Energy Efficiency (2026) 19:1
https://doi.org/10.1007/s12053-025-10381-7

RESEARCH

Energy efficiency in times of geopolitical uncertainty: A global analysis across income levels

Bless Kofi Edziah · Sun Huaping · Emmanuel Anyigbah · Bright Akwasi Gyamfi · Simplice Asongu

Received: 3 April 2025 / Accepted: 23 September 2025

Abstract Macroeconomic uncertainties—such as political risk and economic policy instability—have been widely examined in relation to energy transition, security, and environmental performance. However, their impact on energy efficiency remains underexplored. A key question emerges: do geopolitical risks impede energy efficiency or do they compel governments to enhance efficiency and reduce import dependence? This paradox calls for empirical investigation. While recent studies suggest that geopolitical threats may still improve energy efficiency in Europe due to their advanced infrastructure and technological capacity, it is unclear whether these findings hold globally and how outcomes differ across income groups. To address this gap, we employ a news-based geopolitical risk index and endogenous stochastic frontier analysis (SFA) to provide a comprehensive global assessment across income levels and time periods for 1985–2022. The results show that geopolitical risks significantly increase global energy inefficiency, with low-income countries most severely affected. However, evidence indicates that, over time, countries may adapt by improving efficiency and diversifying energy sources. Counterfactual scenarios analysis further demonstrates that reducing geopolitical risks could lower global energy inefficiency by at least 13%. These findings highlight the importance of policies that both mitigate geopolitical risks and strengthen the resilience of energy systems worldwide.

B. Edziah
Tianjin University, Tianjin, China
e-mail: kofi.edziah@gmail.com

B. Edziah
Vilnius University, Vilnius, Lithuania

S. Huaping
University of Science and Technology Beijing, Beijing, China
e-mail: shp797@163.com

S. Huaping
Xi'an Shiyou University, Xi'an, China

E. Anyigbah
Jiangsu University, Zhenjiang, China
e-mail: eanyigbah@yahoo.com

B. Gyamfi
Multimedia University, Malacca, Malaysia
e-mail: bagyamfi87@gmail.com

S. Asongu (✉)
University of Johannesburg, Johannesburg, South Africa
e-mail: asongusimplice@yahoo.com

S. Asongu
Tashkent State University of Economics, Tashkent, Uzbekistan

S. Asongu
The Institute of Convergence Science, Korea University, Seoul, South Korea

Published online: 16 December 2025

Keywords Energy efficiency · Geopolitical risk · Energy demand · Income levels · Stochastic frontier analysis (SFA)

Introduction

For over a century, fossil fuels—particularly oil and natural gas—have shaped the global geopolitics, granting countries with substantial reserves considerable economic and military leverage (Månberger & Johansson, 2019). The geographic concentration of these resources has reinforced power asymmetries, enabling resource-rich states to exert geopolitical influence over energy-dependent economies (Overland et al., 2022; Scholten et al., 2020).

Much of the scholarly discourse on energy security has therefore focused on the geopolitical implications of oil and gas dependence (Antonakakis et al., 2017; Bouoiyour et al., 2019; Gong et al., 2022; Ivanovski & Hailemariam, 2022; Wang et al., 2021). With fossil fuels also recognized as the leading drivers of climate change, attention has increasingly shifted toward low-carbon energy systems such as renewable energy and energy efficiency (Bricout et al., 2022). While the geopolitical dimensions of renewable energy have been widely examined (see, *inter-lia,* Cai & Wu, 2021; Su et al., 2021; Sweidan, 2021), the role of geopolitical risks in shaping energy efficiency—central to achieving carbon neutrality—remains underexplored (Owjimehr et al., 2023).

Energy efficiency is widely recognized for its potential to reduce energy consumption, alleviate energy poverty, lower household and industrial costs (Agradi et al., 2022), and improve energy resilience against volatile energy markets (Sun et al., 2021). According to the International Energy Agency (IEA), efficiency improvement alone could deliver around 40% of the emissions reductions needed to achieve the Paris Agreement's targets (IEA, 2019). However, the effectiveness of energy efficiency measures may be strongly influenced by geopolitical risks. On the one hand, risks may disrupt energy markets, shift government priorities, and hinder investment in efficiency-enhancing technologies (Overland et al., 2022). On the other hand, they may accelerate efficiency improvements by exposing vulnerabilities in fossil fuel dependence and spurring technological innovation (Owjimehr et al., 2023).

Existing studies have largely examined the effects of political risk and economic policy uncertainty on energy transition and security (Chishti et al., 2023; Lee et al., 2024), renewable energy (Cai & Wu, 2021; Su et al., 2021; Sweidan, 2021) and environmental performance (Hoang et al., 2024). However, the effects of geopolitical risks on energy efficiency remain insufficiently investigated. A notable exception is a recent study by Owjimehr et al. (2023), which analyzed 18 European countries from 1991–2020 using econometric techniques like the Dumitrescu–Hurlin panel causality test, instrumental variable quantile regression (IVQR), and Data Envelopment Analysis (DEA). They found that geopolitical risks generally improved energy efficiency, likely because European countries benefit from advanced energy infrastructure and technological capacity. These findings raise some relevant questions: do such effects hold globally? Do they vary across income groups? If so, what is the direction, magnitude, and persistence of these effects? And how might energy efficiency evolve under counterfactual scenarios with or without geopolitical risks?

To address these questions, this study employs a news-based geopolitical risk index (Caldara & Iacoviello, 2022) within the framework of an endogenous stochastic frontier analysis (SFA). Our contributions are fourfold. First, we examine the global impact of geopolitical risks on energy efficiency, a critical dimension of the clean energy transition that remains underexplored. While risks may encourage efficiency by exposing vulnerabilities, they can also create instability and discourage investment, undermining global efficiency goals. Understanding these dynamics helps policymakers anticipate how geopolitical tensions reshape consumption patterns and efficiency outcomes. Second, we analyze heterogeneity across income groups. Evidence suggests that high-income countries with advanced technologies are more resilient, whereas low-income countries face greater obstacles (Owjimehr et al., 2023). By comparing these differences, we provide insights into how geopolitical risks may promote or hinder efficiency in diverse economic contexts. Third, we compute counterfactual effects to estimate how average energy intensity would evolve with and without geopolitical risks. This approach allows us to quantify the efficiency gains associated with risk mitigation, highlighting the potential benefits of reducing geopolitical uncertainty. Finally, we contribute methodologically by applying an endogenous one-step stochastic frontier analysis (SFA). Unlike the two-step methods commonly used—where efficiency scores from DEA or SFA are subsequently regressed on explanatory variables—our approach jointly estimates efficiency and incorporates geopolitical risks within the frontier. This reduces bias from unobserved heterogeneity and endogeneity, offering more robust insights.

Literature review

Geopolitical risks—broadly understood as disruptions to international relations caused by wars, terrorism, or escalating political tensions (Caldara & Iacoviello, 2022)—play a decisive role in shaping energy outcomes. A substantial body of research documents their negative effects on energy systems. For instance, geopolitical shocks can divert governments toward short-term energy security strategies, such as increasing fossil fuel production or stockpiling reserves, at the expense of long-term efficiency and sustainability goals (Shen & Hong, 2023). The Russia–Ukraine conflict exemplifies this dynamic: sanctions and retaliatory measures have forced several European economies, particularly Germany, to re-activate coal and oil generation, undermining efficiency efforts (Nerlinger & Utz, 2022). Other studies show that geopolitical risks disrupt supply chains for critical inputs such as rare earth elements (Fan et al., 2023), damage key energy infrastructure (Vakulchuk et al., 2020) and weaken prospects for international cooperation on efficiency (Koch & Tynkkynen, 2021).

At the same time, geopolitical crises can also act as catalysts for efficiency improvements (Owjimehr et al., 2023). Historical precedents such as the 1973 OPEC oil embargo, the Gulf War (1990–1991), and the 2003 Iraq invasion prompted many countries to adopt fuel efficiency standards, raise conservation targets, and diversify their energy sources (Overland et al., 2022). More recently, the Russia–Ukraine conflict has accelerated energy-efficiency strategies in countries like China, where policymakers have reframed efficiency as a component of energy security (Wang et al., 2023). This duality highlights the paradoxical nature of geopolitical risks: while they often disrupt efficiency pathways, they may also accelerate innovation and conservation in certain contexts.

Despite its importance, the relationship between geopolitical risks and energy efficiency remains underexplored. Rather, a broader strand of literature has examined how geopolitical risks influence different dimensions of the energy system, ranging from energy transition and security to renewable deployment and environmental outcomes. For instance, In the context of energy transition, Acheampong et al. (2023) show that risks can either impede or facilitate progress toward net-zero goals depending on national capacity in 42 countries. Wang et al. (2024a, 2024b, c) extend this analysis to 38 countries, highlighting the diverse ways geopolitical disruptions alter transition pathways. Zhang et al. (2023) further demonstrate that fluctuations in risk affect renewable technology innovation, sometimes promoting and sometimes constraining transition efforts. In terms of energy security, Wang et al. (2023) apply a mixed-frequency VAR to show how geopolitical risks affect crude oil security in China, while Zhang et al. (2025) use provincial data to capture similar dynamics at sub-national levels. Yilmazkuday (2024) broadens the perspective, showing how global geopolitical risks interact with energy uncertainty to influence domestic and international energy prices across 157 countries.

Environmental implications have also been explored. Borozan (2024) finds that in EU countries, geopolitical and energy security risks jointly shape CO_2 emissions, illustrating how risks extend beyond security into climate outcomes. Other research considers renewables: Cai and Wu (2021) identify dynamic linkages between risk and renewable consumption growth, Su et al. (2021) find time-varying effects, and Sweidan (2021) shows that U.S. renewable deployment is sensitive to geopolitical conditions. Together, these contributions suggest that risks influence not only fossil-based security but also the trajectory of low-carbon systems.

Despite this progress, little attention has been paid to energy efficiency. One study that comes close to addressing that gap is by Owjimehr et al. (2023), who study 18 European countries from 1991–2020 using causality tests, instrumental variable quantile regression (IVQR), and Data Envelopment Analysis (DEA). They report a generally positive association between risks and efficiency, which they attribute to advanced infrastructure and technological resilience. However, these findings are region-specific and may not be generalizable to developing economies where weaker institutions and limited technology heighten vulnerability. In contrast, our study takes a global perspective, examining the effects of geopolitical risks across income groups and exploring how efficiency may evolve with or without such risks. Also, unlike earlier studies, such as Owjimehr et al. (2023), which used a two-step technique to examine the effect of such risks on energy efficiency, our study uses a one-step approach. The two-step method, which first estimates energy efficiency using SFA or DEA, is often criticized for potential random errors (Sun et al., 2021). In contrast, following Adom et al. (2023), we use the endogenous one-step SFA, allowing us to estimate energy efficiency and address endogeneity simultaneously, thus avoiding biases inherent in the two-step approach.

Model specification and data

Stochastic energy demand frontier (SEDF) model

Our estimation of energy efficiency is based on the stochastic frontier framework introduced by Kopp (1981), who proposed a non-radial, input-specific approach to measure technical efficiency by comparing observed input use with a minimum feasible benchmark. Building on this foundation, Filippini and Hunt (2011) developed the theoretical basis for applying the method to energy demand. They conceptualized energy use as a derived demand, since it provides energy services rather than direct utility. Rational agents therefore aim to minimize energy input while maintaining the same level of services—an optimization problem analogous to profit or production maximization, except that the relevant inputs are energy resources and energy-using technologies rather than labor or capital. Following this reasoning, we adopt the input-specific conditional SEDF proposed by Filippini and Hunt (2011) to empirically estimate energy efficiency. Mathematically, the model is specified as follows in Eq. (1):

$$ED_{ct} = f\left(X_{ct};\beta\right)e^{\left(v_{ct}+u_{ct}\right)} \quad (1)$$

here, ED_{ct} denotes the observed energy demand for country c at time t. The function $f\left(X_{ct};\beta\right)$ represents the optimal level of energy use conditional on a vector of explanatory variables X_{ct}, with β denoting parameters to be estimated. The error term is decomposed into two components: v_{ct}, a two-sided random error assumed to follow a normal distribution, capturing random shocks and unobserved heterogeneity; and u_{ct} a one-sided inefficiency term, assumed to follow a half-normal distribution, reflecting non-negative deviations from the efficiency frontier. In this formulation, the conditional frontier $f\left(X_{ct};\beta\right)e^{v_{ct}}$ represents the minimum feasible energy demand, while inefficiency is captured by the multiplicative term $e^{u_{ct}}$. Thus, efficiency is interpreted as the degree to which actual energy demand converges to the frontier benchmark.

Empirical model of stochastic energy demand frontier (SEDF)

Following demand theory, the frontier specification incorporates (green) GDP per capita, energy prices, industrial activity, and temperature in the vector X. Green GDP ($lnGGDC_{ct}$) following Stjepanovic et al. (2022) —captures not only economic output but also environmental externalities such as resource depletion, pollution intensity, and carbon emissions. Energy price ($lnprice_{ct}$) reflects the cost of energy inputs; industrial activity ($lnind_{ct}$) proxies structural shifts in the economy and temperature ($lnTemp_{ct}$) controls for climatic influences on energy demand. In addition, a linear (t_{ct}) and quadratic ($t^2{}_{ct}$) time trend capture long-term dynamics in energy use. The log-linear frontier is specified as follows in Eq. (2):

$$\begin{aligned} lnEne_{ct} =& \alpha + \beta^{ggdpc} lnGGDPC_{ct} + \beta^{price} lnPrice_{ct} \\ &+ \beta^{Ind} lnind_{ct} + \beta^{temp} lnTemp_{ct} + \beta^{t} T_{ct} \\ &+ \beta^{t^2} T^2{}_{ct} + v_{ct} - u_{ct} \end{aligned} \quad (2)$$

As before, v_{ct} is the random noise term, while u_{ct} captures inefficiency. Country-level efficiency is then derived as in Eq. (3):

$$EE_{ct} = exp\left(-u_{ct}\right) \quad (3)$$

Following Battese and Coelli (1995), the inefficiency term is modeled as a function of geopolitical risks and controls as presented in Eq. (4):

$$u_{ct} = \alpha_0 + \beta_1 GPR_{ct} + \beta_2 Con_{ct} + \eta_{ct} \tag{4}$$

where, GPR_{ct} is the geopolitical risk index, Con_{ct} denotes control variables and η_{ct} is the error term. Negative coefficients imply reductions in inefficiency (greater efficiency), while positive coefficients indicate efficiency losses.

Econometric issues

Several econometric challenges should be addressed to ensure robust efficiency estimates. First, the significance of inefficiency effects and the appropriate frontier specification are tested. Following Schmidt and Sickles (1984) we use the skewness of Ordinary Least Square (OLS) residuals to validate the SFA model applying the Coelli (1995) test for confirmation. Second, potential endogeneity bias in the frontier equation is considered. Since income may be endogenous, the relationship between the income coefficients in the frontier and the estimated energy efficiency could be biased. As noted by Adom et al. (2023), national income data are often of poor quality and subject to underreporting, particularly in developing countries with large informal economies. In addition, income and energy use are mutually interdependent, which may bias the estimation of income elasticity in the frontier equation (Edziah & Opoku, 2024). To address this, we apply the Karakaplan and Kutlu (2017) endogenous SFA framework, using life expectancy at birth as an instrument for real GDP per capita. Theoretically, life expectancy can influence income in two ways: by raising productivity and human capital (Lorentzen et al., 2008) or by reducing income per capita through faster population growth (Acemoglu & Johnson, 2007). Thus, life expectancy affects energy consumption only indirectly through its impact on income and population, satisfying the exclusion restriction. Instrument validity is confirmed using the Cragg-Donald F-statistics. Third, the choice of functional form is tested. Both Cobb–Douglas and Translog specifications are estimated, with the log-likelihood ratio (LR) test used to determine the preferred form (Adom et al., 2023; Sun et al., 2019). Finally, multicollinearity among regressors is assessed using the variance inflation factor (VIF), ensuring stable parameter estimates. Figure 1 summarizes the methodological framework.

Data selection

The primary aim of this study is to examine the effect of geopolitical risks on global energy efficiency and to assess whether these effects vary across regions and levels of economic development. To this end, we select 40 countries from diverse regions, chosen because their data series are consistently available for the full sample period, 1985–2022. Data are drawn from multiple international sources and are categorized according to the two components of the model: the frontier equation and the inefficiency equation.

Frontier equation

In the frontier specification, total primary energy consumption (measured in Btu) serves as the dependent variable, while energy prices, green GDP per capita, industrial activity, and temperature constitute the explanatory variables. Following Adom et al. (2018), energy prices are proxied by the real price of crude oil in global markets. Although crude oil prices capture only oil price elasticities, their global liquidity and influence on energy costs justify their use. For robustness, we also adopt the composite real energy price index proposed by Liddle and Huntington (2020), which weights end-use prices across the residential, industrial, and transport sectors.

To measure economic activity, we use green GDP per capita following Stjepanovic et al. (2022). Unlike conventional GDP per capita, this measure incorporates environmental costs such as pollution, natural resource depletion, and carbon emissions, thus providing a more comprehensive indicator of sustainable economic performance. Temperature is measured as annual average temperature in degrees Celsius, capturing the climate–energy demand relationship as in Adom et al. (2023). Finally, industrial activity is proxied by the share of value added in manufacturing, mining, and construction as a percentage of GDP, following Sun et al. (2021). This variable controls for structural economic effects on energy demand.

Inefficiency equation

In the inefficiency model, the dependent variable is the inefficiency component from the frontier estimation, with the geopolitical risk index as the main explanatory variable and additional controls for human capital

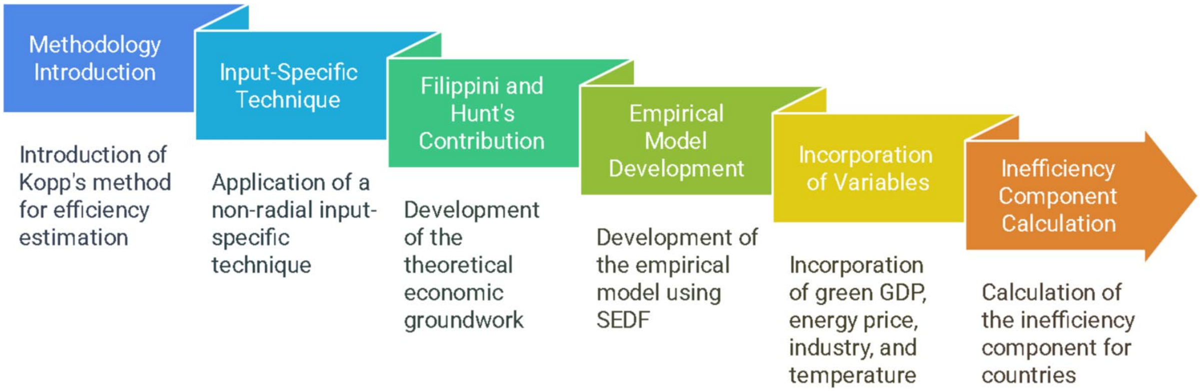

Fig. 1 Methodological Chart flow (Source: Authors)

and urbanization. The geopolitical risk index, developed by Caldara and Iacoviello (2022) quantifies geopolitical tensions—including wars, terrorist attacks, and interstate conflicts—based on the frequency of related terms in 11 leading international newspapers. The index captures the intensity and volatility of global geopolitical risks, with notable spikes corresponding to major events such as the Gulf War (1990–1991), the 9/11 terrorist attacks, the 2003 Iraq War, the Russia–Ukraine gas disputes, the Fukushima nuclear disaster, and, more recently, the annexation of Crimea and the ongoing Russia–Ukraine conflict (Asongu, 2012; Sulong et al., 2024). These shocks directly affect global energy security, investment incentives, and efficiency outcomes.

Figure 2 presents a graphical representation of the monthly geopolitical risk index, offering valuable insights into the volatility of geopolitical threats from 1985 to 2022. Notably, the geopolitical risk index spiked during the Gulf War of 1990–1991, reflecting heightened geopolitical tensions at the time. This was followed by a period of relative stability. However, the tragic 9/11 terrorist attacks triggered one of the most significant spikes in the index. Subsequent threats, such as the 2003 invasion and insurgency in Iraq also had far-reaching geopolitical ramifications. The Russia-Ukraine gas crisis further heightened tensions and emerged as a global concern. Similarly, the Fukushima nuclear disaster in Japan significantly affected global energy discussions, prompting renewed scrutiny of nuclear safety and international cooperation. More recently, the Russian annexation of Crimea and the ongoing Russia-Ukraine conflict have added to the complexity of the geopolitical landscape.

These events influence global energy efficiency performance. Ji et al. (2019) argue that the increased prevalence of geopolitical events in the Middle East poses a significant threat to oil supply security. Such disruptions can lead to legislative changes and market realignments, increasing the likelihood that businesses and governments will fall short of energy efficiency targets as immediate energy security takes precedence. Consequently, uncertainty over energy supply may discourage long-term investments in green innovation and energy-efficient technology, further complicating progress toward global sustainability goals.

At the same time, some studies suggest that geopolitical shocks can also stimulate innovation and investment in energy-efficient technology, as countries seek to reduce reliance on energy-exporting countries. Sweidan (2021) highlights that geopolitical risks can serve as a catalyst for investment in energy efficiency and renewable energy, especially among net oil importers. Thus, the influence of geopolitical risks on energy efficiency is dual-faceted, producing both positive and negative effects. However, their overall global effect remains unclear, especially regarding whether countries with different income levels are more vulnerable or responsive to these risks. This research seeks to address these gaps.

For the control variables, we consider human capital and urbanization, as both are widely recognized determinants of energy efficiency. Human capital, measured by the PWT Human Capital Index (Feenstra et al., 2016), reflects the role of education and skills in fostering technological adoption, innovation, and efficiency improvements. Higher levels

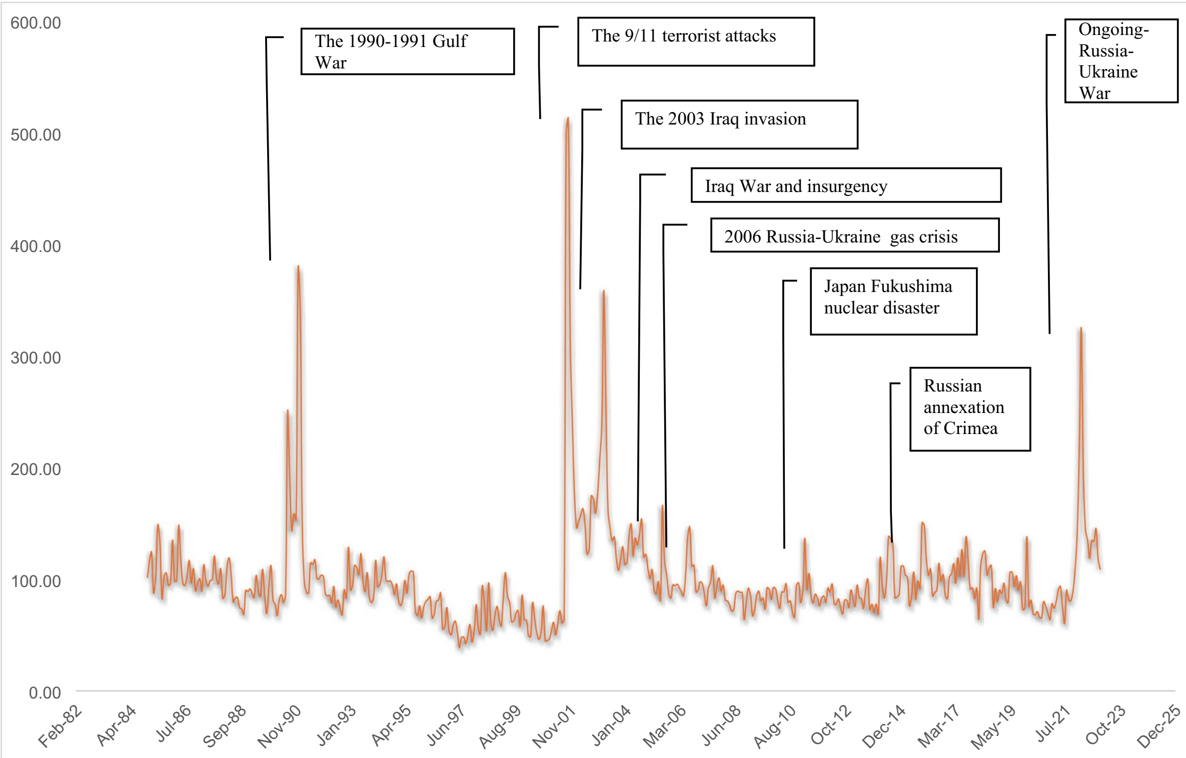

Fig. 2 The geopolitical risk index 1985–2022 [Authors' construct with data from Stjepanovic et al. (2022)]

of human capital enhance a country's capacity to absorb advanced technologies and implement effective energy-saving practices. Urbanization proxied by the ratio of urban population to total population from the World Development Indicators (WDI), is also relevant, as the concentration of population in cities influences energy demand, infrastructure development, and the potential for efficiency gains through economies of scale and modernized systems. These controls are essential as they capture long-term structural factors that significantly affect energy efficiency, independent of geopolitical risk, and provide a more comprehensive analysis of the drivers of energy inefficiency. Table 1 presents the list of variables, while Table 2 reports descriptive statistics for the sample.

Results and discussion

We structure the results presentation as follows. Section "Preliminary analysis" reports the preliminary diagnostic tests. Section "Baseline regression" examines the global effects of geopolitical risks. The results are further validated using series of robustness tests in Section "Robustness checks". We further extend the research in Section "Heterogeneous analysis of income levels of countries" to whether the effects of geopolitical threats vary across different income groups, supported by additional robustness checks. Finally, the last section decomposes the effects of geopolitical risks on efficiency at different time- horizons.

Preliminary analysis

We begin by testing whether the stochastic frontier specification is appropriate and whether inefficiency is statistically significant across sample countries. Using Coelli (1995) skewness test, OLS residuals exhibit a skewness of –0.202. The test statistic of 2.560 rejects the null hypothesis of no skewness, supporting the presence of inefficiency. The next step is to determine the functional form of the stochastic frontier. While both Cobb–Douglas and translog forms are common, a LR test yields

Table 1 Description of variables

Variables	Units of measure	Sources
lnEne	log of total primary energy consumption in British Thermal Unit (BTU)	The United States EIA
lnGGDPC	log of green GDP per capita in constant US$ 2011 prices	Stjepanovic et al. (2022)
lnInd	log of industrial structure in (percentage)	World Development Indicator (WDI)
lnTemp	log of temperature in degrees celsius	WB Climate Change Knowledge
lnP	log of crude oil price in US$ per barrel	BP statistics of world review
lnLE	log of life expectancy at birth (in years)	WDI
lnGPR	Index of geopolitical risk	Caldara and Iacoviello (2022)
lnHC	log of human capital index	Penn World Table (PWT)
lnUrban	log of percentage of total population	WDI
lnEI	log of energy intensity level of primary energy (MJ/$2017 PPP GDP)	WDI

Table 2 Descriptive statistics

Variables	Obs	Mean	Std. Dev	Min	Max
lnEne	1520	1.375	1.255	−1.796	5.142
lnGGDPC	1520	−0.682	1.359	−4.489	1.599
lnP	1520	−0.234	0.692	−1.3	1.017
lnInd	1519	−0.034	0.256	−0.613	0.803
lnTemp	1441	−0.113	0.684	−3.82	0.666
lnGPR	1520	−2.39	1.267	−5.629	1.47
lnHC	1520	1.019	0.221	0.32	1.381
lnUrban	1520	4.232	0.286	3.13	4.587
lnEI	868	1.448	0.379	0.432	2.721

a statistic of 382.66 with ($p < 0.001$), rejecting the null and favoring the translog specification. This choice reflects the ability of the translog to capture nonlinearities, regime shifts, and variable interactions that the Cobb–Douglas cannot. We also assess the time-series properties of the data. Panel unit root tests following Im et al. (2003) reject the null of a unit root, indicating stationarity of the key variables at the 1% level (See results in Appendix Table 8). Finally, multicollinearity was analyzed using the VIF. The median VIF of 3.13 is well below the conventional threshold of 10, suggesting no serious collinearity concerns (Appendix Table 9).

Baseline regression

Table 3 presents the results of estimated endogenous SFA model. The use of life expectancy as an instrument is validated by the Cragg–Donald F-statistic, which exceeds the 10% critical value, while the eta endogeneity test confirms the presence of endogeneity. These results suggest that the exogenous SFA estimates in Appendix Table 11 may be biased, and that the endogenous specification in Table 3 provides more reliable results.[1]

Frontier equation

In the frontier function, income [*ln(GGDPC)*] is positively and significantly associated with energy consumption. The estimated elasticity ranges between 0.614% and 0.798%, indicating that a 1% increase in income leads to a commensurate rise in energy use. This positive result supports extant studies (Adom et al., 2018, 2023; Sun et al., 2020) and implies that as people's economic situations improve, they consume more energy. The square term of income [$ln(GGDPC)^2$] shows a positive coefficient, ruling out the nonlinear relationship between income and energy use.

Energy price [*ln(Price)*] and temperature [*ln(Temp)*] both exert negative and significant effects on energy demand. The negative coefficients show that higher energy prices reduce consumption, consistent with substitution toward less energy-intensive activities. Similarly, higher temperatures are associated with lower demand, reflecting reduced heating

[1] An exogenous model without controls and stepwise inclusion of controls produced an undesirable outcome where the geopolitical variable are positive and but statistically insignificant (See results in Table 11 of the Appendix).

Table 3 Geopolitical risk-energy efficiency nexus

	Column (I) Without controls	Column (II) With controls
Frontier Equation		
Dep var: *lnEne*		
ln(GGDPC)	0.614***	0.798***
	(0.0511)	(0.0682)
ln(Price)	−0.0990***	−0.137***
	(0.0234)	(0.0279)
ln(Indus)	0.752***	0.650***
	(0.0630)	(0.0668)
ln(Temp)	−0.209**	−0.242**
	(0.102)	(0.0970)
*ln(GGDPC)*ln(Price)*	−0.0729**	−0.115***
	(0.0342)	(0.0413)
*ln(GGDPC)*ln(Indus)*	−0.352***	−0.600***
	(0.0841)	(0.0902)
*ln(GGDPC)*ln(Temp)*	0.343***	0.416***
	(0.0506)	(0.0579)
*ln(Price)*ln(Indus)*	0.408***	0.362***
	(0.124)	(0.138)
*ln(Price)*ln(Temp)*	0.104**	0.0741
	(0.0493)	(0.0539)
*ln(Indus)*ln(Temp)*	−1.446***	−1.343***
	(0.159)	(0.168)
$ln(GGDPC)^2$	0.132***	0.194***
	(0.0272)	(0.0349)
$ln(Price)^2$	−0.0934**	−0.120**
	(0.0455)	(0.0514)
$ln(Indus)^2$	−1.864***	−2.982***
	(0.331)	(0.413)
$ln(Temp)^2$	−0.0879*	−0.0984**
	(0.0480)	(0.0477)
T	0.0202***	0.0115***
	(0.00354)	(0.00398)
$(T)^2$	−0.000340***	−0.000272***
	(7.21e-05)	(8.10e-05)
Constant	4.398***	6.146***
	(0.137)	(0.700)
Dep.var: EE: $\ln(\sigma\_u^2)$		
lnGPR	0.0341***	0.0277***
	(0.00627)	(0.00614)
lnHC		0.110*
		(0.0635)
lnUrban		−0.367***
		(0.0574)
Constant	2.392***	4.594***
	(0.238)	(0.331)
Dep.var: $\ln(\sigma\_w^2)$		
eta1_lnGGDPC	−0.513***	−0.662***
	(0.0456)	(0.0634)
eta Endogeneity Test	126.32***	109.27***
Constant	−3.662***	−3.821***
	(0.0378)	(0.0385)
Identify_Frontier		
Cragg_Donald F-stat	531.54***	136.18***
Log Likelihood	−422.14	−238.86
Observations	1,440	1,440

The frontier equation presents the factors that drive energy consumption. The inefficiency equation examines the factors that drive inefficiency in energy consumption, and energy efficiency (EE) is the dependent variable. Table 4 assumes that the frontier equations are endogenous and that life expectancy at birth is used to instrument real GGDPC per capita. Information about the instrument validity test is at the bottom of the inefficiency equation. lnGPR stands for Geopolitical Risk, lnHC for Human Capital, and lnUrban for the extent of urbanization. The standard errors are figures enclosed in brackets. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

needs in warmer regions. The square terms of both price [$ln(Price)^2$] and temperature [$ln(Temp)^2$] are also negative, reinforcing the finding that sensitivity to price and temperatures rise increases at higher levels.

The level of industrialization [*ln(Indus)*] shows a positive and significant relationship with energy consumption, confirming that greater industrial output raises energy demand. Like in other studies (Sun et al., 2020), these results confirm that industrialization increases energy usage. Thus, when countries or regions develop industrially, energy demand is expected to rise due to significant energy required for industrial activities. However, the negative coefficient on the squared term indicates that at higher levels of industrialization, technological improvements mitigate the rate of increase in energy consumption, pointing to efficiency gains in advanced industrial economies.

Finally, the interaction of these variables—income, price, industrialization, and temperature—reveals additional dynamics. A negative income–price interaction [*ln(GGDPC)*ln(Price)*] suggests that higher incomes may offset the impact of rising energy prices, potentially through the adoption of energy-efficient technologies.

Table 4 Geopolitical risk-energy efficiency nexus (energy intensity as dependent variable)

VARIABLES	(1) GPR	(2) GPR_HC	(3) GPR_HC_Urban	(4) GPR_HC_Urban
lnGPR	0.0570***	0.0571***	0.0491***	0.0651***
	(0.00938)	(0.0101)	(0.0101)	(0.00875)
lnHC		−0.00404	0.264***	0.735***
		(0.0741)	(0.0991)	(0.0955)
lnUrban			−0.297***	−0.134***
			(0.0524)	(0.0443)
lnService				−1.248***
				(0.0918)
Year Effects	YES	YES	YES	YES
Constant	1.326***	1.332***	2.293***	6.203***
	(0.0686)	(0.117)	(0.177)	(0.328)
Observations	868	868	868	867
R-squared	0.127	0.127	0.151	0.319

lnGPR is Geopolitical Risk; lnHC is Human capital; lnUrban is Urbanization level; and lnService denotes economic structure. The standard errors are figures enclosed in brackets. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Similarly, the negative coefficient of the income–industrialization interaction [*ln(GGDPC)*ln(Indus)*] implies that wealthier economies are better positioned to manage the energy intensity of industrial growth. By contrast, income–temperature [*ln(GGDPC)*ln(Temp)*] suggests that rising incomes amplify heating and cooling demand. A positive price-industrialization interaction [*ln(Price)*ln(Indus)*] suggests that even when energy prices rise, industrial activity still absorbs higher energy costs. Likewise, the positive price-temperature interaction [*ln(Price)*ln(Temp)*], indicates that higher energy prices in regions with extreme temperatures further elevate energy use. Finally, the negative industrialization–temperature interaction [*ln(Indus)*ln(Temp)*] illustrates that industrialized economies adapt to climate variation by deploying energy-saving technologies, thereby dampening the effect of temperature shocks on energy use.

The inefficiency equation with emphasis on the geopolitical risk variable

We now turn to the inefficiency equation, where we examine the influence of geopolitical risk on energy inefficiency. The results in column (I) show a statistically significant positive relationship between geopolitical risk and efficiency. Quantitatively, a one-unit increase in the geopolitical risk index reduces global energy efficiency by roughly 0.034 percentage points. In column (1I), after adding controls, the coefficient declines slightly by 0.0064 but remains positive and significant. These findings suggest that geopolitical instability—whether arising from conflict, terrorism, or political unrest— constraint countries' ability to improve energy efficiency.

According to Yoshino et al. (2021), geopolitical events create uncertainty and instability, leading to misallocation of resource, higher energy prices, and delays in infrastructure globally especially in emerging and developing countries. Geopolitical risk also undermines investor confidence and impedes long-term energy–oriented investment (Overland et al., 2022). Political uncertainty, shifting legislation, and the prospect of resource nationalization discourage private sector participation, further impeding the adoption of efficient technologies in fragile states (Overland, 2019). Furthermore, geopolitical tensions such as trade restrictions and embargoes destabilize energy markets (Scholten et al., 2020), generating supply–demand imbalances that exacerbate inefficiencies. Our findings contrast with Owjimehr et al. (2023), who report that geopolitical shocks exert a mitigating influence on energy inefficiency in Europe. As mentioned in their study a plausible explanation lies in regional resilience and institutional capacity. Advanced economies, particularly in Europe, often respond to crises by accelerating reforms, investing in renewable energy, and tightening conservation policies. By contrast, developing and emerging economies—where exposure to geopolitical risk is higher—face institutional fragility, fiscal limitations, and weak governance. These conditions may amplify the adverse impact of geopolitical instability on energy efficiency.

Regarding the controls, human capital has a positive statistically significant effect, implying that greater levels of human capital are associated with energy inefficiency. This outcome may reflect the heterogeneity of the sample. In developing economies, rising human capital often fuels industrial growth and higher energy demand, while in advanced economies it supports innovation and efficiency. The aggregate positive effect therefore likely captures the dominance of the former dynamic in the global sample. In contrast, urbanization has a statistically negative effect, suggesting that more urbanized economies tend to be more energy efficient. This result is consistent with the idea that urban areas benefit from agglomeration economies, denser infrastructure, and greater access to modern technologies, all of which can facilitate more efficient energy use.

Robustness checks

To address potential concerns about the validity of our results, we employed an alternative measure of energy efficiency to reassess the impact of geopolitical risks.[2] Energy efficiency is commonly measured using single-factor energy efficiency (SFEE) or total factor energy efficiency (TFEE). While SFEE (also known as energy intensity), measures energy consumption per unit of GDP, TFEE accounts for multiple production inputs and thus provides a broader perspective. So far, we have employed the TFEE. Now, we re-estimate the relationship using SFEE, while also incorporating year effects to control for confounding variables.

Table 4 reports the results. Column (1) presents estimates including year effects, while Columns (2)– (4) sequentially add control variables. Across all specifications, geopolitical risk remains positively and statistically associated with energy intensity. This reinforces our earlier conclusion that geopolitical instability undermines efficiency improvements. Among the control variables, human capital increases energy intensity, whereas urbanization and higher service quality reduce it, likely reflecting gains from better infrastructure, planning, and improved public services.

Using the estimate from the final specification, we computed the counterfactual outcomes. Figure 3 compares the energy intensity levels with and without geopolitical risks. The red bar represents energy intensity level under geopolitical risks, while the green bar shows energy intensity level without geopolitical risks. Although energy intensity declines over time in both cases, the reduction is considerably greater when geopolitical risks are lower—by at least 13% on average. This finding suggests that the geopolitical risks may slow progress toward attaining carbon neutrality by 2050.

Heterogeneous analysis of income levels of countries

Using the baseline endogenous SFA Model

Thus far, our analysis has documented the global impact of geopolitical risk on energy efficiency. However, the magnitude of this effect may differ across countries' economic structures, development levels, energy reliance, and institutional resilience. Geopolitical risks such as conflicts or sanctions can destabilize energy markets, but while advanced economies often have the capacity to such shocks, low-income countries remain highly vulnerable due to limited access to efficient technologies and weaker institutional framework. To explore this heterogeneity, we divided the sample into high- and low-income groups.[3]

Table 5 reports the results. Column (I) and (II) present estimates for low- and high-income countries, respectively. Geopolitical risk exerts a positive and statistically significant effect on energy inefficiency in both groups. For the high-income group, the coefficient is 0.0242, implying that a one-unit increase in geopolitical risk raises inefficiency by 0.0242 percent. This is considerably larger in low-income countries, where

[2] We also considered an alternative specification by replacing the original energy price with the economy-wide real price index (Liddle & Huntington, 2020) and removing the time-square interaction term (T^2). The results remain robust: a one-unit increase in geopolitical risk reduces global energy efficiency by 0.0134%, confirming the negative and significant effect of geopolitical risk on efficiency improvements (see results in Table 11 in appendix).

[3] We also differentiated between energy-importing and energy-exporting countries. While the results remained consistent, the effect was more pronounced among energy importers than exporters.

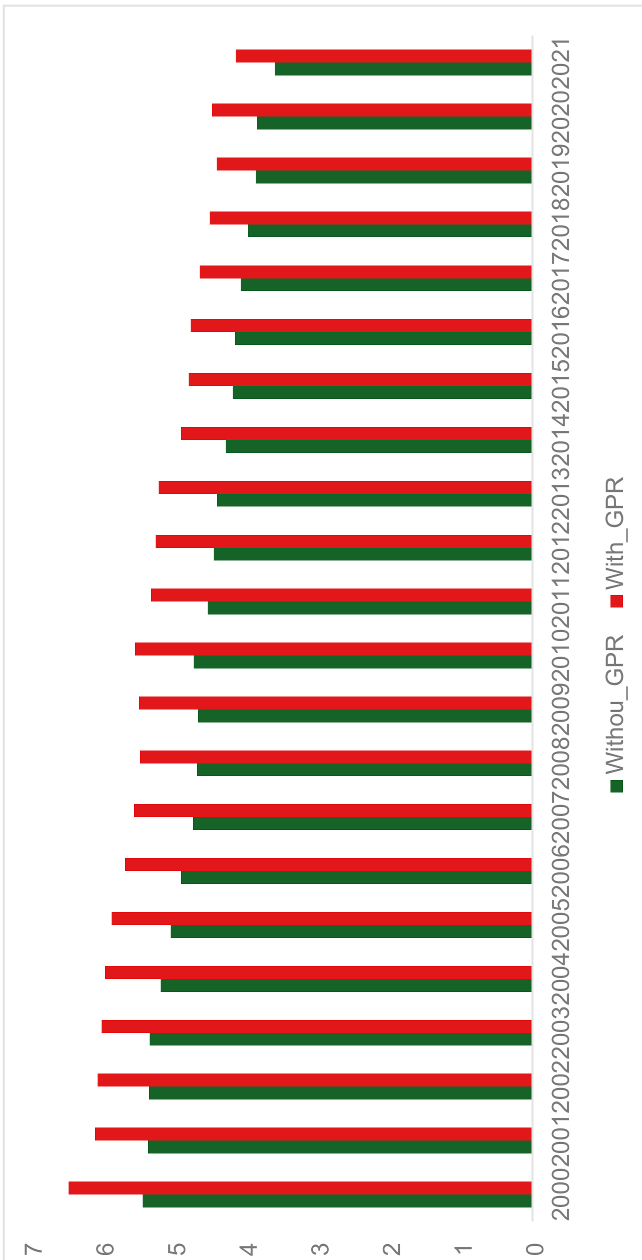

Fig. 3 Level of energy intensity with and without geopolitical risks

Table 5 Results of heterogeneous analysis of income levels of countries

	Column (1) Low-income group	Column (II) High-income group
Frontier Equation		
Dep var: *lnEne*		
ln(GGDPC)	4.218***	1.325***
	(1.057)	(0.137)
ln(Price)	−2.278***	−0.402***
	(0.589)	(0.0679)
ln(Indus)	0.378	−0.338***
	(0.462)	(0.104)
ln(Temp)	−2.497***	−1.039***
	(0.587)	(0.115)
*ln(GGDPC)*ln(Price)*	−2.321***	0.342***
	(0.611)	(0.101)
*ln(GGDPC)*ln(Indus)*	−0.614	1.141***
	(0.441)	(0.271)
*ln(GGDPC)*ln(Temp)*	−1.781***	1.981***
	(0.454)	(0.251)
*ln(Price)*ln(Indus)*	−1.311*	−0.270
	(0.687)	(0.234)
*ln(Price)*ln(Temp)*	1.180**	−0.826***
	(0.460)	(0.146)
*ln(Indus)*ln(Temp)*	−1.900**	−1.827***
	(0.878)	(0.253)
$ln(GGDPC)^2$	1.738***	0.202***
	(0.459)	(0.0532)
$ln(Price)^2$	0.643**	−0.285***
	(0.272)	(0.0783)
$ln(Indus)^2$	−0.0287	−1.675***
	(1.277)	(0.386)
$ln(Temp)^2$	3.785***	−0.251***
	(1.229)	(0.0464)
T	0.0417***	−0.0131**
	(0.0140)	(0.00615)
$(T)^2$	−0.00107***	−0.000106
	(0.000349)	(0.000113)
Constant	10.02***	4.089***
	(1.972)	(0.0935)
Dep.var: EE: $\ln(\sigma\_u^2)$		
Constant	4.707***	2.405***
	(0.552)	(0.598)
lnGPR	0.0696***	0.0242**
	(0.0165)	(0.0109)
lnHC	0.234**	−0.330**
	(0.110)	(0.129)
lnUrban	−0.351**	0.0759
	(0.138)	(0.127)

Table 5 (continued)

	Column (1) Low-income group	Column (II) High-income group
Dep.var: ln (σ_w^2)		
Constant	−3.833***	−4.247***
	(0.0596)	(0.0504)
eta1_lnGGDPC	−4.192***	−1.028***
	(1.053)	(0.134)
eta Endogeneity Test	109.27***	76.21***
Identify_Frontier		
Cragg_Donald F-stat	14.03***	169.51***
Log Likelihood	415.84	383.12
Observations	608	832

The standard errors are figures enclosed in brackets. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

the coefficient of 0.0696 implies an additional increase of 0.0454 percent points relative to the high-income group. These findings highlight the disproportionate vulnerability of low-income economies to geopolitical shocks, where dependence on imported fossil fuels, limited fiscal capacity, and weaker institutions amplify the disruptive impact of geopolitical shocks. However, high-income countries possess more diversified energy systems, better technology, infrastructure and stronger policy mechanisms, which mitigate the adverse effects on efficiency.

Turning to the controls, human capital reduces inefficiency in high-income countries: a 1 percent increase lowers inefficiency by 0.330%, highlighting its role in fostering innovation and efficiency. In contrast, in low-income countries, the same increase raises inefficiency by 0.234%, suggesting that without complementary institutions and technologies, human capital may fuel energy demand rather than efficiency gains. As observed in the baseline (homogeneous) model, the coefficient is positive, indicating that human capital increases inefficiency on average. These results highlight the importance of accounting for cross-country heterogeneity to properly identify the efficiency effects of human capital. Urbanization has no significant effect in high-income countries, probably because urban infrastructure and energy systems are already well developed. Most efficiency gains from density, transport networks, and planning have long been realized. Moreover, advanced economies often experience diminishing returns to urbanization (Gaspar & Glaeser, 1998): further increases in urban population may yield little additional efficiency and, in some cases, may be offset by higher consumption patterns. However, in low-income countries, urbanization significantly reduces inefficiency, consistent with the view that rapid urban growth often brings new infrastructure and more efficient energy use, making the benefits more pronounced.

Using energy intensity as an alternative measure of energy efficiency

As in the robustness tests, we employ energy intensity as an alternative measure of energy efficiency to provide additional perspective on how geopolitical risks affect countries at different stages of development. Table 6 summarizes the results. Column (I) reports estimate for high-income countries, while Columns (II) focuses on low-income countries. Across both groups, geopolitical risks exert a consistently positive and statistically significant effect on energy intensity, highlighting its disruptive influence on energy efficiency.

For the high-income countries, the estimated coefficient is 0.0566, while for the low-income countries it is 0.0726, indicating that the disruptive effect of geopolitical risk is considerably stronger among low-income economies. This pattern is consistent with the results from the endogenous SFA model, where the adverse effects of geopolitical risk was also found to be larger in the low-income group.

Figure 4 compare energy intensity trends in high- and low-income countries with or without geopolitical risks.

Table 6 Results for the income levels

VARIABLES	Column (I) Low-income group	Column (II) High-income group
lnGPR	0.0726***	0.0566***
	(0.0143)	(0.0106)
lnHC	1.739***	0.262**
	(0.142)	(0.103)
lnUrban	−0.395***	0.494***
	(0.0681)	(0.0899)
lnService	−0.682***	−1.219***
	(0.175)	(0.0912)
Constant	4.345***	4.032***
	(0.588)	(0.497)
Year Effects	YES	YES
Observations	363	504
R-squared	0.409	0.298

In both scenarios, energy intensity declines steadily between 2000 and 2021, reflecting global improvements in efficiency and structural transformation. However, the levels and trajectories differ markedly across income groups and between the two scenarios.

In the absence of geopolitical risks (Fig. 4), high-income countries reduce energy intensity from roughly 5 MJ/USD in 2000 to below 3 MJ/USD by 2021, while low-income countries decline from around 6 MJ/USD to just above 4 MJ/USD. Although both groups achieve gains, the sharper decline in high-income countries reflects their stronger institutional capacity, technological base, and diversification, which allow them to sustain long-term efficiency improvements. Low-income countries, by contrast, face persistent structural and infrastructural barriers that slow the pace of efficiency gains.

With geopolitical risk (Fig. 5), both groups exhibit higher intensity levels, indicating that geopolitical instability directly undermines efficiency progress. Low-income countries are particularly affected: their intensity rises to nearly 8 MJ/USD in 2000 and declines only to about 5 MJ/USD by 2021, while high-income countries start near 6 MJ/USD and fall to just above 4 MJ/USD. The persistence of this gap illustrates that geopolitical shocks exacerbate existing vulnerabilities in low-income countries, where reliance on imported fuels, weak governance, and limited fiscal capacity magnify the inefficiency effects of instability. However, high-income countries are better able to adapt, leveraging stronger institutions and innovation to cushion the adverse impact of geopolitical risk.

Decomposing the effects of geopolitical risks at different time- horizons

Up to this point, our estimations have assumed that inefficiency in energy consumption exhibits high temporal variation across countries. This assumption may not hold in practice. For many economies—particularly those transitioning between energy technologies— energy users might apply different discount rates (Adom et al., 2023). Additionally, business cycle effects could influence the results. If unaddressed, this dynamic can bias the estimates and weaken causal inference. To account for this, we follow Adom et al. (2023) and Liu et al. (2024) to implement a multi-period regression strategy, using 3-year, 5-year, and 7-year average data.

Table 7 reports the results. Across all time periods, geopolitical risk exerts a positive and statistically significant effect on energy inefficiency, suggesting that geopolitical instability consistently undermines energy performance. The estimated coefficients range from 0.0455 for the 3-year average (significant at 1%) to 0.0483 for the 5-year average (5% significant) and 0.0486 for the 7-year averages (10% significance). These magnitudes suggest a one-unit increase in geopolitical risk raises energy inefficiency by roughly 4.5 to 4.9 percent, with the strongest and most precise effect observed over shorter horizons. The declining levels of statistical significance over longer periods indicate that while the immediate effects of geopolitical shocks are disruptive, their impact diminishes as countries adapt over time.

Conclusions and policy implications

Conclusions

Geopolitical events have the potential to disrupt oil supplies, induce market volatility, and deter long-term investments in green innovation and energy-efficient technologies. At the same time, such events may also encourage efficiency-enhancing investments, especially in countries seeking to reduce their dependence on energy exports. This duality motivates our analysis of the relationship between geopolitical risk and energy

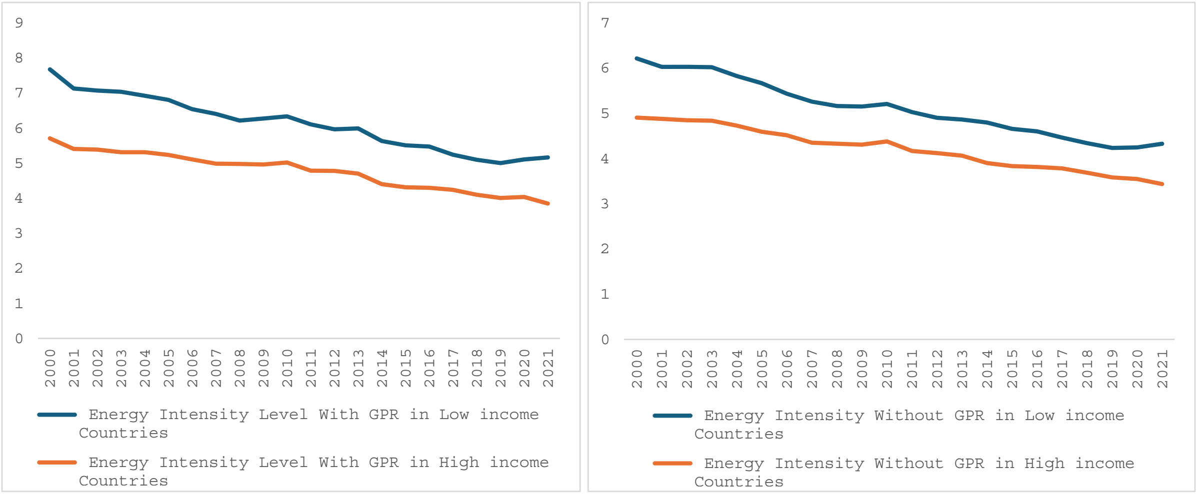

Fig. 4 Energy intensity levels of high- and low-income countries with and without geopolitical risks

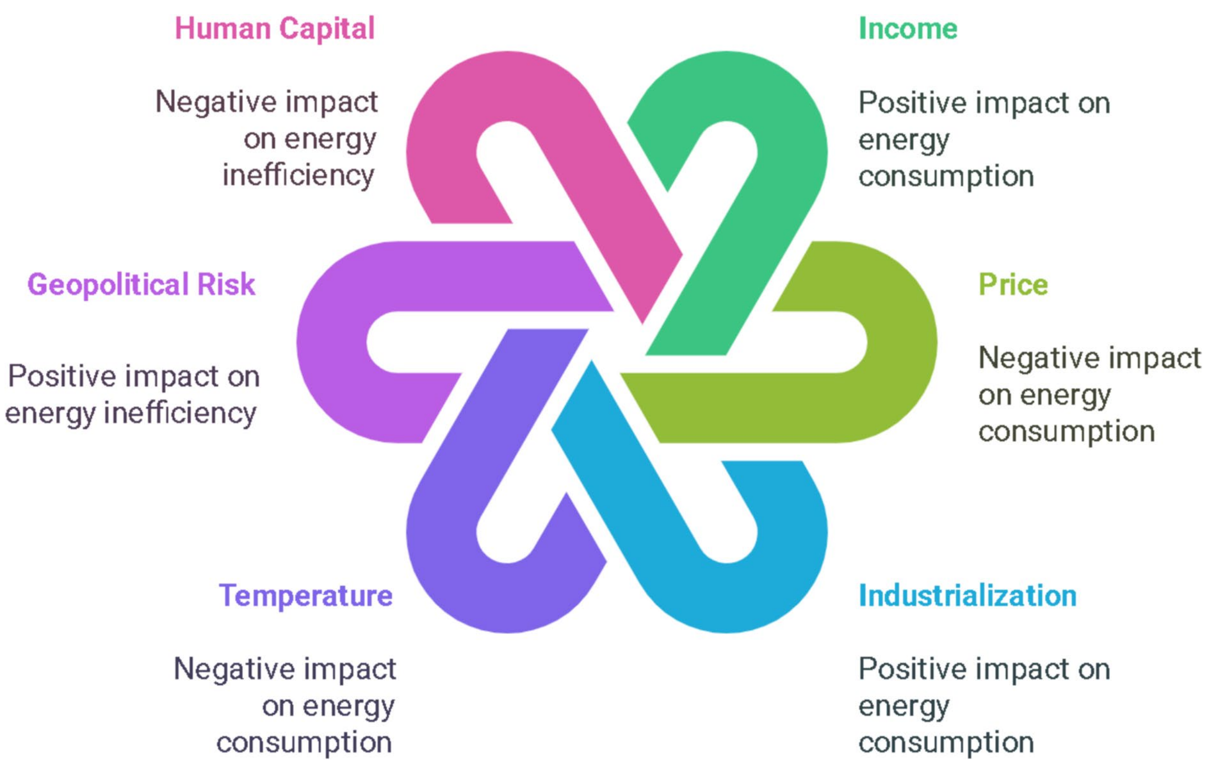

Fig. 5 Graphical representation of the findings

efficiency. Using a newly developed measure of geopolitical risk and an efficiency framework that addresses potential endogeneity in the frontier, we investigate these effects globally and across countries at different stages of economic development. We also compute counterfactual scenarios and employ multi-period regressions to capture longer-term dynamics. Five main results emerge:

Table 7 The effects of geopolitical risk over different time horizon

	Column (1)	Column (2)	Column (3)
Frontier Equation	3 years	5 years	7 years
Dep var: *lnEne*			
Constant	4.512***	4.104***	4.153***
	(0.312)	(0.221)	(0.288)
ln(GGDPC)	0.651***	0.546***	0.513***
	(0.0988)	(0.103)	(0.118)
ln(Price)	−0.145***	−0.143**	−0.0927
	(0.0499)	(0.0664)	(0.0769)
ln(Indus)	0.662***	0.686***	0.653***
	(0.116)	(0.158)	(0.190)
ln(Temp)	−0.145	−0.186	−0.161
	(0.277)	(0.226)	(0.279)
*ln(GGDPC)*ln(Price)*	−0.110	−0.100	−0.0802
	(0.0699)	(0.0898)	(0.108)
*ln(GGDPC)*ln(Indus)*	−0.546***	−0.559***	−0.631**
	(0.160)	(0.211)	(0.254)
*ln(GGDPC)*ln(Temp)*	0.279**	0.166	0.151
	(0.109)	(0.142)	(0.171)
*ln(Price)*ln(Indus)*	0.428*	0.565*	0.644*
	(0.230)	(0.303)	(0.362)
*ln(Price)*ln(Temp)*	0.133	0.166	0.172
	(0.0994)	(0.124)	(0.150)
*ln(Indus)*ln(Temp)*	−1.381***	−1.541***	−1.553***
	(0.295)	(0.401)	(0.481)
$ln(GGDPC)^2$	0.145***	0.113*	0.0888
	(0.0517)	(0.0629)	(0.0750)
$ln(Price)^2$	−0.177	−0.111	−0.0916
	(0.110)	(0.186)	(0.234)
$ln(Indus)^2$	−2.327***	−1.927**	−1.825**
	(0.619)	(0.774)	(0.928)
$ln(Temp)^2$	−0.103	−0.208	−0.168
	(0.135)	(0.159)	(0.231)
T	0.0225***	0.0314***	0.0259*
	(0.00808)	(0.0106)	(0.0150)
$(T)^2$	−0.000399***	−0.000471**	−0.000382
	(0.000145)	(0.000187)	(0.000246)
Dep.var: EE: $\ln(\sigma\_u^2)$			
Constant	4.045***	3.786***	3.760***
	(0.514)	(0.651)	(0.761)
lnGPR	0.0455***	0.0483**	0.0486*
	(0.0127)	(0.0206)	(0.0274)
lnHC	0.148	0.142	0.112
	(0.108)	(0.147)	(0.178)
lnUrban	−0.397***	−0.361**	−0.347**
	(0.110)	(0.148)	(0.176)
Dep.var: $\ln(\sigma\_w^2)$			
Constant	−3.857***	−3.880***	−3.848***

Table 7 (continued)

	Column (1)	Column (2)	Column (3)
	(0.0707)	(0.0941)	(0.115)
eta1_lnGGDPC	−0.555***	−0.480***	−0.448***
	(0.0847)	(0.0996)	(0.122)
eta Endogeneity Test	42.97***	23.24***	13.54***
Identify_Frontier			
Cragg_Donald F-stat	111.22***	63.61***	51.08***
Log Likelihood	−131.12	−114.83	−111.69
Observations	456	266	190

The standard errors are figures enclosed in brackets. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

(i) In the frontier equation, income and industrialization drive energy demand, while energy prices and temperature exert an negative relationship.
(ii) In the inefficiency equation, geopolitical risk contributes to energy inefficiency. This result holds across alternative efficiency measures, heterogeneity adjustments, and multi-period specifications.
(iii) The counterfactual analysis indicates that reducing geopolitical risks could lower energy intensity considerably by at least 13%, with a substantial effect in low-income countries.
(iv) The efficiency trend also suggests that over time, energy intensity has declined in both income groups, but high-income countries show greater resilience. For example, without geopolitical risks, their energy intensity fell from 5 MJ/USD in 2000 to 3 MJ/USD by 2021, compared to 6 to 4 in low-income countries. However, geopolitical risks widen this gap a bit.
(v) Finally, geopolitical risk significantly raises energy inefficiency in the short term, but its impact weakens over longer horizons as countries adapt through diversification, technology, and policy measures.

Policy implications

In the light of these outcomes, we proposed several policy recommendations with tailored approaches for both high-income and low-income countries. First, geopolitical crises should be addressed through diplomatic channels and multilateral agreements, such as global climate accords and energy security treaties. For high-income countries, government-backed investment in green innovation should be scaled up, focusing on renewable energy technologies like solar, wind, and hydrogen. The $20bn US clean energy investment can be expanded to incentivize private sector innovation.[4] In Europe, energy efficiency programs like the EU's Energy Efficiency Directive can be enhanced to support industries in reducing energy consumption.

For low-income countries, strengthening energy infrastructure is crucial. Governments should prioritize off-grid renewable energy projects, such as solar mini-grids or wind farms, to reduce reliance on centralized power imports. Programs like the World Bank's Scaling Solar initiative can be expanded. Moreover, energy storage technologies should be integrated into these projects to improve energy reliability. Additionally, international cooperation on technology transfer and public–private partnerships (PPP) should be promoted to scale energy-efficient solutions. Strengthening institutions through national energy policy frameworks and capacity-building programs will help manage geopolitical risks effectively. Finally, targeted investment in R&D, with increased public funding, should support the development of next-generation clean technologies, including advanced grid systems and carbon capture.

[4] https://impact-investor.com/20bn-us-government-funding-in-clean-energy-and-climate-solutions-offers-potential-blueprint-for-europe/

Limitations and future research directions

This research is not without limitations. First, future research could improve established findings by using a more specific measure of geopolitical uncertainty, rather than the broad measure applied here. Focusing on types of geopolitical risks—such as trade wars, military conflicts, and cyber threats—could provide a clearer understanding of their distinct impacts on energy performance. Additionally, this study focuses on transient energy efficiency, which captures short-term fluctuations in performance. However, energy efficiency also includes a persistent component, shaped by long-term factors like technology, infrastructure, and policy. Future studies should incorporate both transient and persistent energy efficiency to offer a more comprehensive view of how geopolitical uncertainty affects energy systems. Finally, country-specific analyses could provide further insights into how geopolitical risks vary across different national contexts, revealing their diverse impacts on energy performance.

Appendix

Preliminary tests

Table 8 Test of Unit root robust to cross sectional dependence

Variables	Statistics	*p*-values
lnEne	-2.3791	0.0087
lnGGDPC	-8.2674	0.0000
lnP	-11.6626	0.0000
lnIndus	-1.7993	0.0360
lnTemp	-18.8970	0.0000
lnLE	-1.5393	0.0619
lnGPR	-12.8163	0.0000
lnUrban	-2.018	0.0218

Table 9 VIF Multicollinearity test

Variables	VIF	I/VIF
lnGGDPC	6.61	0.151228
lnP	2.32	0.431910
lnIndus	1.65	0.606707
lnTemp	4.32	0.231715
0.5*lnGGDPC^2	7.02	0.142500
0.5*lnP^2	1.65	0.607557
0.5*lnIndus^2	1.76	0.568270
0.5*lnTemp^2	3.92	0.255369
0.5*lnGGDPC* lnP	4.50	0.222176
0.5*lnGGDPC* lnIndus	2.01	0.498173
0.5*lnGGDPC* lnTemp	2.72	0.367158
0.5*lnP* lnIndus	1.66	0.603161
0.5*lnP* lnTemp	2.35	0.425993
0.5*lnIndus* lnTemp	1.40	0.713045
Mean VIF	3.13	

Table 10 List of countries

Low income countries	High income countries
Argentina	Australia
Brazil	Belgium
China	Canada
Columbia	Switzerland
Egypt	Chile
Indonesia	Germany
India	Denmark
Mexico	Spain
Malaysia	Finland
Philippines	France
Russia	United Kingdom
Thailand	Hungary
Tunisia	Israel
Turkiye	Italy
Ukraine	Japan
Venezuela	Korea
South Africa	Netherland
	Norway
	Poland
	Portugal
	Saudi Arabia
	Sweden
	United States

NB: This categorization of income group is based on the WDI

Table 11 Exogenous regression results

	(1)	(2)	(3)
Frontier Equation	GPR	GPR_HC	GPR_HC_UR
Dep var: *lnEne*			
ln(GGDPC)	0.138***	0.123***	0.156***
	(0.0262)	(0.0255)	(0.0243)
ln(Price)	-0.00977	0.00304	-0.00408
	(0.0147)	(0.0148)	(0.0138)
ln(Indus)	0.609***	0.571***	0.482***
	(0.0563)	(0.0555)	(0.0522)
ln(Temp)	-0.539***	-0.465***	-0.428***
	(0.104)	(0.103)	(0.0962)
*ln(GGDPC)*ln(Price)*	0.0966***	0.130***	0.0989***
	(0.0219)	(0.0229)	(0.0216)
*ln(GGDPC)*ln(Indus)*	-0.171**	-0.230***	-0.277***
	(0.0711)	(0.0708)	(0.0665)
*ln(GGDPC)*ln(Temp)*	0.0910**	0.0550	0.0611
	(0.0408)	(0.0418)	(0.0401)
*ln(Price)*ln(Indus)*	0.504***	0.559***	0.495***
	(0.0893)	(0.0894)	(0.0836)
*ln(Price)*ln(Temp)*	0.166***	0.183***	0.151***
	(0.0366)	(0.0367)	(0.0349)
*ln(Indus)*ln(Temp)*	-0.830***	-0.793***	-0.639***
	(0.122)	(0.120)	(0.113)
$ln(GGDPC)^2$	-0.121***	-0.136***	-0.0776***
	(0.0124)	(0.0126)	(0.0133)
$ln(Price)^2$	-0.0862***	-0.0938***	-0.0810***
	(0.0287)	(0.0285)	(0.0267)
$ln(Indus)^2$	0.468**	0.409**	0.0413
	(0.196)	(0.194)	(0.182)
$ln(Temp)^2$	-0.218***	-0.191***	-0.170***
	(0.0450)	(0.0445)	(0.0414)
T	0.0309***	0.0269***	0.0181***
	(0.00237)	(0.00249)	(0.00255)
$(T)^2$	-0.000441***	-0.000429***	-0.000388***
	(4.51e-05)	(4.49e-05)	(4.22e-05)
Constant	4.151***	4.261***	9.571***

Table 11 (continued)

	(1)	(2)	(3)
	(0.0712)	(0.0870)	(1.226)
Dep.var: EE: $\ln(\sigma_{\_u}^2)$			
lnGPR	0.00401	0.00197	0.00162
	(0.00504)	(0.00498)	(0.00186)
lnHC		-0.257***	-0.169***
		(0.0536)	(0.0265)
lnUrban			-0.252***
			(0.0395)
Constant	2.359***	2.643***	5.487***
	(0.233)	(0.241)	(0.276)
Dep.var: $\ln(\sigma_{\_v}^2)$			
Constant	-3.551***	-3.568***	-3.713***
	(0.0378)	(0.0378)	(0.0386)
Log Likelihood	358.28	369.49	435.92
Observations	1,440	1,440	1,440

The frontier equation presents the factors that drive energy consumption. The inefficiency equation examines the factors that drive inefficiency in energy consumption, and energy efficiency (EE) is the dependent variable. Table 11 assumes that there is no endogeneity present in the frontier equations. lnGPR stands for Geopolitical Risk, lnHC for Human Capital, and lnUrban for the extent of urbanization. The standard errors are figures enclosed in brackets. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 12 Replacement of energy price data and model adjustment

	(1) GPR	(2) GPR_HC	(3) GPR_HC_URB
Frontier Equation			
Dep var: *lnEne*			
ln(GGDPC)	0.605***	0.756***	0.811***
	(0.0497)	(0.0617)	(0.0521)
ln(Price)	-0.0108	0.00318	0.0309
	(0.0459)	(0.0505)	(0.0529)
ln(Indus)	0.716***	0.734***	0.669***
	(0.0578)	(0.0613)	(0.0586)
ln(Temp)	0.0221	-0.00211	0.103
	(0.101)	(0.0981)	(0.0944)
*ln(GGDPC)*ln(Price)*	0.244***	0.362***	0.352***
	(0.0674)	(0.0751)	(0.0773)
*ln(GGDPC)*ln(Indus)*	0.319***	0.0233	0.0251
	(0.0705)	(0.0830)	(0.0818)
*ln(GGDPC)*ln(Temp)*	0.409***	0.373***	0.399***
	(0.0401)	(0.0413)	(0.0434)
*ln(Price)*ln(Indus)*	1.672***	1.746***	1.660***
	(0.239)	(0.257)	(0.269)
*ln(Price)*ln(Temp)*	0.651***	0.900***	0.824***
	(0.123)	(0.143)	(0.138)
*ln(Indus)*ln(Temp)*	-0.540***	-0.602***	-0.660***

Table 12 (continued)

	(1) GPR	(2) GPR_HC	(3) GPR_HC_URB
	(0.159)	(0.169)	(0.170)
ln(GGDPC)^2	0.0994***	0.124***	0.133***
	(0.0213)	(0.0244)	(0.0192)
ln(Price)^2	0.0313	0.0319	0.122
	(0.0758)	(0.0825)	(0.0871)
ln(Indus)^2	-1.538***	-2.653***	-2.785***
	(0.317)	(0.403)	(0.354)
ln(Temp)^2	-0.0237	-0.0646	-0.00356
	(0.0582)	(0.0585)	(0.0580)
T	0.00536***	0.00234	-0.00143
	(0.00147)	(0.00159)	(0.00166)
Constant	4.670***	4.980***	5.251***
	(0.0985)	(0.104)	(0.110)
Dep.var: EE: ln(σ_u^2)			
lnGPR	0.0134**	0.0101*	0.0143***
	(0.00600)	(0.00579)	(0.00549)
lnHC		0.0235	0.132**
		(0.0610)	(0.0578)
lnUrban			-0.270***
			(0.0589)
Constant	2.414***	2.484***	3.640***
	(0.240)	(0.247)	(0.334)
Dep.var: ln (σ_w^2)			
eta1_lnGGDPC	-0.455***	-0.585***	-0.634***
	(0.0469)	(0.0567)	(0.0475)
eta Endogeneity Test	89.41***	70.33***	96.20***
Constant	-3.820***	-3.884***	-3.952***
	(0.039)	(0.039)	(0.039)
Identify_Frontier			
Cragg_Donald F-stat	366.77***	68.24***	93.34***
Log Likelihood	-237.47	-99.39	-47.77
Observations	1,347	1,347	1,347

Author contributions B.K.E., S. H., E. A., B.A.G. and S.A.A wrote the main manuscript. All authors reviewed the manuscript.

Funding Open access funding provided by University of Johannesburg. This research is supported by the National Natural Science Foundation of China (72350410488, 72243005, 72243009 and 72174141), the Key Program of the National Social Science Fund of China (21AZD067), and the Project of Innovation Center for Digital Business and Capital Development of Beijing Technology and Business University (SZSK202308).

Data availability Data would be made available upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

References

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

Acemoglu, D., & Johnson, S. (2007). Disease and development: the effect of life expectancy on economic growth. *Journal of political Economy, 115*(6), 925–985.

Adom, P. K., Amakye, K., Abrokwa, K. K., & Quaidoo, C. (2018). Estimate of transient and persistent energy efficiency in Africa: A stochastic frontier approach. *Energy Conversion and Management, 166*, 556–568. https://doi.org/10.1016/j.enconman.2018.04.038

Adom, P. K., Amuakwa-Mensah, F., & Akorli, C. D. (2023). Energy efficiency as a sustainability concern in Africa and financial development: How much bias is involved? *Energy Economics, 120*, 106577. https://doi.org/10.1016/j.eneco.2023.106577

Agradi, M., Adom, P. K., & Vezzulli, A. (2022). Towards sustainability: Does energy efficiency reduce unemployment in African societies? *Sustainable Cities and Society, 79*, 103683. https://doi.org/10.1016/j.scs.2022.103683

Antonakakis, N., Gupta, R., Kollias, C., & Papadamou, S. (2017). Geopolitical risks and the oil-stock nexus over 1899–2016. *Finance Research Letters, 23*, 165–173. https://doi.org/10.1016/j.frl.2017.07.017

Asongu, S. A. (2012). The 2011 Japanese earthquake, tsunami and nuclear crisis: Evidence of contagion from international financial markets. *Journal of Financial Economic Policy, 4*(4), 340–353. https://doi.org/10.1108/17576381211279307

Battese, G. E., & Coelli, T. (1995). A model for technical inefficiency effects in a stochastic frontier production function for panel data. *Empirical Economics, 20*, 325–332.

Borozan, D. (2024). Do geopolitical and energy security risks influence carbon dioxide emissions? Empirical evidence from European Union countries. *Journal of Cleaner Production, 439*, 140834.

Bouoiyour, J., Selmi, R., Hammoudeh, S., & Wohar, M. E. (2019). What are the categories of geopolitical risks that could drive oil prices higher? Acts or threats? *Energy Economics, 84*, 104523. https://doi.org/10.1016/j.eneco.2019.104523

Bricout, A., Slade, R., Staffell, I., & Halttunen, K. (2022). From the geopolitics of oil and gas to the geopolitics of the energy transition: Is there a role for European supermajors? *Energy Research & Social Science, 88*, 102634. https://doi.org/10.1016/j.erss.2022.102634

Cai, Y., & Wu, Y. (2021). Time-varying interactions between geopolitical risks and renewable energy consumption. *International Review of Economics & Finance, 74*, 116–137. https://doi.org/10.1016/j.iref.2021.02.006

Caldara, D., & Iacoviello, M. (2022). Measuring geopolitical risk. *American Economic Review, 112*, 1194–1225. https://doi.org/10.1257/aer.20191823

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 Economics, 119*, Article 106570.

Coelli, T. J. (1995). Recent developments in frontier modelling and efficiency measurement. *Australian Journal of Agricultural Economics, 39*, 219–245. https://doi.org/10.1111/j.1467-8489.1995.tb00552.x

Edziah, B. K., & Opoku, E. E. O. (2024). Enhancing energy efficiency in Asia-Pacific: Comprehensive energy policy analysis. *Energy Economics, 138*, 107831.

Fan, J. H., Omura, A., & Roca, E. (2023). Geopolitics and rare earth metals. *European Journal of Political Economy, 78*, 102356.

Feenstra, R. C., Inklaar, R., & Timmer, M. P. (2016). *What is new in PWT 9.0*. Groningen Growth and Development Centre, University of Groningen.

Filippini, M., & Hunt, L. C. (2011). Energy demand and energy efficiency in the OECD countries: A stochastic demand frontier approach. *Energy Journal, 32*, 59–80.

Gaspar, J., & Glaeser, E. L. (1998). Information technology and the future of cities. *Journal of Urban Economics, 43*(1), 136–156.

Gong, X., Sun, Y., & Du, Z. (2022). Geopolitical risk and China's oil security. *Energy Policy, 163*, Article 112856. https://doi.org/10.1016/j.enpol.2022.112856

Hoang, D. P., Chu, L. K., To, T. T., & Pham, N. X. (2024). Exploring the nexus between fiscal decentralization and

ecological sustainability: A fresh perspective from the moderating role of geopolitical risk and updated international evidence. *Environmental Science and Pollution Research, 31*(10), 15689–15715.
IEA (2019). World Energy Outlook 2019. Paris. https://www.iea.org/reports/world-energy-outlook-2019
Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal Of Econometrics, 115*, 53–74. https://doi.org/10.1016/S0304-4076(03)00092-7
Ivanovski, K., & Hailemariam, A. (2022). Time-varying geopolitical risk and oil prices. *International Review of Economics & Finance, 77*, 206–221. https://doi.org/10.1016/j.iref.2021.10.001
Ji, Q., Zhang, H. Y., & Zhang, D. (2019). The impact of OPEC on East Asian oil import security: A multidimensional analysis. *Energy policy, 126*, 99–10.
Karakaplan, M., & Kutlu, L. (2017). Handling endogeneity in stochastic frontier analysis. *Economic Bulletin, 37*, 889–901.
Koch, N., & Tynkkynen, V. P. (2021). The geopolitics of renewables in Kazakhstan and Russia. *Geopolitics, 26*, 521–540. https://doi.org/10.1080/14650045.2019.1583214
Kopp, R. J. (1981). The measurement of productive efficiency: A reconsideration. *The Quarterly Journal of Economics, 96*, 477–503.
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 Economics, 129*, 107245.
Liddle, B., & Huntington, H. (2020). Revisiting the income elasticity of energy consumption: A heterogeneous, common factor, dynamic OECD & non-OECD country panel analysis. *The Energy Journal, 41*(3), 207–230.
Liu, F., Sim, J. Y., Kofi Edziah, B., Sun, H., Sarkodie, S. A., & Adom, P. K. (2024). Machinery import, R&D spillover, and energy efficiency. *Journal of Environmental Planning and Management, 67*(6), 1258–1279.
Lorentzen, P., McMillan, J., & Wacziarg, R. (2008). Death and development. *Journal of Economic Growth, 13*(2), 81–124.
Månberger, A., & Johansson, B. (2019). The geopolitics of metals and metalloids used for the renewable energy transition. *Energy Strategy Reviews, 26*, 100394. https://doi.org/10.1016/j.esr.2019.100394
Nerlinger, M., & Utz, S. (2022). The impact of the Russia-Ukraine conflict on energy firms: A capital market perspective. *Finance Research Letters, 50*, 103243.
Overland, I. (2019). The geopolitics of renewable energy: Debunking four emerging myths. *Energy Research & Social Science, 49*, 36–40. https://doi.org/10.1016/j.erss.2018.10.018
Overland, I., Juraev, J., & Vakulchuk, R. (2022). Are renewable energy resources more evenly distributed than fossil fuels? Renew. *Energy, 200*, 379–386. https://doi.org/10.1016/j.renene.2022.09.046
Owjimehr, S., Meybodi, M. E., & Jamshidi, N. (2023). Can geopolitical risk improve energy efficiency in European countries? *Energy Strategy Reviews, 49*, 101145.
Schmidt, P., & Sickles, R. C. (1984). Production frontiers and panel data. *Journal of Business & Economic Statistics, 2*, 367–374.
Scholten, D., Bazilian, M., Overland, I., & Westphal, K. (2020). The geopolitics of renewables: New board, new game. *Energy Policy, 138*, 111059. https://doi.org/10.1016/j.enpol.2019.111059
Shen, L., & Hong, Y. (2023). Can geopolitical risks excite Germany economic policy uncertainty: Rethinking in the context of the Russia-Ukraine conflict. *Finance Research Letters, 51*, 103420.
Stjepanovic, S., Tomic, D., & Skare, M. (2022). A new database on green GDP; 1970–2019: A framework for assessing the green economy. *Oeconomia Copernicana, 13*, 949–975. https://doi.org/10.24136/oc.2022.027
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
Sulong, Z., Abdullah, M., Abakah, E. J. A., Adeabah, D., & Asongu, S. (2024). Russia-Ukraine war and G7 debt markets: Evidence from public sentiment towards economic sanctions during the conflict. *International Journal of Finance & Economics, 29*(4), 4569–4589.
Sun, H., Edziah, B. K., Kporsu, A. K., Sarkodie, S. A., & Taghizadeh-Hesary, F. (2021). Energy efficiency: The role of technological innovation and knowledge spillover. *Technological Forecasting And Social Change, 167*, 120659.
Sun, H., Edziah, B. K., Song, X., Kporsu, A. K., & Taghizadeh-Hesary, F. (2020). Estimating persistent and transient energy efficiency in belt and road countries: A stochastic frontier analysis. *Energies, 13*, 3837. https://doi.org/10.3390/en13153837
Sun, H., Edziah, B. K., Sun, C., & Kporsu, A. K. (2019). Institutional quality, green innovation and energy efficiency. *Energy Policy, 135*, 111002.
Sweidan, O. D. (2021). The geopolitical risk effect on the US renewable energy deployment. *Journal of Cleaner Production, 293*, 126189. https://doi.org/10.1016/j.jclepro.2021.126189
Vakulchuk, R., Overland, I., & Scholten, D. (2020). Renewable energy and geopolitics: A review. *Renewable & Sustainable Energy Reviews, 122*, 109547. https://doi.org/10.1016/j.rser.2019.109547
Wang, K. H., Su, C. W., & Umar, M. (2021). Geopolitical risk and crude oil security: A Chinese perspective. *Energy*. https://doi.org/10.1016/j.energy.2020.119555
Wang, Q., Wang, X., & Li, R. (2024a). Geopolitical risks and energy transition: The impact of environmental regulation and green innovation. *Humanities and Social Sciences Communications, 11*(1), 1–22.
Wang, Q., Zhang, C., & Li, R. (2024b). Geopolitical risk and ecological efficiency: A combination approach based on super-efficiency-DEA and extended-STIRPAT models. *Journal of Environmental Management, 351*, 119867.
Wang, Q., Zhang, C., & Li, R. (2024c). Impact of different geopolitical factors on the energy transition: The role of geopolitical threats, geopolitical acts, and geopolitical risks. *Journal of Environmental Management, 352*, 119962.
Wang, S., Wang, J., & Wang, W. (2023). Do geopolitical risks facilitate the global energy transition? Evidence from 39 countries in the world. *Resources Policy, 85*, 103952.

Yilmazkuday, H. (2024). Geopolitical risks and energy uncertainty: Implications for global and domestic energy prices. *Energy Economics, 140*, 107985.

Yoshino, N., Taghizadeh-Hesary, F., & Otsuka, M. (2021). COVID-19 and optimal portfolio selection for investment in sustainable development goals. *Finance Research Letters, 38*, 101695. https://doi.org/10.1016/j.frl.2020.101695

Zhang, B., Liu, Z., Wang, Z., & Zhang, S. (2023). The impact of geopolitical risk on energy security: Evidence from a GMM panel VAR approach. *Resources Policy, 86*, 104222.

Zhang, Y., Liu, B., Xue, J., Chen, Y., & Zhao, F. (2025). Would geopolitical risks be the new driver of the energy transition? An empirical study on renewable energy technology innovation. *Energy Economics, 141*, 108100.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.