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Renewable energy and energy security under geopolitical vulnerability: New evidence from fragile regions

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ABSTRACT

This study investigates the strategic determinants of energy security across 13 geopolitically vulnerable and fragile transition economies from 2000 to 2023. Given the compounding risks of global shocks, we examine how renewable energy deployment, industrialization, urbanization, and energy import dependence interact under varying degrees of institutional stress. Methodologically, the study addresses common diagnostic challenges, including cross-sectional dependence, slope heterogeneity, and endogeneity, by employing a robust suite of second-generation panel econometric frameworks. To capture institutional and geopolitical vulnerability, the Fragile States Index (FSI) is incorporated into the model specification. The empirical findings show that renewable energy deployment and industrialization significantly bolster long-term energy security, whereas structural institutional fragility and high energy import dependence are severe impediments. Crucially, the estimates confirm that high institutional fragility acts as a structural barrier that reduces the efficiency of green energy infrastructure investments. Consequently, policy frameworks in these vulnerable regimes must prioritize mitigating institutional risk premiums alongside accelerating renewable energy diversification to secure continuous energy stability.

1. Introduction

In recent years, the world has seen a resurgence in attention given to discussions regarding energy security. The combination of geopolitical instability and volatility in the energy market has forced policymakers and researchers to evaluate energy security from an evolving perspective rather than a static one (Z. Liu et al., 2025; Zhang et al., 2023). Discussions surrounding energy security operating from today's perspective must account for the complex array of geopolitical, environmental, market, and macroeconomic changes that governments have to address over time as they secure energy supply chains; thus, governments are now seeking to ensure energy security as a multidimensional objective (World Energy Council, 2022). While security of energy supply requires an adequate supply of energy and a stable (affordable) price, energy security increasingly requires consideration of the resilience of the energy system to shocks and natural disasters, the sustainability of energy systems, and the ability of nations to respond effectively to shocks (Qian et al., 2025; Yu et al., 2022). Many countries with economies located in conflict zones, heavily reliant on imported fuels, and possessing a history of weak state institutions experience an increased loss of energy security as they face energy supply disruptions as a result of natural disasters or significant external shocks (Albanese, 2025; Cappelli and Carnazza, 2025). Renewable energy is one of the major areas of opportunity to address vulnerability to energy insecurity (*IRENA, 2025*; *OECD, 2024)*. There are significant strategic benefits from renewable energy sources that exceed the focus on decarbonization. Increasing renewable-energy capacity decreases reliance on imported fossil fuels, increases the diversification of energy sources within individual economies, decreases the volatility of energy prices, and increases the ability of economies to respond to international price shocks from energy sources (Khan et al., 2024). Renewable energy also provides an opportunity for countries exposed to geopolitical risks to address their vulnerabilities by increasing domestic energy autonomy. Although there has been an increasing interest in the link between renewable energy and energy security, significant gaps exist in the current body of research. The majority of empirical evidence that includes the link between renewable energy and energy security has been exclusively focused on advanced economies and large emerging

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markets, whereas the experiences of smaller nations characterized by institutional weaknesses and dependence on external energy suppliers have been poorly studied.

While existing studies have extensively documented the general benefits of renewable energy, there is a lack of empirical evidence focusing specifically on countries characterized by high geopolitical vulnerability and institutional fragility. Most current models fail to account for the 'security-buffer' role of renewables under conditions of external shocks. This research fills this void by investigating 13 economically vulnerable nations, thereby shifting the focus from stable economies to high-risk contexts. Consequently, this study contributes to the literature in the following ways:1) Many of the empirical studies have focused on advanced economies (Chu, 2023) or large emerging markets (Sotnyk et al., 2021), so little is known about how the dynamics of renewable energy and energy security occur in smaller, geopolitically sensitive countries with structural features such as institutional fragility and dependence on external suppliers. 2) Reliance upon narrow measures of energy security such as import dependence, restricts our understanding of how renewable energy contributes to energy security as a multidimensional and comprehensive measure of resilience of energy systems. 3) Lack of studies touching potential endogeneity between renewable energy and energy security. These research gaps are particularly prominent in regions such as Eastern Europe, the South Caucasus, and parts of North Africa that have experienced geopolitical tensions, exposure to international energy shocks, and varying degrees of institutional weakness.

Research has conceptualized geopolitical vulnerability as not just an ephemeral geopolitical risk but rather as a structural condition in a fragile economy's energy systems. The reasons for a fragile economy to be vulnerable include a multitude of external factors: political events isolated from one another do not cause a fragile economy's energy systems to become vulnerable; exposure to interruptions in supply, energy dependencies on imports and therefore the ability to influence market prices internationally; institutional weaknesses, and lack of resilience to instability in the region. Thus, geopolitical vulnerability is a function of many interrelated channels of interaction. Dependence on energy imports creates exposure to global price volatility, sanctions, conflict-related supply disruptions, and supply disruptions due to logistical disruptions. Political fragility creates challenges for governments to develop, fund, and implement a cohesive, effective energy security strategy. Regional instability, as well as shocks from outside of the region (i.e., the conflict between Russia and Ukraine), elevate the strategic value of creating a domestic renewable energy capacity as an alternative to buying energy on the global market when a disruption occurs. Renewable energy can be an effective means to create energy security through both environmental sustainability and reducing dependence on traditional imported fossil fuel energy sources and, therefore, enhancing the domestic capacity to use energy from renewable sources.

This study examines the relationship between renewable energy development and energy security in a panel of thirteen geopolitically vulnerable countries: Algeria, Armenia, Azerbaijan, Bosnia-Herzegovina, Egypt, Georgia, Jordan, Lebanon, Moldova, Morocco, North Macedonia, Serbia, and Tunisia. These thirteen countries possess many of the same characteristics such as dependence on energy imports, exposure to conflict and instability within their regions, and many have weak state institutions. However, they differ considerably with respect to their rates of development, levels of renewable energy deployment, and institutional fragility.

This study provides a contribution to the body of literature in four primary areas. First, it provides one of the few empirical assessments focused specifically on geopolitically vulnerable countries. Second, it utilizes a multidimensional indicator of energy security to measure energy security performance from a multidimensional perspective and to reflect the complex interactions and dependencies that occur among multiple sources of energy and institutions rather than to rely only on a single proxy for energy security. Third, it directly incorporates institutional weakness into the empirical model, showing how institutional weaknesses may severely weaken energy system performance. Finally, the paper addresses possible endogeneity of the renewable energy and energy security relationship through the use of a fixed-effects IV–2SLS estimator. Since countries that have better energy security systems may also have greater capacity to invest in renewable energy, renewable energy is potentially endogenous and is instrumented using the first lag of renewable energy. In this way, the data complement the findings of the baseline PCSE, FGLS, and FMOLS estimates with IV-based information suitable for causal explanation.

Despite the expanding literature on the drivers of energy transition, existing studies exhibit three critical gaps that this paper systematically intends to fill, thereby establishing its core theoretical and empirical significance. First, the conceptual gap: while the mainstream energy economics literature extensively evaluates the economic determinants of energy security, it largely treats institutional structures as static controls or omits them entirely. This study bridges this gap by explicitly integrating the Fragile States Index (FSI) to explore how multi-dimensional institutional stress and geopolitical vulnerability directly moderate or impede the efficacy of renewable energy deployment. Second, the contextual gap: prior research predominantly aggregates developing nations into broad, heterogeneous panels, which blurs the unique realities of states experiencing structural transition. We isolate a targeted sample of 13 geopolitically vulnerable and fragile transition economies, providing a dedicated analytical framework for regions where institutional volatility directly threatens grid infrastructure and energy planning. Third, the empirical gap most existing studies utilize first-generation panel estimators that fail to simultaneously account for cross-sectional dependence, slope heterogeneity, and reverse causality between institutional factors and industrial expansion. By executing a robust suite of second-generation estimators alongside an instrumental variable strategy (FE-2SLS), this work delivers highly resilient, unbiased parameters that fortify the empirical reliability of the energy-governance nexus.

2. Review of the literature

2.1. Understanding energy security through multiple dimensions

Within the last two decades, energy security has developed greatly (Cherp and Jewell, 2014; Moghani and Loni, 2025; Siksnelyte-Butkiene et al., 2025; Sovacool and Mukherjee, 2011). The early days of energy security were around understanding energy security as being able to get continuous access to energy at stable and affordable prices. Later, with increased interdependence of global energy systems as well as increasing political, environmental and technological risk, it has become obvious that a single-dimension definition of energy security is not adequate (Cherp and Jewell, 2011; Galimova et al., 2025; Kruyt et al., 2009). More contemporary literature on energy security increasingly discusses energy security from a multi-dimensional point of view (Cergibozan, 2022; Kim et al., 2025; Strojny et al., 2023; Wang et al., 2024). Most current research reflects the fact that energy availability, affordability, sustainability, and institutional integrity are all things that must be viewed collectively (Schmitz et al., 2025; Šprajc et al., 2019; Wejnert-Depue et al., 2025), as opposed to solely when looking at individual energy resources. Another very common theme in the literature regarding perspectives on energy security is the sovereignty of countries, the complexity and cross-border nature of energy security, and its role in establishing a robust system of energy delivery. Each of these perspectives focuses on a different type of vulnerability that can lead to energy security threats. Sovereignty emphasizes a country's strategic vulnerability to foreign suppliers, robustness emphasizes the reliability of energy supply technologies and physical infrastructure (Akhundzadah and Kassam, 2025; LaBelle, 2024), while resilience addresses how complex systems respond to environmental and regulatory shocks (Amanfo et al., 2024; Ibekwe et al., 2024). The collective body of knowledge indicates that energy security is a complex and multidimensional characteristic of energy systems (Fouladvand et al., 2024; Mara et al., 2022; Samusevych et al., 2021). For example, according to Paravantis (2019) import dependency alone can not provide an adequate measure of energy security since it might not take into consideration domestic technical inefficiencies and price stability does not automatically mean structural resilience. Therefore, the increasing interest in composite defined energy security indices is indicative of the fact that researchers are attempting to find ways to develop a better understanding of how multi-dimensional energy systems are being developed.

Energy security is increasingly conceptualized as a multidimensional concept rather than a single indicator of supply availability. In addition to the traditional focus on secure and continuous access to energy, recent studies emphasize the interaction between availability, affordability, diversification, sustainability, and resilience. Bigerna et al. (2021), for example, show that renewable-energy penetration affects energy security in the context of decarbonization and technological transition. Later, in another study, Bigerna et al. (2024) highlight the potential tension between net-zero policies and energy-security objectives, particularly in energy-exporting economies. These studies suggest that the effect of renewable energy on energy security depends on the structure of the energy system, the degree of import dependence, and the institutional capacity to manage the transition.

Indices created from composite spectra of information on energy systems generally include data related to energy availability (Z. Yu et al., 2022), affordability (Srinivasan et al., 2025), sustainability (Alpha et al., 2025), diversity (Dao et al., 2025), and the quality of energy institutions (Azimi et al., 2025). When researchers have used these types of composite data to examine how each of these variables has impacted the energy security profiles of different countries, they have found that a majority of countries, as a result of the technological advancements in energy technologies, show that many countries' energy security performance has stagnated or declined since the time the study was published (Carmon et al., 2025; Zhang and Zhou, 2024; Zhu et al., 2023).

2.2. *Renewable energy, energy security and geopolitical uncertainty*

The body of empirical research currently available regarding renewable energy consumption has largely been focused on the environmental outcome of renewable energy consumption and the link to the reduction of GHG emissions (Amin et al., 2024; Amponsah et al., 2014; Attanayake et al., 2024; Chen et al., 2023; Hasan et al., 2026; Sohaib et al., 2025). Studies have regularly confirmed the conclusion that increased use of renewable energy reduces GHGs (Li et al., 2023; X. Liu et al., 2023) and that non-renewable energy use increases GHG emissions (Farooq et al, 2024; Khurshid et al., 2024). This relationship has been shown to hold for both developed (Ma et al., 2025; Shah et al., 2024) and developing (Ito, 2017; Turedi and Turedi, 2021) nations, indicating a clear connection between the stimulation of economic activity by renewable energy and the achievement of environmental goals. A newer group of studies, however, takes the relationship between renewable energy and GHG greatest environmental outputs to a new, more complex, question: In addition to having less environmental impact, does the use of renewable energy provide for greater energy security?

Sharma (2023), in the case of Norway, found that higher shares of renewables in the electricity mix are associated with better scores across availability, affordability, accessibility and acceptability dimensions of energy security. While in case of G7 countries, the authors conclude that the increases in renewable electricity generation significantly reduce measured energy-security risks, mainly by lowering import dependence and exposure to fossil-fuel price volatility (Tansel Tugcu and Menegaki, 2024). From recent works Behera et al. (2025) found that higher levels of renewable energy penetration reduce the growth-dampening effects of energy insecurity, indicating an enhanced capacity of energy systems to absorb shocks in 27 net oil-importing G20 countries. Because the deployment of greater penetration of renewable energy results in reduced reliance on fossil fuel imports (Yadav and Mahalik, 2024); the development of renewable energy increases the diversification of a nation's energy mix (Hoang et al., 2025; Nibedita and Irfan, 2024) and thus provides a hedge against both foreign energy supplies being disrupted and against the risks posed by price volatility.

Evidence from studies conducted on cases of individual Nations/Regions, Emerging European and North African markets that have rapidly expanded their development of solar capacity have produced results supporting the notion that new renewable energy sources can serve to strengthen domestic energy production capabilities, stimulate domestic investments in renewable energy and reduce strategic vulnerability (Ainou et al., 2023; Brand and Zingerle, 2011; Mohr, 2025; Vasylieva et al., 2025). However, the literature also demonstrates that the benefits of renewables as an increase in energy security, are not guaranteed (Fernandez et al., 2024; Khalid, 2024). Some studies that have focused on the geopolitical aspect of energy security have utilized existing geopolitical risk indices and demonstrated that an increase in risk related to geopolitics tends to create tighter-than-normal credit conditions, which in turn reduce investment and create instability within the macro-economic structure (Caldara and Iacoviello, 2022; Hodula et al., 2024; Lee et al., 2024). Energy markets are highly integrated into the global economy; therefore, any geopolitical shocks that occur as a result of conflict, sanctions, and political instability can lead to a subsequent occurrence of volatility in the supply and price of energy (Aizenman et al., 2024; Goodell et al., 2023; Olasehinde-Williams and Akadiri, 2025). According to Deng and Jiang (2025) geopolitical risk hastens the transformation of global energy trade networks, leading to unpredictability and volatility in the global energy sector. Furthermore, Wen (2024) mentioned that significant price volatility caused by geopolitical risks can lead to disruptions in the order of the oil and gas market and exacerbate uncertainty in investment and trade. In addition to the geopolitical aspect of energy security, differing bodies of research have developed energy-specific risk indices that address the many different environmental, climate exposure, policy uncertainty and clean energy investment metrics that impact the security of energy supply (Dagar et al., 2024; Ivanovski and Marinucci, 2021; Iyke, 2023). Recently, there is a growing amount of energy-economics based research that analyzes the geopolitical aspects of renewable energy and energy security. He et al. (2025) revealed that geopolitical risk causes a more rapid transition to renewable energy, particularly among energy-dependent nations. Ren et al. (2024), found that geopolitical risk will hinder the convergence of renewable energy consumption, while Zhang et al. (2025), suggest that geopolitical risks might spur on innovations in renewable energy technologies. Collectively, these works illustrate that although geopolitical risk has the potential to limit the transition toward renewables through its introduction of uncertainty about future energy markets, it may provide an enhanced strategic reason for energy-dependent countries to reduce their reliance upon fossil fuels by pushing for the deployment of renewables. However, the majority of recent research has been conducted using large economies or aggregated global panel datasets. This research intends to add to existing research by evaluating much smaller countries that are considered to be geopolitically vulnerable by virtue of their dependence on imports and the constraints of their infrastructure. In the literature, only very few studies have included analyses of smaller, more geopolitically vulnerable nations that are also resource poor and institutionally fragile. In addition, many studies have used single-dimensional proxy measures of energy security therefore not providing broad systemic analyses.

3. Data and methodology

3.1. *Data sources and sample description*

The study uses an unbalanced panel data set from 13 countries deemed vulnerable due to their geopolitical positions (Algeria, Armenia, Azerbaijan, Bosnia-Herzegovina, Egypt, Georgia, Jordan, Lebanon, Moldova, Morocco, North Macedonia, Serbia, and Tunisia) spanning the years 2000-2023 (Table 1). Countries in this sample of 13 do not necessarily comprise one geographic region; instead, they have been selected based on their commonalities in terms of certain vulnerability characteristics. While sub-regions (e.g., Eastern Europe, South Caucasus, North Africa, and Middle East) are each represented, these countries share enough structural characteristics to form a common empirical framework. This includes all of these countries being affected by geopolitical tensions (through direct involvement or proximity to conflict zones, competing energy routes, or instability within their larger region) and exhibiting varying degrees of institutional weakness. These latter two characteristics are particularly important because they may also limit the degree to which countries can become actively involved in designing and implementing long-term policies related to energy security. Lastly, all of the countries in this sample can be vulnerable to externally produced shocks due to a combination of their dependence on energy imports, lack of energy system diversification, infrastructure shortcomings, and susceptibility to changes in the global price of fossil fuels. Despite similarities among the samples regarding vulnerabilities, they also demonstrate differences. For example, North African economies such as Algeria and Egypt are markedly different from Eastern European and South Caucasus economies with respect to the availability of resources and patterns of energy imports. In addition to decreasing dependence on imported energy in countries that are net importers of energy, renewable energy could also assist in increasing the diversification of economies that are net exporters of energy or in different stages of transition to net energy exporter status, helping to reduce their exposure to volatility within the global fossil fuel marketplace. As such, the sample should be considered as having all of these economies collectively as being vulnerable to geopolitical and structural factors rather than having one common geographic affiliation.

Other countries (for example, Ukraine, Belarus, Libya, Syria) originally included in the study's population were eliminated because of the lack of complete and consistent data for the Energy Security Index (ES) and the Fragile States Index (FSI) and other renewable energy variables. The data was collected from established international resources. The Energy Trilemma Index published by the World Energy Council provides annual scores that measure the energy security of these countries with respect to availability, affordability, diversification, and overall system-level resilience. The remaining components of the data set, which include renewable energy, energy imports, industrial value added, and urbanization, were obtained from World Development Indicators (WDI) and the World Energy Council (WEC). The level of institutional fragility is measured using the Fragile States Index (FSI) developed by the Fund for Peace. The FSI is used as an indicator for the institutional/geopolitical capacity portion of the overall geopolitical vulnerability of a country. Although we can also quantify geographical risk via event-based indicators, such as the Caldara and Iacoviello Geopolitical Risk Index, the global GPR provides mostly temporal variations in measures and is thus not particularly helpful for determining cross-country heterogeneity between a sample of small and geographically vulnerable countries. In addition, consistent country-specific GPR data are not available for all countries in our study sample throughout the entire time frame of our study. Therefore, our empirical strategy focused on structural geopolitical vulnerabilities, as measured by institutional fragility and dependence on energy imports, rather than on one global geopolitical risk index. This further support our overall objective to evaluate how long-term vulnerability conditions have impacted the relationship between renewable energy and energy security within fragile areas.

To ensure the highest degree of data integrity, reliability, and cross-country consistency, our panel dataset is exclusively compiled from established international institutional databases that represent the empirical benchmark in recent macro-energy and environmental economics literature. Specifically, macro-developmental indicators (industrialization, urbanization, and energy import dependence) are sourced from the World Bank's World Development Indicators (WDI), a repository universally recognized for its strict quality-control protocols and longitudinal standardization across heterogeneous. Our primary

Table 1
Sample classification and vulnerability rationale.

Country	Subregion	Energy-system profile	Vulnerability rationale
Algeria	North Africa	Hydrocarbon-exporting economy with diversification needs	Exposure to fossil-fuel market volatility, energy-transition pressure, and the need to diversify away from hydrocarbon dependence
Armenia	South Caucasus	Import-dependent and geopolitically exposed economy	High sensitivity to external energy dependence, regional security risks, and limited domestic energy diversification
Azerbaijan	South Caucasus	Hydrocarbon-exporting transition economy	Dependence on fossil-fuel revenues, exposure to global energy-market volatility, and the need for renewable-energy diversification
Bosnia and Herzegovina	Western Balkans	Transition economy with fragmented institutional structure	Institutional fragmentation, infrastructure constraints, and exposure to regional energy-market instability
Egypt	North Africa/ MENA	Mixed energy profile with rising domestic demand	Rapid demand growth, regional instability, infrastructure pressure, and the need for long-term energy diversification
Georgia	South Caucasus	Import-dependent and transit-oriented economy	External energy dependence, exposure to regional geopolitical tensions, and vulnerability to supply-route disruptions
Jordan	Middle East	Highly import-dependent economy	Limited domestic energy resources, high exposure to imported-fuel price shocks, and strong need for renewable-energy expansion
Lebanon	Middle East	Fragile and highly constrained energy system	Severe institutional fragility, infrastructure weakness, supply instability, and chronic energy-security challenges
Moldova	Eastern Europe	Highly import-dependent economy	Strong exposure to external energy-supply disruptions, limited diversification, and geopolitical vulnerability in the regional energy system
Morocco	North Africa	Import-dependent economy with active renewable-energy transition	High dependence on imported energy, but strong strategic potential for solar and wind diversification
North Macedonia	Western Balkans	Import-dependent transition economy	Infrastructure constraints, limited diversification, and exposure to regional energy-market instability
Serbia	Western Balkans	Transition economy with energy-system modernization needs	Dependence on traditional energy infrastructure, regional exposure, and the need for modernization and diversification
Tunisia	North Africa	Import-dependent transition economy	External energy dependence, institutional-transition pressures, and vulnerability to fossil-fuel price volatility

Note: The sample is classified according to a vulnerability-based logic rather than a purely geographical logic. The selected countries differ in resource endowments and regional location, but they share exposure to geopolitical instability, institutional fragility, external energy dependence, infrastructure constraints, or sensitivity to global energy-market shocks.
Source: Author's construction

Table 2
Variable description and expected signs.

Variable	Symbol	Description	Expected Sign	Source
Energy Security	*ES*	Composite index measuring availability, affordability, and diversification of energy supply (0–100 scale).	—	The World Energy Council's Energy Trilemma Index
Renewable Energy	*RE*	Share of renewable energy (solar, wind, hydro, geothermal, and biomass) in total energy production (%).	+	World Development Indicators (Wen, 2024; IEA, 2023)
Energy Imports	*EIMP*	Ratio of energy imports to GDP (%), representing external dependence on fossil fuels.	–	World Development Indicators (Wen, 2024)
Industrialization	*IND*	Industry value added as a percentage of GDP (%), indicating productive capacity and structural transformation.	+	World Development Indicators (Wen, 2024)
Urbanization (Growth Rate)	*URB*	Annual growth rate of urban population.	–	World Development Indicators (Wen, 2024)
Institutional Fragility	*FSI*	Fragile States Index score (0 = stable; 120 = highly fragile), reflecting governance, stability, and social cohesion.	–	Fund for Peace

In the analysis above, Table 2 displays all variables utilized for the analysis along with their respective expected signs and data source information. All index based variables (ES and FSI) are maintained on their original scale.
Source: Author's construction

energy security parameters are retrieved from the World Energy Council (WEC) databases, which utilize multi-stage data alignment and cross-verification to compile composite energy trilemma dimensions, ensuring exceptional metric consistency across non-homogeneous regional blocks. Lastly, the multi-dimensional facets of institutional and state fragility are extracted from the Fund for Peace's Fragile States Index (FSI). The FSI employs a highly rigorous, triangulated data processing methodology blending content analysis, quantitative indicators, and qualitative expert reviews, which has been widely adopted in modern institutional economics to capture macro-level socioeconomic and political vulnerabilities.

3.1.1. *Descriptive statistics and heterogeneity*

Between 2000 and 2023, the ES index for 13 countries changed significantly as shown in Fig. 1. The difference between the countries' trajectories is apparent and consistent with the structural diversity indicated by the descriptive statistics. There is one group of countries, including Bosnia & Herzegovina, Serbia, North Macedonia, and Morocco all of which show generally stable and relatively high energy security through the entire time period, reflecting a diversification of their supply structures and an overall consistency of policy framework. Alternatively, there are other countries, most notably Georgia, Moldova, Lebanon and Jordan, who have experienced pronounced fluctuations in their energy security index values indicating that they are more susceptible to external shocks, geopolitical unrest or the limitations of domestic infrastructure. In addition, Azerbaijan and Algeria experienced moderate increases in their energy security indices during the early 2000s; however, like Georgia, Moldova, Lebanon and Jordan, these two countries also experienced significant fluctuations due to both global energy market cycles and the transitional impact of the domestic economy. The decline of the energy security index within certain countries towards the end of the second decade demonstrates the impact of recent geopolitical unrest and supply chain disruptions.

Furthermore, the visual inspections of cross-sectional and temporal patterns (Figs. 1 and 2) showed marked differences across countries and gradual long-run shifts in energy security over time. These features suggest that the data are characterized by cross-sectional dependence and slope heterogeneity, motivating the use of second-generation panel estimators (see Fig. 3).

The fact that descriptive statistics precede the beginning of the econometric process is important for gaining a prior overview of the characteristics of the data and for identifying the variables. This paper also begins the analysis under the leadership of descriptive statistics, and the characteristics of the variables are presented in Table 3. The baseline empirical profiles presented in Table 3 reveal critical distributional insights across the 13 transition economies. First, the substantial spread between the minimum and maximum values of the Fragile States Index (FSI) and Renewable Energy deployment (RE) highlights a profound degree of cross-country structural heterogeneity within the macro-panel, confirming that these nations experience highly divergent institutional trajectories and green investment spaces. Second, the standard deviation parameters demonstrate relatively low volatility in urbanization and industrialization metrics, indicating stable, long-term secular trends, whereas energy import dependence showcases pronounced variance, exposing the sample countries to highly asymmetric external economic shocks. Lastly, the Jarque-Bera (JB) diagnostic statistics systematically reject the null hypothesis of normal distribution for the primary variables at the 1% significance level. This non-normal, leptokurtic distribution profile strongly invalidates classical, first-generation panel estimators and serves as a strict econometric justification for deploying advanced, robust second-generation estimators capable of accommodating non-linearity, slope heterogeneity, and cross-sectional dependence.

3.1.2. *Correlation matrix*

The correlations between the main analysis variables are described in Fig. 4. The findings demonstrate a general conformity to expected relationships that do not reveal potential issues of multicollinearity. Energy security and its association with renewable energy ($r = 0.17$) and industrialization ($r = 0.58$) suggest a correlation between a country's ability to utilize renewable energy and its ability to produce goods, thus providing a country with an increased ability to maintain stability in its energy system. On the other hand, ES and EIMP ($r = -0.50$) show a negative correlation, indicating that countries which rely on EIMP experience greater vulnerability due to the dependency of their economies on external sources of energy. The strong positive nexus between industrialization and energy security ($r = 0.58$) warrants a deeper structural explanation. Within the context of the examined fragile regions, this link operates primarily through an infrastructure-led demand mechanism. As industrial value-added expands, it necessitates advanced, high-capacity, and reliable energy grids, thereby compelling policymakers to prioritize national energy infrastructure and diversification. Industrial modernization also introduces technological innovations that optimize energy efficiency across productive sectors. Empirically, our FE-2SLS instrumental variable results validate this direction, confirming that industrialization acts as a robust driver of energy security. Nonetheless, this relationship is inherently cyclical; while

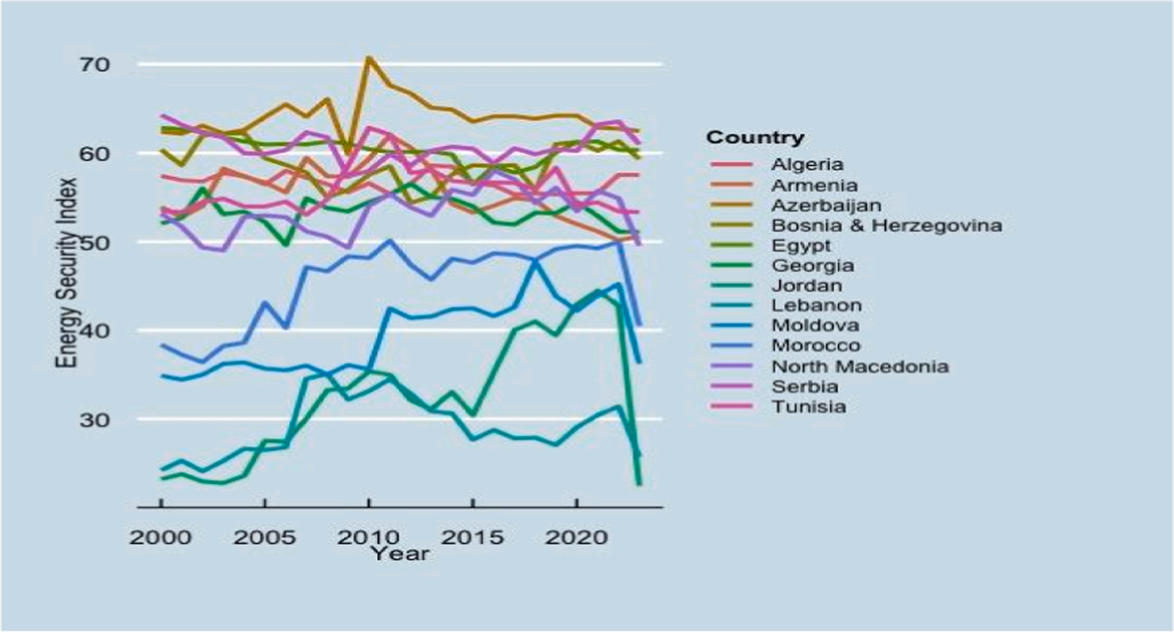

Fig. 1. Energy Security Trends of Vulnerable Countries (2000-2023)
Source: Author's calculation.

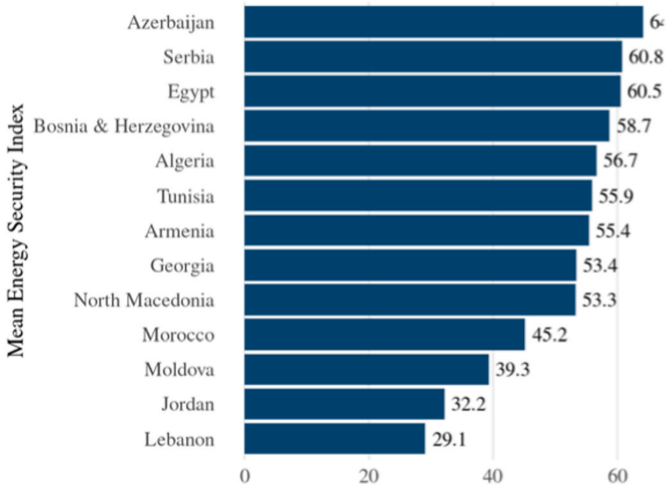

Fig. 2. Heterogeneity of energy security across countries.

Fig. 3. Heterogeneity of Energy Security Across Years
Source: Author's calculation.

industrial growth accelerates infrastructure development, the resulting energy security establishes the foundational stability required to sustain continuous industrial production and mitigate supply-side bottlenecks.

These correlational data provide an overview of how these variables interact with each other and support the more rigorous methods of estimating the relationships that were addressed in a subsequent section of this paper.

3.2. Methodology

The empirical analysis investigates the relationship between renewable energy, industrialization, and energy security within a multi-country panel framework.

The general form of the estimated model is specified as:

$$ES_{it} = \alpha_i + \beta_1 \, RE_{it} + \beta_2 \, EIMP_{it} + \beta_3 \, IND_{it} + \beta_4 \, URB_{it} + \beta_5 \, FSI_{it} + \varepsilon_{it} \tag{1}$$

where:

ES_{it} — energy security index for country i at time t

RE_{it}— renewable energy share in total energy consumption (proxy for energy transition);

$EIMP_{it}$— energy import dependence;

IND_{it}— industry value added (% of GDP), capturing industrialization;

URB_{it}— urban population (% of total population);

FSI_{it}— fragile states index (proxy for institutional and geopolitical vulnerability);

α_i— unobserved country-specific effects;

ε_{it}— idiosyncratic error term.

The short-run dynamics were first estimated using the Panel-Corrected Standard Errors (PCSE) approach of.

Three model variants were employed:

1. PCSE **(Default)** — assumes panel-heteroskedastic errors and contemporaneous correlation across countries with no serial correlation correction.
2. PCSE-**AR** — incorporates autoregressive disturbances of order p to mitigate serial correlation.

Table 3
Descriptive stats.

Statistics	ES	RE	EIMP	IND	URB	FSI
Mean	52.12597	13.25520	8.123752	27.82840	60.41543	76.34638
Median	54.99000	11.60000	52.36214	24.67130	57.40800	75.79000
Maximum	70.75000	39.10000	103.8038	66.16033	92.02000	91.80000
Minimum	22.42000	0.100000	−457.0693	2.086302	42.49000	60.30000
Std. Dev.	10.07079	9.935018	126.7849	10.85878	13.85837	7.137494
Skewness	−1.035919	0.611307	−1.907567	1.386178	0.762502	0.300392
Kurtosis	3.284211	2.600224	5.518492	5.423427	2.918337	2.418015
Jarque-Bera	40.27068	15.23614	192.4361	124.8553	21.47665	6.442580
Probability	0.000000	0.000491	0.000000	0.000000	0.000022	0.039904
Sum	11519.84	2929.400	1795.349	6150.077	13351.81	16872.55
Sum Sq. Dev.	22312.59	21715.01	3536373.	25940.89	42251.97	11207.64
Observations	221	221	221	221	221	221

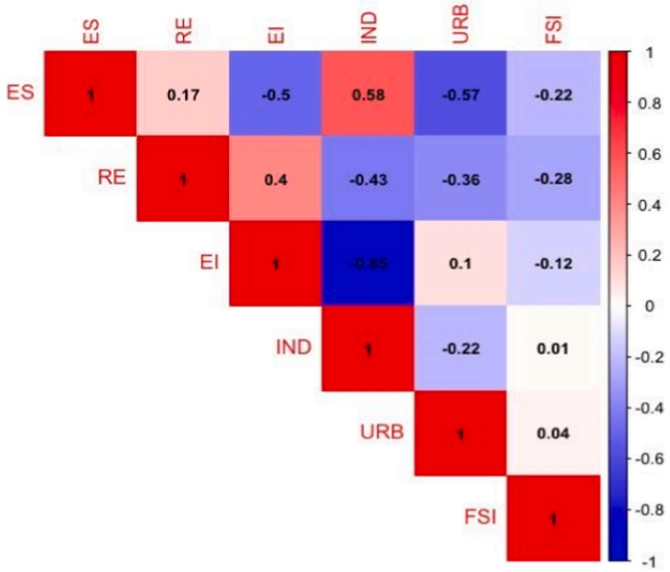

Fig. 4. Correlation Matrix
Source: Author's calculation.

3. PCSE **-AR(1)** — includes an AR (1) structure in the residuals, assuming:

$$\varepsilon_{it} = \rho\varepsilon_{i,t-1} + u_{it}, |\rho| < 1. \tag{2}$$

ensuring efficient and unbiased estimates under weakly dependent panels.

The PCSE estimator provides consistent coefficients even under heteroskedasticity and contemporaneous correlation, making it suitable for cross-country analyses with moderate *N* and *T*. As robustness checks, three **FGLS** specifications were estimated:

$$ES_{it} = \alpha_i + X'_{it}\beta + \mu_{it} \tag{3}$$

where X'_{it} is the vector of explanatory variables.

The FGLS models differ by their treatment of the variance–covariance matrix:

1. **FGLS-I:** assumes cross-section independence but panel heteroskedasticity;
2. **FGLS-II:** allows cross-sectional correlation and heteroskedasticity;
3. **FGLS-III:** includes both cross-section correlation and AR (1) disturbances within panels. The FGLS estimator improves efficiency compared to PCSE when the structure of heteroskedasticity and autocorrelation is well specified. To examine long-run relationships among variables, the study employs FMOLS (Pedroni, 2000; Phillips and Hansen, 1990). The FMOLS estimator corrects for both serial correlation and endogeneity arising from cointegration among the regressors and the dependent variable.

3.3. Cross-section dependence (CD), unit root, and cointegration test

3.3.1. Cross-section dependence test

During data analysis, it is common to encounter cross-sectional correlations among variables. This issue arises due to interactions among countries within the same economic and social network, geographical proximity, and other forms of spatial or structural linkages (Baltagi and Pirotte, 2010; Sarafidis and Wansbeek, 2012). By considering cross-sectional dependence in the estimation, prediction errors and inconsistencies can be reduced (Chudik and Pesaran, 2013). The classical Lagrange Multiplier (LM) test for cross-sectional dependence proposed by Breusch and Pagan (1980) is formulated as:

$$LM = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} T\,\widehat{\rho_{ij}}^{2} \tag{4}$$

where $\widehat{\rho_{ij}}$ denotes the sample correlation coefficient of the residuals between cross-sectional units *i* and *j*,

T is the number of time periods, and *N* is the number of cross-sectional units. Indicating the presence of cross-sectional dependence.

Since the LM test can be oversized in large panels (N > T), Pesaran (2004, 2006) proposed a modified version, known as the Pesaran CD test, defined as:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho_{ij}}\right) \tag{5}$$

Here, $\widehat{\rho_{ij}}$ is the pairwise correlation coefficient of the residuals obtained from the baseline model for each cross-section *i*. In this expression, *T* represents the time dimension and *N* the cross-sectional dimension of the panel. Under the null hypothesis of cross-sectional independence, the *CD* statistic is asymptotically distributed as a standard normal, and significant *p*-values indicate the existence of cross-sectional dependence.

3.3.2. Panel cointegration test

After confirming the presence of unit roots through the second-generation CADF test, the existence of a long-run relationship among energy security, renewable energy, industrialization, and other variables was examined using the Westerlund (2007) panel cointegration test. The Westerlund (2007) panel cointegration test statistic is computed as:

$$W = \frac{1}{N}\sum_{i=1}^{N}\frac{\widehat{\delta_i}}{\widehat{\sigma_{\delta_i}}} \tag{6}$$

where $\widehat{\delta_i}$ is the estimated adjustment coefficient for each cross-sectional unit *i*, and $\widehat{\sigma_{\delta_i}}$ is its standard error. Test employs bootstrapped p-values to control for cross-sectional dependence and provides robust inference under both homogeneous and heterogeneous alternatives.

3.3.3. Slope heterogeneity tests

To assess whether the slope coefficients are homogeneous across countries, this study applies the second-generation slope heterogeneity tests proposed by Pesaran (2006) and Blomquist and Westerlund (2013). The rejection of slope homogeneity implies that the impact of explanatory variables such as renewable energy and industrialization on energy security differs across countries, which supports the use of heterogeneous estimators such as PCSE, FGLS, and FMOLS.

The test statistic is expressed as:

$$Delta = \sqrt{N}\,\frac{(\widetilde{S}-k)}{\sqrt{2k}} \tag{7}$$

and its adjusted version as:

$$Delta_{adj} = \sqrt{N}\,\frac{(\widetilde{S}-E(\widetilde{S}))}{\sqrt{Var(\widetilde{S})}} \tag{8}$$

where $\widetilde{S}$ denotes the Swamy test statistic, k is the number of regressors, and N is the number of cross-sectional units. The Blomquist and Westerlund (2013) test further extends this approach by improving small-sample properties and accounting for cross-sectional dependence. The null hypothesis is the same as in the Pesaran &Yamagata test, while the test statistic is based on the standardized differences between individual and pooled slope estimates.

3.4. Endogeneity and instrumental variable (IV–2SLS) strategy

A major methodological issue associated with estimating the effects of renewable energy on energy security is that the renewable energy variable is endogenous. This can lead to biased and inconsistent coefficients in fixed-effect estimates. Potential sources of bias include reverse causality, where countries with high energy security increase investment in renewables after they have increased investment; simultaneity bias, which occurs because geopolitical shocks affect both the timing of renewable energy and energy security; and omitted variable bias, which is when unobserved factors (for example technological capability, regulatory quality and/or long-term energy diversification policies) affect renewable energy and energy security. One of the concerns is whether renewable energy is endogenous, meaning that countries that have strong energy security also tend to invest in renewables. To overcome this challenge, the analysis uses a fixed-effect two-phase least squares (FE-2SLS) estimator and the first lag of renewable energy serves as the instrumental variable. The justification for this instrument is based on the persistence and path dependency of renewable energy development as well as on the fact that there is no contemporaneous effect on energy security after controlling for covariates and fixed effects. The methodology used is displayed in Fig. 5 below:

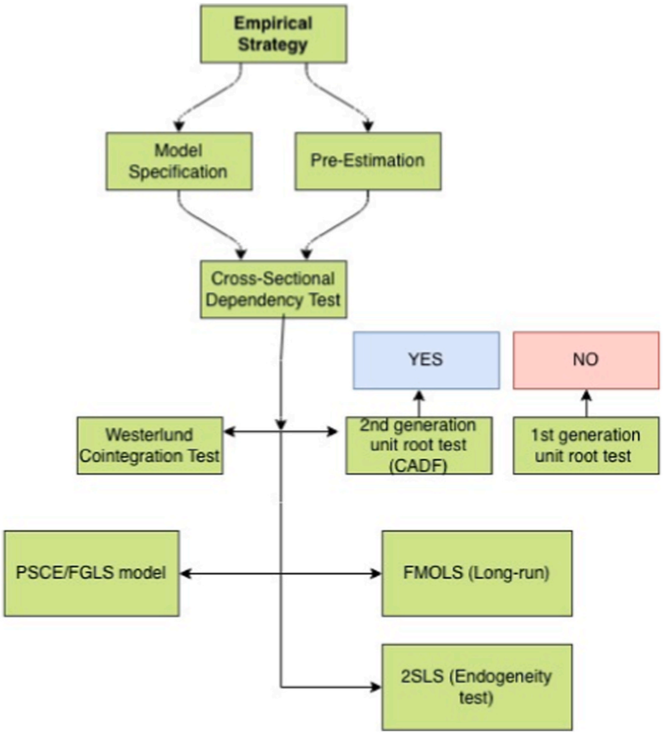

Fig. 5. Estimation strategy.

4. Discussion of results

4.1. Pre-estimation panel diagnostics

The results of the pre-estimation diagnostic tests reported in Table 4 support the dataset's suitability for a long-run econometric model. The results of the Pesaran (2004) Cross-Sectional Dependence (CSD) test indicate significant cross-sectional dependence among countries, which means there is evidence that shocks to the energy sector of one country could have an impact on the energy sector of other countries.

The results from the Pesaran (2007) CADF second-generation unit root test indicate that although all variables in their level form are non-stationary, after 1st differencing all variables become stationary. Thus, all variables are integrated of order I (1). However, the variable of urbanization was still found to be non-stationary even after differencing. Therefore, to make it stationary, the urbanization variable was transformed to an annual growth rate which reflects the percentage change in the urbanizations year to year. This transformation allowed urbanization to be made stationary and allowed the econometric model to satisfy the assumptions of time-series stability and avoid spurious regressions. Finally, using the Westerlund (2007) test of cointegration, the null hypothesis of no long-run relationship was rejected ($p = 0.0315$), thus implying that there exists a stable long-run relationship among renewable energy, energy security, industrialization, EIMP, annual growth rate of urbanization and fragility of institutions.

Table 4
Cross-sectional dependency, second-generation unit root, and Westerlund Cointegration Test.

Variable	Pesaran Cross-sectional Test	Pesaran CADF (Level)	Pesaran CADF (First Difference)
ES	2.06**	−2.357	−3.270***
RE	−1.26	−2.275	−3.129***
EIMP	1.44	0.900	−3.071***
IND	0.27	−0.014	−4.766***
URB	15.02***	−1.539	−2.668***
FSI	17.90***	−1.630	−2.337**
Westerlund Cointegration Test		Variance ratio −1.8588***	

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Author's calculation

4.2. Baseline model

Table 5 summarizes the results of baseline models calculated using the Panel-Corrected Standard Errors (PCSE) methodology, specifically the Default, AR, and PSAR(1) specifications. The findings highlight a strong degree of agreement across all three models regarding the directionality and statistical significance of the coefficients for all of the independent variables, thus reinforcing confidence in the robustness of

Table 5
PCSE **Models estimation results (ES-dependent variable).**

Variable	(1) PCSE Default	(2) PCSE AR	(3) PCSE PSAR(1)
RE	0.314*** (0.054)	0.135** (0.069)	0.095** (0.046)
EIMP	−0.020*** (0.005)	−0.022*** (0.007)	−0.023*** (0.004)
IND	0.433*** (0.072)	0.300*** (0.058)	0.157*** (0.041)
URB	−0.233*** (0.033)	−0.323*** (0.053)	−0.521*** (0.093)
FSI	−0.190*** (0.029)	−0.164*** (0.055)	−0.187*** (0.047)
Constant	64.65*** (4.61)	73.75*** (6.41)	91.87*** (6.38)
R^2	0.637	0.749	0.968
Wald χ^2	1127.97***	171.95***	217.86***
Observations	221	221	221

Robust standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Author's calculation

the estimated relationships among the variables and our general empirical approach to estimating these relationships.

There is a consistently positive and statistically significant effect from the degree of renewable energy (RE) utilization (0.095 to 0.314) in the PCSE models. Greater RE utilization within a country is associated with increased levels of energy security; this relationship is strongest within the default PCSE model and likely represents early security benefits experienced from increased penetration of renewable energy before autoregressive adjustments are made. These findings are consistent with current research literature demonstrating that diversification of RE sources materially contributes to improved national energy resilience through a reduction in vulnerability to geopolitical disruption and volatility (Apergis and Payne, 2010; Shahbaz et al., 2020). In the context of the global panel of countries studied, investments in renewable energy not only reduce the reliance on external, fossil fuel resources but also stabilize the domestic supply of energy from both volatility and price fluctuations. The coefficient for EIMP is consistently negative and statistically significant across all specifications (−0.020 to −0.023), indicating that an increased dependency on imported energy reduces the level of energy security for a country. These findings are consistent with existing literature that demonstrates that increased import dependence increases exposure to fluctuations in global prices and geopolitical risks, particularly in economies that are not otherwise diversified (Narayan and Smyth, 2009; Yilmazkuday, 2024). The continuing presence of these negative coefficients across all PCSE models reaffirms that externally-dependent energy sources remain structurally vulnerable, and that development of domestic RE systems should be prioritized as a pathway toward enhancing self-sufficiency. The findings indicate a strong positive and statistically significant relationship between industrialization (as measured by industry value added) and energy security across all three specifications, with coefficients of between 0.157 and 0.433. This implies that the development of additional industrial capacity, combined with improvements to the efficiency of industrial practice and technological modernization of industrial sectors, is associated with increased stability within that country's energy infrastructure. Industries have been associated with stimulating investment into energy infrastructure and to promoting innovation in energy-efficient technology, which in turn promote increased stability in energy supply systems (Omri and Kahouli, 2014; Zhang et al., 2025). The decline in coefficient magnitude across both the AR and PSAR(1) specifications implies that while the effect of industrialization on energy stability can be most pronounced in the short term, industrialization can tend to reach a level of stability once autoregressive effects are taken into account. The findings suggest that urbanization is negatively associated with energy security in all three PCSE model specifications (−0.233 to −0.521). This indicates that rapid urbanization creates short-term pressures on the existing energy systems within a country by causing a significant increase in the overall intensity of energy demand and therefore subsequently putting stress on the energy infrastructure. Supporting evidence has also been provided in the literature demonstrating that if the expansion of urbanization is not accompanied by a corresponding expansion of the energy infrastructure, rapid urbanization can create supply shortages and reduce the reliability of energy deliveries (Y. Yu et al., 2020). The much larger negative coefficients in the autoregressive models demonstrate that the effects of urbanization on the energy systems are realized gradually over time, as an urban area continues to expand and as urban demand for energy increases. The findings demonstrate a negative and statistically significant correlation between the FSI and ES, demonstrating that the level of institutional fragility, political instability, and weak governance frameworks impede the ability for a country to become energy stable. Government failures represent potential barriers to developing and investing in renewable energy, potentially delaying the completion of infrastructure projects and reducing the efficiency of the energy use in the host country (Charfeddine and Kahia, 2019; Nathaniel et al., 2021). The negative coefficients (−0.164 to −0.190) are evidence of the fact that in order for countries to achieve a sustainable energy transition and long-term energy security, robust institutions must exist to support this transition. The results of the PCSE analyses indicate a strong degree of explanatory power, with the R^2 statistic for the default model being 0.637 and increasing to 0.968 for the PSAR(1) model. The significant increase in explanatory power resulting from the autoregressive components suggests that energy security exhibits a degree of temporal persistence; that is, it is influenced by prior observations. Furthermore, the Wald F-statistic values are all very significant ($p < 0.01$), which indicates joint explanatory relevance of the variables. In total, these findings provide substantial support for the proposition that countries that invest in expanding renewable energy along with their degree of industrialization can possess enhanced energy security, while also indicating that dependence on EIMP, rapid urbanization, and institutional fragility can increase the risk of reduced energy security. These findings are consistent with the expectations of our theoretical framework, and provide further validation of the argument that countries can be better positioned to secure their energy future through investments in sustainable industrialization and development of renewable energy sources. Thus, the findings of the study support the argument that energy security is not solely a function of available resources, but also encompasses institutional fragility, consistency of policy, and the ability to manage structural shifts within the energy systems of countries.

4.3. *Robustness analysis*

Using the Feasible Generalized Least Squares (FGLS) methodology, we evaluate the stability of the PCSE baseline estimates. In order to mitigate any effect of possible heteroskedasticity, autocorrelation, and cross-sectional dependence, we also developed three alternative specifications: when assuming that the data consists of independent panels, allowing for AR (1) errors, and allowing for PSAR(1) errors. This permits the efficient use of more general assumptions about macro-panel data across diverse economic systems.

4.4. *Long-run estimation result*

The long-term FMOLS (Fully Modified Ordinary Least Squares) estimate results indicate that the selected independent variables exhibit an effect on Energy Security over time. The FMOLS estimates support the short-term evidence provided by the PCSE and FGLS techniques in identifying persistent, structural variables that affect Energy Security over time.

Long-run FMOLS results in Table 7 indicates that as renewable energy expands, it helps to create permanent improvements in energy security by bolstering the structural integrity of national energy systems. Depending on how energy is imported into a country, the dependence on imported energy decreases over time due to both diversification and substitution. Therefore, the negative impact of imported energy is mostly short-to medium-term (as shown by the lack of significance in the long run). The long run doesn't account for how countries have become

Table 6
FGLS Models Estimation Results (ES-dependent variable).

Variable	FGLS (Independent)	FGLS (AR1)	FGLS (PSAR1)
RE	0.314*** (0.0618)	0.135* (0.0700)	0.095 (0.0566)
EIMP	−0.020** (0.0069)	−0.022** (0.0075)	−0.023*** (0.0066)
IND	0.433*** (0.0901)	0.300*** (0.0822)	0.157** (0.0683)
URB	−0.233*** (0.0375)	−0.323*** (0.0525)	−0.521*** (0.0599)
FSI	−0.190*** (0.0617)	−0.164** (0.0780)	−0.187*** (0.0585)
Constant	64.65*** (7.47)	73.76*** (8.43)	91.87*** (6.55)
R^2	0.63	0.75	0.97
Wald χ^2	387.65	161.67	216.56
Log-likelihood	−711.57	–	–
Observations	221	221	221

Robust standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Author's calculationTable 6 indicates that the FGLS estimates fully corroborate the PCSE results in terms of sign, magnitude, and statistical significance. Renewable energy and industrialization remain positively associated with energy security, while energy imports, urbanization, and institutional fragility exert negative effects. The consistency across alternative variance and covariance structures confirms the robustness of the baseline findings.

Table 7
FMOLS Moldel result (ES-dependent variable).

Variable	Coefficient	Std. Error	t-Statistic	p-value
RE	0.407	0.139	2.93	0.004***
EIMP	−0.012	0.0159	−0.75	0.453
IND	0.620	0.204	3.04	0.003***
URB	−0.210	0.085	−2.47	0.015**
FSI	−0.249	0.139	−1.79	0.075*
Constant	61.18	16.88	3.62	0.000***
Observations	221			
Countries	13			

Robust standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Author's calculation

more resilient to external energy shocks through diversification and other forms of substitution. As with the short and long run, weak institutions will remain negatively associated with energy security. The lack of institutional capacity can continue to limit the positive impacts of improved energy security in the long run. In terms of the control variables, industrialization will have a positive relationship with energy security in the long run, whereas urbanization will continue to put downward pressure on energy security, creating continued demand for energy. The FMOLS findings support the need to consider both structural and institutional factors when examining long-term energy security trends and development.

4.5. *Endogeneity test results*

In order to test for endogeneity of renewable energy, the Fixed Effects Two-Stage Least Squares (FE-2SLS) estimator was utilized. This estimator used the first lag of renewable energy as an instrument for estimating the true effect of renewable energy on the ES Index. Table 8 provides a summary of the estimation results. The positive and statistically significant coefficient estimates for renewable energy remain the same when accounting for endogeneity. The Instrumental Variable (IV) estimate of 0.325 ($Z = 4.50$, $p < 0.001$) indicates that the increases in renewable energy lead to increases in Energy Security Index. The estimated amount is also similar to the estimates from the PCSE, FGLS and FMOLS test results and further supports the idea that renewable energy has a strong positive effect on energy security rather than being explained by reverse causation or omitted variable bias. The effect of Industrialization on energy security remains positive and statistically significant, suggesting that an economy that undergoes structural change through industrialization is more likely to have a reliable and resilient energy system. The estimated coefficient of urbanization changes from negative in the non-IV models to positive and statistically significant in the IV model. This sign change suggests the negative effect seen in the earlier models may have been related to the endogeneity of renewable energy. When correcting for endogeneity, the effect Urban Development has on improving energy infrastructure and increasing the capacity of the system becomes apparent. The effects of energy imports and institutional fragility on ES remain statistically insignificant while Institutionally Fragility is not significant in the IV estimates, indicating that their previously noted effects on energy security could be a result of correlation with the endogenous component of renewable energy. Instrument validity tests confirm that the identification strategy used was appropriate. The Kleibergen-Paap LM statistic $\chi 2 = 4.642$ ($p = 0.031$) rejects the null hypothesis of underidentification. Additionally, this statistic shows that there is a correlation between the lagging renewable energy variable and the current value of renewable energy. Weak instrument diagnostic tests indicate that there is strong relevance for the instrument used to estimate the effects of renewable energy: the Cragg-Donald F-statistic (535.07) and the Kleibergen-Paap Wald F-statistic (1007.66) are much higher than the Stock-Yogo Maximum Bias Critical Values at 10% (16.38). The Durbin-Wu-Hausman (DWH) endogeneity test result of $\chi 2 = 3.67$ ($p = 0.055$) indicates the presence of some endogeneity, but sufficient evidence is provided to support the use of an Instrumental Variable estimator instead of Fixed Effects in estimating the effects of renewable energy. Since only one instrument was used, the Hansen-J test was not applicable for this model. The IV results support the findings from the previously mentioned PCSE, FGLS and FMOLS estimators. These results confirm a causal effect of renewable energy on energy security rather than a correlation driven by reverse causality.

Table 8
FE–2SLS (IV) Estimation Results (ES-dependent variable).

Variable	FE–2SLS (IV)
RE (instrumented)	0.325*** (0.0722)
EIMP	−0.00454 (0.00510)
IND	0.156*** (0.0511)
URB	0.348** (0.1454)
FSI	0.0808 (0.0600)
Constant	—
Model Fit and Diagnostics	
R^2 (within)	0.147
Wald χ^2	9.10
Underidentification (Kleibergen–Paap LM)	4.642***
Weak-ID test (Cragg–Donald F)	535.07
Weak-ID test (KP Wald F)	1007.66
Endogeneity test (Durbin–Wu–Hausman χ^2)	3.67*
Observations	221
Countries	13

Robust standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Author's calculation

More emphasis is placed on the fixed effects of two-stage least squares results due to a potential problem of endogeneity with renewable energy. Reverse causation is one potential explanation of why this endogeneity exists, as it is possible that a country with stronger energy security systems would have more capacity to invest in renewables. Additionally, endogeneity could arise from omitted technologies and policies that affect both renewable energy and energy security. This issue is resolved by using the first lag of renewable energy consumption as an instrument. The validity of this instrument is supported by the path dependency exhibited in renewable energy development in which there are significant impacts from historical levels of renewable energy on current levels of renewables. The use of instrumental variables resulted in statistical findings that support a positive and substantially significant connection between renewable energy and energy security. The

Kleibergen-Paap LM test indicates that the renewable energy variable was properly identified as an underidentified instrument. Additionally, the Cragg-Donald and Kleibergen-Paap Wald F-statistics indicate that there are not concerns with weak identification of the renewable energy variable used in the analysis. In other words there is evidence to support the notion that the use of the IV procedures helps to mitigate potential issues with endogeneity. The Durbin-Wu-Hausman Test outcome indicates that using renewable energy as an IV was relevant to resolving endogeneity. Since the model runs were exactly identified the Hansen J-test was unnecessary. Evidence from the fixed effects two-stage least squares models are consistent with baseline results and are consistent with a causal interpretation given the validity of the instrumental variable technique used in the analysis.

4.6. Slope heterogeneity tests

Table 9 presents the results of the Pesaran and Yamagata, 2008 and Blomquist and Westerlund (2013) slope heterogeneity tests. Both tests reject the null hypothesis of slope homogeneity at the 1 percent significance level. The very high test statistics ($\Delta = 84.782$ and adj. $\Delta = 154.790$ for Pesaran–Yamagata; $\Delta = 13.294$ and adj. $\Delta = 10.854$ for Blomquist–Westerlund) with p-values of 0.000 indicate substantial parameter heterogeneity across countries.

The results provide evidence that the relationships between energy security and the factors that influence it (renewable energy use, industrialization, EIMP, urbanization, and institutional weakness) are substantially different among the countries in the sample. As such, the influence of increased use of renewable energy or greater levels of industrialization on energy security cannot be generalized across all the nations but can be impacted by the economic, political, and geopolitical structures, as well as specific country experiences, within the country providing that influence. The determination to reject the severity of slope homogeneity has major implications on the selection of models used in this analysis. In addition, the use of FMOLS is justified for the determination of long run relationships. The strong evidence of heterogeneity identified in this research fits intuitively with the overall structure of the panel that it is utilizing for this analysis.

5. Discussion and conclusion

5.1. Discussion

The study's empirical data shows that there is strong support for the theory that increased investment in renewable energy is critical to creating energy security and therefore increasing macroeconomic stability in those countries at significant geopolitical risk. It is shown that there is a commonality in the results of the various methodologies used (PCSE, FGLS, FMOLS): that both renewable energy and industrialization lead to increased energy security, while energy dependence on imports, urbanization, and institutional fragility decrease it. All estimates of renewable energy gave positive, statistically significant coefficients and support the conclusion that a larger renewable energy supply reduces the intensity of external shocks and market volatility from fossil fuel sources. This finding indicates that renewable energy is an important strategic asset, as well as an environmental tool. For the majority of the developing nations analysed many of which are energy importers dependent on energy for their economies, and therefore at significant geopolitical risk expanding the energy mix from importing fuels to producing renewables can have both a positive economic effect and a positive national security consequence. Industrialization is additionally proven to be an important structural factor influencing the stability of energy supplies. The positive and substantial effect of industrial value added on energy security indicates that productive transformation with the introduction of technology enhances energy efficiency, investment in infrastructure and innovation. The FMOLS estimates confirm that industrial development supports renewable energy integration on a much larger scale, and thus indicate an interrelatedness of industrialization and energy security as it relates to development. The dependence of energy on imports can always have a negative impact on energy security, particularly over the near-term. This relates to the ongoing vulnerability of many countries in the sample to disturbances resulting from energy price fluctuations and geopolitical disruptions. The FSI is consistently and significantly negatively correlated with energy security, indicating that governance and institutional credibility are major factors in determining how renewable energy investments can be transformed into sustainable energy security. Weak institutions limit the design and implementation of comprehensive energy strategies, create barriers to private investment, and create inefficiencies.

Table 9
Slope homogeneity test.

Pesaran (2006) Slope heterogeneity test	
Delta	P-Value
84.782	0.000
adj. 154.790	0.000
Blomquist and Westerlund (2013) Slope heterogeneity test	
Delta	P-Value
13.294	0.000
adj. 10.854	0.000

Source: Author's calculation

The positive coefficient of renewable energy should be viewed in light of the many dimensions of the Energy Security Index. In fragile, geopolitically exposed economies, renewable energy is likely to strengthen energy security primarily through diversification and availability, by providing additional domestic supply options to reduce dependence on imported fossil fuels and to reduce exposure to disruptions in external supply. The affordability channel is also of significance, but it can likely function over a longer time frame. In the short term, expansion of renewable energy may require investment in grid modernization, storage and capacity to regulate, while in the long run it can lower exposure to international fuel price fluctuations and enhance price stability. Thus, the results indicate that renewable energy enhances energy security through improved diversification and resilience, while the benefits of affordability depend on the degree to which the renewable energy system and its supportive infrastructure have matured.

This finding indicates that without governance structures or institutional capabilities, a country, regardless of whether it is a resource-based economy or has the capacity to invest in renewable energy resources, remains vulnerable to disruption. The results of heterogeneity tests indicate that the magnitude and direction of the mechanisms influencing the relationship between energy security and variables of interest varied greatly across the analysed countries, again indicating that there is no one-size-fits-all policy approach to this issue.

As observed in Fig. 6, different regional clusters show differing levels of renewable energy use compared to overall Energy Security. One can draw the following conclusions about what one sees in each region: There is a clear asymmetry, where the regions of Eastern Europe, the Western Balkans and the Middle East can see a similar positive relationship between expansion of renewables and improvements in energy security as suggested by the positive findings in the Baseline Model and Long Run Model; on the other hand, other regions, such as South Caucasus and North Africa have a weaker or negative association because of structural factors, import dependence, or institutional barriers. In this sense, the econometric results are supported by these visual representations. Further, the relationship between enhancing ES through RE use is highly dependent on multiple factors such as current and future geopolitical and Institutional conditions. In particular, countries with good renewable resources and a well-established industrial base such as Azerbaijan and Algeria do benefit from using renewable energy to

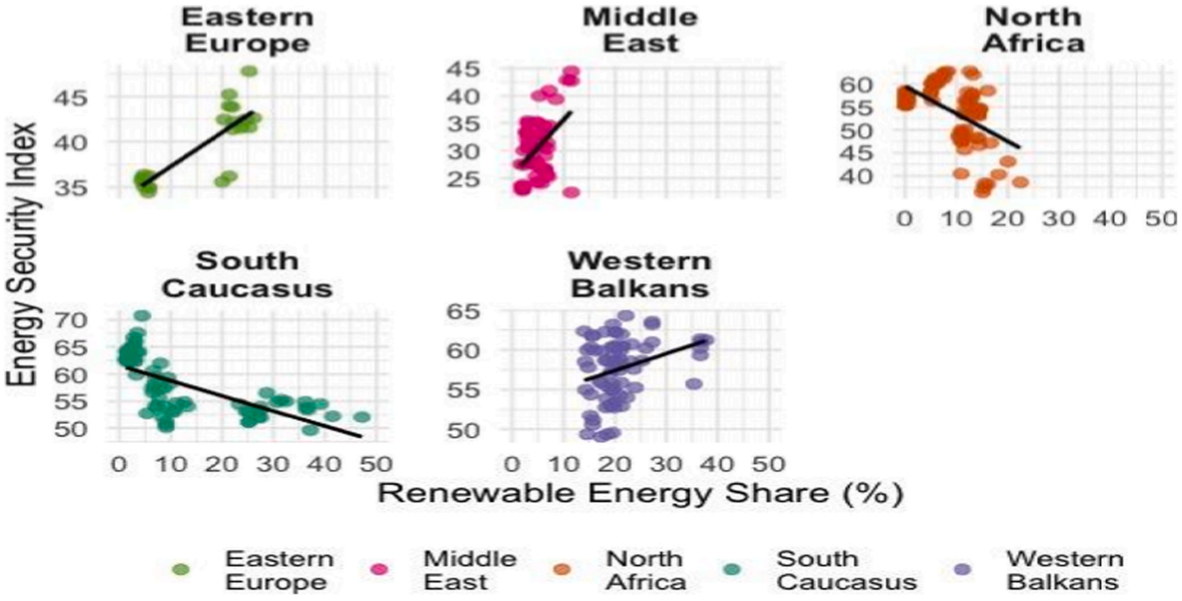

Fig. 6. Divergent Regional Patterns Between Renewable Energy Penetration and Energy Security
Source: Author's calculation.

achieve energy security while countries with poor industrial infrastructure such as Lebanon or Moldova cannot benefit from the use of renewable sources. For this reason, each country can need to tailor their national energy strategy to take these different energy scenarios into account by aligning their strategy.

5.2. Policy implications

The empirical findings of this study offer several critical policy directions for the 13 economically vulnerable countries under analysis. Given their susceptibility to geopolitical shocks and structural dependencies, the following strategies are recommended:

First, the positive statistically significant coefficient for renewable energy indicates that renewables should be viewed as a security strategy. They are not simply environmental policies. Fragile, and geopolitically vulnerable, economies should consider renewable projects that can directly decrease their reliance on fossil fuels imported for energy sources (electricity and municipal) as a best practice.

Secondly, the negative coefficient for energy imports indicates that an economy that relies on imported energy diminishes its energy security. Therefore, countries in the sample with a high dependence on imports for energy should use development of renewable resources as an opportunity to implement import substitution through solar, wind, hydro, and other decentralized options. Secure private investors should be attracted through the use of competitive bids, power purchase contracts, and transparent rules for access to an electrical grid.

Thirdly, the positive coefficient for industrialization implies that energy security also improves with a stronger productive capacity and associated energy infrastructure. Therefore, the development of renewable resources should be associated with that of green industrialization by developing local capacity for installation, maintenance, operation, and energy-efficient services.

Fourthly, the negative coefficient for urbanization indicates that growing urbanization can diminish energy security if not supported by adequate infrastructure built to meet the demand generated by such growth. Governments should integrate their energy policies with urban planning through the use of energy-efficient buildings, smart meters, decentralized systems for solar, and municipal renewables.

Finally, while this study establishes a robust foundational link between institutional fragility, renewable energy transition, and energy security, it opens several compelling avenues for future research. Future scholarly efforts could employ non-linear panel threshold frameworks to isolate the precise inflection points at which institutional degradation begins to completely neutralize the benefits of green investments. Additionally, integrating predictive machine learning models could offer real-time forecasting tools for policy-makers to anticipate energy supply chain disruptions caused by sudden geopolitical shocks. Lastly, shifting the analytical lens from macro-level panel matrices to micro-level household surveys would provide highly nuanced insights into how national energy insecurity translates into localized energy poverty within these geopolitically vulnerable contexts.

The negative coefficient for institutional fragility indicates that weak institutions diminish energy security performance. Therefore, fragile countries should focus their attention on institutional de-risking through transparent procurement of renewable energy, independent regulatory authority for energy, stable rules for tariffs, and clearly defined procedures for connecting to the grid.

5.3. Conclusion

This study investigated the determinants of energy security within a panel of 13 economically vulnerable countries from 2000 to 2023. By employing advanced panel econometric techniques, we analysed the interplay between renewable energy, urbanization, import dependency, and institutional fragility. under conditions of geopolitical vulnerability.

The results confirm that while renewable energy consumption is a robust driver of energy security, its effectiveness is significantly moderated by the structural and institutional weaknesses prevalent in these nations. Urbanization and energy import dependency were found to be the primary drivers of energy insecurity, exacerbating the impact of external geopolitical shocks. Furthermore, the study highlights that without a stable institutional framework, the transition to green energy remains insufficient to ensure comprehensive energy resilience.

Despite its contributions, this study has limitations. The analysis is limited to a specific group of vulnerable countries, and the data availability for certain institutional metrics was constrained. Future research could expand this scope by conducting a comparative analysis between these vulnerable economies and highly stable OECD nations. Additionally, investigating the role of specific digital infrastructures in enhancing energy efficiency could provide deeper insights into the technological dimensions of energy security in the 21st century.

The research demonstrates the importance of renewable energy on ES and economic stability in politically-vulnerable countries. The impact of renewable energy can also provide non-environmental benefits, such as reducing reliance, increasing economic growth, and increasing resilience. The viability of the aforementioned statements is very much reliant upon good institutional governance and industrial modernization. Without good governance and good coordination of efforts, the possibility of achieving the benefits of RE can continue to be limited and unfruitful. The findings from this research illustrate the need to advance both aspects (rapid deployment of RE) at the same time, with appropriate industrial modernization and institutional reform providing for security and economic viability in the long term. One area in which the research was limited was the use of index-based measures, as they are not sufficient in covering short-term disruptions and/or informal energy markets. Future research could include micro-based data or other indicators of energy-resilience for a more in-depth analysis of potential system vulnerability.

Consequently, our empirical finding that energy import dependency drives insecurity carries severe macroeconomic stemming. For these 13 economically vulnerable nations, shifting toward localized renewable energy platforms is not merely an environmental target but a vital fiscal imperative to conserve scarce foreign exchange reserves, reduce vulnerability to imported inflation, and alleviate chronic balance-of-payments pressures.

This highlights a critical institutional risk premium. In highly fragile environments, structural deficiencies and political instability elevate sovereign risk profiles and inflate the cost of capital. Therefore, lowering institutional fragility is an economic prerequisite; it acts as a catalyst to unlock private financing and attract foreign direct investment (FDI) necessary for high-capital energy transition projects.

CRediT authorship contribution statement

Azer Dilanchiev: Conceptualization, Investigation, Methodology, Resources, Writing – original draft. **Ibrahim Cutcu:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2026.115470.

Data availability

Data will be made available on request.

References

Ainou, F.Z., Ali, M., Sadiq, M., 2023. Green energy security assessment in Morocco: green finance as a step toward sustainable energy transition. Environ. Sci. Pollut. Res. Int. 30 (22), 61411–61429. https://doi.org/10.1007/s11356-022-19153-7.

Aizenman, J., Lindahl, R., Stenvall, D., Uddin, G.S., 2024. Geopolitical shocks and commodity market dynamics: new evidence from the Russia-Ukraine conflict. Eur. J. Polit. Econ. 85 (C). https://ideas.repec.org//a/eee/poleco/v85y2024ics0176268024000764.html.

Akhundzadah, N.A., Kassam, K.-A., 2025. Water sovereignty as a pathway to food and energy security in Afghanistan. Discover Sustainability 6 (1), 628. https://doi.org/10.1007/s43621-025-01535-9.

Albanese, Francesco, 2025. Navigating trade-offs: Energy dependency, geopolitical shocks, and sustainability in European parliamentary debates. Energy Res. Soc. Sci. 127, 104198. https://doi.org/10.1016/j.erss.2025.104198, 104198. https://linkinghub.elsevier.com/retrieve/pii/S2214629625002798.

Alpha, M.A., Yiadom, E.B., Ahenkan, A., 2025. A comprehensive assessment of Ghana's energy security dimensions and environmental sustainability in a multi-indices analysis. Sci. Rep. 15 (1), 43745. https://doi.org/10.1038/s41598-025-05407-0.

Amanfo, S.E., Puthenkalam, J.J., Amanfo, S.E., Puthenkalam, J.J., 2024. Perspective chapter: the regime matters – a multidisciplinary perspective on energy security in the era of climate change and growing uncertainties for resilience in sustainable energy development. In: Power Quality and Harmonics Management in Modern Power Systems. IntechOpen. https://doi.org/10.5772/intechopen.1003092.

Amin, N., Shabbir, M.S., Song, H., Abbass, K., 2024. Renewable energy consumption and its impact on environmental quality: a pathway for achieving sustainable development goals in ASEAN countries. Energy Environ. 35 (2), 644–662. https://doi.org/10.1177/0958305X221134113.

Amponsah, N.Y., Troldborg, M., Kington, B., Aalders, I., Hough, R.L., 2014. Greenhouse gas emissions from renewable energy sources: a review of lifecycle considerations. Renew. Sustain. Energy Rev. 39, 461–475. https://doi.org/10.1016/j.rser.2014.07.087.

Apergis, N., Payne, J.E., 2010. The emissions, energy consumption, and growth nexus: evidence from the commonwealth of independent states. Energy Policy 38 (1), 650–655.

Attanayake, K., Wickramage, I., Samarasinghe, U., Ranmini, Y., Ehalapitiya, S., Jayathilaka, R., Yapa, S., 2024. Renewable energy as a solution to climate change: insights from a comprehensive study across nations. PLoS One 19 (6), e0299807. https://doi.org/10.1371/journal.pone.0299807.

Azimi, M.N., Rahman, M.M., Maraseni, T., 2025. Powering progress: the interplay of energy security and institutional quality in driving economic growth. Appl. Energy 378, 124835. https://doi.org/10.1016/j.apenergy.2024.124835.

Baltagi, B.H., Pirotte, A., 2010. Panel data inference under spatial dependence. Econ. Modell. 27 (6), 1368–1381. https://doi.org/10.1016/j.econmod.2010.07.004.

Behera, M.K., Paul, A., Sahoo, D., 2025. The moderating role of renewable energy in the energy insecurity-economic growth nexus in the net oil-importing countries of G20. Energy RESEARCH LETTERS 7. https://doi.org/10.46557/001c.132424 (Early View).

Bigerna, S., D'Errico, M.C., Polinori, P., 2021. Energy security and RES penetration in a growing decarbonized economy in the era of the 4th industrial revolution. Technol. Forecast. Soc. Change 166, 120648. https://doi.org/10.1016/j.techfore.2021.120648.

Bigerna, S., D'Errico, M.C., Polinori, P., Simshauser, P., 2024. Net-zero policy vs energy security: the impact on GCC countries. Energy J. 45* (1_Suppl. l), 133–164. https://doi.org/10.5547/01956574.45.SI1.sbig.

Blomquist, J., Westerlund, J., 2013. Testing slope homogeneity in large panels with serial correlation. Econ. Lett. 121 (3), 374–378. https://doi.org/10.1016/j.econlet.2013.09.012.

Brand, B., Zingerle, J., 2011. The renewable energy targets of the Maghreb countries: impact on electricity supply and conventional power markets. Energy Policy 39 (8), 4411–4419. https://doi.org/10.1016/j.enpol.2010.10.010.

Breusch, T.S., Pagan, A.R., 1980. The lagrange multiplier test and its applications to model specification in econometrics. Rev. Econ. Stud. 47 (1), 239. https://doi.org/10.2307/2297111.

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

Cappelli, F., Carnazza, G., 2025. Close ties: How trade dynamics and environmental regulations shape international dependence on oil. https://doi.org/10.13140/RG.2.2.25081.99688.

Carmon, O., Teschner, N., Zemah-Shamir, S., Parag, Y., 2025. Evaluating energy security in decentralized systems: review and new index. Energy Strategy Rev. 60, 101754. https://doi.org/10.1016/j.esr.2025.101754.

Cergibozan, R., 2022. Renewable energy sources as a solution for energy security risk: empirical evidence from OECD countries. Renew. Energy 183, 617–626. https://doi.org/10.1016/j.renene.2021.11.056.

Charfeddine, L., Kahia, M., 2019. Impact of renewable energy consumption and financial development on CO2 emissions and economic growth in the MENA region: a panel vector autoregressive (PVAR) analysis. Renew. Energy 139 (C), 198–213.

Chen, Y., Chen, Y., Zhang, L., Li, Z., 2023. Revealing the role of renewable energy consumption and digitalization in energy-related greenhouse gas emissions—Evidence from the G7. Front. Energy Res. 11. https://doi.org/10.3389/fenrg.2023.1197030.

Cherp, A., Jewell, J., 2011. The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration. Curr. Opin. Environ. Sustain. 3 (4), 202–212. https://doi.org/10.1016/j.cosust.2011.07.001.

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.

Chu, L.K., 2023. The role of energy security and economic complexity in renewable energy development: evidence from G7 countries. Environ. Sci. Pollut. Control Ser. 30 (19), 56073–56093. https://doi.org/10.1007/s11356-023-26208-w.

Chudik, A., Pesaran, M.H., 2013. *Large Panel data models with Cross-Sectional Dependence: a Survey* (SSRN scholarly paper no. 2316333). Soc. Sci. Res. Netw. https://doi.org/10.2139/ssrn.2316333.

Dagar, V., Dagher, L., Rao, A., Doytch, N., Kagzi, M., 2024. Economic policy uncertainty: global energy security with diversification. Econ. Anal. Pol. 82 (C), 248–263.

Dao, T., Awijen, H., Ahmed, R., Ameur, H.B., 2025. Understanding energy security in geopolitical contexts: insights from decomposing energy diversification indexes. Energy Econ. 152, 108947. https://doi.org/10.1016/j.eneco.2025.108947.

Deng, Y., Jiang, H.-D., 2025. Are geopolitical risks reshaping the global energy trade networks? A global perspective. Energy Econ. 149, 108717. https://doi.org/10.1016/j.eneco.2025.108717.

Farooq, F., Leong, C. W., Faheem, M., Chebab, D., & Nousheen, A. (n.d.). Non-Renewable Energy, Green Technological Innovation, and CO_2 Emissions in South Asia.

Fernandez, M.I., Go, Y.I., Wong, D.M.L., Früh, W.-G., 2024. Review of challenges and key enablers in energy systems towards net zero target: renewables, storage, buildings, & grid technologies. Heliyon 10 (23), e40691. https://doi.org/10.1016/j.heliyon.2024.e40691.

Fouladvand, J., Sarı, Y., Ghorbani, A., 2024. Infrastructure and governance: prioritising energy security dimensions for community energy systems. Energy Res. Social Sci. 116, 103676. https://doi.org/10.1016/j.erss.2024.103676.

Galimova, T., Chou, C., Keiner, D., Breyer, C., 2025. Geopolitical risk index for guiding international sustainable energy trade. Smart Energy 19, 100200. https://doi.org/10.1016/j.segy.2025.100200.

Goodell, J.W., Gurdgiev, C., Paltrinieri, A., Piserà, S., 2023. Global energy supply risk: evidence from the reactions of European natural gas futures to Nord Stream announcements. Energy Econ. 125 (C). https://ideas.repec.org//a/eee/eneeco/v125y2023ics0140988323003365.html.

Hasan, M., Eiti, H.T., Hossain, Md S., Amin, M.B., Rahaman, Md A., Oláh, J., 2026. Evaluating the role of renewable energy and government consumption in reducing CO2 emissions: a dynamic panel data analysis. Sustainable Horizons 17, 100164. https://doi.org/10.1016/j.horiz.2025.100164.

He, Z.-W., Lee, C.-C., Sharma, S.S., 2025. The impact of geopolitical risks on the renewable energy transition. Energy Econ. 143, 108278. https://doi.org/10.1016/j.eneco.2025.108278.

Hoang, D.P., Chu, L.K., To, T.T., Le, H.T., 2025. The interaction of energy diversification policy and geopolitical uncertainty in sustaining the environment: international evidence. Energy Policy 200, 114560. https://doi.org/10.1016/j.enpol.2025.114560.

Hodula, M., Janku, J., Malovana, S., Ngo, N.A., 2024. Geopolitical risks and their impact on global macro-financial stability: literature and measurements. Working Papers. Article 2024/8. https://ideas.repec.org//p/cnb/wpaper/2024-8.html.

Ibekwe, Kenneth Ifeanyi, Etukudoh, Emmanuel Augustine, Nwokediegwu, Zamathula Queen Sikhakhane, Umoh, Aniekan Akpan, Adefemi, Adedayo, Ilojianya, Valentine Ikenna, 2024. Energy security IN the global context: a comprehensive review of geopolitical dynamics and policies. Engineering Science & Technology Journal 5 (1), 152–168. https://doi.org/10.51594/estj.v5i1.741.

IEA, 2023. The International Energy Agency. The IEA World Energy Outlook. https://doi.org/10.4337/eecj.2023.03.05.

IRENA, 2025. Renewable Energy in Climate Change Adaptation: Metrics and Risk Assessment Framework. https://www.irena.org/Publications/2025/Apr/Renewable-energy-in-climate-change-adaptation.

Ito, K., 2017. CO2 emissions, renewable and non-renewable energy consumption, and economic growth: evidence from panel data for developing countries. Int. Econ. 151, 1–6.

Ivanovski, K., Marinucci, N., 2021. Policy uncertainty and renewable energy: exploring the implications for global energy transitions, energy security, and environmental risk management. Energy Res. Social Sci. 82. https://doi.org/10.1016/j.erss.2021.102415.

Iyke, B., 2023. Climate change, energy security risk, and clean energy investment. Energy Econ. 129, 107225. https://doi.org/10.1016/j.eneco.2023.107225.

Khalid, M., 2024. Smart grids and renewable energy systems: perspectives and grid integration challenges. Energy Strategy Rev. 51, 101299. https://doi.org/10.1016/j.esr.2024.101299.

Khan, K., Khurshid, A., Cifuentes-Faura, J., Xianjun, D., 2024. Does renewable energy development enhance energy security? Util. Policy 87, 101725. https://doi.org/10.1016/j.jup.2024.101725.

Khurshid, N., Egbe, C.E., Akram, N., 2024. Integrating non-renewable energy consumption, geopolitical risks, economic development with the ecological intensity of wellbeing: evidence from quantile regression analysis. Front. Energy Res. 12. https://doi.org/10.3389/fenrg.2024.1391953.

Kim, J., Jaumotte, F., Panton, A.J., Schwerhoff, G., 2025. Energy security and the green transition. Energy Policy 198, 114409. https://doi.org/10.1016/j.enpol.2024.114409.

Kruyt, B., Van Vuuren, D.P., De Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy 37 (6), 2166–2181. https://doi.org/10.1016/j.enpol.2009.02.006.

LaBelle, M.C., 2024. Breaking the era of energy interdependence in Europe: a multidimensional reframing of energy security, sovereignty, and solidarity. Energy Strategy Rev. 52, 101314. https://doi.org/10.1016/j.esr.2024.101314.

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 (C). https://ideas.repec.org//a/eee/eneeco/v129y2024ics0140988323007430.html.

Li, R., Wang, Q., Li, L., 2023. Does renewable energy reduce per capita carbon emissions and per capita ecological footprint? New evidence from 130 countries. Energy Strategy Rev. 49, 101121. https://doi.org/10.1016/j.esr.2023.101121.

Liu, X., Niu, Q., Dong, S., Zhong, S., 2023. How does renewable energy consumption affect carbon emission intensity? temporal-Spatial impact analysis in China. Energy 284, 128690. https://doi.org/10.1016/j.energy.2023.128690.

Liu, Z., Wang, Y., Yuan, X., Ding, Z., Ji, Q., 2025. Geopolitical risk and vulnerability of energy markets. Energy Econ. 141, 108055. https://doi.org/10.1016/j.eneco.2024.108055.

Ma, X., He, Q., Zhang, L., Wu, W., Li, W., 2025. Forecasting fossil fuel consumption and greenhouse gas emissions using novel multi-variable grey system model with convolution integrals. Energy 326, 135981. https://doi.org/10.1016/j.energy.2025.135981.

Mara, D., Nate, S., Stavytskyy, A., Kharlamova, G., 2022. The place of energy security in the national security framework: an assessment approach. Energies 15 (2), 658. https://doi.org/10.3390/en15020658.

Moghani, A.M., Loni, R., 2025. Review on energy governance and demand security in oil-rich countries. Energy Strategy Rev. 57, 101625. https://doi.org/10.1016/j.esr.2024.101625.

Mohr, L.-M., 2025. The energy community. In: Estermann, A., Schrade, M., Anderson, L. (Eds.), European Electricity Market Coupling. Springer, Nature Switzerland, pp. 279–301. https://doi.org/10.1007/978-3-031-86315-8_13.

Narayan, P.K., Smyth, R., 2009. Multivariate granger causality between electricity consumption, exports and GDP: evidence from a panel of Middle Eastern countries. Energy Policy 37 (1), 229–236.

Nathaniel, S.P., Yalçiner, K., Bekun, F.V., 2021. Assessing the environmental sustainability corridor: linking natural resources, renewable energy, human capital, and ecological footprint in BRICS. Resour. Policy 70, 101924. https://doi.org/10.1016/j.resourpol.2020.101924.

Nibedita, B., Irfan, M., 2024. Energy mix diversification in emerging economies: an econometric analysis of determinants. Renew. Sustain. Energy Rev. 189, 114043. https://doi.org/10.1016/j.rser.2023.114043.

OECD, 2024. A Comprehensive Overview of the Renewable Energy Industrial Ecosystem. OECD. https://www.oecd.org/en/publications/a-comprehensive-overview-of-the-renewable-energy-industrial-ecosystem_94dce592-en.html.

Olasehinde-Williams, G., Akadiri, S.S., 2025. Is there a connection between the Sino-US tensions and global energy market uncertainty? Statistical evidence from the GETS-VAR. Energy RESEARCH LETTERS 7. https://doi.org/10.46557/001c.146293 (Early View).

Omri, A., Kahouli, B., 2014. Causal relationships between energy consumption, foreign direct investment and economic growth: fresh evidence from dynamic simultaneous-equations models. Energy Policy 67, 913–922. https://doi.org/10.1016/j.enpol.2013.11.067.

Paravantis, J.A., 2019. Dimensions, components and metrics of energy security: review and synthesis. SPOUDAI Journal of Economics and Business 69, 38–52. https://www.semanticscholar.org/paper/Dimensions%2C-Components-and-Metrics-of-Energy-Review-Paravantis/be4e7427389a00f43180f25c2c03eecbd88e390c.

Pedroni, P., 2000. Fully modified OLS for heterogeneous cointegrated panels. Adv. Econom. 15, 93–130. https://doi.org/10.1016/S0731-9053(00)15004-2. Emerald (MCB UP).

Pesaran, M.H., 2004. General diagnostic tests for cross section dependence in panels. *Available at: SSRN 572504* https://papers.ssrn.com/sol3/papers.cfm?abstract_id=572504.

Pesaran, M.H., 2006. Estimation and inference in large heterogeneous panels with a multifactor error structure. Econometrica 74 (4), 967–1012. https://doi.org/10.1111/j.1468-0262.2006.00692.x.

Pesaran, M.H., 2007. A simple panel unit root test in the presence of cross-section dependence. J. Appl. Econom. 22 (2), 265–312. https://doi.org/10.1002/jae.951.

Hashem Pesaran, M., Yamagata, T., 2008. Testing slope homogeneity in large panels. J. Econom. 142 (1), 50–93. https://doi.org/10.1016/j.jeconom.2007.05.010.

Phillips, P.C.B., Hansen, B.E., 1990. Statistical inference in instrumental variables regression with I(1) processes. Rev. Econ. Stud. 57 (1), 99. https://doi.org/10.2307/2297545.

Šprajc, P., Bjegović, M., Vasić, B., 2019. Energy security in decision making and governance—Methodological analysis of energy trilemma index. Renew. Sustain. Energy Rev. 114, 109341. https://doi.org/10.1016/j.rser.2019.109341.

Qian, Yu, Xu, Zeshui, Qin, Yong, Gou, Xunjie, 2025. A critical review on the multidimensional complexity of sustainable energy development. Appl. Energy 394, 126194. https://doi.org/10.1016/j.apenergy.2025.126194, 126194. https://linkinghub.elsevier.com/retrieve/pii/S0306261925009249.

Ren, X., Yang, W., Jin, Y., 2024. Geopolitical risk and renewable energy consumption: evidence from a spatial convergence perspective. Energy Econ. 131, 107384. https://doi.org/10.1016/j.eneco.2024.107384.

Samusevych, Y., Vysochyna, A., Vasylieva, T., Lyeonov, S., Pokhylko, S., 2021. Environmental, energy and economic security: assessment and interaction. E3S Web of Conferences 234, 00012. https://doi.org/10.1051/e3sconf/202123400012.

Sarafidis, V., Wansbeek, T., 2012. Cross-Sectional dependence in Panel data analysis. Econom. Rev. 31 (5), 483–531.

Schmitz, R., Flachsbarth, F., Plaga, L.S., Braun, M., Härtel, P., 2025. Energy security and resilience: revisiting concepts and advancing planning perspectives for transforming integrated energy systems. Energy Policy 207, 114796. https://doi.org/10.1016/j.enpol.2025.114796.

Shah, W.U.H., Hao, G., Yan, H., Zhu, N., Yasmeen, R., Dincă, G., 2024. Role of renewable, non-renewable energy consumption and carbon emission in energy efficiency and productivity change: evidence from G20 economies. Geosci. Front. 15 (4), 101631. https://doi.org/10.1016/j.gsf.2023.101631.

Shahbaz, M., Raghutla, C., Chittedi, K.R., Jiao, Z., Vo, X.V., 2020. The effect of renewable energy consumption on economic growth: evidence from the renewable energy country attractive index. Energy 207, 118162. https://doi.org/10.1016/j.energy.2020.118162.

Sharma, P., 2023. Analyzing the role of renewables in energy security by deploying renewable energy security index. Journal of Sustainable Development of Energy, Water and Environment Systems] 11 (4), 1–21.

Siksnelyte-Butkiene, I., Streimikiene, D., Karpavicius, T., Balezentis, T., 2025. Societal challenges to ensure energy security: a systematic critical review of the concept, indicators, and low-carbon transition policies. Energy Res. Social Sci. 127, 104219. https://doi.org/10.1016/j.erss.2025.104219.

Sohaib, M., Majeed, A., Liu, J., Oláh, J., 2025. The role of renewable energy in mitigating carbon emissions: insights from China's energy consumption patterns. Energy Strategy Rev. 61, 101860. https://doi.org/10.1016/j.esr.2025.101860.

Sotnyk, I., Kurbatova, T., Kubatko, O., Prokopenko, O., Prause, G., Kovalenko, Y., Trypolska, G., Pysmenna, U., 2021. Energy security assessment of emerging economies under global and local challenges. Energies 14 (18), 5860. https://doi.org/10.3390/en14185860.

Sovacool, B.K., Mukherjee, I., 2011. Conceptualizing and measuring energy security: a synthesized approach. Energy 36 (8), 5343–5355. https://doi.org/10.1016/j.energy.2011.06.043.

Srinivasan, A., Gabrielli, P., Sansavini, G., 2025. Trade-offs of affordability, sustainability and security in the optimal design of multi-energy systems. Appl. Energy 383, 125299. https://doi.org/10.1016/j.apenergy.2025.125299.

Strojny, J., Krakowiak-Bal, A., Knaga, J., Kacorzyk, P., 2023. Energy security: a conceptual overview. Energies 16 (13), 5042. https://doi.org/10.3390/en16135042.

Tansel Tugcu, C., Menegaki, A.N., 2024. The impact of renewable energy generation on energy security: evidence from the G7 countries. Gondwana Res. 125, 253–265. https://doi.org/10.1016/j.gr.2023.08.018.

Turedi, S., Turedi, N., 2021. The effects of renewable and non-renewable energy consumption and economic growth on CO2 emissions: empirical evidence from developing countries. Bus. Econ. Res. J. 12 (4), 751–765.

Vasylieva, T., Derkacz, A., Popp, J., Horsch, A., 2025. From energy dependency to energy security: how the war in Ukraine accelerated renewable deployment in Europe. Economics & Sociology 18 (3), 229–253. https://doi.org/10.14254/2071-789X.2025/18-3/13.

Wang, Q., Ren, F., Li, R., 2024. Geopolitics and energy security: a comprehensive exploration of evolution, collaborations, and future directions. Hum. Soc. Sci. Commun. 11 (1), 1071. https://doi.org/10.1057/s41599-024-03507-2.

Wejnert-Depue, C., Zhang, Y., Casper, K., O'Neill, B.C., Waldhoff, S.T., 2025. A conceptual framework for residential energy security in the context of clean energy transitions. Energy Res. Social Sci. 126, 104096. https://doi.org/10.1016/j.erss.2025.104096.

Wen, Z., 2024. Impact of Political Changes in Middle Eastern Energy on Global Energy Security, pp. 454–461. https://doi.org/10.2991/978-2-38476-277-4_51.

Westerlund, J., 2007. Testing for error correction in Panel data. Oxf. Bull. Econ. Stat. 69 (6), 709–748. https://doi.org/10.1111/j.1468-0084.2007.00477.x.

World energy council, 2022. (n.d.). Retrieved December 19, 2025, from https://trilemma.worldenergy.org/.

Yadav, A., Mahalik, M.K., 2024. Does renewable energy development reduce energy import dependency in emerging economies? Evidence from CS-ARDL and panel causality approach. Energy Econ. 131, 107356. https://doi.org/10.1016/j.eneco.2024.107356.

Yilmazkuday, H., 2024. Geopolitical risks and energy uncertainty: implications for global and domestic energy prices. Energy Econ. 140, 107985. https://doi.org/10.1016/j.eneco.2024.107985.

Yu, Y., Zhang, N., Kim, J.D., 2020. Impact of urbanization on energy demand: an empirical study of the Yangtze River Economic Belt in China. Energy Policy 139, 111354. https://doi.org/10.1016/j.enpol.2020.111354.

Yu, Z., Li, J., Yang, G., 2022. A review of energy security index dimensions and Organization. Energy RESEARCH LETTERS 3 (1). https://doi.org/10.46557/001c.28914.

Zhang, B., Liu, Z., Wang, Z., Zhang, S., 2023. The impact of geopolitical risk on energy security: evidence from a GMM panel VAR approach. Resour. Policy 86, 104222. https://doi.org/10.1016/j.resourpol.2023.104222.

Zhang, H., Zhang, K., Yan, T., Cao, X., 2025. The impact of digital infrastructure on regional green innovation efficiency through industrial agglomeration and diversification. Hum. Soc. Sci. Commun. 12 (1), 220. https://doi.org/10.1057/s41599-025-04512-9.

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 Econ. 141, 108100. https://doi.org/10.1016/j.eneco.2024.108100.

Zhang, L.P., Zhou, P., 2024. Reassessing energy security risk incorporating external shock: a variance-based composite indicator approach. Appl. Energy 358, 122665. https://doi.org/10.1016/j.apenergy.2024.122665.

Zhu, B., Deng, Y., Hu, X., 2023. Global energy security: do internal and external risk spillovers matter? A multilayer network method. Energy Econ. 126, 106961. https://doi.org/10.1016/j.eneco.2023.106961.