

Article

The European Union's Energy Security Challenges: Import Dependency, Volatility, and Differences Across Member States

László Török 

Department of Engineering Management, Industrial Process Management Institute, Faculty of Engineering, University of Debrecen, Ótmető u.2-4, 4028 Debrecen, Hungary; dr.torok.laszlo@eng.unideb.hu

Abstract

This study examines the evolution of the European Union's (EU) energy security and import dependence over the period 2014–2023, shaped by global energy price shocks, the COVID-19 pandemic, and Russia's war against Ukraine. This research aims to explore how the structure of energy imports, domestic production capacities, and the composition of electricity generation shape the vulnerability of EU Member States. It highlights that energy is not only an economic input but also a determinant of social stability and political space. The analysis is based on Eurostat data for 27 Member States. This study combines several methods: panel regression to explore the structural determinants of energy dependence, absolute and relative volatility indicators to measure exposure to shocks, and K-means clustering to map heterogeneity across Member States. The comparison between the pre-2020 and post-2020 periods serves as a robustness check. The results point to three main conclusions. First, natural gas and oil imports remain the primary source of dependency, while domestic electricity generation and balanced gas supply mitigate vulnerability. Second, based on volatility, smaller Member States—particularly the Baltic States and Malta—are disproportionately exposed to shocks. Third, Member States can be grouped into three clusters, although the post-2020 crisis has partly rearranged the grouping of countries. The policy lesson is clear: reducing energy dependency requires diversification, targeted support for smaller Member States, strengthening crisis management capacities, and accelerating the green transition. Energy security and sustainability are not contradictory but mutually reinforcing objectives that will determine the future resilience of the EU.

Keywords: energy dependency; security of supply; volatility; cluster analysis; European Union; energy policy



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1. Introduction

Energy is one of the most fundamental organizing principles of human societies and economic systems. Historical experience consistently shows that every major technological leap—from the Industrial Revolution to the digital age—has been accompanied by an increase in energy consumption. A historical review indicates that during energy transitions, demand for energy services has typically increased, while new technologies have not entirely supplanted prior ones [1]. This observation is further reinforced by [2], who shows that major technological transitions are slow, often additive, and, in the long run, lead to an increase in total energy consumption. Another study reaches a similar conclusion, emphasizing that large-scale technological and institutional changes take decades to unfold, while infrastructure expansion itself increases energy demand [3]. Methodological

reflections further point out that the measurement of historical technological transitions was dominated by their “additive” nature, resulting in a permanent increase in total energy use [4].

However, the literature on the relationship between technological progress and energy efficiency also warns that efficiency gains do not necessarily reduce energy consumption. Comprehensive empirical evidence underscores the importance of rebound effects [5], while Fich et al. (2022) demonstrate—through a modern interpretation of the Jevons paradox—that technological progress often induces excess consumption in complex economic systems [6]. According to the dynamic panel model of Jin et al. (2018) [7], in the short run, innovation increases energy consumption, whereas in the long run, a bidirectional positive relationship emerges between innovation and energy use. Sorrell’s (2010) [8] comprehensive theoretical and empirical review also concludes that historical experience has shown that absolute energy consumption has increased despite efficiency improvements.

These historical patterns are also observed in the current digital era. The rise of artificial intelligence, large data centers, and the digital economy is generating new, unprecedented levels of electricity demand. Several recent studies analyze the rapidly increasing energy demand of AI-based data centers and the associated data-collection challenges [9], while other work quantifies how the cumulative power demand of AI accelerators can affect electricity systems [10]. Model-based analysis further highlights the structural tension between the rapid growth in digital data demand and the limitations of renewable capacity scalability [11]. Several recent studies warn that digital demand could soon exceed realistic electricity generation capacity [12–14]. At the same time, ref. [15] emphasizes that data centers can also enhance system flexibility within appropriate regulatory and technological environments.

The relationship between energy and economic performance is extremely close. GDP and energy use have historically moved together, as energy is a fundamental input to all technological and production processes. Nevertheless, traditional economic models often under-represent the role of energy, which can also lead to distortions in policy-making. The energy crisis of the 2020s—and the subsequent wave of inflation—once again highlighted that the stability of energy supply is a key factor in the economic and social order of the European Union. A wide range of empirical evidence supports a strong link between energy and economic growth [16,17], whereas some studies present a more nuanced picture, noting that a decrease in energy consumption does not always lead to a decline in growth [18].

In Europe, the intertwining of energy, prosperity, and social complexity has been particularly acute amid dependence on Russian energy sources. In the wake of the 2022 war in Ukraine, energy security has clearly acquired a geopolitical and social dimension. The adoption of the REPowerEU program is a good example of how crises accelerate institutional and policy innovation to strengthen energy security [19]. However, several analyses point out that the early effectiveness of policy responses is significantly influenced by external factors, such as global price movements and Russian strategic decisions [20–22].

Three studies on the EU’s energy independence are similar [23–25]. Their common conclusion is that the EU’s energy independence is not a goal that can be captured by a single indicator, but rather the result of a systemic transformation: it is shaped by security of supply, import exposure, energy mix, and transitional performance. All three works emphasize that the shocks of the 2020s (especially the European energy crisis) accelerated the political weight of the energy transition and forced new paths in the Member States. They also consistently point to heterogeneity within the EU: the starting energy structures and adaptability of the Member States differ, and therefore, the path towards energy independence differs for each group of countries. Finally, all three studies implicitly

suggest that energy independence can only be meaningfully interpreted in conjunction with diversification, decarbonization, and institutional/political adaptation.

Several studies emphasize that the EU's energy security is a multidimensional issue: the stability of supply is not only a function of import exposure, but also of technological, systemic, and institutional "readiness". A common element is that the transition (decarbonization) only strengthens energy security if the system's flexibility—especially that of the electricity system—develops in parallel (e.g., storage, integration, and operational adaptation). In addition, all three articles implicitly point to heterogeneity within the EU: the initial energy structures and the "secure transition" trajectories of the Member States differ; therefore, a differentiated policy toolbox is needed [26–28].

Recent research highlights that the transition to a high share of renewable energy in interconnected energy systems involves significant operational risks and uncertainties, as inadequate grid flexibility and storage capacity can lead to instability and limit renewable energy generation, increasing the likelihood of system disruptions even if fossil fuel sources are gradually phased out [29]. The energy transition creates new, difficult-to-predict risks to system stability due to the rise of variable and low-inertia renewables. Therefore, flexibility tools (especially storage) are crucial to maintain a reliable supply [30].

This study provides a comprehensive picture of the security of energy supply and the evolution of import dependence in the European Union, with a particular focus on the period 2014–2023, focusing on the structure of energy imports, degree of energy dependence, gas balance, and source mix of electricity generation. It also reveals that energy is not just an economic input, but also a key factor in social stability, competitiveness, and political space in the EU.

The novelty of the study lies in the fact that it uses a combination of quantitative methods—panel regression, volatility indicators, and cluster analysis—to examine the relationships between energy dependence and security of supply. Through robustness tests (pre- and post-2020), the study provides a reliable picture of how the Russian–Ukrainian war and energy market shocks have transformed the vulnerability and relative position of the Member States.

The originality of the research lies in the fact that it captures energy dependence in a multidimensional way by taking into account import volumes, domestic production capacities, and the structure of the energy mix. This method allows the identification of which EU countries are particularly vulnerable and which are relatively stable.

The contributions of the study are twofold: on the one hand, it provides new scientific evidence of the close relationship between energy and economic performance and its regime-dependent development; on the other hand, it provides guidance for the EU from a policy perspective. Based on the results, the key to increasing energy security is diversification, expanding domestic production capacities, and strengthening flexible crisis management mechanisms. This research thus contributes to reducing the EU's energy dependency and maintaining long-term supply security. The analysis aims to highlight that energy is not just an input to the economy, but also a determinant of social stability and political space.

In response to the geopolitical shock following Russia's invasion of Ukraine, the European Union articulated a strategic objective of eliminating its structural dependence on Russian pipeline gas. This objective has been accompanied by a rapid expansion of LNG import capacity and the development of alternative supply routes, including the Balkan vertical gas corridor, aimed at strengthening interconnectivity between Southern and Central Europe. These measures represent not only short-term crisis management but a structural reconfiguration of the EU's external energy exposure.

The study interprets energy dependence as the proportion of imported energy in a country's total energy consumption, i.e., as a measure of structural exposure to external sources. Security of supply, on the other hand, means the extent to which the energy system can provide a stable, continuous, and affordable energy supply even in the event of external shocks, while energy vulnerability is the combined consequence of dependence and volatility: the extent to which a country is vulnerable to geopolitical, market, or infrastructural disruptions. The three concepts are thus hierarchically linked: high energy dependence increases potential vulnerability, which can ultimately weaken security of supply, especially with low diversification and high volatility.

The research hypotheses are formulated as follows:

H1: *Energy import dependency increases structural vulnerability in the EU, but its effects differ across Member States depending on volatility and diversification levels.*

(Member States with high and volatile import dependency exhibit greater exposure to external shocks, although the magnitude of vulnerability is not uniform.)

H2: *Diversification of the energy mix significantly reduces vulnerability and volatility in the EU energy system.*

(Member States with a more balanced electricity generation structure are more resilient to market and geopolitical disruptions.)

H3: *Deterioration in supply security is associated with heightened macroeconomic pressures, particularly through volatility effects rather than dependency levels alone.*

(Periods of increased energy price volatility and supply instability are linked to inflationary pressures and economic stress in Member States.)

H4: *Coal imports no longer constitute a statistically significant determinant of overall energy dependency in the European Union.*

(Although coal historically played a central role in industrial production and electricity generation, empirical evidence suggests that its current contribution to structural energy dependency is limited compared to gas and oil.)

2. Materials and Methods

2.1. Materials

The analysis uses Eurostat's time series for 2014–2023 and applies multivariate econometric and statistical methods—panel regression, volatility indicators, and clustering—to explore energy dependence and supply security risks among EU Member States.

2.1.1. Eurostat Databases, Their Availability, and Descriptive Data

This subsection presents the names, availability, sources, and verbal analysis of the descriptive data from the previously mentioned Eurostat databases, which form the basis of the analysis.

In order: `nrg_ind_id`: Energy dependency [31]; `nrg_ti_gas`: Imports of natural gas by partner country [32]; `nrg_ti_oil`: Imports of oil and petroleum products by partner country [33]; `nrg_ti_coal`: Imports of solid fossil fuels by partner country [34]; `nrg_cb_gas`: Supply, transformation and consumption of gas [35]; `nrg_cb_em`: Gross and net production of electricity and derived heat by type of plant and operator [36].

2.1.2. Time-Series Analysis of Data from Database

The energy import dependency of the EU27 Member States ranged, on average, from around 33% to 40% between 2014 and 2023, but rose sharply to over 57% in 2023. There

are significant differences between Member States: while some countries have an import dependency of close to 100%, others have significantly lower levels. The increase in the standard deviation in the period 2022–2023 suggests that the effects of the energy crisis have manifested themselves in very different ways across countries.

The natural gas imports of the EU27 Member States showed a slightly increasing trend between 2014 and 2021 and then reached extreme levels during the energy crisis in 2022. The differences between countries are substantial: while some smaller Member States have close to zero gas imports, Germany and Italy imported hundreds of thousands of gigawatt hours of gas annually. The increase in the standard deviation in 2022 reflects the different national energy policies and sources of supply.

EU27 oil imports increased gradually between 2014 and 2019, before falling significantly in 2020 during the COVID-19 pandemic. The largest importers (e.g., Germany, Italy, and France) imported nearly 800,000 GWh annually, while imports from several smaller Member States were negligible. After 2021, the level of imports increased again, but in the period 2022–2023, the standard deviation indicates that the energy crisis affected the Member States differently.

EU27 coal imports decreased continuously between 2014 and 2019, reflecting decarbonization targets and the reduction in coal use. In 2020, import values fell further during the COVID-19 pandemic, followed by a temporary increase in 2021, but the trend slowed down again during the energy crisis of 2022–2023. Differences between countries are significant, with the largest importers (e.g., Germany and Poland) importing orders of magnitude more than smaller, less coal-reliant states.

Gas consumption in the EU27 Member States showed moderate growth between 2014 and 2019, fell during the pandemic in 2020, and then rose again in 2021. During the energy crisis of 2022, gas consumption dropped dramatically, especially in high-consuming countries (e.g., Germany and Italy), while imports in several smaller countries fell to zero. The standard deviation increased gradually until 2021, indicating a growing gap in consumption between countries, before decreasing in 2022–2023 due to a general decline in demand.

Electricity production in the EU27 Member States showed moderate growth between 2014 and 2019, before declining in 2020 due to the COVID-19 pandemic. A temporary increase followed in 2021, but production decreased again in the period 2022–2023 due to the energy crisis and the decline in demand. The differences between countries are enormous: the most prominent producers (e.g., France and Germany) exceed the capacities of the smaller Member States by orders of magnitude, which is also reflected in the outliers in the standard deviation.

Table 1 contains the statistical indicators (mean, min, max, standard deviation) of all five variables (gas imports, oil imports, coal imports, gas balance, electricity production) by country for the period under review.

Table 1 presents the descriptive statistical indicators (mean, minimum, maximum and standard deviation) for all five energy-related variables across the EU27 Member States over the period 2014–2023. The table provides an overview of both the scale and dispersion of national energy supply structures, highlighting the substantial heterogeneity across countries. The mean values reflect the structural size differences of national energy systems, while the minimum and maximum indicators capture the range of variation within the observed period. The standard deviation serves as a first indication of absolute volatility, offering insight into the stability of import flows and domestic production levels over time.

Taken together, the descriptive statistics establish the empirical foundation for the subsequent econometric and clustering analyses by illustrating the magnitude, dispersion, and temporal variability of key energy supply indicators across the European Union.

Table 1. Descriptive statistics on energy supply in the EU27 (2014–2023), data in GWh.

Variable	Value	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Gas imp.	mean	19,413	20,243	20,670	21,952	20,449	21,932	19,196	20,369	22,400	19,390
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	393,355	357,206	368,295	389,909	362,242	405,229	361,800	374,411	405,517	35,888
	std	54,876	58,016	59,595	63,401	58,459	64,265	58,005	60,989	66,549	58,046
Oil imp.	mean	0.00	0.00	44,487	45,424	44,827	44,395	38,294	40,315	42,356	42,263
	min	0.00	0.00	0.00	32.00	0.00	32.00	30.00	30.00	27.00	29.00
	max	796,776	848,637	853,437	868,407	856,724	846,962	745,108	770,748	808,886	785,478
	std	124,477	132,497	133,175	135,433	133,500	132,005	117,342	123,023	129,099	126,714
Coal imp.	mean	988	832	763	775	705	625	541	665	626	525
	min	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
	max	13,951	12,969	12,584	11,591	9993	8987	9085	11,211	10,191	8489
	std	2850	2605	2497	2306	2005	1783	1758	2169	1981	1658
Gas bal	mean	941,910	983,800	1,041,409	1,100,201	1,080,105	1,114,700	1,087,761	1,132,058	986,024	913,983
	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	max	13,186,744	13,773,201	14,579,727	15,402,817	15,121,470	15,605,800	15,228,655	15,848,814	13,804,329	12,795,757
	std	2,509,386	2,622,159	2,777,797	2,935,075	2,879,237	2,971,780	2,897,621	3,017,686	2,632,380	2,440,667
Elec gene	mean	197,435	200,561	202,048	204,313	203,084	200,613	192,505	201,217	194,803	189,695
	min	2014	1305	857	1652	1962	1908	2020	2021	2022	2023
	max	2,861,798	2,907,124	2,928,685	2,961,525	2,943,714	2,907,879	2,790,313	2,916,638	2,823,631	2,749,567
	std	535,693	544,553	547,748	553,531	550,542	543,014	520,321	543,539	512,052	511,198

Source: Own calculation.

Table 2 summarizes the link between the Eurostat energy databases, the indicators derived from them, the applied analytical methods, and the specific research hypotheses they are intended to test.

Table 2. Data sources, indicators, methods, and related hypotheses.

Eurostat Database	Indicator (Example)	Method Applied	Related Hypothesis
nrg_ind_id–Energy dependency	Share of energy imports in total consumption (%)	Descriptive statistics, correlation analysis, panel regression	H1
nrg_ti_gas, nrg_ti_oil, nrg_ti_sff–Imports of energy products	Share of gas, oil, and coal imports by partner country	Diversification indices, panel regression	H1, H2
nrg_cb_gas–Gas balance	Imports and gross inland consumption of natural gas	Panel regression, K-means clustering	H1, H2
nrg_ind_peh–Electricity generation by source	Share of fossil, renewable, and nuclear in power generation	Diversification indices, K-means clustering	H2
Integrated dataset (from multiple sources)	Country energy security profile (dependency + energy mix)	K-means clustering (country typology)	H1, H2, H3
nrg_ti_coal (imports of energy products)	Share of coal imports in total energy supply	Panel regression	H4,

Source: Own compilation.

2.2. Methods

The methodological framework used in this research provides a multidimensional and reliable assessment of energy dependence and supply security risks among EU Member States using various quantitative techniques—panel regression, volatility indicators, cluster analysis, and robustness tests. Analyses were performed by running Python 3.13. algorithms.

2.2.1. Panel Regression (Fixed-Effect Model/Random-Effect Model)

The aim of using panel regressions is to measure the impact of energy dependence and the energy mix on economic and political risk indicators (e.g., energy prices, inflationary pressures, and social welfare proxies).

The panel regression framework is applied to identify the structural determinants of energy dependency in the European Union. The objective of this model is not to estimate macroeconomic performance directly, but to examine how fossil fuel import flows and diversification patterns shape the level of dependency across Member States.

The gas balance variable also indirectly captures the effects of post-2022 infrastructure expansion, including LNG terminal development and the reinforcement of cross-border corridors such as the Balkan vertical route. As such, it reflects not only domestic availability but also the evolving architecture of EU gas security policy.

Panel regression formula:

$$Dependency_{it} = \alpha + \beta_1 GasImport_{it} + \beta_2 OilImport_{it} + \beta_3 CoalImport_{it} + \beta_4 Diversification_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where i denotes the Member State and t the year (2014–2023). The dependent variable

$Dependency_{it}$ represents the energy dependency rate as reported by Eurostat (database: `nrg_ind_id`), measured as the percentage share of net energy imports in gross available energy. This indicator captures the structural exposure of national energy systems to external supply sources.

The key explanatory variables include fossil fuel imports—natural gas (`nrg_ti_gas`), oil (`nrg_ti_oil`), and coal (`nrg_ti_coal`)—measured in physical energy units (GWh or equivalent, harmonised across datasets). These variables reflect the quantitative dimension of external energy reliance. In addition, a diversification index (Shannon or Herfindahl–Hirschman type) is included to account for the structural composition of the electricity generation mix. The diversification indicator is dimensionless and captures the balance between renewable, nuclear, and fossil energy sources.

The term μ_i denotes country-specific fixed effects, capturing time-invariant structural characteristics such as historical energy system design, geographical constraints, and institutional factors. The time fixed effects λ_t control for common shocks affecting all Member States, including global energy price fluctuations, the COVID-19 pandemic, and the geopolitical consequences of Russia's invasion of Ukraine. The error term ε_{it} captures idiosyncratic disturbances not explained by the model.

A fixed-effects estimator is applied as the baseline specification to control for unobserved heterogeneity across countries. Random-effects models are also estimated for robustness comparison, with the Hausman test guiding model selection.

The panel regression methodology is widely used in macroeconomic research, and this procedure was used in [37,38].

2.2.2. Absolute Volatility (Standard Deviation)

Absolute volatility measures the actual quantitative fluctuations in the import and production of energy carriers, expressed in GWh, providing an accurate picture of which Member States experienced the most significant actual volatility in their supply during the period under review. The results reveal which Member States are most in need of security of supply buffers, such as expanding storage capacities or strategic reserves.

Absolute volatility formula:

$$\sigma_i = \sqrt{1/T \sum_{t=1}^T (x_{it} - \bar{x})^2} \quad (2)$$

where σ_i : the absolute volatility value for country i (and given indicator); x_{it} : the value of the indicator related to energy dependence, imports, or production in country i , in year t ; $\bar{x}_i$: the period average of the given indicator for country i ; T : length of the period (in this study, 2014–2023, i.e., 10 years).

Absolute volatility (standard deviation) measures how volatile a given Member State's energy imports or energy balance is over time; higher standard deviations indicate greater exposure to external market and geopolitical shocks. Member States with volatility persistently above the EU average face greater operational uncertainty and may therefore need to strengthen strategic reserves, storage capacities, or diversification “buffers”.

The study does not set a normative threshold but adopts a relative approach: volatility values in the upper quintile (or above the EU average plus 1 standard deviation) are considered high risk. These ranges indicate countries where strengthening the energy system with stabilizing instruments is politically more justified.

The absolute volatility method is a frequently used methodology in macroeconomic research, and this procedure was used in [39,40].

2.2.3. Relative Volatility

Relative volatility, or the coefficient of variation, shows the volatility relative to the average level and is therefore an excellent indicator of the vulnerability of small, import-dependent countries. This indicator highlights that even if the absolute amounts are low, relative volatility can pose a serious risk to smaller economies. This is particularly important in the EU's security of supply policy, as it helps identify seemingly marginal Member States that are actually vulnerable.

Relative volatility formula:

$$CV_i = \sigma_i / \bar{x}_i \quad (3)$$

where CV_i : relative volatility calculated for country i , and σ_i : absolute volatility of a given energy indicator for country i .

According to the guideline often used in the statistical literature, $CV < 0.10$ is considered low, 0.10–0.20 moderate, 0.20–0.30 high, and >0.30 very high volatility [41].

The relative volatility methodology is a frequently used procedure in macroeconomic analyses and has been used in [42,43].

2.2.4. Cluster Analysis/Country Typology

This method groups the EU27 Member States based on their energy policy profile.

The K-means clustering method groups EU countries based on their energy supply and volatility profiles, thus providing a structured picture of the similarities and differences between Member States. The results show which Member States fall into the categories of small, volatile importers and medium-sized, moderate-risk, and large, stable systems. This methodology contributes to the EU's policy clustering in addressing the challenges of energy security and energy dependency.

The K-means methodology uses the following equation:

$$\mu_l = 1/C_l \sum (x_i \in C_l) X_i \quad (4)$$

where μ_l is the centroid of the l th cluster, C_l is the set of the l th cluster, and X_i is the i th data point belonging to the l th cluster.

Link to hypothesis: all three, but especially H1 and H2.

The K-means clustering procedure is applied to classify EU Member States according to their combined structural exposure and volatility characteristics in the energy system. Prior to clustering, all variables—absolute volatility (standard deviation), relative volatility (coefficient of variation), and energy dependency rate—are standardized (z-scores) to

ensure comparability across different measurement scales. This normalization prevents variables with larger numerical ranges from dominating the clustering outcome.

The algorithm partitions the 27 Member States into K clusters by minimizing within-cluster variance (sum of squared Euclidean distances from cluster centroids). The optimal number of clusters is determined using the elbow criterion and variance-explained diagnostics, balancing interpretability with statistical coherence. The clustering process is iterative: initial centroids are randomly assigned, countries are allocated to the nearest centroid, and cluster centers are recalculated until convergence is reached.

The resulting clusters reflect distinct structural profiles rather than purely size-based groupings. Specifically, the classification differentiates between highly volatile and import-dependent systems, moderately exposed and partially diversified systems, and relatively stable, diversified systems with lower structural vulnerability. By combining both absolute and relative volatility indicators, the clustering captures not only the magnitude of fluctuations but also their proportional significance within national energy systems.

This multivariate approach provides a policy-relevant segmentation of Member States, enabling differentiated strategic responses tailored to volatility intensity, structural dependency, and diversification capacity.

Clustering is a frequently used methodology in macroeconomic research and has been used in [44,45].

2.2.5. Robustness Test

The inclusion of robustness tests in this study is essential, as the energy dependence and security of supply of the EU and its Member States may be affected by sudden shocks, such as the COVID-19 pandemic and the energy crisis of 2022. Without testing the stability of the results across time periods and methodological variations, there is a risk that the results may only reflect short-term distortions rather than structural relationships.

$$y_{it} = \alpha_i + \tau_t + \beta'X_{it} + \gamma'(X_{it} \times Post_t) + u_{it} \quad (5)$$

where y_{it} is the energy import dependency (EU Member State i , year t), X_{it} is the vector of energy indicators (e.g., ln gas/oil/coal import, gas balance, electricity production), $Post_t$ is the indicator for the period after 2020, and α_i and τ_t are country and year fixed effects. The u_{it} at the end of the equation represents the error or residual term.

The inclusion of robustness testing in this study is essential, as the energy dependence and security of supply of the EU and its Member States may be significantly influenced by extraordinary shocks, including the COVID-19 pandemic and the 2022 energy crisis. To ensure that the estimated relationships reflect structural dynamics rather than short-term disturbances, a structured robustness framework is applied.

First, temporal stability is tested by re-estimating the panel regression model for two sub-periods (2014–2019 and 2020–2023). This split-sample approach allows us to assess whether the estimated coefficients—particularly those related to gas and oil imports and diversification—remain consistent before and after the crisis period. Stability of coefficient signs and statistical significance across sub-periods is interpreted as evidence of structural robustness.

Second, model specification robustness is examined by comparing fixed-effects and random-effects estimations. The Hausman test is employed to determine whether country-specific unobserved heterogeneity is correlated with the explanatory variables. Consistency between estimators strengthens confidence in the validity of the baseline specification.

Third, alternative operationalizations of diversification (Shannon index vs. Herfindahl–Hirschman index) are used to verify that the identified relationship between diversification and dependency is not sensitive to the choice of index. If the direction and magnitude

of coefficients remain comparable across index specifications, the results are considered methodologically robust.

Together, these robustness checks confirm that the main findings—namely the dominant role of gas and oil imports and the mitigating effect of diversification—are not artifacts of a specific time window or variable definition, but reflect stable structural characteristics of EU energy dependency.

The study tests robustness using four complementary procedures. First, the panel regression was re-estimated using both fixed-effects and random-effects specifications, and additionally for two sub-periods (2014–2019 and 2020–2023). Coefficient signs, magnitudes and statistical significance were compared across models to assess structural stability.

Second, absolute volatility (σ) rankings were recalculated for the two sub-periods, and Spearman rank correlations were computed to evaluate temporal stability. High correlation values indicate persistent absolute fluctuation patterns.

Third, relative volatility (coefficient of variation) rankings were similarly compared using rank correlations to determine whether proportional vulnerability changed over time.

Fourth, K-means clustering was re-estimated for the full sample and sub-period datasets. Cluster similarity was evaluated using the Adjusted Rand Index (ARI), which measures the degree of agreement between cluster solutions.

These procedures ensure that the reported results reflect structural relationships rather than period-specific distortions.

Robustness testing is a frequently used methodology in macroeconomic research and has been used in [46,47].

3. Results

The results presented below reveal how energy import structure, domestic production capacities, and volatility patterns affect the energy dependence and security of supply situation of EU Member States, highlight structural differences between countries, and provide a basis for subsequent policy interpretation.

3.1. Panel Regression Results (FE vs. RE)

The main results are shown in Table 3 (coefficient (SE), significance: *** $p < 0.001$, * $p < 0.05$).

Table 3. Panel regression results on EU energy dependency.

Variable	Fixed Effects (FE)	Random Effects (RE)
in_coal_import	−0.12 (0.54)	−0.15 (0.28)
in_electricity_generation	−4.10 (4.19)	−8.40 (2. 27) ***
in_gas_balance	−6.09 (1.28) ***	−6.15(0.69) ***
in_gas_import	9.99 (2.17)	20.21 (1.02) ***
in_oil_import	9.71 (6.65)	6.44 (2.91) *

Source: Own calculation. *** $p < 0.001$, * $p < 0.0$.

The economic interpretation of the panel estimates clearly outlines the structural determinants of the European Union’s energy dependence. The positive and significant coefficient for the logarithm of natural gas imports in both the fixed- and random-effects models suggests that increases in gas imports disproportionately strengthen import dependence. Since gas plays a key role in the EU energy system—especially in industrial use and electricity balancing—exposure to external gas sources creates structural vulnerability.

For oil imports, the positive relationship is significant only in the random-effects model, suggesting that oil continues to contribute to energy dependence. Still, its impact is less homogeneous across Member States. This is consistent with the fact that oil is primarily dominant in the transport sector, where demand elasticity and substitutability

are limited. At the same time, the diversification of supply sources is more advanced than for natural gas.

Coal imports do not show a stable and significant relationship with energy dependence in any of the models. This suggests that the role of coal in the EU energy structure is no longer a determining structural factor, which empirically supports the realignment within the fossil energy mix and the gradual relegation of coal to the background.

The negative, highly significant coefficient for the gas balance (supply/use ratio) indicates that strengthening domestic availability—for example, through storage, LNG capacity, or alternative supply routes—reduces energy dependence. This expresses economically that supply-side stabilizing mechanisms reduce the structural weight of external exposure.

The negative sign of the logarithm of electricity production—especially pronounced in the random effects model—indicates that higher domestic production capacity reduces overall import dependence. This suggests that electrification and strengthening the domestic production base (especially renewables and nuclear sources) represent a structural advantage for EU member states not only from a climate policy perspective, but also from an energy security perspective.

The R^2 of 0.968 means that the model “captures” the differences between countries and between years very well, i.e., the development of energy dependence can be largely explained by the factors involved. The fact that the random effects model gives similar results shows that the main conclusions do not depend on a single calculation method, but reflect a stable pattern.

The regression results indicate that natural gas and oil imports are statistically significant determinants of energy dependency, while coal imports do not exert a robust and significant effect. This finding suggests that the contemporary structure of EU energy vulnerability is primarily linked to gas and oil exposure rather than coal reliance. The diversification variable shows a negative and significant coefficient, indicating that a more balanced electricity generation structure mitigates structural dependency. Country fixed effects confirm persistent heterogeneity across Member States, while time effects reveal a marked post-2020 increase in common volatility without fundamentally altering the underlying structural drivers of dependency.

According to the verbal assessment of the data, (1) Hypothesis H1 (import dependence vs. vulnerability) is supported by the fact that the coefficients for gas and oil imports are consistently positive and (especially for gas) highly significant. (2) H2 (diversification reduces risks) is indirectly supported: the negative sign of the gas balance and domestic electricity production suggests that higher domestic availability/production is associated with lower dependence. (3) The effect of coal imports is not significant; this may be consistent with the persistent decline in the weight of coal in the EU energy mix and with the fact that the variance in the dependency ratio is predominantly driven by gas and oil.

For the EU as a whole, the panel regression results clearly show that the most significant drivers of EU energy dependence are natural gas and oil imports. In other words, the greater the proportion of these that an EU Member State has to obtain from abroad, the more vulnerable the economy and society are. This relationship was also statistically robust, especially in the case of natural gas. This resonates with the experience of the 2022 energy crisis, when disruptions in Russian gas supplies directly drove up prices and triggered a wave of inflation in the EU.

However, the impact of import dependence is tempered by the role of domestic resources and production: where domestic electricity generation is high (for example, in France thanks to nuclear power plants, or in the Scandinavian countries based on hydropower), the economy is less dependent on external energy suppliers. Similarly, in the gas balance, the existence of domestic production and storage capacity (for example, the

Netherlands, while still producing large volumes of natural gas from the Groningen field) significantly reduced dependence. This kind of “energy self-sufficiency” is also a key issue in political decision-making, because it is directly related to security of supply and the daily livelihood of the population (utilities, fuel prices).

The extremes in each Member State further illustrate the complexity of the situation. The import dependence of the Baltic States (Estonia, Latvia, Lithuania) and Finland was almost 100% for natural gas between 2014 and 2021, which means that they were almost entirely dependent on a single (Russian) source—this meant not only economic but also geopolitical vulnerability.

The results also show that Hungary is the most vulnerable economy in the EU to energy price shocks, as it is both highly import-dependent and highly energy-intensive. In the event of an EU-wide Russian gas embargo, Hungary would suffer the most significant GDP drop in the EU, of more than 4%.

Germany and Italy are among the largest gas and oil importers in the EU: the development of consumption in these countries directly affected the priorities of the EU’s energy policy, as these countries are decisive in terms of inflation and industrial competitiveness in the EU.

On the other extreme are countries such as France (nuclear self-sufficiency) and Sweden (hydro and wind energy), where high domestic energy production acts as a protective shield and has mitigated the risks arising from import dependence.

In addition to the aggregated EU-level results, the country-specific effects of the panel estimates also show well-interpretable patterns. In the case of France and Sweden, the negative sign of the country-fixed effects and the significant role of diversification indicate that nuclear and renewable electricity production reduce the structural level of import dependence. The energy dependence of these two countries is less sensitive to changes in gas imports than the EU average.

In the case of the Netherlands, the coefficient for gas imports is positive and strong, suggesting that the country has become more sensitive to external procurement following the decline in its domestic production capacity. According to the model, the change in the gas market position significantly increases the dependency indicator.

In Estonia, Latvia, and Lithuania, the effect of gas imports is particularly pronounced, which can be explained by historical Russian exposure and small-scale energy systems. When interpreted together with the volatility indicators, these countries belong to the most shock-sensitive group.

In Finland, the model shows a moderate but positive gas import effect, while diversification of the electricity generation structure partially dampens dependency. The results indicate signs of structural adjustment after 2022.

In Hungary, gas imports have a strong, positive relationship with the dependency indicator, while the effect of diversification is weaker. This indicates that the system is sensitive to external gas sources and that structural exposure is permanent.

For Germany, the coefficients for gas and oil imports are positive, but the growth in electricity generation (especially the increase in the share of renewables) partially offsets the dependency effect. The model reflects the structural consequences of the high gas exposure before 2022.

In Italy, the role of oil imports is more pronounced. At the same time, gas imports are also significant, suggesting an import-oriented structure stemming from the country’s geographical location and Mediterranean supply routes.

Overall, the panel regression results show that, while gas and oil are the most important determinants for the EU as a whole, structural differences across the individual

Member States—energy mix, size, historical trajectory, and diversification—significantly influence the intensity and sensitivity of dependency.

The strong and statistically robust impact of gas imports on dependency levels provides empirical support for the EU’s strategic objective of phasing out Russian gas supplies. The results suggest that diversification through LNG imports and alternative transit corridors is economically justified, as gas dependency constitutes the most structurally significant driver of vulnerability within the Union.

Overall, the panel regression analysis provides quantitative evidence that EU energy dependency is shaped by both import structure and internal diversification capacity, highlighting the differentiated nature of vulnerability across Member States.

3.2. Results of Absolute Volatility Calculation

Table 4 shows the standard deviations for gas, oil, coal imports, gas balance, and electricity production by EU Member States.

Table 4. Absolute volatility values by EU Member State, data in GWh.

Country	Gas Imports σ	Oil Imports σ	Coal Imports σ	Gas Balance σ	Electricity Generation σ
Austria	2282.99	773.33	12.66	27,985.69	3252.56
Belgium	2523.96	3732.34	200.81	53,164.18	1,025,437
Bulgaria	235.41	999.87	12.69	9707.96	3328.48
Croatia	685.79	374.04	3.19	8272.36	1741.29
Cyprus	0.00	149.46	11.52	0.00	311.14
Czechia	841.65	571.22	1363.90	30,651.25	3253.78
Denmark	2492.0	1382.53	8.14	17,691.13	2141.21
Estonia	64.86	231.65	8.83	2613.54	2842.13
Finland	488.88	1508.84	51.91	20,334.38	4126.57
France	4244.85	9526.76	63.08	128,896.32	32,850.86
Germany	12,895.35	6113.72	527.77	242,001.17	45,133.05
Greece	1137.85	1313.11	6.28	43,092.32	2541.22
Hungary	1434.93	556.01	221.95	34,575.71	2364.96
Ireland	965.9	465.12	27.53	14,165.36	2183.95
Italy	5558.78	5942.49	66.75	196,223.72	8946.65
Latvia	211.41	282.95	208.73	8022.56	769.43
Lithuania	420.07	936.77	8.18	13,580.98	743.91
Luxembourg	123.69	228.55	4.54	4834.01	312.62
Malta	179.61	253.75	4.54	6966.07	490.11
Netherlands	5361.17	7578.52	562.43	155,492.70	6391.59
Poland	2172.63	2737.23	1858.49	68,109.37	7381.12
Portugal	782.02	1443.58	21.41	31,341.65	4134.41
Romania	1073.74	1098.19	201.18	12,162.58	1224.34
Slovakia	837.39	324.67	7.70	324.67	7.70
Slovenia	55.37	417.14	0.37	2123.14	1078.29
Spain	2410.46	5166.26	339.42	109,404.37	7849.65
Sweden	207.53	1868.41	37.08	8267.25	6170.99
EU	21,572.60	42,440.40	558.96	1,075,480.00	70,307.58

Source: Own calculation.

Based on the calculation of absolute volatility, this study reveals that the most significant fluctuations in the European Union’s energy imports and consumption are observed in the oil and gas markets. The standard deviation for oil imports is in the order of several ten thousand GWh, while that for the gas balance is also outstanding. This high volatility reflects the extent to which the EU’s energy system is exposed to external shocks, including global price fluctuations, geopolitical events (e.g., sanctions and war conflicts), and changes in market demand and supply.

In contrast, the electricity generation sector is characterized by a greater degree of stability than the gas balance. The absolute volatility here is lower, which means that the domestic production capacities of EU Member States (e.g., nuclear power plants, renewables, and conventional power plants) can ensure a more continuous supply to meet consumption. This highlights that domestic energy production is a key stabilizing factor in the EU's security of supply.

There are countries in the EU with significant fluctuations, such as Germany, Italy, and France. These large economies exhibit a substantial absolute variance in oil and gas imports. The magnitude alone explains the high volatility: with annual imports of hundreds of billions of GWh, even a slight percentage fluctuation represents a significant absolute fluctuation. This magnitude is why the political decisions of these countries have a direct impact on the entire EU energy market.

The case of Poland is unique: It has exceptionally high volatility in coal imports and coal-related energy consumption. This is a sign of the transformation of the coal-based energy mix: due to the phase-out policy and market forces (e.g., CO₂ quota prices), the volume of coal imports has fluctuated strongly.

There are countries in the EU with low volatility, but these Member States are highly vulnerable. These countries include the Baltic States (Estonia, Latvia, and Lithuania) and smaller Member States (Malta, Cyprus, and Luxembourg), for which the absolute standard deviations are low, because the total volume of energy imports is also low. However, this does not mean a lower risk: these countries typically rely on a few sources, so the loss of even one supplier can have dramatic consequences. Absolute volatility in itself can therefore be misleading—in relative terms (based on the CV to be calculated in the next step), these countries show a much more volatile picture. Finally, this study highlights special case countries, such as France: Although its import volatility is significant, its electricity production is remarkably stable (relative to the size of the country's electricity production). This is due to the large nuclear capacity, which ensures quasi-constant production, highlighting that domestic, low-carbon energy sources support not only climate protection goals but also supply security goals.

Figure 1 illustrates the 15 Member States of the European Union with the highest energy volatility, based on data from 2014 to 2023.

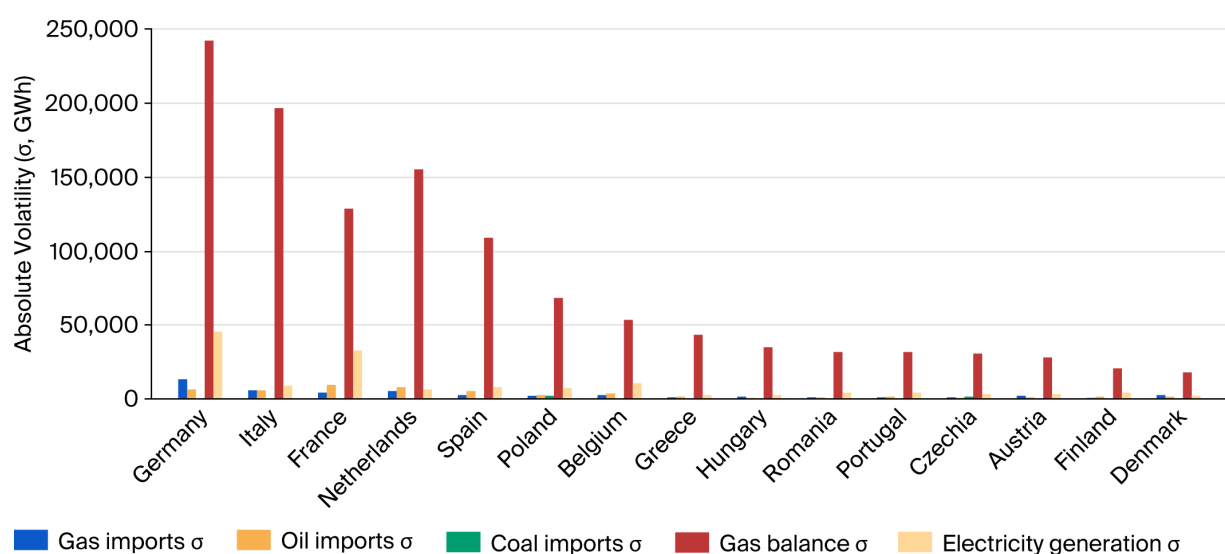


Figure 1. Top 15 EU Member States based on total (aggregated) absolute volatility.

This study ranked the countries based on the aggregated absolute volatility of the five indicators examined (gas, oil, coal imports, gas balance, and electricity production).

For each country, five columns are displayed, indicating the standard deviation (volatility) of the different energy sources in GWh. The diagram clearly highlights that Germany, Italy, and France exhibit the highest volatility, particularly in the areas of gas and oil imports. In contrast, in the case of several Central and Eastern European countries, coal-related volatility is dominant, while electricity production is relatively stable everywhere.

3.3. Relative Volatility Results

The relative indicator of absolute volatility in Table 5 shows that it is not only large EU importers that are vulnerable. The CV values of oil and gas imports are lower in several large Member States (e.g., Germany, around 0.05–0.14), while in smaller states, they are often above 0.3–0.5. This indicates that small and medium-sized EU economies are more susceptible to relative volatility.

Table 5. Relative volatility values.

Country	Gas Imports CV	Oil Imports CV	Coal Imports CV	Gas Balance CV	Electricity Generation CV
Austria	0.287	0.055	0.408	0.084	0.046
Belgium	0.123	0.063	0.444	0.081	0.120
Bulgaria	0.079	0.119	1.960	0.082	0.073
Croatia	0.357	0.079	1.398	0.078	0.128
Cyprus	0.000	0.060	2.531	0.063	0.081
Czechia	0.104	0.051	0.447	0.097	0.039
Denmark	1.214	0.121	1.173	0.174	0.068
Estonia	0.137	0.124	1.553	0.149	0.296
Finland	0.203	0.091	0.814	0.222	0.058
France	0.091	0.105	1.274	0.078	0.059
Germany	0.141	0.049	0.284	0.073	0.074
Grece	0.236	0.041	1.354	0.230	0.049
Hungary	0.168	0.057	0.619	0.092	0.071
Ireland	0.305	0.054	0.932	0.071	0.071
Italy	0.084	0.077	0.268	0.073	0.031
Latvia	0.186	0.122	0.835	0.176	0.127
Lithuania	0.155	0.091	0.963	0.163	0.160
Luxembourg	0.163	0.085	1.686	0.154	0.133
Malta	0.697	0.092	2.381	0.700	0.257
Netherlands	0.155	0.052	0.565	0.115	0.055
Poland	0.141	0.080	0.170	0.094	0.044
Portugal	0.146	0.091	2.465	0.145	0.080
Romania	0.568	0.098	1.652	0.075	0.067
Slovakia	0.167	0.045	0.121	0.066	0.044
Slovenia	0.064	0.096	0.655	0.065	0.067
Spain	0.068	0.062	0.612	0.087	0.028
Sweden	0.202	0.068	1.046	0.200	0.038

Source: Own calculation.

Member States with high CV values, such as Cyprus, Malta, Croatia, Bulgaria, and the Baltic States (especially in coal and gas imports), exhibit extreme volatility in relative terms (e.g., Cyprus's coal import CV exceeds 2.5). This suggests that the energy supply structure in these EU Member States is highly vulnerable, and even minor market shocks can have a significant socio-economic impact.

Contrary to the previous statement, Member States with low CV values, such as those for Germany, France, Italy, and Spain, generally range between 0.05 and 0.15, reflecting the stabilizing effect of the order of magnitude and the multi-tiered energy structure.

The results also show sectoral differences, for example, for coal imports: it shows exceptionally high relative volatility in several Central and Eastern European countries (Bulgaria, Croatia, and Poland). This is the result of the coal phase-out and market uncertainties.

Gas imports present a different picture: their relative volatility is significantly higher in smaller EU Member States, while it is more moderate in larger economies; however, in absolute terms, it remains the most critical factor.

EU electricity production is stable in most Member States, with CV values between 0.05 and 0.15. This confirms that domestic production is much less volatile than import-dependent sources.

Relative volatility is a significant indicator because it indicates which EU Member States are most exposed to security of supply risks. Smaller Member States such as Cyprus, Malta, or Lithuania, despite being in the “low-risk” category based on absolute variance, are highly vulnerable in relative terms. This situation is also politically sensitive, as fluctuations in household prices can directly trigger social discontent.

Figure 2 shows the 15 EU Member States with the highest relative volatility (CV) in energy supply between 2014 and 2023.

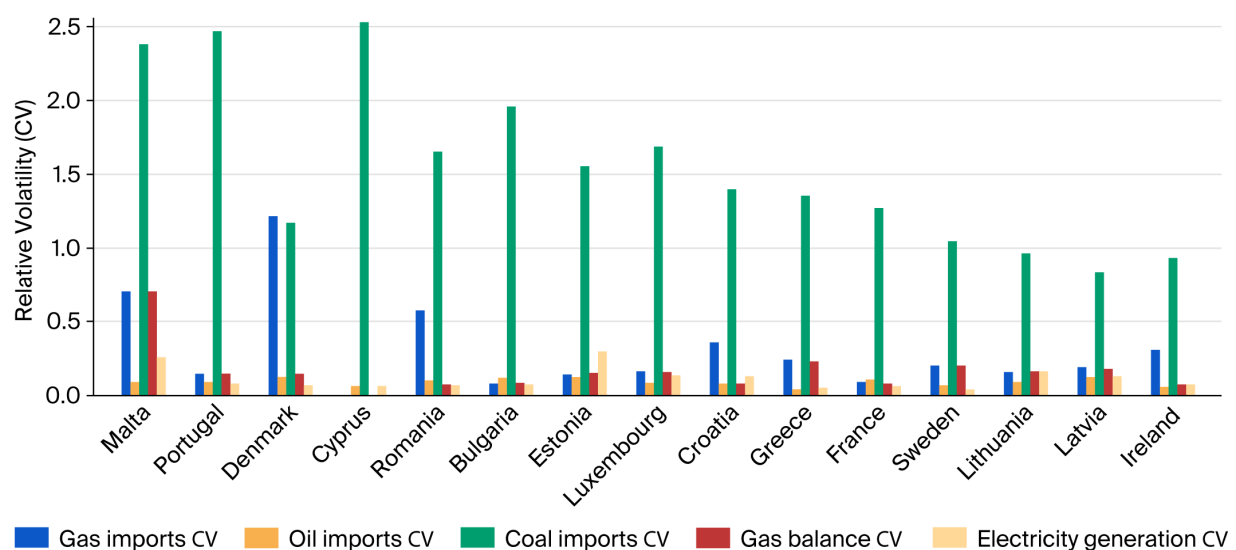


Figure 2. Top 15 EU Member States, ranked by total relative volatility (CV).

The study ranked the countries based on the combined magnitude of relative volatility in gas, oil, coal imports, gas balance, and electricity generation.

For each country, five columns are displayed, showing the volatility of each energy source relative to the average for that country. The results show that smaller and more import-dependent countries (e.g., Cyprus, Malta, and Lithuania) are much more volatile in relative terms than larger economies (e.g., Germany, France, Italy).

The more robust volatility indicates that smaller EU Member States face higher security of supply risks, even if they have smaller energy flows in absolute terms.

3.4. Clustering Results

K-means clustering distinguished three distinct clusters, which are presented in detail below.

Cluster 1—Cluster of small, volatile importers: The first cluster comprises countries whose energy systems have a small absolute size but exhibit the most significant fluctuations in relative terms. The CV values of gas and coal imports are particularly high (Gas imports CV $\approx$ 0.42; Coal imports CV $\approx$ 1.97), meaning that the volume of imports varies very strongly from year to year compared to the average. Due to the low volume in these EU Member States, even a slight actual fluctuation can represent a relatively profound economic shock. The Member States classified here are Cyprus, Malta, Luxembourg, Lithuania, Latvia, Estonia, Croatia, and Bulgaria. Their common feature is strong import

dependence and limited diversification of supply routes. From a policy perspective, this means that even minor market disruptions can easily compromise the stability of their energy supply. They need to strengthen regional integration, for example, by building new interconnectors, increasing access to LNG terminals, and developing strategic reserves.

Cluster 2—Medium-sized, moderate-risk countries: The second cluster includes countries with medium-sized energy systems and moderate volatility. The absolute volatility (σ) values are medium (Gas $\sigma \approx 949$; Oil $\sigma \approx 1058$; Electricity $\sigma \approx 3081$), and the relative CV is lower than in Cluster 1 but higher than in the largest economies. These countries tend to have a diversified energy mix, but are still significantly affected by external shocks. Examples include the Czech Republic, Slovakia, Slovenia, Portugal, Greece, Ireland, Hungary, and Romania. In this group, the most critical issue for energy policy is to maintain the existing diversification and increase demand-side flexibility (energy efficiency, consumption reduction, and demand response). These countries exhibit a medium level of vulnerability; however, EU energy policy coordination can serve as a valuable safety net for them.

Cluster 3—Cluster of large, stable, systemic countries: The third cluster includes the Member States with the largest energy systems, which show extremely high volatility in absolute terms (Gas $\sigma \approx 6094$; Oil $\sigma \approx 6866$; Gas balance $\sigma \approx 166,404$; Electricity $\sigma \approx 20,234$), but in relative terms these fluctuations are more minor (Gas CV ≈ 0.11 ; Oil CV ≈ 0.07 ; Electricity CV ≈ 0.05). This means that although their markets are subject to huge volumes, these shocks have a less significant impact on the economy compared to their size. The countries included here are Germany, France, Italy, Spain, the Netherlands, Poland, Sweden, Belgium, Austria, Finland, and Denmark. These large systems are, in fact, key players in the stability of the EU's energy policy: if a severe disruption occurs in them, the consequences will also be felt at the EU level. From a political perspective, the countries in this cluster are therefore responsible not only for their own stability but also for the resilience of the EU's energy market as a whole. In their case, the primary challenge is to manage systemic risks (e.g., the loss of Russian imports during the 2022 gas crisis) and to refine the mechanisms of the internal energy market to prevent price crises.

The countries are arranged in three clusters in Figure 3, which are separated by colors (red, blue, and green). The figure, therefore, provides a visual summary of how EU Member States are separated by their energy profile and highlights the distances between the clusters.

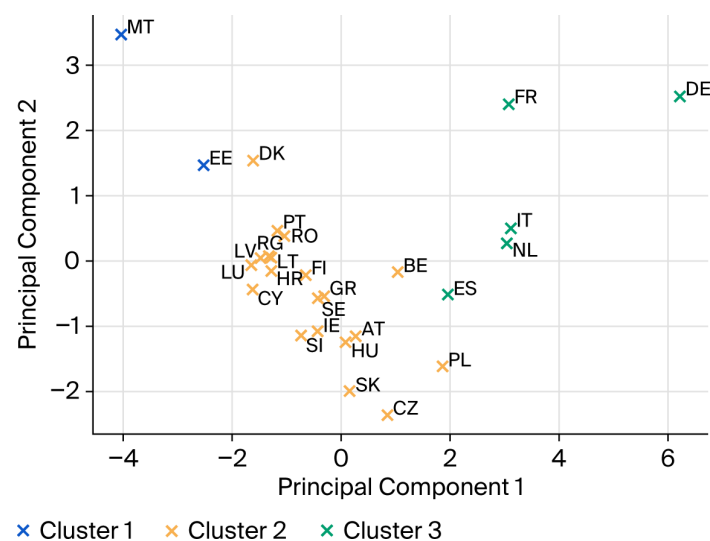


Figure 3. Clusters of EU Member States based on energy profile.

3.5. Robustness Checks and Results

By demonstrating that the main drivers of dependency remain robust, while the relative vulnerability of Member States has shifted, robustness checks ensure that the conclusions are scientifically credible and policy-relevant, providing a sound basis for long-term energy security strategies.

The results of the robustness tests for the four methodologies used in the study are presented in Table 6.

Table 6. Summary table—robustness checks.

Method	Stability Result	Key Message
Panel regression	Stable coefficients (gas & oil +; gas balance & electricity −; coal)	Structural drivers of dependency unchanged
Absolute volatility (σ)	High correlation ($\rho = 0.72\text{--}0.91$)	Countries with largest absolute swings remained the same
Relative volatility (CV)	Low correlation ($\rho \approx 0.1\text{--}0.2$, n.s.)	Relative vulnerability of small/medium states reshaped
K-means clustering	Moderate stability (ARI = 0.45)	Tripartite structure intact, but membership partly changed

Source: own calculation.

To check the stability of the empirical results, the dataset was split into two sub-periods: 2014–2019 (pre-shock period) and 2020–2023 (shock/post-shock period), reflecting the structural break caused by the COVID-19 pandemic and the subsequent European energy crisis. Panel regression analyses, volatility indicators, and cluster analyses were repeated in these two regimes. The results show that while the structural drivers of energy dependence remain robust, the relative positions of EU Member States show a significant rearrangement after 2020.

The panel regression results indicate that natural gas and oil imports consistently increase energy dependence, whereas a stronger domestic gas balance and increased electricity generation reduce it. Coal imports are not significant in either period. Absolute volatility indices (σ) were found to be stable, with Spearman rank correlations above 0.7 between the two time windows, meaning that the EU Member States with the most considerable absolute fluctuations remained unchanged. In contrast, relative volatility ranks (CV) were much less stable ($\rho \approx 0.1\text{--}0.2$, not significant), indicating that a shift in the relative vulnerability of several smaller and medium-sized Member States occurred.

Robustness checks confirm the temporal consistency of the results, but also highlight that the EU energy vulnerability map has evolved since 2020, necessitating more flexible energy security strategies, particularly those tailored to smaller Member States.

4. Discussion and Conclusions

The results of the study clearly show that the European Union's energy security remains heavily dependent on fossil fuel imports. Panel regressions indicate that natural gas and oil imports are strongly and positively correlated with the energy dependency indicator; that is, the more a country relies on these sources, the more vulnerable it becomes to external shocks. In contrast, diversification of domestic production capacities, especially in electricity generation, reduces dependency and contributes to stability. This is particularly evident in the case of France, where nuclear capacity has reduced import dependency, and in Sweden and Finland, where a high share of renewable generation has strengthened resilience.

The volatility analyses also revealed that the magnitude and relative importance of energy imports vary considerably across Member States. While absolute volatility was

significant in Germany and Italy due to their large volumes, relative volatility was high in many smaller Member States, such as Estonia, Latvia, and Croatia. This suggests that although larger Member States consume more energy overall, smaller economies are relatively more vulnerable to supply disruptions, as they have smaller internal markets and fewer alternative sources of supply.

The cluster analysis identified three relatively well-defined groups. The first cluster comprises large, stable countries with internal production capacities (e.g., France and Sweden), characterized by low dependence and moderate volatility. The second cluster includes medium-sized countries with moderate exposure (e.g., Spain, Portugal, and Poland), which are in a balanced situation but not free from risks. The third cluster comprises smaller, highly volatile, and import-dependent countries (e.g., the Baltic States and Malta), where the security of supply is most at risk. This three-tier structure has persisted during the post-2020 shocks. Still, the cluster classification of several countries—such as Hungary and Slovakia—has shifted, indicating that the crisis has rearranged the relative positions of the Member States.

The first three hypotheses of the research have been fully confirmed. The structure and volume of energy imports are indeed decisive in dependence; internal production capacities and a diversified energy mix mitigate risks. The post-2020 period has clearly demonstrated that shocks have reshaped the vulnerabilities of Member States. Overall, energy is not just an economic input for the EU, but also a crucial factor in maintaining social and political stability.

However, the fourth hypothesis was not confirmed, as the results showed that coal imports have now become a marginal factor and that the EU's energy dependence is fundamentally determined by its exposure to gas and oil imports.

Figure 4 illustrates the average level and volatility of energy dependence in the 27 EU Member States between 2014 and 2023. Countries with a high average dependence and high relative fluctuations (e.g., Malta, Lithuania, Latvia, and Estonia) appear in the upper right quadrant, highlighting their structural vulnerability. In contrast, large Member States with significant domestic production capacity, such as France (nuclear energy) and Sweden (renewables and hydropower), exhibit relatively low dependence and volatility. Germany and Italy exhibit medium to high levels of dependence, characterized by significant absolute volatility, which reflects their exposure to fossil fuel import shocks. Hungary and Slovakia occupy an intermediate position, characterized by moderate reliance, which is expected to increase in volatility after 2020. Southern European countries, such as Spain and Portugal, are closer to the EU average and benefit from the gradual diversification of electricity generation. Finally, Poland still has an exceptionally high dependency on fossil fuels, although diversification efforts have somewhat mitigated volatility. Overall, the figure shows that the EU's energy dependency is unevenly distributed across Member States, with small, import-dependent economies facing disproportionately higher risks compared to larger, diversified producers.

One limitation of the research is that it is based solely on Eurostat data, and thus cannot fully capture the unobservable institutional, contractual, or geopolitical dimensions of security of supply. Another limitation is that the analysis focuses on the national level and therefore cannot address regional differences or the detailed company-level adaptation of supply chains.

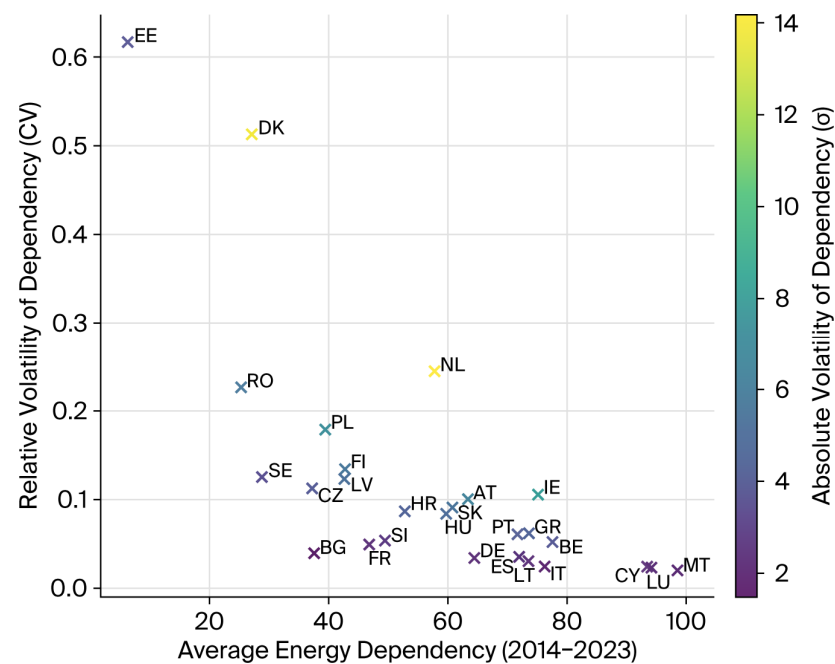


Figure 4. Energy dependency in the EU: average levels and volatility, 2014–2023.

5. Policy Implications

The results have direct policy implications. The first and most important lesson is that diversification remains key. Reducing dependence on Russian fossil fuels has become an urgent necessity following the events of 2022. Although the EU has made significant progress in building alternative sources, such as LNG imports and new supplier relationships, the data show that several EU Member States still have overly concentrated procurement structures. Future policies should therefore aim to ensure that a broader range of supply sources is available to all Member States.

Secondly, the research highlights that smaller and more vulnerable Member States, such as the Baltic States, Malta, and Cyprus, are particularly exposed to volatility. For them, standard EU mechanisms such as strategic stocks, a common gas procurement platform, or better interconnection of electricity networks can play a key role. These instruments can mitigate asymmetric exposures and address imbalances within the internal market.

Thirdly, the study underlines the importance of developing crisis management capabilities. The post-2020 period has demonstrated that shocks can impact the energy system rapidly and unexpectedly. Therefore, EU policy should place greater emphasis on measures to increase resilience—including encouraging demand-side responses, developing energy storage technologies, and rapidly activating crisis management protocols.

Ultimately, strengthening the EU's energy security cannot be divorced from its climate policy objectives. The results of the study show that expanding renewable energy sources and decarbonizing electricity generation are also the most effective ways to reduce dependency. This means that energy security and climate protection are not mutually exclusive, but can be complementary objectives if implemented within the proper policy framework. This insight is directly linked to the UN Sustainable Development Goals, in particular Goal 7 (Affordable and Clean Energy). Improving security of supply, reducing import dependency, and increasing the share of clean energy sources not only strengthens the EU's internal stability but also contributes to global sustainability efforts. The research indicates that providing affordable and clean energy simultaneously serves economic competitiveness, social well-being, and environmental sustainability, ensuring that the EU's energy policy decisions are closely aligned with the long-term goals set by the international community.

The findings of this study indicate that the EU's objective of achieving full independence from Russian gas is not merely a political declaration but a statistically grounded structural necessity. Expanding LNG infrastructure enhances short-term shock absorption capacity, while the development of alternative corridors—such as the Balkan vertical gas corridor—strengthens regional interconnectivity and reduces concentration risk. Together, these measures contribute to lowering systemic volatility and mitigating structural energy dependency across Member States. Importantly, the empirical results show that gas dependency remains the primary channel of vulnerability, reinforcing the strategic priority of sustained diversification efforts.

Overall, the research suggests that general targets are insufficient to enhance the EU's energy security. A specific, differentiated approach is needed, taking into account the different situations of individual Member States and simultaneously striving to promote diversification, internal capacity development, crisis resilience, and climate policy goals.

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Data Availability Statement: The data supporting the results reported in this study are from public databases of Eurostat. Links to the datasets can be found under references [31–36].

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The European Union (EU) consists of 27 countries: Sweden (SE), Spain (ES), Slovenia (SI), Slovakia (SK), Romania (RO), Portugal (PT), Poland (PL), the Netherlands (NL), Malta (MT), Luxemburg (LU), Lithuania (LT), Latvia (LV), Italy (IT), Ireland (IE), Hungary (HU), Greece (EL), Germany (DE), France (FR), Finland (FI), Estonia (EE), Denmark (DK), the Czech Republic (CZ), Cyprus (CY), Croatia (HR), Bulgaria (BG), Belgium (BE), and Austria (AU).

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