

The rise of renewable energy: How it shapes dependency, diversity, and geopolitical risk in the European Union[☆]

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HIGHLIGHTS

- Investigated the relationship between renewable energy and energy security risks.
- Renewable energy reduces energy diversity risk and energy geopolitical risk.
- Renewable energy reduces energy dependency risk only in countries with higher levels of renewable energy adoption.

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ABSTRACT

As the European Union advances its shift toward cleaner energy to address climate challenges, a pressing question emerges: can this shift also strengthen energy security in an increasingly volatile global landscape? This study investigates the impact of renewable energy on energy security risks across 27 EU countries over the period 2010 to 2022. It measures energy security through three key dimensions—energy dependency risk, energy diversity risk, and geopolitical risk. The findings reveal that renewable energy significantly mitigates energy diversity risk and geopolitical risk across the EU. However, its impact on energy dependency risk is statistically insignificant in the overall sample. Notably, further non-linear analyses show that in countries with higher levels of renewable energy deployment, renewables significantly reduce dependency risk on foreign energy sources. This highlights the importance of reaching a critical threshold of renewable integration to unlock broader energy security benefits.

1. Introduction

As the world fights climate change, the European Union (EU) has increasingly promoted the deployment of renewable energy as a central component of its decarbonization strategy and its objective of achieving climate neutrality by 2050 (Gajdzik et al., 2024). Supported by initiatives such as the European Green Deal and the Paris Climate Agreement, EU member states have steadily expanded the use of renewable energy sources within their energy systems. In recent years, the share of renewable energy in the EU's energy mix has grown steadily, reaching over 23% in 2022 (Nagaj et al., 2024). Policies to reduce the dependence on imported fossil fuels (such as REPowerEU plan) have further accelerated this trend. Beyond reducing greenhouse gas (GHG) emissions, renewable energy deployment is also expected to strengthen energy security in the EU, a priority underscored by the Green Deal's three key principles, one of which is ensuring a secure and reliable energy supply

(European Commission, 2022). These objectives align closely with the EU's broader goal of ensuring a secure, reliable, and resilient energy system.

Energy security is a multidimensional concept that reflects the ability of a nation to ensure a stable, affordable, and sustainable energy supply (Muhammad et al., 2025). In this study, energy security is captured through three key indicators: energy dependency risk, energy diversity risk, and geopolitical risk. Energy security has become a critical concern for EU countries, as the EU imports about 65% of its total available energy supply (Eurostat, 2022b). While the majority of energy produced domestically within the EU is renewable, imported energy consists nearly entirely of non-renewable sources (Eurostat, 2022a). Fig. 1 graphically represents the energy flow of EU countries in 2022. It highlights the imbalance between imported and domestically produced energy, as well as the share of each energy type. Concerns over energy security

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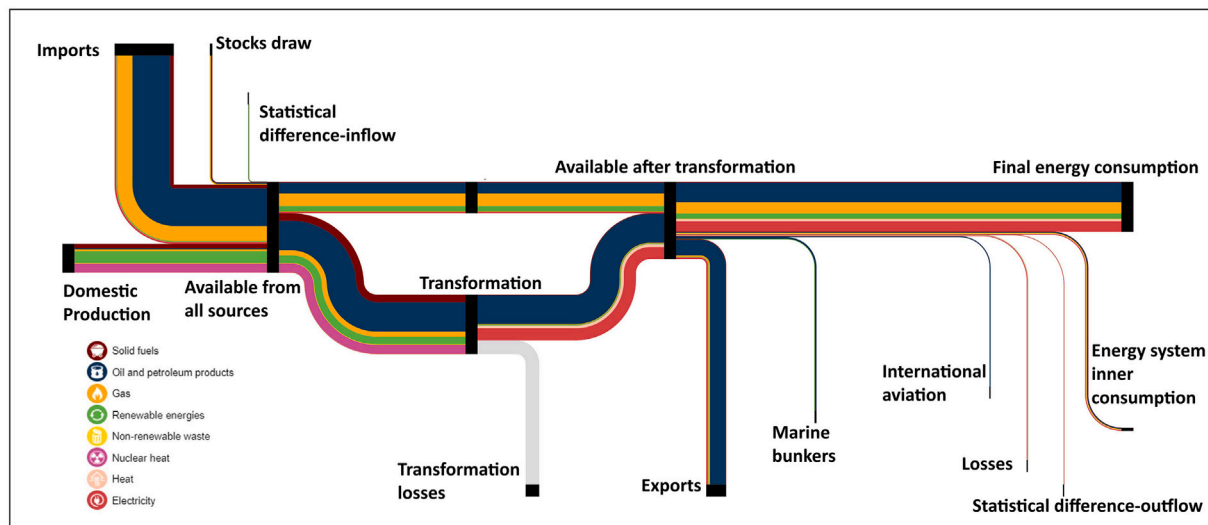


Fig. 1. Energy flow of EU countries for the year 2022 (kilo-tonne of oil equivalent) (Eurostat, 2022a).

have intensified, particularly after the Russia-Ukraine war, which triggered a severe energy crisis and exposed the EU's vulnerabilities in maintaining a stable and secure energy supply. The crisis unfolded as the EU, historically reliant on Russian oil and gas, faced supply disruptions following sanctions and retaliatory cutbacks in energy exports (Mikulska and Finley, 2024). As a result, energy prices soared, forcing governments to implement emergency measures, including price caps, energy subsidies, and efforts to secure alternative suppliers (Kuzemko et al., 2022). This crisis underscored the risks of high energy dependency (measured as the share of imported energy in gross available energy), making especially vulnerable households more susceptible to supply shocks (Becker and Aslund, 2024). Next to energy dependency, energy diversity risk (measured as the share of each energy source in the total energy supply) has also become a major concern. While some EU countries have made progress in expanding their renewable energy mix, it remains insufficient to achieve complete self-reliance. This leaves those countries vulnerable to market volatility (Lekavičius et al., 2024). Geopolitical risk (measured as the share of energy imports multiplied by the geopolitical risk associated with each supplier country) further compounds the issue, as energy has become a strategic tool in global conflicts. The Russia-Ukraine war demonstrated how energy supplies could be weaponized, with supply cuts used as leverage in political disputes (Hartvig et al., 2024). This multifaceted energy security challenge underscores the fragility of the EU's energy system in an increasingly unstable geopolitical landscape.

The relationship between renewable energy and energy security was largely overlooked in the past. However, the recent Russia-Ukraine war has brought this nexus into focus, making it a hot topic among researchers. The majority of studies in the literature have relied on composite indices to measure energy security (Cergibozan, 2022; Bashir et al., 2025; Chu et al., 2023; Aslam et al., 2024b). Most of these studies have used composite indices to measure energy security. However, given the complex nature of energy security, such indices often fail to capture its nuanced and multidimensional aspects. By aggregating multiple dimensions into a single score, composite indices can obscure the underlying factors that influence energy security. Other studies have measured energy security through indicators such as the share of renewable energy (Aslam et al., 2024a), energy consumption, energy production per capita, and CO₂ emissions (Yang and Zhan, 2024). Nevertheless, these metrics come with notable shortcomings, as they tend to capture the outcomes of energy security vulnerabilities rather than providing a direct evaluation of energy security itself.

We address this gap by examining the nexus between renewable energy adoption and energy security. Specifically, we analyze the impact

of renewable energy adoption on energy security using three distinct indicators: energy dependency, energy diversity, and geopolitical risk. Rather than relying on a composite measure, the study provides a comprehensive assessment of these three dimensions within a unified empirical framework. In addition, we identify a non-linear relationship between renewable energy deployment and import dependency, highlighting that the effects of renewable energy on energy security indicators are not uniform across different dimensions.

2. Background and literature

Energy security is a critical factor in a country's economic stability, national security, and social well-being. A secure energy system ensures a stable and affordable energy supply, reducing vulnerability to external shocks and price fluctuations (Månsson et al., 2014). The three main pillars of energy security—energy dependency risk, energy diversity risk, and geopolitical risk—play a crucial role in determining a nation's resilience against potential disruptions (De Rosa et al., 2022). Energy dependency risk reflects reliance on external sources, making nations vulnerable to supply disruptions or price volatility if imports dominate (Henriques et al., 2024). Energy diversity risk, the second pillar, emphasizes the need for a balanced energy mix—relying on varied sources like renewables, fossil fuels, and nuclear power reduces exposure to shortages in any single resource (Chalvatzis and Ioannidis, 2017). Geopolitical risk, the third pillar, arises from tensions or instability in energy-producing regions, which can threaten supply chains through sanctions, conflicts, or trade disputes (Hille, 2023). These factors collectively influence a country's energy supply: high dependency can lead to economic strain if suppliers cut exports, limited diversity risks over-exposure to a single energy type's failure, and geopolitical unrest can halt critical energy imports overnight.

Energy security is influenced by broader structures of the political economy, shaped by power relations between energy-importing and energy-exporting countries, where asymmetric interdependence can create strategic leverage and geopolitical vulnerability (DaDalt and Park, 2021). Institutional choices—such as market liberalization frameworks, long-term contracting arrangements, subsidy schemes, and regulatory design—also influence how energy systems evolve and how resilient they become to external shocks (Ilie et al., 2007). Moreover, energy security has distributional effects, as diversifying the energy mix does not affect all actors equally. Expanding renewables, reducing imports, or changing supplier structures can benefit some sectors and regions while imposing adjustment costs on others, such as fossil-fuel-intensive industries or energy-dependent households (Aghion et al., 2016). As

a result, policies aimed at improving energy security involve political trade-offs between keeping energy affordable, maintaining industrial competitiveness, and strengthening strategic autonomy.

Renewable energy plays a crucial role in enhancing energy security by promoting domestic energy production and reducing dependence on imported energy. For many nations, particularly in the European Union (EU), where a significant portion of energy is imported, expanding renewable energy deployment strengthens energy independence and mitigates the risks associated with geopolitical conflicts and global market volatility (Joita et al., 2023). This objective has been further reinforced through the European Green Deal, introduced in 2019, which provides a comprehensive framework for climate action, sustainable industry, clean and secure energy, energy efficiency, and a just transition (Sandri et al., 2025). By accelerating renewable energy deployment, improving energy efficiency, and reducing reliance on imported fossil fuels, the European Green Deal aims to achieve climate neutrality by 2050 while strengthening the EU's long-term energy security and resilience (Hinrichs-Rahlwes, 2024). Unlike fossil fuels, which are concentrated in specific regions and subject to geopolitical tensions, renewable energy sources—such as solar, wind, and biofuels—are widely available (Shahzad, 2012), ensuring a more equitable and stable energy distribution across nations. This decentralization of energy production reduces the likelihood of supply disruptions caused by political instability, trade restrictions, or resource scarcity. However, while renewable energy enhances energy security, it also presents certain challenges. The intermittent nature of some renewables, such as solar and wind, makes them vulnerable to weather-related disruptions (Farahmand et al., 2021). In such cases, energy diversification remains a key pillar for enhancing energy security by integrating different types of renewable sources to ensure a resilient supply system. The shift from non-renewable to renewable energy not only strengthens energy security but also has broader economic and political implications. Countries investing in renewables can achieve greater economic stability, reduce exposure to volatile fossil fuel prices, and foster innovation in energy technologies (Lin et al., 2022). Moreover, as renewable energy becomes more accessible, the likelihood of international conflicts over energy resources may diminish, paving the way for a more stable and cooperative global energy landscape.

Fig. 2 presents the mechanisms by which renewable energy deployment affects energy dependency risk, energy diversity risk, and geopolitical risk. Regarding energy dependency risk, renewable energy deployment can significantly reduce energy import dependency by decreasing reliance on foreign fossil fuels (Carfora et al., 2022). Through the deployment of domestic renewable sources such as solar, wind, and hydropower, countries can harness locally available resources, thereby decreasing the need to import oil, gas, or coal. This shift enhances energy security by mitigating vulnerabilities tied to the international energy market or supply disruptions. Furthermore, renewable energy systems, once installed, have lower operational costs and no fuel expenses, contrasting with fossil fuel imports that drain national budgets (Bogdanov et al., 2021). Over time, the expansion of renewable energy fosters economic resilience, stabilizes energy prices, and promotes self-sufficiency, fundamentally reshaping a nation's energy landscape.

A handful of studies have explored the relationship between renewable energy and energy dependency. Vaona (2016) studied the nexus between electricity generated from renewable sources and energy imports across 26 countries. Using an unbalanced panel dataset and estimating the model through the system Generalized Method of Moments (GMM), the study concludes that higher renewable electricity production contributes to a decline in overall import growth. Using a system dynamics model, Aslani et al. (2014) found that increasing renewable energy capacity in Finland could save 4 billion USD in natural gas import costs. Similarly, in a simulation-based study on the U.S. state of Illinois, Hosseinabad and Moraga (2020) found that replacing imported energy with renewable sources could save 17 billion USD over five years. Carfora et al. (2022) examined the impact of domestic energy production

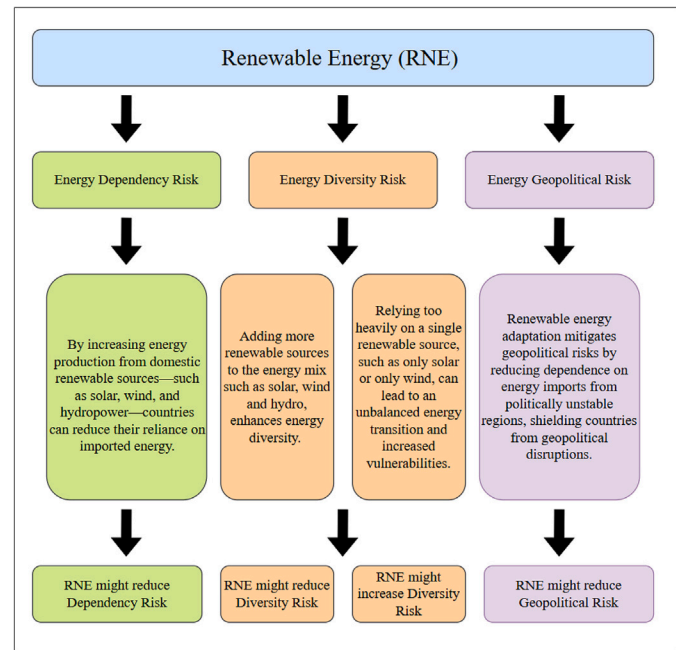


Fig. 2. Impact mechanism between renewable energy and energy security risk indicators.

on foreign energy imports in EU countries using GMM (Generalized Method of Moments) regression and found that increasing domestic energy production—both renewable and non-renewable—reduces dependence on imported energy. Yadav and Mahalik (2024) examined the effect of renewable energy on net energy imports in 16 developing countries. Their study found that renewable energy consumption marginally substitutes energy imports. Ürkmez and Okyar (2022) analyzed how renewable electricity generation affects Turkey's energy import dependency over the period 1990–2018. Applying the ARDL bounds testing approach, they found that greater renewable energy consumption significantly lowers reliance on energy imports. Khan and Shaheen (2020) investigated the impact of renewable energy expansion on crude oil imports in China, India, Japan, and the United States using a time-series framework. Their findings indicate that expanding renewable energy significantly reduces crude oil imports in China, India, and Japan, whereas the effect is statistically insignificant in the United States.

Renewable energy and energy diversity risk have a two-way mechanism, where integrating a diverse mix of renewable energy sources, such as solar, wind, and hydropower, reduces energy diversity risk and strengthens energy security (Aslam et al., 2024b). A well-balanced energy portfolio reduces reliance on a single source, mitigating risks associated with supply fluctuations and seasonal variability. However, an overdependence on a single renewable source, such as solar or wind energy alone, can create an unbalanced energy mix, increasing vulnerabilities to weather conditions and intermittency issues (Solaun and Cerdá, 2019). A diversified renewable energy mix ensures a more stable and resilient energy system, reducing supply risks while supporting a more sustainable and reliable energy system (Seriño, 2022). To the best of our knowledge, no existing study in the literature has analyzed the relationship between renewable energy and energy diversity risk.

Regarding geopolitical risk, renewable energy deployment can reduce reliance on imported fossil fuels, which are often subject to political tensions and international conflicts. Flourous et al. (2022) examined the effect of geopolitical risk on renewable energy investments using a large panel of 171 economies. Applying a flexible Autoregressive Distributed Lag (ARDL) model, the study finds that geopolitical risk has a negative impact on renewable energy production in both the short and long run, indicating that higher geopolitical risk reduces the share of renewable

energy. Sweidan (2021) examined the impact of renewable energy on geopolitical risk across 10 countries and found that renewables stimulate renewable energy consumption. Similarly, Su et al. (2021) identified a positive relationship between geopolitical risk and renewable energy adoption. In contrast, Zhao et al. (2023) found that geopolitical risks reduce the demand for renewable energy, arguing that geopolitical risks slow down the economy, leading to a decline in overall energy consumption, including renewable energy. Zhao et al. (2024) analyzed the relationship between renewable energy sub-sector markets and geopolitical risk (GPR) using daily data from 2012 to 2022. The results show that renewable energy indices are significantly affected by geopolitical risk. However, the direction of the impact differs across sub-sectors: bio-clean fuels, fuel cell, and geothermal indices respond positively, while solar and wind indices respond negatively. Overall, the findings indicate that geopolitical risk influences renewable energy markets, but the effects vary by sector. Sarker et al. (2023) examined the asymmetric effects of geopolitical risk on clean energy prices in the United States using a non-linear ARDL (NARDL) model. The study finds that higher geopolitical risk increases volatility in clean energy markets and has significant short- and long-run effects on returns, indicating that geopolitical tensions disrupt the renewable energy sector. The main limitation of these studies is that they measure geopolitical risk solely in terms of security and political instability within the host country. They fail to consider the role of energy imports, the stability of exporting nations, and the broader impact of regional political instability on energy supply. This narrow approach ignores how external geopolitical tensions, such as supply chain disruptions or trade restrictions, can influence a country's energy security. We address this gap by measuring geopolitical risk while considering the diversity of importing partners, the volume of imported energy, and the geopolitical stability of the region.

3. Methodology and data

In this section, we first outline the methodological framework used to examine the relationship between renewable energy and energy security risk indicators. We then describe the data, variables, and sources employed in the empirical analysis.

3.1. Methodology

To study the relationship between renewable energy and energy security risk indicators, we construct our baseline econometric model following the studies of Aslam et al. (2024b) and Cergibozan (2022).

$$\ln ES_{Kit} = \alpha_i + \beta_{RNE} \ln RNE_{it} + \beta_{TET} \ln TET_{it} + \beta_{PGDP} \ln PGDP_{it} + \lambda_t + \epsilon_{it} \quad (1)$$

where ES represents our dependent variable, energy security risk. We employ three separate indicators for energy security risk, indicated by K .

In ES_K :

$$K \in \{DEPR, DIVR, GPOR\}$$

where $DEPR$ represents the energy import dependency risk of a country, $DIVR$ reflects the diversity risk of a country's energy supply, and $GPOR$ indicates its exposure to geopolitical risk. RNE as our core independent variable represents renewable energy. TET and $PGDP$ represent total environmental taxes and economic growth per capita, respectively. i and t denote country (i) and year (t), respectively. The coefficients are represented by β , whereas α , λ , and ϵ denote country fixed effects, year fixed effects, and the error term, respectively. We include two control variables in the model.

Environmental taxes (TET) influence key factors associated with energy security risks. Raising these taxes incentivizes diversification towards renewable energy sources, reducing dependency on external energy supplies. Additionally, the tax influences energy consumption patterns and encourages improvements in energy efficiency. By accounting for TET , we isolate the specific impact of renewable energy on energy

security, ensuring that energy security measures remain unbiased by the separate influence of environmental taxes.

Economic growth ($PGDP$) significantly influences energy security risks. Higher GDP per capita levels are often associated with increased energy demand, which can affect a country's energy dependency and diversification strategies. Wealthier economies also have greater financial capacity to invest in energy infrastructure, renewable energy development, and efficiency improvements, mitigating potential security risks. By controlling for $PGDP$, we ensure that the effect of renewable energy development is not biased by the impact of economic growth.

In the next step, the baseline model is extended by including three additional control variables to better isolate the effect of renewable energy on energy security risks.

$$\ln ES_{Kit} = \alpha_i + \beta_{RNE} \ln RNE_{it} + \beta_{TET} \ln TET_{it} + \beta_{PGDP} \ln PGDP_{it} + \beta_{INE} \ln INE_{it} + \beta_{TRO} \ln TRO_{it} + \beta_{IND} \ln IND_{it} + \lambda_t + \epsilon_{it} \quad (2)$$

First, innovation in energy technology (INE) captures the role of technological progress in shaping energy structures. Advancements in energy-related innovation can facilitate the deployment of renewables, enhance efficiency, and reduce vulnerability to external shocks (Lee and Wang, 2022). Second, trade openness (TRO) reflects the degree of a country's exports and imports, indicating greater economic activity and, consequently, higher energy consumption. This may increase the overall energy demand, which in turn affects a country's energy dependency and exposure to geopolitical risks (Ibrahiem and Hanafy, 2021). Finally, a secondary industry (IND) is included to account for the structural composition of the economy. Economies with larger secondary industrial sectors tend to exhibit higher energy-intensive demand, which directly influences dependency, diversification, and exposure to risks. By adding these variables, we control for important economic and structural factors that may otherwise confound the estimated relationship between renewable energy development and energy security.

3.2. Data

This study utilizes the data of 27 EU countries from 2010 to 2022 on an annual level. The 13-year period is a result of data availability. Energy security risk indicators, $DEPR$, $DIVR$, and $GPOR$, are defined in the sub-sections below. Higher values for the energy security risk indicator indicate higher risk, and vice-versa. RNE represents renewable energy consumption, measured as the percentage share of renewable energy in the final energy consumption. TET represents total environmental taxes, measured as the sum of energy and environmental taxes in millions of Euros. $PGDP$ indicates economic growth per capita, measured in Euros. INE represents technological innovation in the energy sector, measured as the number of patent applications in energy and environment-related technologies. The values of INE include decimals due to the fractional counting of patents. TRO represents trade openness, measured as the share of exports and imports in the country's GDP. IND denotes the secondary industry, measured as the share of the secondary industry (excluding construction) in the total GDP. REG represents renewable energy growth, measured as the annual percentage growth rate of renewable energy consumption. GEF denotes government effectiveness, capturing the quality of public services, policy implementation, and government credibility. Meanwhile, RGQ represents regulatory quality, reflecting the government's ability to formulate and implement policies that support private sector development. Higher values of GEF and RGQ indicate more effective governance and better regulatory frameworks, and vice versa. EML represents energy market liberalization, measured using the OECD Product Market Regulation (PMR) index for the energy sector, where higher values indicate lower levels of market liberalization and vice versa. Table 1 displays the descriptive summary and sources of explanatory variables. Table 2 represents the correlation matrix of variables used in Eq. (2). The correlation matrix indicates no serious multicollinearity among the explanatory variables, as all pairwise correlations remain below the conventional threshold of 0.80.

Table 1
Descriptive summary of explanatory variables.

Variable	Symbol	Unit	Mean	St. dev	Min	Max	Source
Energy Dependency Risk	DEPR	Index	56.925	24.242	−16.235	104.139	Eurostat (2022b)
Energy Diversity Risk	DIVR	Index	0.199	0.076	0.120	0.550	Eurostat (2022b)
Geopolitical Risk	GPOR	Index	0.022	0.017	0.004	0.081	Eurostat (2022b) ICRG (2024)
Renewable Energy Consumption	RNE	%	20.812	11.817	0.979	66.002	Eurostat (2022b)
Economic Growth	PGDP	Euros	26,034.700	17,097.010	5080	86,540	Eurostat (2022b)
Environmental Taxes	TET	Million Euros	11,174.390	16,409.320	190.480	68,238.330	Eurostat (2022b)
Innovation in Energy Technologies	INE	No. of patents	517.973	1480.730	0.25	8649.480	OECD (2025)
Trade Openness	TRO	Ratio	1.296	0.634	0.502	3.852	WDI (2024)
Secondary Industry	IND	Ratio	14.235	5.521	3.884	37.147	WDI (2024)
Renewable Energy Growth	REG	Ratio	5.751	10.920	−23.415	88.968	Eurostat (2022b)
Government Effectiveness	GEF	Index	72.528	12.286	45.588	95.538	WDI (2024)
Regulatory Quality	RGQ	Index	71.977	8.195	56.740	87.442	WDI (2024)
Energy Market Liberalization	EML	Index	1.654	0.796	0.145	3.333	OECD (2025)

Table 2
Correlation matrix of Variables.

Variables	DEPR	DIVR	GPOR	RNE	TET	PGDP	INE	TRO	IND
DEPR	1.0000								
DIVR	0.3804 (0.0000)	1.0000							
GPOR	−0.1598 (0.0027)	0.0061 (0.9093)	1.0000						
RNE	−0.4638 (0.0000)	−0.2351 (0.0000)	−0.0024 (0.9643)	1.0000					
TET	0.0499 (0.3514)	−0.1278 (0.0166)	−0.3120 (0.0000)	−0.1462 (0.0061)	1.0000				
PGDP	0.2621 (0.0000)	−0.1321 (0.0132)	−0.3662 (0.0000)	−0.0647 (0.2267)	0.1774 (0.0008)	1.0000			
INE	−0.0088 (0.8695)	−0.1677 (0.0016)	−0.1597 (0.0027)	−0.0726 (0.1731)	0.7353 (0.0000)	0.1542 (0.0038)	1.0000		
TRO	0.3489 (0.0000)	0.1853 (0.0005)	0.1600 (0.0472)	−0.3842 (0.0000)	−0.4297 (0.0000)	0.4647 (0.0000)	−0.2821 (0.0000)	1.0000	
IND	−0.2873 (0.0000)	−0.4186 (0.0000)	0.2799 (0.0000)	0.0626 (0.2507)	0.0217 (0.6903)	−0.1353 (0.0128)	0.1402 (0.0098)	−0.0535 (0.3266)	1.0000

Values in parentheses represent p-values (significance level).

3.2.1. Energy dependency risk (DEPR)

Energy dependency risk measures how reliant a country is on external sources to meet its energy needs. It shows the share of a nation's energy supply that is sourced from abroad rather than produced domestically. The indicator is typically derived by taking the difference between energy imports and exports (net imports) and comparing it to the gross available energy within the country (see Eq. 3). A higher value signifies greater reliance on foreign energy.

$$DEPR = \frac{EN_{import} - EN_{export}}{EN_{gross}} \quad (3)$$

Here, EN_{import} represents the total volume of energy imported into the country, while EN_{export} accounts for the energy exported to other nations. EN_{gross} indicates the gross available energy, including both imported and domestically produced energy. These data are obtained from Eurostat (Eurostat, 2022b).

3.2.2. Energy diversity risk (DIVR)

The diversity risk index offers a measure of the variety of a country's energy sources, indicating the overall structure of its energy mix. It is calculated using the Herfindahl-Hirschman Index (HHI) (see Eq. 4), where lower values indicate a more diversified energy system, meaning a lower risk of energy diversity.

$$DIVR = \sum_F \left(\frac{(PDP_F + RCR_F + IMP_F + STD_F)}{(PDP_{TOTAL} + RCR_{TOTAL} + IMP_{TOTAL} + STD_{TOTAL})} \right)^2 \quad (4)$$

Here, PDP indicates primary production at the domestic level, RCR represents recycled and recovered energy, IMP denotes imported energy,

and STD refers to stock draw. F represents fuel type. These data are sourced from Eurostat (Eurostat, 2022b).

3.2.3. Geopolitical risk (GPOR)

Geopolitical risk (GPOR) captures the importing country's geopolitical exposure arising from its energy import structure. The index combines information on the political and institutional conditions of supplier countries with the concentration of energy imports, thereby reflecting both supplier risk and import dependence. The index is constructed using the Herfindahl-Hirschman Index (HHI) (see Eq. 5), taking into account not only how much energy is imported from each source country, but also the level of geopolitical risk linked to those countries.

$$GPOR = \sum_{x=1}^N (D_x R_x)^2 \quad (5)$$

D_x indicates the share of energy imports from country x , while R_x represents the geopolitical risk associated with that country x . The value of R_x is taken from the International Country Risk Guide (ICRG) (ICRG, 2024), which provides a composite measure of the political and institutional environment in each supplier country. Although the ICRG does not directly measure energy supply disruption risk, it serves as a proxy for broader political and institutional conditions that may influence the reliability of international energy trade through channels such as political instability, conflict, and governance-related uncertainties. A lower value of GPOR represents lower geopolitical risk, and vice versa. The share of energy imports for each country is taken from Eurostat (Eurostat, 2022b).

Fig. 3 represents energy imports to the EU by source country and energy type.

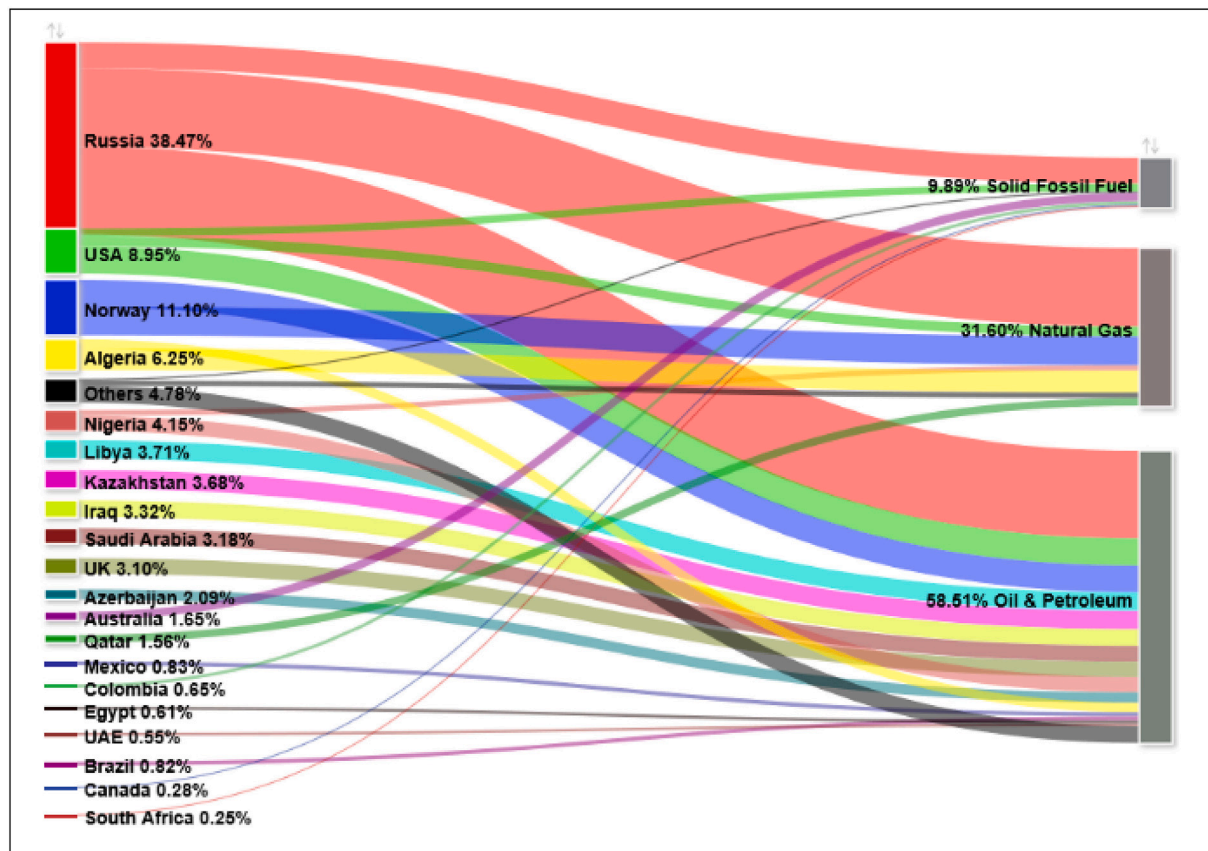


Fig. 3. Energy import partners of the EU by energy type for the year 2021 (Author's own visualization based on Eurostat data (Eurostat, 2022b)).

4. Results and discussion

This section presents the empirical findings of the study and discusses their implications in the context of energy security and renewable energy in EU countries. The analysis is structured in two parts. First, we conduct preliminary tests to examine the statistical properties of the data. Second, we present the panel regression results to evaluate the relationships among the key variables and to assess the robustness of the estimated effects.

4.1. Preliminary tests

Before presenting the econometric analysis, we examine the time-series properties of the panel data, specifically the variables included in Eq. (2), to ensure their suitability for regression modeling. We conducted two panel unit root tests: the Im, Pesaran, and Shin (IPS) test (Im et al., 2003) and the Fisher-type Phillips-Perron (PP) test (Maddala and Wu, 1999). Both tests assess whether the variables are characterized by non-stationarity across panel units. The results indicate that while several variables are non-stationary in their levels, all achieve stationarity after first differencing. This confirms that the variables are integrated of the order one, $I(1)$, and are thus appropriate for subsequent econometric analysis. Table 3 presents the results of the IPS and Fisher PP unit root tests.

To assess whether a stable long-run relationship exists among the variables in our baseline model, we applied the Kao cointegration test (Kao, 1999). The test is based on five parameters, which include modified Dickey-Fuller, Dickey-Fuller, Augmented Dickey-Fuller, unadjusted modified Dickey-Fuller, and unadjusted Dickey-Fuller. The test examines the null hypothesis of no cointegration among the series. Our results indicate a statistically significant rejection of the null for a majority of

Table 3

Panel stationarity test.

Variables	Fisher PP test		IPS test	
	Level	First-Difference	Level	First-Difference
LnDEPR	100.572***	433.955***	-1.553*	-8.064***
LnDIVR	71.846*	369.667***	-0.724	-7.726***
LnGPOR	74.452**	235.145***	-0.503	-5.577***
LnRNE	59.254	371.145***	2.547	-7.353***
LnTET	80.021**	325.190***	0.825	-6.689***
LnPGDP	35.667	308.422***	4.368	-7.847***
LnINE	57.419	248.141***	3.830	-3.268***
LnTRO	27.527	234.978***	3.526	-6.793***
LnIND	56.516	231.263***	0.823	-6.281***

H_0 : A unit root exists in the data.

H_1 : A unit root does not exist in the data.

*, **, and *** indicate rejection of the null hypothesis at the 10%, 5%, and 1% levels, respectively.

the parameters, suggesting that the variables are indeed cointegrated. This finding provides empirical support for the presence of a long-term association and validates the use of level-based estimations in our analysis. Table 4 presents the Kao cointegration results.

4.2. Panel analysis

This subsection presents the core empirical analysis based on a series of panel regression models. We begin by estimating the baseline fixed-effects specifications to establish the relationship between renewable energy deployment and energy security risk indicators. Next, we address potential endogeneity concerns using a two-stage least squares (2SLS) framework. We then examine possible non-linear effects of renewable

Table 4
Kao test for cointegration.

Kao test parameters	Model 1 (DEPR)	Model 2 (DIVR)	Model 3 (GPOR)
Modified Dickey-Fuller t	3.316***	−0.112	−1.308*
Dickey-Fuller t	2.699***	−2.199**	−0.328
Augmented Dickey-Fuller t	4.094***	−0.594	−2.379***
Unadjusted modified Dickey-Fuller t	−4.236***	−3.801***	−2.976***
Unadjusted Dickey-Fuller t	−4.215***	−4.489***	−1.275

H₀: Cointegration does not exist among the variables.

H₁: Cointegration exists among the variables.

*, **, and *** indicate rejection of the null hypothesis at the 10%, 5%, and 1% levels, respectively.

energy deployment on energy security by incorporating a quadratic specification. Finally, a series of robustness checks is conducted to assess the consistency and reliability of the findings.

4.2.1. Baseline regression

We employ a fixed-effect model with country and year effects to control for unobserved, time-invariant differences across countries and for common shocks or trends over time, ensuring that the estimated coefficients are identified from within-country variation. The results of the panel fixed effects for the energy security indicators and determinants are presented in Table 5 (Models 1, 3, and 5). The results show that the coefficient of renewable energy is not statistically significant, indicating that renewable energy does not have an effect on energy dependency risk (DEPR) (see Model 1 in Table 5). Regarding energy diversity risk (DIVR), the results show that an increase in renewable energy decreases energy diversity risk at a 1% significance level (see Model 3 in Table 5). This suggests that as countries expand the share of renewables in their energy mix, their energy systems become less reliant on a limited number of sources or suppliers. This effect can be attributed to renewable energy introducing new and varied sources into the energy portfolio—such as wind, solar, and hydro—which are not subject to the same market or geopolitical constraints as fossil fuels. As a result, the overall composition of the energy supply becomes more balanced, therefore reducing

the diversity risk associated with the energy supply. Importantly, this reduction in diversity risk does not necessarily imply that each country is using many different renewable energy sources. Rather, it suggests that the increase of renewables weakens the dominance of traditional sources, thereby improving the overall risk profile of the energy mix. This shift makes energy systems more resilient to disruptions in any single energy market or supply chain. It also enables more flexibility in energy planning, allowing countries to respond more effectively to demand fluctuations or supply shocks. The strong statistical significance underscores the robustness of this relationship across the sample of EU countries.

Regarding geopolitical risk (GPOR), the results show that an increase in renewable energy reduces geopolitical risk at a 5% significance level (see Model 5 in Table 5). This indicates a robust inverse relationship between renewable energy deployment and exposure to external geopolitical tensions in the energy sector. Higher renewable energy adoption reduces reliance on imported fossil fuels, particularly from geopolitically sensitive regions. Many EU countries traditionally depend on energy imports from politically unstable or strategically contentious suppliers, which expose them to supply disruptions, price shocks, and political pressure. By shifting towards domestically produced renewables—such as wind, solar, and hydro—countries lower their dependence on external energy, thereby reducing their vulnerability to geopolitical conflicts or market manipulations. Moreover, renewable energy systems are less affected by international supply chain bottlenecks or transit routes (e.g., pipelines or maritime chokepoints), which are often at the center of geopolitical disputes. The expansion of renewable energy decreases a country's exposure to foreign policy risks and energy-driven diplomatic tensions.

Regarding the control variable, the total environmental taxes (TET) (the sum of energy and environmental taxes) reveal that increases in taxes are associated with reductions in geopolitical risk. This outcome aligns with the policy intent behind such taxes: by raising the cost of fossil fuel consumption—particularly imported energy—governments create economic incentives to reduce reliance on external energy sources. These taxes push both producers and consumers toward energy efficiency improvements and clean energy production. Consequently, the

Table 5
Panel regression analysis for energy security indicators.

Variables	LnDEPR		LnDIVR		LnGPOR	
	Model 1 (Baseline Model)	Model 2 (Extended Controls)	Model 3 (Baseline Model)	Model 4 (Extended Controls)	Model 5 (Baseline Model)	Model 6 (Extended Controls)
LnRNE	0.039 (0.072)	−0.002 (0.077)	−0.137*** (0.026)	−0.144*** (0.027)	−0.198** (0.079)	−0.196** (0.086)
LnTET	−0.196 (0.124)	−0.338** (0.160)	0.017 (0.044)	0.053 (0.056)	−0.389*** (0.136)	−0.300* (0.177)
LnPGDP	−0.153 (0.210)	−0.195 (0.227)	−0.024 (0.075)	−0.117 (0.080)	−1.239*** (0.232)	−1.293*** (0.252)
LnINE		0.007 (0.040)		0.023 (0.014)		0.020 (0.044)
LnTRO		0.776*** (0.292)		0.124 (0.102)		−0.155 (0.322)
LnIND		−0.155 (0.161)		0.173*** (0.056)		0.160 (0.177)
Constant	6.959*** (1.941)	9.039*** (2.122)	−1.157* (0.694)	−1.063 (0.746)	11.710*** (2.140)	11.036*** (2.356)
Observations	348	335	351	338	351	338
R-Squared	0.063	0.088	0.246	0.285	0.373	0.369
Number of id's	27	26	27	26	27	26
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Panel fixed effect regression.

Standard errors in parentheses.

*** p<0.01, ** p<0.05, * p<0.1.

The difference in the number of IDs is due to unbalanced panel data, specifically the missing data of LnIND for Bulgaria.

need for energy imports declines, which in turn reduces vulnerability to foreign supply disruptions and geopolitical tensions tied to international energy markets. Regarding economic growth (PGDP), the results show that an increase in PGDP reduces geopolitical risk. However, its impact on energy dependency risk and energy diversity risk is statistically insignificant.

4.2.2. Extended controls

To better isolate the impact of renewable energy on energy security risk indicators, we extend our baseline model by including three additional control variables: technological innovation in the energy sector (INE), trade openness (TRO), and secondary industry (IND). The results of the extended controls are presented Table 5 (Models 2, 4, and 6).

For energy dependency risk (DEPR) (Model 2 in Table 5), renewable energy remains statistically insignificant, consistent with the baseline result. However, total environmental taxes (TET) show a significant negative effect, indicating that higher environmental taxes reduce import dependency by discouraging fossil fuel consumption and stimulating efficiency or renewable alternatives. Trade openness (TRO) is positively and significantly associated with dependency risk, suggesting that greater economic integration raises reliance on imported energy. Neither technological innovation nor industrial structure shows significance in this specification.

For energy diversity risk (DIVR) (Model 4 in Table 5), renewable energy continues to exert a negative and significant impact, reinforcing the baseline finding that renewables lower diversity risk. Among the controls, secondary industry (IND) has a positive and significant coefficient, implying that countries with a larger industrial base face heightened diversity risks due to concentrated reliance on specific fuels. In contrast, TET, TRO, and INE are not statistically significant in this model.

For geopolitical risk (GPOR) (Model 6 in Table 5), renewable energy again exhibits a negative and significant effect, confirming that expanding renewables reduces vulnerability to external geopolitical pressures. Similarly, TET is negative and statistically significant, suggesting that environmental taxes mitigate geopolitical risks by discouraging fossil fuel dependence and incentivizing cleaner energy use. By contrast, technological innovation, trade openness, and industrial structure do not show significant effects.

Overall, the extended models reinforce our baseline findings and strengthen the conclusion that renewable energy consistently lowers diversity risks and geopolitical risks. Importantly, environmental taxes emerge as a complementary policy instrument, reducing both energy dependency risks and geopolitical risks.

4.2.3. Two-stage least-squares (2SLS) analysis

To ensure the validity and consistency of our baseline results, we employ a Two-Stage Least Squares (2SLS) estimation framework. This approach addresses potential endogeneity concerns, particularly the possibility of reverse causality, by using instrumental variables (IVs) (Angrist and Krueger, 2001). In our analysis, we use internal instruments, specifically lagged values of the endogenous regressor (renewable energy), ensuring their relevance while being predetermined with respect to the current error term. To confirm instrument validity, we conduct standard diagnostic tests for instrument strength and overidentification. This approach enhances the robustness of our findings and supports a more credible interpretation of the estimated relationship.

The validity of the instruments is verified through the Kleibergen–Paap rk Wald F-statistic and the Hansen J test. The Kleibergen–Paap statistic assesses the strength of the instruments, and the reported values exceed the conventional critical threshold of 10, indicating that the instruments are sufficiently strong. The Hansen J test evaluates the overidentifying restrictions, and the insignificant p-values indicate that the null hypothesis of instrument validity cannot be rejected, suggesting that the instrumental variables (IVs) are valid.

Table 6 presents the findings of the 2SLS estimation, which are broadly consistent with the baseline results. The estimates indicate

Table 6
Two-Stage Least Squares (2SLS) regression analysis.

Variables	LnDEPR	LnDIVR	LnGPOR
LnRNE	0.056 (0.176)	−0.187*** (0.034)	−0.363** (0.182)
LnTET	−0.333 (0.386)	−0.012 (0.081)	−0.433 (0.431)
LnPGDP	−0.146 (0.338)	0.020 (0.126)	−1.106* (0.575)
LnINE	−0.024 (0.056)	0.011 (0.009)	0.016 (0.052)
LnTRO	0.694 (0.767)	0.065 (0.142)	−0.154 (0.453)
LnIND	−0.208 (0.236)	0.185*** (0.053)	0.220 (0.326)
Observations	285	286	286
R-Squared	0.077	0.282	0.344
Number of id's	26	26	26
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
KP rk Wald F	280.9	280.5	280.5
Hansen J	1.872	0.007	1.229
Hansen p-value	0.171	0.932	0.268

H₀: All instruments are valid and not overidentified.

H₁: At least one instrument is invalid.

Standard errors in parentheses.

*** p<0.01, ** p<0.05, * p<0.1.

Reduced number of IDs (26) due to the missing data for LnIND for Bulgaria.

that renewable energy has a statistically significant negative effect on energy diversity risk and geopolitical risk, suggesting that higher renewable penetration reduces these risks. In contrast, its effect on energy dependency risk remains statistically insignificant.

4.2.4. Testing for non-linear relationships

To further examine the relationship between renewable energy adoption and energy security risks, we extend the baseline model by incorporating a quadratic term of renewable energy. This approach allows us to formally test for potential non-linear effects and identify whether the impact of renewable energy varies across different levels of adoption.

The estimation results are reported in Table 7. For energy dependency risk, the coefficient of LnRNE is positive and statistically significant, while the coefficient of LnRNE² is negative and highly significant. This combination indicates an inverted U-shaped relationship between renewable energy and energy dependency risk. In the early stages of renewable energy expansion, increases in renewable energy may not immediately reduce dependence on imported energy, as renewable energy deployment typically begins from a relatively low base and remains insufficient to replace a substantial share of imported fossil fuels. This may even lead to an increase in energy dependency, as the variable nature of renewable generation—particularly wind and solar—requires flexible backup capacity, which in many EU countries is largely provided by imported fossil fuels, especially natural gas. As a result, initial increases in renewable energy can be accompanied by higher demand for imported backup energy to ensure system stability. In addition, during the early stages, renewable energy is typically added to the existing energy mix rather than fully replacing imported conventional energy, thereby limiting any immediate reduction in import dependence. However, once renewable energy reaches a sufficiently high level of penetration, its substitution effect becomes stronger, allowing domestic renewable generation to increasingly replace imported fossil fuels and thereby reduce energy dependency risk. This finding highlights the importance of scale and system maturity in achieving the energy security benefits of renewable energy expansion.

Table 7
Non-linear fixed effects regression analysis.

Variables	LnDEPR	LnDIVR	LnGPOR
LnRNE	0.482** (0.193)	-0.045 (0.067)	-0.226 (0.213)
LnRNE ²	-0.149*** (0.055)	-0.030 (0.019)	0.009 (0.060)
LnTET	-0.293* (0.159)	0.062 (0.056)	-0.302* (0.178)
LnPGDP	-0.362 (0.233)	-0.151* (0.082)	-1.282*** (0.261)
LnINE	-0.004 (0.040)	0.021 (0.014)	0.020 (0.045)
LnTRO	0.797*** (0.289)	0.125 (0.102)	-0.155 (0.322)
LnIND	0.014 (0.171)	0.209*** (0.060)	0.148 (0.191)
Constant	9.785*** (2.117)	-0.908 (0.750)	10.989*** (2.379)
Observations	335	338	338
R-Squared	0.111	0.291	0.359
Number of id's	26	26	26
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

Standard errors in parentheses.

*** p<0.01, ** p<0.05, * p<0.1.

Reduced number of IDs (26) due to the missing data for LnIND in Bulgaria.

In contrast, for both energy diversity risk and geopolitical risk, the coefficients of the linear and quadratic terms are statistically insignificant. This indicates that renewable energy does not exhibit a non-linear effect on these dimensions of energy security within the sample period.

4.2.5. Robustness analysis

To assess the robustness of our baseline results, we replace our main explanatory variable for renewable energy, previously measured as the

share of final energy consumption, with the annual growth rate of renewable energy consumption (Fig. 4). This alternative specification captures the dynamic dimension of renewable energy deployment, reflecting not only the existing level of renewable penetration but also the pace at which countries are expanding their renewable capacity.

The results of this robustness check, presented in Table 8, are broadly consistent with the baseline findings and further strengthen the reliability of the estimated relationships between renewable energy development and energy security indicators. The results show that an increase in renewable energy growth lowers both energy diversity risk and geopolitical risk, while its effect on energy dependency risk is not statistically significant. These outcomes align with the findings from our baseline regression model.

4.2.6. Political economy and crisis-year analysis

To check the influence of political economy factors and the 2022 energy crisis on the relationship between renewable energy and energy security risks, we conduct an additional analysis in two steps. First, we re-estimate the baseline model excluding the year 2022 to assess whether the main findings are driven by the exceptional circumstances associated with the Russia–Ukraine energy crisis. This analysis allows us to determine whether the relationship between renewable energy and energy security risks persists under more typical market conditions. Second, we incorporate political economy variables, namely government effectiveness (GEF), regulatory quality (RGQ), and energy market liberalization (EML), to account for the role of institutions and market structures in shaping energy security outcomes. Government effectiveness reflects the quality of public institutions, policy implementation, and government credibility, all of which can affect a country's ability to formulate and execute energy policies, manage supply disruptions, and coordinate responses to energy crises. Regulatory quality captures the government's ability to design and implement policies that support private sector development, which may facilitate investment in energy infrastructure, renewable energy deployment, and technological innovation. Energy market liberalization reflects the degree of competition

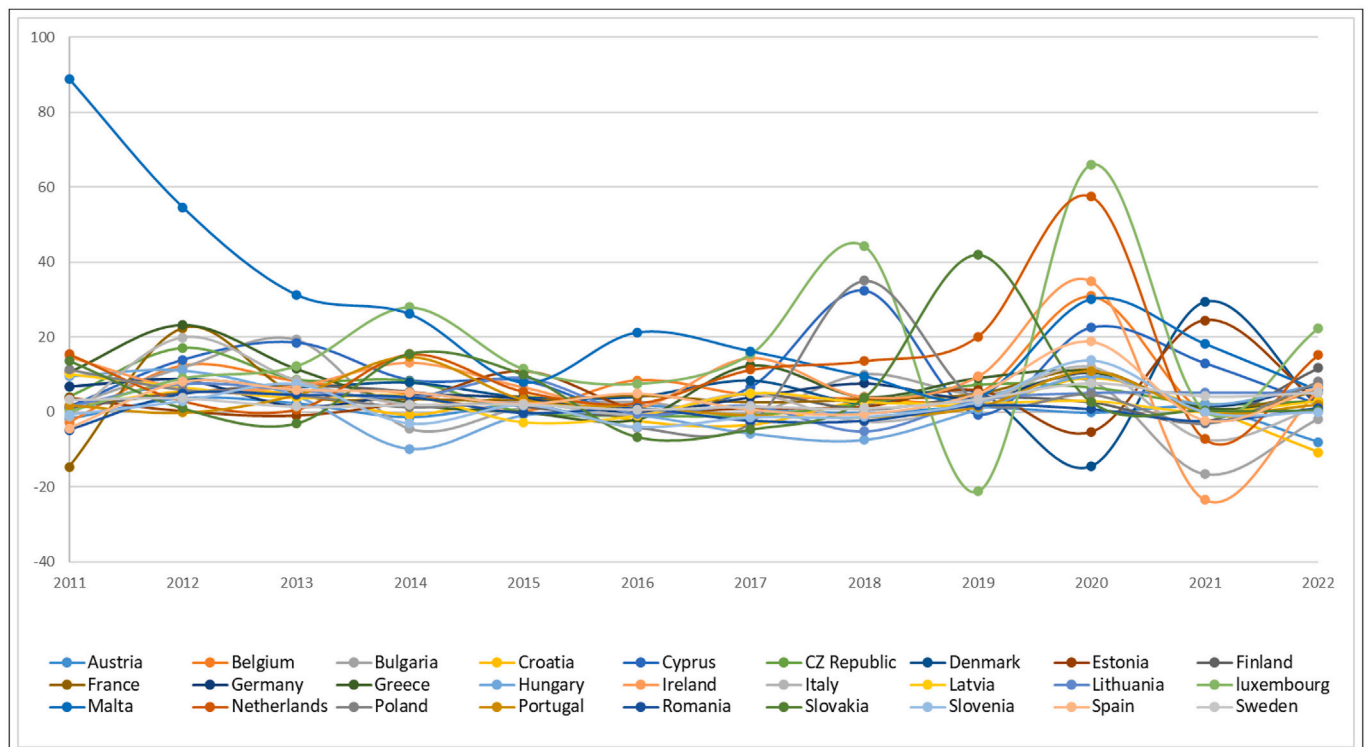


Fig. 4. Growth rate of renewable energy consumption in EU countries (Eurostat, 2022b).

Table 8
Robust analysis for energy security indicators.

Variables	LnDEPR		LnDIVR		LnGPOR	
	Model 1 (Baseline Model)	Model 2 (Extended Controls)	Model 3 (Baseline Model)	Model 4 (Extended Controls)	Model 5 (Baseline Model)	Model 6 (Extended Controls)
LnREG	−0.020 (0.015)	−0.019 (0.016)	−0.017*** (0.005)	−0.020*** (0.005)	−0.029* (0.017)	−0.033* (0.017)
LnTET	−0.288 (0.178)	−0.372* (0.207)	−0.049 (0.059)	−0.043 (0.067)	−0.510** (0.200)	−0.359 (0.234)
LnPGDP	−0.320 (0.285)	−0.379 (0.311)	0.042 (0.095)	−0.082 (0.101)	−1.124*** (0.321)	−1.220*** (0.351)
LnINE		0.011 (0.048)		−0.004 (0.016)		−0.012 (0.054)
LnTRO		0.717* (0.371)		0.017 (0.120)		−0.292 (0.416)
LnIND		−0.128 (0.210)		0.248*** (0.068)		0.307 (0.234)
Constant	9.542*** (2.649)	11.112*** (2.815)	−1.587* (0.886)	−1.704* (0.916)	11.236*** (2.982)	10.276*** (3.179)
Observations	254	246	256	248	256	248
R-Squared	0.095	0.117	0.222	0.278	0.340	0.336
Number of id's	27	26	27	26	27	26
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Panel fixed effects regression.

Standard errors in parentheses.

*** p<0.01, ** p<0.05, * p<0.1.

The difference in the number of IDs is due to unbalanced panel data, specifically the missing data of LnIND for Bulgaria.

Table 9
Political economy extension and crisis-year analysis.

Variables	<2022			Political Economy								
				LnDEPR			LnDIVR			LnGPOR		
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
LnRE	−0.030 (0.086)	−0.120*** (0.029)	−0.134* (0.076)	0.012 (0.080)	0.013 (0.080)	0.034 (0.130)	−0.130*** (0.028)	−0.130*** (0.028)	−0.127*** (0.040)	−0.159* (0.089)	−0.158* (0.089)	0.022 (0.123)
LnTET	−0.428** (0.192)	0.112* (0.066)	0.076 (0.171)	−0.337** (0.160)	−0.371** (0.162)	−0.380* (0.194)	0.053 (0.056)	0.057 (0.057)	−0.003 (0.059)	−0.300* (0.177)	−0.325* (0.179)	−0.214 (0.183)
LnPGDP	−0.200 (0.256)	−0.172* (0.088)	−1.693*** (0.229)	−0.222 (0.231)	−0.158 (0.236)	−0.487 (0.337)	−0.143* (0.081)	−0.149* (0.083)	−0.322*** (0.103)	−1.363*** (0.255)	−1.316*** (0.261)	−0.868*** (0.316)
LnINO	0.018 (0.044)	0.022 (0.015)	0.008 (0.040)	0.007 (0.040)	0.005 (0.040)	0.067 (0.082)	0.023* (0.014)	0.024* (0.014)	0.031 (0.025)	0.020 (0.044)	0.019 (0.044)	−0.075 (0.077)
LnTO	1.087*** (0.326)	0.140 (0.111)	−0.270 (0.289)	0.792*** (0.293)	0.800*** (0.293)	0.980* (0.516)	0.138 (0.102)	0.137 (0.102)	0.376** (0.155)	−0.117 (0.322)	−0.111 (0.322)	−0.302 (0.477)
LnIND	−0.219 (0.178)	0.191*** (0.061)	0.364** (0.158)	−0.161 (0.161)	−0.199 (0.164)	0.064 (0.331)	0.168*** (0.056)	0.171*** (0.057)	0.239** (0.098)	0.147 (0.176)	0.119 (0.180)	−0.479 (0.303)
LnGEF				0.265 (0.403)	0.122 (0.419)	−0.164 (0.557)	0.260* (0.140)	0.274* (0.146)	0.296* (0.169)	0.702 (0.443)	0.597 (0.462)	1.330** (0.520)
LnRGQ					0.703 (0.572)	−0.007 (0.804)		−0.067 (0.200)	−0.027 (0.246)		0.515 (0.633)	0.661 (0.757)
LnEML						−0.098 (0.077)			0.029 (0.023)			−0.029 (0.072)
Constant	10.020*** (2.296)	−1.096 (0.787)	11.295*** (2.055)	8.151*** (2.518)	5.496* (3.316)	12.346*** (4.986)	−1.933** (0.878)	−1.679 (1.160)	−0.017 (1.517)	8.686*** (2.779)	6.743* (3.666)	−0.692 (4.668)
Observations	309	312	312	335	335	257	338	338	260	338	338	260
R-Squared	0.097	0.263	0.448	0.090	0.094	0.127	0.293	0.293	0.318	0.364	0.366	0.406
Number of id's	26	26	26	26	26	20	26	26	20	26	26	20
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Panel fixed effect regression.

Standard errors in parentheses.

*** p<0.01, ** p<0.05, * p<0.1.

Difference in the number of IDs is due to unbalanced panel data.

26 IDs due to the missing data of LnIND for Bulgaria.

20 IDs due to missing data of LnEML for 7 countries.

and openness in energy markets. More liberalized markets may enhance energy diversification, improve supply flexibility, and encourage efficient allocation of resources, thereby strengthening resilience to external shocks and reducing energy security risks.

The results of the crisis-year analysis are reported in Models 1, 2 and 3 of Table 9. The results show that the main findings remain consistent with the baseline results, even after excluding the year 2022. Renewable energy continues to exhibit a negative and statistically significant effect on energy diversity risk and geopolitical risk, while its effect on energy dependency risk remains statistically insignificant. These results are consistent with the baseline estimates. This suggests that the observed relationship between renewable energy and energy security indicators is not solely driven by the extraordinary market disruptions associated with the Russia–Ukraine energy crisis, but instead reflects a more persistent and structural effect of renewable energy on reducing energy diversification and geopolitical risks across EU countries.

Models 4–12 in Table 9 present the results after incorporating the political economy variables. Overall, the inclusion of government effectiveness (GEF), regulatory quality (RGQ), and energy market liberalization (EML) does not materially alter the baseline results. Renewable energy continues to exhibit a negative and statistically significant effect on energy diversity risk and geopolitical risk, while its effect on energy dependency risk remains statistically insignificant. These findings suggest that the role of renewable energy in reducing energy security risks is robust even after accounting for differences in institutional quality and market structures across EU countries. Among the political economy variables, government effectiveness is positively and significantly associated only with energy diversity risk, whereas regulatory quality and energy market liberalization remain statistically insignificant across all specifications.

5. Conclusion and policy implications

We examine the impact of renewable energy adoption on energy security risks across 27 EU countries between 2010 and 2022. Renewable energy adoption is measured by the share of renewable energy in final energy consumption. We employ energy dependency risk, energy diversity risk, and geopolitical risk as three measures of energy security.

The results indicate that renewable energy mitigates energy diversity risk and geopolitical risk across EU countries. However, its impact on energy dependence risk is statistically insignificant in the baseline specification. Interestingly, the non-linear analysis reveals an inverted U-shaped relationship between renewable energy and energy dependence risk. This finding suggests that, at lower levels of renewable energy adoption, increases in renewable energy may not immediately reduce dependency because renewable energy initially constitutes a small share of the energy mix and remains insufficient to replace imported fossil fuels. However, beyond a certain threshold, further expansion of renewable energy significantly reduces dependency on foreign energy sources. This highlights the importance of achieving a sufficiently high level of renewable energy penetration, particularly in countries with relatively low levels of renewable energy deployment. To ensure the robustness of the results, we also employed the growth rate of renewable energy as an alternative measure, and the findings remain consistent with the baseline estimates.

These findings underscore a broader point: while the expansion of renewable energy in the EU has primarily been driven by climate and environmental objectives, it also plays a critical role in strengthening energy security. By reducing reliance on imported fossil fuels, renewable energy helps mitigate the risks of energy dependency, supply disruptions, and geopolitical tensions. As renewables are largely domestically produced, their expansion reduces vulnerability to external shocks and price volatility in global energy markets. Thus, beyond its environmental benefits, renewable energy contributes strategically to reducing the EU's exposure to external energy shocks and enhancing the resilience of its energy system.

Based on the analysis, we outline the following policy measures to enhance energy security through renewable energy deployment:

1. The results indicate that renewable energy significantly reduces energy dependency risks in countries with high levels of renewable penetration. This highlights the importance of accelerating renewable deployment in lagging countries. In this regard, EU initiatives such as the REPowerEU plan and the Fit for 55 package play a crucial role by setting binding renewable energy targets and providing financial support mechanisms to scale up renewable capacity across member states. Strengthening the implementation of these policies can help countries reach the critical threshold at which renewable energy effectively reduces dependency on imported fossil fuels.
2. To ensure that the expansion of renewable energy does not lead to concentration risks, policymakers should promote a diversified renewable energy mix. This can be achieved through the stringent implementation of the European Green Deal and the EU Energy System Integration Strategy, which emphasize the integration of multiple renewable energy sources, storage technologies, and sector coupling. Supporting a balanced portfolio—including solar, wind, hydro, and biomass—can enhance system resilience and minimize risks associated with intermittency and over-reliance on a single energy source.
3. The EU should further strengthen regional coordination and cross-border energy infrastructure to improve energy security. Existing frameworks such as the Trans-European Networks for Energy (TEN-E) and the broader Energy Union strategy provide a foundation for enhancing interconnectivity and facilitating energy sharing among member states. Expanding these initiatives can improve grid flexibility, enable better integration of renewable energy, and reduce collective exposure to supply disruptions and geopolitical risks.

Limitations This study has several limitations. First, there are data constraints, as the dataset covers the period from 2010 to 2022. Future research could benefit from incorporating a longer time series to capture more structural trends and external shocks. Second, the geopolitical risk index is constructed using country-level risk indicators and import shares, which may not fully capture intra-country heterogeneity or the strategic features of long-term energy contracts due to the unavailability of detailed and harmonized cross-country data. Future research could address this limitation by incorporating more granular data on contract structures, supplier-level dynamics, and intra-country variations, thereby enabling a more refined assessment of geopolitical risk in energy markets.

CRediT authorship contribution statement

Sulaman Muhammad: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Christin Hoffmann:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Felix Müsgens:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data for this article can be found online at doi:10.1016/j.enpol.2026.115570.

Data availability

Data and code files are attached in the supplementary material.

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