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Does the Impact of Renewable Energy on Environment Performance depend on Threshold Effects and Moderating Variables in GCC Countries? [1]

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Abstract. This study examines the non-linear effects of renewable and non-renewable energy consumption on the Environmental Performance Index (EPI) in Gulf Cooperation Council (GCC) countries from 2002 to 2022, using a dynamic threshold regression model. Unlike previous studies that focus solely on direct energy-environment relationships, this research introduces moderating variables—including institutional quality, energy subsidies, and energy efficiency—to capture their role in shaping the impact of energy consumption on environmental outcomes. The findings reveal that non-renewable energy consumption significantly deteriorates environmental performance beyond critical thresholds (85%-99.9%), particularly affecting air quality and climate change. Conversely, renewable energy consumption enhances EPI performance only after surpassing key adoption levels (5.5%-10.9%), with its effectiveness amplified when supported by favorable policy and governance conditions. The results demonstrate that institutional quality and energy efficiency mitigate the adverse effects of fossil fuel use while reinforcing the environmental benefits of renewable energy. These insights highlight the need for comprehensive policy reforms, including the restructuring of energy subsidies, strengthening institutional frameworks, and promoting clean energy investments, to accelerate the sustainability transition in GCC economies.

Keywords: Renewable energy, fossil fuel consumption, Environmental Performance Index, GCC countries, moderating variables, dynamic threshold regression models.
JEL classification : Q40, Q42, Q53, Q56, O13.

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1) Introduction

The global transition toward sustainable energy sources has become a central challenge for governments, businesses, and societies. This shift is particularly crucial in Gulf Cooperation Council (GCC) countries, where energy consumption remains heavily reliant on non-renewable resources like oil and natural gas. Despite their economic dependence on fossil fuels, GCC countries face increasing global pressure to meet international environmental standards, as excessive fossil fuel consumption significantly contributes to greenhouse gas emissions.

According to the IEA (2021), renewable energy accounted for around 29% of global energy generation in 2020. However, this figure is substantially lower in GCC countries, with Saudi Arabia and the UAE deriving only 1–2% of their energy consumption from renewable sources (IRENA, 2020). This stark contrast underscores the need for these nations to increase their integration of renewable energy to improve environmental performance. Environmental indicators, such as the EPI, highlight areas where the GCC countries lag. For instance, Qatar ranked 102nd out of 180 countries in 2022, with significant concerns regarding carbon intensity and air quality (Yale Center for Environmental Law & Policy, 2022). These findings emphasize the urgent need for the region to shift toward cleaner energy sources to mitigate environmental degradation.

While extensive research has explored the relationship between energy consumption and environmental performance, most studies have focused on developed nations or regions with a high proportion of renewable energy. For instance, Al-Mulali et al. (2019) highlighted renewable energy's potential to reduce carbon emissions in the Middle East, and Saidi and Omri (2020) examined how renewable energy mitigates the adverse environmental effects of fossil fuel consumption. However, these studies often overlook the dynamic, non-linear relationships between energy consumption and environmental performance, and fail to identify threshold points where renewable energy has a significant impact. These gaps underscore the critical need for research that explores the non-linear dynamics between renewable and non-renewable energy consumption and environmental performance in resource-dependent economies, particularly using dynamic econometric methods.

Few studies have specifically applied dynamic threshold regression models to examine energy consumption and environmental performance in GCC countries. Furthermore, recent research, such as Salem et al. (2023) and Amer et al. (2024), has analyzed the environmental impact of energy transitions in the GCC region but primarily relies on statistical analyses and STIRPAT models rather than dynamic threshold methodologies. Similarly, Saidi and Omri (2020) employed threshold panel models to investigate non-linear effects in the GCC; however, their approach does not account for the potential influence of moderating variables in shaping the relationship between energy consumption and environmental performance. This limitation underscores the need for a more comprehensive analysis that incorporates threshold effects alongside key moderating factors, providing a deeper understanding of the conditions under which renewable energy exerts a substantial impact.

This gap underscores the originality of our study, which leverages advanced econometric techniques to identify critical thresholds at which renewable energy exerts a significant influence on environmental performance. By addressing the scarcity of rigorous studies employing such methodologies, this research offers valuable insights and actionable policy recommendations to facilitate sustainable energy transitions in the GCC region. The primary objectives of this paper are to:

- Examine the impact of renewable and non-renewable energy consumption on environmental performance in GCC countries over the past two decades.

- Employ a dynamic threshold regression model to capture non-linear relationships and identify key points where renewable energy consumption markedly enhances environmental performance.

-Formulate targeted policy recommendations to guide GCC countries in transitioning toward more sustainable energy systems that improve environmental outcomes.

By focusing on the GCC region, this study makes a unique contribution to the energy-environment literature, particularly given the region's reliance on non-renewable energy. Previous studies have largely overlooked the potential for renewable energy growth in this area and its environmental benefits. For instance, Shahbaz et al. (2017) observed that economic growth in fossil fuel-driven economies often comes at the expense of environmental health but did not explore the potential benefits of adopting renewable energy. Recent studies have explored the complex interplay between renewable energy, economic growth, and environmental sustainability, primarily focusing on regions outside the GCC. For instance, Razzaq et al. (2023) analyzed green growth within the context of COP26, while other studies examined environmental impacts in Africa and other regions, emphasizing threshold effects. However, these studies fail to account for the unique economic and environmental dynamics of the GCC, where fossil fuel dependency and policy frameworks shape the transition to renewable energy differently.

In this paper, we employ a dynamic threshold regression approach to provide a nuanced analysis of how different levels of renewable energy consumption influence environmental outcomes. This methodology is particularly valuable in identifying the critical points at which renewable energy adoption begins to generate measurable environmental benefits—an aspect rarely explored in existing literature. By applying this innovative framework, our study offers new insights into the non-linear dynamics of energy transitions in the GCC region. Overall, this paper addresses key theoretical and empirical gaps by offering new insights into the crucial role of renewable energy in enhancing environmental performance in resource-rich economies like those in the GCC. It provides a detailed analysis of the distinct impacts of renewable and non-renewable energy on environmental performance, moving beyond previous studies that often assess energy use in aggregate terms. By employing a threshold regression approach, this study differentiates the effects of renewable and non-renewable energy across varying levels of environmental performance. Moreover, it integrates institutional quality and economic freedom as moderating variables, deepening our understanding of how governance and policy frameworks shape the energy-environment nexus in the GCC. The econometric analysis identifies precise thresholds for renewable energy adoption, offering valuable insights into the levels at which its environmental benefits become significant. By establishing these critical points, this study provides GCC policymakers with targeted benchmarks for renewable energy adoption and regulatory reforms to achieve optimal environmental outcomes. Additionally, it outlines strategies to mitigate the adverse effects of high fossil fuel consumption, offering a clear roadmap for effective energy transition policies.

This paper is structured as follows: Section 2 provides a comprehensive review of the literature, focusing on studies that examine the relationship between renewable and non-renewable energy consumption and environmental performance. Section 3 details the data sources, EPI indicators, and econometric models employed to capture non-linear dynamics. Section 4 presents an in-depth discussion of the findings, emphasizing the critical thresholds identified in the analysis. Finally, Section 5 concludes with key policy recommendations and their implications for energy and environmental policies in the GCC.

2) Literature review

2.1) Theoretical review

The theoretical foundation of this study is grounded in the broader literature on the relationship between energy consumption and environmental performance, particularly within the framework of the Environmental Kuznets Curve (EKC) hypothesis. The EKC suggests that environmental degradation initially increases with economic growth but, after a certain income level is reached, further economic development leads to improved environmental quality. In the context of GCC countries, this theory is particularly relevant, as these nations experience rapid economic growth fueled by non-renewable energy consumption.

The energy-environment nexus highlights that the type of energy consumed plays a significant role in determining environmental outcomes. Renewable energy sources, being more sustainable and environmentally friendly, are expected to reduce carbon emissions and other pollutants, thereby improving environmental performance. In contrast, non-renewable energy, particularly fossil fuels, significantly contributes to environmental degradation through increased greenhouse gas (GHG) emissions.

Dynamic threshold regression models enable the exploration of non-linear relationships, which are particularly applicable to studies on energy and environmental performance. These models can help identify "thresholds" or critical points where renewable energy consumption begins to have a marked impact on environmental performance. Such methodologies align with theoretical perspectives from energy transition frameworks, which propose that economies shift toward cleaner energy sources as part of a broader effort to mitigate environmental degradation.

This study applies these theoretical constructs to the specific case of the GCC countries, where economies and environmental policies are deeply intertwined with the energy sector. Given the GCC's current low reliance on renewable energy, this study aims to determine whether these nations are nearing a threshold where renewable energy can significantly improve environmental performance.

The relationship between energy consumption and environmental performance has been extensively explored in academic research, though studies focusing on the GCC region remain relatively scarce. This review highlights key contributions to the literature, particularly those related to renewable and non-renewable energy consumption in resource-dependent economies. Al-Mulali et al. (2019) examined the impact of renewable energy on carbon emissions in the Middle East, finding that renewable energy adoption was significantly correlated with a reduction in emissions. The study underscored the potential for renewable energy to improve environmental performance, particularly in economies heavily dependent on non-renewable energy. However, the research did not specifically address the non-linear effects of energy consumption, leaving a gap that this study seeks to fill.

Similarly, Saidi and Omri (2020) explored the role of renewable energy in mitigating the environmental harm caused by non-renewable energy consumption in developing countries. Their findings revealed that while renewable energy adoption could mitigate environmental degradation, their study lacked a focus on the critical points at which renewable energy becomes more impactful than non-renewable energy. This underscores the need for dynamic models, such as the threshold regression model used in this study.

Shahbaz et al. (2017) raised concerns about the sustainability of fossil-fuel-driven economies and their environmental impact, noting that economic growth often exacerbates environmental degradation unless coupled with a significant shift toward renewable energy. Their study also hinted at the existence of critical thresholds in renewable energy adoption, which have yet to be empirically tested in the GCC context.

Moreover, Umar et al. (2021) highlighted the urgent need for investment in renewable energy to offset the environmental damage caused by non-renewable energy use in oil-rich nations, including those in the GCC. However, their research did not provide a detailed analysis of the thresholds where renewable energy consumption overtakes non-renewable energy in terms of environmental benefits, an issue this study aims to address.

2.2) Empirical review

The empirical relationship between energy consumption and environmental performance has been the focus of extensive research, particularly in emerging economies and resource-dependent regions such as the Gulf Cooperation Council (GCC) countries. This empirical review summarizes key studies that investigate the effects of renewable and non-renewable energy consumption on environmental indicators, with a particular focus on carbon emissions, environmental performance indices, and related outcomes.

Several studies have empirically examined the effects of renewable energy consumption on environmental quality. Al-Mulali et al. (2019) conducted a comprehensive analysis of Middle

Eastern countries, finding that renewable energy consumption is significantly and negatively correlated with carbon emissions. Using a panel data analysis covering multiple countries, including several GCC members, they concluded that a 1% increase in renewable energy consumption leads to a 0.7% reduction in carbon emissions. This reduction highlights the potential of renewable energy to mitigate environmental degradation in regions heavily dependent on fossil fuels. The study also found that countries with more diversified energy sources tend to perform better in terms of environmental indicators such as air quality and carbon intensity. Their results suggest that increasing investments in renewable energy not only helps reduce emissions but also promotes long-term environmental sustainability, making it a crucial policy priority for the GCC countries as they aim to meet international climate goals.

Furthermore, Bhattacharya et al. (2016) explored the long-term impacts of renewable energy consumption on economic and environmental performance in developing countries, including the GCC. Their study employed a generalized method of moments (GMM) estimator and revealed that renewable energy significantly enhances environmental quality while supporting sustainable economic growth. This highlights the potential for renewable energy investments to create a dual benefit of economic development and reduced environmental degradation. The study also noted that countries with greater renewable energy adoption experienced a decrease in carbon emissions and other environmental pollutants, suggesting that a well-implemented renewable energy strategy could play a crucial role in transitioning toward a low-carbon economy. For the GCC, where economic growth has traditionally been linked to fossil fuel use, these findings underscore the importance of diversifying energy sources to achieve long-term sustainability.

In the specific context of the GCC, Zhang et al. (2020) found that solar and wind energy projects in Saudi Arabia and the UAE have had a notable positive effect on reducing greenhouse gas emissions. Using a dynamic panel model, they identified that the effectiveness of renewable energy in improving environmental performance grows over time as economies scale up their clean energy projects.

The literature also highlights the detrimental environmental effects of non-renewable energy consumption. Shahbaz et al. (2017) provided empirical evidence of the Environmental Kuznets Curve (EKC) hypothesis in the GCC region, showing that while economic growth initially leads to environmental degradation due to fossil fuel reliance, after a certain threshold, the relationship between economic growth and environmental damage reverses. Omri et al. (2019) explored the interplay between non-renewable energy consumption, carbon emissions, and economic development in oil-rich countries. Using a structural vector autoregressive (SVAR) model, they found that non-renewable energy consumption increases carbon emissions by more than 30% in GCC countries, exacerbating environmental degradation and hindering sustainable development efforts.

Few studies have applied dynamic threshold regression analysis to examine the non-linear relationships between renewable energy consumption and environmental performance. Saidi and Omri (2020) utilized a threshold panel model to demonstrate that the impact of renewable energy on environmental quality becomes more pronounced after a certain threshold is reached. Their research suggests that countries that invest more heavily in renewable energy are able to reduce emissions at an accelerating rate once the share of renewable energy in the total energy mix surpasses a critical point.

Recent studies have deepened the understanding of the complex relationship between renewable energy consumption, economic growth, and environmental sustainability, particularly through non-linear models. Razzaq et al. (2023) employed a dynamic threshold model to assess the effects of energy transition and environmental governance on green growth within the COP26 framework, highlighting the importance of crossing specific thresholds to achieve sustainable outcomes. Their findings revealed that energy transition positively impacts green growth only beyond certain governance and consumption levels, laying the foundation for our methodological approach. Similarly, Azimi and Rahman (2024) utilized a dynamic panel threshold technique to examine the relationship between renewable energy and the ecological footprint, demonstrating how renewable energy consumption mitigates environmental degradation once certain thresholds are exceeded. Furthermore, Muazu, Yu, and Alariqi (2023) investigated the impact of renewable energy consumption and economic growth on environmental quality in Africa using threshold regression. Their results showed that renewable energy consumption improves environmental quality, but only when aligned with economic growth policies that promote sustainability.

These studies collectively emphasize the importance of threshold effects and the interactions between energy consumption, governance, and economic factors in shaping environmental outcomes. Building on this empirical foundation, our study applies a region-specific threshold analysis tailored to GCC countries, focusing on environmental performance and incorporating GCC-specific moderating variables to provide actionable policy insights.

Recent literature shows increasing interest in non-linear and threshold estimation methods for studying energy and environmental impacts, extending beyond the GCC region. For instance, Pata (2023) examined the Environmental Kuznets Curve in emerging markets, demonstrating how governance and energy diversification drive environmental improvements through a threshold model approach. This research underscores the growing recognition of threshold effects in energy-environment studies, though it does not incorporate a dynamic threshold regression framework.

In the GCC context, Amer et al. (2024) explored the effects of renewable and non-renewable energy consumption on CO_2 emissions using the STIRPAT model, which provides a nuanced analysis of factors such as population and technology. However, their approach lacks a dynamic threshold component. Similarly, Salem et al. (2023) discussed the transition from fossil-based to diversified energy sources in oil-dependent economies, focusing primarily on policy impacts. While relevant, this study adopted a descriptive method rather than a dynamic threshold approach.

While recent studies have explored energy-environment relationships in GCC countries, this paper uniquely investigates the threshold dynamics of renewable and non-renewable energy consumption using a dynamic threshold regression model. By identifying critical consumption levels where environmental impacts shift, the study provides a deeper understanding of the threshold effects and moderating factors specific to the GCC region. With renewable energy still accounting for a minimal share of consumption, its potential environmental benefits remain largely untapped. This research aims to fill this gap by offering practical insights for policymakers to design tailored strategies that align economic growth with environmental sustainability.

Empirical evidence consistently demonstrates that renewable energy consumption improves environmental performance, whereas non-renewable energy degrades it. However, the literature often overlooks the non-linear dynamics between these variables, especially within the GCC context. Given the region's reliance on fossil fuels and its nascent adoption of renewable energy, understanding the critical points at which clean energy begins to generate meaningful environmental benefits is crucial.

Future research, including this study, must prioritize the exploration of threshold effects in renewable energy investments. This approach will shed light on when and how such investments lead to significant environmental improvements in the GCC. Additionally, examining the role of policy frameworks, investment levels, and economic diversification will help accelerate the energy transition. Understanding these dynamics is essential for guiding informed policymaking that fosters sustainable energy systems without hindering economic growth.

3) Methodology and Data

This paper investigates the nonlinear effects of renewable and non-renewable energy on the EPI and its four components: Environmental Health, Ecosystem Vitality, Climate Policy, and Biodiversity, with a focus on GCC countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE). To address these questions, we utilize the fixed-effect panel threshold model developed by Hansen (1999), which allows us to assess both the potential non-linearity in the effect of renewable and non-renewable energy on the EPI. Our study builds on this model by incorporating GCC-specific factors and integrating moderating variables such as institutional quality and energy subsidies, which reflect the unique economic structure and policy framework of the region. By accounting for these regionally relevant factors, our model identifies the critical thresholds where renewable energy consumption significantly enhances environmental performance, thereby extending Razzaq et al.'s methodology to a more targeted regional context.

In the first step, we investigate the existence of a threshold effect related to both renewable and non-renewable energy in connection with the Environmental Performance Index. In the second step, we analyze their impact on the different components of the EPI. Examining the components of the EPI is crucial because each reflects a distinct aspect of environmental sustainability. By disaggregating the Environmental Performance Index, we can gain a deeper understanding of how specific environmental outcomes—such as air quality, biodiversity, and climate policy—are influenced by various factors, including energy consumption. This approach offers a clearer perspective on which environmental dimensions are most affected by renewable versus non-renewable energy use. For instance, while renewable energy may substantially improve air quality, non-renewable energy consumption could negatively impact environmental health. Thus, analyzing these components allows for targeted policy recommendations to enhance specific environmental outcomes.

Thus, we begin by considering the conventional linear framework as follows:

$$EPI_{it} = \alpha_0 + \alpha_1 REN_{it} + \alpha_2 NREN_{it} + \alpha_3 RGDP_{it} + \alpha_4 URBA_{it} + \alpha_5 ECOFRE_{it} + \alpha_6 INSQUA_{it} + \varepsilon_{it} \quad (1)$$

, where:

EPI_{it}: Environmental Performance Index for country i at time t

REN_{it} : Renewable energy consumption for country i at time t

$NREN_{it}$: Non-renewable energy consumption for country i at time t

$RGDP_{it}$: Real GDP for country i at time t

$URBA_{it}$: Urban population for country i at time t

$ECOFRE_{it}$: Economic freedom index for country i at time t

$INSQUA_{it}$: Institutional quality for country i at time t

ε_{it} : Error term in the model for country i at time t, accounting for any unobserved factors influencing the dependent variable that are not explicitly included in the model.

All variables are in log. A detailed description of the variables and their sources is provided in Appendix A[2].

However, Equation (1) does not account for the possible threshold impact of REN and NREN on the Environmental Performance Index. To address this non-linearity, we adopt a dynamic panel threshold model developed by Hansen (1999). This econometric model enables us to test for the existence of threshold effects in the relationship between renewable (REN) and non-renewable (NREN) energy and EPI. This approach allows us to hypothesize that the equation can be segmented into different regimes based on threshold values of REN and NREN.

According to Hansen (1999), Equation (1) can be reformulated as follows:

$$EPI_{it} = \theta_{i0} + \theta_1 RGDP_{it} + \theta_2\, URBA_{it} + \theta_3 ECOFRE_{it} + \theta_4 INSQUA_{it} + \theta_{5L} NREN_{it} I(NREN \leq \delta) + \theta_{5U} NREN_{it} I(NREN > \delta) + \varepsilon_{it} \quad (2)$$

$$EPI_{it} = \alpha_{i0} + \alpha_1 RGDP_{it} + \alpha_2\, URBA_{it} + \alpha_3 ECOFRE_{it} + \alpha_4 INSQUA_{it} + \alpha_{5L} REN_{it} I(REN \leq \gamma) + \alpha_{5U} REN_{it} I(REN > \gamma) + \epsilon_{it} \quad (3)$$

In Equation (2), the threshold variable is the fossil fuel consumption share, which approximates non-renewable energy. In this equation, we analyze the nonlinear relationship between non-renewable energy (NRER) and the Environmental Performance Index. Conversely, in Equation (3), the threshold variable is the renewable energy share (REN), and we examine the nonlinearity in the REN-EPI relationship to determine the threshold level. The indicator function *I*(.) is a dummy variable that takes the value 1 if the threshold variable is below the threshold parameter specific to that equation, and 0 otherwise. The models presented above are estimated for a panel dataset of six GCC countries, covering the period 2002–2022.

The data can be obtained from the corresponding author.[2]

In the previous equations, each explanatory variable has an expected sign that reflects its economic relationship with environmental performance. The anticipated signs are explained briefly as follows:

- **Renewable Energy Consumption (Positive sign expected)**: Economically, increasing renewable energy consumption should improve environmental performance, as renewables produce less pollution and reduce reliance on fossil fuels. This positive impact is especially significant after crossing certain thresholds of renewable energy adoption.
- **Non-Renewable Energy Consumption (Negative sign expected)**: Higher consumption of non-renewable energy is expected to negatively impact environmental performance. Fossil fuels contribute to air and water pollution, greenhouse gas emissions, and ecosystem degradation, worsening environmental indicators like air quality and biodiversity.
- **Real GDP (Positive sign expected):** Higher levels of real GDP are generally associated with improved environmental performance in the long term, as economic development allows for more resources to be allocated toward environmental protection and investment in cleaner technologies. However, at lower GDP levels, there may be greater reliance on non-renewable energy, which could initially have a negative effect.
- **Urbanization (Negative sign expected)**: Rapid urbanization, without adequate planning and infrastructure, often leads to environmental degradation due to increased energy consumption, waste, and pollution. However, the sign might vary depending on the country's urban management policies.
- **Economic Freedom (Ambiguous sign)**: Economic freedom can have mixed effects. On the one hand, it promotes innovation and investment in cleaner technologies (positive effect), but on the other, it might encourage environmentally harmful economic activities if regulations are weak (negative effect).
- **Institutional Quality (Positive sign expected)**: Stronger institutions are expected to improve environmental governance and regulatory enforcement. Higher institutional quality can lead to more effective implementation of environmental policies, thus enhancing overall environmental performance.

In this paper, we will also estimate the effect of renewable and non-renewable energy consumption on each of the Environmental Performance components (Environmental Health, Ecosystem Vitality, Climate Policy, and Biodiversity) by replacing the EPI variable in Equations (2) and (3) with the corresponding component.

Next, we analyze the existence of a non-linear relationship between renewable energy consumption and Environmental Performance, conditional on country-level variables that may moderate the effect of renewable energy (REN) on the EPI. Highlighting the non-linearity of this relationship, a critical level of these moderating variables must be reached for their effect to become significant. In our study, we introduce moderating variables that reflect these factors, providing a clearer understanding of the indirect pathways through which renewable and non-renewable energy consumption affect EPI. The key moderating variables are economic freedom, institutional quality, and economic development (measured by GDP per capita).

Each of these variables—economic freedom, institutional quality, and economic development—plays a crucial role in moderating the relationship between renewable energy consumption and environmental performance. Economic freedom serves as an ambiguous moderator: it fosters a business-friendly environment that promotes investments in renewable energy through deregulation and incentives for innovation. In contexts where economic freedom leads to easier market entry and fewer regulatory barriers, renewable energy adoption can thrive, enhancing environmental outcomes. However, without robust environmental regulations, economic freedom might also allow environmentally harmful activities, such as over-exploitation of natural resources or pollution from non-renewable sources, making its moderating effect uncertain. In contrast, institutional quality acts as a positive moderator. High institutional quality ensures strong governance, effective legal frameworks, and transparency in policy implementation, which rigorously enforce environmental regulations. This support enables renewable energy initiatives to succeed, leading to positive environmental outcomes, such as reduced emissions and improved air quality. Finally, economic development also serves as a positive moderator by enhancing a country's capacity to invest in renewable energy infrastructure and technologies. Economically developed nations have better access to financial resources and technologies, supporting the transition to renewable energy and amplifying its environmental benefits. Additionally, higher levels of economic development lead to greater environmental awareness and the ability to fund large-scale sustainability projects, making renewable energy initiatives more impactful in reducing environmental degradation.

Equations (2) and (3) can be written as follows:

$$EPI_{it} = \beta_{i0} + \beta_1 RGDP_{it} + \beta_2\, URBA_{it} + \beta_3 ECOFRE_{it} + \beta_4 INSQUA_{it} + \beta_{5L} NREN_{it} I(Moderate \leq \gamma) + \beta_{5U} NREN_{it} I(Moderate > \gamma) + \epsilon_{it} \quad (4)$$

$$EPI_{it} = \alpha_{i0} + \alpha_1 RGDP_{it} + \alpha_2\, URBA_{it} + \alpha_3 ECOFRE_{it} + \alpha_4 INSQUA_{it} + \alpha_{5L} REN_{it} I(Moderate \le \gamma) + \alpha_{5U} REN_{it} I(Moderate > \gamma) + \epsilon_{it} \quad (5)$$

, where *Moderate* represents one of the moderating variables (Economic Freedom, Institutional Quality, or Economic Development). For each equation, we estimate three models, each examining the effect of a moderating variable on the relationship between renewable (or non-renewable) energy and the Environmental Performance Index (EPI).

By incorporating the EPI and its components as dependent variables and introducing key moderating factors, we capture the complex interactions shaping environmental performance in the GCC region. While the study by Razzaq et al. (2023) serves as a foundational reference, our extension of their empirical approach offers new insights into the relationship between energy consumption and environmental performance within the GCC context.

4) Results and economic discussion

a) Threshold effects of renewable and non-renewable energy consumption on the Environmental Performance Index

Table 1 presents the estimation results of the first equation with the three moderating variables (economic freedom, institutional quality, and economic development). The analysis in Table 1 reveals that the threshold effect for fossil fuel consumption in GCC countries is highly significant ($p < 0.001$) across all models. When the share of fossil fuel consumption exceeds the threshold (approximately 99.9%), the negative impact of non-renewable energy (NREN) on EPI becomes more pronounced, as indicated by the large negative coefficients. Below this threshold, the negative effects of fossil fuel consumption remain significant but are less severe. This finding suggests that policymakers in the GCC should prioritize reducing fossil fuel consumption, particularly keeping it below critical levels to mitigate environmental damage. On the other hand, urbanization has a statistically significant positive impact on EPI ($p < 0.05$), indicating that sustainable urban planning and energy-efficient infrastructure could improve environmental performance. Other variables, such as real GDP, institutional quality, and trade, do not show significant effects, suggesting that economic growth or institutional improvements alone may not lead to better environmental outcomes unless they are accompanied by targeted energy policies.

Table 1: Threshold Effects of Fossil Fuel Consumption on the Environmental Performance Index in GCC Countries

	Model (1)	**Model (2)**	**Model (3)**
Threshold level (p-value)	99.91***(0.001)	99.88***(0.0007)	99.84***(0.0007)
F-stat	110.83	110.52	116.5
Critical value at 5%	53.4	53.94	52.93
Real GDP	0.002(1.42)	0.002(1.45)	0.002(1.42)
Institutional quality	0.0009(0.45)		0.001(0.49)
Economic freedom	-0.02(-0.67)	-0.03(-0.7)	
Population	-0.1(-1.22)	-0.1(-1.23)	-0.1(-1.31)
Trade	0.012(0.73)	0.01(0.78)	0.01(0.62)
Urbanisation	0.18**(2.43)	0.18**(2.44)	0.19**(2.49)
Fossil consumption share (below threshold)	-8.16***(-3.9)	-8.34***(-3.98)	-2.24***(-5.74)
Fossil consumption share (above threshold)	-198.18***(-13.9)	-198.35***(-13.8)	-202.26***(-15.7)
Constant	915.26***(13.94)	916.08***(14.01)	933.96***(15.75)
Number of countries	6	6	6
Number of observations	126	126	126

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

Table 2 presents the estimation results for equation (2) with the three moderating variables. It reveals that the threshold level for renewable energy consumption is highly significant ($p < 0.001$), indicating that renewable energy has a positive effect on environmental performance in both regimes, but especially once it surpasses the threshold level (around 10.9%). In this higher regime (above the threshold), the coefficient for renewable energy is consistently positive and significant. Conversely, in the lower regime, when renewable energy consumption is below the threshold, its effect is limited, emphasizing the need for large-scale adoption to achieve meaningful environmental benefits. Population growth also shows a marginally significant positive effect on EPI (p between 0.05 and 0.10), suggesting that when paired with renewable energy, population expansion can contribute to improved environmental outcomes. However, trade openness has a significant negative impact on EPI ($p < 0.01$), indicating that increased trade, especially when dependent on fossil fuels, may harm the environment. The role of institutional quality is important, though not statistically significant in this table; improved institutions can support the enforcement of environmental policies and promote renewable energy projects. Finally, real GDP remains insignificant ($p > 0.05$), suggesting that economic growth alone cannot improve environmental outcomes unless it is paired with sustainable energy policies. This underscores the need for comprehensive reforms to promote renewable energy, manage trade policies, and strengthen institutions.

Table 2: Threshold Effects of Renewable Energy Consumption on the Environmental Performance Index in GCC Countries.

	Model (1)	**Model (2)**	**Model (3)**
Threshold level (p-value)	10.92***(0.000)	10.9***(0.000)	10.93***(0.000)
F-stat	84.98	82.99	86.59
Critical value at 5%	24.66	24.71	22.68
Real GDP	0.001**(2.08)	0.001**(2.02)	0.001**(2.09)
Institutional quality	-0.0009(-1.18)		-0.0009(-1.2)
Economic freedom	0.0007(0.05)	0.002(0.18)	
Population	0.05*(1.75)	0.058*(1.78)	0.05*(1.77)
Trade	-0.04***(-7.47)	-0.048***(-7.67)	-0.04***(-7.55)
Urbanisation	-0.09***(-3.12)	-0.09***(-3.13)	-0.09***(-3.15)
Renewable energy consumption share (below threshold)	0.2*(1.78)	0.2*(1.66)	0.2***(2.63)
Renewable energy consumption share (above threshold)	0.51***(52.7)	0.51***(52.59)	0.51***(53.82)
Constant	3.75***(40.74)	3.73***(41.05)	3.75***(45.68)
Number of countries	6	6	6
Number of observations	126	126	126

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

To enhance environmental performance, policymakers should focus on subsidizing renewable energy to accelerate its adoption beyond the critical threshold needed for significant benefits.

Reducing fossil fuel subsidies is essential to curb their consumption and promote cleaner energy sources. Additionally, promoting sustainable urbanization through energy-efficient technologies and smart infrastructure is key to leveraging urban growth in a positive way. Finally, trade policies should be designed to support the import and export of renewable energy technologies, facilitating a clean energy transition and reducing reliance on fossil fuels

b) Threshold effects of both renewable and non-renewable energy consumption on the components of the Environmental Performance Index

The results from Table 3 reveal a significant threshold effect of fossil fuel consumption on the components of the Environmental Performance Index in GCC countries. When fossil fuel consumption exceeds the threshold of 99.9%, the negative impacts on environmental performance become increasingly severe. For example, the coefficient for *environmental health* above the threshold is -197.38, indicating that excessive fossil fuel use greatly worsens public health conditions, likely through higher pollution levels. Below the threshold, the negative impact remains but is less drastic, with a coefficient of -7.36. Similarly, *air quality* experiences a substantial decline when consumption surpasses 99.9%, with a large negative coefficient of -212.49. Below this threshold, the impact is still negative but weaker (-2.47). The effect on *biodiversity* follows the same pattern: when consumption is high, biodiversity degradation becomes severe, with a coefficient of -230.09 above the threshold, as fossil fuel reliance leads to habitat destruction and ecosystem damage. *Climate change* is also heavily impacted, with fossil fuel consumption contributing to greater greenhouse gas emissions, evidenced by a coefficient of -174.7 above the threshold. Even below the threshold, the negative impact remains notable (-4.7).

Among the control variables, *real GDP* does not show a significant effect on any of the Environmental Performance components, as the coefficients are close to zero. This suggests that economic growth alone does not necessarily lead to environmental improvements in GCC countries. Similarly, *institutional quality* does not show a significant influence, with coefficients around 0.001 across all components, implying that institutions alone are insufficient to drive better environmental outcomes unless accompanied by robust policies. The effect of *economic freedom* is ambiguous, with generally negative but insignificant coefficients. This suggests that greater market openness does not automatically translate into better environmental performance, especially when fossil fuel consumption is high. *Population growth*, while insignificant for most components, has a notable negative impact on climate change, with a significant coefficient of -0.19, indicating that larger populations exacerbate environmental degradation, particularly through higher emissions and resource use. *Trade openness* shows a marginally significant, weak negative effect on air quality and biodiversity, reinforcing the idea that while trade is essential for economic growth, it can also increase environmental harm by fostering industries reliant on fossil fuels. Lastly, *urbanization* demonstrates a positive and significant effect on environmental health, air quality, and climate change, with coefficients ranging from 0.17 to 0.25. This suggests that well-managed urban development can enhance environmental performance, likely due to improved infrastructure, energy efficiency, and effective resource management.

Table 3: Threshold Effects of Fossil Fuel Consumption on the Components of Environmental Performance Index (EPI) in GCC Countries.

	Endogenous variable			
	Environment Health	**Air quality**	**Biodiversity**	**Climate Change**
Threshold level (p-value)	99.92***(0.001)	99.9***(0.0003)	99.87***(0.0003)	99.91***(0.00)
F-stat	123.68	123.7	123.37	122.22
Critical value at 5%	47.75	46.57	45.43	46.43
Real GDP	0.0008(0.5)	0.001(0.53)	0.001(0.56)	0.0007(0.44)
Institutional quality	0.001(0.63)	0.001(0.61)	0.001(0.58)	0.001(0.65)
Economic freedom	-0.069(-1.6)	-0.07*(-1.64)	-0.08*(-1.66)	-0.06(-1.57)
Population	-0.098(-1.24)	-0.089(-1.02)	-0.07(-0.77)	-0.19***(-2.6)
Trade	-0.02*(-1.64)	-0.029*(-1.68)	-0.03*(-1.74)	-0.01(-1.31)
Urbanisation	0.17**(2.4)	0.17**(2.16)	0.17*(1.9)	0.25***(3.69)
Fossil consumption share (below threshold)	-7.36***(-4.4)	-2.47***(-4.05)	-1.07***(-3.59)	-4.7***(-3.6)
Fossil consumption share (above threshold)	**-197.38***(-14.4)**	**-212.49***(-14.1)**	**-230.09***(-13.6)**	**-174.7***(-13.6)**
Constant	912.03***(14.46)	981.43***(14.08)	1062.27***(13.62)	808.05***(13.65)
Number of countries	6	6	6	6
Number of observations	126	126	126	126

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

Table 4 highlights the significant threshold effects of renewable energy consumption on the various components of the Environmental Performance Index in GCC countries. When renewable energy consumption exceeds the 10.9% threshold, its positive impact on environmental performance becomes highly significant across all components ($p < 0.001$).

For *environmental health*, the coefficient above the threshold is 0.5, suggesting that renewable energy adoption plays a crucial role in improving public health outcomes by reducing pollution and mitigating the negative impacts of fossil fuel consumption. Below the threshold, the impact remains positive but less substantial, with a coefficient of 0.2. This indicates that while renewable energy contributes to better environmental health, its full potential is only realized when the threshold is exceeded. Regarding *air quality*, the coefficient is 0.54 above the threshold, indicating a significant improvement in air quality when renewable energy consumption surpasses the 10.9% mark. Below the threshold, the effect is positive but weaker, with a coefficient of 0.16. For *biodiversity*, the impact is similarly strong above the threshold, with a coefficient of 0.6, showing that renewable energy helps preserve ecosystems by reducing pressures such as pollution and habitat destruction. Below the threshold, the positive effect remains but is smaller, with a coefficient of 0.2. *Climate change* also benefits significantly from renewable energy consumption, with a coefficient of 0.45 above the threshold, demonstrating that increased renewable energy use significantly helps mitigate climate change by reducing greenhouse gas emissions. Below the threshold, the effect is less pronounced but still positive, with a coefficient of 0.17.

The control variables reveal several key impacts, supported by statistical significance. *Real GDP* shows a significant positive effect on all EPI components, with coefficients ranging from 0.001 to 0.002, suggesting that economic growth, combined with renewable energy adoption, positively influences environmental outcomes by enabling investments in sustainable infrastructure. *Institutional quality* has no significant effect, with coefficients around -0.001, implying that institutional frameworks alone are insufficient to improve environmental performance without specific policies. Similarly, *economic freedom* shows no significant influence, as reflected by its small, insignificant coefficients. *Population growth* has a mixed effect; while it does not significantly affect most components, it negatively impacts climate change with a coefficient of -0.1, contributing to worsening climate indicators. *Trade openness* shows a significant negative impact on all Environmental Performance components ($p < 0.001$), with a coefficient of -0.05 for air quality, highlighting the environmental harm caused by current trade patterns focused on fossil fuel exports. *Urbanization* has a negative impact on air quality and biodiversity, with significant coefficients of -0.06 and -0.089, respectively, but positively affects climate change with a coefficient of 0.05. This suggests that urban development, if managed alongside renewable energy policies, could help mitigate climate-related impacts.

Table 4: Threshold Effects of renewable energy Consumption on the Components of Environmental Performance Index in GCC Countries

	Endogenous variable			
	Environment Health	**Air quality**	**Biodiversity**	**Climate Change**
Threshold level (p-value)	10.92***(0.00)	10.9***(0.00)	10.87***(0.00)	10.9***(0.00)
F-stat	137.08	146.25	154.17	138.81
Critical value at 5%	22.87	23.99	20.46	24.69
Real GDP	0.001**(2.59)	0.002***(2.63)	0.002***(2.65)	0.001**(2.26)
Institutional quality	-0.0009(-1.14)	-0.001(-1.23)	-0.001(-1.33)	-0.0008(-1.08)
Economic freedom	0.006(0.45)	0.01(0.63)	0.015(0.83)	0.01(0.93)
Population	0.004(0.15)	0.02(0.57)	0.04(1.04)	-0.1***(-3.33)
Trade	-0.05***(-8.2)	-0.05***(-8.43)	-0.06***(-8.6)	-0.04***(-7.2)
Urbanisation	-0.04(-1.37)	-0.06*(-1.81)	-0.089**(-2.3)	0.05**(1.91)
Renewable energy consumption share (below threshold)	0.2***(2.68)	0.16***(2.85)	0.2**(2.47)	0.17***(4.42)
Renewable energy consumption share (above threshold)	0.5***(51.15)	0.54***(51.27)	0.6***(50.82)	0.45***(48.77)
Constant	3.73***(40.33)	3.6***(35.77)	3.46***(30.92)	4.02***(45.64)
Number of countries	6	6	6	6
Number of observations	126	126	126	126

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

In conclusion, Tables 3 and 4 underscore the significant threshold effects of both fossil fuel and renewable energy consumption on environmental performance in GCC countries. Table 3 reveals that fossil fuel consumption, especially when it exceeds the critical threshold, severely deteriorates air quality, biodiversity, environmental health, and climate change. This finding highlights the destructive environmental impact of reliance on non-renewable energy sources, as the negative effects become far more pronounced above the threshold levels. Conversely, Table 4 demonstrates the pivotal role of renewable energy consumption in enhancing environmental performance across all components. Below the threshold of 10.9%, renewable energy consumption already shows positive effects on environmental health, air quality, biodiversity, and climate change, with coefficients ranging from 0.16 to 0.2. However, once renewable energy consumption surpasses this threshold, the positive impacts become significantly stronger, with coefficients as high as 0.6 for biodiversity and 0.54 for air quality. These results underscore the critical importance of achieving sufficient levels of renewable energy adoption in the GCC region. While moderate renewable energy consumption brings environmental benefits, it is only at higher adoption levels that the full potential of renewable energy in improving environmental performance becomes evident. However, factors like economic freedom, real GDP, and trade openness show mixed or insignificant effects. Economic freedom, for instance, does not significantly influence environmental outcomes unless combined with targeted environmental policies, while trade openness generally has a negative effect due to its association with fossil fuel exports. Real GDP, while contributing positively to environmental outcomes, shows only marginal effects, suggesting that economic growth alone is insufficient to drive substantial environmental improvements without alignment with sustainable energy strategies.

To enhance the analysis of energy consumption's impact on environmental performance, it is essential to incorporate additional *moderating variables*, such as energy efficiency, technological innovation, and environmental regulations. These variables could provide a deeper understanding of how energy consumption affects environmental outcomes, enabling policymakers to craft more effective and nuanced sustainability strategies. For instance, improving energy efficiency could help reduce reliance on fossil fuels, while technological advancements and stronger regulations could foster the growth of renewable energy sources. By focusing on these areas, policymakers in GCC countries can create a comprehensive framework that maximizes the environmental benefits of renewable energy while minimizing the detrimental impacts of fossil fuels.

c) Threshold effects of both renewable and non-renewable energy consumption, through channel variables, on the Environmental Performance

In this section, the effects of non-renewable energy consumption on the Environmental Performance Index are analyzed, accounting for the moderating roles of variables such as the urbanization rate, industrialization, R&D, and environmental regulations. The results, presented in Table 5a, reveal clear threshold effects for some moderating variables. The *urbanization rate* (threshold = 72.91, p = 0.92) does not exhibit a statistically significant threshold effect, suggesting that urbanization alone, at least in the context of GCC countries, may not sufficiently moderate the relationship between non-renewable energy consumption and environmental performance. Similarly, *industrialization* (threshold = 26.29, p = 0.47) does not reach statistical significance, implying that the industrialization process in the region may be ineffective in curbing the negative environmental impacts of non-renewable energy use. However, the threshold effects of *R&D* (threshold = 0.7, p = 0.04) and *environmental regulations* (threshold = 70.32, p = 0.06) are highly significant. When R&D spending surpasses the threshold of 0.7%, the negative impact of non-renewable energy on the EPI becomes more pronounced, underscoring the importance of technological innovation in environmental sustainability. Greater investments in research and development can help mitigate the harmful effects of fossil fuel consumption on environmental outcomes. Similarly, stringent environmental regulations that exceed the threshold of 70.32 have a strong positive moderating effect, reflecting the critical role that well-enforced policies play in enhancing environmental performance in the GCC. The coefficients for *fossil fuel consumption* are significantly negative both below and above the threshold, with even more drastic effects above the threshold. For example, fossil fuel consumption shares below the threshold result in a coefficient of -3.62 ($p < 0.001$), while above the threshold, the coefficient worsens to -213.6 ($p < 0.001$). This indicates that higher levels of non-renewable energy consumption have devastating impacts on the environment, especially when policies or technological measures are not in place to control their effects.

Regarding the control variables, real GDP shows no statistically significant effect, with coefficients ranging from 0.002 to 0.003 across different models, suggesting that economic growth alone does not directly improve environmental outcomes in this context. Institutional quality also shows no significant impact, as reflected by coefficients near zero. However, economic freedom has a positive and significant effect on the EPI, particularly when combined with environmental regulations (coefficient of 0.11, $p < 0.05$), indicating that market openness, when aligned with strict environmental policies, can foster better environmental performance. Conversely, *trade openness* consistently exerts a negative effect, with coefficients as low as -0.07 ($p < 0.001$), underscoring the adverse environmental impacts of trade patterns heavily reliant on fossil fuel exports. *Urbanization* has a mixed effect, showing no significant impact in some models but a positive and significant effect when interacting with environmental regulations (coefficient of 0.22, $p < 0.05$). This suggests that urban development, when guided by proper regulations, can contribute positively to environmental performance.

Table 5a: Effect of Non-Renewable Energy on Environmental Performance Index: Moderating Role of Urbanization, Industrialization, R&D, and Environmental Regulations

	Threshold variable			
	Urbanisation rate	**Industrialization**	**R&D**	**Environmental regulations**
Threshold level (p-value)	72.91(0.92)	26.29(0.47)	0.7**(0.04)	70.32**(0.06)
F-stat	0.95	2.16	21.13	18.42
Critical value at 5%	6.4	5.3	20.61	19.46
Real GDP	0.002(0.97)	0.002(0.84)	0.003(1.38)	0.002(1.09)
Institutional quality	-0.0005(-0.18)	-0.001(-0.37)	-0.0003(-0.14)	0.0007(0.25)
Economic freedom	0.1*(1.8)	0.1*(1.71)	0.08(1.47)	0.11**(1.96)
Population	-0.03(-0.29)	-0.04(-0.39)	0.1(0.96)	-0.08(-0.76)
Trade	-0.04*(-1.87)	-0.04**(-2.03)	-0.07***(-3.41)	-0.03(-1.52)
Urbanisation	0.16(1.49)	0.17*(1.64)	0.02(0.26)	0.22**(2.03)
Fossil consumption share (below threshold)	-2.07***(-9.9)	-9.06***(-9.83)	-3.62***(-11.32)	-7.5***(-10.1)
Fossil consumption share (above threshold)	-202.1***(-9.9)	-199.05***(-9.8)	-213.6***(-11.3)	-197.5***(-10.1)
Constant	932.257***(9.91)	918.4***(9.84)	985.6***(11.1)	911.35***(10.1)
Number of countries	6	6	6	6
Number of observations	126	126	126	126

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

In summary, Table 5a highlights the detrimental effects of non-renewable energy consumption on environmental performance, especially in the absence of strong moderating factors like R&D and environmental regulations. The results suggest that GCC countries should focus on increasing investments in technological innovation and implementing stricter environmental policies to mitigate the harmful impacts of fossil fuel consumption. Additionally, while economic freedom can enhance environmental performance under the right conditions, trade openness remains a major challenge for sustainability in the region.

In Table 5b, the impact of non-renewable energy consumption on the Environmental Performance Index is further examined, considering the moderating role of variables such as fossil fuel subsidies, renewable energy subsidies, and energy efficiency. The analysis reveals significant threshold effects for all moderating variables, indicating their crucial role in shaping the relationship between non-renewable energy consumption and environmental outcomes in GCC countries. The threshold effect of *fossil fuel subsidies* (threshold = 5.2, p = 0.02) is statistically significant. When fossil fuel subsidies exceed this level, the negative impact of non-renewable energy consumption on EPI worsens. This result underscores the detrimental role that continued fossil fuel subsidies play in exacerbating environmental degradation, suggesting that reducing such subsidies is critical to improving environmental performance. Similarly, *renewable energy subsidies* show a significant threshold effect (threshold = 0.17, p = 0.0003). When renewable energy subsidies surpass this threshold, they significantly reduce the negative effects of non-renewable energy consumption on the environment. This implies that increasing support for renewable energy can help counterbalance the harmful effects of fossil fuel use, reinforcing the importance of subsidies in promoting clean energy adoption. *Energy efficiency* also plays a significant moderating role, with a threshold of 0.47 (p = 0.003). When energy efficiency improvements exceed this level, the negative impact of non-renewable energy consumption on the EPI decreases substantially. This highlights the importance of energy efficiency measures in mitigating the environmental harms associated with fossil fuel consumption. By enhancing energy efficiency, GCC countries can reduce their overall energy demand and lessen the environmental burden caused by non-renewable energy sources.

As for the control variables, *real GDP* shows no significant effect across the models, with coefficients close to zero (ranging from 0.001 to 0.001), indicating that economic growth alone does not significantly influence environmental performance in the context of non-renewable energy consumption. Similarly, *institutional quality* has no significant effect, with coefficients near zero, suggesting that institutional frameworks alone are insufficient to moderate the impact of non-renewable energy consumption without specific policies or mechanisms. *Economic freedom* shows a significant positive effect only when combined with energy efficiency, with a coefficient of 0.15

($p < 0.001$). This suggests that economic openness can foster better environmental outcomes, but only when paired with improvements in energy efficiency. Conversely, *trade openness* consistently has a negative impact, particularly under the influence of fossil fuel subsidies, with a significant coefficient of -0.06 ($p < 0.001$). This reinforces the finding that trade patterns centered on fossil fuel exports are harmful to environmental performance, emphasizing the need for trade reforms that prioritize cleaner energy sources. *Urbanization* has a positive and significant effect in the presence of renewable energy subsidies (coefficient of 0.21, $p < 0.05$). This indicates that urban development, when supported by renewable energy initiatives, can contribute positively to environmental performance. In contrast, urbanization shows no significant effect in the other models. The coefficients for *fossil fuel consumption* are highly negative both below and above the threshold for all models. Below the threshold, the coefficients range from -2.3 to -8.79 ($p < 0.001$), while above the threshold, the negative effects worsen, with coefficients as large as -208.7 ($p < 0.001$). This underscores the persistent and severe environmental damage caused by non-renewable energy consumption, particularly in contexts where moderating variables like subsidies and energy efficiency are not optimized.

Table 5b: Effect of Non-Renewable Energy on Environmental Performance Index: Moderating Role of Fossil Fuel Subsidies, Renewable Energy Subsidies, and Energy Efficiency

	Threshold variable		
	Fossil Fuel Subsidies	**Renewable Energy Subsidies**	**Energy Efficiency**
Threshold level (p-value)	5.2**(0.02)	0.17***(0.0003)	0.47***(0.003)
F-stat	66.63	64	61.53
Critical value at 5%	55.01	25.73	33.9
Real GDP	0.001(0.63)	0.001(0.74)	0.001(0.5)
Institutional quality	-0.0001(-0.08)	0.0004(0.18)	0.0004(0.2)
Economic freedom	0.06(1.26)	0.01(0.23)	0.15***(3.18)
Population	0.04(0.45)	-0.09(-1.01)	0.02(0.26)
Trade	-0.06***(-3.12)	-0.01(-0.77)	-0.002(-0.11)
Urbanisation	0.06(0.72)	0.21**(2.47)	0.1(1.19)
Fossil consumption share (below threshold)	-8.79***(-12.57)	-2.3***(-9.68)	-8.009***(-10.5)
Fossil consumption share (above threshold)	-208.7***(-12.5)	-162.28***(-9.68)	-178.02(-10.59)
Constant	963.8***(12.3)	749.53***(9.7)	821.12***(10.54)
Number of countries	6	6	6
Number of observations	126	126	126

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

In summary, Table 5b emphasizes the importance of reducing fossil fuel subsidies and increasing support for renewable energy and energy efficiency to mitigate the negative environmental impacts of non-renewable energy consumption. While economic freedom and urbanization can contribute positively under certain conditions, the consistent negative impact of trade openness suggests that reforms in trade policies are essential for improving environmental performance in the GCC. By focusing on these moderating factors, policymakers can create more effective strategies to limit the environmental harm caused by fossil fuel dependence. Tables 5a and 5b highlight the significant role of moderating variables in influencing the impact of non-renewable energy consumption on environmental performance in GCC countries. R&D, environmental regulations, renewable energy subsidies, and energy efficiency show strong positive effects, helping to mitigate the environmental harm caused by non-renewable energy. In contrast, fossil fuel subsidies exacerbate the negative impact on environmental performance. Other variables, such as urbanization, industrialization, and trade openness, show mixed or insignificant effects, with trade openness consistently exhibiting a negative influence. Economic freedom positively affects environmental outcomes when combined with energy efficiency. Overall, reducing fossil fuel subsidies, increasing support for renewable energy, and enhancing energy efficiency are key strategies for improving environmental performance in the GCC region.

The results underscore the importance of policy reforms in areas like subsidies, energy efficiency, and regulatory frameworks to improve environmental performance in the GCC. By focusing on these moderating factors, GCC countries can better manage the negative effects of non-renewable energy consumption and promote sustainability.

Table 6a explores how the impact of renewable energy consumption on the Environmental Performance changes based on different moderating variables, such as the urbanization rate, industrialization, R&D, and environmental regulations. The focus here is not on the direct effects of these variables on EPI but rather on how they modify the relationship between renewable energy (REN) consumption and environmental performance. The threshold effect of the *urbanization rate* is statistically significant (threshold = 91.45, $p = 0.02$). Below this threshold, renewable energy consumption has a relatively modest positive impact on environmental performance (coefficient = 0.09, $p < 0.10$). However, once urbanization exceeds the threshold, the positive impact of renewable energy becomes much stronger, with a coefficient of 0.49 ($p < 0.001$). This suggests that higher levels of urbanization, when well-managed, amplify the benefits of renewable energy adoption in the GCC region. For the other variables—*industrialization, R&D*, and *environmental regulations*—the threshold effects are not statistically significant. This indicates that these factors do not significantly alter the relationship between renewable energy consumption and EPI. Nevertheless, renewable energy consumption still has a consistently positive impact on environmental performance across all models, with coefficients ranging from 0.4 to 0.49 ($p < 0.001$) above the thresholds, underscoring its strong role in enhancing environmental outcomes.

Among the control variables, *real GDP* shows a positive and significant effect on EPI, while *trade openness* has a consistently negative impact ($p < 0.001$), reflecting the adverse environmental consequences of trade in fossil fuel-related goods. *Population growth* positively affects environmental performance, whereas *urbanization* shows a negative impact in all models (coefficients ranging from -0.14 to -0.17, $p < 0.001$).

In conclusion, Table 6a indicates that renewable energy consumption positively impacts environmental performance in the GCC countries, particularly when urbanization is well-managed and surpasses the critical threshold. Other moderating variables, such as industrialization, R&D, and environmental regulations, do not significantly influence the strength of this relationship.

Table 6b examines how the impact of renewable energy consumption on the Environmental Performance Index changes depending on moderating variables such as fossil fuel subsidies, renewable energy subsidies, and energy efficiency. The threshold effect of *fossil fuel subsidies* is highly significant (threshold = 1.69, $p = 0.001$). Below this threshold, renewable energy consumption shows a weaker effect on environmental performance; however, once fossil fuel subsidies are reduced below this threshold, the positive impact of renewable energy becomes much stronger, reinforcing the idea that reducing fossil fuel subsidies enhances the environmental benefits of renewable energy. *Renewable energy subsidies* show a strong threshold effect (threshold = 0.04, $p < 0.001$). Above this threshold, renewable energy consumption significantly boosts environmental performance, with a coefficient of 0.52 ($p < 0.001$), indicating that financial support for renewable energy is crucial to maximizing its positive impact on the environment. In contrast, *energy efficiency* does not exhibit a statistically significant threshold effect (threshold = 0.46, $p = 0.25$), suggesting that its moderating influence on the relationship between renewable energy consumption and EPI is weaker in this context. However, renewable energy consumption still has a strong positive impact on environmental performance, with a coefficient of 0.46 ($p < 0.001$) above the threshold, highlighting the overall importance of renewable energy adoption.

Regarding the control variables, *real GDP* shows a positive and significant effect on EPI across all models, indicating that economic growth supports environmental performance. *Population growth* has a consistently positive impact, while *trade openness* shows a negative impact ($p < 0.001$), suggesting that trade patterns involving fossil fuel exports harm environmental outcomes. *Urbanization* generally shows a negative effect, particularly in the presence of renewable energy subsidies.

In summary, Table 6b reveals that reducing fossil fuel subsidies and increasing renewable energy subsidies are key strategies for maximizing the positive effects of renewable energy on environmental performance in the GCC. While energy efficiency plays a role, its moderating influence is less significant compared to the other factors. Policymakers should focus on subsidy reforms to enhance the environmental benefits of renewable energy adoption.

Table 6a: Effect of Renewable Energy on Environmental Performance Index: Moderating Role of Urbanization, Industrialization, R&D, and Environmental Regulations

	Threshold variable			
	Urbanisation rate	**Industrialization**	**R&D**	**Environmental regulations**
Threshold level (p-value)	91.45**(0.02)	38.64(0.45)	0.69(0.66)	77.94(0.55)
F-stat	3.74	2.58	3.42	5.5
Critical value at 5%	3.16	5.25	12.06	12.8
Real GDP	0.002**(2.25)	0.001*(1.94)	0.002**(2.34)	0.001*(1.84)
Institutional quality	-0.0007(-0.7)	-0.0003(-0.29)	-0.0005(-0.48)	-0.005(-0.51)
Economic freedom	0.016(0.84)	0.02(1.11)	0.01(0.57)	0.02(1.05)
Population	0.13***(3.06)	0.13***(3.16)	0.15***(3.54)	0.12**(2.86)
Trade	-0.05***(-6.15)	-0.05***(-6.31)	-0.05***(-6.52)	-0.05***(-5.9)
Urbanisation	-0.15***(-3.8)	-0.16***(-3.88)	-0.17***(-4.2)	-0.14***(-3.48)
Renewable energy consumption share (below threshold)	0.09*(1.68)	0.49***(39.02)	0.49***(38.29)	0.48***(38.17)
Renewable energy consumption share (above threshold)	0.49***(38.98)	0.49***(39.09)	0.4***(38.7)	0.48***(37.34)
Constant	3.53***(29.74)	3.51***(29.85)	3.51***(29.8)	3.47***(29.64)
Number of countries	6	6	6	6
Number of observations	126	126	126	126

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

Table 6b: Effect of Renewable Energy on Environmental Performance Index: Moderating Role of Fossil Fuel Subsidies, Renewable Energy Subsidies, and Energy Efficiency

	Threshold variable		
	Fossil Fuel Subsidies	**Renewable Energy Subsidies**	**Energy Efficiency**
Threshold level (p-value)	1.69***(0.001)	0.04***(0.00)	0.46(0.25)
F-stat	49.47	92.93	24.95
Critical value at 5%	28.9	34.10	40.29
Real GDP	0.001**(2.32)	0.001**(2.03)	0.001*(1.67)
Institutional Quality	-0.0008(-0.95)	-0.0007(-0.99)	-0.0006(-0.68)
Freedom economic	0.01(0.89)	0.009(0.69)	0.013(0.74)
Population	0.02(0.67)	0.11***(3.64)	0.12***(3.29)
Trade	-0.049***(-6.92)	-0.04***(-7.8)	-0.034***(-4.01)
Urbanization	-0.06(-1.59)	-0.14***(-5.01)	-0.14***(-3.75)
Renewable energy consumption share (below threshold)	0.02(1.29)	0.01(1.59)	0.47***(40.57)
Renewable energy consumption share (above threshold)	0.5***(46.3)	0.52***(54.43)	0.46***(37.22)
constant	3.62***(35.68)	3.63***(42.4)	3.35***(30.05)
Nombre of countries	6	6	6
Nombre of observations	126	126	126

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

5) Policy discussion: country-specific insights and implications

The Gulf Cooperation Council (GCC) countries exhibit significant differences in economic size, energy resources, and environmental policies, leading to varying approaches to energy transition. In this context, Saudi Arabia, as the region's largest economy, remains highly dependent on oil revenues. However, under Vision 2030, it is actively working to diversify its economy, aiming to generate 50% of its energy mix from renewable sources by 2030. Despite this target, renewables accounted for only 1.36% of the country's electricity production in 2023. In contrast, the United Arab Emirates (UAE) has positioned itself as a regional leader in renewable energy, making substantial investments in large-scale projects such as the Mohammed bin Rashid Solar Park, as well as ambitious initiatives like the 2 GW Al Dhafra Solar Plant.

Meanwhile, Kuwait, despite its vast oil reserves, has lagged behind in renewable energy adoption, relying almost entirely on fossil fuels. However, it plans to develop 17 GW of renewable energy capacity by 2050 as part of its long-term energy strategy. Bahrain, facing the dual challenge of limited natural resources and the need to balance economic growth with sustainability, has joined a $100 billion regional investment in renewables by 2030, aiming to cut carbon emissions by 20%.

As part of the broader effort to diversify energy sources, Qatar, one of the world's largest liquefied natural gas exporters, has also begun expanding its renewable energy investments. A notable example is the Al-Kharsaah Solar Power Plant, which marks an important step toward reducing its carbon footprint, although fossil fuels continue to dominate its energy mix. Oman, on the other hand, faces fiscal pressures due to oil price volatility and has set a goal to generate 30% of its electricity from renewable sources by 2030, recognizing the urgent need for energy diversification amid growing financial constraints.

At the regional level, a more coordinated approach is essential to address common challenges. Electricity demand across the GCC is expected to increase by approximately 100 GW over the next decade, necessitating substantial investment in energy infrastructure. In this regard, energy investments in the Middle East are projected to reach $175 billion in 2024, with 15% allocated to clean energy. Simultaneously, reforming fossil fuel subsidies remains a critical step for all GCC nations to enhance energy efficiency and encourage investment in renewables.

Moreover, strengthening green finance through the issuance of green bonds and sustainability-linked financial instruments could accelerate the energy transition. Regional cooperation in developing a unified GCC renewable energy framework would further enhance energy security and promote cross-border electricity trade. Additionally, the introduction of carbon pricing mechanisms or taxation policies could provide economic incentives for industries to reduce emissions, fostering a more balanced approach between economic growth and environmental preservation. Finally, economic diversification through increased investment in solar, wind, and hydrogen energy remains fundamental to ensuring the long-term sustainability of GCC economies beyond oil and gas dependency.

6) Conclusion and policy implications

This study provides a comprehensive assessment of the non-linear dynamics between energy consumption and environmental performance in GCC countries, emphasizing the crucial role of moderating variables—an aspect often overlooked in previous research. While existing studies have primarily examined the direct relationship between renewable and non-renewable energy and environmental outcomes, they fail to account for the conditional effects of institutional quality, energy subsidies, and energy efficiency, which shape the extent to which energy transitions improve environmental performance. This study fills this gap by employing a dynamic threshold regression approach, allowing for a deeper understanding of how energy consumption influences environmental outcomes only after surpassing specific critical levels.

The findings reveal that non-renewable energy consumption deteriorates environmental performance beyond thresholds of 85%-99.9%, particularly impacting air quality, biodiversity, and climate stability. In contrast, renewable energy consumption improves environmental performance only when it exceeds 5.5%-10.9%, demonstrating that incremental increases in renewables are insufficient to drive meaningful environmental improvements. The originality of this study lies in its identification of key moderating factors that alter these relationships. Unlike previous research that assumes a uniform energy-environment nexus, this study shows that institutional quality enhances the environmental benefits of renewables, while energy efficiency strengthens their effectiveness. Moreover, it confirms that fossil fuel subsidies amplify environmental degradation, underscoring the necessity of policy interventions aimed at gradually phasing them out.

By moving beyond traditional linear models and incorporating threshold effects with policy-relevant moderating variables, this study provides a more detailed and region-specific perspective on energy transitions in GCC economies. These findings offer crucial policy insights**,** as expanding renewable energy beyond the identified thresholds is essential to achieving significant improvements in environmental performance. Additionally, reforming fossil fuel subsidies is key to mitigating the adverse effects of non-renewable energy consumption while redirecting financial resources toward clean energy investments**.**

However, energy policies across GCC countries vary depending on their resources and economic structures. The United Arab Emirates (UAE) has made significant progress in expanding its renewable energy investments through major projects such as the Mohammed bin Rashid Solar Park, while Saudi Arabia remains heavily reliant on fossil fuels despite setting ambitious Vision 2030 targets to increase the share of renewables to 50% by 2030. Kuwait, meanwhile, has lagged in implementing its renewable energy roadmap, necessitating stronger policy commitments, particularly in subsidy reforms and energy efficiency improvements. Similarly, Bahrain faces challenges in balancing economic growth with sustainability, which has led it to participate in major regional investments in renewable energy**.** Qatar, one of the world's largest liquefied natural gas exporters, has also begun expanding its solar energy investments through projects such as the Al-Kharsaah Solar Power Plant, although fossil fuels still dominate its energy mix. Oman, facing financial pressures due to oil price volatility, has set a target to generate 30% of its electricity from renewable sources by 2030, requiring incentive policies and private sector partnerships to achieve this transition.

A more coordinated regional approach that includes subsidy reforms, enhanced governance in the energy sector, and investment in clean energy infrastructure could accelerate the transition toward sustainability in the region. Additionally, strengthening regulatory frameworks, increasing investments in research and development (R&D), and improving energy efficiency will be essential to maximizing the environmental and economic benefits of renewable energy adoption**.**

Ultimately, achieving sustainable environmental performance in GCC countries requires not only expanding renewable energy but also implementing strong policy mechanisms that align economic growth with environmental sustainability. Future research should further explore the long-term economic trade-offs of transitioning to renewables and the role of technological advancements and regulatory reforms in shaping the region's energy future.

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Appendix: Variable Information

Variables	Description	Definition	Source	Unit of Measure
Environmental Performance Index (EPI)	Measures environmental performance across countries.	Composite index of environmental health, ecosystem vitality, climate policy, and biodiversity	Yale Center for Environmental Law & Policy (2022), https://epi.yale.edu/	Index score
Renewable Energy Consumption (REN)	Total renewable energy consumed.	Sum of energy consumption from renewable sources like solar, wind, and hydroelectric.	International Energy Agency (IEA) (2022), https://www.iea.org/	Mtoe (million tons of oil equivalent)
Non-Renewable Energy Consumption (NREN)	Total non-renewable energy consumed.	Sum of energy consumption from fossil fuels such as coal, oil, and natural gas.	International Energy Agency (IEA) (2022), https://www.iea.org/	Mtoe
Real GDP	Economic output adjusted for inflation.	GDP adjusted to account for changes in price level over time.	World Bank (2022), https://data.worldbank.org/	USD (constant prices)
Institutional Quality	Quality of governance and institutions.	Measure of governance effectiveness, regulatory quality, and rule of law.	Worldwide Governance Indicators (2022), https://info.worldbank.org/governance/wgi/	Index score
Economic Freedom Index	Measures economic freedom within a country.	Composite index reflecting rule of law, government size, regulatory efficiency, and open markets.	Heritage Foundation (2022), https://www.heritage.org/index/	Index score
Trade Openness	Extent of a country's openness to trade.	Calculated as the sum of exports and imports as a percentage of GDP.	World Bank (2022), https://data.worldbank.org/	Percentage (%
Urbanization Rate	Proportion of population living in urban areas.	Percentage of the total population residing in urban areas.	World Bank (2023), https://data.worldbank.org/	Percentage (%)
Energy Subsidies (Fossil)	Government support for fossil fuel energy.	Financial assistance or tax incentives for fossil fuel consumption.	International Energy Agency (IEA) (2023), https://www.iea.org/	USD
Energy Subsidies (Renewable)	Government support for renewable energy.	Financial incentives to encourage renewable energy use.	International Energy Agency (IEA) (2023), https://www.iea.org/	USD
Energy Efficiency	Efficiency of energy use relative to economic output.	Energy use per unit of GDP, also known as energy intensity.	International Energy Agency (IEA) (2023), https://www.iea.org/	MJ/USD