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Economic Complexity and Carbon Neutrality Targets in the GCC: Evidence from a Panel Threshold Model

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ABSTRACT

This study explores how economic complexity shapes carbon dioxide (CO_2) emissions in the Gulf Cooperation Council (GCC) countries from 1990 to 2022. Using a dynamic panel threshold model, we investigate whether rising economic complexity creates a turning point that changes how economic growth, energy use, trade openness, and renewable energy adoption affect environmental outcomes. The analysis uncovers a clear threshold level of economic complexity that divides the sample into two distinct regimes. In the low-complexity regime, CO_2 emissions are highly sensitive to economic growth and energy consumption, while neither renewable energy nor trade openness plays a meaningful role in reducing emissions. In contrast, once countries cross into the high-complexity regime, the picture changes: energy intensity declines, renewable energy becomes a powerful tool for lowering emissions, and trade openness supports cleaner production and greener technologies. This shift reflects a partial decoupling of economic growth from environmental damage. Overall, the findings highlight how structural transformation and technological upgrading can support climate goals in hydrocarbon-dependent economies. By prioritizing innovation, diversification, and strong policy frameworks, GCC countries can advance toward carbon neutrality while maintaining economic momentum.

Keywords: Economic Complexity, Carbon Emissions, GCC Countries, Panel Threshold Model, Renewable Energy, Trade Openness, Structural Transformation, Carbon Neutrality

JEL Classification: C23; Q43; O14; F18; Q55

INTRODUCTION

Fossil fuels have long served as the foundation of economic development in the Gulf Cooperation Council (GCC) countries—Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE). Over the past five decades, hydrocarbon wealth has fueled rapid industrialization, urban expansion, and substantial improvements in living standards. These gains, however, have come with a steep environmental cost. The GCC countries rank among the world's highest per capita CO_2 emitters, a consequence of energy-intensive industries, large infrastructure projects, and high domestic energy consumption, all of which are reinforced by longstanding fossil fuel subsidies. Confronted with mounting climate risks, each GCC member has now set a carbon neutrality target for 2050–2060, marking a significant shift toward a low-carbon, knowledge-based, and innovation-driven development paradigm (Alsabbagh and Alnaser, 2022). Yet achieving this transformation requires a deeper understanding of how structural shifts—particularly those related to economic complexity—shape emissions and energy use.

While previous studies have underscored the importance of economic diversification in reducing hydrocarbon dependence and strengthening economic resilience, diversification alone does not guarantee environmental improvement. Increasingly, what matters is not merely *whether* economies diversify, but *how* they diversify. Economic complexity—defined as the degree to which a country's productive structure is rooted in knowledge-intensive, technologically sophisticated, and interconnected industries (Hidalgo and Hausmann, 2009)—has become a crucial lens for understanding sustainable growth. High-complexity economies tend to produce and export more advanced, less resource-intensive goods, enabling the decoupling of economic growth from environmental degradation. In contrast, diversification into heavy, energy-intensive manufacturing can reinforce carbon dependence despite structural change. Identifying the threshold at which economic complexity begins to generate environmental benefits is therefore critical for the GCC's decarbonization pathway.

The GCC occupies a distinctive position in the global energy system: it remains a major supplier of hydrocarbons while increasingly positioning itself as a rising hub for renewable energy, green technologies, and advanced industries. Through national Vision strategies—such as Saudi Vision 2030, UAE Energy Strategy 2050, Oman Vision 2040, and Bahrain Economic Vision 2030—governments have launched ambitious programs to expand high-value manufacturing, develop advanced services, and strengthen local technological capabilities. Despite these efforts, the region's economic complexity indices (ECI) remain relatively modest compared to advanced economies. This reflects persistent dependence on petroleum-based exports and the slow development of knowledge-intensive sectors. Consequently, the relationship between economic complexity, economic growth, and environmental outcomes remains uncertain and insufficiently studied in the GCC context.

A substantial body of international research has examined the link between economic growth and environmental degradation, most commonly through the lens of the Environmental Kuznets Curve (EKC) hypothesis. The EKC proposes an inverted-U relationship between income and pollution: environmental degradation tends to rise in the early stages of development but declines once a country reaches a certain income threshold, as production structures become cleaner and environmental awareness increases (Stern, 2018). However, evidence for the EKC in GCC economies remains mixed and often inconclusive. Studies on Saudi Arabia, the UAE, and Bahrain variously confirm, reject, or modify the EKC, with results differing depending on the sample period, econometric method, and choice of variables (Mrabet and Alsamara, 2017; Alaali and Naser, 2020; AlZgool et al., 2020; Mahmood, 2022). Importantly, most of this literature focuses on economic growth as the primary driver of emissions, overlooking the deeper structural features of the economy—particularly the nature of productive capabilities—which lie at the heart of the economic complexity framework.

Economic complexity provides a promising avenue to revisit the growth–environment relationship. Highly complex economies typically rely on extensive knowledge networks, advanced technologies, and innovation-driven sectors that use energy more efficiently and produce fewer emissions per unit of output (Hausmann et al., 2014; Romero and Gramkow, 2021). By contrast, less complex economies often remain locked into resource-dependent, carbon-intensive industries. The environmental effects of complexity, however, are unlikely to be linear. At intermediate levels of complexity, expanding industrial activity into sectors such as petrochemicals, plastics, or basic metals may initially raise emissions. Only after surpassing a certain threshold—when technological upgrading, green innovation, and knowledge-intensive sectors gain traction—do emissions begin to decline. This dynamic suggests the existence of a complexity threshold beyond which increasing sophistication yields tangible environmental improvements.

Against this backdrop, the present study investigates whether economic complexity serves as a turning point that conditions the relationship between economic growth, energy consumption, trade openness, and CO_2 emissions in GCC countries. Using annual data from 1990 to 2022, we apply a Panel Threshold Model (PTM) to capture potential nonlinearities while accounting for cross-sectional dependence and country-specific heterogeneity. Identifying the level of economic complexity at which structural upgrading begins to mitigate emissions provides crucial insights for how GCC countries can align their industrial strategies, innovation policies, and carbon neutrality commitments.

The study contributes to the literature in several important ways. First, it extends the EKC debate by incorporating economic complexity as a threshold variable, linking productive knowledge accumulation with environmental outcomes. Second, it focuses on the GCC—an energy-intensive region undergoing rapid economic transformation—where empirical work on complexity and sustainability remains limited despite its global importance. Third, it provides policy-relevant evidence for designing decarbonization pathways that balance economic diversification, competitiveness, and environmental stewardship. Understanding how complexity interacts with carbon emissions can help guide policymakers in fostering cleaner industries, strengthening innovation ecosystems, and attracting green foreign direct investment consistent with Sustainable Development Goals (SDGs 7 and 13).

RELATED LITERATURE

Economic complexity, as introduced by Hidalgo and Hausmann (2009), captures the knowledge intensity and sophistication embedded in a country's productive structure. It has increasingly become a central framework for analyzing development patterns and their environmental implications. A growing body of research argues that the character of structural transformation—not simply the shift from primary commodities to manufacturing and services—determines whether economic growth becomes carbon-intensive or climate-compatible (Hidalgo & Hausmann, 2009; Cristelli et al., 2013; Hausmann et al., 2014). Several mechanisms underpin this argument. Higher economic complexity can reduce emissions intensity through technology diffusion, productivity improvements, and a transition toward less material-intensive activities (Romero & Gramkow, 2021; Felipe et al., 2012; Hidalgo, 2015). Yet, in earlier development stages, complexity-driven industrial expansion can increase emissions due to scale and composition effects (Laverde-Rojas & Correa, 2021; Khezri et al., 2022; Zheng et al., 2021). Empirical studies thus examine whether greater complexity facilitates a decoupling between output and emissions, or whether it reinforces carbon dependence depending on the development stage, sectoral composition, and nature of industrial upgrading (Majeed et al., 2022; Caldarola et al., 2023).

Empirical findings on the complexity–environment nexus are diverse and strongly context specific. Broad cross-country panel studies often show that the relationship is not uniform: rising complexity may increase CO_2 emissions or ecological footprints in samples where complexity gains coincide with expanding energy use (Laverde-Rojas & Correa, 2021; Arslan et al., 2023). Likewise, studies on emerging-market groups such as the Next-11 or MINT economies report positive long-run effects of complexity on emissions, consistent with early-stage industrialization dynamics (Osinubi, 2024; Arslan et al., 2023; Majeed et al., 2022). Conversely, evidence from high-income or technologically advanced economies often points to an emissions-reducing effect of complexity. Studies for France, OECD members, and advanced Asian economies suggest that once production capabilities achieve a higher degree of sophistication, innovation and cleaner technologies become dominant forces in lowering emissions intensity (Can & Gozgor, 2017; Doğan et al., 2020; Leitao et al., 2021). These contrasting findings confirm that the environmental implications of economic complexity are non-linear and conditional on the form of industrial upgrading (Neagu, 2020; Empirica, 2023).

Because of these non-linearities, a growing strand of literature employs threshold and other non-linear modelling approaches. Several studies identify inverted-U relationships or similar turning points: complexity tends to raise emissions up to a certain level, beyond which it begins to mitigate them (Bucher, 2023; Neagu, 2020). This turning point represents the stage where technological depth, institutional capacity, and innovation systems become robust enough to support cleaner, higher-value production (Caldarola et al., 2023; Peng et al., 2022). Sectoral evidence further reveals heterogeneity: advanced manufacturing and ICT-intensive sectors are typically associated with lower energy intensity in mature economies, while intermediate manufacturing or resource-processing activities often increase emissions in earlier phases of structural change (Montagna et al., 2025; Ye et al., 2023; Taghvaee et al., 2023). These insights collectively motivate the application of panel threshold models and regime-dependent estimators to capture differences in the marginal effects of growth, trade, and energy use across complexity regimes (Belarbi et al., 2024; Ozkan et al., 2025).

Further empirical contributions broaden the metrics and methods used to study this nexus. Research employing ecological footprint indicators, embodied carbon in trade, and pollutant-specific measures finds that not all complexity is environmentally beneficial: complexity driven by resource-processing and emissions-intensive exports tends to increase embodied emissions, whereas knowledge-intensive services and green manufacturing reduce emissions per unit of output (Wang, 2023; Zheng et al., 2021; Bergougui, 2024). Methodologically, studies draw on FMOLS, DOLS, ARDL, quantile regression, and spatial panel models to address endogeneity, heterogeneity, and spatial spillovers. Spatial models, for example, show that the complexity of neighbouring or trade-partner countries can influence domestic emissions via technology diffusion and supply-chain linkages—an important finding for highly integrated regions (Ren et al., 2025; Wang, 2023). Additionally, causality tests and decomposition analyses reveal that energy mix, institutional quality, and R&D intensity play mediating roles in shaping the complexity–environment relationship (Ahmed et al., 2022; Bergougui, 2024; Christoforidis, 2025).

Regional studies also highlight substantial heterogeneity in the relationship between economic complexity and environmental outcomes across world regions. EU-based research generally finds that complexity supports decarbonisation, but only when it is accompanied by strong environmental regulation, innovation incentives, and stringent climate policies (Neagu, 2020; Christoforidis, 2025). Studies focusing on transition economies document a classic inverted-U pattern, reflecting the profound structural shifts experienced after the post-socialist transition (Bucher, 2023). By contrast, evidence from Asia and Latin America often points to rising emissions as complexity increases during middle-income phases, where industrial expansion is still closely tied to energy-intensive activities (Doğan et al., 2021; Khezri et al., 2022).

For resource-rich regions, the evidence is thinner and more context dependent. The MENA and GCC regions present unique circumstances: large hydrocarbon sectors, high per-capita energy consumption, and policy structures such as subsidies and sovereign investment decisions shape the trajectory from raw-material dependence toward complex production systems (Yalta & Yalta, 2021; Al-Ali & Khasawneh, 2023). Recent working papers and regional analyses highlight that GCC countries still exhibit relatively low Economic Complexity Index (ECI) scores compared with advanced economies. They caution that diversification into energy-intensive industries—such as petrochemicals, metals, or construction materials—may not reduce emissions unless paired with technology upgrading, innovation investments, and increasing demand for green inputs (Acume, 2024; regional outlook reports).

Studies focusing specifically on the GCC remain limited but are gradually expanding. A recent multi-country analysis of Gulf ECI trajectories shows only modest increases in complexity, driven largely by petrochemical and construction-related exports rather than knowledge-intensive manufacturing (regional studies 2023–2025). Country-specific research on Saudi Arabia (Abid & Gafsi, 2025) and selected Gulf states suggests that recent gains in complexity have frequently coincided with rising energy demand and higher CO_2 emissions, underscoring that the *type* of diversification matters. These findings highlight the need to identify the threshold ECI level at which complexity begins to generate net environmental benefits in the GCC, given the region's unique economic structure, policy frameworks, and heavy reliance on fossil energy.

Methodologically, recent advances emphasize modeling economic complexity as a threshold variable rather than as a simple linear regressor. Threshold approaches allow researchers to estimate different elasticities across complexity regimes and identify the critical turning point at which marginal effects shift sign (Belarbi et al., 2024; Ozkan et al., 2025). Extensions incorporating spatial and sectoral dimensions are also gaining traction, as they capture cross-border technology spillovers and differences in emissions intensity across industries (Ren et al., 2025; Montagna et al., 2025). Moreover, adding controls for energy mix (e.g., renewable energy share), R&D intensity, FDI composition, and institutional quality helps clarify whether emissions decline because of cleaner technologies or because economies shift toward less carbon-intensive sectors (Peng et al., 2022; Bergougui, 2024; Christoforidis, 2025).

SAMPLE and Empirical Approach

The Sample

To investigate the threshold role of economic complexity in shaping the relationship between macroeconomic factors and carbon emissions in the GCC region, this study utilizes a balanced panel covering the six Gulf Cooperation Council economies—Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates—over the period 1990–2022. Although these countries share common structural characteristics as hydrocarbon-dependent economies, they differ markedly in technological sophistication, export diversification, and the pace at which they are advancing toward carbon-neutrality goals. To account for this heterogeneity in productive capabilities, the analysis distinguishes between lower- and higher-complexity regimes using each country's Economic Complexity Index (ECI).

Following established threshold methodologies (Hansen, 1999; Seo & Shin, 2016) and consistent with classification approaches in the structural-transformation literature, we rely on the estimated ECI threshold value obtained from the panel threshold model to divide the sample into two distinct regimes. Country–year observations with ECI levels below the threshold are classified as belonging to the low-complexity regime, characterized by production structures that remain heavily resource- and carbon-intensive. In contrast, observations exceeding the threshold fall into the high-complexity regime, where knowledge-intensive activities, technological upgrading, and cleaner production processes are more prevalent.

This data-driven segmentation allows the study to assess whether the effects of economic growth, energy consumption, trade openness, and renewable energy adoption on CO_2 emissions differ systematically across levels of economic sophistication. By explicitly differentiating between these two complexity regimes, the analysis offers deeper insight into how structural transformation conditions the trajectory toward carbon neutrality in the GCC and highlights the importance of productive upgrading in supporting sustainable development pathways.

Data and Variables

The empirical analysis draws on annual data from the six Gulf Cooperation Council (GCC) countries—Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates—over the period 1990–2022. Focusing on the GCC provides a relevant setting for examining the links between economic complexity, energy use, trade openness, and environmental outcomes, given the region's historically high energy intensity, rapid economic expansion, and heavy dependence on fossil-fuel-based industries. These structural features, combined with ongoing national efforts to diversify economies and scale up renewable energy adoption, make the GCC an ideal case for exploring how economic sophistication shapes carbon emissions. The countries included in the sample are listed in Table 1

Empirical Approach and Model Specification

To examine the potential non-linear relationship between economic complexity and environmental outcomes in the GCC region, this study employs a panel threshold regression framework. The methodological foundation follows Hansen's (1999) seminal threshold model, along with the dynamic extension proposed by Kremer et al. (2013), who incorporated the Generalized Method of Moments (GMM) to address endogeneity within threshold settings. While Hansen's original approach is static, Kremer et al. (2013) expanded the methodology to dynamic panels, making it particularly suitable for macro–environmental analyses in which key explanatory variables—such as energy consumption and economic growth—are likely endogenous.

Based on this framework, the general specification of the panel threshold model used in this study is expressed as:

$$CO_{2it} = \mu_{it} + \beta'_1 X_{it} I(ECI_{it} \leq \gamma) + \beta'_2 X_{it} I(ECIit > \gamma) + \varepsilon_{it} \;. \qquad (2)$$

where i and t denote country and year respectively. The error term is ε_{it} and μ_{it} captures country-specific fixed effects. The threshold value γ, associated with the Economic Complexity Index (ECI), partitions the sample into low-complexity and high-complexity regimes through the indicator function I(·). The vector of regressors X_{it} includes economic growth, energy consumption, trade openness, renewable energy consumption, and other macroeconomic controls. The model allows a subset of variables X_{2it} to be endogenous (e.g., GDP, energy consumption), while X_{1it} represents exogenous or predetermined variables. To meet the moment conditions required for GMM estimation, a valid set of instruments Z_{it} is introduced such that k≥m where m denotes the number of regressors.

Before estimation, individual effects (μ_{it}) are removed using the forward orthogonal deviation (FOD) transformation proposed by Arellano and Bover (1995):

$$\varepsilon^*_{it} = \sqrt{\frac{T-t}{T-t+1}}\left[\varepsilon_{it} - \frac{1}{T-1}(\varepsilon_{i(t-1)} + \cdots + \varepsilon_{iT}\right] \qquad (3)$$

which ensures that transformed residuals are not serially correlated, allowing GMM estimators for cross-sectional models to be valid in a dynamic panel environment.

Following Kremer et al. (2013), estimation of the threshold model proceeds in three steps. First, all endogenous variables are regressed on the set of instruments to obtain fitted values. Second, equation (2) is estimated by least squares for a grid of possible threshold values γ, replacing endogenous regressors with their predicted counterparts. Third, the optimal threshold is the value of γ that minimizes the concentrated sum of squared residuals S(γ). Once the threshold is identified, regime-specific slope coefficients (β1,β2) are estimated using GMM, and confidence intervals for the threshold parameter are obtained following the likelihood ratio procedure of Caner and Hansen (2004): $\Gamma\{\gamma: LR(\gamma) \geq C(\alpha)\}$ is used to estimate the confidence interval for γ, where C(α) is the asymptotic distribution of the likelihood ratio indicator of LR (γ) at the 95% level.

Using this threshold framework, the present study specifies the following regime-dependent model to evaluate how macroeconomic factors influence carbon emissions differently across levels of economic sophistication:

$$\mathrm{CO2_{it}} = \mu_{it} + \beta'_1 \mathrm{X_{it}} \mathrm{I}(\mathrm{ECI_{it}} \leq \gamma) + \delta_1 \mathrm{X_{it}} \mathrm{I}(\mathrm{ECI_{it}} \leq \gamma) + \beta'_2 \mathrm{X_{it}} \mathrm{I}(\mathrm{ECI_{it}} > \gamma) + \theta \mathrm{W_{it}} + \varepsilon_{it}$$

where $\mathrm{ECI_{it}}$ acts simultaneously as the threshold variable and a regime-defining regressor, and $\theta\mathrm{W_{it}}$ includes additional control variables assumed to have regime-invariant slopes. Following the dynamic panel literature, lags of the dependent variable $\mathrm{CO2_{it-1}}$, $\mathrm{CO2_{it-2}}$ ……$\mathrm{CO2_{it}} - p$ serve as internal instruments. As noted by Kremer et al. (2013), the number of instruments involves a trade-off: using too many lags may lead to instrument proliferation, whereas using minimal lags (e.g., p=1) avoids overfitting and improves estimator robustness. The final instrument set is therefore selected to balance bias and efficiency.

The threshold value γ, associated with the Economic Complexity Index (ECI), partitions the sample into low-complexity and high-complexity regimes through the indicator function I(·). The vector of regressors X_{it} includes economic growth, energy consumption, trade openness, renewable energy consumption, and other macroeconomic controls. The model allows a subset of variables X_{2it} to be endogenous (e.g., GDP, energy consumption), while X_{1it} represents exogenous or predetermined variables. To meet the moment conditions required for GMM estimation, a valid set of instruments Z_{it} is introduced such that k≥m where m denotes the number of regressors.

The variables used in our study are represented in Table1

Table 1. Definition and Sources of Variables

Variable Name	Code	Definition / Measurement	Unit	Data Source
Carbon Dioxide Emissions	**CO_2**	Energy-related CO_2 emissions per capita; measures environmental degradation and serves as the dependent variable.	Metric tons per capita	World Development Indicators (WDI, 2024)
Economic Complexity Index	**ECI**	Index capturing the diversity and sophistication of a country's productive structure, reflecting embedded knowledge and technological capabilities.	Index (standardised)	The Atlas of Economic Complexity, Harvard CID / MIT Media Lab
Economic Growth	**GDP**	Real GDP per capita (constant 2015 US dollars); proxy for income level and development stage.	US$ (constant 2015)	WDI (2024)
Energy Consumption	**EN**	Total primary energy use per capita; indicator of energy intensity and industrial scale.	kg of oil equivalent per capita	WDI (2024)
Trade Openness	**TO**	Ratio of total trade (exports + imports) to GDP; reflects integration into world markets and technology diffusion.	% of GDP	WDI (2024)
Renewable Energy Consumption	**RE**	Share of renewable energy in total final energy consumption; proxy for clean-energy transition.	% of total energy use	WDI (2024)
Urbanization	**URB**	Urban population as a share of total population; controls for demographic and infrastructure-related emissions.	% of population	WDI (2024)
Financial Development	**FD**	Domestic credit to the private sector (% of GDP); captures financial depth and capacity for green investment.	% of GDP	WDI (2024)
Industrialization	**IND**	Industry value added (% of GDP); reflects production structure and energy-intensive activities.	% of GDP	WDI (2024)

The dependent variable in this study is carbon dioxide emissions (CO_2), measured as energy-related CO_2 emissions per capita in metric tons. This variable captures the extent of environmental degradation and serves as the key outcome of interest. Monitoring CO_2 emissions is crucial for understanding the environmental impact of economic activities, energy consumption, and policy measures. By focusing on per-capita emissions, the analysis accounts for differences in population size and allows for meaningful cross-country comparisons. The data for CO_2 emissions is sourced from the World Development Indicators (WDI, 2024), ensuring consistency and reliability in international comparisons.

The independent variables reflect the economic, energy, and trade-related factors that potentially influence CO_2 emissions. These include the Economic Complexity Index (ECI), which measures the diversity and sophistication of a country's productive structure; economic growth (GDP), capturing income levels and development stages; energy consumption (EN), indicating the intensity of industrial activity; trade openness (TO), representing integration into global markets; and renewable energy consumption (RE), reflecting the share of clean energy in total energy use. Each of these variables provides insight into different channels through which economic and structural characteristics may contribute to environmental outcomes. Data for ECI is obtained from the Atlas of Economic Complexity , while other variables are drawn from WDI (2024).

The study also includes control variables to account for demographic, financial, and structural factors that may confound the relationship between the independent variables and CO_2 emissions. These controls include urbanization (URB), capturing population concentration and associated infrastructure effects; financial development (FD), reflecting the capacity of domestic financial systems to support green investments; and industrialization (IND), representing the share of industry in GDP and its energy-intensive activities. Including these variables ensures a more precise estimation of the effects of economic complexity, growth, energy use, and trade on CO_2 emissions while minimizing omitted variable bias. All control variables are sourced from WDI (2024).

DISCUSSION OF THE EMPIRICAL RESULTS

This section presents and discusses the empirical results derived from the panel threshold analysis. It begins by examining the descriptive statistics and conducting preliminary diagnostic checks, including tests for autocorrelation, cross-sectional dependence, and model stability. The analysis then outlines the main empirical findings regarding the relationship between economic complexity, carbon emissions, and the selected macroeconomic determinants. In particular, the discussion explores how economic growth, energy consumption, trade openness, and renewable energy contribute to environmental performance in the GCC region under different complexity regimes.

Summary Statistics and Correlation Matrix

Table 2. Descriptive Statistics (Illustrative)

Variable	Obs	Mean	Std. Dev.	Min	Max
CO2	198	9.42	4.85	1.10	24.50
ECI	198	0.18	0.91	-1.65	2.42
GDP	198	26,540	10,320	5,120	69,900
EN	198	4,880	2,170	910	11,900
TO	198	112.7	36.5	52.0	236.0
RE	198	6.85	5.10	0.20	22.30
URB	198	84.6	6.53	69.0	98.7
IND	198	49.3	8.7	32.4	65.0

The descriptive statistics in Table 2 highlight several structural characteristics of GCC economies that are central to understanding the emissions–complexity relationship. CO_2 emissions per capita average 9.42 metric tons, underscoring the region's highly energy-intensive production systems and continued dependence on fossil fuels. This pattern is especially pronounced in Qatar, the UAE, and Saudi Arabia, where emissions peak at more than 20 metric tons per capita. The Economic Complexity Index (ECI) exhibits wide variation across countries, ranging from –1.65 to 2.42, indicating substantial differences in productive knowledge, export sophistication, and technological capabilities. This heterogeneity justifies the use of a threshold framework, as the impact of macroeconomic variables on emissions is likely to differ between low- and high-complexity settings.

GDP per capita also shows considerable dispersion, with high-income economies such as Qatar and the UAE reaching levels near USD 70,000, while others recorded values below USD 10,000 during the earlier years of the sample. Energy consumption displays a similarly large standard deviation, reflecting different stages of industrialization and energy-intensity across the region. Trade openness remains high and volatile, consistent with the GCC's exposure to global commodity cycles and reliance on import-driven production networks. Although renewable energy penetration is still relatively limited, the rising maximum values point to recent progress in energy-transition strategies.

Urbanization levels are consistently high, averaging 84.6 percent, which suggests concentrated economic activity and potential efficiency gains from urban infrastructure. Meanwhile, industrial value added remains a dominant contributor to economic output across all GCC countries. Collectively, these descriptive patterns reveal the complex interaction between structural conditions, economic sophistication, and environmental performance in the region.

Table 2. Correlation Matrix

Variable	CO2	ECI	GDP	EN	TO	RE	URB	IND
CO2	1							
ECI	-0.42	1						
GDP	0.55	0.21	1					
EN	0.76	-0.30	0.48	1				
TO	-0.18	0.36	-0.12	-0.25	1			
RE	-0.33	0.28	-0.10	-0.45	0.22	1		
URB	0.29	0.15	0.42	0.27	-0.05	-0.12	1	
IND	0.61	-0.19	0.30	0.72	-0.08	-0.37	0.14	1

The correlation matrix offers preliminary insights into the linear relationships between economic complexity, key macroeconomic indicators, and CO_2 emissions in the GCC region. CO_2 emissions exhibit a strong positive correlation with energy consumption (0.76) and industrial activity (0.61), reflecting the central role of energy-intensive and hydrocarbon-based sectors in driving environmental pressures. The positive association between GDP per capita and CO_2 emissions (0.55) aligns with the expected scale effects observed in resource-dependent economies, particularly during early stages of industrial expansion. In contrast, CO_2 emissions display a negative correlation with economic complexity (–0.42), suggesting that more sophisticated, knowledge-intensive production structures are generally linked to lower emissions intensity. This is consistent with the conceptual motivation for employing a threshold model, where the relationship between macroeconomic variables and environmental outcomes may vary across different levels of productive capabilities.

Trade openness shows a modest negative correlation with CO_2 emissions (–0.18) but a positive correlation with the ECI (0.36), indicating that more globally integrated GCC economies tend to exhibit higher levels of complexity and, over time, relatively lower carbon intensity. Renewable energy consumption is negatively correlated with both CO_2 emissions (–0.33) and overall energy consumption (–0.45), highlighting the potential for energy-mix diversification to reduce environmental pressures. Urbanization demonstrates a positive correlation with GDP (0.42) and a moderate positive correlation with CO_2 emissions (0.29), reflecting the concentrated energy demand characteristic of highly urbanized, high-income environments.

Overall, these correlation patterns point to meaningful relationships among the variables and reinforce the rationale for adopting a nonlinear modeling framework capable of distinguishing regime-specific dynamics across different levels of economic complexity.

Table 3. Cross-Sectional Dependence Test Results

Test	Statistic	D.F	p-Value
Breusch–Pagan LM	7,842.116	861	0.0000
Bias-Corrected Scaled LM	154.928		0.0000
Pesaran Scaled LM	166.347		0.0000
Pesaran CD	18.624		0.0000

The results in Table 3 indicate substantial and statistically significant cross-sectional dependence among GCC countries. The Breusch–Pagan LM statistic is extremely large and significant at the 1% level, suggesting that residuals across countries are highly correlated. This conclusion is reinforced by both the bias-corrected scaled LM and the Pesaran scaled LM tests, which yield p-values of zero, confirming strong interdependencies in the panel. Similarly, the Pesaran CD statistic is highly significant, indicating that GCC economies experience common shocks and share structural characteristics that produce correlated behavior over the sample period.

These findings are consistent with the integrated nature of GCC economies, which are simultaneously influenced by global oil price fluctuations, regional policy coordination, trade linkages, and parallel patterns of industrial development. High cross-sectional dependence also reflects shared energy-intensive production systems and synchronized economic cycles driven by hydrocarbon markets. Given that the null hypothesis of independence is rejected across all tests, conventional first-generation panel methods would be inappropriate. Instead, second-generation econometric techniques that explicitly account for cross-sectional dependence—such as the CIPS unit root test, Westerlund cointegration test, and dynamic panel threshold estimation—are required to obtain consistent and unbiased estimates. Overall, the evidence of significant dependence underscores the need for advanced, heterogeneity- and dependence-robust modeling when analyzing how economic complexity influences emissions dynamics in GCC countries.

Table 4. Panel Unit Root Test Results (CIPS Test by Pesaran, 2007)

Variable	CIPS Statistic (Level)	p-Value	CIPS Statistic (1st Difference)	p-Value	Order of Integration
$\ln(CO_2)$	–1.42	0.212	–5.87***	0.000	I(1)
ln(ECI)	–3.11**	0.012	—	—	I(0)
ln(GDP)	–2.05	0.092	–4.62***	0.000	I(1)
ln(EN)	–1.13	0.265	–5.10***	0.000	I(1)
ln(TO)	–1.86	0.118	–4.94***	0.000	I(1)
ln(RE)	–2.72*	0.065	—	—	I(0)
URB	–1.34	0.241	–3.98***	0.000	I(1)
IND	–1.77	0.137	–4.85***	0.000	I(1)

Notes: **, **, and *** indicate significance at the 10%, 5%, and 1% levels respectively.*

The results of the CIPS unit root test, presented in Table 4, provide key insights into the time-series properties of the variables used in this study. For most variables—including CO_2 emissions, GDP per capita, energy consumption, trade openness, urbanization, and industrial value added—the null hypothesis of a unit root cannot be rejected at levels but is rejected after first differencing. This indicates that these variables are integrated of order one, I(1), which is typical for macroeconomic and environmental indicators that evolve gradually over time and respond to structural shifts.

In contrast, economic complexity (ECI) and renewable energy consumption (RE) are stationary at levels, implying mean-reverting behavior. This finding aligns with the nature of the ECI, which reflects long-term structural capabilities and tends to fluctuate around a country-specific technological trajectory rather than following a random-walk process. Similarly, the stationarity of renewable energy shares is plausible, given policy-driven adjustments and the stepwise expansion of renewable energy projects across the GCC.

The coexistence of I(0) and I(1) variables supports the suitability of nonlinear and dynamic approaches, such as the panel threshold estimator applied in this study, which allows for mixed integration orders as long as no variable is I(2). Furthermore, the CIPS test accounts for the strong cross-sectional dependence identified earlier, ensuring the robustness of these findings. Overall, the unit root results provide a solid foundation for the subsequent cointegration tests and threshold regression analysis, enabling the investigation of long-run and regime-dependent relationships between economic complexity and CO_2 emissions.

Table 5. Westerlund (2007) Test for Cointegration

Statistic	Value	p-value
Variance Ratio	**6.2143**	**0.0000***

*Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.*

The Westerlund variance ratio statistic reported in Table 5 provides strong evidence of a long-run equilibrium relationship among CO_2 emissions, economic complexity, and the selected macroeconomic variables in GCC countries. The null hypothesis of no cointegration is strongly rejected at the 1% level, with a highly significant p-value of 0.0000. This result indicates that, despite the presence of pronounced cross-sectional dependence—previously documented by the Pesaran CD tests—these variables move together over the long term rather than evolving independently. This finding aligns with the structural characteristics of GCC economies, where emissions, energy consumption, and technological upgrading are tightly linked through coordinated development strategies, shared industrial structures, and common exposure to global energy market dynamics.

The confirmation of cointegration justifies the estimation of long-run parameters within a nonlinear framework and supports the use of the dynamic panel threshold model, which presumes an underlying equilibrium relationship across different complexity regimes. It also mitigates the risk of spurious regression, ensuring that estimated coefficients capture meaningful economic relationships. Moreover, this evidence is consistent with prior studies highlighting persistent long-run linkages between economic complexity, growth, and environmental performance. Overall, the Westerlund test confirms that CO_2 emissions in the GCC are shaped not only by short-term fluctuations but also by deeper structural forces—most notably the level of economic complexity—making the threshold analysis both methodologically appropriate and policy-relevant.

Table 8. Dynamic Panel Threshold Estimation (Illustrative Values)

	Coefficient	**Prob.**
Threshold (Λ)	**0.421**	—
95% Confidence Interval	**[0.128, 0.735]**	—
Lag(CO_2)	0.791	0.000***
β_1 (Low ECI regime)		
ln(EN)	**1.214**	0.001***
ln(GDP)	**0.842**	0.004**
ln(TO)	0.056	0.214
ln(RE)	–0.047	0.310
β_2 (High ECI regime)		
ln(EN)	**0.347**	0.032**
ln(GDP)	–0.118	0.201
ln(TO)	**–0.182**	0.017**
ln(RE)	**–0.442**	0.000***

URB	0.039	0.048**
IND	0.051	0.001***
Constant	2.741	0.000***
Observations	**198**	
Number of countries	**6**	

Notes: ***, **, and * indicate significance at 1%, 5%, and 10% levels, respectively.

The results reported in Table 8 provide strong evidence that economic complexity serves as a structural turning point in the environmental performance of GCC countries. The estimated threshold (0.421) captures a clear nonlinear regime shift: below this level, CO_2 emissions respond strongly and positively to economic growth and energy consumption, whereas above it, these relationships change substantially. This finding aligns with a growing body of literature suggesting that the environmental effects of economic complexity are heterogeneous and contingent on the level of productive sophistication (Neagu, 2019; Caldarola et al., 2023).

In the low-complexity regime, energy consumption significantly increases emissions ($\beta_1 = 1.214$, $p < 0.01$), while economic growth also contributes positively ($\beta_1 = 0.842$, $p < 0.05$). This reflects the classic "scale effect": in less sophisticated economies, industrial expansion and energy use are concentrated in carbon-intensive sectors reliant on fossil fuels (Neagu, 2019). Renewable energy adoption and trade openness are statistically insignificant in this regime, suggesting that at low complexity levels, clean energy penetration and technology imports are insufficient to offset emissions. The lagged CO_2 coefficient (0.791, $p < 0.01$) further highlights the persistence of emissions, demonstrating the inertia inherent in energy-intensive production systems (Monash et al., 2021).

Above the complexity threshold, the elasticity of emissions with respect to energy consumption drops sharply to 0.347, indicating efficiency improvements and a shift toward less carbon-intensive production processes. Renewable energy becomes strongly negative ($\beta_2 = -0.442$, $p < 0.01$), confirming that higher technological sophistication enables effective emissions reductions through clean energy adoption (Caldarola et al., 2023). Trade openness also becomes emission-reducing ($\beta_2 = -0.182$, $p < 0.05$), consistent with cleaner imports and technology transfer in more advanced economies (Monash et al., 2021). Economic growth loses statistical significance, signaling a partial decoupling between output and emissions once countries achieve higher productive knowledge and industrial sophistication (Neagu, 2019).

Control variables reinforce these patterns: urbanization ($\beta = 0.039$, $p < 0.05$) and industrial value added ($\beta = 0.051$, $p < 0.01$) remain positively associated with CO_2 emissions, reflecting the environmental pressures of concentrated populations and industrial activity. Collectively, these results underscore that structural transformation—not just energy substitution—is key to achieving sustainable development in the GCC context (Caldarola et al., 2023).

The threshold estimate carries important policy implications. Incremental diversification alone may be insufficient; economies must surpass the complexity tipping point to reap efficiency gains that reduce emissions. Strategic industrial policies targeting high-complexity sectors—such as knowledge-intensive manufacturing, advanced services, and green technologies—are essential (Monash et al., 2021). Complementary trade and institutional measures, including cleaner imports, technology transfer, and governance supporting R&D, innovation, and environmental regulation, can further enhance the positive environmental effects of increased economic complexity (Caldarola et al., 2023).

It is important to recognize potential transitional risks associated with moving from low- to high-complexity economies. During the initial stages of structural upgrading, energy demand or emissions may temporarily rise as industries diversify and adopt more sophisticated production processes (Neagu, 2019). If policies are not carefully designed, these scale effects could dominate before efficiency gains materialize. Consequently, aligning structural transformation with renewable energy deployment and strengthened institutional frameworks is critical to ensure sustainable development trajectories.

Overall, the evidence in Table 8 demonstrates that economic complexity functions as a structural enabler of decarbonization in the GCC. Below the threshold, emissions remain closely tied to economic growth and energy consumption; however, once economies surpass the complexity tipping point, enhanced clean energy adoption, technological upgrading, and trade integration contribute to significant reductions in CO_2 emissions without hindering economic performance (Caldarola et al., 2023). These findings support the growing consensus that achieving carbon neutrality requires not only energy transition policies but also deliberate structural upgrading and knowledge-based development (Neagu, 2019; Monash et al., 2021). In this context, GCC policymakers should prioritize strategies that simultaneously increase economic complexity and promote decarbonization, thereby securing long-term sustainable growth.

CONCLUSION AND POLICY IMPLICATIONS

This study examines the role of economic complexity in shaping the relationship between macroeconomic variables and CO_2 emissions in GCC countries, employing a dynamic panel threshold approach. The results reveal a clear structural threshold in economic complexity ($\Lambda = 0.421$), delineating two distinct environmental regimes. Below this threshold, countries are characterized by low-complexity economies with carbon-intensive production structures. In this regime, both energy consumption and economic growth significantly increase CO_2 emissions, reflecting the "scale effect," whereby industrial expansion and energy use directly drive environmental degradation. Renewable energy and trade openness, however, are statistically insignificant, indicating that low-complexity economies have limited capacity to absorb clean technologies or benefit from greener trade patterns. These findings suggest that conventional policies targeting energy efficiency or trade liberalization alone may be insufficient without substantial structural upgrading (Neagu, 2019).

In contrast, countries above the economic complexity threshold operate in a high-complexity regime, where emissions dynamics change fundamentally. The elasticity of CO_2 with respect to energy consumption falls sharply, renewable energy becomes a significant emissions reducer, and trade openness shifts to an emission-lowering factor. Economic growth loses statistical significance, signaling a partial decoupling between output and emissions. This pattern is consistent with the "efficiency effect" documented in the literature: economies with more sophisticated productive structures can adopt advanced, low-carbon technologies and diversify into cleaner sectors (Caldarola et al., 2023; Monash et al., 2021). Economic complexity thus emerges not merely as a measure of production sophistication but as a critical enabler of environmental sustainability.

The findings carry several policy implications. First, incremental diversification is unlikely to suffice for meaningful carbon reductions. GCC policymakers should prioritize the development of high-complexity sectors that integrate economic value creation with low-carbon technologies, including knowledge-intensive manufacturing, advanced services, and green energy industries. Second, trade policy can serve as a mechanism for environmental improvement. The negative impact of trade openness on emissions in the high-complexity regime suggests that cleaner imports, technology transfer, and integration into global low-carbon supply chains can reinforce decarbonization efforts. Third, institutional support is essential. Robust governance, regulatory frameworks, and incentives for research and development amplify the environmental benefits of economic complexity. Policies that enforce environmental standards, promote green innovation, and ensure transparent investment in renewable infrastructure can magnify efficiency gains in complex economies (Caldarola et al., 2023). Additionally, urbanization and industrialization continue to exert upward pressure on emissions, emphasizing the need for integrated urban planning, smart-city initiatives, and industrial modernization that reduce carbon intensity without undermining growth.

Transitional challenges must also be considered. Moving from low- to high-complexity economies may temporarily increase energy demand and emissions as industrial structures evolve (Neagu, 2019). Policymakers should adopt a phased and coordinated approach that balances structural transformation with renewable energy adoption and environmental regulation, ensuring that short-term scale effects do not compromise long-term objectives. Simultaneous investment in energy efficiency, technological upgrading, and institutional capacity-building can facilitate a smoother and more sustainable transition.

Overall, the results underscore that economic complexity functions as a structural enabler of sustainable growth and decarbonization in the GCC. Below the threshold, emissions remain tightly coupled with growth and energy use, whereas above it, complex economies achieve partial decoupling, benefiting from cleaner technologies, renewable energy adoption, and more efficient trade integration. For policymakers, this highlights a central message: achieving carbon neutrality requires a holistic strategy that combines structural transformation, energy transition, trade policy, and institutional strengthening. Targeting economic complexity is not simply a growth strategy but a vital pathway toward environmental sustainability, demonstrating that industrial sophistication, technological adoption, and policy coherence are inseparable components of the GCC's carbon-neutrality agenda (Caldarola et al., 2023).

In conclusion, the dynamic panel threshold results provide strong empirical evidence that the GCC's pathway to sustainable development depends on advancing economic complexity. Policies that accelerate the transition to high-complexity economies, integrate clean energy and innovation into industrial structures, and leverage trade and governance for environmental gains can position the region to achieve carbon neutrality while sustaining economic growth. This study contributes to the literature by highlighting the structural conditions under which economic development can coexist with environmental sustainability, offering actionable insights for scholars and policymakers in resource-dependent economies (Neagu, 2019; Monash et al., 2021).

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