INTERNATIONAL JOURNAL OF ECONOMICS AND FINANCE STUDIES
Vol: 18 **No:** 02 **Year:** 2026 **ISSN:** 1309-8055 (Online) (**pp.** 99-127) **Doi:** 10.34109/ijefs.2026180205
Received: 10.02.2026 | **Accepted:** 24.05.2026 | **Published Online:** 16.06.2026

-RESEARCH ARTICLE-

HOW GEOPOLITICAL RISK SHAPES THE IMPACT OF ECONOMIC POLICY UNCERTAINTY ON CARBON INTENSITY IN SAUDI ARABIA: ASYMMETRICAL ANALYSIS

Mohammed Sultan Alsubaie

Department of Finance, College of Business Administration, Prince
Sattam Bin Abdulaziz University, 173, Alkharj, 11942, Saudi Arabia
ORCID: https://orcid.org/0009-0002-5121-6365
Email: ms.alsubaie@psau.edu.sa

—Abstract—

Economic Policy Uncertainty (EPU) represents a significant impediment to the advancement of renewable energy transitions within national economies. Against this backdrop, the present study examines the asymmetric influence of EPU on Carbon Intensity (CI) in Saudi Arabia over the period 1970–2024, while additionally assessing the moderating role of Geopolitical Risk (GPR). To achieve this objective, the nonlinear Autoregressive Distributed Lag (NARDL) framework combined with bounds testing is employed. Furthermore, the analysis incorporates both Ng–Perron unit root procedures and structural break tests to ensure the robustness of the empirical findings. The results confirm the validity of the Environmental Kuznets Curve (EKC) hypothesis in the long run, although corresponding evidence for the short run remains inconclusive. Under the long-run symmetric specification, both EPU and GPR exert positive influences on CI, indicating that heightened uncertainty and geopolitical tensions contribute to environmental deterioration. Additionally, the interaction between EPU and GPR magnifies these adverse effects. The long-run asymmetric estimates reveal that positive shocks in GPR elevate CI, whereas negative shocks contribute to its reduction. Similarly, increases in EPU lead to higher CI levels; however, reductions in EPU do not generate a proportionate decline in CI. When the interaction effects are considered, rising EPU continues to intensify CI, while declining EPU becomes effective in lowering CI in the presence of changing GPR conditions. These findings suggest that escalating GPR reinforces the detrimental environmental consequences associated with increasing EPU, whereas declining GPR facilitates the mitigation of environmental pressures arising

Citation (APA): Alsubaie, M. S. (2026). How Geopolitical Risk Shapes the Impact of Economic Policy Uncertainty on Carbon Intensity in Saudi Arabia: Asymmetrical Analysis. *International Journal of Economics and Finance Studies*, 18(02), 99-127. doi: 10.34109/ijefs.2026180205

from reductions in EPU. The evidence highlights the pronounced sensitivity of the Saudi economy to both domestic policy-related uncertainty and broader regional geopolitical disturbances. Consequently, efforts aimed at simultaneously lowering EPU and GPR are likely to contribute to reductions in CI. On this basis, the study advocates the adoption of more predictable and consistent economic policy frameworks alongside initiatives designed to alleviate geopolitical tensions as part of Saudi Arabia's broader environmental sustainability strategy.

Keywords: Carbon Intensity; Economic Growth; Policy Uncertainty; Geopolitical Risk; Asymmetrical Analysis.

INTRODUCTION

CI represents the quantity of carbon emissions generated per unit of Gross Domestic Product (GDP) and is widely employed as an indicator of both environmental sustainability and energy-use efficiency within an economy. Lower CI values signify greater carbon efficiency, indicating that economic output is produced with comparatively fewer emissions. In the case of Saudi Arabia, CI was estimated at approximately 0.42 kg CO_2 per constant USD of GDP in 2022, exceeding the global benchmark of 0.38 reported by Atlas (2025). This comparatively elevated level largely reflects the country's abundant hydrocarbon resources and longstanding dependence on fossil fuel extraction and utilisation (Olaniyi et al., 2026). Although Saudi Arabia has initiated measures to diversify its energy structure through renewable sources, progress has remained relatively modest. Evidence indicates that renewable energy contributed less than 3% of total primary energy supply in 2023 (Alsubaie et al., 2025).

Several theoretical and economic mechanisms explain how uncertainty may influence CI. One important pathway operates through energy markets. Given Saudi Arabia's substantial exposure to fluctuations in international oil prices, uncertainty can alter production decisions, energy demand patterns, and industrial consumption behaviour, thereby affecting CI. A second channel emerges through financial markets, where geopolitical disturbances may influence sovereign creditworthiness, financing costs, and green investment opportunities. Such developments can constrain the capital available for environmentally sustainable projects and delay low-carbon transitions. Consistent with Real Options Theory advanced by Dixit and Pindyck (1994), firms facing elevated uncertainty may postpone irreversible investment decisions, including those involving renewable energy infrastructure and energy-efficient technologies, ultimately sustaining higher CI levels. Furthermore, Institutional Theory (DiMaggio & Powell, 1983) and Upper Echelons Theory (Hambrick & Mason, 1984) suggest that external pressures alone are insufficient to guarantee environmental transformation, as managerial perceptions of risk substantially shape strategic technology adoption decisions. Collectively, these perspectives provide a robust conceptual foundation for examining the nexus between uncertainty and CI.

Despite ongoing efforts to achieve both domestic and international sustainability objectives, Saudi Arabia's transition towards cleaner energy sources continues to advance at a gradual pace. Among the factors constraining this process, EPU occupies a prominent position because it weakens policy consistency and reduces confidence in long-term investment planning. Simultaneously, escalating regional tensions have heightened GPR, creating an additional layer of uncertainty that may hinder the transition process. Existing studies identify both EPU and GPR as influential determinants of environmental and economic performance across countries and regions (Ali, Islam, et al., 2025; Dagar et al., 2025). Likewise, previous research highlights their importance in shaping energy-related outcomes (Borozan, 2025; Liu, 2026). Rising uncertainty disrupts energy-sector planning and investment behaviour, affecting production decisions and resource allocation. Persistent EPU and GPR also deter long-term renewable energy investment and reduce energy productivity by weakening investment incentives (Bello & Abdulwahab Hassan, 2024; Petrović & Ostojić, 2025). Therefore, analysing CI as an economic efficiency indicator helps explain how uncertainty transmits through financial, investment, and energy channels to shape Saudi Arabia's carbon performance.

As the world's leading oil exporter, Saudi Arabia remains particularly vulnerable to volatility in global energy markets and shifts in regional geopolitical conditions (Alqahtani & Klein, 2021). GPR encompasses both regional and international conflicts, which may directly and indirectly affect CI. For example, geopolitical tensions can elevate energy costs (Dutta & Dutta, 2022) while simultaneously redirecting policy priorities towards energy security concerns rather than carbon-efficiency objectives. Such circumstances may reinforce dependence on fossil fuels and contribute to higher CI levels. Although Saudi Vision 2030 seeks to reduce energy and carbon intensity as part of a broader low-carbon development agenda (Shehri et al., 2023), the success of this strategy depends upon policy continuity and sustained long-term commitment. Elevated GPR may undermine these efforts by generating additional EPU, encouraging policymakers to prioritise short-term challenges over long-range environmental objectives. Regional conflicts, for instance, may reduce the government's capacity to finance renewable energy initiatives and redirect resources towards defence expenditures or other immediate policy requirements. In addition, uncertainty surrounding energy subsidies, industrial strategies, and environmental regulations may discourage investment in low-carbon technologies and delay the pace of energy transition.

Given the potential environmental implications of both GPR and EPU, empirical examination of their influence on CI within the Saudi context is warranted. Much of the existing literature has relied on panel-based analyses (Acheampong et al., 2023;

Borozan, 2025; Dagar et al., 2025; Jiatong et al., 2023; Liu, 2026), limiting the ability to capture country-specific dynamics and institutional characteristics. Although several single-country investigations have been conducted (Cheng et al., 2022; Du & Wang, 2023; Rashid & Gopinathan, 2023; Su et al., 2025; Vetrova, 2023), important gaps remain. Within the Saudi context, Alsubaie et al. (2025) employed the ARDL approach to examine the role of GPR in the relationship between globalisation indicators and emissions. Nevertheless, empirical evidence regarding the joint influence of GPR and EPU on CI remains absent. Furthermore, previous studies have predominantly focused on energy-related variables (Bello & Abdulwahab Hassan, 2024; Borozan, 2025; Cheng et al., 2022; Liu, 2026) and aggregate carbon emissions (Ali, Islam, et al., 2025; Dagar et al., 2025; Du & Wang, 2023; Syed et al., 2022), whereas investigations centred specifically on CI remain relatively limited (Shu et al., 2024). This deficiency provides strong motivation for examining the uncertainty–CI relationship within Saudi Arabia's resource-dependent economic structure.

To enhance the study's contribution, the proposed relationship is examined within an asymmetric framework. Such an approach recognises that positive and negative changes in EPU and GPR may not exert identical effects on CI in either direction or magnitude. Additionally, the interaction between EPU and GPR is incorporated to determine whether geopolitical conditions strengthen or weaken the environmental consequences of policy uncertainty. The resulting evidence is expected to provide valuable guidance for policymakers by clarifying how reductions in EPU and GPR may accelerate improvements in CI. Likewise, investors operating in energy-related sectors may benefit from a clearer understanding of risks associated with geopolitical instability and policy uncertainty. Finally, the findings may encourage future researchers to explore asymmetric uncertainty effects on environmental indicators across other resource-intensive economies.

After introducing the research context, Section 2 presents a review of the relevant literature. Section 3 outlines the methodological framework. Section 4 reports the empirical findings and diagnostic assessments. Section 5 interprets the results through an economic lens. Finally, Section 6 concludes the study by presenting policy recommendations, acknowledging limitations, and identifying avenues for future investigation.

LITERATURE REVIEW

Recent scholarship has extensively examined the interconnections among GPR, EPU, and environmental performance indicators. Nevertheless, the empirical evidence remains inconclusive and highly heterogeneous, suggesting that the environmental consequences of GPR and EPU vary across countries, periods, and analytical frameworks. This ambiguity arises because both forms of uncertainty can generate either beneficial or detrimental environmental outcomes. On the one hand, heightened

GPR and EPU may impede environmental progress by discouraging long-term investments in renewable energy projects, delaying technological innovation, and weakening commitments to low-carbon development pathways. On the other hand, elevated uncertainty can suppress economic activity, industrial production, and EC, thereby reducing environmental pressures and emissions. Consequently, the net environmental impact of GPR and EPU depends on the relative strength of these competing mechanisms, making their relationship with environmental indicators complex and context dependent.

Positive Environmental Effects of GPR/EPU

For instance, regarding the potential environmental benefits associated with GPR, Balsalobre-Lorente et al. (2024) applied the FMOLS technique to a panel of G-20 economies over the period 1997–2018 and found that GPR contributes directly to improvements in environmental quality, primarily through the contraction of aggregate economic activity. However, this beneficial effect is found to be weakened when economic complexity is introduced as a moderating factor. Similarly, Rashid and Gopinathan (2023), employing an ARDL framework for India, report that GPR leads to reductions in CH_4 and N_2O emissions, although EC is shown to exert upward pressure on CO_2 emissions. In another study focusing on India, Villanthenkodath and Pal (2024) utilised the NARDL approach for the period 1990–2019 and confirmed that GPR not only reduces emissions but also lowers the load capacity factor. Furthermore, Kayral et al. (2025), using machine learning-based methods on global data spanning 2005–2024, demonstrate that incorporating trade and financial regulatory uncertainty improves the predictive accuracy of CO_2 emissions, with GPR emerging as a significant determinant particularly in the post-2016 period.

Overall, the literature suggests that GPR may improve environmental outcomes by dampening overall economic activity. However, this positive environmental effect tends to be attenuated in the presence of higher economic complexity. Additionally, GPR can contribute to short-term reductions in emissions and the load capacity factor, although broader uncertainty stemming from trade and financial systems plays a critical role in shaping emission forecasting dynamics.

Adverse Environmental Effects of GPR/EPU

In contrast, a substantial strand of the literature predominantly supports the view that GPR exerts detrimental effects on environmental outcomes. For example, Cui et al. (2024), using the CS-ARDL approach for BRICS economies over 1992–2021, demonstrate that both GPR and EPU intensify environmental degradation. However, their findings also indicate that strong institutional frameworks and higher energy productivity can partially offset these adverse effects by reducing emissions. Similarly, Acheampong et al. (2023), employing Lewbel two-stage least squares for a sample of

42 countries, report that GPR contributes to increased GHG emissions, although REC plays a mitigating role; nevertheless, the effectiveness of REC weakens under conditions of elevated GPR. Using the AMG estimator, Jiatong et al. (2023) also confirm that REC reduces ecological footprint, whereas GPR, EPU, and economic growth collectively exacerbate environmental degradation.

Further evidence is provided by Adams et al. (2020), who, using the PMG approach for resource-rich economies between 1996 and 2017, identify bidirectional linkages between EC, GPR, EPU, and emissions, suggesting a reinforcing feedback mechanism whereby environmental degradation and GPR mutually intensify over time. In a qualitative investigation, Vetrova (2023) highlight that geopolitical sanctions and heightened GPR in Russia reduce climate policy commitments, thereby indirectly increasing GHG emissions. Similarly, Shu et al. (2024), applying the CCR estimator to 18 high-GPR economies over 1985–2021, find that GPR elevates CI by deepening reliance on fossil fuels, although REC and financial development are shown to mitigate this effect. In the context of Canada, Ali, Islam, et al. (2025), using an ARDL framework, confirm the validity of the EKC hypothesis while also reporting that GPR increases CO_2 emissions. Likewise, Alsubaie et al. (2025) examine Saudi Arabia over 1985–2023 and find that GPR amplifies the impact of globalization on emissions, thereby strengthening environmental degradation pressures.

Overall, the empirical evidence suggests that both GPR and EPU are generally associated with higher emissions, increased CI, and a larger ecological footprint, primarily through channels such as fossil fuel dependence and weakened climate policy commitment. Although REC and strong institutional structures can alleviate these negative impacts, their effectiveness diminishes under conditions of heightened geopolitical instability. Moreover, several studies highlight the presence of feedback effects, indicating that environmental degradation and GPR may reinforce each other in a dynamic and cyclical manner.

Mixed Effects

A further strand of literature reports mixed and context-dependent effects of EPU and GPR across sectors, time horizons, and methodological settings. For instance, Khan et al. (2023), using the CupFM estimator for BRICS economies over 2000–2021, find that GPR increases production-based CO_2 emissions, EC, and GHG emissions. In contrast, EPU is shown to reduce both emissions and EC in the long run. The same study also identifies bidirectional feedback between GPR and environmental degradation, while militarisation is found to exert a unidirectional causal effect on emissions and EC. Similarly, Kisswani et al. (2024), employing panel cointegration techniques for Southeast Asian economies over 1990–2020, report that both GPR and GDP contribute to higher CO_2 emissions, whereas REC plays a mitigating role. Their results further indicate that climate policy uncertainty reduces emissions through the contraction of industrial activity. Using quantile regression, Chu, Doğan, Abakah, et al. (2023) analyse E7 economies and show that EPU and GPR worsen environmental quality in the short run, whereas their long-run effects are associated with improvements. In addition, EC consistently deteriorates environmental quality, while economic complexity exhibits a nonlinear inverted U-shaped relationship.

At a more disaggregated level, Pata et al. (2023), applying wavelet-based analysis to the Russia–Ukraine conflict period (1997–2022), examine sectoral emissions and find that both GPR and EPU reduce CO_2 emissions in most sectors due to declining production activity. However, the transport sector displays an opposing pattern, where both variables contribute to higher emissions. Notably, EPU is reported to exert stronger effects than GPR across most specifications. Overall, the evidence indicates that the environmental impact of EPU and GPR is not uniform. While EPU may reduce production-based emissions in the long run, GPR is more frequently associated with increased emissions. Moreover, both variables tend to worsen environmental quality in the short run but may produce more favourable outcomes over longer horizons. Sectoral evidence further suggests that GPR can reduce emissions in most industries through output contraction, while simultaneously increasing emissions in transport-intensive activities.

Quantile and Energy-Focused Studies

The literature has further extended this nexus through quantile-based methodologies, highlighting that the effects of GPR and EPU differ substantially across the distribution of carbon emissions. For example, Syed et al. (2022), using the AMG estimator for BRICST economies over 1990–2019 within a quantile framework, report that EPU reduces CO_2 emissions at lower and middle quantiles, whereas it increases emissions at higher quantiles, indicating a rebound effect in high-emitting economies. In contrast, GPR is found to raise emissions at lower quantiles but reduce them at medium and upper quantiles, suggesting that in highly emitting economies, GPR may suppress industrial activity and thereby lower emissions. The same study also confirms that REC mitigates emissions, while non-renewable energy use and urbanisation contribute to environmental degradation.

Similarly, Ali, Rahaman, et al. (2025), applying a quantiles-via-moments approach to Canadian provinces over 1990–2022, find that non-renewable energy consumption increases GHG emissions, whereas REC, eco-innovation, and nuclear energy reduce them. Their results also show that GPR elevates emissions in the middle-to-upper quantiles. Using panel quantile regression, Dagar et al. (2025) examine 27 countries and report that GPR increases both ecological footprint and CO_2 emissions across all quantiles, with stronger effects observed at higher emission levels; however, environmental innovation and regulatory frameworks are found to mitigate these impacts. In the case of China, Du and Wang (2023), employing QARDL for 1995–2020, find that green finance consistently reduces emissions across all quantiles, while GPR increases emissions particularly in higher quantiles, reinforcing the view that geopolitical instability constrains investment in low-carbon technologies.

Beyond environmental outcomes, a growing body of research examines the influence of GPR and EPU on energy-related variables, particularly energy consumption patterns, investment behaviour, and energy security dynamics. Petrović and Ostojić (2025), using panel cointegration for 42 countries over 1990–2020, find no significant long-run effect of GPR and EPU on renewable energy production; however, short-run heterogeneity is evident, with GPR increasing REC in 31% of countries and decreasing it in 19%, while EPU shows similarly mixed directional effects across economies. Their results also indicate that GDP, energy structure, investment, and oil prices generally promote REC, whereas trade openness tends to reduce it. In contrast, Bello and Abdulwahab Hassan (2024), applying system GMM to OECD economies, report that both GPR and resource rents reduce REC, while GDP and globalisation enhance it. Chu, Doğan, Ghosh, et al. (2023) further show that the impact of GPR on REC is contingent on income level, increasing REC in high-income economies but reducing it in middle-income countries, highlighting the role of institutional and developmental heterogeneity. Liu (2026), focusing on emerging economies through panel cointegration techniques, finds that environmental regulation improves energy productivity, whereas GPR exerts a negative effect; importantly, bidirectional linkages among environmental regulation, EPU, GPR, and energy productivity are also observed. Similarly, Borozan (2025), using feasible GLS for the EU, reports that EPU reduces EC, while GPR increases it. Evidence from Chen et al. (2025) further indicates that GPR heightens energy security risks, particularly under conditions of FDI inflows, while Cheng et al. (2022) show that geopolitical restrictions and trade embargoes increase EC in the UK context.

In addition, GPR and EPU influence environmental and energy systems indirectly through financial market channels, particularly via volatility transmission in carbon, energy, and green asset markets. Elevated geopolitical risk increases uncertainty, weakens price signals, and disrupts investment decisions in low-carbon technologies. Adediran and Swaray (2023), analysing the EU Emissions Trading Scheme over 2009–2022, find that both GPR and EPU increase carbon price volatility, thereby discouraging green investment. Similarly, Rao et al. (2023) document significant spillover effects of GPR and EPU across energy markets over medium-term horizons, while Fu and Liao (2025) show that climate policy uncertainty amplifies volatility in carbon and natural gas markets, with cross-market transmission effects from clean energy and fossil fuel assets. Liu et al. (2024) further demonstrate that GPR and pandemic-related uncertainty increase volatility in green financial assets, and Mnif et al. (2024) confirm that GPR intensifies volatility across energy markets, green stocks, and cryptocurrency-related energy channels.

The literature also highlights the role of GPR and EPU in shaping green innovation and energy transition pathways. Attílio (2025), using VECM and cointegration analysis for 10 economies over 1997–2022, finds that both CPU and GPR shocks reduce green innovation, with GPR exerting a relatively stronger effect; heterogeneity is also observed across countries such as Japan, the United States, and South Africa. Conversely, Yuen and Yuen (2024), employing CS-ARDL techniques, show that fiscally capable governments can sustain renewable energy R&D even under conditions of heightened GPR and uncertainty, suggesting that institutional capacity can partially offset adverse innovation effects.

Overall, quantile-based evidence indicates that the impacts of GPR and EPU are highly state-dependent. EPU tends to reduce emissions at lower and middle quantiles but increases them at higher quantiles, consistent with a rebound effect in high-emission environments. GPR, by contrast, may increase emissions at lower quantiles while reducing them at higher quantiles due to output contraction in highly emitting economies. Across broader energy and financial systems, both variables exhibit heterogeneous effects shaped by income levels, institutional strength, and structural conditions, while also contributing to heightened volatility in energy and carbon markets and influencing green innovation trajectories.

Literature Summary and Conceptual Framework

The reviewed body of literature consistently indicates that the environmental effects of GPR and EPU are heterogeneous across countries, time horizons, and methodological approaches. In the majority of empirical studies, both GPR and EPU are associated with intensified environmental degradation and weakened energy security conditions. Nevertheless, the magnitude and direction of these effects are often conditioned by institutional strength and the level of REC, which tend to mitigate the adverse environmental consequences of heightened geopolitical and policy uncertainty. Furthermore, interactions between policy-related uncertainty, climate-related uncertainty, and GPR have been shown to significantly influence carbon markets, innovation dynamics, and energy productivity outcomes. Evidence also suggests that the environmental implications of GPR are time-dependent.

In the short run, GPR may contribute to emissions reductions by constraining aggregate economic activity and dampening industrial output. In contrast, over longer horizons, persistent geopolitical instability is more commonly associated with increased reliance on fossil fuels and slower progress in clean energy transitions, thereby exacerbating environmental degradation. Collectively, GPR and EPU play an important joint role in shaping the environmental consequences of broader macroeconomic growth processes; however, their combined effects remain underexplored, particularly in country-specific contexts such as Saudi Arabia. Against this background, Figure 1 presents the conceptual framework of the present study. It highlights a key gap in the existing literature, namely the absence of empirical evidence on the joint and asymmetric environmental effects of GPR and EPU in Saudi Arabia. To address this gap, the current study extends the EKC framework by incorporating both variables within an asymmetric modelling structure. Specifically, the study hypothesises a direct impact of EPU and GPR on CI, alongside a moderating effect of GPR on the EPU–CI relationship. In addition, both EPU and GPR are decomposed into positive and negative shocks to capture potential asymmetries in their environmental impacts. The EKC hypothesis is further embedded within this integrated framework to account for nonlinear income–environment dynamics.

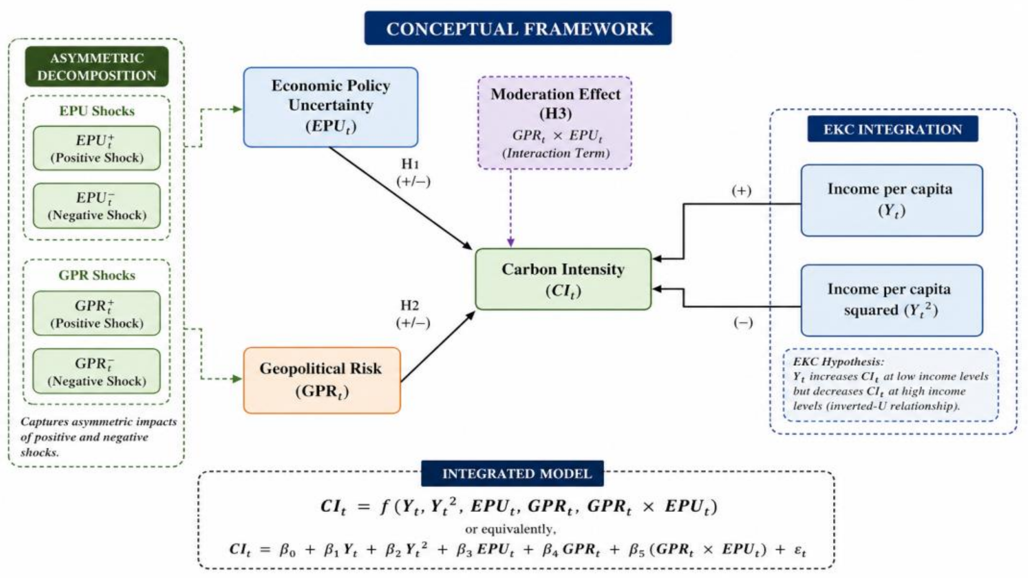

Figure 1: The Conceptual Framework

METHODOLOGY

Theoretical Foundation

Within the growth–environment literature, the EKC, as articulated by Grossman (1991), provides a foundational framework suggesting a nonlinear relationship between economic development and environmental degradation. In the initial stages of economic expansion, environmental pressures tend to intensify due to the dominance of the scale effect, whereby increased production leads to higher emissions and resource depletion. However, at higher income levels, this relationship may reverse as economies transition towards cleaner production technologies, improved regulation, and greater adoption of renewable energy systems, thereby generating a technique and composition effect that improves environmental quality.

In resource-dependent economies such as Saudi Arabia, GPR and EPU are likely to play a critical role in shaping the trajectory of this EKC transition. EPU arising from fiscal, monetary, and regulatory domains can introduce substantial uncertainty into investment decision-making, thereby discouraging long-term commitments to low-carbon technologies. Consistent with Real Options Theory (Dixit & Pindyck, 1994), firms facing heightened uncertainty may rationally defer irreversible investments, including renewable energy infrastructure, in anticipation of more favourable policy environments. This postponement reinforces reliance on fossil fuel-based energy sources, thereby contributing to higher CI and potentially delaying the downward turning point of the EKC.

Similarly, GPR can amplify these effects by increasing perceived investment risk, raising the cost of capital for green projects, and heightening concerns related to supply chain disruptions, policy instability, and market volatility. From the perspective of Upper Echelons Theory (Hambrick & Mason, 1984), managerial perceptions of risk significantly influence strategic investment choices, thereby reinforcing fossil fuel dependence under conditions of geopolitical instability. In this context, GPR may further delay the transition towards the cleaner phase of the EKC and negatively moderate the relationship between EPU and environmental outcomes. In the case of Saudi Arabia, geopolitical tensions in the Gulf region contribute to heightened volatility in global oil markets, which in turn intensifies the adverse environmental effects of domestic EPU. Consequently, firms may continue to rely on carbon-intensive energy sources while reducing investment in renewable alternatives, thereby increasing CI within the economy.

Taking into account the moderating role of GPR in strengthening the impact of EPU within the EKC framework, the following empirical model is proposed:

$$\text{Model 1: } \mathrm{CI}_t = f(\mathrm{Y}_t, Y_t^2, \mathrm{EPU}_t, \mathrm{GPR}_t, \mathrm{GPR}_t * \mathrm{EPU}_t, D_t) \qquad (1)$$

CI_t represents the natural logarithm of territorial CO_2 emissions per unit of GDP ($kgCO_2$/GDP), sourced from Atlas (2025). Y_t denotes the natural logarithm of per capita GDP measured in constant Saudi Riyals, which is also incorporated in squared form (Yt^2) to capture the nonlinear specification of the EKC. GDP data are obtained from Bank (2025). GPRt refers to the annual average Saudi Geopolitical Risk index, obtained from Database (2025), and reflects geopolitical tensions in the Middle East, including Gulf conflicts, Iran–Saudi Arabia relations, and regional military interventions. EPU represents the annual average World Uncertainty Index for Saudi Arabia, sourced from FRED (2025), capturing domestic policy uncertainty across fiscal, monetary, trade, and environmental domains within the Saudi context. The dataset spans the period 1970–2024.

Additionally, Dt is incorporated into the model to account for the most significant structural break in CIt, identified in 1991 and associated with the Gulf War episode. In the baseline specification (Equation 1), EPU, GPR, and their interaction term are assumed to exert symmetric effects on CI. However, this assumption may be restrictive, as increases and decreases in EPU and GPR are not necessarily expected to have identical impacts on CI. Accordingly, asymmetric relationships are also considered. To address this issue, Shin et al. (2014) propose decomposing explanatory variables into their partial sum processes of positive and negative changes in order to separately capture the effects of increasing and decreasing movements. Following this approach, all explanatory variables on the right-hand side of Equation 1—excluding GDP-related variables (which are modelled nonlinearly through the quadratic term)—are decomposed into positive and negative components as follows:

$$\mathrm{GPRP}_t = \sum_{j=1}^{t} GPR_j^{+} = \sum_{j=1}^{t} \max(\Delta GPR_j, 0) \tag{2}$$

$$\mathrm{GPRN}_t = \sum_{j=1}^{t} GPR_j^{-} = \sum_{j=1}^{t} \min(\Delta GPR_j, 0) \tag{3}$$

$$\mathrm{EPUP}_t = \sum_{j=1}^{t} EPU_j^{+} = \sum_{j=1}^{t} \max(\Delta EPU_j, 0) \tag{4}$$

$$\mathrm{EPUN}_t = \sum_{j=1}^{t} EPU_j^{-} = \sum_{j=1}^{t} \min(\Delta EPU_j, 0) \tag{5}$$

$$(GPR * \mathrm{EPU})\mathrm{P}_t = \sum_{j=1}^{t} GPR * \mathrm{EPU})_j^{+} = \sum_{j=1}^{t} \max(\Delta GPR * \mathrm{EPU})_j, 0) \tag{6}$$

$$GPR * \mathrm{EPU})\mathrm{N}_t = \sum_{j=1}^{t} GPR * \mathrm{EPU})_j^{-} = \sum_{j=1}^{t} \min(\Delta GPR * \mathrm{EPU})_j, 0) \tag{7}$$

In Equation 2, 4, and 6, GPRP_t, EPUP_t, and $(\mathrm{GPR*EPU})\mathrm{P}_t$ are the partial sum of positive changes in these series of GPR_t, EPU_t, and (GPR*EPU). Moreover, GPRN_t, EPUN_t, and $(\mathrm{GPR*EPU})\mathrm{N}_t$ are the partial sum of negative changes in these series of GPR_t, EPU_t, and (GPR*EPU). To ensure the valid increasing and decreasing series of (GPR*EPU), both GPR and EPU are multiplied first, and then this interaction series is differentiated to separate the positive and negative changes. Lastly, partial sums are taken for positive and negative changes to generate $(\mathrm{GPR*EPU})\mathrm{P}_t$ and $(\mathrm{GPR*EPU})\mathrm{N}_t$. The positive and negative partial sum decompositions of all relevant variables specified in Equations 2–7 are subsequently incorporated into Equation 1 in order to construct the asymmetric specification of the model. This transformation enables the empirical framework to distinguish between the effects of upward and downward movements in the explanatory variables, thereby allowing a more nuanced assessment of their heterogeneous impacts within the asymmetric setting.

$$CI_t = f(Y_t, Y_t^2, GPRP_t, GPRN_t, EPUP_t, EPUN_{t,}(GPR * EPU)P_t, (GPR * EPU)N_{t,}, D_t) \tag{8}$$

Econometric Strategy

Unit Root and Structural Break Tests

In the subsequent stage of the analysis, all variables specified in Equations 1 and 8 are subjected to unit root testing to ensure their suitability for cointegration analysis. This step is necessary prior to the implementation of the cointegration framework, as it establishes the integration properties of the underlying series. To this end, the Ng and Perron (2001) procedure is employed to examine the stationarity characteristics of all variables included in the model. The corresponding test equations are specified as follows:

$$MZ_a^d = \left[\frac{Y_T^d}{T}\right]^2 /2K - f_0/2K \tag{9}$$

$$MSB^d = \left[\frac{k}{f_0}\right]^{1/2} \tag{10}$$

$$MZ_t^d = MZ_a^d . MSB^d \tag{11}$$

$$MPT_T^d = [c^2 . K + \frac{1-c}{T}] . \frac{Y_T^d}{f_0} \tag{12}$$

Given the long sample period (1970–2024), Zivot and Andrews (1992) unit root test is also applied, allowing for a single endogenous structural break. The identified break date is incorporated into the subsequent cointegration analysis.

ARDL Cointegration and Robustness Testing

After estimating Equations 9–12 for all variables, the cointegration framework proposed by Pesaran et al. (2000) is applied to Equation 1. This is implemented through the Autoregressive Distributed Lag (ARDL) specification in Equation 13, and for the extended asymmetric model, the ARDL formulation is applied to Equation 2 as presented in Equation 14.

$$\begin{aligned}\Delta LCI_t = {} & a_{10} + a_{11}LCI_{t-1} + a_{12}Y_{t-1} + a_{13}Y_{t-1}^2 + a_{14}EPU_{t-1} + a_{15}GPR_{t-1} + \\ & a_{16}(GPR * EPU)_{t-1} + \sum_{i=1}^{j} a_{17i}\Delta LCI_{t-i} + \sum_{i=0}^{j} a_{18i}\Delta Y_{t-i} + \sum_{i=0}^{j} a_{19i}Y_{t-1}^2 + \\ & \sum_{i=0}^{j} a_{20i}\Delta EPU_{t-i} + \sum_{i=0}^{j} a_{21i}\Delta GPR_{t-i} + \sum_{i=0}^{j} a_{22i}\Delta(GPR * EPU)_{t-i} + D_t + e_{1t}\end{aligned} \tag{13}$$

$$\begin{aligned}\Delta LCI_t = {} & b_{10} + b_{11}LCI_{t-1} + b_{12}Y_{t-1} + b_{13}Y_{t-1}^2 + b_{14}EPUP_{t-1} + b_{15}EPUN_{t-1} + \\ & b_{16}GPRP_{t-1} + b_{17}GPRN_{t-1} + b_{18}(GPR * EPU)P_{t-1} + b_{19}(GPR * EPU)N_{t-1} + \\ & \sum_{i=1}^{j} b_{20i}\Delta LCI_{t-i} + \sum_{i=0}^{j} b_{21i}\Delta Y_{t-i} + \sum_{i=0}^{j} b_{22i}Y_{t-1}^2 + \sum_{i=0}^{j} b_{23i}\Delta EPUP_{t-i} + \\ & \sum_{i=0}^{j} b_{24i}\Delta EPUN_{t-i} + \sum_{i=0}^{j} b_{25i}\Delta GPRP_{t-i} + \sum_{i=0}^{j} b_{26i}\Delta GPRN_{t-i} + \\ & \sum_{i=0}^{j} b_{27i}\Delta(GPR * EPU)P_{t-i} + \sum_{i=0}^{j} b_{28i}\Delta(GPR * EPU)N_{t-i} + D_t + e_{2t}\end{aligned} \tag{14}$$

The ARDL equations 13 and 14 will be tested for cointegration in models in equations 1 and 2, respectively. For this purpose, the Bound testing approach will be utilized with a null hypothesis of (H_0: $a_{11}=a_{12}=a_{13}=a_{14}=a_{15}=a_{16}=a_{17}=0$) in Equation 13 and ($H_0$: $b_{11}=b_{12}=b_{13}=b_{14}=b_{15}=b_{16}=b_{17}=b_{18}=b_{19}=0$) in Equation 14. In the presence of valid cointegration in both specifications, long-run coefficients can be obtained through appropriate normalisation procedures. Although potential endogeneity may arise due to bidirectional relationships among certain variables, the ARDL framework addresses this concern by incorporating sufficient lag structures of both dependent and differenced explanatory variables, thereby mitigating endogeneity bias through its dynamic specification. To capture short-run dynamics, Equations 13 and 14 are subsequently re-parameterised into error correction models as follows:

$$\Delta LCI_t = g_{10}ECT_{1t-1} + g_{11}(GPR * EPU)_{t-1} + \sum_{i=1}^{j} g_{12i}\Delta LCI_{t-i} + \sum_{i=0}^{j} g_{13i}\Delta Y_{t-i} + \sum_{i=0}^{j} g_{14i}Y_{t-1}^{2} + \sum_{i=0}^{j} g_{15i}\Delta EPU_{t-i} + \sum_{i=0}^{j} g_{16i}\Delta GPR_{t-i} + \sum_{i=0}^{j} g_{17i}\Delta(GPR * EPU)_{t-i} + D_t + e_{3t} \qquad (15)$$

$$\Delta LCI_t = g_{20}ECT_{2t-1} + g_{21}(GPR * \mathrm{EPU})\mathrm{P}_{t-1} + g_{22}(GPR * \mathrm{EPU})\mathrm{N}_{t-1} + \sum_{i=1}^{j} g_{23i}\Delta LCI_{t-i} + \sum_{i=0}^{j} g_{24i}\Delta Y_{t-i} + \sum_{i=0}^{j} g_{25i}Y_{t-1}^{2} + \sum_{i=0}^{j} g_{26i}\Delta EPUP_{t-i} + \sum_{i=0}^{j} g_{27i}\Delta EPUN_{t-i} + \sum_{i=0}^{j} g_{28i}\Delta GPRP_{t-i} + \sum_{i=0}^{j} g_{29i}\Delta GPRN_{t-i} + \sum_{i=0}^{j} g_{30i}\Delta(GPR * EPU)P_{t-i} + \sum_{i=0}^{j} g_{31i}\Delta(GPR * EPU)N_{t-i} + D_t + e_{4t} \qquad (16)$$

In equations 15 and 16, the lagged-level variables of equations 13 and 14 are replaced with error correction terms of ECT_{1t-1} and ECT_{2t-1}, which can be tested for a short relationship in the models. The short-run effects are subsequently derived from the coefficients of the lagged first-differenced variables specified in Equations 15 and 16. Following the ARDL estimation, the robustness of the long-run results is examined using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS). These estimators are appropriate given that the variables are integrated of order one and the dataset covers a sufficiently long time period, which supports reliable implementation of both approaches for long-run coefficient validation.

DATA ANALYSIS

Unit Root and Structural Break Results

In Table 1, the results of the Ng–Perron unit root test indicate that all variables fail to reject the null hypothesis of a unit root at level form, confirming that the series are non-stationary in levels. However, their first differences, including ΔYt, ΔYt^2, ΔEPUt, ΔGPRt, and ΔGPRPt, reject the null hypothesis at the 5% significance level. The remaining differenced variables are also found to be stationary at the 1% level of significance. These findings confirm that all variables are integrated of order one, I(1), thereby justifying the application of the ARDL bounds testing approach for both model specifications.

Table 2 reports the results of the Zivot–Andrews unit root test with a single endogenous structural break. The findings indicate that all variables are non-stationary in their level form. The estimated break dates correspond to key historical and geopolitical events, including 1990–1991 (Gulf War), 1985 (oil price collapse), 2003 (Iraq War), and 2001 (September 11 attacks).

Table 1: Ng-Perron Results

Series	MZa	MZt	MSB	MPT
CI_t	-1.8364	-0.8067	0.4419	11.6388
Y_t	-10.9776	-2.2974	0.2160	8.1167
Y_t^2	-10.5747	-2.2468	0.2094	8.2146
EPU_t	-13.4755	-2.5974	0.1954	7.9417
$EPUP_t$	-7.8746	-1.8957	0.2496	11.9175
$EPUN_t$	-12.854	-2.5741	0.1974	5.8964
GPR_t	-7.8163	-1.9515	0.2126	9.1755
$GPRP_t$	-6.9745	-1.8175	0.2789	10.7498
$GPRN_t$	-11.8716	-2.2479	0.1946	6.1517
GPR_t*EUP_t	-9.3146	-1.9647	0.2374	9.6418
$(GPR*EPU)P_t$	-7.8468	-1.7466	0.2383	10.5475
$(GPR*EPU)N_t$	-13.9547	-2.8274	0.1924	6.8497
ΔCI_t	-25.1485***	-3.5784***	0.1415***	3.1554***
ΔY_t	-19.5475**	-2.9816**	0.1612**	5.1362**
ΔY_t^2	-18.9548**	-3.0024**	0.1665**	4.4124**
ΔEPU_t	-25.6215***	-3.5146***	0.1295***	3.0115***
$\Delta EPUP_t$	-24.2469***	-3.4975***	0.1615**	3.1249***
$\Delta EPUN_t$	-18.8547**	-2.9547**	0.1579**	4.3946**
ΔGPR_t	-22.5417**	-3.0874**	0.1512**	4.2964**
$\Delta GPRP_t$	-23.1463**	-3.1987**	0.1594**	4.3128**
$\Delta GPRN_t$	-25.1154***	-3.6874***	0.1199***	3.0841***
ΔGPR_t*EPU_t	-26.5413***	-3.8745***	0.1026***	3.1496***
$\Delta\ (GPR*EPU)P_t$	-24.8746***	-3.4562***	0.1244***	3.0974***
$\Delta\ (GPR*EPU)N_t$	-25.8165***	-3.7516***	0.1262***	3.1156***

Note: ** and *** indicate stationarity at 5 percent & 1 percent.

Among these, the break identified in 1991—associated with the Gulf War—is selected for incorporation into the cointegration framework, as it represents the most significant structural shift in CI at its level form.

Table 2: The Zivot-Andrews Test

Series	Level	Break Year	First Difference	Break Year
CI_t	-3.124	1991	-6.845***	2008
Y_t	-2.987	1985	-7.123***	2013
Y_t^2	-3.045	1985	-7.201***	2013
EPU_t	-4.012	2003	-8.456***	2011
$EPUP_t$	-3.856	2003	-8.123***	2011
$EPUN_t$	-3.901	2009	-8.234***	2002
GPR_t	-3.567	1990	-7.894***	2003
$GPRP_t$	-3.445	1990	-7.765***	2003
$GPRN_t$	-3.512	1998	-7.821***	1998
GPR_t*EPU_t	-3.678	2001	-8.567***	2012
$(GPR*EPU)P_t$	-3.589	2001	-8.345***	2012
$(GPR*EPU)N_t$	-3.612	2005	-8.412***	2001

Note: *** indicates stationarity at 1 percent.

Furthermore, all variables become stationary after first differencing, confirming their integration of order one.

Cointegration and Diagnostic Tests

Table 3 reports the ARDL bounds test results for Models 1 and 2. The calculated F-statistics of 6.0566 and 7.5416, respectively, exceed the relevant critical values, thereby confirming the presence of cointegration in both the symmetric and asymmetric specifications. These findings indicate a stable long-run relationship among EPU, GPR, per capita GDP, and CI. In addition, the diagnostic test results are statistically insignificant, suggesting that the models are free from issues of heteroscedasticity, serial correlation, non-normality, and functional form misspecification. This confirms that the estimated ARDL frameworks are econometrically robust and suitable for further analysis.

Table 3: Bound Test

Models	F-Values from the Bound Test	Heteroscedasticity	Serial Correlation	Normality	Functional Form
Equation 13	7.1149***	1.1952 (0.3419)	0.1813 (0.8349)	0.1741 (0.9154)	2.1156 (0.1459)
Equation 14	7.8954***	1.6159 (0.2244)	1.1549 (0.5967)	0.8659 (0.7511)	1.8156 (0.3102)

Note: *** shows cointegration at 1% level of significance.

Furthermore, the stability of the models is verified through the CUSUM and CUSUMSQ tests presented in Figure 2. The plots remain within the 5% critical boundaries, indicating parameter stability over the sample period.

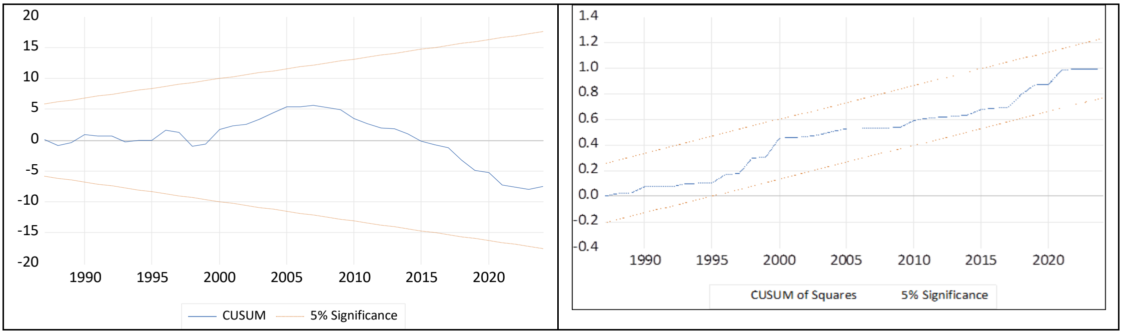

Figure 2: CUSUM and CUSUMsq

Long-Run and Short-Run Results

Table 4 presents the long-run estimates for Models 1 and 2, with CI specified as the dependent variable in both cases. The coefficients of Y_t and Y_t^2 are statistically significant and carry opposite signs, thereby confirming the validity of the EKC hypothesis in the long run across both model specifications. This implies that, beyond a certain income threshold, economic growth in Saudi Arabia contributes to reductions in CI. In Model 1, EPU exhibits a positive and statistically significant effect on CI, thereby supporting H1. Specifically, a one-unit increase in EPU is associated with a 0.5944% rise in CI. Similarly, GPR also exerts a positive and significant impact on CI, supporting H2, with a one-unit increase in GPR raising CI by 0.4967%. Furthermore, the interaction term between GPR and EPU is positive and statistically significant, supporting H3, indicating that GPR amplifies the environmental impact of EPU. In particular, a one-unit increase in GPR strengthens the effect of EPU on CI by 0.2859%.

Table 4: Long Run Results

Variables	Model 1	Model 2
Y_t	19.5674** (0.0124)	27.3091*** (0.0021)
Y_t^2	-0.8561*** (0.0059)	-1.1179*** (0.0005)
EPU_t	0.5944*** (0.0001)	
$EPUP_t$		0.7951*** (0.0000)
$EPUN_t$		0.4279 (0.1645)
GPR_t	0.4967** (0.0211)	
$GPRP_t$		0.6149** (0.0496)
$GPRN_t$		0.2396* (0.0784)
GPR_t*EPU_t	0.2859*** (0.0002)	
$(GPR*EPU)P_t$		0.4155*** (0.0000)
$(GPR*EPU)N_t$		0.2969** (0.0462)
D_t	0.1517** (0.0249)	0.2974** (0.0047)
Intercept	-5.9578*** (0.0000)	-7.6691** (0.0312)

Note: (p-values): *, **, and *** show level of significance at 10%, 5%, and 1%, respectively.

In Model 2, the asymmetric results show that EPUP has a positive and statistically significant effect on CI, whereas EPUN is statistically insignificant. This confirms asymmetric behaviour in the EPU–CI relationship, whereby increases in EPU raise CI, while decreases in EPU do not lead to a corresponding reduction. This pattern suggests that higher uncertainty discourages renewable investment and reinforces dependence on fossil fuels, whereas reductions in uncertainty may not immediately reverse these effects due to irreversibility in energy infrastructure and delayed restoration of policy credibility. The coefficient of EPUP indicates that a one-unit increase in positive EPU shocks raises CI by 0.7951%, further highlighting the stronger impact of upward uncertainty movements relative to downward adjustments.

For GPR, both GPRP and GPRN are statistically significant and positive in relation to CI, confirming asymmetric effects. However, the magnitude of the effect of GPRP (0.6149) is considerably larger than that of GPRN (0.2396), indicating that increases in geopolitical risk exert a stronger influence on CI than decreases. In this context, a one-unit increase in positive GPR shocks raises CI by 0.6149%, while a one-unit increase in negative shocks reduces CI by 0.2396%. The interaction terms, (GPR×EPU)P and (GPR×EPU)N, are also positive and significant, confirming that combined movements in GPR and EPU amplify CI. Notably, the effect of the positive interaction term is stronger, with a coefficient of 0.4155, compared to 0.2969 for the negative interaction term. This suggests that simultaneous increases in both uncertainties intensify environmental degradation more strongly than their mitigating counterparts reduce it. Finally, the dummy variable is positive and statistically significant, reflecting a structural shift in CI associated with the Gulf War period. This result indicates that heightened geopolitical instability during this period may have disrupted renewable energy transition pathways and contributed to increased carbon intensity.

Table 5 reports the short-run estimates for Models 1 and 2. The negative and statistically significant coefficients of the error correction term (ECTt−1) confirm the existence of a stable short-run adjustment process in both specifications, with adjustment speeds of 0.6987 in Model 1 and 0.7155 in Model 2, respectively. The lagged dependent variable (ΔCIt−1) exhibits a positive and significant coefficient in both models, indicating persistence in carbon intensity dynamics whereby increases in CI in the preceding period lead to further increases in the current period. The coefficients of ΔYt are positive and statistically significant across both models, whereas ΔYt^2 remains statistically insignificant. This implies that the EKC hypothesis is not supported in the short run, suggesting that increases in GDP per capita are associated with higher CI without evidence of a turning point effect. Furthermore, the structural dummy variable (Dt) exerts a positive and significant impact on CI, reinforcing the notion that the Gulf War–related structural shift contributed to higher carbon intensity and may have constrained renewable energy transition efforts in Saudi Arabia.

In Equation 15, ΔEPU exerts a positive and statistically significant effect on ΔCI, indicating that a one-unit increase in EPU raises CI by 0.4149% in the short run. However, its lagged term is statistically insignificant, suggesting that this effect does not persist over time. Similarly, ΔGPR has a positive and significant impact on ΔCI, with a one-unit increase in GPR increasing CI by 0.4376% in the short run. The contemporaneous interaction term Δ(GPR×EPU) is statistically insignificant, whereas its lagged specification is positive and significant, indicating a delayed moderating effect of GPR on the EPU–CI relationship. Specifically, a one-year lagged interaction effect of GPR increases the impact of EPU on CI by 0.1674.

Table 5: Short Run Results

Variables	Model 1	Model 2
ΔCI_{t-1}	0.1964** (0.0111)	0.2674** (0.0196)
ΔY_t	18.5471** (0.0496)	20.1596** (0.0115)
ΔY_t^2	-0.7159 (0.3247)	-0.7354 (0.2796)
ΔEPU_t	0.4149** (0.0429)	
ΔEPU_{t-1}	0.2296 (0.1957)	
$\Delta EPUP_t$		0.6349*** (0.0009)
$\Delta EPUN_t$		0.2949 (0.2679)
$\Delta EPUN_{t-1}$		0.1367*** (0.0008)
ΔGPR_t	0.4376*** (0.0000)	
$\Delta GPRP_t$		0.5957*** (0.0000)
$\Delta GPRP_{t-1}$		0.2496 (0.3964)
$\Delta GPRN_t$		0.3324 (0.3964)
$\Delta GPRN_{t-1}$		0.1846 (0.4632)
ΔGPR_t*EPU_t	0.2187 (0.1322)	
$\Delta GPR_{t-1}*EPU_{t-1}$	0.1674* (0.0874)	
$\Delta\,(GPR*EPU)P_t$		0.3641** (0.0354)
$\Delta\,(GPR*EPU)N_t$		0.1333** (0.0267)
D_t	0.2796*** (0.0027)	0.5196* (0.0674)
ECT_{t-1}	-0.6987*** (0.0000)	-0.7155*** (0.0000)

Note: (p-values): *, **, and *** show level of significance at 10%, 5%, and 1%, respectively.

In Model 2, the asymmetric short-run results show that ΔEPUP has a positive and significant effect on CI, whereas ΔEPUN is statistically insignificant. This implies that positive shocks to EPU increase ΔCI, while negative shocks do not produce a meaningful effect. The coefficient of ΔEPUP indicates that a one-unit increase in positive EPU shocks raises ΔCI by 0.6349%, while a one-unit increase in negative shocks (ΔEPUN) reduces ΔCI by 0.1367% with a one-year lag effect. For GPR, ΔGPRP has a positive and significant effect on ΔCI, whereas ΔGPRPt−1, ΔGPRN, and ΔGPRNt−1 are statistically insignificant. This confirms a short-run asymmetric response of CI to geopolitical risk, with positive shocks in GPR increasing ΔCI by 0.5957%. Finally, the interaction terms Δ(GPR×EPU)P and Δ(GPR×EPU)N are both positive and significant, with coefficients of 0.3641 and 0.1333, respectively. These results indicate that increases in GPR amplify the effect of EPU on CI in the short run, while decreases in GPR weaken this transmission channel.

Robustness Tests through FMOLS and DOLS

The robustness of the ARDL long-run estimates is further assessed using FMOLS and DOLS for Models 1 and 2, as reported in Table 6. The FMOLS and DOLS results exhibit broadly consistent coefficient signs and significance patterns with the baseline ARDL estimates, confirming the stability of the core long-run relationships.

Table 6: FMOLS and DOLS Results

Variables	FMOLS	DOLS
Y_t	22.7479* (0.0541)	20.2069** (0.0124)
Y_t^2	-0.9946** (0.0214)	-0.9197** (0.0121)
EPU_t	0.6457** (0.0167)	0.5994*** (0.0096)
GPR_t	0.5897** (0.0111)	0.5674* (0.0598)
GPR_t*EPU_t	0.3156*** (0.0006)	0.2917** (0.0279)

Note: (p-values): *, **, and *** show level of significance at 10%, 5%, and 1%, respectively.

However, the magnitude of the estimated effects is generally higher under FMOLS, followed by DOLS, with ARDL producing comparatively smaller coefficients. The EKC hypothesis is also supported in both FMOLS and DOLS estimations, as evidenced by the positive coefficient of Y_t and the negative coefficient of Yt^2. In line with the ARDL findings, both EPU and GPR exert positive and statistically significant effects on CI, while their interaction term remains positive and significant, reinforcing the moderating role of GPR in amplifying the environmental impact of EPU. However, the asymmetric specifications are not replicated in the FMOLS and DOLS estimations, as these methods are not fully suited to nonlinear ARDL-type decompositions. In addition, the dummy variable (Dt) is excluded from FMOLS and DOLS estimations due to its level stationarity properties, which introduce a mixed order of integration within the model framework.

DISCUSSION

The Results of the EKC

The long-run estimates confirm the validity of the EKC in Saudi Arabia, indicating that an initial increase in GDP per capita is associated with higher CI, whereas beyond a certain threshold, further income growth contributes to a reduction in CI. This pattern reflects the structural characteristics of an oil-dependent economy, in which early-stage growth is driven by expansion in petrochemical industries and fossil-fuel-intensive production, thereby increasing carbon intensity. At higher income levels, however, the observed EKC relationship suggests the emergence of decarbonisation dynamics. In this context, ongoing economic diversification—particularly investment in tourism and renewable energy projects—plays a key role in shifting the production structure towards relatively less carbon-intensive sectors. These structural changes support gradual improvements in energy efficiency and environmental performance. In contrast, the EKC hypothesis is not supported in the short run, implying that the benefits of cleaner sectoral transformation and renewable energy investment require time to materialise. Consequently, short-run increases in GDP per capita continue to exert upward pressure on CI, while the environmental gains associated with structural transition remain delayed.

EPU and CI

The positive relationship between EPU and CI suggests that policy instability constitutes a significant barrier to structural transition towards a low-carbon economy. In particular, elevated EPU increases investment risk and discourages long-term capital allocation to renewable energy and energy-efficient sectors. Under conditions of heightened uncertainty, firms tend to defer or scale back investment in emerging clean technologies, prioritising short-term financial stability over long-term sustainability commitments. Although Saudi Arabia is gradually advancing towards a cleaner economic structure, the pace of this transition remains constrained by the need for policy consistency and regulatory certainty. In the presence of elevated EPU, firms are more likely to adopt risk-averse strategies, thereby limiting engagement in capital-intensive clean energy projects and reinforcing dependence on existing fossil-fuel-based systems.

GPR and CI

Similarly, GPR has a positive effect on CI. In Saudi Arabia, GPR originates from Middle East geopolitical conflicts, which also contribute to global geopolitical tensions. Increasing GPR may prioritise energy security concerns and reinforce existing industrial dependence. In addition, rising GPR may increase government military expenditure, thereby reducing available funds for investment in renewable energy infrastructure and slowing the renewable transition process. Moreover, higher GPR may discourage both domestic and foreign investment. The asymmetric results further indicate that reductions in GPR alone may not be sufficient to improve investor confidence, highlighting the need for supportive policy measures to facilitate the renewable energy transition.

Interaction Effects

In addition, the interaction between EPU and GPR intensifies the overall uncertainty channel by combining domestic policy uncertainty with external geopolitical risk, thereby jointly increasing CI in Saudi Arabia. Under conditions of simultaneous uncertainty, both firms and policymakers may adopt more cautious and pessimistic investment behaviour, which can delay energy reforms and reinforce reliance on fossil-fuel-based energy sources perceived as more stable under uncertainty. As a result, CI increases more sharply when both uncertainties rise together, indicating that uncertainty shocks are interdependent and mutually reinforcing in their environmental impact. Furthermore, the asymmetric results indicate that positive shocks in both EPU and GPR increase CI more strongly than the reduction in CI associated with negative shocks in these variables. Overall, the findings confirm the dominant adverse effects of the combined increases in GPR and EPU on CI.

Link to Energy Transition Policies

The findings are directly relevant to energy transition policy. EPU and GPR both exert a positive effect on CI, indicating that renewable energy investments are highly sensitive to policy and geopolitical uncertainty. In particular, the short-run results suggest that even temporary episodes of policy instability or geopolitical tension can discourage capital-intensive green projects. Accordingly, the Saudi government requires stable and long-term policy frameworks to support the renewable energy transition. Instruments such as fixed feed-in tariffs and green bonds can help reduce investor exposure to regulatory uncertainty. In addition, carbon pricing mechanisms and fossil fuel subsidy reforms should ideally be introduced during periods of relatively low GPR, given that CI increases when both GPR and EPU rise simultaneously. Furthermore, the design of multi-year green tariff agreements, potentially supported by risk-sharing or insurance mechanisms against GPR, could help protect renewable investments from annual fiscal volatility and EPU-driven policy fluctuations. Overall, the results indicate that economic growth alone is insufficient to ensure a transition towards sustainability in Saudi Arabia. Instead, stable policy environments and reduced geopolitical uncertainty are also necessary to reduce dependence on a fossil-fuel-based economic structure in line with Saudi Vision 2030 objectives.

CONCLUSION

EPU and GPR can constrain an economy’s transition towards a green future. This study examines the moderating role of GPR on the EPU–CI nexus within the EKC framework for the resource-abundant Saudi economy over the period 1970–2024 using a nonlinear ARDL approach. The EKC hypothesis is validated in the long run, while it is not supported in the short run. This indicates that economic growth contributes to reductions in CI only after a threshold level is reached. In the long-run symmetric results, both EPU and GPR, individually and jointly, exert a positive effect on CI. In the asymmetric long-run specification, positive shocks in EPU increase CI, whereas negative shocks in EPU do not significantly reduce CI. Similarly, positive shocks in GPR increase CI, while negative shocks reduce CI. The moderating effect of GPR on EPU is also positive for both positive and negative EPU shocks, indicating that GPR amplifies the environmental impact of EPU. Consequently, reductions in GPR facilitate the potential environmental benefits associated with declines in EPU. Moreover, the effects of positive shocks in both GPR and EPU are stronger than those of their negative counterparts, suggesting that adverse environmental impacts arising from increases in uncertainty are not fully offset by equivalent improvements when uncertainty declines. In the short-run symmetric results, both EPU and GPR individually exert positive effects on CI, while their combined effect becomes significant with a one-year lag. In the asymmetric short-run analysis, positive shocks in EPU increase CI, whereas negative shocks reduce CI with a lagged effect. Likewise, positive shocks in GPR increase CI, while negative shocks are statistically insignificant. The interaction terms further indicate that negative combined shocks in GPR and EPU contribute to reductions in CI in the short run, whereas positive combined shocks increase CI with a larger magnitude.

POLICY IMPLICATIONS

Based on the results, EPU contributes to an increase in CI. In response, the fiscal framework could incorporate counter-cyclical budgeting alongside a public–private financing mechanism dedicated to renewable energy investment, which would automatically disburse funds for clean energy projects during periods of elevated EPU and/or GPR. In addition, while the Saudi government currently utilises energy subsidies to stabilise production costs and consumer prices, a clearly defined fossil fuel subsidy phase-out schedule should be introduced and communicated to market participants. This would convert policy uncertainty into predictable adjustment costs for firms. In parallel, gradually phased renewable energy subsidies could be implemented to incentivise investment in low-carbon technologies.

In terms of investment incentives, a green investment guarantee scheme could be established, offering partial risk coverage for losses associated with heightened EPU or GPR. Such a mechanism would reduce perceived investment risk and encourage continued capital allocation to renewable energy projects even under unstable policy or geopolitical conditions. From an energy diversification perspective, binding energy efficiency standards could be imposed across industrial sectors, with enforcement maintained independently of fluctuations in EPU or GPR. This would ensure a persistent downward pressure on energy intensity and emissions. Furthermore, dedicated zones for solar, wind, and green hydrogen development could be established, with regulatory frameworks fixed for long-term horizons (e.g., 20 years), thereby providing institutional certainty for clean energy investments regardless of uncertainty shocks.

LIMITATIONS AND FUTURE RESEARCH

The study is subject to certain limitations. First, data availability constraints restrict the inclusion of GPR and EPU measures for other GCC economies. Future research could address this gap by constructing comparable datasets using the methodologies of FRED (2025) and Database (2025), enabling cross-country analysis within the GCC region to examine similarities and differences among economies with shared geographical and energy market structures. Second, the EPU and GPR indices employed in this study are global in nature. Future studies may improve measurement precision by developing Saudi-specific EPU and GPR indices that better capture country-level institutional, political, and economic dynamics. Finally, future research may extend the analysis by examining the sectoral effects of GPR and EPU within Saudi Arabia, thereby providing a more granular understanding of how different industries respond to uncertainty shocks.

FUNDING

The author extends his appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2025/02/34174).

REFERENCES

Acheampong, A. O., Opoku, E. E. O., & Aluko, O. A. (2023). The roadmap to net-zero emission: Do geopolitical risk and energy transition matter? *Journal of Public Affairs*, *23*(4), e2882. https://doi.org/10.1002/pa.2882

Adams, S., Adedoyin, F., Olaniran, E., & Bekun, F. V. (2020). Energy consumption, economic policy uncertainty and carbon emissions; causality evidence from resource rich economies. *Economic Analysis and Policy*, *68*, 179-190. https://doi.org/10.1016/j.eap.2020.09.012

Adediran, I. A., & Swaray, R. (2023). Carbon trading amidst global uncertainty: The role of policy and geopolitical uncertainty. *Economic Modelling*, *123*, 106279. https://doi.org/10.1016/j.econmod.2023.106279

Ali, M. I., Islam, M. M., & Ceh, B. (2025). Assessing the impact of three emission (3E) parameters on environmental quality in Canada: A provincial data analysis using the quantiles via moments approach. *International Journal of Green Energy*, *22*(3), 551-569. https://doi.org/10.1080/15435075.2024.2421329

Ali, M. I., Rahaman, M. A., Ali, M. J., & Rahman, M. F. (2025). The growth–

environment nexus amid geopolitical risks: cointegration and machine learning algorithm approaches. *Discover Sustainability*, *6*(1), 78. https://doi.org/10.1007/s43621-025-00872-z

Alqahtani, A., & Klein, T. (2021). Oil price changes, uncertainty, and geopolitical risks: On the resilience of GCC countries to global tensions. *Energy*, *236*, 121541. https://doi.org/10.1016/j.energy.2021.121541

Alsubaie, M. S., Tanveer, M., & Mahmood, H. (2025). The moderating effect of geopolitical risk in the nexus between trade openness, FDI, and carbon emissions in Saudi Arabia. *Environmental and Sustainability Indicators*, *28*, 100967. https://doi.org/10.1016/j.indic.2025.100967

Atlas, G. C. (2025). Carbon intensity data. Global Carbon Project. from , November 01, 2025. https://globalcarbonatlas.org/emissions/carbon-emissions/

Attílio, L. A. (2025). Spillover effects of climate policy uncertainty on green innovation. *Journal of Environmental Management*, *375*, 124334. https://doi.org/10.1016/j.jenvman.2025.124334

Balsalobre-Lorente, D., Nur, T., Topaloglu, E. E., & Evcimen, C. (2024). The dampening effect of geopolitical risk and economic policy uncertainty in the linkage between economic complexity and environmental degradation in the G-20. *Journal of Environmental Management*, *351*, 119679. https://doi.org/10.1016/j.jenvman.2023.119679

Bank, W. (2025). World Development Indicators. *The World Bank Group*. https://databank.worldbank.org/source/world-development-indicators

Bello, S., & Abdulwahab Hassan, Y. (2024). Examining the effect of geopolitical risks on renewable energy consumption in OECD countries. *Environmental Economics*. https://doi.org/10.17863/CAM.110584

Borozan, D. (2025). Assessing the impact of geopolitical risk, energy import dependence, and economic policy uncertainty on energy consumption. *Energy Efficiency*, *18*(6), 59. https://doi.org/10.1007/s12053-025-10340-2

Chen, Z., He, M., & Ali, M. (2025). Natural resources and geopolitical risk impact on energy security risk: The role of renewable energy consumption and foreign direct investment. Natural resources forum, https://doi.org/10.1111/1477-8947.70006

Cheng, X., Hu, Y., & Varga, L. (2022). 5G network deployment and the associated energy consumption in the UK: A complex systems' exploration. *Technological Forecasting and Social Change*, *180*, 121672. https://doi.org/10.1016/j.techfore.2022.121672

Chu, L. K., Doğan, B., Abakah, E. J. A., Ghosh, S., & Albeni, M. (2023). Impact of economic policy uncertainty, geopolitical risk, and economic complexity on carbon emissions and ecological footprint: an investigation of the E7 countries. *Environmental Science and Pollution Research*, *30*(12), 34406-34427. https://doi.org/10.1007/s11356-022-24682-2

Chu, L. K., Doğan, B., Ghosh, S., & Shahbaz, M. (2023). The influence of shadow economy, environmental policies and geopolitical risk on renewable energy: A comparison of high- and middle-income countries. *Journal of Environmental Management*, *342*, 118122. https://doi.org/10.1016/j.jenvman.2023.118122

Cui, X., Wang, W., Işık, C., Uddin, I., Yan, J., Gu, X., & Ahmad, M. (2024). Do geopolitical risk and economic policy uncertainty cause CO2 emissions in BRICS? The role of institutional quality and energy productivity. *Stochastic Environmental Research and Risk Assessment*, *38*(5), 1685-1699. https://doi.org/10.1007/s00477-023-02646-3

Dagar, V., Rao, A., Dagher, L., Kagzi, M., & Acevedo-Duque, Á. (2025). Geopolitical instability and environmental sustainability. *Environmental Economics and Policy Studies*, *28*(1), 445-471. https://doi.org/10.1007/s10018-025-00451-6

Database, E. P. U. (2025). Geopolitical Risk Index. . https://www.policyuncertainty.com/gpr.html?utm_source

DiMaggio, P. J., & Powell, W. W. (1983). The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. *American sociological review*, *48*(2), 147-160. https://www.torrossa.com/en/resources/an/5564159#page=123

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton university press. https://books.google.com.pk/books?id=VahsELa_qC8C&printsec=frontcover#v=onepage&q&f=false

Du, Y., & Wang, W. (2023). The role of green financing, agriculture development, geopolitical risk, and natural resource on environmental pollution in China. *Resources Policy*, *82*, 103440. https://doi.org/10.1016/j.resourpol.2023.103440

Dutta, A., & Dutta, P. (2022). Geopolitical risk and renewable energy asset prices: Implications for sustainable development. *Renewable Energy*, *196*, 518-525. https://doi.org/10.1016/j.renene.2022.07.029

FRED. (2025). World Uncertainty Index for Saudi Arabia. *Federal Reserve Bank of St. Louis;*. https://fred.stlouisfed.org/series/WUISAU

Fu, Y., & Liao, H. (2025). Dynamic Spillover Effects of Climate Policy Uncertainty on Energy and Carbon Markets. *International Journal of Finance & Economics*. https://doi.org/10.1002/ijfe.70111

Grossman, G. M., Krueger, A.B. (1991). Environmental impacts of the North American Free Trade Agreement. . *Cambridge Working Paper 3914*. https://doi.org/10.3386/w3914

Hambrick, D. C., & Mason, P. A. (1984). Upper echelons: The organization as a reflection of its top managers. *Academy of management review*, *9*(2), 193-206. https://doi.org/10.5465/amr.1984.4277628

Jiatong, W., Xu, Q., Sibt-e-Ali, M., Shahzad, F., & Ayub, B. (2023). How economic policy uncertainty and geopolitical risk affect environmental pollution: does renewable energy consumption matter? *Environmental Science and Pollution Research*, *30*(45), 101858-101872. https://doi.org/10.1007/s11356-023-29553-

y

Kayral, İ. E., Aktaş Bozkurt, M., Sarı, T., & Tandoğan Aktepe, N. Ş. (2025). Forecasting Global CO2 Emissions Under Economic, Geopolitical, and Policy Uncertainties: A Novel Hybrid Model. *Computational Economics*, *68*(1), 257-305. https://doi.org/10.1007/s10614-025-11060-6

Khan, A., Sun, C., Xu, Z., & Liu, Y. (2023). Geopolitical risk, economic uncertainty, and militarization: Significant agents of energy consumption and environmental quality. *Environmental Impact Assessment Review*, *102*, 107166. https://doi.org/10.1016/j.eiar.2023.107166

Kisswani, K. M., Elian, M. I., Lahiani, A., & Mefteh-Wali, S. (2024). The role of climate policy uncertainty, renewable energy use, and geopolitical risk towards low-carbon emission: Evidence from selected ASEAN countries. *Environmental Economics and Policy Studies*, *28*(1), 219-247. https://doi.org/10.1007/s10018-024-00430-3

Liu, T., Zhang, Y., Zhang, W., & Hamori, S. (2024). Quantile connectedness of uncertainty indices, carbon emissions, energy, and green assets: Insights from extreme market conditions. *Energies*, *17*(22), 5806. https://doi.org/10.3390/en17225806

Liu, Y. (2026). Environmental regulation, economic policy uncertainty, and geopolitical risk: Impacts on energy productivity in OECD countries. *Renewable Energy*, *257*, 124766. https://doi.org/10.1016/j.renene.2025.124766

Mnif, E., Jarboui, A., & Mouakhar, K. (2024). Strategic insights into carbon markets, digital finance and geopolitical risks for advancing green sustainability investments. *Management of Environmental Quality: An International Journal*, *35*(7), 1622-1649. https://doi.org/10.1108/MEQ-10-2023-0369

Ng, S., & Perron, P. (2001). Lag length selection and the construction of unit root tests with good size and power. *Econometrica*, *69*(6), 1519-1554. https://doi.org/10.1111/1468-0262.00256

Olaniyi, C. O., Al-Faryan, M. A. S., & Tabash, M. I. (2026). Does economic complexity have an asymmetric effect on natural resource rents? Evidence-based perspectives from Saudi Arabia. *Mineral Economics*. https://doi.org/10.1007/s13563-026-00611-4

Pata, U. K., Kartal, M. T., & Zafar, M. W. (2023). Environmental reverberations of geopolitical risk and economic policy uncertainty resulting from the Russia-Ukraine conflict: A wavelet based approach for sectoral CO2 emissions. *Environmental Research*, *231*, 116034. https://doi.org/10.1016/j.envres.2023.116034

Pesaran, M. H., Shin, Y., & Smith, R. J. (2000). Structural analysis of vector error correction models with exogenous I(1) variables. *Journal of Econometrics*, *97*(2), 293-343. https://doi.org/10.1016/S0304-4076(99)00073-1

Petrović, P., & Ostojić, I. (2025). Effects of policy induced uncertainty and geopolitical risk on renewable energy production: Econometric analysis. *Renewable Energy*, *255*, 123783. https://doi.org/10.1016/j.renene.2025.123783

Rao, A., Lucey, B., & Kumar, S. (2023). Climate risk and carbon emissions: Examining their impact on key energy markets through asymmetric spillovers. *Energy Economics*, *126*, 106970. https://doi.org/10.1016/j.eneco.2023.106970

Rashid, A., & Gopinathan, R. (2023). Revisiting the nexus between economic growth and disaggregated greenhouse gases in India: Evidence from necessary and sufficient conditions. *Journal of Cleaner Production*, *430*, 139514. https://doi.org/10.1016/j.jclepro.2023.139514

Shehri, T. A., Braun, J. F., Howarth, N., Lanza, A., & Luomi, M. (2023). Saudi Arabia's Climate Change Policy and the Circular Carbon Economy Approach. *Climate Policy*, *23*(2), 151-167. https://doi.org/10.1080/14693062.2022.2070118

Shin, Y., Yu, B., & Greenwood-Nimmo, M. (2014). Modelling Asymmetric Cointegration and Dynamic Multipliers in a Nonlinear ARDL Framework. In R. C. Sickles & W. C. Horrace (Eds.), *Festschrift in Honor of Peter Schmidt: Econometric Methods and Applications* (pp. 281-314). Springer New York. https://doi.org/10.1007/978-1-4899-8008-3_9

Shu, Y., Hossain, M. R., Tillaguango, B., Alvarado, R., Işık, C., Murshed, M., & Chen, Z. (2024). Geo-political risks, uncertainty, financial development, renewable energy, and carbon intensity: Empirical evidence from countries at high geo-political risks. *Applied Energy*, *376*, 124321. https://doi.org/10.1016/j.apenergy.2024.124321

Su, X., Razi, U., Zhao, S., Li, W., Gu, X., & Yan, J. (2025). Geopolitical risk and energy markets in China. *International Review of Financial Analysis*, *103*, 104187. https://doi.org/10.1016/j.irfa.2025.104187

Syed, Q. R., Bhowmik, R., Adedoyin, F. F., Alola, A. A., & Khalid, N. (2022). Do economic policy uncertainty and geopolitical risk surge CO2 emissions? New insights from panel quantile regression approach. *Environmental Science and Pollution Research*, *29*(19), 27845-27861. https://doi.org/10.1007/s11356-021-17707-9

Vetrova, M. A., Pakhomova, N. V., & Richter, K. K. (2023). Strategies for the development of the Russian energy industry in the conditions of climate challenges and geopolitical instability. *Vestnik Sankt-Peterburgskogo Universiteta. Ekonomika*, *39*(4), 439-469. https://doi.org/10.21638/spbu05.2023.401

Villanthenkodath, M. A., & Pal, S. (2024). Environmental degradation in geopolitical risk and uncertainty contexts for India: a comparison of ecological footprint, CO2 emissions, and load capacity factor. *Energy and Climate Change*, *5*, 100122. https://doi.org/10.1016/j.egycc.2023.100122

Yuen, T. H. A., & Yuen, W. K. T. (2024). Public investment on renewable energy R&D Projects: The role of geopolitical risk, and economic and political uncertainties. *Energy Economics*, *138*, 107837. https://doi.org/10.1016/j.eneco.2024.107837

Zivot, E., & Andrews, D. W. (1992). Further Evidence on the Great Crash, the Oil-Price

Shock, and the Unit-Root Hypothesis. *Journal of Business & Economic Statistics*, *10*(3). https://doi.org/10.2307/1391541