Energy Economics 157 (2026) 109253

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Does geopolitical risk shape energy consumption and carbon emissions? The role of technology innovation and energy security☆

Tiantian Tang [a], Yafei Li [b,*], Liping Zou [c]

[a] The Center for Economic Research, Shandong University, Jinan 250100, Shandong, China
[b] College of Economics and Management, China Agricultural University, Beijing, China
[c] School of Economics and Finance, Massey University, Auckland 0632, New Zealand

ARTICLE INFO

JEL classifications:
F51
O13
O31
O44

Keywords:
Geopolitical risk
Renewable energy
Carbon emission
Technology innovation
Energy security

ABSTRACT

This study examines the relationship between geopolitical risk (GPR) and renewable energy consumption (REC) from multiple perspectives, addressing a critical gap in the literature. Using the latest GPR index and a panel data of 43 countries and regions between 1985 and 2021, we conclude that GPR has a negative impact on REC while increasing reliance on fossil fuels, thereby contributing to higher CO_2 emissions. Mechanism analysis demonstrates the mediating role of technological innovation and energy security. Heterogeneity analysis indicates that the negative GPR–REC relationship is weaker in energy exporting and developed countries. Additionally, our analysis shows that the negative impact of GPR weakens over time, and there exists a nonlinear relationship between GPR and REC. Our findings provide critical insights into GPR's dual-edged role and its implications. They offer valuable guidance for policymakers seeking to strengthen institutional capacity, expand energy reserves, and promote innovation in renewable energy. Such measures can help mitigate the short-term suppressive effects of geopolitical risk, while also capitalizing on long-term opportunities to accelerate the transition toward a secure, resilient, and low-carbon energy system.

1. Introduction

Renewable energy (RE) is essential for sustainable development, providing a pathway to energy security, reduced carbon emissions, and enhanced economic resilience (Flouros et al., 2022; Akintande et al., 2020). Sovacool et al. (2021) emphasize its role in reducing fossil fuel dependency and promoting technological innovation. Socially, renewable energy improves public health by reducing air pollution and preventing premature deaths, thereby lowering healthcare costs (Jacobson et al., 2017). Kammen and Sunter (2016) also highlight its potential to expand affordable energy access. The disruption of global energy markets by Russia's invasion of Ukraine underscores Europe's vulnerability due to its reliance on energy imports. Many argue that the crisis may accelerate the transition away from fossil fuels, ultimately improving energy security and contributing to emissions reductions (Meckling et al., 2022; Mathews and Tan, 2014).

Existing literature presents mixed findings on the impact of geopolitical risk (GPR) on energy consumption. Sweidan (2021) demonstrates that GPR shocks positively influence REC growth, which subsequently reduces GPR. Conversely, other studies highlight the negative effects of GPR, such as increased private-sector investment costs (Gozgor and Paramati, 2022) and reduced government efficiency (Wang et al., 2022). Alsagr and van Hemmen (2021) argue that rising living costs, exacerbated by GPR, divert household spending from RE. Zhao et al. (2023) suggest that GPR diminishes RE demand and undermines climate policies. However, Song et al. (2019) assert that GPR-induced energy price volatility can, in the long term, enhance the attractiveness of RE investments as substitutes for fossil fuels. These contrasting findings underscore the need for further exploration of how GPR impacts shifts in energy consumption preferences. While substantial research has examined the economic impacts of GPR and the factors influencing REC, there is limited literature systematically exploring the relationship between GPR and RE, particularly the mediating effects of technological advancements and energy security. Therefore, in this study, we aim to answer the following questions: 1. What is the relationship between GPR and energy consumption including both renewable energy and fossil fuel consumption? 2. What are the mediating factors, if any, that affect the way GPR influences energy consumption? 3. Is there a long-term impact

☆ This article is part of a Special issue entitled: 'Geopolitical Conflicts' published in Energy Economics.

* Corresponding author at: College of Economics and Management, China Agricultural University, Beijing 100083, China.
E-mail address: lyf94@cau.edu.cn (Y. Li).

https://doi.org/10.1016/j.eneco.2026.109253
Received 31 December 2024; Received in revised form 19 February 2026; Accepted 2 March 2026
Available online 3 March 2026

and a nonlinear relationship between GPR and REC?

Using the GPR index with a panel dataset of 43 countries and regions from 1985 to 2021, we investigate the impact of GPR on energy consumption, especially focusing on REC. The descriptive statistics reveal that some of our sample countries are heavily dependent on energy imports, while others completely rely on traditional energy sources. This emphasizes the heterogeneity across our sample countries. Our baseline panel regression concludes a negative impact of GPR on REC, where increased GPR reduces REC and increases fossil fuel use. We subsequently employ the Generalized Method of Moments (GMM) to address potential endogeneity concerns. The estimation results remain consistent with the baseline analysis, thereby reinforcing the robustness and credibility of our primary findings.

We further explore the mechanisms through which GPR influences a country's carbon emissions and energy consumption structure, using technological investment and energy security as the explanatory factors. Results suggest that both energy security and technological innovation have mediating effects on GPR-REC relationship. Specifically, GPR operates through these channels to curb REC and reinforce reliance on fossil fuels, thereby contributing to higher CO_2 emissions. Further analysis is conducted to analyze the long-term impact of GPR on REC over a 5-year horizon. Our results are consistent with baseline results and indicate a long-term impact; however, the impacts are weakened over time. We also find a nonlinear relationship between GPR and REC, highlighting the significant dual effects of GPR on carbon emissions and energy consumption. In addition, we find that national institutional endowments exert a moderating effect: countries with stronger institutional capacity demonstrate reduced dependence on conventional fossil fuels in the context of heightened geopolitical risk, thereby sustaining a relatively higher proportion of renewable energy consumption.

The heterogeneity analysis indicates that national energy reserves play a crucial role in alleviating the detrimental effects of geopolitical risk on renewable energy use. Similarly, the adverse association between GPR and REC is less pronounced in developed economies than in developing ones, implying that the degree of regional economic development substantially shapes the impact of geopolitical risk on a nation's energy consumption structure.

This study offers four significant contributions to the existing literature: 1. We investigate the nexus between GPR and energy consumption, with a particular focus on renewable energy consumption. Prior research has focused primarily on GPR's effects on economic growth, government investment, and energy supply (Bilgin et al., 2020; Wang et al., 2022). 2. We use technological investment and energy security as two mediating variables to examine the mechanisms through which GPR affects REC. No prior literature integrates these mechanisms within a unified framework linking GPR to REC. Although the role of energy security in shaping REC has been explored (Hamed and Bressler, 2019), the influence of GPR in this context remains underexamined. 3. We present a novel exploration of the long-term dynamics between GPR and REC, an area that has been largely overlooked in previous studies. We document a long-term negative effect of GPR on REC, which diminishes over time. 4. We also address a critical gap by investigating a nonlinear relationship between GPR and REC. Existing literature presents conflicting views, with some scholars emphasizing positive effects of GPR (Sweidan, 2021; Cai and Wu, 2021) and others highlighting negative impacts (Gozgor and Paramati, 2022; Alsagr and Van Hemmen, 2021). This research helps clarify these contradictions by examining the complex, non-linear nature of GPR's effects on REC.

2. Literature review and hypotheses

2.1. Geopolitical risk

GPR refers to adverse events that disrupt international peace and stability, including conflicts and crises such as violent interstate conflicts, domestic civil unrest, terrorist activities, and governance breakdowns. These risks stem from various factors, including geopolitical politics, economic tensions, and cultural differences between nations or regions (Caldara and Iacoviello, 2022). GPR may create significant uncertainty in global markets, impacting not only a country's political, economic, and energy landscapes but also energy consumption patterns and sustainability goals.

GPR has increasingly become a critical factor influencing economic activities, particularly in the context of environmental pollution, natural resource management, and energy markets. Previous studies have examined the nexus between GPR and CO_2 emissions using proxies such as political unrest, terrorism, and warfare (Hashmi et al., 2022). In BRICS nations, for example, China, geopolitical factors and government effectiveness have contributed to reducing CO_2 emissions (1990–2018) through the Environmental Kuznets Curve framework. Conversely, terrorism events have generated negative impacts, leading to an increase in CO_2 emissions, energy use, and ecological footprints in Pakistan and China (Fayyaz, 2019; Kannadhasan and Das, 2020). Manufacturing and GPR also exacerbate emissions, as documented in prior literature focus on renewable energy in the U.S. (Safi et al., 2022; Sweidan, 2021). GPR further accelerates emissions by disrupting tourism and trade (Suman, 2021). As China experiences increasing global geopolitical tensions, its environmental challenges intensify (Chiang, 2021; Sweidan, 2021). These findings highlight the need for further research on mitigating GPR and reducing carbon-intensive resource reliance.

Prior literature suggests that the impact of GPR on natural resources is not uniform. For example, Dogan et al. (2021) observed that while GPR had an insignificant impact on natural rents at lower quantiles, its adverse effects were pronounced at higher quantiles. Lau et al. (2023) further highlighted the time-varying nexus between GPR and oil prices across quartiles, underscoring the complex and multifaceted influence of GPR on economic and energy systems. Regarding the energy transition, Chishti et al. (2023) demonstrated that the impacts of GPR are varied. Jiao et al. (2022) found that GPR reduces energy consumption and promotes environmental protection in China. However, Du and Wang (2023) concluded that GPR worsens environmental damage, leading to more carbon emissions. Zhang et al. (2023a, 2023b), on the other hand, documented that GPR's impact on green finance can enhance environmental risk management, thereby promoting stability in green financial markets. These findings highlight the dual nature of GPR's impact on environmental outcomes, where it can either stimulate environmental protection efforts or exacerbate ecological challenges, depending on the context and specific factors involved.

2.2. Renewable energy

RE consumption is influenced by a combination of economic, political, technological, environmental, and social factors. Economic development and energy prices are significant determinants of RE consumption, as higher energy prices often encourage a shift toward renewable sources due to due to the growing cost competitiveness of renewables. Sadorsky (2009) demonstrates a positive relationship between economic development and RE consumption in emerging markets, while Aguirre and Ibikunle (2014) conclude that higher income levels in developed countries enable greater investment in RE infrastructure. Government policies and incentives are also crucial in promoting the adoption of RE. Subsidies, tax credits, and renewable portfolio standards are key factors consistently recognized as essential in promoting RE development. Effective government intervention, as highlighted in Marques and Fuinhas (2011), is critical in fostering RE deployment, with International Renewable Energy Agency IRENA (2019) report emphasizing that policy stability is key to attracting sustainable investments.

Moreover, global market integration serves as a critical factor in advancing RE adoption by promoting efficiency gains through foreign direct investment (FDI) and international trade (Fang et al., 2021; Lu et al., 2022). Global market integration also facilitates technological advancements by optimizing production efficiency through "energy-saving" and "energy-cost reduction" pathways (Shahbaz et al., 2016). Therefore, innovation in technology is one of the key drivers in the growth of RE consumption. Technological advancements in solar power, wind energy, and related fields have significantly reduced the costs of RE production and enhanced efficiency, facilitating greater accessibility and widespread adoption. For example, Lund (2007) highlights the importance of technological advancements in RE systems to ensure scalability and effective integration into existing energy markets. In addition, Popp et al. (2011) document that R&D efforts in green technologies are instrumental in enhancing the competitiveness of RE.

The growing awareness of climate change and environmental concerns is another major driver of RE consumption. Apergis and Payne (2010) identify a strong connection between environmental consciousness and the adoption of RE in OECD countries. The Paris Agreement (2015) underscores the global commitment to transitioning to cleaner energy sources to achieve climate goals. Social factors, such as public acceptance and community participation, also shape the RE deployment. Sovacool and Ratan (2012) argue that strong community support significantly contributes to the successful implementation of RE initiatives, while local opposition can impede these efforts.

2.3. Geopolitical risk and renewable energy

The nexus between GPR and REC has been explored in several studies. However, the existing studies have not yet reached a definitive consensus regarding the nature of the nexus between the two variables and their impacts on carbon emissions. Analyzing U.S. data from 1974 to 2020, Sweidan (2021) provides evidence that geopolitical uncertainties can stimulate RE adoption. The study demonstrates that heightened GPR positively impacts RE deployment by incentivizing investments in RE as a response to energy insecurity. Similarly, Cai and Wu (2021), using data from 1985 to 2018, identify a bidirectional causal relationship: geopolitical disruptions drive RE consumption growth, while increased RE adoption reduces GPR. This creates a reinforcing cycle, suggesting that geopolitical threats prompt RE consumption, which in turn reduces the impact of future geopolitical conflict, leading to greater stability and further increases in RE adoption. Alsagr and Van Hemmen (2021) broaden their analysis to include emerging markets, examining the influence of geopolitical uncertainty on RE consumption across a sample of 19 countries spanning the period from 1996 to 2015. Utilizing a system GMM approach, their study provides empirical evidence supporting a positive long-term association between geopolitical uncertainty and the adoption of sustainable energy. Specifically, countries experiencing geopolitical uncertainty tend to diversify their energy production resources to decrease reliance on traditional energy usage. This highlights the strategic importance of RE in mitigating geopolitical vulnerabilities, particularly in emerging economies that are more susceptible to the economic and political disruptions associated with GPR.

Under heightened GPR, fossil fuel supplies also face significant disruptions, resulting in severe economic costs, particularly when energy supply is suddenly interrupted (Zhao et al., 2023). For instance, Russia's invasion of Ukraine caused substantial volatility in fossil fuel markets, highlighting the vulnerabilities of relying on conventional fossil fuels (Meckling et al., 2022). Thus, persistent geopolitical uncertainties incentivize energy diversification and increased investments in renewables to reduce reliance on fossil fuels and mitigate energy security risks (Alsagr and Van Hemmen, 2021; Meckling et al., 2022). Emerging economies are increasingly turning to RE as a strategic tool to enhance energy independence and resilience against global supply disruptions (IRENA, 2020; Cai and Wu, 2021). From an environmental perspective, reducing fossil fuel consumption and increasing RE use are critical for environmental improvement, as they lead to significant reductions in carbon emissions.

Contrasting evidence emerges from Zhao et al. (2023), who analyze the 20 OECD countries over the period 1970–2019 using the system GMM methodology. Their results indicate a negative impact of GPR on RE consumption in advanced economies. Heightened GPR may hinder RE investments due to financial constraints, political instability, or a shift toward traditional energy sources to ensure short-term energy security. Su et al. (2021) report both positive and negative effects of GPR on RE, verifying the non-linear effects of GPR on RE. Given the lack of consensus in the existing literature regarding the relationship between GPR and RE, we explicitly propose that the impact of geopolitical tension on RE may be non-monotonic and non-linear.

The contentious impact of GPR on the energy consumption structure, particularly on RE consumption, inevitably sparks debates about their effects on carbon emissions and environmental issues. This prompts us to explore the discussion from two perspectives. First, moderate levels of GPR tend to increase fossil fuel consumption and CO_2 emissions because fossil fuel supplies are perceived as more stable and reliable compared to RE sources. During periods of uncertainties, fossil fuels are often viewed as a preferred solution to ensure energy security, despite their environmental consequences (Sadorsky, 2009; Apergis and Payne, 2010). This is due to the fact that GPR can disrupt investment in RE, particularly in economies with greater financial and/or political constraints. Heightened uncertainties often lead to a reallocation of resources toward traditional energy sources, which are perceived as more reliable during periods of instability (Zhao et al., 2023; Apergis and Payne, 2010). For example, financial and policy uncertainties caused by geopolitical crises can undermine investor confidence in RE projects, resulting in delays in implementation (Sadorsky, 2021).

Under heightened geopolitical risk, fossil fuel supply chains become increasingly unable to meet the core energy security criteria of accessibility, affordability, and sustainability. According to energy security theory, elevated geopolitical risk significantly increases the fragility of fossil fuel supply chains, making them more susceptible to external shocks and supply disruptions. Fossil energy resources such as oil and natural gas are geographically concentrated in politically sensitive regions—including the Middle East, Russia, and North Africa—where production and exports are tightly intertwined with geopolitical conflicts and diplomatic tensions (Yergin, 2006). From an accessibility standpoint, cross-border transportation of fossil fuels depends heavily on strategic chokepoints such as the Strait of Hormuz and the Strait of Malacca. These critical transit routes become particularly vulnerable to military threats or blockades during periods of heightened geopolitical tension, thereby constraining global energy flows (Brown and Yücel, 2002).

Moreover, geopolitical conflict is frequently accompanied by export controls, economic sanctions, and intensified policy interventions, which further exacerbate uncertainties surrounding fossil fuel supply (Kilian and Murphy, 2014). Such disruptions substantially increase price volatility, undermine the affordability of traditional energy sources, and diminish their long-term sustainability. As a result, fossil fuel systems exhibit strong "geopolitical embeddedness", whereby political shocks propagate rapidly from the production and transportation stages to global energy markets, generating pronounced supply-disruption risks in high-GPR environments (Caldara and Iacoviello, 2022). The geopolitical dependence of fossil fuel supply, the fragility of transportation routes, and the sensitivity to policy intervention collectively render fossil energy systems especially prone to disruption under elevated geopolitical risk.

Additionally, when GPR intensifies, countries often seek to enhance the autonomy and controllability of their energy systems by reducing reliance on politically sensitive external energy sources (Yergin, 2006). Because fossil fuel resources and trade networks are deeply embedded in international political structures, conflicts or sanctions substantially heighten the risk of supply interruption. Consequently, as GPR rises, governments tend to shift toward energy sources that are domestically available, decentralized, and less politically contingent—such as wind, solar, and hydropower. This strategic substitution reduces dependence on imported fossil fuels and facilitates the "de-depoliticization" of the national energy structure.

Based on the dual impacts of GPR on RE consumption and carbon emissions, we propose the following opposing hypotheses:

H1a. GPR increases fossil fuel consumption and decreases RE consumption, resulting in higher carbon emissions.

H1b. GPR decreases fossil fuel consumption and increases RE consumption, resulting in lower carbon emissions.

2.4. The impact of energy security and technology innovation

The effect of GPR on energy consumption and carbon emissions can vary on the basis of a country's energy and technological capacities. There are two critical factors – energy security and technological innovation that can shape how GPR influences a nation's energy consumption patterns and environmental outcomes.

Sufficient energy supply security allows a country to effectively respond to energy crises triggered by GPR. This perspective gained more attention and became widely recognized following the two oil crises in the 1970s. Since then, energy security has been primarily defined as ensuring the availability of affordable oil, particularly under the threat of supply disruptions caused by embargoes. This consumer-centred perspective has been adopted and expanded internationally by various global organizations and agencies. While significant academic research has explored the economic effects of GPR and the factors influencing energy consumption, few studies have comprehensively examined how GPR affects energy security, highlighting a critical gap in the existing literature.

Geopolitical disruption can negatively affect energy security by disrupting both energy supply chains and energy demand. Geopolitical events such as terrorist activities, territorial conflicts, and political tensions can reduce or interrupt energy supplies, particularly in energy-exporting nations (Gong et al., 2022; Hussain et al., 2022). Kollias et al. (2013) demonstrate that violent events, such as terrorist attacks, lead to elevated energy prices, further exacerbating supply uncertainties. These disruptions disproportionately affect RE compared to fossil fuels. Fossil fuels are viewed as stable and reliable sources of energy, particularly during periods of geopolitical uncertainty. In contrast, the development of RE requires substantial investments and long-term planning, which are often undermined during high GPR periods due to increased uncertainty and diminished investor confidence (Meckling et al., 2022; Zhao et al., 2023). Consequently, heightened geopolitical uncertainty reinforces reliance on existing fossil fuel reserves, perceived as more reliable for ensuring energy stability in the short term. This shift alters the energy consumption structure, leading to increased fossil fuel use—associated with greater CO_2 emissions—and reduced adoption of RE. According to this discussion, we put forward the following hypothesis:

H2. Energy security intensifies reliance on fossil fuels, leading to increased CO_2 emissions and exacerbates the reduction in RE consumption.

In addition to energy security, technological investment is crucial in promoting RE adoption. The development of RE largely relies on advanced technologies, which require significant R&D investment for effective innovation, transfer, and deployment. Technology innovation such as advanced wind turbines, efficient solar panels, and energy storage systems rely on global investments (Lema and Lema, 2013; Meckling et al., 2022).

Geopolitical risk has been found to stimulate renewable energy technological innovation through several channels. The heightened geopolitical uncertainty often generates volatility in global fossil fuel markets, raising concerns about price stability and supply security. Such disruptions create incentives for governments and firms to invest in renewable energy research and development (R&D) as a more resilient alternative (Johnstone et al., 2010). Moreover, policy responses to energy insecurity—such as fiscal subsidies, tax incentives, and targeted R&D support—further encourage innovation in renewable energy technologies, particularly during periods of heightened risk (Popp, 2002). Third, from a strategic perspective, firms frequently adopt a “defensive innovation” approach in uncertain environments, seeking to enhance energy system resilience and reduce dependence on cross-border fossil fuel supplies. Given their localized resource base and relative independence from international markets, renewable energy technologies naturally become a priority area of innovation (Aghion et al., 2016). Finally, long-term national energy strategies also play a role, as persistent geopolitical tensions increase the urgency of energy diversification and accelerate investments in renewable technologies to enhance autonomy and security (Cherp and Jewell, 2014). Therefore, geopolitical risk, while disruptive in the short term, can act as a catalyst for renewable energy innovation by reshaping both market incentives and strategic policy priorities.

However, although geopolitical risk can stimulate technological innovation in renewable energy, the short-term effect manifests as a suppression of renewable energy consumption due to commercialization lags, carbon lock-in effects, and the prevailing preference for energy security. First, GPR, as an exogenous uncertainty shock (Caldara and Iacoviello, 2022), amplifies fossil fuel price volatility and heightens supply insecurity, thereby intensifying concerns over energy security. In response, governments and firms redirect resources toward renewable energy R&D and patenting activities, consistent with the “defensive innovation” hypothesis (Johnstone et al., 2010; Popp, 2002). This is also in line with theories of directed technical change and path dependency, which suggest that under uncertainty shocks, innovation is channelled into technologies that reduce dependence on external fossil fuel supply, albeit constrained by institutional and infrastructural inertia (Aghion et al., 2016; Acemoglu et al., 2012; Unruh, 2000).

Second, an increase in renewable energy patents does not necessarily translate into immediate deployment. Empirical studies have shown that energy-related technologies are characterized by significant time lags between invention and commercialization (Popp, 2002), while “carbon lock-in” arising from sunk investments, infrastructure, and institutional arrangements further impedes the diffusion of renewable energy (Unruh, 2000; Seto et al., 2016). In the short run, energy security priorities and rigid demand growth encourage reliance on dispatchable fossil-fuel-based generation, given its perceived stability and availability. In contrast, variable renewable energy (VRE) such as wind and solar face intermittency, declining marginal system value at higher penetration, and integration costs, which are exacerbated under geopolitical uncertainty (Joskow, 2011; Hirth, 2013). This leads to the paradoxical outcome of rising innovation but constrained renewable deployment.

Third, GPR affects both supply chains and investment dynamics in ways that reinforce fossil fuel reliance. Critical minerals and renewable energy are highly vulnerable to geopolitical disruptions, raising costs and delaying project implementation (International Energy Agency (IEA), 2021; International Energy Agency (IEA), 2023). Simultaneously, uncertainty elevates investment risk premia and induces delays in irreversible capital commitments (Dixit and Pindyck, 1994; Bloom, 2009; Baker et al., 2016). Given the capital-intensive nature of renewable energy projects, these barriers are particularly salient (Polzin, 2017). Under such conditions, short-term demand rigidities are met by increasing utilization of existing fossil fuel infrastructure, thereby pushing up total energy consumption and CO_2 emissions (Sovacool and Brown, 2010; Cherp and Jewell, 2014; Grubb et al., 2014).

Therefore, these mechanisms suggest that the rise in renewable energy patenting under heightened GPR primarily reflects the accumulation of potential innovation capacity rather than an immediate restructuring of the energy consumption mix. This leads to a transitional equilibrium characterized by suppressed renewable energy consumption, reinforced fossil fuel dependence, and rising CO_2 emissions. On this basis, we propose the following hypothesis:

H3. Technology innovation suppresses renewable energy consumption but strengthens dependence on fossil fuel, which in turn increases CO_2 emissions.

3. Research design

3.1. Data and sample

We select the sample from multiple databases. The country-specific GPR indices, created by Caldara and Iacoviello (2022), quantify geopolitical risks for 43 countries and regions using automated text analysis of newspaper archives. They calculate the monthly share of articles that meet GPR criteria and mention a country's name or major cities, capturing a U.S.-centric perspective on risks from 1900 to present (or 1985 onward for the Recent Index). We obtain GPR Index data from Caldara and Iacoviello's website.[1] Historical GPR Indices are also employed as an alternative measure. Energy consumption data, carbon emission data, and other country-level data are sourced from the World Development Indicators (WDI) database and the International Energy Agency (IEA) database. Based on data availability from sources mentioned above, we compile an unbalanced panel dataset of 43 countries and regions over a 36-year period from 1985 to 2021. Table A1 in Appendix A provides details on the country sample.

3.2. Model specification

This study employs the following fixed-effects model in our baseline estimations:

$$Y_{i,t} = \beta_0 + \beta_1 GPR_{i,t} + \gamma_1 Control_{it} + \delta_i + \delta_t + \varepsilon_{i,t} \tag{1}$$

Where i represents the country, and t denotes year. $Y_{i,t}$ refers to one of the following dependent variables: the proportion of RE within total energy consumption (*REC*), total energy consumption (*LnEnergy*), CO_2 emission (*LnCO2*) and CO_2 emission per capita (*CO2_Capita*). This study primarily considers the proportion of RE consumption as the main dependent variable. However, total energy consumption and CO_2 emissions are also incorporated into the analysis to explore whether GPR induces structural shifts in energy consumption preferences when accounting for other energy sources. This is particularly relevant given the strong correlation between fossil fuel usage and carbon emissions. Consequently, the dependent variable in Eq. (1) is further disaggregated into four distinct variables to enable a more comprehensive examination, as mentioned in previous sections. $Control_{it}$ represents a set of control variables. δ_i and δ_t represent country and year fixed effects, respectively.

To investigate the underlying mechanisms, we construct the following mediating effect model:

$$M_{i,t} = \beta_0 + \beta_1 GPR_{i,t} + \gamma_1 Control_{i,t} + \delta_i + \delta_t + \varepsilon_{i,t} \tag{2}$$

$$Y_{i,t} = \alpha_1 + \alpha_2 GPR_{i,t} + \alpha_3 M_{i,t} + + \gamma_1 Control_{i,t} + \delta_i + \delta_t + \varepsilon_{i,t} \tag{3}$$

Where $M_{i,t}$ represents two dimensions of mechanism variables: (1) technological investment, measured by the natural logarithm of renewable energy patent applications (*lnRenewPat*), the natural logarithm of renewable energy patent citations (*lnRenewCit*), the natural logarithm of environmental protection patent applications (*lnEPpat*), the natural logarithm of environmental protection patent citations (*lnEPCit*), and (2) energy security (*ES*), calculated as the ratio of total energy production to total energy consumption. In the examination of the mediating effect, the empirical strategy proceeds in two stages. First, Eq. (1) is estimated to ascertain whether a statistically significant causal relationship exists between geopolitical risk (GPR) and the mediating variable $M_{i,t}$. Second, the analysis evaluates whether the coefficient of GPR in the baseline specification exhibits changes in magnitude or statistical significance once $M_{i,t}$ is incorporated into the regression model. Such a comparison provides an indication of the extent to which the mediator accounts for, or transmits, the influence of GPR on the outcome of interest.

We utilize the following two models to investigates the long-term effects by regressing *REC* and other dependent variables as mentioned above on *GPR* values from the following 1 to 5 years and examine the potential non-linear relation between *GPR* and *REC* respectively:

$$Y_{i,t+j} = \beta_0 + \beta_1 GPR_{i,t} + \gamma_1 Control_{i,t} + \delta_i + \delta_t + \varepsilon_{i,t} (\mathrm{j} = 1, 2 \ldots 5) \tag{4}$$

$$Y_{i,t} = \beta_0 + \beta_1 GPR_{i,t} + \beta_2 {GPR_{i,t}}^2 + \gamma_1 Control_{i,t} + \delta_i + \delta_t + \varepsilon_{i,t} \tag{5}$$

3.3. Variable construction

3.3.1. Independent variables

To measure GPR, we use the annualized monthly GPR index developed by Caldara and Iacoviello (2022). This index is based on automated text analysis of articles from major global newspapers and captures news of geopolitical tensions, conflicts, and uncertainties. It distinguishes between realized events (such as wars and terrorist attacks) and potential threats (such as military actions and sanctions). By quantifying these occurrences on a monthly basis, the GPR index offers a standardized measure of GPR, which can be applied in economic and policy research across various contexts. We also use the historical geopolitical risk index (*GPRH*) as an alternative measure when conducting robustness tests.

3.3.2. Dependent variables

Our main dependent variable is RE consumption (*REC*), defined as the ratio of the RE to the total energy consumption. To provide a broader perspective, we introduce three additional dependent variables: the natural logarithm of total energy consumption (*LnEnergy*), which includes both fossil fuel and RE consumption; the natural logarithm of CO_2 emissions (*LnCO2*); and CO_2 emissions per capita (*CO2_Capita*). All data for these indicators were sourced from the WDI database to ensure consistency and comparability across countries.

3.3.3. Mechanism variables

To examine the mechanisms through which GPR influences RE consumption, the following mechanism variables are introduced. First, we use the natural logarithm of renewable energy patent applications (*lnRenewPat*), the natural logarithm of renewable energy patent citations (*lnRenewCit*), the natural logarithm of environmental protection patent applications (*lnEPpat*), and the natural logarithm of environmental protection patent citations (*lnEPCit*), to examine the role of technological innovation and research capacity in driving energy transitions. Second, energy security (*ES*) is calculated as the ratio of total energy production to total energy consumption, serving as an indicator of a country's ability to meet energy demand domestically. This approach is consistent with previous studies by Lee et al. (2022). The raw data for energy security are obtained from the IEA database, for the same sample period.

3.3.4. Control variables

Following conventions in prior literature, our control variables include total population (*POP*), output from the secondary industry (Secondary), output from the tertiary industry output (*Tertiary*), the proportion of FDI net inflows to GDP (*FDI_in*), GDP per capita (*PGDP*), GDP per capita growth (*PGDP_growth*), and the proportion of agricultural land to the total land area (*Agric_land*).

Appendix Table A2 presents a detailed description of all variables.

3.4. Descriptive statistics

Table 1 presents the summary statistics for our sample variables. The

[1] https://www.matteoiacoviello.com/gpr_country.htm.

Table 1
Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
GPR	1591	0.204	0.406	0.004	4.350
GPRH	1591	0.204	0.450	0.003	4.679
REC	1376	17.766	15.663	0	75.900
LnEnergy	1302	7.679	0.847	5.579	9.043
LnCO2	1591	5.281	1.342	2.472	9.451
CO2_capita	1591	6.935	4.644	0.303	21.013
POP	1591	17.448	1.314	15.239	21.069
Secondary	1436	29.699	8.468	5.989	66.429
Tertiary	1426	56.401	10.554	27.851	91.922
FDI_in	1535	0	0.001	−0.005	0.012
PGDP	1543	2.164	1.953	0.045	8.852
PGDP_growth	1570	2.073	3.819	−22.517	16.28
Agric land	1562	39.556	21.736	2.508	80.888
lnRenewPat	1591	6.206	3.869	0	13.862
lnEPpat	1591	4.385	2.996	0	12.015
ES	1213	1.437	0.156	1.145	2.226
Voice	1118	0.473	0.956	−1.910	1.800
GoverEffect	1118	0.733	0.897	−1.870	2.350
Law	1118	0.590	0.995	−2.330	2.120

Notes: WDI is World Development Indicators. IEA denotes International Energy Agency. Matteo Iacoviello's website is https://www.matteoiacoviello.com.

average level of *GPR* is 0.204, ranging from 0.004 to 4.350 with a standard deviation of 0.406, indicating significant variation in GPR across the sample countries. The historical GPR (*GPRH*), used as an alternative measure, shows similar trends to the primary *GPR*. The average share of RE consumption (*REC*) is 17.766% of total energy consumption, suggesting that RE represents a meaningful portion of the total national energy mix. The maximum *REC* value of 75.9% highlights that some countries in our sample rely heavily on RE, enabling them to reduce the dependence on traditional energy sources. The minimum *REC* value of zero reveals that some countries still rely entirely on traditional energy sources.

The results of natural logarithm of total energy consumption (*LnEnergy*) show the variation from 5.579 to 9.043 with standard deviation of 0.847, indicating total energy consumption remains relatively stable over sample period. The level of CO_2 emissions (*LnCO2*) ranges from 2.472 to 9.451, with a mean value of 5.281. The relatively higher standard deviation of 1.342 suggests significant disparities in fossil fuel consumption across our sample countries. The CO_2 emissions per capita (*CO2_capita*) variable exhibits an even greater standard deviation of 4.644, ranging from 0.303 to 21.013. This indicates that regional economic development potentially accelerates fossil fuel consumption, contributing to higher emissions levels. The mean values of our sample country outputs from secondary and tertiary industries are 29.699 and 56.401, with standard deviation of 8.468 and 10.544, respectively. The R&D expenditure (*RD_expend*) exhibits considerable variation, with a standard deviation of 1.093, highlighting significant differences in technology investment across countries. This variation is crucial, as technological investment plays a pivotal role in advancing RE production and fosters innovation capabilities. There is also a large deviation in GDP growth, agricultural land area. Regarding energy security (*ES*), the index ranges from a minimum value of 0.156 to a maximum value of 2.226. This broader range reflects substantial contrasts in countries' energy reliance.

The descriptive statistics reveal that while some nations are heavily dependent on energy imports, others not only meet their domestic energy needs but also export surplus energy, ensuring the stability of their energy consumption and contributing to national energy resilience. These results emphasize the heterogeneity across countries in terms of GPR exposure, RE adoption, fossil fuel reliance, and energy security.

Table 2 presents the correlation coefficient matrix for all variables, highlighting the relationships between the independent and dependent variables. Most correlation coefficients between the independent variables are relatively low, suggesting minimal multicollinearity issues

Table 2
Correlation analysis.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1) REC	1												
(2) lnEnergy	−0.461***	1											
(3) lnCO2	−0.313***	0.285***	1										
(4) CO2_capita	−0.467***	0.878***	0.419***	1									
(5) GPR	−0.253***	0.294***	0.543***	0.444***	1								
(6) GPRH	−0.220***	0.271***	0.531***	0.438***	0.968***	1							
(7) POP	0.047*	−0.356***	0.796***	−0.157***	0.347***	0.349***	1						
(8) Secondary	0.073***	−0.218***	0.164***	−0.101***	−0.155***	−0.131***	0.262***	1					
(9) Tertiary	−0.288***	0.520***	−0.033	0.355***	0.251***	0.222***	−0.323***	−0.804***	1				
(10) FDI_in	−0.115***	0.113***	−0.118***	0.022	−0.067***	−0.069***	−0.164***	−0.239***	0.242***	1			
(11) GDPpercpt	−0.033	0.726***	−0.061**	0.560***	0.223***	0.200***	−0.448***	−0.441***	0.642***	0.095***	1		
(12) GDPgrwth	0.088***	−0.185***	0.065**	−0.118***	−0.024	−0.019	0.151***	0.132***	−0.196***	0.019	−0.143***	1	
(13) Agric_land	−0.328***	0.011	0.245***	0.066***	0.107***	0.074***	0.188***	−0.049*	0.005	−0.042*	−0.136***	−0.036	1

Notes: This table presents the correlation coefficient matrix of the man variables. The variable definitions are provided in Table 1.

among the predictors. The correlation between *GPR* and *REC* is negative and statistically significant. This indicates an inverse relationship between GPR and RE adoption, implying that higher GPR is associated with lower levels of RE consumption. Similarly, both measures of CO_2 emissions (*LnCO2* and *CO2_Capita*) exhibit statistically significant positive correlations with GPR at the 1% level. This suggests that higher GPR is associated with increased fossil fuel consumption, therefore, leading to higher carbon emissions, which is consistent with our first hypothesis that geopolitical instability can exacerbate reliance on traditional energy sources and contribute to more carbon emissions.

4. Empirical discussions

4.1. Baseline regression

Table 3 presents the results of our first investigation into the GPR-REC nexus using OLS regression. We regress the following dependent variables on GPR: renewable energy consumption (*REC*) in Column 1, total energy consumption (*LnEnergy*) in Column 2, total CO_2 emissions (*LnCO2*) in Column 3, and per capita CO_2 emissions (*CO2_capita)* in Column 4. The country level CO_2 emissions are used as an indirect measure of REC, serving as a proxy for fossil fuel consumption.

The coefficient of *GPR* in Column 1 is negative and statistically significant at the 1% level, indicating that GPR significantly reduces the proportion of RE consumption during our sample period. In contrast, when total energy consumption (*LnEnergy*) is used as independent variable is Column 2, CO_2 emissions (*LnCO*$_2$) in Column 3, and CO_2 emissions per capita (*CO*$_2$*_capita*) in Column 4, all coefficients on GPR are positive and statistically significant at the 1% level. The positive coefficients suggest that rising GPR leads to a significant increase in total energy consumption, with fossil fuel consumption rising and renewable energy consumption decreasing.

Table 3
Baseline results.

	(1)	(2)	(3)	(4)
VARIABLES	REC	LnEnergy	LnCO2	CO2_capita
GPR	−2.410***	0.085***	0.158***	1.314***
	(0.843)	(0.025)	(0.041)	(0.346)
POP	−18.194***	0.339***	1.663***	6.360***
	(2.593)	(0.092)	(0.105)	(0.579)
Secondary	−0.344***	0.014***	0.025***	0.058***
	(0.079)	(0.002)	(0.003)	(0.013)
Tertiary	−0.310***	0.007***	0.020***	0.045***
	(0.066)	(0.002)	(0.004)	(0.014)
FDI_in	−514.237***	3.977	16.283***	89.458***
	(109.199)	(4.629)	(4.686)	(34.282)
GDPpercpt	4.426***	−0.011	−0.139***	0.050
	(0.513)	(0.019)	(0.021)	(0.141)
GDPgrwth	−0.028	−0.003**	−0.004*	−0.031***
	(0.050)	(0.001)	(0.002)	(0.010)
Agric_land	−0.514***	0.003	0.013***	0.040***
	(0.118)	(0.002)	(0.004)	(0.012)
Constant	376.215***	0.807	−25.917***	−110.852***
	(42.849)	(1.591)	(1.744)	(10.039)
Observations	1271	1113	1383	1383
R^2	0.931	0.980	0.981	0.950
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Notes: This table presents the baseline results on the total sample for regressions of GPR on country-level RE consumption and CO_2 emissions. The independent variable represents the proxy measure of country-level GPR. The dependent variables represent are: the ratio of RE consumption (*REC*) and natural logarithm of energy consumption (*LnEnergy*), the natural logarithm of CO_2 emissions (*LnCO2*) and CO_2 emissions per capita (*CO2_capita*). Table A2 outlines definitions of the variables. All results are estimated with country and year fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate statistical significance at 0.1, 0.05, and 0.01 levels, respectively.

For the control variables, the coefficients on *POP, Secondary, Tertiary, FDI_in, and Agri_land* in Column 1 are negative and statistically significant at the 1% level. These results indicate that RE consumption is lower in countries with larger populations, greater outputs from secondary and tertiary industries, more FDI inflows, and larger agricultural land areas. The coefficient on *GDPpercpt* is positive and statistically significant at the 1% level, suggesting RE consumption is higher in countries with higher GDP per capita.

These findings highlight the short-term (contemporaneous) effects of GPR on energy consumption preferences. Increased GPR prompts countries to raise total energy consumption, likely driven by the need to secure strategic reserves. However, these production activities rely more heavily on fossil fuels, given their relatively stable supply and availability compared to RE. Previous studies have concluded that geopolitical crises and terrorist attacks can increase energy prices and drive nations to secure their energy needs through fossil fuels, which are perceived as less volatile and more readily available in crisis situations (Caldara and Iacoviello, 2022; Kollias et al., 2013). Our results provide consistent evidence that fossil fuels are perceived as more dependable during global uncertainties, reducing the short-term appeal of RE investments. Consequently, during periods of heightened GPR, national energy consumption preferences shift toward fossil fuels, resulting in a reduced share of RE in the overall energy mix.

4.2. Robustness tests and endogeneity analyses

As a crucial part of our robustness checks, we replace the baseline measure of geopolitical risk with alternative indicators. Given that geopolitical risk is a complex concept with multiple operationalizations, relying on a single measure may introduce bias or measurement error. Consistent results across different indicators enhance the reliability, external validity, and persuasiveness of our findings.

Table 4 presents the robustness test results when using historical geopolitical risk (*GPRH*) as an alternative independent variable. Results in Table 4 are consistent with our baseline results presented in Table 3. The coefficient on *GPRH* in Column 1 is negative and statistically significant at the 5% level. The coefficients on *GPRH* remain positive and statistically significant at the 1% level in Columns 2, 3, and 4, when total energy consumption and CO_2 emissions are used as indirect measures for fossil fuel utilization. These results confirm our baseline results that GPR leads to a reduction in RE consumption, indicating our baseline results are robust.

Previous studies emphasize the existence of an inverse causality between GPR and energy consumption transition. The shift toward RE has significant geopolitical implications, as highlighted by various

Table 4
Robustness results: alternative measure of geopolitical risk.

	(1)	(2)	(3)	(4)
VARIABLES	REC	LnEnergy	LnCO2	CO2_capita
GPRH	−1.941**	0.092***	0.140***	1.320***
	(0.933)	(0.035)	(0.046)	(0.491)
Control variables	Yes	Yes	Yes	Yes
Observations	1271	1113	1383	1383
R^2	0.931	0.980	0.981	0.949
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Notes: This table presents the robustness results by replacing the independent variable. The replaced independent variable is country-level historical geopolitical risk (*GPRH*). The dependent variables represent are: the ratio of RE consumption (*REC*) and natural logarithm of energy consumption (*LnEnergy*), the natural logarithm of CO_2 emissions (*LnCO2*) and CO_2 emissions per capita (*CO2_capita*). Table A2 outlines definitions of the variables. All results are estimated with country and year fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate statistical significance at 0.1, 0.05, and 0.01 levels, respectively.

studies. Rothkopf (2009) concluded that the increasing adoption of RE could exacerbate GPR, potentially causing instability as petro-states decline, with adverse consequences for global systems. Similarly, Laird (2013) argued that RE's replacement of fossil fuels with RE may introduce new risks, becoming a key driver of future geopolitical tensions. De Ridder (2013) further noted that the development of RE may foster a more multipolar global system, in which access to critical mineral reserves enhances the geopolitical influence of resource-rich nations, allowing them to gain political power. This reflects the high costs associated with RE adoption. Paltsev (2016) highlighted that while the transition from traditional energy to renewables increases diversity of energy systems, it may also diminish energy security and introduce new geopolitical challenges, particularly due to global reliance on critical materials. Collectively, these studies illustrate that while RE development is essential for sustainability, it also brings complex geopolitical dynamics, including shifts in power structures, risks related to resource dependency, and challenges to energy security. These findings underscore the need for comprehensive strategies to address the GPR associated with the global energy transition. To address the issue of endogeneity, we employ the Generalized Method of Moments (GMM) approach.

In Table 5, we present the GMM estimation results. From the estimation results, geopolitical risk exerts a significantly negative effect on the share of renewable energy consumption (REC), with a coefficient of −11.837, significant at the 10% level. This finding suggests that when geopolitical risk intensifies, countries tend to revert to traditional fossil fuels in order to safeguard energy security and supply stability. Since renewable energy development typically relies on cross-border supply chains, long-term investments, and international cooperation, heightened uncertainty discourages policymakers and firms from depending on renewables. Instead, they shift toward increasing fossil fuel consumption as a short-term strategy to secure energy availability.

Regarding total energy consumption (*LnEnergy*), the coefficient of GPR is 0.361 and statistically significant at the 10% level, indicating that rising geopolitical risk leads to higher overall energy demand. This result may reflect that, under high-risk circumstances, countries increase their energy stockpiling and usage for strategic reserve and energy security purposes, thereby driving up total consumption. Correspondingly, in terms of environmental outcomes, the coefficient of GPR on total carbon emissions (*LnCO2*) is 2.484, significant at the 5% level. This suggests that geopolitical risk not only expands the scale of energy consumption but also substantially increases the reliance on fossil fuels, thereby raising carbon emissions and exacerbating environmental pressures. Similarly, the coefficient for per capita carbon emissions (*CO2_capita*) is 25.587, also significant at the 5% level, further underscoring the environmental deterioration at the individual level: in the context of heightened geopolitical risk, each resident's carbon footprint rises significantly due to intensified reliance on conventional energy sources.

Table 5
GMM results.

	(1)	(2)	(3)	(4)
VARIABLES	REC	LnEnergy	LnCO2	CO2_capita
GPR	−11.837*	0.361*	2.484**	25.587**
	(6.680)	(0.212)	(0.980)	(10.194)
Control variables	Yes	Yes	Yes	Yes
Observations	1271	1113	1383	1383
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes
AR(1) test	0.006	0.041	0.004	0.025
AR(2) test	0.278	0.838	0.899	0.155
Hansen test	1.000	1.000	1.000	1.000

Notes: This table presents the results by using GMM method. The independent variable represents the proxy measure of country-level GPR. The dependent variables represent are: the ratio of RE consumption (*REC*) and natural logarithm of energy consumption (*LnEnergy*), the natural logarithm of CO_2 emissions (*LnCO2*) and CO_2 emissions per capita (*CO2_capita*). Table A2 outlines definitions of the variables. All results are estimated with country and year fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate statistical significance at 0.1, 0.05, and 0.01 levels, respectively.

It is noteworthy that the robustness tests of the GMM model support the reliability of the above findings. First, the AR(1) test is significant across all models (e.g., $p = 0.006$ in the REC specification), which is a common feature in dynamic panel models and does not undermine the validity of the estimates. Second, the AR(2) test results are uniformly insignificant (e.g., $p = 0.278$ in the REC model), indicating the absence of second-order serial correlation in the residuals and confirming the appropriateness of the model specification. Finally, the Hansen over-identification test yields p-values of 1.000 across specifications, suggesting that the instruments employed are overall exogenous and valid, with no evidence of over-identification. Taken together, these diagnostic tests demonstrate that the GMM estimations are free from serious serial correlation and invalid instruments, thereby ensuring the robustness and credibility of the reported results.

Overall, the GMM estimation results reinforce the baseline findings both methodologically and empirically. Specifically, geopolitical risk significantly affects a country's energy transition and environmental quality by suppressing renewable energy consumption, increasing overall energy demand, and intensifying fossil fuel use, which in turn drives up carbon emissions. This conclusion is consistent with the baseline regression results, thereby mitigating the endogeneity issue and enhancing the robustness and credibility of our overall findings.

4.3. Mechanism analysis: technologic innovation and energy security

Next, we further explore the mechanisms through which GPR influences a country's carbon emissions and energy consumption structure, focusing on two key factors discussed in Hypotheses H2 and H3: technological innovation and energy security.

As proxies for green technological innovation, we utilize the number of renewable energy invention patents (*lnRenewPat*) and the number of environmental protection invention patents (*lnEPpat*). The raw data for these two variables are obtained from the incoPat database. However, we manually extracted and organized the patent information by downloading patents classified under renewable energy and environmental protection categories separately for each country, based on their respective patent classification codes. The processed datasets were then incorporated into the mediation effect regressions for empirical estimation. Compared with the conventional proxies such as total R&D expenditure or aggregate patent counts, these two measures are more specific and targeted, thereby allowing for a more effective examination of the green innovation mechanism. The use of renewable energy and environmental protection patent counts as indicators remains relatively uncommon in the existing literature, which highlights the novelty and contribution of this study.

As proxies for energy security (*ES*), we use energy supply per unit of energy consumption according to Lee et al. (2024), investigating the explanatory power of energy security on the relationship between GPR and REC. This indicator provides a more comprehensive reflection of the balance between energy supply and consumption than conventional single-dimensional measures, such as energy price volatility or import dependence ratios, thereby enhancing its validity for cross-country comparisons and policy-oriented assessments.

4.3.1. Technologic innovation

To empirically test the technological innovation mechanism, we employ the mediation effect model regressions and report the corresponding results in Table 6 Panels A1 and A2. The results reported in Column 1 show that the effect of geopolitical uncertainty on renewable energy invention patents (*lnRenewPat*) is significantly positive at the 1% level, with a coefficient of 2.474. This finding indicates that under

Table 6
Mechanism results: technology innovation and energy security.

Panel A1: Renewable energy invention patents

	(1)	(2)	(3)	(4)	(5)
VARIABLES	lnRenewPat	REC	LnEnergy	LnCO2	CO2_capita
GPR	2.474***	−2.045**	0.071***	0.120***	1.192***
	(0.642)	(0.810)	(0.024)	(0.037)	(0.344)
lnRenewPat		−0.164***	0.008***	0.015***	0.049***
		(0.049)	(0.001)	(0.002)	(0.010)
Control variables	Yes	Yes	Yes	Yes	Yes
Observations	1383	1271	1113	1383	1383
R^2	0.510	0.932	0.980	0.982	0.951
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Sobel test (Z Score)		−2.535	3.156	3.479	2.994
Bootstrap test		Yes	Yes	Yes	Yes

Panel A2: Renewable energy invention patent citations

	(1)	(2)	(3)	(4)	(5)
VARIABLES	lnRenewCit	REC	LnEnergy	LnCO2	CO2_capita
GPR	1.908***	−1.998**	0.065***	0.117***	1.165***
	(0.567)	(0.799)	(0.024)	(0.037)	(0.346)
lnRenewCit		−0.259***	0.013***	0.021***	0.078***
		(0.053)	(0.002)	(0.002)	(0.014)
Control variables	Yes	Yes	Yes	Yes	Yes
Observations	1382	1270	1113	1382	1382
R^2	0.707	0.933	0.981	0.983	0.952
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Sobel test (Z Score)		−2.780	3.002	3.177	2.905
Bootstrap test		Yes	Yes	Yes	Yes

Panel A3: Environmental protection invention patents

	(1)	(2)	(3)	(4)	(5)
VARIABLES	lnEPpat	REC	LnEnergy	LnCO2	CO2_capita
GPR	1.736***	−1.877**	0.063***	0.117***	1.145***
	(0.480)	(0.782)	(0.024)	(0.037)	(0.347)
lnEPpat		−0.354***	0.016***	0.023***	0.097***
		(0.061)	(0.002)	(0.003)	(0.014)
Control variables	Yes	Yes	Yes	Yes	Yes
Observations	1383	1271	1113	1383	1383
R^2	0.571	0.933	0.981	0.983	0.952
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Sobel test (Z Score)		−3.074	3.314	3.360	3.224
Bootstrap test		Yes	Yes	Yes	Yes

Panel A4: Environmental protection invention patent citations

	(1)	(2)	(3)	(4)	(5)
VARIABLES	lnEPCit	REC	LnEnergy	LnCO2	CO2_capita
GPR	1.410***	−1.740**	0.055**	0.108***	1.089***
	(0.467)	(0.780)	(0.025)	(0.037)	(0.354)
lnEPCit		−0.580***	0.026***	0.035***	0.161***
		(0.057)	(0.003)	(0.003)	(0.018)
Control variables	Yes	Yes	Yes	Yes	Yes
Observations	1382	1270	1112	1382	1382
R^2	0.766	0.935	0.983	0.984	0.954
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Sobel test (Z value)		−2.895	2.889	2.945	2.864
Bootstrap test		Yes	Yes	Yes	Yes

Panel B: Energy security

	(1)	(2)	(3)	(4)	(5)

(continued on next page)

Table 6 (*continued*)

Panel B: Energy security

	(1)	(2)	(3)	(4)	(5)
VARIABLES	ES	REC	LnEnergy	LnCO2	CO2_capita
VARIABLES	ES	REC	LnEnergy	LnCO2	CO2_capita
GPR	0.021**	−1.708***	0.071***	0.147***	0.970***
	(0.009)	(0.572)	(0.023)	(0.039)	(0.306)
ES		−18.181***	0.503***	0.791***	6.435***
		(2.597)	(0.102)	(0.111)	(0.676)
Control variables	Yes	Yes	Yes	Yes	Yes
Observations	1083	1028	870	1083	1083
R^2	0.887	0.950	0.975	0.985	0.949
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Sobel test (Z value)		−2.194	2.092	2.197	2.245
Bootstrap test		Yes	Yes	Yes	Yes

Notes: This table presents the results of the mediation effect models for technology investment and energy security. The independent variable represents the proxy measure of country-level GPR. The dependent variables represent are: The ratio of RE consumption (*REC*) and natural logarithm of energy consumption (*LnEnergy*), the natural logarithm of CO2 emissions (*LnCO2*) and CO2 emissions per capita (*CO2_capita*). The mediating variables are the natural logarithm of renewable energy patent applications (*lnRenewPat*), the natural logarithm of renewable energy patent citations (*lnRenewCit*), the natural logarithm of environmental protection patent applications (*lnEPpat*), the natural logarithm of environmental protection patent citations (*lnEPCit*), and energy security (*ES*). Panels A1, A2, and B report the corresponding results, respectively. Table A2 outlines definitions of the variables. All results are estimated with country and year fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate statistical significance at 0.1, 0.05, and 0.01 levels, respectively.

heightened geopolitical risk, the number of renewable energy invention patents increases. We argue that geopolitical risk leads to sharp fluctuations in fossil fuel prices and heightened investment uncertainty, thereby shifting market capital and investors toward renewable energy projects supported by government policies such as fiscal subsidies and tax incentives, which in turn stimulates the growth of renewable energy patent applications (Johnstone et al., 2010). Moreover, from a strategic perspective, firms often adopt a "defensive innovation" approach in high-uncertainty environments, seeking to enhance supply chain and energy system resilience through technological breakthroughs (Aghion et al., 2016). Given their localized resource base and lower dependence on cross-border supply chains, renewable energy technologies become a priority innovation direction. From this defensive innovation perspective, the significant increase in renewable energy invention patents observed under conditions of heightened geopolitical risk can be well explained.

We further test the statistical significance of the mediation effect using both the Sobel test and the bootstrap procedure, and the results are reported in the last two rows of each panel. Specifically, when *lnRenewPat* serves as the mediating variable, we compute the standard errors of the indirect effects and construct the corresponding *Z*-statistics. The results show that the Z-statistics are significant at the 5% level for all outcome variables, providing evidence in support of a statistically significant mediation effect. We also present whether the results from a 1000-resample nonparametric bootstrap for mediation effect are statistically significant because the confidence interval excludes zero. All results in bootstrap confirm that *lnRenewPat* exhibits a statistically significant mediation effect.

Columns 2–5 of Panel A1 in Table 6 present the results after incorporating *lnRenewPat* into the baseline regressions. We find that for all dependent variables (*REC*, *LnEnergy*, CO_2, and CO_2*_capita*), the coefficients remain statistically significant and preserve their original signs, although their magnitudes are reduced. Taken together with the results in Column 1, this provides evidence supporting the mediating role of *lnRenewPat*. In addition, we observe that *lnRenewPat* itself has a significantly negative effect on REC (−0.164), a significantly positive effect on total energy use (0.008), and significantly promotes fossil fuel consumption, as reflected in the positive coefficients for CO_2 and CO_2*_capita* (0.015 and 0.049, respectively).

Patent citation counts are commonly employed as a proxy for patent quality in empirical research (Harhoff et al., 1999; Kogan et al., 2017). Panel A2 of Table 6 reports the results after employing the citation count of renewable energy invention patents (*lnRenewCit*) to capture technological innovation with an emphasis on patent quality rather than patent quantity. The estimated coefficients remain broadly consistent with those reported in Panel A1. Specifically, we find that GPR exerts a significantly positive impact on *lnRenewCit* (1.908), indicating that heightened geopolitical risk is associated with an improvement in the quality of renewable energy innovation rather than merely an expansion in the number of patents. Moreover, after including *lnRenewCit* as a mediating variable, the coefficients on all outcome variables decline in magnitude relative to the baseline regressions while preserving their original signs. Furthermore, the results of the Sobel tests and bootstrap tests confirm the validity of mediation effect for patent quality.

This attenuation suggests that part of the effect of GPR on energy consumption and carbon emissions is transmitted through changes in technological innovation quality. These results imply that rising geopolitical risk induces firms and governments to shift resources toward higher-quality renewable energy innovation, which in turn affects the energy mix and emissions outcomes by improving the effectiveness and productivity of clean technologies. As a result, patent quality serves as an important channel through which geopolitical risk influences the pace and direction of the energy transition.

We interpret these findings as follows. First, the increase in both quantity and quality patent counts reflects heightened R&D investment and innovation activity, but the transformation of technological achievements into commercial applications is subject to substantial time lags, limiting the immediate expansion of renewable energy consumption (Popp, 2002). Second, innovation activities may generate a "lock-in effect", whereby resources devoted to R&D and patent protection constrain the scaling-up of existing renewable energy production and deployment (Unruh, 2000). Finally, energy demand is inherently rigid, and the processes of technological development and experimentation themselves require energy inputs. Under conditions of sustained demand growth, overall energy use may rise, with fossil fuels continuing to play a dominant role in the short term (Grubb et al., 2014). Therefore, the increase in renewable energy patents reflects an enhancement of potential innovation capacity rather than an immediate restructuring of the energy consumption mix.

Panel A3 reports similar findings when technological investment is proxied by environmental protection invention patents (*lnEPpat*). Column 1 shows that GPR exerts a significantly positive effect on *lnEPpat*. Columns 2–5 indicate that the magnitudes of the coefficients for all dependent variables are consistently smaller than those in the baseline regressions, thereby confirming the mediating role of *lnEPpat*. Moreover, *lnEPpat* itself has a significantly negative effect on REC at the 1% level, while its effects on total energy consumption and fossil fuel consumption are significantly positive. Similarly, we further examine the mediation effect using the citation number of environmental protection invention patents (*lnEPCit*) as an alternative proxy for technological innovation quality. The results in Panel A4 of Table 6 indicate that GPR has a significantly positive effect on *lnEPCit*, suggesting that heightened geopolitical risk is associated with improvements in the quality of environmental protection–related innovation. In addition, *lnEPCit* exerts a significantly negative impact on REC (−0.580) and also has negative effects on total energy consumption and carbon emissions. These findings imply that improvements in the quality of environmental innovation facilitate energy substitution away from fossil fuels and enhance energy efficiency, thereby contributing to lower overall energy use and reduced emissions. Collectively, the evidence reinforces the role of patent quality as a key technological channel through which geopolitical risk influences energy structure and environmental outcomes. Overall, these results are consistent with those reported in Panel A1, reinforcing the conclusion that technological investment plays an important mediating role in the relationship between GPR, renewable energy consumption, and fossil fuel use.

4.3.2. Energy security

Regarding the mediating role of energy security, we report its evidence about mediating role in Panel B of Table 6. Column 1 indicates that geopolitical risk significantly increases the ratio of energy supply to energy consumption, thereby reinforcing energy security. Furthermore, the results in Column 2 show that the magnitude of the coefficient on renewable energy consumption (REC) declines and reaches −1.708 after incorporating *ES* into the baseline specification. Taken together, these findings demonstrate the statistically significant mediating function and explanatory power of *ES* in the relationship between GPR and REC. In addition, the coefficient on REC remains significantly negative at the 1% level (−18.181), further underscoring the conclusion that higher levels of energy security suppress the use of renewable energy.

At the same time, the results reported in Column 3 reveal that the coefficient magnitude of *LnEnergy* decreases to 0.071 compared with its coefficient at 0.092 in baseline test, and both estimates are statistically significant at the 1% level. A similar pattern is observed in Columns 4 and 5, where the coefficients for fossil fuel utilization—proxied by total CO_2 emissions and per capita CO_2 emissions—also decline once energy security is introduced into the specification. These results indicate that *ES* mediates and explains the effect of GPR on both aggregate energy consumption and fossil fuel use. Moreover, the positive and highly significant coefficients of *ES* for *LnEnergy*, $LnCO_2$, and CO_2_capita (0.503, 0.791, and 6.435, respectively, at the 1% level) further demonstrate that stronger energy security promotes reliance on fossil fuels. Taken together, the evidence suggests that energy security intensifies dependence on traditional energy sources, thereby elevating CO_2 emissions and exacerbating the decline in renewable energy consumption, lending strong support to Hypothesis 2.

An increase in energy security often reflects a greater degree of self-sufficiency and reliability in energy supply, which may unintentionally reduce reliance on renewable energy while encouraging higher fossil fuel consumption and overall energy demand. First, improvements in energy security are frequently achieved through the expansion or stabilization of fossil fuel extraction and utilization capacities, thereby reinforcing fossil fuel dependence (Cherp and Jewell, 2014). Second, the availability of stable and abundant energy supply reduces the perceived urgency of transitioning to renewable sources, creating a crowding-out effect that diminishes renewable energy's share in the total energy mix (Sovacool and Brown, 2010). Finally, higher energy security fosters confidence in supply continuity, which in turn stimulates energy-intensive economic activity and drives up aggregate energy consumption (Winzer, 2012). Consequently, while enhanced energy security strengthens supply stability, it may paradoxically undermine renewable energy development and exacerbate fossil fuel reliance.

The above findings suggest that while GPR may lead to increased carbon emissions and exacerbate environmental degradation in the short term, countries are likely to respond by boosting technological investments over the long term. Such investments help offset the adverse effects of GPR by improving energy efficiency and fostering the development of RE technologies. These results align with the perspectives of Alsagr and Van Hemmen (2021) and reinforce the role of technological advancements in addressing the challenges posed by GPR.

4.4. Heterogeneity analysis

4.4.1. Energy reserve

The suppressive effect of geopolitical risk on renewable energy utilization may vary under different conditions. Existing studies widely acknowledge that national energy reserves play a central role in safeguarding energy security and, by shaping the security framework, exert a direct influence on renewable energy consumption.

Evidence from the International Energy Agency (International Energy Agency (IEA), 2024) highlights strategic reserves as key policy instruments for mitigating supply disruptions and price volatility. Comparative research further shows that reserve systems in Japan and other OECD countries effectively reduce risks arising from geopolitical tensions and supply uncertainty (Zhang, 2024). Empirical studies also reveal a close link between energy security and renewable energy development: reliance on fossil fuel rents often crowds out renewable investment (Alsagr and Ozturk, 2024), while renewable expansion helps reduce security risks (Zhang, 2024). More recent evidence from OPEC+ countries suggests that oil rents exert threshold effects on renewable energy development, with financial development conditioning this relationship (Baudino, 2024). Taken together, these findings imply that energy reserves, by shaping national energy security, directly affect renewable energy consumption patterns.

Following OPEC's classification, we distinguish energy-exporting from energy-importing countries and construct a dummy variable (*EnergyExport*) equal to 1 for exporters and 0 otherwise. As energy exports often dominate national revenues and fiscal income, this classification captures structural differences in energy dependence. Panel A of Table 7 presents the baseline regression results incorporating the interaction between GPR and *EnergyExport*.

Results in Panel A of Table 7 indicate that the coefficient of the interaction term between GPR and *EnergyExport* is 3.395, which is statistically significant at the 5% level. This finding suggests that the abundance of a country's energy reserves effectively mitigates the adverse impact of GPR on renewable energy consumption (REC).

Moreover, the results in Column 2 indicate that the interaction term for total energy consumption is significantly negative (−0.182), implying that higher levels of energy reserves attenuate the overall impact of GPR on energy consumption. Consistent with this, the findings further suggest that energy reserves moderate the positive association between GPR and fossil fuel consumption. Specifically, the significantly negative coefficients for CO_2 emissions and per capita CO_2 emissions in Columns 3 and 4 demonstrate that greater energy reserves reduce the extent to which GPR heightens dependence on fossil fuels.

The mitigating role of national energy reserves may be attributed to several potential mechanisms. First, while geopolitical risk tends to suppress a country's consumption of renewable energy by heightening supply uncertainty and market volatility, energy reserves can mitigate this adverse effect. Sizable reserves serve as a buffer by stabilizing domestic energy supply and prices, thereby reducing the disruptive impact of geopolitical shocks. Second, adequate reserves expand the policy space for governments to sustain investment in renewable energy rather than diverting resources to address immediate energy shortages. Third, the presence of reserves provides a stabilizing market signal that alleviates investor and consumer concerns, thus weakening the constraining

Table 7
Heterogeneous effects.

Panel A: Energy exporting countries				
	(1)	(2)	(3)	(4)
VARIABLES	REC	LnEnergy	LnCO2	CO2_capita
GPR × EnergyExport	3.395**	−0.182***	−0.322***	−1.996***
	(1.317)	(0.061)	(0.075)	(0.656)
Control variables	Yes	Yes	Yes	Yes
Observations	1271	1113	1383	1383
R^2	0.931	0.980	0.982	0.951
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Panel B: Developed countries				
	(1)	(2)	(3)	(4)
VARIABLES	REC	LnEnergy	LnCO2	CO2_capita
GPR × Developed	6.605**	−0.178*	−0.276**	−2.496***
	(3.095)	(0.101)	(0.117)	(0.827)
Control variables	Yes	Yes	Yes	Yes
Observations	1271	1113	1383	1383
R-squared	0.932	0.980	0.982	0.951
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Notes: This table presents the heterogeneous results. The independent variables are interaction terms country-level GPR with country types (energy exporting countries *EnergyExport* and developed countries *Developed*). *EnergyExport* is a dummy variable that equals 1 if a country is classified by OPEC as an energy exporter, and 0 otherwise. "Energy-exporting countries" are defined as those nations with positive net exports of energy commodities, primarily crude oil and natural gas. The dependent variables represent are: the ratio of RE consumption (*REC*) and natural logarithm of energy consumption (*LnEnergy*), the natural logarithm of CO_2 emissions (*LnCO2*) and CO_2 emissions per capita (*CO2_capita*). *Developed* is equals 1 if a country is classified as developed and 0 otherwise. Table A2 outlines definitions of the variables. All results are estimated with country and year fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate statistical significance at 0.1, 0.05, and 0.01 levels, respectively.

effect of geopolitical risk on renewable energy consumption.

4.4.2. Regional economic

The level of economic development directly shapes a country's capacity to invest in renewable energy technologies, thereby influencing renewable energy utilization and consumption. Empirical studies show that higher economic development is associated with greater renewable energy investment and technological innovation (Apergis and Payne, 2010; Sadorsky, 2009). Evidence from OECD and European countries further confirms that economic growth, coupled with R&D expenditure, significantly drives the expansion of renewable energy use (Marques, Fuinhas, & Manso, 2010). Therefore, the level of economic development may exert a significant influence on the relationship between geopolitical risk (GPR) and renewable energy consumption (REC).

We further explore the role of regional economic development in shaping the relationship between GPR and REC. To this end, we construct a dummy variable, Developed, which equals 1 if a country is classified as developed and 0 otherwise. The results presented in Panel B of Table 7 indicate that being a developed country helps to alleviate the suppressive effect of geopolitical risk on REC. Specifically, Column 1 shows that the interaction term *GPR*×*Developed* has a coefficient of 6.605, which is statistically significant at the 5% level.

Moreover, the interaction term for total energy consumption is significantly negative, suggesting that higher levels of economic development weaken the overall effect of GPR on energy consumption. Consistently, the results also show that economic development moderates the positive effect of GPR on fossil fuel consumption. In Columns 3 and 4, the significantly negative coefficients for CO_2 emissions and per capita CO_2 emissions indicate that higher levels of economic development reduce the extent to which GPR increases dependence on fossil fuels.

Although geopolitical risk generally suppresses renewable energy consumption, higher levels of economic development can mitigate this adverse effect through several channels. In terms of technological innovation capacity, developed countries possess stronger indigenous R&D capabilities and higher-quality patent output in renewable energy, which enhances the technological resilience of energy transition. Popp (2002) identifies technological progress as a key driver of renewable energy expansion, while Aghion et al. (2016) show that advanced economies benefit from more effective institutional frameworks and incentive mechanisms for green innovation, allowing them to sustain R&D investment even under heightened uncertainty. In contrast, developing countries rely more heavily on external technology transfer, making their renewable energy sectors more vulnerable to geopolitical disruptions that restrict international cooperation and equipment imports.

With respect to energy policy systems, developed countries typically implement more mature and credible policy frameworks, including renewable energy subsidies, carbon pricing schemes, and green finance mechanisms, which provide stable expectations for investors (Organisation for Economic Co-operation and Development (OECD), 2017). Polzin et al., 2015 further argue that higher institutional quality mitigates policy inconsistency and strengthens long-term commitment to energy transition. By contrast, developing countries are more likely to adjust subsidy policies or delay green investment in response to economic slowdowns or external shocks, thereby amplifying the negative effects of GPR.

Regarding energy structures, developed economies generally exhibit higher renewable energy penetration and more diversified energy systems, which reduce dependence on imported fossil fuels (International Energy Agency (IEA), 2021). Moreover, the expansion of distributed generation and smart grids improves system flexibility and shock absorption capacity. Developing countries, however, remain heavily reliant on fossil fuels and global energy markets, making them more susceptible to geopolitical disturbances that reinforce traditional energy dependence. Therefore, stronger innovation capacity, more stable policy institutions, and more resilient energy structures jointly attenuate the negative effect of geopolitical risk on renewable energy development in developed countries.

5. Further analysis

5.1. GPR long-term impact on REC

Generally, there are two primary strategies to address energy crises induced by GPR: (1) increasing the security of fossil fuel supplies and (2) developing energy-saving and RE technologies. The first approach typically focuses on short-term measures, such as expanding fossil fuel reserves to mitigate the effect of GPR, which may result in higher CO_2 emissions. In contrast, the second approach addresses the long-term impacts of GPR by enhancing fossil fuel efficiency and promoting the development of RE technologies. These approaches have two important implications: First, the intensity of GPR may drive governments to adopt different strategies for managing energy crises, leading to a nonlinear relationship between GPR and energy consumption or carbon emissions. When GPR is low, governments may prioritize energy supply security, focusing on short-term measures. However, as risks escalate, governments may be compelled to adopt RE technologies to address long-term energy supply challenges. Second, in the long run, the influence of GPR depends on the dynamic interplay between these two strategies. Therefore, we further explore the long-term influence of GPR and its nonlinear impact on energy consumption and carbon emissions.

This section analyzes the long-term influence of current GPR on CO_2 emissions and energy consumption over a 1–5 year horizon. Results are reported in Panels A to E in Table 8. Across all panels, statistics of all coefficients on GPR are consistent with those in the baseline results reported in Table 3, confirming that our baseline results are robust. The magnitude of the *GPR* coefficients gradually decreases, indicating that the long-term influence of GPR on CO_2 emissions and energy consumption weakens over time.

We understand that this trend may stem from the distinct short- and long-term government responses to GPR. In the short term, governments are more likely to increase the proportion and total consumption of fossil fuels to ensure energy supply security and mitigate potential energy crises, resulting in higher CO_2 emissions. In the long term, governments tend to prioritize the development of energy-efficient technologies and renewable energy sources to address the persistent energy challenges associated with GPR. As these advanced technologies become more widely adopted, the reliance on fossil fuel decreases, leading to observable emission reductions. Consequently, the marginal impact of GPR on CO_2 emissions and energy consumption diminishes over time.

5.2. Nonlinear relation between GPR and REC

Next, we investigate the nonlinear effects of GPR on RE consumption in this section, specifically testing for the presence of a "U-shaped" relationship. To explore potential nonlinear relationships, we examine the associations between GPR and four dependent variables: the share of renewable energy consumption (*REC*), total energy consumption (*LnEnergy*), total CO_2 emissions (*LnCO2*), and per capita CO_2 emissions (*CO2_capita*). We present the scatter plots of GPR against the four dependent variables. Fig. 1 illustrates both the linear fit lines and the nonlinear ones for these relationships. As shown in Fig. 1, the R^2 values for the nonlinear fit lines are consistently and significantly greater than those of the linear fit lines. This initial evidence supports the presence of a nonlinear relationship between GPR and the four dependent variables, establishing a foundation for further analysis.

To further analyze the nonlinear characteristics of the impact of GPR on RE consumption and CO_2 emissions, we introduce the squared term of the geopolitical risk index (GPR^2) into the baseline models. Table 9 shows the regression results.

The coefficient of the linear term *GPR* is negative and statistically significant at the 1% level, while the coefficient of the squared term GPR^2 becomes positive and statistically significant at the 5% level. This suggests a U-shaped effect of GPR on the proportion of RE consumption (*REC*): at lower levels of GPR, RE consumption decreases; however, as GPR intensifies, RE consumption begins to rise. From an economic perspective, the turning point for the impact of *GPR* on *REC* is 3.30. The statistical summary of Table 1 indicates that the GPR index has a mean of 0.204, a variance of 0.406, with values ranging from a minimum of 0.004 to a maximum of 4.35. The inflection point in renewable energy consumption (REC) is identified at GPR = 3.3, suggesting that this level lies in the extreme upper tail of the sample distribution and is substantially above the long-run average, thereby representing an "exceptionally high-risk" regime. According to Caldara and Iacoviello (2022), GPR values of this magnitude are typically associated with major geopolitical disruptions, including large-scale military conflicts, war escalations, and global security shocks, such as the 2003 Iraq War, the 2014 Crimea crisis, the 2022 Russia–Ukraine war, and major terrorist attacks. At this stage, the GPR index no longer reflects ordinary fluctuations in uncertainty, but instead captures conditions of systemic geopolitical crisis, under which the nature of risk faced by the economy shifts from marginal disturbances to structural shocks.

This U-shaped pattern between GPR and REC can be understood through a two-stage mechanism involving (i) an "investment uncertainty effect" at low-to-moderate levels of geopolitical risk and (ii) a "energy security–driven effect" at extreme levels of geopolitical stress. When geopolitical risk remains within a low to moderate range, rising GPR primarily manifests as elevated macroeconomic uncertainty and financial market volatility, which discourages long-term capital

Table 8
Long-term impact between GPR and REC.

Panel A: T + 1 period

	(1)	(2)	(3)	(4)
VARIABLES	REC_{t+1}	$LnEnergy_{t+1}$	$LnCO2_{t+1}$	$CO2\_capita_{t+1}$
GPR_t	−1.943**	0.092***	0.142***	1.182***
	−0.78	−0.025	−0.04	−0.338
Control variables	Yes	Yes	Yes	Yes
Observations	1253	1071	1342	1342
R^2	0.931	0.981	0.982	0.951
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Panel B: T + 2 period

	(1)	(2)	(3)	(4)
VARIABLES	REC_{t+2}	$LnEnergy_{t+2}$	$LnCO2_{t+2}$	$CO2\_capita_{t+2}$
GPR_t	−1.744**	0.082***	0.128***	1.100***
	−0.72	−0.024	−0.037	−0.323
Control variables	Yes	Yes	Yes	Yes
Observations	1234	1029	1300	1300
R^2	0.931	0.983	0.983	0.953
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Panel C: T + 3 period

	(1)	(2)	(3)	(4)
VARIABLES	REC_{t+3}	$LnEnergy_{t+3}$	$LnCO2_{t+3}$	$CO2\_capita_{t+3}$
GPRt	−1.418**	0.063***	0.107***	0.955***
	−0.654	−0.022	−0.035	−0.323
Control variables	Yes	Yes	Yes	Yes
Observations	1215	987	1258	1258
R2	0.931	0.984	0.984	0.954
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Panel D: T + 4 period

	(1)	(2)	(3)	(4)
VARIABLES	REC_{t+4}	$LnEnergy_{t+4}$	$LnCO2_{t+4}$	$CO2\_capita_{t+4}$
GPRt	−1.216**	0.050***	0.093***	0.861***
	−0.588	−0.019	−0.031	−0.301
Control variables	Yes	Yes	Yes	Yes
Observations	1195	945	1216	1216
R2	0.932	0.985	0.985	0.956
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Panel E: T + 5 period

	(1)	(2)	(3)	(4)
VARIABLES	REC_{t+5}	$LnEnergy_{t+5}$	$LnCO2_{t+5}$	$CO2\_capita_{t+5}$
GPRt	−1.064**	0.038**	0.070***	0.600**
	−0.537	−0.019	−0.027	−0.266
Control variables	Yes	Yes	Yes	Yes
Observations	1174	903	1174	1174
R2	0.933	0.986	0.985	0.958
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Notes: This table presents the nonlinear regression results. The independent variable represents the proxy measure of country-level GPR. The dependent variables represent are: the ratio of RE consumption (*REC*) and natural logarithm of energy consumption (*LnEnergy*), the natural logarithm of CO_2 emissions (*LnCO2*) and CO_2 emissions per capita (*CO2_capita*). Table A2 outlines definitions of the variables. All results are estimated with country and year fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate statistical significance at 0.1, 0.05, and 0.01 levels, respectively.

investment. Renewable energy projects are typically characterized by large upfront costs, long payback periods, and strong dependence on policy credibility and regulatory stability. As geopolitical tensions intensify, risk premiums increase and financing constraints become more binding, leading private firms and governments to defer or scale back renewable energy investments in favor of short-term economic stabilization and conventional energy supply. A growing body of empirical literature confirms that geopolitical risk significantly depresses green investment through heightened uncertainty and financial frictions (Balcilar et al., 2018). In this regime, the uncertainty-induced contraction in capital formation dominates, giving rise to the downward-sloping segment of the U-shaped curve.

However, once geopolitical risk surpasses a critical threshold, its economic implications fundamentally change. When GPR reaches extremely high levels—such as during major wars, international conflicts, or severe geopolitical confrontations—the nature of policy priorities shifts from growth-oriented objectives toward security-oriented imperatives. At this stage, heavy reliance on imported fossil fuels is recognized as a major strategic vulnerability, elevating energy security to the forefront of national security and macroeconomic stability. Consequently, renewable energy transitions from being merely an environmental or economic policy instrument to a strategic asset for enhancing energy independence and resilience. Prior studies have shown that countries facing acute geopolitical threats tend to accelerate renewable energy deployment to reduce dependence on politically unstable regions and volatile fossil fuel markets (Cherp and Jewell, 2014; Flouros et al., 2022). Moreover, Lee et al. (2024) provide cross-country evidence that geopolitical risk itself exhibits a U-shaped relationship with energy security, with the upward-sloping segment operating predominantly through intensified government support for

Table 9
Nonlinear regression results.

	(1)	(2)	(3)	(4)
VARIABLES	REC	LnEnergy	LnCO2	CO2_capita
PR	−5.948***	0.242***	0.369***	2.576***
	(2.063)	(0.067)	(0.083)	(0.576)
GPR^2	0.901**	−0.038***	−0.055***	−0.330***
	(0.362)	(0.012)	(0.015)	(0.118)
Control variables	Yes	Yes	Yes	Yes
Observations	1271	1113	1383	1383
R^2	0.932	0.980	0.982	0.950
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Notes: This table presents the nonlinear regression results. The independent variables represent the proxy measure of country-level GPR and its squared term (GPR^2). The dependent variables represent are: the ratio of RE consumption (*REC*) and natural logarithm of energy consumption (*LnEnergy*), the natural logarithm of CO_2 emissions (*LnCO2*) and CO_2 emissions per capita (*CO2_capita*). Table A2 outlines definitions of the variables. All results are estimated with country and year fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate statistical significance at 0.1, 0.05, and 0.01 levels, respectively.

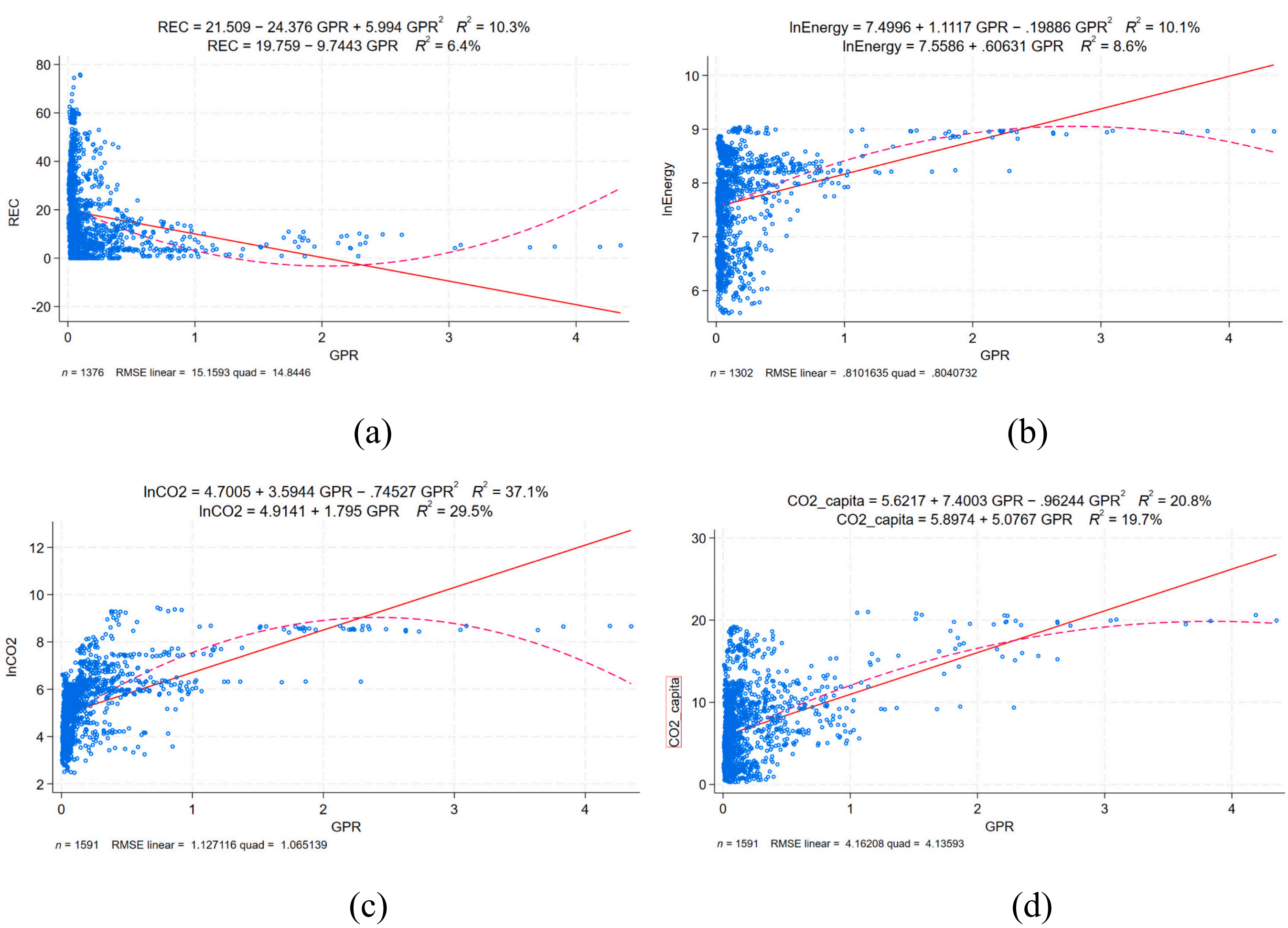

Fig. 1. Fitted line of GPR and four dependent variables.

renewable energy technologies and innovation. In extreme-risk regimes, governments systematically expand public investment, subsidies, and regulatory facilitation for clean energy projects under a "strategic substitution" logic, thereby reversing the initial negative impact of geopolitical risk on renewable energy consumption. In such circumstances, the energy security effect dominates the uncertainty effect, generating the upward-sloping portion of the U-shaped curve identified in this study.

In contrast, the coefficients of *GPR* are positive and statistically significant, while the coefficients of GPR^2 are negative and statistically significant, both at the 1% level in Columns 2 to 4. This suggests an inverted U-shaped effect of GPR on total energy consumption (*LnEnergy*), total CO_2 emissions (*LnCO2*), and per capita CO_2 emissions (*CO2_capita*), with a turning point at 3.18, 3.35, and 3.90, respectively.

These findings highlight the significant dual effects of GPR on carbon emissions and energy consumption, resulting in both negative and positive outcomes. The underlying rationale for this duality stems from the heightened tension in energy markets due to geopolitical conflicts, which raise energy costs and increase the risk of supply disruptions, particularly for countries heavily reliant on energy imports. In response to these challenges, countries may actively invest in RE development and improve fossil fuel efficiency to ensure energy security. Our results align with the findings of Lee et al. (2024), reinforcing that while GPR presents challenges, it can also stimulate advancements in energy sustainability.

5.3. Institutional endowment

Existing research indicates that institutional endowment plays a crucial role in mitigating the adverse impact of geopolitical risk on energy use. First, stronger institutional quality enhances policy stability and governance capacity, allowing governments to maintain long-term energy strategies under external shocks (Kaufmann et al., 2011). Second, greater public participation and accountability encourage governments to sustain green policies and renewable energy investments even in the context of geopolitical uncertainty (Fredriksson and Svensson, 2003). Third, improvements in the rule of law and contract enforcement reduce investment uncertainty, safeguard property rights, and attract long-term renewable energy investment (Acemoglu and Robinson, 2013). Finally, high-quality institutions facilitate energy efficiency improvements and structural transformation of the energy mix, thereby reducing dependence on fossil fuels and lowering the sensitivity of total energy consumption to external risks (Sadorsky, 2009; Marques et al., 2010). Taken together, strong institutional endowment not only alleviates the suppressive effect of geopolitical risk on renewable energy consumption but also mitigates reliance on traditional energy and improves the overall structure of energy use.

We incorporate this analysis by measuring institutional endowment across three dimensions—Voice and accountability, Government effectiveness, and Rule of law. We then construct interaction terms between GPR and each of these institutional variables to assess their moderating effects on the GPR–REC nexus.

Specifically, the definitions of these institutional variables are drawn from the Worldwide Governance Indicators (WGI) database compiled by the World Bank. *Voice and accountability* reflect perceptions of the extent to which a country's citizens are able to participate in selecting their government, together with freedoms of expression, association, and a free media. *Government effectiveness* captures perceptions of the quality of public services, the capacity and independence of the civil service, the quality of policy formulation and implementation, and the credibility of government commitments to such policies. *Rule of law* reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, including the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.

Panel A of Table 10 presents the baseline regression results augmented with interaction terms between geopolitical risk (GPR) and the institutional endowment variables. As shown in Column 1, the coefficient of the interaction term is significantly positive at the 1% level (2.604), indicating that greater *Voice and accountability* mitigates the suppressive effect of GPR on renewable energy consumption. The results in Column 2 further suggest that the protection of citizens' participatory rights also moderates the extent to which GPR increases overall energy demand. Similarly, the significantly negative coefficients in Columns 3 and 4 at the 1% level imply that the influence of GPR on dependence on traditional energy consumption is weakened as voice and accountability improves.

Table 10
Institutional endowment moderating effects.

Panel A: Voice and accountability

	(1)	(2)	(3)	(4)
VARIABLES	REC	LnEnergy	LnCO2	CO2_capita
GPR × Voice	2.604***	−0.045	−0.127***	−0.876***
	(0.779)	(0.039)	(0.046)	(0.318)
Control variables	Yes	Yes	Yes	Yes
Observations	1081	811	1081	1081
R^2	0.941	0.988	0.988	0.960
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Panel B: Government effectiveness

	(1)	(2)	(3)	(4)
VARIABLES	REC	LnEnergy	LnCO2	CO2_capita
GPR × GoverEffect	−0.809	0.061*	0.111***	0.801***
	(0.762)	(0.035)	(0.038)	(0.256)
Control variables	Yes	Yes	Yes	Yes
Observations	1081	811	1081	1081
R^2	0.946	0.988	0.989	0.965
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Panel C: Rule of law

	(1)	(2)	(3)	(4)
VARIABLES	REC	LnEnergy	LnCO2	CO2_capita
GPR × Law	1.514**	−0.034	−0.058	−0.676*
	(0.742)	(0.050)	(0.046)	(0.361)
Control variables	Yes	Yes	Yes	Yes
Observations	1081	811	1081	1081
R^2	0.942	0.987	0.988	0.960
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Notes: This table presents the results of moderating effects of institutional endowment on GPR-REC relation. The independent variables are interaction terms country-level GPR with indicators of institutional endowment: *Voice and accountability, Government effectiveness and Rule of law*. *Voice and accountability* reflect perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media. *Government effectiveness* reflects perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. *Ruel of law* reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence. The dependent variables represent are: the ratio of RE consumption (*REC*) and natural logarithm of energy consumption (*LnEnergy*), the natural logarithm of CO_2 emissions (*LnCO2*) and CO_2 emissions per capita (*CO2_capita*). Table A2 outlines definitions of the variables. All results are estimated with country and year fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate statistical significance at 0.1, 0.05, and 0.01 levels, respectively.

The results in Panel B indicate that improvements in Government effectiveness significantly mitigate the impact of geopolitical uncertainty on total energy consumption. This moderating effect is even more pronounced for fossil fuel use, as evidenced by the interaction terms for CO_2 emissions and per capita CO_2 emissions, which are both positive and statistically significant at the 1% level (0.111 and 0.801, respectively).

The results in Panel C indicate a consistent conclusion when institutional endowment is measured by the Rule of law. Notably, the coefficient of the interaction term for REC is 1.514 and significant at the 5% level, while the coefficient for per capita CO_2 emissions is −0.676 and significant at the 10% level. These findings suggest that in countries with stronger Rule of law, the adverse effects of geopolitical uncertainty—namely the reduction in renewable energy use and the increased dependence on non-renewable energy—are mitigated.

6. Conclusions

This study investigates the intricate and evolving nexus between GPR and RE consumption, providing insightful observations into the explanatory power of energy security and technological innovation. Our findings reveal that GPR negatively influences RE consumption in the short term, with heightened geopolitical uncertainty driving countries to prioritize energy security by increasing reliance on fossil fuels, leading to higher CO_2 emissions. Fossil fuels are often favoured during crises due to their perceived stability.

The results of the heterogeneity analysis reveal that national energy reserves can effectively mitigate the adverse impact of geopolitical risk on renewable energy utilization. Similarly, the negative relationship between GPR and REC is weaker in developed countries compared to developing ones, suggesting that the level of regional economic development significantly shapes the influence of geopolitical risk on a country's energy consumption structure.

Over the long term, however, persistent geopolitical tensions prompt governments to invest in RE technologies and innovation to enhance energy security. This transition results in a gradual shift in energy consumption preferences from fossil fuels to renewables, as advancements in energy technologies reduce costs, improve efficiency, and promote national energy self-sufficiency.

Moreover, this research identifies a non-linear relationship between GPR and RE consumption. Moderate GPR levels amplify fossil fuel consumption and emissions due to their relative stability, whereas high GPR levels disrupt fossil fuel supplies, creating economic costs and accelerating the transition to RE as a sustainable and resilient solution.

Finally, our study finds that a nation's institutional endowments also play a moderating role: countries with stronger institutional capacity exhibit a lower reliance on conventional fossil fuels under high geopolitical risk, thereby maintaining a relatively higher share of renewable energy consumption.

The empirical findings of this study shed light on several ways in which geopolitical risk (GPR) shapes energy consumption structures and carbon emissions, offering a number of implications that may be of relevance to policymakers and stakeholders.

First, the short-term results suggest that GPR tends to suppress renewable energy (RE) consumption while reinforcing reliance on fossil fuels. This pattern implies that efforts to support RE markets during periods of elevated uncertainty may be particularly important. Measures such as temporary financial incentives, tax relief, or more accessible financing arrangements could help mitigate the additional costs and risks of RE investment, thereby reducing the likelihood of setbacks in the transition process.

Second, the heterogeneity analysis underscores the buffering role of national energy reserves. This finding suggests that the design and management of reserve systems, especially when linked with RE strategies, may help reduce dependence on conventional fossil fuels in uncertain times. For energy-exporting countries, abundant energy reserves can buffer the adverse effects of rising geopolitical risk; however, this should not justify continued reliance on fossil fuels. Governments should allocate resource revenues toward economic diversification and renewable energy deployment, transforming resource endowments into long-term drivers of green transition and reducing vulnerability to a fossil-fuel–dependent growth path. For energy-importing countries, market mechanisms alone are insufficient to cope with geopolitical shocks. Strengthening strategic energy reserves and optimizing energy structures are essential to enhance energy security. In particular, accelerating the deployment of renewable energy can effectively reduce external energy dependence and serve as a critical policy response to rising geopolitical uncertainty.

From a development-stage perspective, countries with higher levels of economic development are less likely to passively increase fossil fuel consumption in response to geopolitical shocks, indicating that strong economic fundamentals and institutional capacity themselves constitute a critical "security buffer". Developed economies should continue to leverage their technological advantages to improve energy infrastructure and enhance the stability and flexibility of energy systems, thereby ensuring that the pace of low-carbon transition is not disrupted under conditions of heightened uncertainty. In contrast, developing countries are more prone to expanding fossil fuel reliance under short-term energy security pressures and therefore should place greater emphasis on international financing, technology transfer, and multilateral cooperation to reduce the cost of clean energy adoption and avoid long-term entrenchment in high-carbon pathways.

Third, the evidence regarding institutional endowments highlights their role in moderating fossil fuel dependence under high GPR. Strengthening institutional frameworks—such as regulatory quality, contract enforcement, and policy transparency—appears to contribute not only to broader economic stability but also to the durability of RE transition. Institutional development may therefore be viewed as a complementary pathway for supporting long-term sustainability.

Finally, the non-linear relationship between GPR and RE consumption indicates that while moderate levels of GPR often reinforce fossil fuel use, higher levels can act as a catalyst for change by encouraging investment in RE. This suggests that moments of heightened geopolitical stress, though challenging, may also create opportunities to accelerate structural adjustment and innovation within the energy sector.

In summary, these results point to the importance of balancing short-term stabilization with longer-term transformation. By reducing the immediate risks of RE suppression during crises and, at the same time, fostering institutional improvements and technological innovation, governments may be better positioned to achieve both energy security and sustainability goals. In this way, energy systems can become more resilient to geopolitical uncertainty while continuing to advance toward a low-carbon future.

CRediT authorship contribution statement

Tiantian Tang: Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yafei Li:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Liping Zou:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

Acknowledgment

This research was supported by the National Social Science Foundation of China (Grant number: 23CJY022).

Appendix A. Appendix

Table A1
Country and region list.

No.	Country Name
1	Argentina
2	Australia
3	Belgium
4	Brazil
5	Canada
6	Chile
7	China
8	Colombia
9	Denmark
10	Egypt, Arab Rep.
11	Finland
12	France
13	Germany
14	Hong Kong SAR, China
15	Hungary
16	India
17	Indonesia
18	Israel
19	Italy
20	Japan
21	Korea, Rep.
22	Malaysia
23	Mexico
24	Netherlands
25	Norway
26	Peru
27	Philippines
28	Poland
29	Portugal
30	Russian Federation
31	Saudi Arabia
32	South Africa
33	Spain
34	Sweden
35	Switzerland
36	Thailand
37	Tunisia
38	Turkiye
39	Ukraine
40	United Kingdom
41	United States
42	Venezuela, RB
43	Viet Nam

Table A2
List of variables and definitions.

Variable	Definition	Source
GPR	Geopolitical risk index	Caldara and Iacoviello Website
GPRH	Historical geopolitical risk index	Caldara and Iacoviello Website
LnEnergy	Natural logarithm of energy consumption (kg of oil equivalent per capita)	WDI
REC	Renewable energy consumption (% of total final energy consumption)	WDI
LnCO2	Natural logarithm of CO_2 emissions	WDI
CO2_capita	CO_2 emissions per capita	WDI
POP	Natural logarithm of total population	WDI
Secondary	Secondary industry output (% of GDP)	WDI
Tertiary	Tertiary industry output (% of GDP)	WDI
FDI_in	Net inflows of foreign direct investment (% of GDP)	WDI
PGDP	GDP per capita	WDI
PGDP_growth	GDP per capita growth (%)	WDI

(*continued on next page*)

Table A2 (*continued*)

Variable	Definition	Source
Agric land	Agricultural land (% of land area)	WDI
lnRenewPat	The natural logarithm of renewable energy patent applications plus one	incoPat
lnRenewCit	The natural logarithm of renewable energy patent citations plus one	incoPat
lnEPpat	The natural logarithm of environmental protection patent applications plus one	incoPat
lnEPCit	The natural logarithm of environmental protection patent citations plus one	incoPat
ES	Energy security which is calculated as energy supply / energy consumption	IEA
Voice	Voice and accountability index in the WGI dataset.	World Bank
GoverEffect	Government effectiveness index in the WGI dataset.	World Bank
Law	Rule of law index in the WGI dataset.	World Bank
EnergyExport	Energy exporting countries.	OPEC/IEA
Developed	Developed countries.	IMF

Notes: WDI is World Development Indicators. IEA denotes International Energy Agency. Matteo Iacoviello's website is https://www.matteoiacoviello.com. WGI is Worldwide Governance Indicators in World Bank. OPEC denotes Organization of the Petroleum Exporting Countries. IMF is International Monetary Fund.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2026.109253.

References

Acemoglu, D., Robinson, J.A., 2013. Why Nations Fail: The Origins of Power, Prosperity, and Poverty. Crown Currency.

Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D., 2012. The environment and directed technical change. Am. Econ. Rev. 102 (1), 131–166. https://doi.org/10.1257/aer.102.1.131.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., Van Reenen, J., 2016. Carbon taxes, path dependency, and directed technical change: evidence from the auto industry. J. Polit. Econ. 124 (1), 1–51. https://doi.org/10.1086/684581.

Aguirre, M., Ibikunle, G., 2014. Determinants of renewable energy growth: a global sample analysis. Energy Policy 69, 374–384. https://doi.org/10.1016/j.enpol.2014.02.036.

Akintande, O.J., Olubusoye, O.E., Adenikinju, A.F., Olanrewaju, B.T., 2020. Modeling the determinants of renewable energy consumption: evidence from the five most populous nations in Africa. Energy 206, 117992. https://doi.org/10.1016/j.energy.2020.117992.

Alsagr, N., Ozturk, I., 2024. Natural resources rent and green investment: does institutional quality matter? Res. Policy 90, 104709. https://doi.org/10.1016/j.resourpol.2024.104709.

Alsagr, N., Van Hemmen, S., 2021. The impact of financial development and geopolitical risk on renewable energy consumption: evidence from emerging markets. Environ. Sci. Pollut. Res. 28, 25906–25919. https://doi.org/10.1007/s11356-021-12447-2.

Apergis, N., Payne, J.E., 2010. Renewable energy consumption and economic growth: evidence from a panel of OECD countries. Energy Policy 38 (1), 656–660. https://doi.org/10.1016/j.enpol.2009.09.002.

Baker, S.R., Bloom, N., Davis, S.J., 2016. Measuring economic policy uncertainty. Q. J. Econ. 131 (4), 1593–1636. https://doi.org/10.1093/qje/qjw024.

Balcilar, M., Bonato, M., Demirer, R., Gupta, R., 2018. Geopolitical risks and stock market dynamics of the BRICS. Econ. Syst. 42 (2), 295–306. https://doi.org/10.1016/j.ecosys.2017.05.008.

Baudino, M., 2024. Oil rents, renewable energy and the role of financial development: Evidence from OPEC+ members. Res. Policy 99, 105419. https://doi.org/10.1016/j.resourpol.2024.105419.

Bilgin, M.H., Gozgor, G., Karabulut, G., 2020. How do geopolitical risks affect government investment? An empirical investigation. Def. Peace Econ. 31 (5), 550–564. https://doi.org/10.1080/10242694.2018.1513620.

Bloom, N., 2009. The impact of uncertainty shocks. Econometrica 77 (3), 623–685. https://doi.org/10.3982/ECTA6248.

Brown, S.P., Yücel, M.K., 2002. Energy prices and aggregate economic activity: an interpretative survey. The Quart. Rev. Econ. Financ. 42 (2), 193–208. https://doi.org/10.1016/S1062-9769(02)00138-2.

Cai, Y., Wu, Y., 2021. Time-varying interactions between geopolitical risks and renewable energy consumption. Int. Rev. Econ. Financ. 74, 116–137. https://doi.org/10.1016/j.iref.2021.02.006.

Caldara, D., Iacoviello, M., 2022. Measuring geopolitical risk. Am. Econ. Rev. 112 (4), 1194–1225. https://doi.org/10.1257/aer.20191823.

Cherp, A., Jewell, J., 2014. The concept of energy security: beyond the four as. Energy Policy 75, 415–421. https://doi.org/10.1016/j.enpol.2014.09.005.

Chiang, T.C., 2021. Geopolitical risk, economic policy uncertainty and asset returns in Chinese financial markets. China Fin. Rev. Int. 11 (4), 474–501. https://doi.org/10.1108/CFRI-08-2020-0115.

Chishti, M.Z., Sinha, A., Zaman, U., Shahzad, U., 2023. Exploring the dynamic connectedness among energy transition and its drivers: understanding the moderating role of global geopolitical risk. Energy Econ. 119, 106570. https://doi.org/10.1016/j.eneco.2023.106570.

De Ridder, M., 2013. The Geopolitics of Mineral Resources for Renewable Energy Technologies. The Hague Centre for Strategic Studies.

Dixit, A., Pindyck, R., 1994. Investment under Uncertainty. Princeton University Press.

Dogan, E., Madaleno, M., Taskin, D., 2021. Which households are more energy vulnerable? Energy poverty and financial inclusion in Turkey. Energy Econ. 99, 105306. https://doi.org/10.1016/j.eneco.2021.105306.

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

Fang, J., Gozgor, G., Mahalik, M.K., Padhan, H., Xu, R., 2021. The impact of economic complexity on energy demand in OECD countries. Environ. Sci. Pollut. Res. 1–10.

Fayyaz, M., 2019. China-Pakistan economic corridor (CPEC): the road to Indian ocean and its geopolitical implications for the India-Pakistan strategic relations. Int. J. Educ. Res. Stud. 1 (1).

Flouros, F., Pistikou, V., Plakandaras, V., 2022. Geopolitical risk as a determinant of renewable energy investments. Energies 15 (4), 1498. https://doi.org/10.3390/en15041498.

Fredriksson, P.G., Svensson, J., 2003. Political instability, corruption and policy formation: the case of environmental policy. J. Public Econ. 87 (7–8), 1383–1405. https://doi.org/10.1016/S0047-2727(02)00036-1.

Gong, E., Ali, S., Hiragond, C.B., Kim, H.S., Powar, N.S., Kim, D., In, S.I., 2022. Solar fuels: research and development strategies to accelerate photocatalytic CO 2 conversion into hydrocarbon fuels. Energy Environ. Sci. 15 (3), 880–937. https://doi.org/10.1039/D1EE02714J.

Gozgor, G., Paramati, S.R., 2022. Does energy diversification cause an economic slowdown? Evidence from a newly constructed energy diversification index. Energy Econ. 109, 105970. https://doi.org/10.1016/j.eneco.2022.105970.

Grubb, M., Hourcade, J.C., Neuhoff, K., 2014. Planetary Economics: Energy, Climate Change and the Three Domains of Sustainable Development. Routledge.

Hamed, T.A., Bressler, L., 2019. Energy security in Israel and Jordan: the role of renewable energy sources. Renew. Energy 135, 378–389. https://doi.org/10.1016/j.renene.2018.12.036.

Harhoff, D., Narin, F., Scherer, F.M., Vopel, K., 1999. Citation frequency and the value of patented inventions. Rev. Econ. Stat. 81 (3), 511–515. https://doi.org/10.1162/003465399558265.

Hashmi, S.M., Bhowmik, R., Inglesi-Lotz, R., Syed, Q.R., 2022. Investigating the environmental Kuznets curve hypothesis amidst geopolitical risk: global evidence using bootstrap ARDL approach. Environ. Sci. Pollut. Res. 29 (16), 24049–24062. https://doi.org/10.1007/s11356-021-17488-1.

Hirth, L., 2013. The market value of variable renewables: the effect of solar wind power variability on their relative price. Energy Econ. 38, 218–236. https://doi.org/10.1016/j.eneco.2013.02.004.

Hussain, M., Mir, G.M., Usman, M., Ye, C., Mansoor, S., 2022. Analysing the role of environment-related technologies and carbon emissions in emerging economies: a step towards sustainable development. Environ. Technol. 43 (3), 367–375. https://doi.org/10.1080/09593330.2020.1788171.

International Energy Agency (IEA), 2021. The Role of Critical Minerals in Clean Energy Transitions. International Energy Agency. Retrieved from. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

International Energy Agency (IEA), 2023. Renewables 2023. Retrieved from. https://www.iea.org/reports/renewables-2023.

International Energy Agency (IEA), 2024. Oil Security and Emergency Response Policies. Retrieved from. https://www.iea.org/about/oil-security-and-emergency-response.

International Renewable Energy Agency (IRENA), 2019. Renewable Power Generation Costs in 2019. IRENA.

International Renewable Energy Agency (IREA), 2020. Renewable Capacity Statistics 2020. IREA. https://www.irena.org/Publications/2020/Mar/Renewable-Capacity-Statistics-2020.

Jacobson, M.Z., Delucchi, M.A., Bauer, Z.A., Goodman, S.C., Chapman, W.E., Cameron, M.A., Yachanin, A.S., 2017. 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. Joule 1 (1), 108–121.

Jiao, Y., Xiao, X., Bao, X., 2022. Economic policy uncertainty, geopolitical risks, energy output and ecological footprint—empirical evidence from China. Energy Rep. 8, 324–334. https://doi.org/10.1016/j.egyr.2022.03.105.

Johnstone, N., Haščič, I., Popp, D., 2010. Renewable energy policies and technological innovation: evidence based on patent counts. Environ. Resour. Econ. 45 (1), 133–155. https://doi.org/10.1007/s10640-009-9309-1.

Joskow, P.L., 2011. Comparing the costs of intermittent and dispatchable electricity generating technologies. Am. Econ. Rev. 101 (3), 238–241. https://doi.org/10.1257/aer.101.3.238.

Kammen, D.M., Sunter, D.A., 2016. City-integrated renewable energy for urban sustainability. Science 352 (6288), 922–928. https://doi.org/10.1126/science.aad9302.

Kannadhasan, M., Das, D., 2020. Do Asian emerging stock markets react to international economic policy uncertainty and geopolitical risk alike? A quantile regression approach. Financ. Res. Lett. 34, 101276. https://doi.org/10.1016/j.frl.2019.08.024.

Kaufmann, D., Kraay, A., Mastruzzi, M., 2011. The worldwide governance indicators: methodology and analytical issues1. Hague J. Rule Law 3 (2), 220–246. https://doi.org/10.1017/S1876404511200046.

Kilian, L., Murphy, D.P., 2014. The role of inventories and speculative trading in the global market for crude oil. J. Appl. Econ. 29 (3), 454–478. https://doi.org/10.1002/jae.2322. Digital Object Identifier (DOI).

Kogan, L., Papanikolaou, D., Seru, A., Stoffman, N., 2017. Technological innovation, resource allocation, and growth. Q. J. Econ. 132 (2), 665–712. https://doi.org/10.1093/qje/qjw040.

Kollias, C., Kyrtsou, C., Papadamou, S., 2013. The effects of terrorism and war on the oil price–stock index relationship. Energy Econ. 40, 743–752. https://doi.org/10.1016/j.eneco.2013.09.006.

Laird, F.N., 2013. Against transitions? Uncovering conflicts in changing energy systems. Sci. Cult. 22 (2), 149–156. https://doi.org/10.1080/09505431.2013.786992.

Lau, C.K., Soliman, A.M., Albasu, J., Gozgor, G., 2023. Dependence structures among geopolitical risks, energy prices, and carbon emissions prices. Res. Policy 83, 103603. https://doi.org/10.1016/j.resourpol.2023.103603.

Lee, C.C., Yuan, Z., Wang, Q., 2022. How does information and communication technology affect energy security? International evidence. Energy Econ. 109, 105969. https://doi.org/10.1016/j.eneco.2022.105969.

Lee, C.C., Yuan, Z., He, Z.W., Xiao, F., 2024. Do geopolitical risks always harm energy security? Their non-linear effects and mechanism. Energy Econ. 129, 107245. https://doi.org/10.1016/j.eneco.2023.107245.

Lema, A., Lema, R., 2013. Technology transfer in the clean development mechanism: insights from wind power. Glob. Environ. Chang. 23 (1), 301–313. https://doi.org/10.1016/j.gloenvcha.2012.10.010.

Lu, Z., Gozgor, G., Mahalik, M.K., Padhan, H., Yan, C., 2022. Welfare gains from international trade and renewable energy demand: evidence from the OECD countries. Energy Econ. 112, 106153. https://doi.org/10.1016/j.eneco.2022.106153.

Lund, H.G., 2007. Accounting for the world's rangelands. Rangelands 29 (1), 3–10. https://doi.org/10.2111/1551-501X(2007)29[3:AFTWR]2.0.CO;2.

Marques, A.C., Fuinhas, J.A., 2011. Drivers promoting renewable energy: A dynamic panel approach. Renew. Sustain. Energy Rev. 15 (3), 1601–1608. https://doi.org/10.1016/j.rser.2010.11.048.

Marques, A.C., Fuinhas, J.A., Manso, J.P., 2010. Motivations driving renewable energy in European countries: a panel data approach. Energy Policy 38 (11), 6877–6885. https://doi.org/10.1016/j.enpol.2010.07.003.

Mathews, J.A., Tan, H., 2014. Economics: Manufacture renewables to build energy security. Nature 513 (7517), 166–168. https://doi.org/10.1038/513166a.

Meckling, J., Lipscy, P.Y., Finnegan, J.J., Metz, F., 2022. Why nations lead or lag in energy transitions. Science 378 (6615), 31–33. https://doi.org/10.1126/science.adc9973.

Organisation for Economic Co-operation and Development (OECD), 2017. Investing in Climate, Investing in Growth. OECD Publishing, Paris.

Paltsev, S., 2016. The complicated geopolitics of renewable energy. Bull. At. Sci. 72 (6), 390–395. https://doi.org/10.1080/00963402.2016.1240476.

Polzin, F., 2017. Mobilizing private finance for low-carbon innovation–a systematic review of barriers and solutions. Renew. Sust. Energ. Rev. 77, 525–535. https://doi.org/10.1016/j.rser.2017.04.007.

Polzin, F., Migendt, M., Täube, F.A., Von Flotow, P., 2015. Public policy influence on renewable energy investments—a panel data study across OECD countries. Energy Policy 80, 98–111. https://doi.org/10.1016/j.enpol.2015.01.026.

Popp, D., 2002. Induced innovation and energy prices. Am. Econ. Rev. 92 (1), 160–180. https://doi.org/10.1257/000282802760015658.

Popp, D., Hascic, I., Medhi, N., 2011. Technology and the diffusion of renewable energy. Energy Econ. 33 (4), 648–662. https://doi.org/10.1016/j.eneco.2010.08.007.

Rothkopf, D.J., 2009. Is a green world a safer world? Not necessarily. Foreign Policy (174), 134.

Sadorsky, P., 2009. Renewable energy consumption, CO2 emissions and oil prices in the G7 countries. Energy Econ. 31 (3), 456–462. https://doi.org/10.1016/j.eneco.2008.12.010.

Sadorsky, P., 2021. A random forests approach to predicting clean energy stock prices. J. Risk Financ. Manage. 14 (2), 48. https://doi.org/10.3390/jrfm14020048.

Safi, A.R., Karimi, P., Mul, M., Chukalla, A., de Fraiture, C., 2022. Translating open-source remote sensing data to crop water productivity improvement actions. Agric. Water Manag. 261, 107373. https://doi.org/10.1016/j.agwat.2021.107373.

Seto, K.C., Davis, S.J., Mitchell, R.B., Stokes, E.C., Unruh, G., Ürge-Vorsatz, D., 2016. Carbon lock-in: types, causes, and policy implications. Annu. Rev. Environ. Resour. 41 (1), 425–452. https://doi.org/10.1146/annurev-environ-110615-085934.

Shahbaz, M., Mallick, H., Mahalik, M.K., Sadorsky, P., 2016. The role of globalization on the recent evolution of energy demand in India: implications for sustainable development. Energy Econ. 55, 52–68. https://doi.org/10.1016/j.eneco.2016.01.013.

Song, Y., Ji, Q., Du, Y.J., Geng, J.B., 2019. The dynamic dependence of fossil energy, investor sentiment and renewable energy stock markets. Energy Econ. 84, 104564. https://doi.org/10.1016/j.eneco.2019.104564.

Sovacool, B.K., Brown, M.A., 2010. Competing dimensions of energy security: an international perspective. Annu. Rev. Environ. Resour. 35, 77–108. https://doi.org/10.1146/annurev-environ-042509-143035.

Sovacool, B.K., Hess, D.J., Cantoni, R., 2021. Energy transitions from the cradle to the grave: a meta-theoretical framework integrating responsible innovation, social practices, and energy justice. Energy Res. Soc. Sci. 75, 102027. https://doi.org/10.1016/j.erss.2021.102027.

Sovacool, B.K., Ratan, P.L., 2012. Conceptualizing the acceptance of wind and solar electricity. Renew. Sustain. Energy Rev. 16 (7), 5268–5279. https://doi.org/10.1016/j.rser.2012.04.048.

Su, C.W., Khan, K., Umar, M., Zhang, W., 2021. Does renewable energy redefine geopolitical risks? Energy Policy 158, 112566. https://doi.org/10.1016/j.enpol.2021.112566.

Suman, A., 2021. Role of renewable energy technologies in climate change adaptation and mitigation: a brief review from Nepal. Renew. Sust. Energ. Rev. 151, 111524. https://doi.org/10.1016/j.rser.2021.111524.

Sweidan, O.D., 2021. The geopolitical risk effect on the US renewable energy deployment. J. Clean. Prod. 293, 126189. https://doi.org/10.1016/j.jclepro.2021.126189.

Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28 (12), 817–830. https://doi.org/10.1016/S0301-4215(00)00070-7.

Wang, E., Gozgor, G., Mahalik, M.K., Patel, G., Hu, G., 2022. Effects of institutional quality and political risk on the renewable energy consumption in the OECD countries. Res. Policy 79, 103041. https://doi.org/10.1016/j.resourpol.2022.103041.

Winzer, C., 2012. Conceptualizing energy security. Energy Policy 46, 36–48. https://doi.org/10.1016/j.enpol.2012.02.067.

Yergin, D., 2006. Ensuring energy security. Foreign Aff. 69–82. https://doi.org/10.2307/20031912. Accessed 26 Nov. 2025.

Zhang, L., 2024. A comparative study of strategic petroleum reserve policies of major countries in the world. Energy Policy 195, 114362. https://doi.org/10.1016/j.enpol.2024.114362.

Zhang, Y., Zhang, L., Yu, H., Tu, Y., 2023a. Does geopolitical risk drive natural resources extraction globally? A case of global. Res. Policy 82, 103450. https://doi.org/10.1016/j.resourpol.2023.103450.

Zhang, Z., Wang, Y., Li, B., 2023b. Asymmetric spillover of geopolitical risk and oil price volatility: a global perspective. Res. Policy 83, 103701. https://doi.org/10.1016/j.resourpol.2023.103701.

Zhao, Z., Gozgor, G., Lau, M.C.K., Mahalik, M.K., Patel, G., Khalfaoui, R., 2023. The impact of geopolitical risks on renewable energy demand in OECD countries. Energy Econ. 122, 106700. https://doi.org/10.1016/j.eneco.2023.106700.