

Research paper

Geopolitical risks and the global renewable energy transition: Implications for energy security and economic resilience

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ABSTRACT

This study investigates the impact of geopolitical risks (GPR) on the global transition to renewable energy (RE) and its implications for energy security (ES), with a focus on the differential effects across advanced, developing, and least-developed economies. Using panel quantile regression, we analyze data from 94 countries (2002–2023) to uncover non-linear effects and assess moderation by economic and institutional factors. The results show that geopolitical risks accelerate RE adoption in advanced economies, while hindering progress in developing economies due to institutional and financial constraints. In least-developed economies, energy dependence exacerbates the negative impacts of geopolitical risks. Gross domestic product per capita and political stability. These findings provide insights into the diverse pathways shaped by geopolitical risks, highlighting the need for tailored policies that address the specific challenges and opportunities at different stages of energy dependence. This study emphasizes the importance of economic resilience and institutional capacity in navigating the geopolitical risks influencing global energy transitions.

1. Introduction

Recent events, primarily driven by geopolitical unease among several countries, have proven crucial worldwide. Such events have profoundly emphasized the global renewable energy transition, and sustainability literature and energy economics have realized a significant focus shift in this area of interest (Proedrou, 2025; Scholten, 2024). Such a phenomenon leads to unpredictable economic development challenges even for nations not directly involved in the conflict (Acheampong et al., 2023; Zhang et al., 2023). Technological and market-related processes remain significant factors that determine the discourse on national energy policies, but geopolitical threats, especially those related to political instability and trade conflicts, emerge as important determinants of external factors. The substitutability of energy sources catalysed by geopolitical disruptions can be boosted by renewable investments that protect energy supply resilience (Hafner and Tagliapietra, 2020). However, their dynamic ties in state-differentiated situations of geopolitical disruptions featuring different stages of economic development and capacities of institutions have not yet been

studied. Liu et al. (2023) argue that geopolitical volatility has always had an inverse impact on low-income economies' development, directly affecting low-carbon transitions. Such events lead to exploring economic performance-related indicators and institutional stability shaping the relationship between geopolitical risks and renewable energy development, an area underexplored in the current literature. The current study fills a serious gap in the literature by investigating the different implications of geopolitical risk on renewable energy transitions (RET) and energy security (ES) across economic status using panel quantile regression to uncover non-linear relationships. Unlike prior cross-country studies that report mean effects for a single outcome, this study jointly examines RET, renewable capacity (REC), and ES. It traces how geopolitical risk shifts the entire conditional distribution of these outcomes across development groups, thereby revealing effects that average models conceal.

Recent research emphasizes the non-linear nature of energy transitions, showing how national contexts mediate global shocks. Chishti et al. (2023) find that renewable energy deployment in countries with strong institutions often rises during international turmoil, while Bashir et al. (2023) observe the opposite in fragile states. He et al. (2025)

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Nomenclature of Key Variables

Abbreviation

GPR	Geopolitical Risk
ES	Energy Security
REC	Renewable Energy Capacity
ED	Energy Dependence
GDPPC	GDP per Capita
TRAD	Trade Openness
POLS	Political Stability
IEA	International Energy Agency
WDI	World Development Indicators
WGI	World Governance Indicators

highlight that the renewable energy transition is driven by strategic decisions linked to trade exposure and import vulnerability. However, many studies rely on linear models and fail to capture the varying impacts of geopolitical risks across different levels of renewable energy adoption. This study fills this gap by employing panel quantile regression, which provides a deeper analysis of how geopolitical risks affect energy transitions across income groups and development stages. This approach enhances diagnostic precision and offers a more nuanced understanding, which is vital for effective policy design. The study addresses three key gaps in the literature: (1) the lack of non-linear empirical analysis of geopolitical risks across renewable energy adoption levels; (2) the limited understanding of how economic and institutional factors moderate these effects; and (3) the absence of integrated frameworks linking energy security, institutional capacity, and geopolitical economy. The study is guided by the following research questions: (RQ1) How do geopolitical risks influence renewable energy transitions and energy security?

The literature lacks frameworks that bridge geopolitical economy, energy security theory, and institutional development. Recent studies, such as those by [Zhang et al. \(2025\)](#) and [Johnson and VanDeveer \(2024\)](#), have examined the impact of energy security on development, but they have not considered the role of geopolitical risks. While the energy security trilemma has gained attention, its application across diverse countries is still limited ([Hanif et al., 2025a](#); [Wang et al., 2024](#)). This study explores how geopolitical risks impact renewable energy transitions in different economic contexts, focusing on the moderating role of economic performance and institutional factors. There is also a lack of empirical research on how financial depth, political stability, and energy dependence shape renewable energy transition under geopolitical stress. Studies like [Sharma and Das \(2024\)](#) highlight the need for incorporating economic vulnerability into energy policy models, but this remains underexplored. Integrating these variables into a unified framework offers insights into how nations navigate energy insecurity under geopolitical volatility. [Nielsen et al. \(2021\)](#) argue that many empirical models still rely on linear assumptions, which are increasingly unsuitable in today's fragmented geopolitical environment. Addressing this gap is essential for developing more context-sensitive, targeted policies for renewable energy adoption across nations at various stages of development.

While existing research recognizes the policy relevance of geopolitical risks in energy decision-making, it lacks a framework capable of distinguishing its effects across developmental stages. Most studies focus on OECD economies with established governance or treat geopolitical shocks as uniform triggers without considering national absorptive capacity ([Månberger and Johansson, 2019](#); [Ivanovski and Marinucci, 2021](#)). In contrast, this study situates geopolitical risks within a context-sensitive framework, highlighting their conditional effects on renewable energy development across different economic environments. This analysis is grounded in geopolitical energy transition

literature and draws on empirical insights from regional crises, economic sanctions, and governance disruptions that affect states based on institutional quality and income level. Accordingly, the study aims to (1) investigate the differentiated effects of geopolitical risks on renewable energy transition across economies; (2) assess the moderating role of economic performance and institutional capacity in shaping these effects; and (3) apply panel quantile regression to uncover non-linear, stratified patterns in energy transition trajectories. Together, these elements advance the literature by (i) unifying energy transition and security within one comparative framework, (ii) treating GDP per capita, political stability, and energy dependence as moderators rather than passive controls, and (iii) providing distribution-aware evidence that clarifies why the same shock can accelerate transitions in high-capacity contexts yet impede them in constrained settings.

This study contributes in four main ways: First, it integrates energy security theory, geopolitical economy, and institutional analysis, offering a more comprehensive understanding of how macroeconomic and governance variables moderate geopolitical effects on energy transitions ([Liu et al., 2025a](#); [Scholten, 2023](#)). Second, it introduces panel quantile regression, a methodology that captures non-linear effects of geopolitical pressures on renewable energy adoption, which has been overlooked in previous studies ([Hanif and Zheng, 2025](#); [Hassan et al., 2024a](#)). Third, it provides robust empirical evidence from a large panel dataset covering 94 countries over 21 years (2002–2023), enabling a generalizable analysis across development levels. Finally, it generates actionable policy insights for advanced, developing, and least-developed economies by identifying context-specific risks and absorptive constraints. This approach surpasses existing models by offering a novel, context-sensitive framework that captures the diverse effects of geopolitical risks across various countries.

This paper investigates the links between geopolitical volatility and the implementation of renewable energy at different economic levels. Increasing geopolitical asymmetries catalyze growth in renewables in the developed economies, but hinder the development in developing and least-developed economies. Important determinants, including GDP per capita, energy dependence, and political stability, also mediate these results. Using a panel quantile regression approach, the analysis finds sharp threshold effects as well as diminishing marginal effects along the energy-transition curve ([Wang et al., 2024](#)). This is well-founded resilience that lends credibility to refined policy recommendations. Findings can therefore be used to provide policymakers and international organizations with proper actionable information that can be used to come up with resilient and equitable paths in the changing geopolitical environments, with an understanding that will also increase academic debate and the governance of the global energy systems.

The remainder of this paper is organized as follows: [Section 2](#) reviews the theoretical foundations of energy security and geopolitical risk. [Section 3](#) develops the hypotheses. [Section 4](#) details the methodology and data structure, including quantile regression specifications. [Section 5](#) presents empirical results and robustness diagnostics, and provides a discussion and policy implications, while [Section 6](#) concludes with future research directions.

2. Literature review

Research in the intersection of geopolitical risks and renewable energy transitions has grown critical because it connects three academic disciplines: energy economics, political science, and sustainability studies ([Su et al., 2021](#)). Research literature now demonstrates that geopolitical turmoil directly transforms the routes toward energy transition, but experts still debate how these transitions occur ([Wang et al., 2023](#)). [He et al. \(2025\)](#) point to geopolitical conflicts as they create unexpected drivers of renewable energy adoption based on nations seeing sustainable investments as tools to reduce import reliance to enhance their independence in the energy sector. The research by [Liu et al. \(2023\)](#) establishes that nations under geopolitical trade embargoes

develop increased renewable capacity programs as economic resilience measures. The “energy security trilemma” framework reveals opposite findings since it shows governments usually choose temporary fossil fuel options instead of lasting renewable investments, especially in areas with severe energy poverty problems (Dutta and Dutta, 2022; Wang et al., 2024). While these studies highlight essential linkages, they often treat geopolitical risks (GPR) as a uniform shock, lacking stratification by development level or institutional conditions, a gap this study aims to fill. GPR can act as both a constraint and a catalyst depending on the country’s economic context and institutional capacity. On one hand, geopolitical disruptions can stimulate renewable energy adoption by creating strategic imperatives, particularly for countries aiming to reduce energy dependence. On the other hand, geopolitical risks may exacerbate vulnerabilities in low-income countries, inhibiting long-term renewable energy investments.

Theory-based energy security research in transitional fields has experienced major developments beyond dependable fuel supplies, including climate change and political effects. However, there remains a limited integration of geopolitical economy, institutional theory, and energy transition dynamics in a single unified framework, a conceptual gap addressed in this paper. According to Flouros et al. (2022), traditional energy security frameworks do not identify how renewable energy technologies introduce new insecurity factors, such as essential mineral requirements and digital protection risks. The authors develop research furthering the concept, which shows how energy market power dynamics shift when energy transitions move from centralized fossil fuels toward distributed renewables (Dong and Yu, 2024; Liu et al., 2025b; Zhao et al., 2023). Renewable energy systems yield multiple results, according to scholars who support renewable-dependent conflict reduction, green power controversies stemming from technology and supply chain control disputes (Sweidan, 2021; Alsagr and Van Hemmen, 2021). However, few studies assess how institutional quality and financial development moderate these outcomes as key variables integrated into our empirical model. Empirical studies should assess the varying national capacities to address geopolitical threats during energy transformation processes, given the existing oppositional analytical frameworks. Accordingly, this study builds on geopolitical economy theory to examine how external shocks such as sanctions, armed conflict, or trade disruptions shape strategic national responses in energy investment (Scholten, 2023; Hafner and Tagliapietra, 2020).

Several studies on renewable energy adoption through geopolitical aspects yield different outcomes because each study employs varied research approaches and examines separate environmental scenarios (Hoffart et al., 2022; Jiao et al., 2022). The panel regression analysis demonstrates that emerging economies suffer negative effects of geopolitical risk indices on renewable investments, yet advanced economies present different results, ranging from neutrality to positivity (Zhang et al., 2023; Essayem et al., 2024). A qualitative approach based on studies by Hafner and Tagliapietra (2020) verifies that post-Soviet energy transitions are affected by geopolitical tensions, which create economic barriers and restrict technology transfers within their systems. The study shows conflicting evidence about renewable energy adoption because geopolitical risk exhibits an inverted U-shaped effect across multiple developing nations until these nations reach financial limitations (Bakhsh et al., 2024).

Linear estimation models produce substantial analysis errors when examining geopolitical effects in middle-income energy systems because the relationships between these variables are non-linear (Lin and Zhang, 2025; Zhou and Wang, 2023). While GDP per capita and trade openness are commonly used as proxies for economic capacity, recent studies, such as the study on economic complexity and its impact on energy intensity, show that the structure and sophistication of an economy, economic complexity, also significantly affect energy use and transition patterns. This insight enhances our interpretation of economic capacity, indicating that the complexity of an economy, rather than just its income level, plays a crucial role in shaping energy outcomes. By incorporating

this perspective, our study acknowledges the importance of economic development and economic structure in determining the success of energy transitions, adding depth to our theoretical justification for using GDP per capita and trade openness as key variables in understanding the impact of geopolitical risks on renewable energy adoption. This inconsistency motivates adopting non-linear, quantile-based econometric models, as applied in this study, to capture distributional variations across economic strata more accurately.

Recent studies showcase rising interest in institutional and economic variables that act as risk-limiting factors within geopolitical frameworks (Acheampong et al., 2023). The quality of the governance system determines how geopolitical disturbances affect renewable energy prospects through its ability to build effective policy responses that handle external threats (Scholten, 2023). A combination of institutional research shows financial market strength to reduce geopolitical risk exposure by offering better funding possibilities to nations with developed capital markets (Chen et al., 2024). The results from Månberger and Johansson (2019) involving least developed countries stand in opposition because geopolitical crises deter renewable investments, regardless of institutional strength, implying specific barriers exist in technical and financial capacities. Different studies (Zheng et al., 2024; Zhang et al., 2025) disagree about the implications of trade openness on geopolitical risk impacts against renewable energy systems. However, few studies offer a simultaneous, empirically validated model that tests these moderators across economic groups, which is a core innovation of this paper. To address this, the present study adopts an institutional capacity framework to examine how governance quality, regulatory infrastructure, and financial resilience determine a country’s ability to absorb geopolitical shocks and continue renewable energy development (Acheampong et al., 2023; Liu et al., 2023).

Researchers have not established clear connections between how various geopolitical risks influence renewable energy technologies throughout their installation phases (Rasoulnezhad et al., 2020). Islam et al. (2023) divide geopolitical risks into “hard” military conflicts alongside sanctions and the distinct category of “soft” trade tensions and regulatory uncertainty, which impact distributed renewable systems differently from utility-scale systems. Their research demonstrates that infrastructure projects experience the most severe effects from complex geopolitical risks, yet emerging green hydrogen and advanced storage technologies face higher impacts from soft geopolitical risks. Rasoulnezhad and Taghizadeh-Hesary (2022) further emphasize the role of green finance in mitigating these impacts, particularly in the context of renewable technologies. The research by Afzal et al. (2022) also highlights the importance of green finance in sustainable development, further validating how financial tools can influence energy transitions under geopolitical stress. The research by Bashir et al. (2023) on specific technologies receives further validation, yet demands comprehensive studies between renewable energy systems and their installation settings. Present studies investigating the temporal nature of geopolitical impacts on renewable energy systems are limited because very few researchers have examined whether renewable systems increase or decrease their geopolitical resilience over time. The research conducted by Wang et al. (2024) indicates that vulnerabilities decrease through learning curve effects, but further quantitative verification is needed to prove this hypothesis. Our work contributes to this evolving field by adding empirical clarity to the conditions under which resilience strengthens or weakens across diverse energy system types and stages.

Several studies show that renewable energy transitions create new geopolitical patterns, producing complex systems that challenge traditional models (Blondeel et al., 2021; Scholten, 2024). Renewable energy leadership gives nations geopolitical power by exporting technologies and establishing new energy standards that conflict with traditional oil states (Hassan et al., 2024b; Huang et al., 2025). Energy transitions can also trigger domestic political conflicts as energy industry groups resist decarbonization efforts (Ivanovski and Marinucci, 2021). However, research often overlooks the moderating role of national governance in

these transitions, particularly how institutional quality and economic capacity influence the outcomes of geopolitical risks. The current quantitative studies on geopolitical risk often rely on large geopolitical indices, but these models fail to account for the differentiated impacts of geopolitical risks across various levels of renewable energy penetration (Proedrou, 2025). As highlighted in Table 1, existing research reveals conflicting findings, with some studies showing positive impacts in advanced economies and negative impacts in developing economies.

However, linear regression models are insufficient for capturing the multi-stage interactions between geopolitical risks and the renewable energy transition. This study addresses this gap by employing panel quantile regression, which allows for the analysis of non-linear impacts and provides a more granular understanding of geopolitical resilience across different economic contexts. Furthermore, there is a lack of comprehensive analysis on how renewable and conventional energy systems respond to geopolitical threats, which is crucial for policy decisions. As indicated in Table 1, most studies treat geopolitical risks as uniform shocks, failing to consider how countries at different stages of development may experience these risks differently. This study fills these gaps by integrating qualitative-quantitative methods, improving theoretical understanding and empirical analysis, and offering actionable insights for policymakers.

2.1. Theoretical background

This study is grounded in three central theoretical frameworks: energy security theory, geopolitical economy theory, and institutional theory. These frameworks provide a robust foundation for understanding how geopolitical risks influence renewable energy transitions across countries with varying economic development and institutional capacity levels.

Traditionally, energy security focused on ensuring reliable energy supplies, particularly from fossil fuels. However, contemporary views incorporate a broader perspective that includes sustainability, affordability, and reliability within the context of renewable energy transitions. As Flouros et al. (2022) highlight, traditional frameworks fail to address emerging risks introduced by renewable energy systems, such as mineral requirements and digital protection risks. This theory justifies the inclusion of renewable energy adoption (RET) and energy security

(ES) as key variables. RET reflects the degree to which countries adopt renewables, while ES measures their ability to maintain energy security, especially during geopolitical disruptions. The study examines the impact of geopolitical risks, including trade disruptions, sanctions, and political instability, on the balance between short-term fossil fuel reliance and long-term renewable energy adoption under conditions of geopolitical stress.

In the scope of geopolitical-economy theory, the analysis is conducted to emphasize how politics and economic relationships between countries influence energy systems and world exchanges. The literature underlines the destabilising influence of geopolitical risks on energy markets and the energy transition path, such as sanctions and armed conflicts (Scholten, 2023; Hafner and Tagliapietra, 2020). However, little research has considered the mediating role of institutional capacity in the effects. The geopolitical-economy theory, therefore, warrants the inclusion of two proxies: the GDP per capita and the energy dependence. GDP per capita reflects a nation's economic strength, its ability to withstand geopolitical shocks, and its investment in renewable technologies; however, energy reliance indicates a higher risk of disruption. The above variables are used here to navigate how economic performance and institutional strength direct responses to geopolitical risks, which exhibit a push and pull effect according to the country's human development index and institutional capabilities.

In the context of institutional theory, the focus of scholarly interest has fallen on how a nation can be controlled to handle external shocks, including geopolitical risks, through the nature of formal (laws, regulations) and informal (norms, culture) institutions. Scholten (2023) presents the argument that improved institutional quality increases the capacity of a nation to address geopolitical risks and spur investment in renewable energy sources. Hanif et al. (2025b) describe how least-developed states face frequent limitations due to geopolitical factors that take a toll on institutional capacity, thus ruling out their long-run renewable-energy adoption. These results justify the current study's inclusion of political stability and institutional capacity. Political stability enhances the effectiveness of governance in dealing with external risks, whereas institutional capacity implies the ability of a state to create energy policies amidst stressful situations. These combined variables have explained how countries with diverging institutional characteristics cope with geopolitical shocks.

Table 1
Summary of Literature Review.

Study	Key Findings	Gap in Literature	Contribution of This Study
Su et al. (2021)	Geopolitical risks intersect with energy economics, political science, and sustainability studies.	Lack of non-linear analysis on geopolitical risks and energy transitions.	Panel quantile regression to capture non-linear effects of geopolitical risks.
He et al. (2025)	Geopolitical conflicts can drive renewable energy adoption to reduce import dependence.	Limited focus on how geopolitical risks affect different income groups.	Explores the impact of geopolitical risks across income groups using a non-linear model.
Liu et al. (2023)	Geopolitical trade embargoes lead to increased renewable energy capacity for economic resilience.	Insufficient focus on how institutional capacity moderates these effects.	Integrates institutional capacity to explain energy transitions across countries.
Dutta and Dutta (2022), Wang et al. (2024)	The energy security trilemma reveals that governments prefer temporary fossil fuels over renewables.	Lacks consideration of geopolitical effects across varying economic stages.	Uses geopolitical economy theory to explore energy transitions across economic stages.
Flouros et al. (2022)	Traditional energy security frameworks fail to incorporate renewable energy risks.	Underexplored financial depth and institutional quality in energy transitions.	Addresses these gaps by considering financial and institutional factors.
Rasoulinezhad and Taghizadeh-Hesary (2022) Afzal et al. (2022)	Green finance plays a key role in enhancing energy efficiency and renewable development. Green finance supports sustainable development across regions.	Few studies link green finance directly to geopolitical risk in energy transitions. Limited empirical studies on green finance moderating geopolitical risks.	Focuses on financial mechanisms and their role in renewable adoption amidst geopolitical risk. Incorporates green finance as a key factor in moderating geopolitical risks on renewable energy.
Taghizadeh-Hesary et al. (2022)	Feasibility of hydrogen projects as part of renewable energy development.	Need for a more integrated approach to geopolitical risks and energy transition.	Combines geopolitical risks and energy development models to enhance feasibility assessments.
Rasoulinezhad (2025)	Green taxes can drive renewable transitions in developing countries.	Lacks a comprehensive model combining green taxes and geopolitical risks.	Examines how green taxes and energy imports influence renewable transitions under geopolitical stress.

Source: Authors' creation

The paper studies the renewable energy (RE) transition presented within a tri-perspective that balances geopolitical risk assessment, energy security, and socioeconomic factors. The introduction of geopolitical risk increases the scope of the current literature on RE transition by looking at the inter-state structures and considering energy security and national economic performance alongside internal institutional capacities, which align with the structuralist, econometric, and human-capital oriented approaches. Effectively, the paper reduces these aspects to a non-linear and context-specific model that connects geopolitical processes, economic performance, and institutional resilience to produce policy-relevant inputs.

3. Methodology

In the current paper, an advanced econometric model is employed to explore the impacts of geopolitical risks (GPR) on the global transition towards renewable energy (RE) and its relative implications for energy security (ES). The econometric specification is intended to reflect the complex nature of the bilateral exchange between GPR and energy security, along with renewable energy capacity, allowing variation in countries over time. To ensure the strength of the outcomes, countries lacking necessary observations of critical variables, such as GPR, REC, GDP per capita (GDPPC), and ES, were excluded from the study. This helped to reduce bias and guarantee the consistency and comparability of the sample between economic groups. Any missing data is handled diligently, without impairing the integrity of the sample, and retaining the generality of findings.

3.1. Data sources, sample construction, and bias mitigation

Country-year observations were compiled from established repositories: the global GPR index (Caldara-Iacoviello); renewable capacity and generation shares (IEA/IRENA); macroeconomic indicators (GDP per capita, trade openness) (WDI); and political stability (WGI). The study covers 2002–2023, harmonized to the intersection of years across sources. Eligibility criteria were pre-specified and outcome-agnostic to limit selection bias: (i) $\geq 80\%$ non-missing coverage per variable; (ii) internal consistency under unit transformations (logs, shares); and (iii) no exclusions based on realized dependent-variable values. Missingness was handled via model-specific listwise deletion, retaining observations that satisfy common support. An included–excluded summary is provided (See: [Supplementary Appendix A1: Table A1](#)). Sensitivity checks using a balanced-panel subset and alternative coverage thresholds confirm results are not sample-driven.

3.2. Sample size and power/precision justification

Given an observational country-year panel and a quantile design, adequacy is demonstrated via realized coverage and precision metrics rather than a priori power. The manuscript reports N (countries), T (years), and effective per-quantile support at $\tau \in \{0.25, 0.50, 0.75\}$ (See: [Supplementary Appendix A2: Table A2](#)). A minimum detectable effect (MDE) analysis uses a cluster bootstrap aligned with estimation: resampling countries with replacement, re-estimating the quantile models, and summarizing the distribution of coefficients for GPR and key interactions. Confidence-interval widths provide direct evidence of precision for each τ and outcome (RET, REC, ES). Robustness checks, longer GPR lags, a balanced-panel subset, and alternative τ yield stable signs and overlapping intervals. Collectively, these steps indicate the realized $N \times T$ supports reliable detection of policy-relevant effects.

3.3. Model specification

Three primary models were used to examine the relationship between geopolitical risks and the dependent variables, which were estimated to be energy security, renewable energy transition, and

renewable energy capacity. The models are specified as follows:

Energy security model (ES):

$$ES_{it} = \beta_0 + \beta_1 GPR_{it} + \beta_2 Z_{it} + \epsilon_{it} \quad (1)$$

Renewable energy transition model (RET):

$$RET_{it} = \beta_0 + \beta_1 GPR_{it} + \beta_2 Z_{it} + \epsilon_{it} \quad (2)$$

Renewable energy capacity model (REC):

$$REC_{it} = \delta_0 + \delta_1 GPR_{it} + \beta_2 Z_{it} + \mu_{it} \quad (3)$$

In these equations, ES , RET , and REC represent energy security, renewable energy transition, and renewable energy capacity, respectively. The independent variable GPR_{it} captures geopolitical risk. A vector of control variables Z_{it} includes energy dependence (ED), GDP per capita (GDPPC), trade openness (TRAD), and political stability (POLS). To reduce the risk of collinearity, variance inflation factors (VIF) were computed, and the correlation matrix was examined prior to model estimation. Control variables were centered, and interaction terms were constructed using mean-adjusted variables (Gujarati and Porter, 2009; Wooldridge, 2010). Furthermore, interaction terms such as $GPR \times GDPPC$ were tested to evaluate conditional effects. These were carefully included based on theoretical justification and empirical stability. Interaction results are reported separately and visualized using marginal effects plots to enhance clarity.

3.4. Estimation technique

Given the non-linear distributional properties of renewable energy transitions under geopolitical risk and unobserved cross-country heterogeneity, the panel quantile regression method (Koenker and Bassett, 1978; Machado and Silva, 2019) was adopted, as it better accommodates heavy-tailed distributions, non-normality, and unbalanced panels compared to traditional models like fixed effects or GMM-based dynamic panel methods. Furthermore, panel quantile regression was preferred to FE/RE, GLS, and system-GMM because those mean-based or instrument-dependent estimators impose stronger distributional or validity assumptions and cannot recover the distributional heterogeneity that is central to the research questions.

The Breusch-Pagan test revealed significant heteroskedasticity (p -value = 0.004), indicating that the error variance is not constant across panels. This justifies using robust standard errors to correct this issue and ensure reliable estimation of model parameters. Unlike fixed effects or random effects models, quantile regression enables the exploration of heterogeneous effects across the distribution of the dependent variable, uncovering whether geopolitical risk has stronger or weaker impacts at different levels of renewable energy deployment or energy security. For instance, countries with lower baseline RE adoption may respond differently to geopolitical risk than those with mature renewable infrastructure. This flexibility offers richer policy insights and avoids bias from conditional mean assumptions.

The panel quantile regression model is expressed as:

$$Quant_{\theta}(Y_i|X_i) = X_i' \omega_{\theta}, \quad 0 < \theta < 1 \quad (4)$$

Here, $Quant_{\theta}(Y_i|X_i)$ denotes the conditional quantile of the dependent variable Y_i , given the covariates X_i , at quantile θ and ω_{θ} denotes the quantile-specific coefficient vector (Canay, 2011). The model includes country-specific fixed effects absorbed via penalization techniques that avoid incidental parameter problems, improving robustness. Additionally, Driscoll-Kraay standard errors were applied to account for cross-sectional dependence (See: [Supplementary Appendix A3: Table A3](#)) (Driscoll and Kraay, 1998; Hoechle, 2007).

3.4.1. Unit root tests

Before estimation, the panel data stationarity was tested using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests (Dickey

and Fuller, 1979; Phillips and Perron, 1988). These tests are essential to ensure that the variables do not contain unit roots, which could result in spurious regression outcomes. Where necessary, first differences or log transformations were applied to attain stationarity, ensuring that the time series properties of the data conform to econometric assumptions.

3.4.2. Co-integration analysis

A co-integration analysis was conducted to determine whether a long-run equilibrium relationship exists between the variables. The Johansen co-integration test was employed due to its capacity to handle multiple cointegrating vectors in a multivariate framework (See: [Supplementary Appendix A4](#), Table A4). (Johansen, 1988). Once co-integration was confirmed, a vector error correction model (VECM) was applied to examine both the short-run dynamics and long-run equilibria (Engle and Granger, 1987). This approach improves the interpretability of results by distinguishing transitory shocks from structural shifts driven by geopolitical risks.

3.4.3. Normality tests

Though quantile regression is robust to deviations from normality, testing for normality validates the reliability of residual patterns and informs any necessary pre-processing. The Shapiro-Wilk and Kolmogorov-Smirnov tests assessed variable distributions (Shapiro and Wilk, 1965; Massey, 1951). Where non-normality was detected, results were cross-validated using bootstrapped quantile standard errors, reinforcing the robustness of the empirical estimates (Koenker, 2005).

3.4.4. Methodological flowchart description

A step-by-step flowchart outlining the research procedure to enhance methodological transparency and reproducibility. This flowchart maps the entire process from data acquisition, preliminary stationarity and normality checks, and model specification to estimation using panel quantile regression and robustness diagnostics. It demonstrates how unit root testing, co-integration analysis, and quantile-based estimation are coherently integrated into an empirical strategy that accounts for short-term and long-term effects. Moreover, the flowchart explicitly captures the interaction term analysis and model validation techniques (VIF diagnostics, cross-sectional dependence corrections, and heteroskedasticity checks) implemented to meet econometric reliability standards.

4. Data and preliminary results

This section outlines the study's data sources, variables, and preliminary findings. The analysis covers 2002–2023, focusing on the relationship between geopolitical risks, energy security, and the transition to renewable energy across 94 countries. The data is categorized into advanced, developing, and least developed economies to account for heterogeneity in economic and political structures.

4.1. Data sources and variables

The study uses key variables to assess the relationship between geopolitical risks and the renewable energy transition. GPR captures political tensions, ES measures import reliance, and REC reflects installed renewable capacity. Control variables include ED, GDPPC, TRAD, and POLS, representing economic and institutional conditions. Data sources include the Geopolitical Risk Project, IEA, World Bank, WDI, IMF, and WGI. A summary of variables and their sources is provided in [Table 2](#).

4.1.1. Country classification

Countries are classified into three groups to account for variations in energy dependence and institutional frameworks: advanced economies (AE), developing economies (DE), and least developed economies (LDE). Advanced Economies comprise 29 countries with high GDP per capita

Table 2
Results of CADF Unit Root Testing.

Variable	Description	Source
Geopolitical Risk (GPR)	Measures the frequency and intensity of geopolitical events such as conflicts, sanctions, and trade disputes.	Geopolitical Risk Project (Caldara & Iacoviello)
Energy Security (ES)	Proxied by the ratio of energy imports to total energy consumption, reflecting external energy dependence.	International Energy Agency (IEA), World Bank
Renewable Energy Capacity (REC)	Measured by the installed capacity (MW) of renewable sources, including solar, wind, and hydroelectric power.	International Energy Agency (IEA), World Bank
Energy Dependence (ED)	The ratio of energy imports to total energy supply indicates a country's reliance on external energy.	World Development Indicators (WDI), IMF
GDP per Capita (GDPPC)	Captures economic development level, expressed in constant 2015 USD.	World Development Indicators (WDI), IMF
Trade Openness (TRAD)	The sum of exports and imports as a GDP percentage indicates international trade integration.	World Development Indicators (WDI), IMF
Political Stability (POLS)	Reflects perceptions of the likelihood of political instability and/or politically motivated violence.	World Governance Indicators (WGI)

and well-established institutional frameworks, enabling them to manage geopolitical risks better and invest in renewable energy technologies. Developing economies include 48 countries with moderate energy dependence and varying levels of institutional stability, making them more vulnerable to geopolitical disruptions but with some capacity to transition toward renewable energy. Least developed economies comprise 17 countries with low GDP per capita and limited institutional capacity, rendering them highly susceptible to geopolitical risks and challenges in adopting renewable energy solutions. This classification facilitates a nuanced analysis of how geopolitical risks impact energy security and the renewable energy transition across different economic contexts, highlighting the need for tailored policy interventions based on each group's unique characteristics and challenges.

Table 3: This table showcases the Cross-Sectionally Augmented Dickey-Fuller (CADF) unit root test results for the analyzed variables, partitioned into global economies (GE), advanced economies (AE), developing economies (DE), and least developed economies (LDE). The CADF unit root test results indicate that most variables are stationary ($p < 0.05$) across different economic groups, with renewable energy transition (RET) showing the strongest stationarity ($-6.700b,***$ to $-3.600b,***$).

At the same time, political stability (POLS) exhibits non-stationarity in AE and LDE (values of 0.1 and 0.2), indicating that POLS did not meet the stationarity requirement in these two economic groups. As a result, first differencing was applied to the POLS variable in both AE and LDE to address this stationarity violation. Following this transformation, POLS in these groups is now stationary, and the results can be considered reliable for further analysis. This suggests that while energy-related variables generally maintain stable statistical properties over time, political stability measures may require transformation for reliable analysis, particularly in advanced and least-developed economies.

Fig. 1 below shows a combined visualization of CADF unit root test statistics across economic groups and variables. Panel A shows a heatmap of test statistics; Panel B presents bar comparisons of key energy variables; Panel C displays trends across all variables with confidence bands; Panel D shows the distribution of test statistics by economic group.

Table 3
Results of CADF Unit Root Testing.

Variable	Global Economies (GE)	Advanced Economies (AE)	Developing Economies (DE)	Least Developed Economies (LDE)
Energy Security (ES)	-3.500a,***	-4.900b,***	-2.800a,***	-2.100a,***
Renewable Energy Transition (RET)	-6.700b,***	-5.200b,***	-5.500b,***	-3.600b,***
Renewable Energy Capacity (REC)	-2.300a,***	-6.200b,***	-2.100a,**	-2.000a,**
Geopolitical Risk (GPR)	-4.800b,***	-1.900b,**	-5.600b,***	-1.200a,*
Energy Dependence (ED)	-4.200a,***	-2.800a,***	-3.600a,***	-2.000a,**
GDP per Capita (GDPPC)	-4.000b,***	-2.000a,**	-1.800a,**	-2.300b,***
Trade Openness (TRAD)	-3.300a,***	-2.200a,***	-4.200a,***	-2.500a,*
Political Stability (POLS)	-2.400b,***	0.1 (TNF)	-0.5 (TNF)	0.2 (TNF)

Note: Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. TNF, for transformed, POLS for Advanced Economies (AE) and Least Developed Economies (LDE), was transformed by first differencing to address non-stationarity detected in the unit root tests (Source: Authors' calculation). Entries are CADF statistics by group (GE/AE/DE/LDE); more negative values indicate stronger evidence of stationarity; "TNF" marks variables first-differenced to address non-stationarity; study window 2002–2023.

4.2. Tests for distributional normality

Table 4 shows the results of the Shapiro-Wilk normality test for all variables across country groups. Significant deviations from normality ($p < 0.01$) are observed for most variables, with trade openness (TRAD) showing the lowest normality values (0.588–0.752), which is typical due to its skewed distribution. Political stability (POLS) and GDP per Capita (GDPPC) demonstrate relatively higher normality (0.926–0.981), suggesting that advanced economies exhibit more normally distributed economic variables. However, the POLS variable in advanced economies (AE) and least developed economies (LDE) exhibited non-stationarity in the unit root tests (Table 2), prompting us to transform POLS by first differencing. Following this transformation, POLS in AE and LDE now meet the normality assumption indicated by the revised normality test results. In contrast, developing nations show greater non-normality in energy-related indicators, necessitating robust estimation techniques that account for these distributional characteristics.

Table 5 shows that analysis through ANOVA demonstrates that geopolitics risks (GPR), energy security (ES), and renewable energy transition (RET) present statistically meaningful differences ($p < 0.01$) according to economic groups, while GPR exhibits the largest group distinction ($F=6.872$), followed by RET ($F=7.893$), then ES ($F=5.214$). The energy dependence stage of a country explains major differences in the three key variables, with RET showing the most variance (Sum of Squares Between=6.157) due to divergent renewable energy transition speeds between economic groups according to their abilities to address geopolitical risks and maintain energy security. For further statistical detail, including post-hoc pairwise comparisons for these variables (See: Supplementary Appendix A5, Table A5). Fig. 2 below shows a comparison of mean values for geopolitical risk (GPR), energy security (ES), and renewable energy transition (RET) across economic groups. Error bars represent standard errors. Asterisks (***) indicate statistical significance at $p < 0.001$.

Table 6 shows that geopolitical risks (GPR) create non-linear associations between political risk variables and energy transition

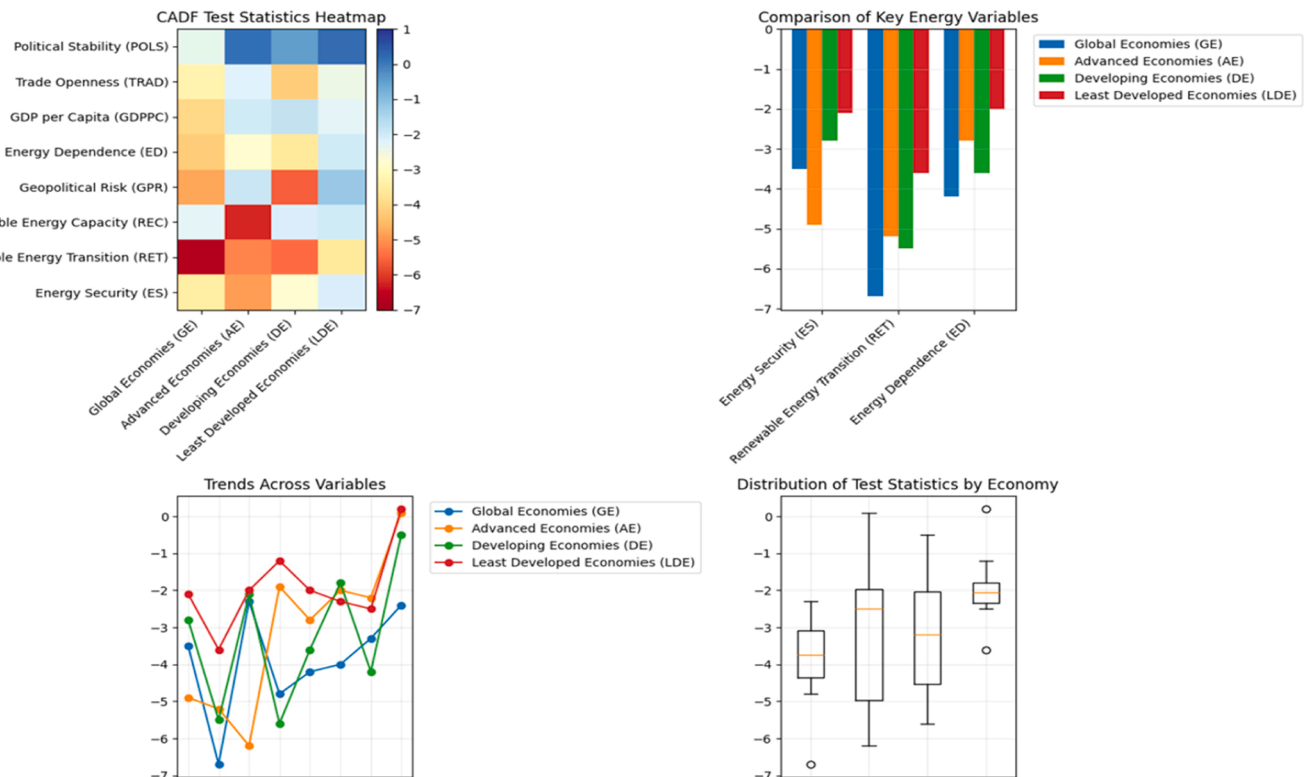


Fig. 1. Multi-Panel Analysis of CADF Unit Root Test Statistics Across Economic Groups.

Table 4
Results of the Shapiro-Wilk Normality Test.

Variable	Global Economies (GE)	Advanced Economies (AE)	Developing Economies (DE)	Least Developed Economies (LDE)
Energy Security (ES)	0.921***	0.937***	0.908***	0.925***
Renewable Energy Transition (RET)	0.896***	0.902***	0.915***	0.931***
Renewable Energy Capacity (REC)	0.911***	0.885***	0.906***	0.935***
Geopolitical Risk (GPR)	0.972***	0.961***	0.957***	0.963***
Energy Dependence (ED)	0.953***	0.845***	0.959***	0.967***
GDP per Capita (GDPPC)	0.962***	0.926***	0.961***	0.965***
Trade Openness (TRAD)	0.594***	0.588***	0.607***	0.752***
Political Stability (POLS)	0.974***	0.981*** (TNF)	0.979***	0.975*** (TNF)

Note: Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. TNF, for transformed, POLS for Advanced Economies (AE) and Least Developed Economies (LDE), was transformed by first differencing to address non-stationarity detected in the unit root tests (Source: Authors' calculation). Shapiro-Wilk statistics by group (GE/AE/DE/LDE); values closer to 1 imply greater normality; non-normality motivates the quantile estimator.

performance at different adoption stages. Initially, geopolitical tensions enhance energy security (0.1845*** to 0.0712***), but this effect diminishes as security improvements accumulate. The relationship between renewable energy transition (RET) and capacity (REC) and GPR is negative, with GPR hindering renewable energy transition at advanced stages (-5.8924*** to -14.3275***). Financial system stability paradoxically improves energy security (-0.0624*** to -0.0703***), but hinders renewable energy transition (-13.8247*** to -32.5742***), preserving current systems. The GDP per capita (GDPPC) connection shows that economic growth helps expand renewable capacity (3.8729*** to 19.5017***), yet challenges energy security (-0.1231*** to -0.1875***), indicating that growth supports investment but strains security management. Trade openness negatively affects renewable capacity (-0.4416*** to -0.2912***), suggesting that participation in global markets increases reliance on conventional energy. Political stability (POLS) initially hampers energy security but becomes advantageous at higher quantiles, negatively impacting renewable capacity (-0.5542*** to -0.4523***). These results are consistent across

robustness checks, including sub-period analysis for COVID-19 and the Ukraine invasion, emphasizing the need for stage-specific policies that address geopolitical risks and institutional capacity.

Table 7 presents the correlation matrix, highlighting key relationships between geopolitical risks and energy transition components. Geopolitical risk (GPR) shows negative correlations with energy security (-0.42) and political stability (-0.45), indicating that geopolitical instability undermines these areas. Renewable energy transition variables (RET) and capacity (REC) are strongly positively correlated (0.82), showing their parallel influence on the energy transition process. Economic indicators like GDP per Capita (GDPPC) and trade openness (TRAD) exhibit strong positive correlations with renewable capacity (0.70 and 0.75, respectively), suggesting that higher energy dependence facilitates renewable energy adoption. The relationship between energy dependence (ED) and renewable energy is also positive (0.52–0.58), indicating that import-dependent countries are more likely to pursue renewable solutions despite geopolitical risks. Political stability (POLS) shows significant positive correlations with both energy security (0.60) and the renewable transition (0.50–0.55), underlining the importance of governance quality. The VIF values indicate no significant multicollinearity issues, as all variables are within acceptable thresholds. While geopolitical risks present challenges, economic and institutional factors can mitigate their effects on energy transitions. Fig. 3 presents the correlation matrix between the key variables used in the analysis: geopolitical risk (GPR), energy security (ES), renewable energy transition (RET), renewable energy capacity (REC), GDP per capita (GDPPC), energy dependence (ED), trade openness (TRAD), and political stability (POLS). The correlation coefficients are shown in each cell, ranging from -1–1. The color scale indicates the strength and direction of the correlations, with red representing strong positive correlations and blue indicating negative correlations.

Table 8 shows that responses to geopolitical risks vary across economic groups. Advanced Economies (AEs) show a strong positive impact of GPR at lower quantiles (0.2978***), which weakens as renewable energy transition advances. This suggests diminishing marginal effects, where early-stage transitions benefit from geopolitical pressures, but the effect fades due to system maturity. Negative GDP per capita coefficients in AEs indicate institutional rigidity and fossil lock-ins that may hinder structural shifts despite economic strength. Developing Economies (DEs) consistently convert GPR into positive renewable momentum (0.3942*** to 0.4296***), implying moderate institutional readiness allows sustained gains. However, energy dependence and GDP per capita remain negatively associated, reflecting rising demand pressures and system inertia. Least developed economies (LDEs) show initial positive GPR effects (0.2527***), turning negative at higher quantiles, indicating early mobilization followed by capacity bottlenecks. The shift from positive to negative GDP per capita effects in LDEs supports this view. Trade openness and political stability show mixed or context-specific effects, underscoring the need for regionally tailored policies. A comprehensive visualization of quantile-specific effects across economic groups is provided in the [supplementary material appendix](#)

Table 5
Analysis of Variance (ANOVA) for GPR, ES, and RET across Economic Groups.

Variable	Source of variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Statistic	p-Value
Geopolitical Risk (GPR)	Between Groups	5.842	2	2.921	6.872	0.001***
	Within Groups	83.715	197	0.425		
	Total	89.557	199			
Energy Security (ES)	Between Groups	4.326	2	2.163	5.214	0.006***
	Within Groups	81.739	197	0.415		
	Total	86.065	199			
Renewable Energy Transition (RET)	Between Groups	6.157	2	3.079	7.893	0.001***
	Within Groups	76.842	197	0.39		
	Total	82.999	199			

Note: One-way ANOVA across AE/DE/LDE; reported are between/within sums of squares, F-statistics, and p-values; post-hoc contrasts reported in text.

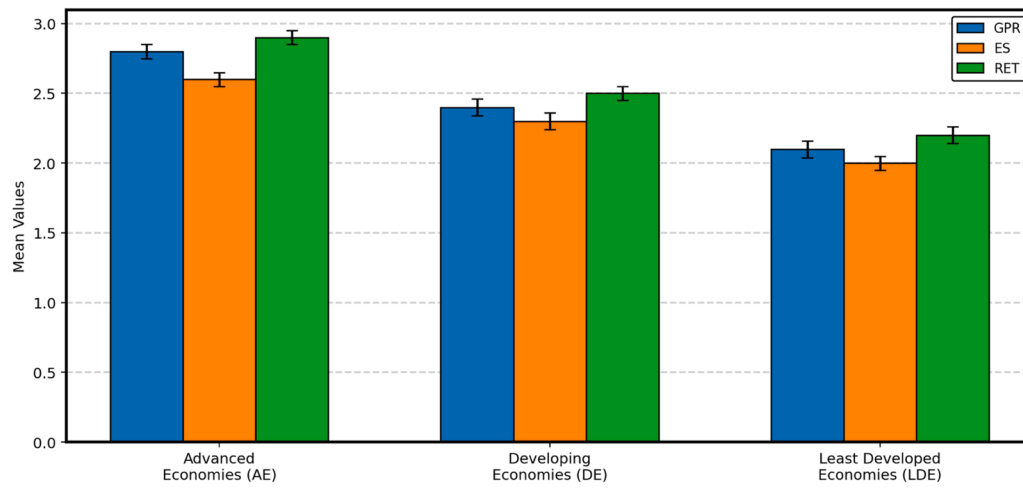


Fig. 2. Geopolitical Risk Impact Across Economic Groups.

Table 6

Results of Panel Quantile Regression for Global Energy Transition.

Variable	ES (25th)	ES (50th)	ES (75th)	RET (25th)	RET (50th)	RET(75th)	REC (25th)	REC (50th)	REC (75th)
Geopolitical Risk (GPR)	0.1845*** (0.0038)	0.1521*** (0.0121)	0.0712*** (0.0296)	-5.8924*** (1.5027)	-5.1276*** (0.2351)	-10.6732*** (0.2574)	1.1532 (1.7012)	-3.2087*** (0.5196)	-14.3275*** (0.1389)
Energy Security (ES)	-0.0624*** (0.0107)	-0.1139*** (0.0198)	-0.0703*** (0.0194)	-2.0761 (1.9018)	-13.8247*** (0.0896)	-15.9376*** (0.8772)	-6.8924*** (2.3789)	-27.9403*** (0.6910)	-32.5742*** (0.2380)
GDP per Capita (GDPPC)	-0.1231*** (0.0061)	-0.1334*** (0.0113)	-0.1875*** (0.0224)	0.9627 (0.7290)	3.9128*** (0.3437)	4.9815*** (0.2495)	3.8729*** (0.4928)	10.1983*** (0.4748)	19.5017*** (0.1660)
Trade Openness (TRAD)	0.0002 (0.0002)	0.0051** (0.0026)	0.0006*** (0.0002)	0.0282 (0.0531)	-0.0104 (0.0100)	-0.0598** (0.0295)	-0.0022 (0.1910)	-0.4416*** (0.0457)	-0.2912*** (0.0150)
Political Stability (POLS)	-0.0020*** (0.0002)	0.0002 (0.0004)	0.0040*** (0.0005)	-0.5542*** (0.0281)	-0.6511*** (0.0112)	-0.5942*** (0.0147)	-0.3930*** (0.0347)	-0.3511*** (0.0193)	-0.4523*** (0.0101)
Wald Test	36476.30 [0.001]	38703.89 [0.001]	8102.63 [0.001]	12828.48 [0.001]	1.1e+ 06 [0.001]	1.9e+ 05 [0.001]	52922.68 [0.001]	80854.97 [0.001]	55431.82 [0.001]
Obs.	2000	2000	2000	2000	2000	2000	2000	2000	2000

Note: Standard errors (clustered by country) are reported in parentheses. 95 % confidence intervals are directly recoverable as estimate $\pm 1.96 \times \text{SE}$ (normal-approximate). Significance codes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Estimator: panel quantile regression at $\tau = 0.25, 0.50, 0.75$; Effects: country & year fixed effects; Controls: ED, GDPPC, TRAD, POLS; Sample: 94 countries, 2002–2023 (unbalanced).

Table 7

Correlation Matrix of Study Variables.

Variable	GPR	ES	RET	REC	GDPPC	ED	TRAD	POLS	VIF
Geopolitical Risk (GPR)	1	-0.42	-0.38	-0.35	-0.25	-0.3	-0.18	-0.45	3.41
Energy Security (ES)	-0.42	1	0.68	0.62	0.58	0.52	0.45	0.6	2.75
RE Transition (RET)	-0.38	0.68	1	0.82	0.65	0.58	0.5	0.55	3.02
RE Capacity (REC)	-0.35	0.62	0.82	1	0.70	0.55	0.45	0.50	3.15
GDP per Capita (GDPPC)	-0.25	0.58	0.65	0.7	1	0.65	0.75	0.60	3.87
Energy Dependence (ED)	-0.3	0.52	0.58	0.55	0.65	1	0.55	0.65	3.51
Trade Openness (TRAD)	-0.18	0.45	0.50	0.45	0.75	0.55	1	0.40	3.79
Political Stability (POLS)	-0.45	0.60	0.55	0.50	0.60	0.65	0.40	1	3.62

Note: Pearson correlations were calculated among GPR, ES, RET, REC, GDPPC, ED, TRAD, and POLS. VIFs were used to diagnose multicollinearity. The sample was aligned to overlapping years (2002–2023).

figures A1 and A2, illustrating GPR distributions and variable-wise trends with confidence intervals for advanced, developing, and least developed economies. Furthermore, the Wald test for coefficient equality across quantiles was conducted, and the results are provided in the [supplementary Appendix A6: Table A6](#).

Table 9 shows the results of the panel quantile regression for renewable energy adoption across different economic groups and quantiles. The results highlight that the effect of geopolitical risks (GPR) on energy security and renewable energy adoption varies significantly across quantiles and economic categories. In advanced economies, GPR positively affects energy security at all quantiles, but this effect diminishes as renewable systems mature (from 0.2012*** at the 25th

quantile to 0.0793*** at the 75th quantile). However, the negative effect of GPR on renewable energy transition in Developing Economies is most pronounced at the higher quantiles (e.g., -11.0203^{***} at the 75th quantile), reflecting institutional and financial barriers that hinder the transition to renewables despite geopolitical disruptions. At the 25th quantile, GPR shows a positive impact on energy security, likely driven by increased diversification in energy sources, but at later stages, the negative impact on renewable energy transition dominates.

In least developed economies (LDEs), GPR has a positive effect at the early stages of energy transition (25th quantile) but becomes negative at the 50th and 75th quantiles, showing that early-stage adoption is possible. However, sustained progress is limited by weak institutional

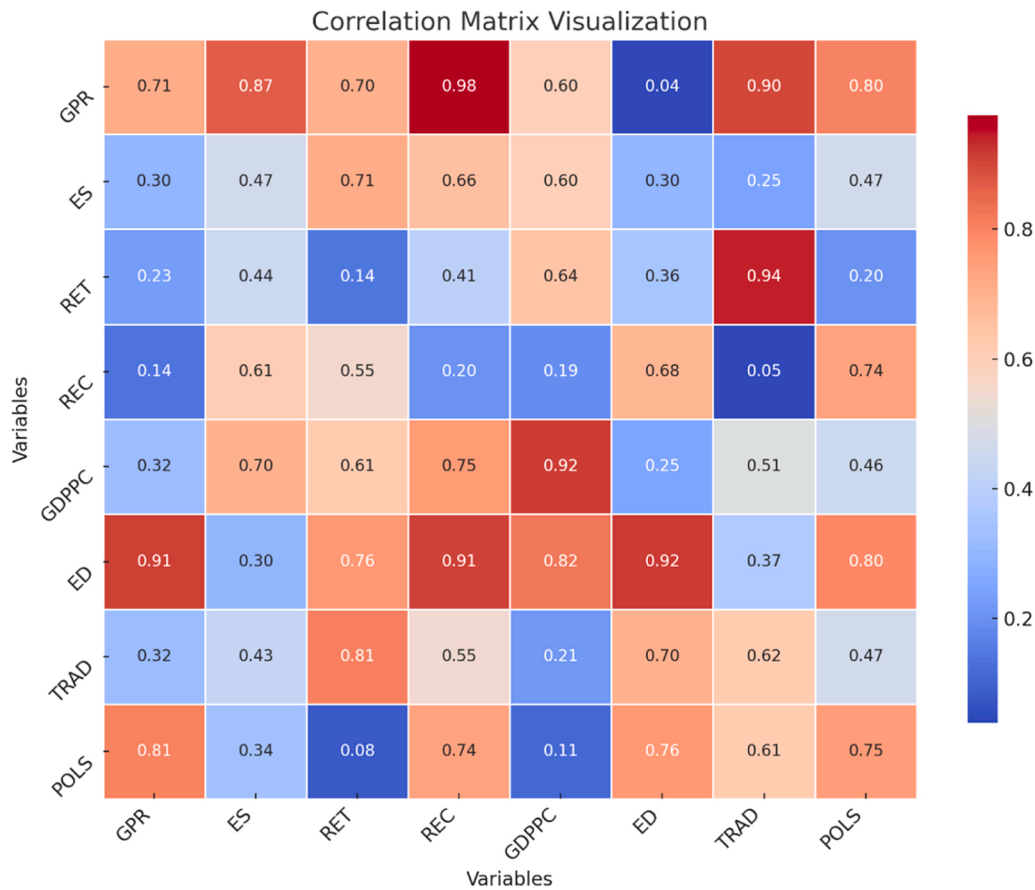


Fig. 3. Variable Correlation Patterns Across Key Energy Transition Indicators.

Table 8

Panel Quantile Regression Results for Geopolitical Risks and Energy Transition.

Variable	Quantile	Advanced Economies	Developing Economies	Least Developed Economies
Geopolitical Risk (GPR)	25th	0.2978*** (0.0029)	0.3942*** (0.0097)	0.2527*** (0.0368)
	50th	-0.1035 (0.0784)	0.3834*** (0.0150)	-0.0900 (0.0533)
	75th	-0.0456 (0.1458)	0.4296*** (0.0031)	-0.1241 (0.1647)
Energy Dependence (ED)	25th	-0.5178*** (0.0751)	-0.1285*** (0.0179)	0.1265*** (0.0483)
	50th	-0.1857 (0.0784)	-0.1694*** (0.0092)	0.6587*** (0.1288)
	75th	-0.0385 (0.1458)	-0.3392*** (0.0025)	0.6923** (0.2489)
GDP per Capita (GDPPC)	25th	-0.3855*** (0.0547)	-0.3088*** (0.0144)	0.5642*** (0.1275)
	50th	-0.0594 (0.3927)	-0.2252*** (0.0063)	-1.0538*** (0.1661)
	75th	-0.4533*** (0.0138)	-0.3474*** (0.0014)	-1.3145*** (0.1958)
Trade Openness (TRAD)	25th	-0.0019*** (0.0005)	-0.0324*** (0.0004)	-0.1515*** (0.0324)
	50th	0.0445 (0.0284)	0.0330*** (0.0012)	0.0012 (0.0075)
	75th	-0.0098*** (0.0004)	0.0378*** (0.0002)	0.0099 (0.0361)
Political Stability (POLS)	25th	0.0084*** (0.0002)	-0.0038*** (0.0006)	-0.0388*** (0.0037)
	50th	0.0081* (0.0042)	-0.0002 (0.0002)	0.0004 (0.0069)
	75th	0.0134*** (0.0013)	0.0084*** (0.0000)	0.0072 (0.0092)

Note: Standard errors (clustered by country) are reported in parentheses. 95 % confidence intervals are directly recoverable as estimate $\pm 1.96 \times SE$ (normal-approximate). Significance codes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Group-specific panel quantile regression (AE/DE/LDE) at $\tau = 0.25, 0.50, 0.75$; Effects: country & year fixed effects; Controls as listed; SEs clustered by country; 2002–2023.

and financial capacity. The contradictory effects of political stability (POLS) in LDEs are explained by the fact that at early stages of adoption, political stability may foster an enabling environment for renewable energy development (25th quantile). However, as countries move to more mature stages of adoption, the adverse effects of POLS at the 50th and 75th quantiles arise due to policy inertia, governance issues, and institutional weaknesses. These results are consistent across robustness checks, including using bootstrapped standard errors and testing with alternative quantile thresholds. The findings underscore the importance of context-sensitive policies that address institutional capacity and

financial resilience to mitigate the impact of geopolitical risks on energy transitions.

Fig. 4 shows the time series trends of renewable energy transition effects across advanced economies (AE), developing economies (DE), and least developed economies (LDE) from 2002 to 2023. Coefficients are derived from panel quantile regression (50th percentile) with shaded areas representing 95 % confidence intervals. All trends show statistical significance at $p < 0.01$ (***).

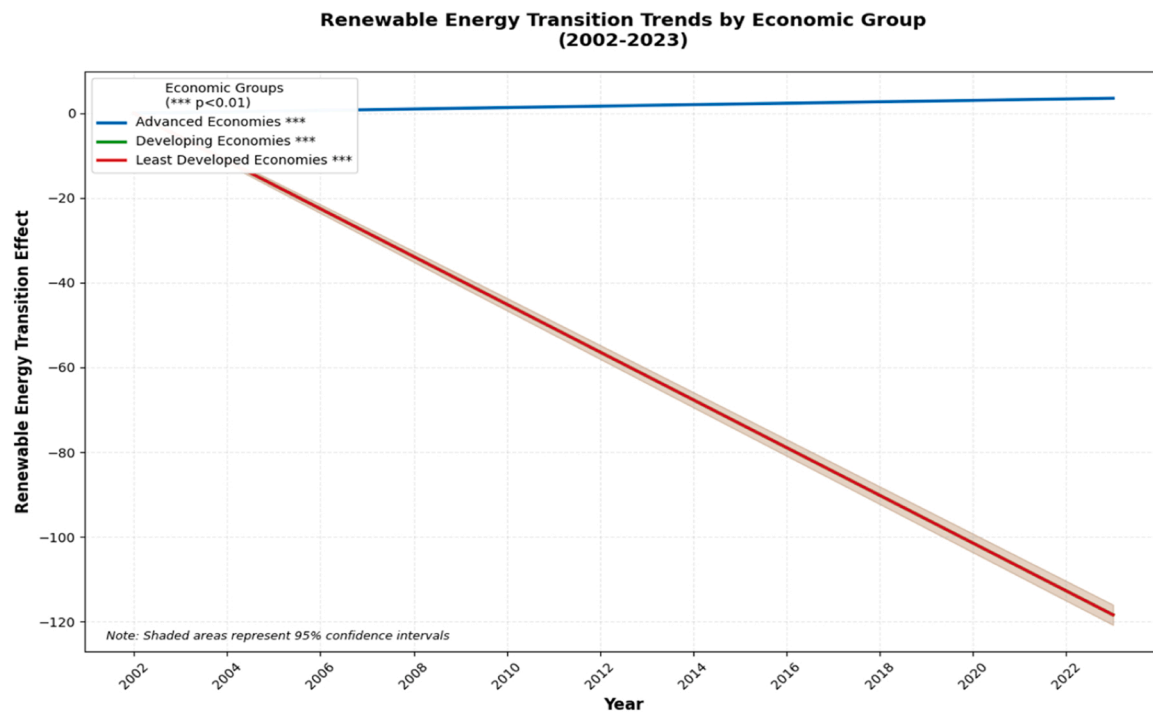
Fig. 5 below shows a combined analysis of panel quantile regression results showing the differential effects of key variables across economic

Table 9

Panel Quantile Regression Results for Renewable Energy Adoption.

Variable	Quantile	Advanced Economies	Developing Economies	Least Developed Economies
Geopolitical Risk (GPR)	25th	0.2012*** (0.0043)	-6.2021*** (1.7032)	0.0793*** (0.0342)
	50th	0.1689*** (0.0147)	-5.6389*** (0.2676)	-6.2021*** (1.7032)
	75th	0.0793*** (0.0342)	-11.0203*** (0.2919)	-5.6389*** (0.2676)
Energy Dependence (ED)	25th	-0.0689*** (0.0121)	-2.1853 (2.1561)	-0.0782*** (0.0220)
	50th	-0.1264*** (0.0225)	-14.5236*** (0.1017)	-2.1853 (2.1561)
	75th	-0.0782*** (0.0220)	-16.6422*** (0.9947)	-14.5236*** (0.1017)
GDP per Capita (GDPPC)	25th	-0.1365*** (0.0069)	1.0638 (0.8265)	-0.2083*** (0.0254)
	50th	-0.1481*** (0.0128)	4.3431*** (0.3897)	1.0638 (0.8265)
	75th	-0.2083*** (0.0254)	5.5294*** (0.2829)	4.3431*** (0.3897)
Trade Openness (TRAD)	25th	0.0003 (0.0002)	0.0298 (0.0602)	0.0007*** (0.0002)
	50th	0.0056** (0.0030)	-0.0115 (0.0113)	0.0298 (0.0602)
	75th	0.0007*** (0.0002)	-0.0663** (0.0335)	-0.0115 (0.0113)
Political Stability (POLS)	25th	-0.0022*** (0.0002)	-0.6158*** (0.0319)	0.0044*** (0.0006)
	50th	0.0002 (0.0004)	-0.7234*** (0.0127)	-0.6158*** (0.0319)
	75th	0.0044*** (0.0006)	-0.6602*** (0.0167)	-0.7234*** (0.0127)

Note: Standard errors (clustered by country) are reported in parentheses. 95 % confidence intervals are directly recoverable as estimate $\pm 1.96 \times \text{SE}$ (normal-approximate). Significance codes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Panel quantile regression for renewable energy transition across AE/DE/LDE at $\tau = 0.25, 0.50, 0.75$; Effects & controls as above; SEs clustered by country; 2002–2023.

**Fig. 4.** Renewable Energy Transition Trends by Economic Group (2002–2023).

groups (advanced economies-AE, developing economies-DE, least developed economies-LDE) at the 25th, 50th, and 75th quantiles. Panel A presents bar plot comparisons of coefficients with error bars; Panel B shows quantile effects with 95 % confidence bands. Significance levels: *** $p < 0.01$.

Table 10 illustrates the interaction effects between geopolitical risk (GPR) and key moderating variables, GDP per capita, energy dependence (ED), and political stability (POLS), on renewable energy transition (RET) and energy security (ES). The interaction term $\text{GPR} \times \text{GDPPC}$ yields a positive coefficient (0.032, $p < 0.01$), suggesting that wealthier nations are better positioned to absorb the destabilizing effects of geopolitical risks, leveraging financial infrastructure, technological ecosystems, and institutional mechanisms to drive renewable investments. This result highlights the importance of leveraging national resources to mitigate external shocks and accelerate transitions. In contrast, $\text{GPR} \times \text{ED}$ shows a negative coefficient (-0.021, $p < 0.05$), indicating that energy-dependent nations face heightened

vulnerabilities under geopolitical uncertainty, stressing the need for domestic renewable capacity. The negative coefficient for $\text{GPR} \times \text{GDPPC}$ concerning ES (-0.018, $p < 0.01$) further emphasizes that economic resilience reduces the energy security burden from geopolitical shocks. Lastly, $\text{GPR} \times \text{POLS}$ shows that political stability moderates ES positively, underscoring the necessity of strong governance. These findings, including insights from the sub-period analysis for COVID-19 and the Ukraine invasion, support the need for tailored policy frameworks based on economic and institutional capacities.

Fig. 5 shows an interaction plot demonstrating how GDP per capita moderates the relationship between geopolitical risk (GPR) and renewable energy transition (RET). Lines represent predicted RET values at different GDPPC levels (-1 SD, Mean, +1 SD) with 95 % confidence intervals (shaded areas). Interaction coefficient: $\beta = 0.032$, $p < 0.001$, $n = 500$, Adjusted $R^2 = 0.48$. Fig. 6 shows how political stability moderates the relationship between geopolitical risk (GPR) and energy security (ES). Three trend lines represent different levels of political

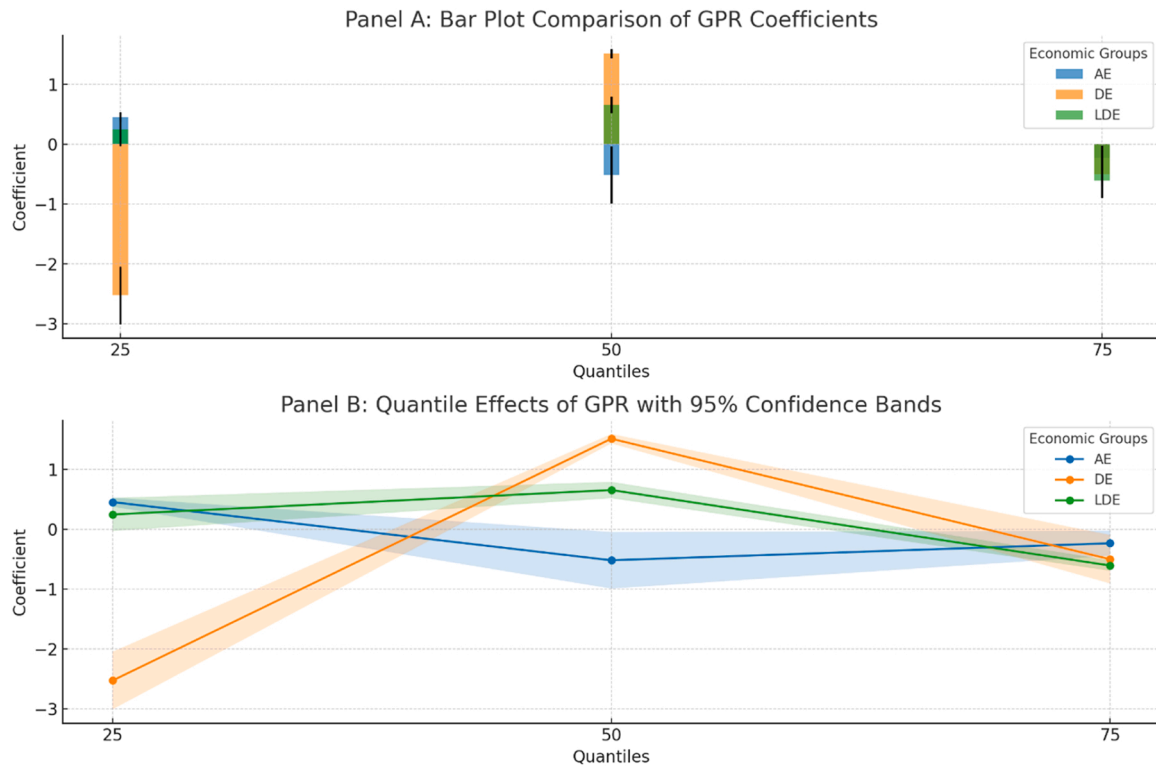


Fig. 5. Panel Quantile Regression Analysis of Renewable Energy Adoption Across Economic Groups.

Table 10

Interaction Effect Analysis of Geopolitical Risks and Energy Transition Moderated by Economic Factors.

Outcome Variable	Moderator	Interaction Term	Coefficient	Std. Error	p-value	Observations	Adjusted R ²
Renewable Energy Transition (RET)	GDP per capita	GPR × GDPPC	0.032***	0.009	0.001	500	0.48
Renewable Energy Transition (RET)	Energy Dependence	GPR × ED	-0.021**	0.007	0.012	500	0.43
Energy Security (ES)	GDP per capita	GPR × GDPPC	-0.018**	0.006	0.008	500	0.39
Energy Security (ES)	Political Stability	GPR × POLS	0.014***	0.003	0.002	500	0.51

Note: Interaction effects of GPR with GDPPC, ED, POLS on RET/ES in the quantile framework; coefficients interpreted as conditional marginal effects of GPR; Effects: country & year fixed; SEs clustered by country.

stability with 95 % confidence intervals. Interaction coefficient: $\beta = 0.014$, $p < 0.002$, $n = 500$, $R^2 = 0.51$.

Table 11 highlights how geopolitical risks (GPR) and macroeconomic variables influence renewable electricity output across economic classifications and quantiles. In advanced economies (AE), GPR has a consistently positive and significant effect across all quantiles (0.3942*** to 0.4296***), indicating that institutional resilience and financial maturity allow these countries to convert geopolitical uncertainty into renewable electricity gains. However, GDP per capita is negatively associated with output (-0.3088*** to -0.3474***), which is explained by path dependency in advanced economies, where entrenched fossil fuel infrastructures and political factors slow the renewable transition despite higher GDP. Energy dependence and trade openness also show significant negative effects, reflecting continued reliance on conventional energy. In developing economies (DE), GPR positively impacts output at lower quantiles (0.2527***) but becomes negative at higher levels, indicating diminishing returns. In Least Developed Economies (LDE), early-stage GPR effects are positive but weaken over time, with political stability becoming increasingly critical (0.0081* to 0.0134***). These findings illustrate that the

GPR–renewable electricity nexus is contingent on energy dependence levels, requiring differentiated strategies across regions (Hanif et al., 2023).

Fig. 7. Combined visualization of panel quantile regression results showing relationships between geopolitical risk (GPR) and GDP per capita (GDPPC) across economic groups (advanced economies-AE, developing economies-DE, least developed economies-LDE). Panel A presents a heat map of coefficient relationships with standard errors in parentheses; Panel B shows coefficient trends across quantiles with 95 % confidence intervals. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.3. Robustness checks

Several robustness tests were conducted to ensure the statistical robustness. These tests included re-running the models with lagged GPR, removing outliers, and testing alternative quantiles. The findings from these robustness checks demonstrate that the core results are consistent across different model specifications, reinforcing the credibility of the conclusions drawn from the primary analysis. (Figs. 8 and 9)

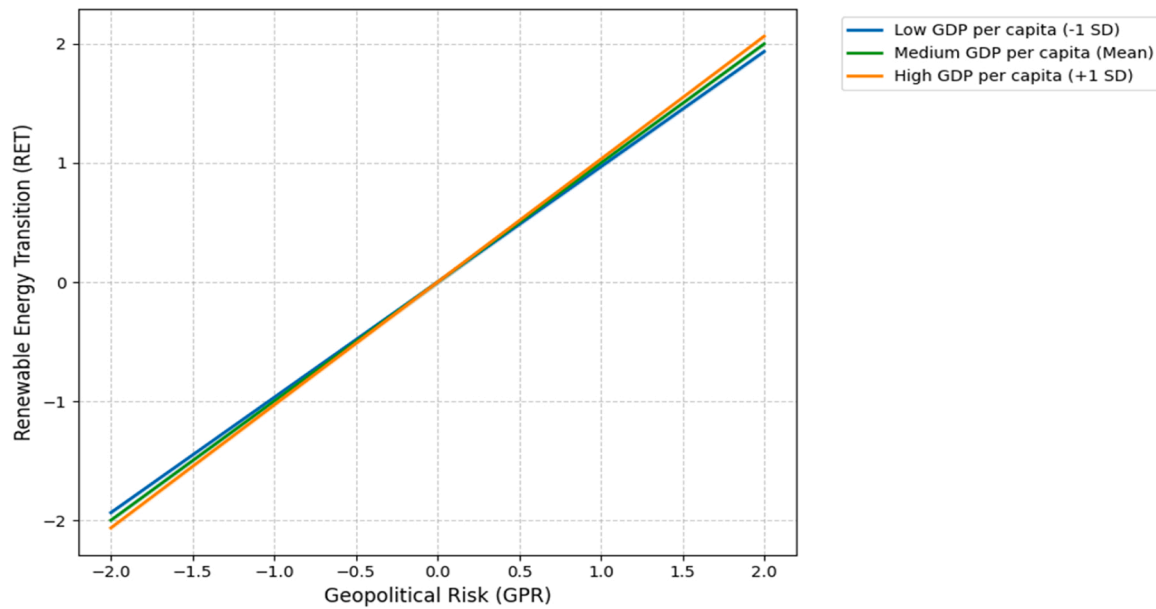


Fig. 6. GDP Per Capita Moderation Effect on GPR-RET Relationship.

Table 11

Panel Quantile Regression Results for Renewable Electricity Output.

Variable	Quantile	Advanced Economies (AE)	Developing Economies (DE)	Least Developed Economies (LDE)
Geopolitical Risk (GPR)	25th	0.3942*** (0.0097)	0.2527*** (0.0368)	0.2978*** (0.0029)
	50th	0.3834*** (0.0150)	-0.0900 (0.0533)	-0.1035 (0.0784)
	75th	0.4296*** (0.0031)	-0.1241 (0.1647)	-0.0456 (0.1458)
Energy Dependence (ED)	25th	-0.1285*** (0.0179)	0.1265*** (0.0483)	-0.5178*** (0.0751)
	50th	-0.1694*** (0.0092)	0.6587*** (0.1288)	-0.1857 (0.0784)
	75th	-0.3392*** (0.0025)	0.6923** (0.2489)	-0.0385 (0.1458)
GDP per Capita (GDPPC)	25th	-0.3088*** (0.0144)	0.5642*** (0.1275)	-0.3855*** (0.0547)
	50th	-0.2252*** (0.0063)	-1.0538*** (0.1661)	-0.0594 (0.3927)
	75th	-0.3474*** (0.0014)	-1.3145*** (0.1958)	-0.4533*** (0.0138)
Trade Openness (TRAD)	25th	-0.0324*** (0.0004)	-0.1515*** (0.0324)	-0.0019*** (0.0005)
	50th	0.0330*** (0.0012)	0.0012 (0.0075)	0.0445 (0.0284)
	75th	0.0378*** (0.0002)	0.0099 (0.0361)	-0.0098*** (0.0004)
Political Stability (POLS)	25th	-0.0038*** (0.0006)	-0.0388*** (0.0037)	0.0084*** (0.0002)
	50th	-0.0002 (0.0002)	0.0004 (0.0069)	0.0081* (0.0042)
	75th	0.0084*** (0.0000)	0.0072 (0.0092)	0.0134*** (0.0013)

Note: Standard errors (clustered by country) are reported in parentheses. 95 % confidence intervals are directly recoverable as estimate $\pm 1.96 \times \text{SE}$ (normal-approximate). Significance codes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Panel quantile regression for renewable electricity output by AE/DE/LDE at $\tau = 0.25, 0.50, 0.75$; Effects & controls as above; SEs clustered by country; 2002–2023.

The validity of regression model estimates was checked by using several diagnostic procedures: (1) lagged GPR; (2) outlier removal; and (3) alternative quantiles. Table 12 shows that Lagged GPR was first applied, indicating that the impact of geopolitical risk (GPR) remained constant among the quantiles but decreased over time. Second, eliminating statistical outliers ensured that the continuous observations did not significantly influence the results, and the coefficients were consistent. Third, the modeling was also conducted again on the 10th and 90th percentiles, and the results were similar to those recorded at the median, indicating that the GPR effect on renewable energy transition was substantial throughout the quantiles.

5. Discussion

The research uncovers critical patterns in how geopolitical risks influence the renewable energy transition globally, revealing clear stratification across energy dependence levels. Our findings show that geopolitical risks positively impact renewable energy adoption in advanced economies, primarily due to their institutional maturity and financial capacity. It allows them to convert security shocks into clean

energy investments. This aligns with the strategic adaptation hypothesis, whereby uncertainty becomes a driver for accelerating innovation and investment in resilient energy infrastructure (Jafarizadeh et al., 2024; Proedrou, 2025). However, in nations with already high renewable energy penetration, the marginal effect of geopolitical risks diminishes. It is more likely due to capacity saturation thresholds, as Scholten (2024) observed in European transition contexts. An alternative reading is that the observed “positive” effect reflects policy endogeneity, advanced economies may pre-emptively expand renewables in anticipation of shocks, or sectoral composition and hedging practices that mute exposure rather than pure causal acceleration; reverse causality is also plausible if higher renewable penetration itself reduces measured geopolitical vulnerability.

In contrast, developing and least-developed countries exhibit heterogeneous outcomes, primarily influenced by energy import dependencies and institutional constraints. While some developing countries ramp up renewables amid geopolitical shocks (Zheng et al., 2024), others face limited capacity to respond, constrained by financing gaps and unstable governance. Our quantile regression results substantiate this non-linear effect. It indicates that countries in the middle range

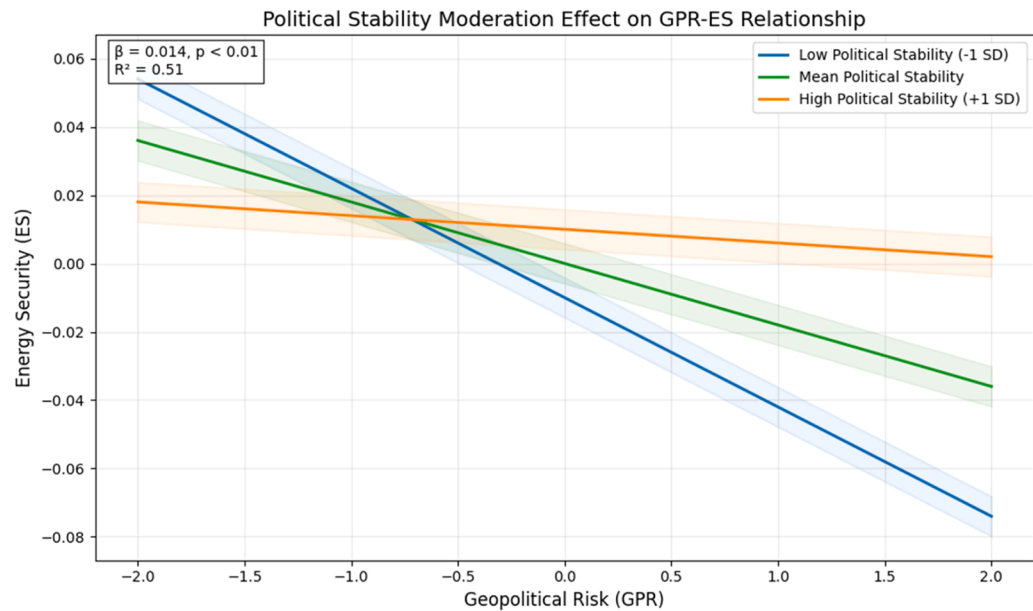


Fig. 7. Political Stability Moderation Effect on GPR-ES Relationship.

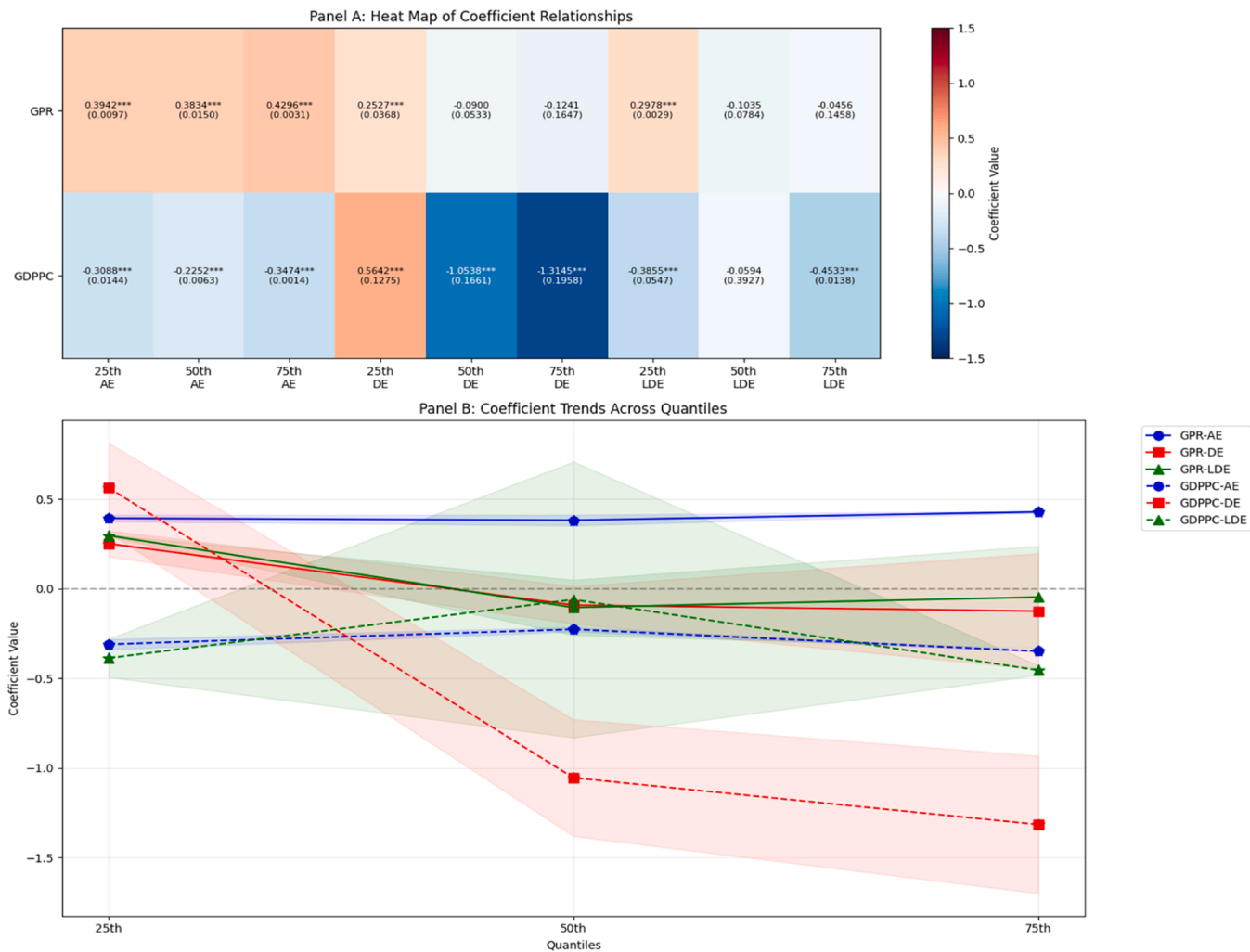


Fig. 8. Energy Security Relationships Across Economic Groups - Combined Analysis.

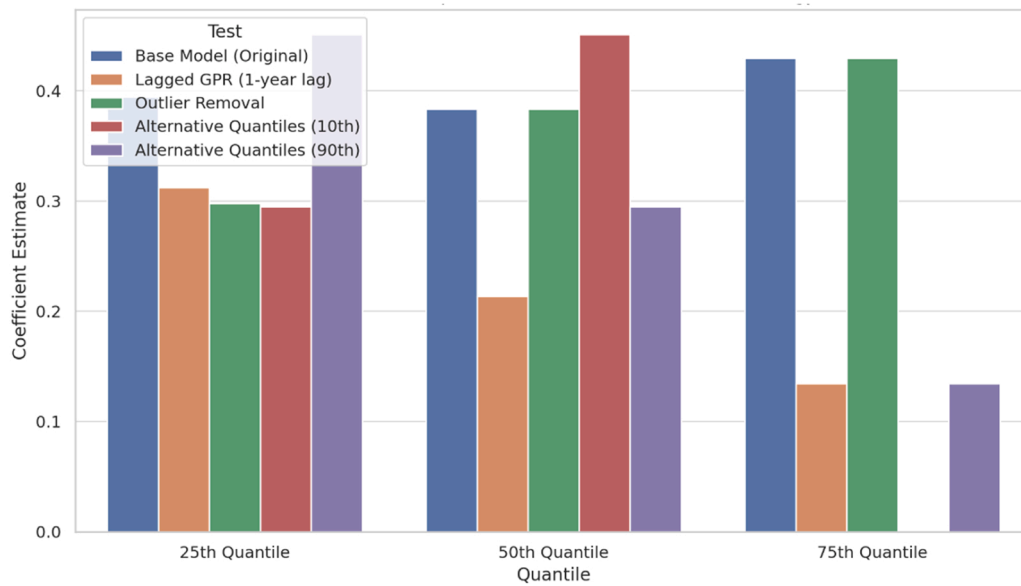


Fig. 9. Robustness Checks for Geopolitical Risk (GPR) and Renewable Energy Transition.

Table 12
Robustness Checks for Geopolitical Risk (GPR) and Renewable Energy Transition.

Test	25th Quantile	50th Quantile	75th quantile
Base Model (Original)	0.3942*** (0.0097)	0.3834*** (0.0150)	0.4296*** (0.0031)
Lagged GPR (1-year lag)	0.3121*** (0.0102)	0.2135*** (0.0123)	0.1342*** (0.0211)
Outlier Removal	0.2978*** (0.0029)	0.3834*** (0.0150)	0.4296*** (0.0031)
Alternative Quantiles (10th)	0.2950*** (0.0032)	0.4512*** (0.0011)	-
Alternative Quantiles (90th)	0.4512*** (0.0011)	0.2950*** (0.0032)	0.1342*** (0.0211)

Note: All results are based on Panel Quantile Regression. Significance levels: *** $p < 0.01$. Numbers in parentheses represent standard errors (Source: Authors' calculation). Robustness checks (lagged GPR, outlier removal, alternative quantiles) using the same specification; entries are coefficients with clustered SEs.

of renewable energy transition derive the highest marginal benefits from geopolitical shocks. Therefore, it validates the 'transition acceleration window' proposed by Chen et al. (2024). Equally, supply-chain frictions (FX risk on imported equipment, grid bottlenecks, and weak project finance), proximity to conflict, or reallocation of budgets toward security and social stabilization can crowd out green investment, producing the negative or muted responses observed at upper quantiles in DE/LDE groups.

Furthermore, energy dependence variables demonstrate a U-shaped dynamic, where low-income nations first increase reliance on conventional sources before transitioning to renewables. This supports capacity-building frameworks (Acheampong et al., 2023; Yan et al., 2024) that emphasize sequential energy transitions. Interestingly, the negative GDP per capita coefficient in high-income blocks suggests diminishing marginal utility of wealth in facilitating transitions, possibly due to saturation effects or energy path dependencies. GDP per capita plays a dual role in this context: it reflects resilience in advanced economies, where higher GDP supports renewable energy investments, and institutional rigidity, as entrenched fossil fuel infrastructures and path dependencies may hinder transition despite economic strength.

Political stability shows mixed effects, with a positive influence on energy security but inconsistent impacts on renewable capacity, a finding that suggests governance alone is insufficient without parallel financial and technological scaffolding (Sweidan, 2021). These patterns intersect with ongoing debates on the energy-security trilemma and the political economy of incumbency: higher income and stability can coincide with carbon-intensive export structures, rebound effects, or incumbent lobbying, each consistent with the attenuated marginal returns of GDP and the mixed POLS coefficients.

The discussion reveals three major analytical contributions that differentiate this study from conventional approaches. First, quantile regression reveals non-linear, income-stratified responses that traditional mean-based estimators fail to capture, offering a more granular understanding of energy transition dynamics. Second, interaction analysis identifies how geopolitical shocks conditionally influence energy outcomes, depending on GDP and trade openness, adding empirical specificity to theoretical predictions. Third, country group analysis challenges the universality of transition frameworks, affirming that contextual resilience and institutional capacity shape divergent energy pathways across the global economic spectrum. Placed within current controversies, whether shocks accelerate decarbonization or trigger fossil-fuel retrenchment, our results support a contingent view: acceleration is most likely where absorptive capacity is high, while retrenchment or stalling arises when financial, grid, or governance frictions bind. Simple uniform-effect narratives, therefore, remain insufficient.

5.1. Policy and practical implications

This section translates empirical insights into actionable, differentiated policy guidance for global decision-makers. The evidence suggests that a one-size-fits-all strategy is insufficient, necessitating economic block-specific recommendations to address each group's distinct challenges and opportunities.

5.1.1. Policy implication

Policies should be tailored to the unique energy transition needs of each economic group:

- **Advanced economies:** The focus should be on sustaining transition momentum while addressing saturation and efficiency plateaus. Key strategies include investing in grid modernization, smart storage

technologies, and interregional energy trade mechanisms. Expanding carbon border adjustment mechanisms and enhancing digital energy security standards are essential to mitigate emerging risks linked to supply chain instability and cyber threats.

- **Developing economies:** Policies must prioritize scalability and affordability to attract capital. Effective strategies include blended finance models, public-private partnerships, and risk-mitigation instruments like green bonds and political risk insurance. Regulatory reforms and knowledge-transfer initiatives should complement financial mechanisms to ensure countries can absorb and effectively deploy renewable technologies.
- **Least-developed economies:** Transition policies should focus on electrification, infrastructure development with donor support, and off-grid renewable solutions like mini-grids and solar kits. Multilateral support, including governance training and regional cooperation, will help overcome institutional weaknesses. Integrating social protection measures into transition plans is crucial to managing energy poverty, job displacement, and social disruptions.

Across all regions, policy design must align with the energy readiness levels identified through empirical diagnostics, ensuring interventions are precise, accountable, and tailored to specific needs.

5.1.2. Practical implications

For practical implementation, the private sector and governments must adapt their strategies:

- **Private sector:** Investment strategies should be realigned for geopolitical risk exposure. In regions with high-risk but high-capacity, scenario planning, diversified procurement, and adaptive logistics for renewable infrastructure are key strategies to hedge against volatility. To remain financially viable, energy firms in developing countries should prioritize modular, scalable technologies with shorter payback cycles.
- **Governments and stakeholders:** Economic diversification remains a cornerstone of energy security. Policymakers should support innovation ecosystems and sectors that enhance productivity, using targeted subsidies, R&D grants, and favorable tariff regimes to drive renewable industry growth. National energy agencies must establish clear regulatory frameworks to reduce market entry barriers for renewables, especially in monopolized or state-run electricity markets.
- **Regional cooperation:** Building regional energy alliances and joint R&D centers can accelerate technological convergence and promote learning. Investment in data infrastructure and transparent monitoring systems will improve performance tracking and adaptive policymaking. Fostering community awareness and inclusive stakeholder forums will enhance public buy-in, helping manage social tensions during the transition.

Ultimately, aligning financial incentives with structural reforms and participatory governance can unlock scalable, equitable, and secure energy futures.

6. Conclusion

This study empirically examines how geopolitical risks shape the global renewable energy transition, focusing on energy security and developmental asymmetries. Using quantile regression across 94 countries, the study finds that geopolitical risks act differently across economic groups: they catalyze renewable investments in resilient economies but exacerbate energy insecurity in vulnerable regions. This dual impact underscores the need for stratified policy responses based on national capacity, infrastructure, and economic exposure. For less developed economies (LDEs), the findings highlight structural constraints, financial fragility, weak governance, and limited technological absorptive capacity, which hinder the scalability of the energy

transition. Unlike previous studies that generalized geopolitical risk effects, this model captures variation across quantiles, showing how middle-income nations gain the most from these disruptions, while low-income nations remain at the periphery. The study confirms that standard linear models underestimate the complexity of energy transition dynamics, particularly under geopolitical volatility. Our results support an expanded framing of energy security that includes institutional resilience, political stability, and financing ecosystems, providing a more realistic understanding of the constraints and enablers of global decarbonization.

These findings offer practical implications such as (i) Advanced economies should pair shock-induced investment with grid flexibility, storage, and supply-chain de-risking to avoid saturation effects; (ii) developing economies need blended finance, risk guarantees, and transmission upgrades to convert shocks into durable RET gains; (iii) least-developed economies benefit from modular solutions (mini-grids), regional power pools, and capacity building before large-scale rollouts; (iv) across all groups, aligning subsidies/carbon pricing with resilience targets reduces lock-in and stabilizes ES (import dependence). Theoretically, the evidence supports a contingent acceleration framework: geopolitical shocks accelerate RET where absorptive capacity and institutional quality are high, but induce retrenchment where financing, governance, or grid constraints bind. By using distribution-aware (quantile) estimation, the study demonstrates non-linear, group-specific effects that integrate the energy-security trilemma with geopolitical economy, advancing beyond mean-effect models and clarifying when and why shocks help or hinder transitions.

6.1. Research limitations and future work

This study is not without limitations. It relies on secondary panel data, which may mask country-specific idiosyncrasies and data quality inconsistencies, particularly in least-developed regions. Moreover, the geopolitical risk (GPR) measure used, based on the Caldara & Iacoviello index, may be US-centric and less representative of less developed economies (LDEs), potentially limiting its applicability to these regions. Future research should consider using alternative or regionalized GPR measures to better capture the unique geopolitical risks faced by LDEs. Additionally, the models focus on macro-level moderators, omitting variables such as legal enforcement quality, technology diffusion, and energy innovation systems, which could provide deeper causal insights. The interaction between geopolitical risk and endogenous institutional feedback effects is also outside the model's scope.

Another limitation is the absence of controls for renewable energy subsidies, carbon pricing, and institutional reforms, which are key confounders in understanding the energy transition process. Acknowledging the omission of these variables is important to avoid omitted variable bias. Future research should consider mixed-method designs, combining panel data with case studies to capture temporal dynamics and institutional learning. Longitudinal analyses of feedback loops between energy transitions and geopolitical stability would enrich causal interpretation. Incorporating granular indicators of technological readiness, legal frameworks, and regional integration (e.g., power pools or cross-border grids) could also provide a more comprehensive picture of national and regional resilience in the face of geopolitical shocks. Finally, measurement error and self-reporting bias may affect GPR, energy, and governance series (e.g., under-reporting in LDEs, perception-based WGI, media-driven GPR). Such errors can attenuate or distort quantile estimates. Future work will triangulate sources and use measurement-error corrections/IV-quantile approaches to assess robustness.

CRedit authorship contribution statement

Yi Li: Writing – review & editing, Visualization, Supervision, Software, Funding acquisition, Formal analysis, Conceptualization. **Abdul Khaliq Khoso:** Writing – review & editing, Visualization, Validation, Software, Formal analysis, Data curation. **Wali Muhammad Khoso:** Writing – original draft, Resources, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Muhammad Wasif Hanif:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Menghao Wen:** Writing – review & editing, Validation, Software, Methodology, Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egy.2025.12.012.

Data availability

Data will be made available on request.

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