneity. Key statistics from the Pedroni test including the Modified Phillips-Perron t (2.551, p<0.01), Phillips-Perron t (-3.363, p<0.01), and Augmented Dickey-Fuller t (-3.400, p<0.01), all lead to a strong rejection of the null hypothesis of no cointegration. The robustness of this finding is confirmed by two alternative tests including the Kao test, which assumes common Autoregressive coefficients, and the Westerlund test, which is based on structural rather than residual dynamics. All tests provide consistent evidence, with all relevant statistics significant at the 1% and 5% levels.

4.1.5 Slope Heterogeneity Test

The cross-sectional dependence test is further substantiated by an equally critical test for slope heterogeneity. The Pesaran and Yamagata (2008) test, reported in Table 5, formally assesses the null hypothesis that the slope coefficients are homogeneous across the BRICS+ countries. The results are conclusive: both the Delta and Adjusted Delta statistics are statistically significant (at the 5% and 1% levels, respectively), leading us to firmly reject the null hypothesis. This confirms that the impact of our explanatory variables on energy transition is not uniform but varies significantly across the economies in our panel.

4.2 Discussion of Results

Our results exhibit heterogeneity across the distribution of our core variables of interest. Following Koenker (2005) quantile treatment effects, we find that the tests between the 25th and 75th quantiles and between the 50th and 75th quantiles reject the null hypothesis of equal coefficients at the 1% level for CO_2 emissions, and GDP, and at the 5% level for ecological footprint. These findings confirm that the relationships vary across the conditional distribution of the dependent variable, supporting our robust methodological approach (see Table A4).

4.2.1 Heterogenous Effects

Based on the empirical findings presented in Table 6, we observe a statistically significant negative relationship between CO_2 emissions and energy transition across all quantiles, though the magnitude of this effect varies substantially. A 1% increase in emissions corresponds to a substantial decrease in energy transition of -2.296%, -2.177%, and -1.504% at the low, median, and high quantiles, respectively, suggesting that countries with relatively low levels of energy transition are particularly sensitive to emissions pressures. This finding aligns with theoretical expectations that nations in early transition stages face higher marginal costs of decarbonization (Baker *et al.,* 2014). The findings are consistent with Lau *et al* (2023) and Taghizadeh-Hesary & Rasoulinezhad (2020) who posit that countries with high carbon emissions exhibit slower pace of transition due to the structural reliance on carbon-intensive

Table 5
Slope Heterogeneity Test Results

Delta	*p*-Value	Delta Adj.	*p*-Value
5.523 ***	0.000	7.088***	0.000

*** $p<0.01$, ** $p<0.05$, * $p<0.10$

infrastructure. This further indicates that countries at early stages of transition are often those most deeply trapped in a carbon-intensive regime, where the immediate costs of systemic overhaul are considered as prohibitively high.

These conditions have likely been reinforced by the global energy crisis in 2021-2022, which temporarily soared fossil fuel revenues and strengthened interests in existing fossil fuel consumption. Moreover, the weakening negative effect at the 75th quantile (almost 2 times less than in q25 and q50), while still significant, reveals a crucial insight into countries at advanced stages of the transition. We interpret this as evidence of countries in advanced stages of the transition being better able to manage rising emissions compared to countries just at the early transition stages and face the full, upfront costs of breaking away from fossil-fuel dependent regimes.

The relationship between economic growth and energy transition exhibits striking heterogeneity across the conditional distribution, with economic growth serving as a significant driver of the transition, but for the 75th quantile where the growth effect largely declines. This means that for nations in the early and middle stages (q25, q50), a 1% rise in GDP is associated with a significant 0.817-0.370% acceleration in the transition. Specifically, the contribution of economic growth is 1.2 times higher than that of ecological footprint in q25. This indicates that economic growth provides the essential capital for the early phase of the transition, which is characterized by large-scale, lump-sum investments in core green infrastructure. Here, GDP growth directly fuels this capital-intensive process, explaining significant positive coefficients. This positive association aligns with theoretical expectations that rising incomes enable greater investment in renewable infrastructure and facilitate policy support for decarbonization (Amri, 2017). However, the results contrast with Rasoulinezhad *et al.* (2020) and Yu & Guo (2023) who find that economic growth inhibits the progress in energy transition. While notable, these studies are single-country specific, limiting the nuances captured in multi-country contexts.

Moreover, this effect dulls at advanced transition nations (q75). We argue that this decline may be because of advanced transition countries encountering diminishing marginal returns. This nonlinear trajectory implies that economic development initially accelerates energy transition but reaches a saturation point where additional GDP growth no longer significantly influences renewable adoption rates. The diminishing returns at higher quantiles may reflect several underlying mechanisms. First, nations achieving advanced transition levels often possess mature renewable energy markets where further expansion requires overcoming structural challenges (Huang *et al.*, 2019). In this case, the low-hanging fruits of decarbonization measures such as substituting some types of fossil fuels with solar and wind energy systems have already been captured. What then remains is the decarbonization of hard-to-abate sectors such as heavy industry, agriculture, and transport systems that are technologically and economically more demanding (Bataille, 2020). Second, the composition of GDP growth such as service-led expansion in high-income countries typically carries lower energy transition pressures compared to industrial growth in developing economies (Voigt *et al.*, 2014). Third, policy prioritization may shift at higher income levels, with economic competitiveness concerns potentially outweighing environmental objectives in some contexts.

Regarding macroeconomic stability variables, inflation, and oil price, the findings reveal muted and insignificant effects across quantiles. The muted role of these effects, which contrasted with conventional theory even before the COVID-19 pandemic, has become a cornerstone of energy security strategy for countries after the Ukraine invasion. Particularly for inflationary effects, a 1% increase in emissions is associated with 0.064%, 0.052%, and 0.189% decline at the low, median and high quantiles, respectively. This pattern suggests that, at all transition stages, inflation may act as a strain by increasing the cost of capital for complex projects.

More so, the role of oil price volatility on the energy transition appears muted in our sample as the effects are near-zero (0.018%-0.024% between q25 and q75) across quantiles. Contrary to conventional economic theory, which states that higher fossil fuel prices should incentivize a shift to alternatives, our results suggest this price signal is being muted or entirely offset by other structural and policy-driven factors. We argue that, this is because many nations in the BRICS+ bloc employ various forms of fossil fuel subsidies that insulate the domestic economy from international price volatility, suppressing the link between world oil prices and the effective price signal received by end-users (Coady *et al.*, 2019). Additionally, some of the developing and emerging countries in BRICS+ are still coal-dominated and therefore switch to their use in the event of oil price volatilities. In this case, a rise in oil prices does little to make renewables more competitive against the dominant incumbent fuel, which is often cheaper than domestic coal.

Similarly, the findings show a somewhat similar influence on exchange rate. A 1% rise in exchange rate leads to a 0.036% and 0.087% decline in the transition at the low and high quantiles respectively. This indicates that the energy transition is no longer primarily an import-dependent process vulnerable to currency risk except for advanced economies. The globalized renewable energy supply chain and the dominance of long-term financing appear to have largely insulated investments from such volatility. Overall, these null effects across early and mid-transition stages suggest that macroeconomic instability should not be used as a pretext for delaying decarbonization. These results partially contrast with earlier literature that argue a significant role for macroeconomic stability in enabling green investment (Attílio, 2025; Jin *et al.*, 2024).

The findings further reveal that ecological footprint is a strong enabler of energy transition with the effect ten times smaller at advanced stages (from 0.719% in q25 to 0.069% in q75) due to the moderating role of political stability in the 75th quantile. This suggests that countries in early stages of transition respond to environmental degradation by accelerating renewable energy adoption, potentially reflecting growing public awareness of ecological limits and policy responses to biodiversity loss (Jie *et al.*, 2023). While ecological footprint remains a positive driver of energy transition, political stability reduces the marginal importance of ecological pressure. This suggests that in countries with advanced transition levels, stable political institutions enable energy transition through long-term planning and policy consistency, diminishing the reliance on ecological crisis as a primary motivator.

A notable finding concerns the heterogeneous impact of technology adoption across transition stages. While technology adoption shows positive coefficients across quantiles (0.444% in early stages to 0.352% in advanced stages), statistical significance is confined to early-transition economies (25th quantile). This pattern challenges the assumption of linear technological optimism and reveals a stage-specific enabling role of technology adoption. In early-transition economies (where technology adoption is significant), we interpret this as evidence that basic technology diffusion such as importing standardized renewable equipment or adopting off-shelf efficiency solutions can provide measurable transition gains.

Table 6
Smoothed (CCE) IV-Quantile Regression Model

	(1)	(2)	(3)
VARIABLES	q25	q50	q75
lco2	-2.296***	-2.177***	-1.504***
	(0.091)	(0.132)	(0.164)
lex	-0.036	-0.048	-0.087**
	(0.028)	(0.036)	(0.037)
lgdp	0.817***	0.700***	0.370*
	(0.095)	(0.153)	(0.201)
leco_fp	0.719***	0.709***	0.113
	(0.081)	(0.094)	(0.242)
leco_fp#lpol_stab	-0.009	-0.102	-0.069
	(0.044)	(0.175)	(0.186)
linfl	-0.064	-0.052	-0.189*
	(0.048)	(0.061)	(0.106)
lpop	-0.184	-0.180*	-0.106
	(0.146)	(0.103)	(0.070)
lr_oil_px	0.018	0.010	0.024
	(0.015)	(0.013)	(0.020)
lpol_stab	0.201	2.078	1.439
	(0.881)	(3.575)	(3.776)
ltech	0.444**	0.102	0.352
	(0.209)	(0.329)	(0.276)
Constant	-20.267***	-19.366***	-3.771
	(2.217)	(2.705)	(4.622)
Observations	260	260	260
R^2	0.68	0.65	0.59

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.10$

These economies likely face lower technological entry barriers and can leverage existing global innovation without extensive complementary investments.

Conversely, the insignificant effects in mid- and advanced-transition stages suggest diminishing returns and increasing complexity. At these stages, transition challenges shift from technology access to technology integration and system optimization. This finding echoes research in developing contexts (Babayomi *et al.*, 2022) and extends it by showing how the technology-transition relationship evolves across development stages. Technology adoption appears necessary but insufficient beyond initial transition phases, where complementary institutional and human capital investments become critical bottlenecks.

4.2.2 Robustness Checks and Instrument Validity

From both theoretical and empirical perspectives, several key regressors in our model including CO_2 emissions (lco2), exchange rate (lex), economic growth (lgdp) and inflation rate (linfl), ecological footprint (leco_fp), interaction terms involving ecological footprint and political stability (leco_fp#lpol_stab) were potentially endogenous due to simultaneity with the energy transition process. To address this, we employed an instrumental variable approach and control function test (Wooldridge, 2015) to ensure model parsimony and robust identification. We use the first and second lags of endogenous variables as our instruments, which are mostly utilized in addressing these challenges (Arellano & Bond, 1991). Initial tests of a more comprehensive model (specification B), which included inflation as an endogenous variable, yielded weak instrument diagnostics (Table A1) with Kleibergen-Paap F-statistic of 2.68 below conventional thresholds (see Table A2).

On this basis, we conducted control function tests (see Table A3) by estimating first-stage regressions for the weakly identified regressor and included its residuals in the second-stage model (D'Haultfœuille *et al.*, 2024; Navarro, 2010; Wooldridge, 2015). The control function test results showed that residual coefficient for inflation was 0.307 with a p-value of 0.246, hence confirming the treatment of inflation as exogenous in our model. Following this outcome, and in line with achieving model parsimony, our final model followed specification A as reported in Table A3 as our primary endogenous variables. This focused approach yielded strong instrument relevance with a Kleibergen-Paap Wald rk F-statistic of 6559.845. Post-estimation tests for overidentifying restrictions yield Hansen J statistics with p-value of 0.757 failing to reject the null hypothesis of instrument exogeneity. This provides empirical support for the exclusion restriction assumption that our instruments affect energy transition only through their impact on endogenous variables.

Table 7.
Standard (Simultaneous) Quantile Regression Results

	(1)	(2)	(3)
VARIABLES	q25	q50	q75
lco2	-2.240***	-2.157***	-1.397***
	(0.113)	(0.211)	(0.094)
lex	-0.042	-0.048	-0.070
	(0.026)	(0.055)	(0.046)
lgdp	0.747***	0.694***	0.255
	(0.123)	(0.230)	(0.194)
linfl	-0.024	-0.011	-0.049
	(0.042)	(0.050)	(0.071)
lpop	-0.086	-0.165	-0.148
	(0.082)	(0.104)	(0.102)
lr_oil_px	0.002	0.000	0.007
	(0.012)	(0.015)	(0.022)
leco_fp	0.756***	0.703***	0.092
	(0.046)	(0.104)	(0.171)
lpol_stab	1.259	1.731	1.123
	(1.059)	(2.585)	(2.281)
leco_fp#lpol_stab	-0.059	-0.085	-0.055
	(0.053)	(0.127)	(0.113)
ltech	0.221	0.080	0.212
	(0.225)	(0.271)	(0.199)
Constant	-21.499***	-19.277***	-3.922
	(1.734)	(2.959)	(2.898)
Observations	280	280	280

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.10$

Alternative model specifications provide additional robustness checks. Tables 7 and 8 display robustness checks for the effect of CO_2 emissions and other macroeconomic variables on energy transition. The results of the standard QR model in Table 7 yield similar causal effects to the smoothed (CCE) IV-QR model. A comparison with the results of our primary model shows that the signs and significance of the coefficients remain predominantly unchanged across some of the key variables while deviations emerge for some others. The standard QR shows insignificant effects for variables like population growth and technology adoption, which become significant in our CCE-IV QR model for certain quantiles. This discrepancy is consistent with the presence of endogeneity. The standard model likely captures spurious associations across the distribution. The convergence of our CCE-IV QR for these variables after instrumentation increases our confidence that we are isolating a more plausible causal effect. These differences confirm that failing to address endogeneity and cross-sectional dependence can lead to misleading inferences, thereby validating the necessity of our more robust CCE-IV QR framework.

The construction of coefficient plots with confidence bands in Fig. 1 across the quantile process provides a robust visual confirmation of the heterogeneity identified in our discrete quantile estimations. The plots verify that the evolving relationships for core variables such as GDP and ecological footprint are not limited to our chosen quantile points but represent smooth, continuous transitions. Crucially, the stability of the confidence bands and the clear trajectories of the point estimates reinforce that the stage-dependent effects we identify are statistically meaningful and not driven by isolated fluctuations, thereby validating the overall pattern of our findings.

With the aim of ensuring our findings are not driven by the data interpolation process, we re-estimated our CCE-IV QR model using the original, non-interpolated dataset. The results, presented in Table 11, demonstrate a high degree of robustness for most of our key findings, thereby significantly strengthening the credibility of our conclusions. Specifically, the effect sizes and significance of CO_2 emissions, economic growth, and ecological footprint were hugely similar. However, the most telling discrepancy emerged for political stability, technological adoption, and interaction terms. In our primary CCE-IV QR model, the political stability variable has a large and insignificant coefficient across quantiles, but the non-interpolated results show significant effects at the 75th quantile. Likewise, the CCE-

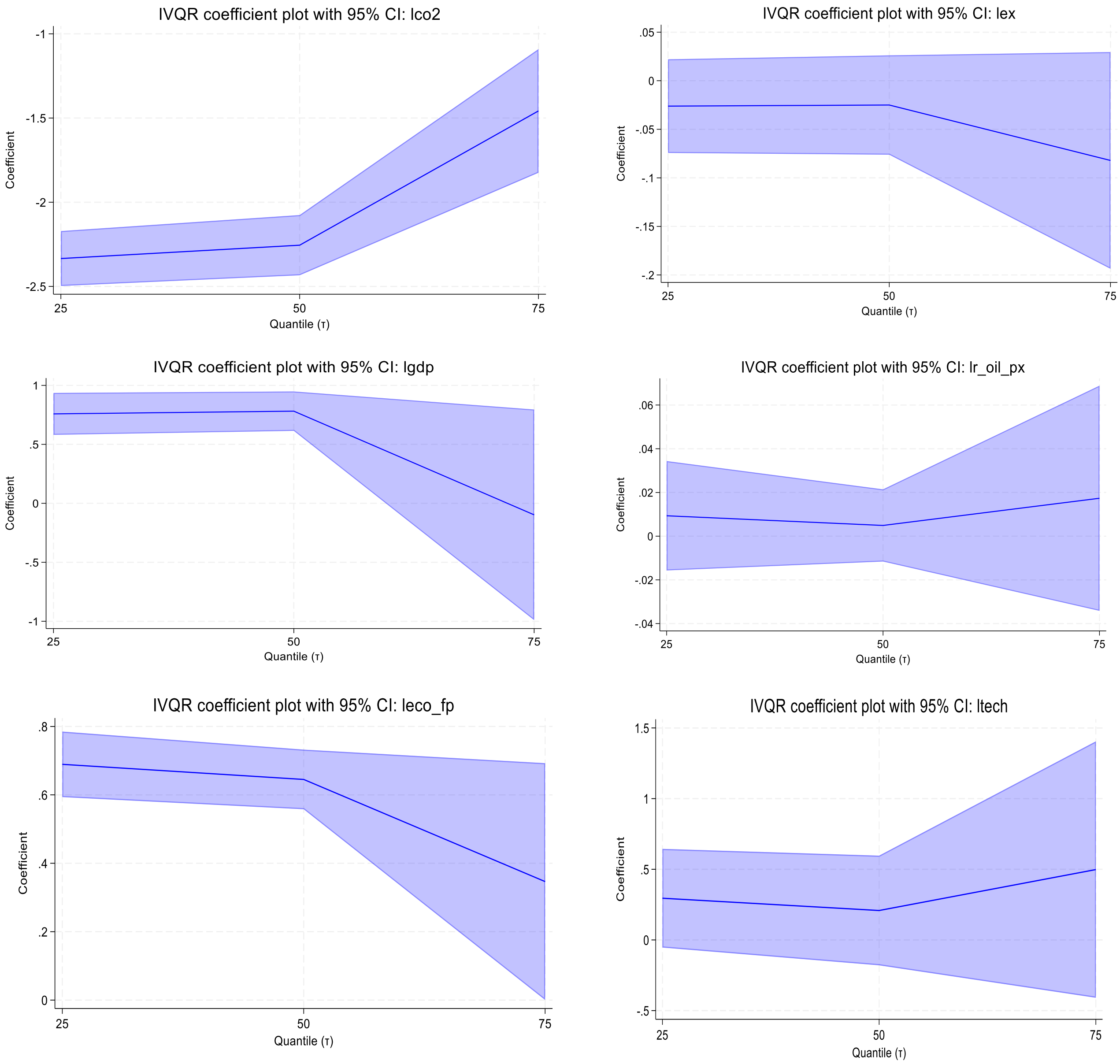

Fig. 1. CCE-IV QR Coefficient Plots with Confidence bands

IV QR correctly instruments the interaction term with the coefficient insignificant. However, in the non-interpolated model where it is treated as exogenous due to weak instrument after implementing the fitted value approach, the coefficient becomes small (0.025) and significant at the 75^{th} quantile. This discrepancy demonstrates that failing to instrument the interaction term between ecological footprint and political stability masks its true, significant moderating effect for advanced transition countries. The spurious correlation absorbed by the exogenous specification nullifies the finding. The weak instrument in the non-interpolated data unfortunately prevents a consistent estimation of this effect in the reduced sample, but in doing so, it strongly validates the necessity of our instrumentation strategy in the primary model.

We further test the structural validity of our findings by conducting a critical robustness check by segmenting the sample into fossil fuel-exporting and fossil fuel-importing nations. This methodological choice directly addresses potential omitted variable bias related to a country's foundational role in the global energy architecture. The results, presented in Table 8, do not only reveal heterogeneity but divergent causal mechanisms governing the transition in these two groups. For fossil fuel exporters, a larger ecological footprint acts as a strong enabler of the transition, a relationship that is significantly amplified by political stability. This indicates that in resource-rich states, stable governance provides the long-term horizon necessary to strategically leverage resource wealth and the environmental pressure it creates to finance a state-led transition. However, political stability presents a strong negative direct effect on the transition at median and high quantiles. This suggests that in the absence of strong ecological pressure or deliberate environmental policy, political stability may inherently reinforce the status quo and protect the existing fossil fuel regime from disruptive change.

Conversely, for fossil fuel importers, the primary constraint is one of scale and dependency. Here, population

Table 8.
CCE-IV QR Results for Fossil Fuel exporters and Fossil Fuel Importers

	Fossil Fuel Exporter			Fossil Fuel Importer		
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	q25	q50	q75	q25	q50	q75
lco2	-2.062***	-1.863***	-1.482***	-1.707***	-1.290	-1.506***
	(0.314)	(0.349)	(0.567)	(0.269)	(3.055)	(0.127)
lex	-0.068	-0.232**	-0.441**	-0.123	0.366	-0.026
	(0.124)	(0.114)	(0.221)	(0.239)	(0.946)	(0.172)
lgdp	0.641	-0.480	-1.731	-0.073	0.178	0.727***
	(0.776)	(0.653)	(1.356)	(0.365)	(1.917)	(0.212)
leco_fp	1.194***	0.574**	-0.026	0.512	0.002	-0.039
	(0.303)	(0.265)	(0.537)	(0.326)	(2.080)	(0.084)
leco_fp#lpol_stab	0.563	0.892***	1.651*	0.088	0.144	0.014
	(0.353)	(0.308)	(0.854)	(0.105)	(0.752)	(0.085)
linfl	-0.101	-0.196	-0.497	-0.037	-0.274	-0.055
	(0.083)	(0.152)	(0.391)	(0.048)	(0.272)	(0.049)
lpop	-0.012	-0.017	0.024	-0.354	-0.227	-0.018
	(0.037)	(0.050)	(0.132)	(0.604)	(0.791)	(0.029)
lr_oil_px	0.023	0.042*	0.081	0.005	0.008	0.003
	(0.026)	(0.024)	(0.081)	(0.007)	(0.025)	(0.005)
lpol_stab	-11.419	-18.122***	-33.525*	-1.581	-2.573	-0.243
	(7.169)	(6.247)	(17.302)	(1.897)	(16.551)	(1.643)
ltech	-0.035	-0.636	-1.105**	-0.166	-0.822	-0.156
	(0.406)	(0.539)	(0.439)	(0.329)	(1.562)	(0.226)
Constant	-26.457**	-6.060	14.456	-10.387	-2.804	-2.663
	(12.747)	(9.573)	(21.181)	(7.313)	(50.020)	(2.123)
Observations	130	130	130	130	130	130
	0.67	0.53	0.52	0.48	0.47	0.55

Robust standard errors in parentheses *** *p<0.01*, ** *p<0.05*, * *p<0.10*

growth emerges as a major, significant barrier, reflecting the intense pressure to meet rising energy demand, often through readily available fossil fuels rather than capital-intensive green alternatives. Most critically, the analysis uncovers a unifying yet counter-intuitive finding. The effect of technological adoption is consistently negative across both samples but is most pronounced and statistically significant among mid-transition and advanced stage transition oil exporters as well as mid-transition fuel importers. This provides compelling evidence that, in the absence of directed policy, technological innovation often serves to optimize and entrench incumbent fossil-fuel systems rather than disrupt them. This sample split confirms that the full-sample estimates mask these opposing dynamics. The robustness of our core model is therefore strengthened, as it reliably reflects a composition of these distinct underlying processes, yielding policy implications that are not one-size-fits-all but are precisely targeted to a country's position in the global energy order.

Kernel sensitivity analysis demonstrates the stability of results across different bandwidth selections. Using Silverman's rule-of-thumb bandwidth, our results show equal results and thus indicate robustness to arbitrary bandwidth selection in quantile regression (see Table 12). The results across different bandwidths were identical, confirming the stability of our estimates. Meanwhile, upon introducing a squared GDP term (lgdp2), the results revealed a significant non-linear, inverted U-shaped relationship for countries at advanced stages of the energy transition process (q75), suggesting that after a certain point, further economic growth may not aid the transition. This nuance is concealed in the core model specification but does not alter the finding that GDP is an enabler of the transition at lower transition levels (see Table 13).

To enhance the validity of our results, we conducted two crucial post-estimation diagnostics to confirm that our model has adequately accounted for dependence structures. First, a Pesaran CD test on the residuals of our CCE-IV QR model (Table 10) yielded a statistically insignificant CD statistic (p-

Table 9.
Moran test for spatial dependence

Variable	Statistic	p-value
Residual	1.54	0.214

**** p<0.01, ** p<0.05, * p<0.10*

Table 10.
Post-Estimation Pesaran's CD Test

Variable	CD-test	p-value	average joint T	mean ρ	mean abs(ρ)
Residual	-0.192	0.848	28.00	0.01	0.46

****p<0.01, **p<0.05, *p<0.10*

value = 0.848). This confirms that the inclusion of cross-sectional averages successfully filtered out common factors, leaving no remaining strong cross-sectional dependence. Second, we performed a Moran (1950) *I* test for spatial dependence (Table 9). The statistically insignificant result (p-value = 0.214) indicates no evidence of spatial autocorrelation in the residuals. Together, these tests validate that the CCE component of our model has effectively captured the relevant dependence, and no major omitted variable bias manifests as spatial or cross-sectional correlation.

Cross-validation exercises further support the model's predictive validity. Out-of-sample forecasting results obtained using 2015 as cut-off point, in Fig. 2 reinforce the clear superiority in predictive accuracy of our CCE-IV QR model, compared with a benchmark model (standard quantile regression model). The model achieves its lowest mean check loss at the 25th quantile, indicating strong predictive performance in the lower tail of the distribution. At the median (50th quantile), the model's loss increases, and further increases in the 75th quantile, suggesting somewhat less precise predictions in the upper tail of the distribution.

4.1.8 Implications of Results

The quantile regression results demonstrate that the energy transition is a stage-dependent evolution, but its trajectory is fundamentally shaped by concrete institutional and structural rigidities.

CO_2 emissions and energy transition: The strong, consistent negative effect of CO_2 emissions across quantiles reflects the presence of carbon lock-in and institutional path dependencies. These phenomena emphasize the notion that the economic and institutional structures of countries in the bloc are deeply rooted in fossil fuels regime (Unruh, 2000). While mutually reinforcing channels, the structural rigidities pertain to the long-standing physical and technological architecture of economies such as fossil-backed energy infrastructure and institutional rigidities pertain to the formal and informal rules that govern energy systems such as fossil fuel-enabling regulations and policies. For example, as an early-stage transition country in BRICS+ (see Table 14), Russia's fossil fuel lock-in is implied in an existing federal budget rule, which

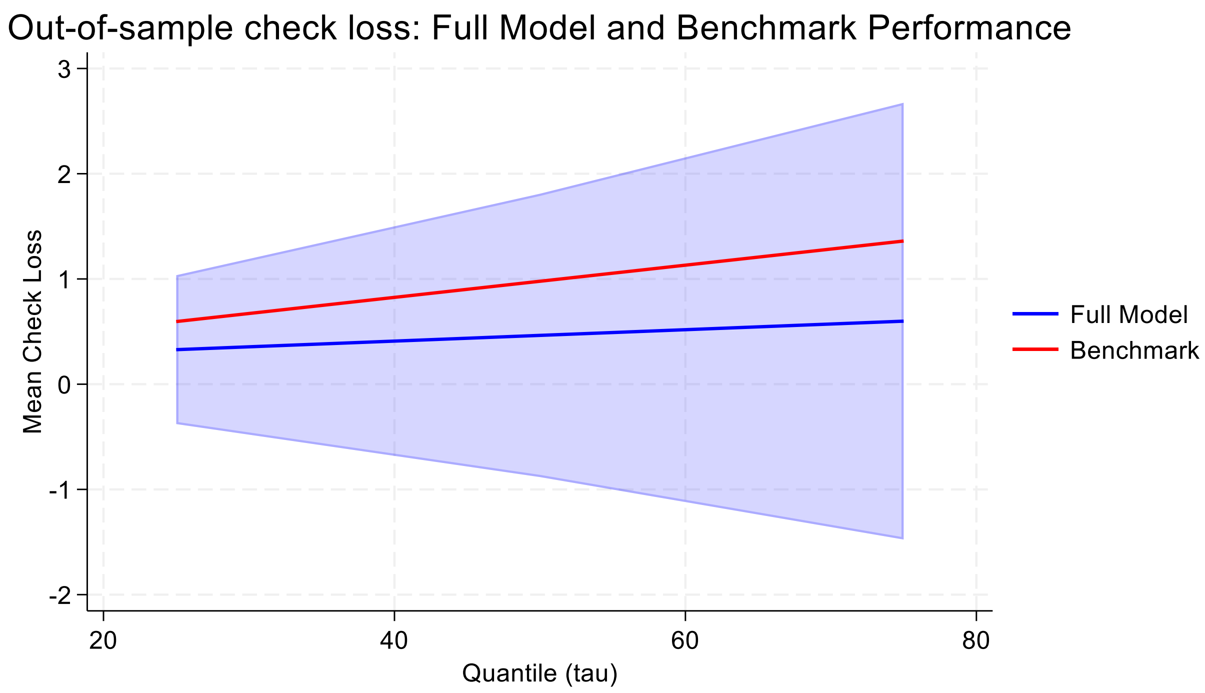

Fig. 2. Pseudo Out-of-Sample Mean Check Loss Validation

Table 11
CCE IV-QR Model with non-interpolated data (Sensitivity Analysis)

	(1)	(2)	(3)
VARIABLES	q25	q50	q75
lco2	-2.340***	-2.280***	-1.281***
	(0.090)	(0.090)	(0.400)
lex	-0.036	-0.017	-0.078
	(0.027)	(0.022)	(0.100)
lgdp	0.856***	0.766***	-0.304
	(0.141)	(0.147)	(1.094)
leco_fp	0.725***	0.671***	0.315
	(0.056)	(0.048)	(0.435)
linfl	0.011	-0.017	0.005
	(0.066)	(0.040)	(0.137)
lpop	-0.208*	-0.291***	-0.113*
	(0.117)	(0.064)	(0.066)
lr_oil_px	0.009	0.005	0.028
	(0.011)	(0.009)	(0.039)
lpol_stab	0.051	0.025	0.071
	(0.083)	(0.045)	(0.050)
leco_fp#pol	-0.003	0.003	0.025*
	(0.009)	(0.008)	(0.014)
ltech	0.234	0.208	0.863
	(0.161)	(0.149)	(1.132)
Constant	-19.508***	-18.176***	-3.264
	(1.923)	(1.713)	(2.718)
Observations	183	183	183
R^2	0.77	0.73	0.63

Robust standard errors in parentheses *** *p<0.01, ** p<0.05, * p<0.10*

perpetuates the country's reliance on oil and gas for 30%-50% of federal budget revenues in the last decade (Yermakov, 2025). This dependence creates a strong fiscal disincentive for decarbonization.

In addition to this fiscal rule, the government provides direct fossil fuel subsidies to the oil and gas industry totaling $30.7 billion in 2022 (IEA, 2023), artificially sustaining the profitability of the existing fossil fuel regime. The government's primary policy is not an acceleration towards renewable energy but carbon neutrality by 2060 (Korppoo & Alisson, 2025), a distant goal that avoids disrupting the current rent-seeking model. Like Russia, South Africa's struggle is a textbook case of institutional path dependency. The primary barrier is Eskom's legal monopoly and its deep financial and operational crisis (Kessides, 2020). The country's $8.5 billion Just Energy Transition Partnership (JETP) is explicitly designed to break this lock-in by providing concessional finance to retire coal plants and fund renewables (Seiler *et al.*, 2023). However, its success depends on overcoming Eskom's institutional deficiencies and reforming the electricity market to allow greater private sector participation.

Brazil, on the other hand, exemplifies an advanced country with diminishing emissions effect on its transition journey. The country's emissions profile is fundamentally different from that of fossil fuel-dependent economies in the bloc. The energy sector is predominantly green, with over 85% of its electricity coming renewables, especially hydropower (Ribeiro *et al.,* 2023). Consequently, the country's most significant emissions do not come from electricity generation but from land-use change and agriculture, and the transport sector. This creates a decoupled emissions structure where progress in the energy sector can be undermined by trends in completely different economic domains.

Economic growth and energy transition: The link between economic growth and achieving a low-carbon economy via renewable energy transition is complex. While economic growth is crucial for funding the initial shift to clean energy, its importance fades for countries that are already transition leaders. This finding adds a critical detail to the Environmental Kuznets Curve hypothesis (Grossman and Krueger, 1995). It shows that the relationship evolves through different stages. This is vividly illustrated in China, where Beijing has successfully addressed the low-hanging fruit of the transition.

Table 12.
CCE-IV QR Results at different bandwidths

	Bandwidth=1.0			Bandwidth=0.8		
	(1)	(2)	(3)	(1)	(2)	(3)
VARIABLES	q25	q50	q75	q25	q50	q75
lco2	-2.296***	-2.177***	-1.504***	-2.296***	-2.177***	-1.504***
	(0.091)	(0.132)	(0.164)	(0.091)	(0.132)	(0.164)
lex	-0.036	-0.048	-0.087**	-0.036	-0.048	-0.087**
	(0.028)	(0.036)	(0.037)	(0.028)	(0.036)	(0.037)
lgdp	0.817***	0.700***	0.370*	0.817***	0.700***	0.370*
	(0.095)	(0.153)	(0.201)	(0.095)	(0.153)	(0.201)
leco_fp	0.719***	0.709***	0.113	0.719***	0.709***	0.113
	(0.081)	(0.094)	(0.242)	(0.081)	(0.094)	(0.242)
leco_fp#lpol_stab	-0.009	-0.102	-0.069	-0.009	-0.102	-0.069
	(0.044)	(0.175)	(0.186)	(0.044)	(0.175)	(0.186)
linfl	-0.064	-0.052	-0.189*	-0.064	-0.052	-0.189*
	(0.048)	(0.061)	(0.106)	(0.048)	(0.061)	(0.106)
lpop	-0.184	-0.180*	-0.106	-0.184	-0.180*	-0.106
	(0.146)	(0.103)	(0.070)	(0.146)	(0.103)	(0.070)
lr_oil_px	0.018	0.010	0.024	0.018	0.010	0.024
	(0.015)	(0.013)	(0.020)	(0.015)	(0.013)	(0.020)
lpol_stab	0.201	2.078	1.439	0.201	2.078	1.439
	(0.881)	(3.575)	(3.776)	(0.881)	(3.575)	(3.776)
ltech	0.444**	0.102	0.352	0.444**	0.102	0.352
	(0.209)	(0.329)	(0.276)	(0.209)	(0.329)	(0.276)
Constant	-20.267***	-19.366***	-3.771	-20.267***	-19.366***	-3.771
	(2.217)	(2.705)	(4.622)	(2.217)	(2.705)	(4.622)
Observations	260	260	260	260	260	260
R^2	0.68	0.65	0.59	0.68	0.65	0.59

Robust standard errors in parentheses
*** *p<0.01*, ** *p<0.05*, * *p<0.10*

China is the global leader in renewable energy manufacturing and deployment, with massive, centralized investments in solar and wind energy having already drastically reduced the carbon intensity of its power sector (Ye *et al.*, 2024). The structural challenge has now shifted. The next stage is the quest to decarbonize hard-to-abate sectors like steel, cement, chemicals, and long-haul transport, which together constitute a different class of problems for the country's transition. These sectors are deeply embedded in the core of China's industrial economy and global supply chains. Progress here cannot be achieved by simply scaling up manufacturing of known technologies; it requires fundamental process innovation, such as hydrogen-based direct reduced iron (H-DRI) or commercial-scale carbon capture, which are technologically complex and not yet cost-competitive.

Ecological footprints, energy transition and the mediating role of political stability: Our findings refine the theoretical expectation that ecological pressure automatically induces a corrective response. Instead, we demonstrate that the relationship between ecological footprint and energy transition evolves significantly across development stages, with political stability playing a crucial but complex moderating role. The negative interaction between ecological footprint and political stability at advanced transition stages reveals a substitution effect where institutional quality reduces the marginal importance of ecological pressure. This suggests that countries at different stages of energy transition follow distinct pathways.

For example, as an advanced-stage transition country, Brazil presents a critical case study of institutional fragmentation. While its energy sector is predominantly green, its significant ecological footprint stems from land-use change, governed by a different set of institutions namely, the agricultural lobby and environmental enforcement agencies (Padovezi *et al.*, 2025). The persistent reversal of ecological progress under changing governments demonstrates how ecological pressure fails to translate into comprehensive transition when governance of ecological pressure sources is disconnected from energy institutions. Brazil's challenge isn't lacking stability in energy governance but rather coordinating across fragmented institutional domains. A suitable policy focus

Table 13.
CCE-IV QR Model (with squared GDP)

VARIABLES	q25	q50	q75
lco2	-2.282***	-2.159***	-1.636***
	(0.115)	(0.337)	(0.158)
lex	-0.040	-0.062	-0.113**
	(0.031)	(0.109)	(0.045)
lgdp	1.020	1.703	3.569
	(0.663)	(2.070)	(2.561)
lgdp2	-0.013	-0.062	-0.195
	(0.036)	(0.146)	(0.161)
leco_fp	0.744***	0.646**	0.028
	(0.080)	(0.272)	(0.105)
leco_fp#pol	-0.016	-0.089	-0.029
	(0.038)	(0.142)	(0.094)
linfl	-0.057	-0.050	-0.187**
	(0.047)	(0.057)	(0.088)
lpop	-0.126	-0.142	-0.090*
	(0.193)	(0.106)	(0.053)
lr_oil_px	0.013	0.006	0.020
	(0.013)	(0.010)	(0.017)
lpol_stab	0.340	1.800	0.627
	(0.766)	(2.917)	(1.891)
ltech	0.265	-0.058	-0.063
	(0.281)	(0.384)	(0.369)
Constant	-23.187***	-21.202***	-14.232
	(3.577)	(2.683)	(8.931)
Observations	270	270	270
R^2	0.68	0.65	0.61

Robust standard errors in parentheses
**** p<0.01, ** p<0.05, * p<0.10*

Table 14
Country Quantiles

Country	Mean fitted values	Quantiles
Brazil	-0.433	Q75
China	-1.756	Q50
Egypt	-2.814	Q50
Ethiopia	2.637	Q75
India	-0.623	Q75
Indonesia	-1.417	Q50
Iran	-4.568	Q25
Russia	-4.388	Q25
South Africa	-4.696	Q25
UAE	-6.713	Q25

is to institutionalize environmental protection beyond political cycles, making ecological stress a green advantage rather than a liability.

In the case of India, the country faces a significant challenge with the political economy of coal (Montrone *et al.*, 2021). The sector is dominated by state-owned Coal India Limited, a major employer and political entity, and provides cheap fuel for a power distribution sector plagued by technical and commercial losses. This creates a strong, self-reinforcing coalition against a rapid phase-down of coal. India's energy transition success rests on leveraging its political stability to orchestrate a just transition that manages coal phase-down while scaling renewable manufacturing and grid modernization (Montrone *et al.*, 2021). India represents the stage where both ecological pressure and institutional capacity must work in concert, requiring careful navigation of institutional fragmentation between central and state governments.

Technology adoption and energy transition: The muted role of technology in mid-and-advanced stages, while surprising underscores the fact that technology does not work in a vacuum but is conditioned on other factors. This is starkly evident in South Africa, where despite technological access, the transition is constrained by the institutional path dependency of its state-owned utility Eskom. Eskom's legal monopoly, its reliance on coal-linked labor unions, and its massive debt create a governance constraint that actively impedes the integration of renewable technology, regardless of its price competitiveness (Kessides, 2020). Likewise, Iran is trapped in a perfect storm of geopolitically enforced lock-in. International sanctions cripple technology transfer and investment, while massive domestic fossil fuel subsidies which is among the highest globally per capita make energy practically free, destroying any price signal for efficiency or alternatives (Aryanpur *et al.*, 2022). The transition is paralyzed not because of a lack of resources but by a catastrophic failure of governance and international relations.

5. Conclusion and Recommendations

5.1. Conclusions

The global energy transition is not a smooth uniform process but a complex synergy of heterogeneous national pathways. This study has dissected these diverse trajectories within the critical and expanding BRICS+ bloc, employing a novel methodological approach to move beyond uniform, mean-based estimates. By applying a smoothed (CCE) Instrumental Variable Quantile Regression (IV-QR) framework to data from 1996-2023, we have empirically demonstrated that the drivers of energy transition spanning macroeconomic, environmental, and governance domains are fundamentally contingent on a country's specific stage in the transition journey.

Our analysis directly addresses several unresolved questions in existing literature. First, our findings demonstrate that the relationship between GDP and the transition is stage dependent. Second, the significant heterogeneity in coefficients for CO_2 emissions, ecological footprint, and exchange rates across the conditional distribution proves that the energy transition is a multi-stage journey with distinct economic realities. Overall, the findings strengthen calls for phasing out inefficient fossil fuel subsidies (SDG Target 12.c) and reallocating those resources toward socially protective just transition mechanisms. The findings further highlight debates on adaptation finance and loss and damage. For low-transition countries, ecological stress can serve as a trigger for renewable investment but only if accompanied by adequate international climate finance. The operationalization of the Loss and Damage Fund at COP28 must therefore prioritize early-stage transition countries facing acute ecological vulnerability.

Despite these insights, several limitations merit a cautionary interpretation of the findings. The dataset ends in 2023 and thus does not capture potential structural disruptions caused by shocks from post-2024 events, such as the recent US trade tariffs. The new global tensions sparked by the trade tariffs could disrupt the flow of critical renewable energy technology components such as solar panels, batteries and rare earth minerals. Due to this, the patterns observed in this study should be interpreted as reflective of pre-tariff structural dynamics, and future updates using post-2024 data are needed to validate whether these relationships have persisted or fundamentally shifted. Second, the smoothed Common Correlated Effects Instrumental Variable Quantile Regression (CCE-IV QR) model, while robust in addressing endogeneity and cross-sectional dependence, is a static framework. It does not account for potential dynamic feedback mechanisms or temporal causality between variables. Our theoretical framework focuses primarily on the economic realities of the transition, thus providing a narrow investigation into the factors driving the transition.

Future research could extend this analysis in several directions. The identified heterogeneity demands a micro-level investigation into the specific political economy factors such as the structure of energy incumbency and the power of utility lobbies that explain the quantile-specific effects of variables. Expanding the theoretical framework to not only focus on economic drivers but other socio-technical transitions and wider energy transition factors not captured in our model could enhance a broader application of research results and better-inform policy makers of the diverse drivers of the transition. Worth considering is the development of a formal typology of transition blocks, classifying countries not just by income but by their positioning in clean energy supply chains, their fossil fuel endowments, and their institutional governance models. Finally, testing for regime shifts or structural breaks across policy cycles would strengthen the temporal robustness of the findings.

5.2 Policy Recommendations

Based on the findings of the study, we propose a dynamic and tiered framework where policy priorities evolve in lockstep with a country's position on the transition curve, moving from overcoming foundational barriers to navigating systemic transformation.

a. Early Transition Economies

For early-transition economies trapped in structural and fiscal carbon lock-in, the immediate policy action is to deconstruct the economic disincentives for decarbonization. In Russia, this requires a binding schedule to reduce the share of fossil fuel revenues in the federal budget to below 20%, channeling revenues into a sovereign future fund dedicated to digital and green infrastructure. The government should prioritize the need to reallocate close to $50 billion in annual fossil fuel subsidies towards a national grid modernization fund and incentives for distributed renewable energy in remote regions.

Given its geopolitical conundrum, Iran must critically focus on accelerating and publicizing its long- stalled fossil fuel subsidy reform program, to replace universal subsidies with targeted cash transfers to low-income households. The resulting savings can then be used to fund a sanctions-resilient solar manufacturing base. Given its vast gas reserves, the government must mandate and incentivize the replacement of inefficient gas-fired power plants with modern combined-cycle plants, freeing up gas for higher-value exports or blue hydrogen production.

To become a transition success story, South Africa needs to fast-track the unbundling of Eskom's monopoly, legally allowing for private sector participation in generation and streamlining the grid connection for renewable independent power producers (IPPs). More importantly, the government must establish an independent, technically efficient body that can effectively manage its billion-dollar JTEP project, focusing on decommissioning coal plants, retraining workers, and stimulating new industries in coal-producing regions.

The UAE, despite its vast oil wealth, must issue sovereign green bonds and use its low credit risk (AAA) rating to attract massive foreign investment for its net zero initiatives, positioning Dubai and Abu Dhabi as global green finance hubs. Additionally, the government must leverage low-cost solar, existing gas infrastructure, and strategic location to become a major exporter of green hydrogen or ammonia to Europe and Asia. Moreover, the government must capitalize on investing in carbon capture utilization and storage (CCUS) for its remaining gas-fired power and industrial plants with the aim to achieve carbon-neutral fossil fuel production.

b. Mid-Transition Economies

For mid-transition economies, policy must shift from merely creating space for renewables to actively managing the scaling of new industries and the decline of incumbent fuels. Being a global leader in renewable energy technology, China's next transition phase is to decarbonize its hard-to-abate industrial sector, requiring state-mandated deployment of commercial-scale technologies such as the hydrogen-based direct reduced iron (DRI) and carbon capture at flagship state-owned steel and cement plants. Beijing must focus on reforming the power market to create a robust, national green certificate and carbon trading system, providing a clear price signal for industrial decarbonization.

For Indonesia, the government must move beyond its planned coal phase-out by enacting a moratorium on new mines and power plants, using revenues from a coal severance tax to fund a just transition in mining regions such as Kalimantan. Another crucial pathway is for policy makers to create financial instruments where proceeds from sovereign green bonds are directly tied to verified reductions in deforestation. Apart from these, the government should prioritize decentralized solar and battery storage systems for the thousands of islands outside the main Java-Bali grid, avoiding costly submarine cable projects.

With regards to Egypt, national efforts should be channeled towards leveraging political stability and vast solar and wind resources to aggressively implement its planned green hydrogen deals, focusing on creating specialized industrial zones and export infrastructure on the Suez Canal. The government must prioritize grid modernization by channeling direct international climate finance and concessional loans towards smart grid and transmissions infrastructure to absorb the massive renewable capacity. Likewise, emphasis should be placed on integrating desalination plants powered by dedicated solar farms into national water and energy planning to address water scarcity without increasing the fossil fuel burden.

c. Advanced Transition Economies

For advanced-transition economies, the focus turns to systemic integration, niche leadership, and resolving institutional fragmentation. Brazil must establish a permanent, high-level inter-ministerial council with authority to align agricultural, land-use and energy policies, thereby addressing its existing transition challenges with institutional fragmentation. With a focused strategy of becoming a bioenergy champion, Brazil needs to double down on this strategy and include aspirations of becoming a global leader in sustainable aviation fuel and second-generation biofuels from agricultural residues, creating a new green export industry. Furthermore, Brazil must legally enforce and technologically verify zero-deforestation supply chains for key exports (soy, beef), using this as a competitive advantage in green markets.

The Indian government should establish a dedicated and independent statutory body to manage the phase down of coal, including mine closure, land reclamation, and a just transition fund for affected communities and workers. Furthermore, the government should double down on the Production Linked Incentive (PLI) Scheme to make India a global hub for solar modules, advanced battery, and electrolyzer manufacturing. Policy makers should make federal financing conditional on state-level electricity distribution companies meeting pre-defined targets for reducing technical and commercial losses and integrating renewable energy in the energy mix.

Despite its renewable potential, Ethiopia remains constrained by renewable financing and institutional capacity. To avert these, policy makers should address energy access gaps by creating a streamlined regulatory and fiscal framework for private investment in mini-grids and off-grid solar systems, moving beyond a sole dependence on large-scale dams. Also, the government must apply public funds and international grants judiciously by conducting initial exploration drilling for geothermal projects, which would then de-risk the sector for subsequent private investment.

Overall, our findings emphasize the complex interplay of economic, environmental, and institutional factors in driving energy transitions, highlighting the need for coordinated, context-specific strategies to achieve global sustainability goals. Despite its limitations, this study makes a novel contribution by showing that the drivers of energy transition are not uniform across the distribution, and that effective policy must be tailored to a country's current position along the transition spectrum. Our quantile-based approach offers a valuable framework for guiding differentiated climate and energy strategies in developing and emerging markets. These insights serve as a foundation for advancing both academic discourse and practical policymaking in the critical quest for a sustainable energy future.

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Appendix

Table A1
First Stage Regression

	(1)	(2)	(3)	(4)	(5)	(6)
	first	first	First	first	first	first
VARIABLES	lco2	lgdp	Lex	linfl	leco	leco_pol
Llex	0.002	-0.002*	0.998***	-0.036	0.001	0.001
	(0.001)	(0.001)	(0.005)	(0.024)	(0.001)	(0.001)
Llgdp	0.063	1.264***	-0.440	0.203	0.016	0.085
	(0.088)	(0.061)	(0.312)	(1.525)	(0.072)	(0.071)
l2lgdp	-0.068	-0.275***	0.409	-0.348	-0.016	-0.081
	(0.087)	(0.060)	(0.308)	(1.506)	(0.071)	(0.070)
Llinfl	-0.001	0.001	0.019*	0.401***	-0.001	-0.006**
	(0.003)	(0.002)	(0.011)	(0.052)	(0.002)	(0.002)
Lpop	0.000	-0.002	0.005	0.018	0.001	-0.003
	(0.003)	(0.002)	(0.012)	(0.060)	(0.003)	(0.003)
lr_oil_px	-0.001	0.001**	0.001	0.084***	-0.000	0.000
	(0.001)	(0.000)	(0.002)	(0.012)	(0.001)	(0.001)
Lleco	0.008**	0.006***	-0.004	-0.124**	0.999***	0.003
	(0.003)	(0.002)	(0.011)	(0.056)	(0.003)	(0.003)
leco_pol_inst	-0.001	0.004*	-0.001	-0.099*	0.002	0.991***
	(0.003)	(0.002)	(0.011)	(0.053)	(0.003)	(0.002)
lpol_stab_int	0.019	-0.079*	0.017	1.831*	-0.034	0.169***
	(0.060)	(0.041)	(0.213)	(1.041)	(0.049)	(0.048)
Ltech	-0.015	-0.014**	0.019	-0.170	-0.017**	-0.010
	(0.010)	(0.007)	(0.037)	(0.180)	(0.008)	(0.008)
llco2	0.996***	0.002	0.017	0.073	-0.000	-0.003
	(0.005)	(0.004)	(0.019)	(0.094)	(0.004)	(0.004)
Constant	-0.038	0.033	0.292	4.596***	0.093	-0.040
	(0.091)	(0.063)	(0.321)	(1.571)	(0.074)	(0.073)
Observations	260	260	260	260	260	260
R^2	0.999	0.999	0.997	0.495	0.999	1.000

Robust standard errors in parentheses *** *p<0.01*, ** *p<0.05*, * *p<0.10*

Table A2
First Stage Results (F-statistic)

Variables	Specification A (Selective)		Specification B (Full)	
	First-stage F	**p-value**	**First-stage F**	**P-value**
lco2	27531.47***	0.000	23834.63 ***	0.000
lex	9490.31***	0.000	7930.97***	0.000
leco_fp	38268.63***	0.000	34346.52***	0.000
leco_fp#lpol_stab	12933.09***	0.000	11727.28***	0.000
lgdp	42278.48***	0.000	44868.85***	0.000
linfl	— (Exogenous)	—	8.88***	0.000
Weak ID-tests				
Cragg-Donald Wald F-statistic	4535.775	—	8.62	—
Kleibergen-Paap rk Wald F-statistic	6559.845	—	2.68	—
Hansen J-statistic	0.096	0.757	0.779	0.757

****p<0.01, **p<0.05, *p<0.10*
Note: — denotes values do not apply or are not available

Table A3
Control Function Test

Variable	residual_coeff	residual_se	p_value	F_statistic	Conclusion
linfl	0.307	60.284	0.246	49.85	Exogenous
lr_oil_px	-0.163	4.775	0.345	2.240	Exogenous

****p<0.01, **p<0.05, *p<0.10*

Table A4
Quantile Treatment Effects (Equality of Coefficients)

VARIABLES	lco2	lex	Lgdp	linfl	leco_fp
q25 and q50	-0.120	0.012	0.116	-0.011	0.011
	(0.208)	(0.049)	(0.229)	(0.054)	(0.105)
q25 and q75	-0.792***	0.051	0.447*	0.126	0.606***
	(0.125)	(0.041)	(0.250)	(0.089)	(0.162)
q50 and q75	-0.673***	0.039	0.330	0.137	0.596***
	(0.242)	(0.062)	(0.342)	(0.084)	(0.150)

Standard errors in parentheses ****p<0.01, **p<0.05, *p<0.10*

Table A5.
Cross-sectionally Augmented lm-Pesaran-Shin (CIPS) test

	Constant	Constant & Trend
Variable	CIPS	CIPS
let	-0.377	-1.783
lco2	-1.130	-2.045
lex	-2.462**	-3.092**
lgdp	-2.339**	-2.079
lpop	-1.633	-3.354***
linfl	-3.026***	-3.821***
lr_oil_px	-3.573***	-3.490***
lpol_stab	-2.776***	-3.659***
leco_fp	-1.453	-2.931**
ltech	-1.082	-1.881
Δlet	-3.906***	-4.209***
Δlco2	-4.132***	-4.120***
Δlex	-4.187***	-4.431***
Δlgdp	-3.218***	-3.776***
Δlpop	-3.721***	-3.718***
Δlinfl	-5.463***	-5.460***
Δlr_oil_px	-5.625***	-5.786***
Δlpol_stab	-5.460***	-5.525***
Δleco_fp	-4.263***	-4.468***
Δltech	-4.551***	-4.979***

Source: Authors' Computation *** *p<0.01*, ** *p<0.05*, * *p<0.10*