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ECONOMETRIC ASSESSMENT OF EU ENERGY MARKET RESILIENCE

ЕКОНОМЕТРИЧНА ОЦІНКА СТІЙКОСТІ ЕНЕРГЕТИЧНОГО РИНКУ ЄС

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Abstract*. The article explores the EU Energy Union as a strategic mechanism for strengthening the resilience of European energy markets amid geopolitical instability and energy transition. Resilience is assessed in three areas: price stability and integration, security of supply through diversification, and resilience to transition risks. The assessment used σ- and β-convergence in electricity prices for households and industry (2013–2024), the Herfindahl–Hirschman Index (HHI) for electricity trading (2010–2023), and a synthetic stability index based on k-means clustering. The results show a clear segmentation: β-convergence is confirmed for industrial prices, whereas household end prices do not converge. Their dispersion increases sharply in crisis years. The concentration of partners in electricity trading declines on average after 2015, indicating a more diverse geography of flows. Countries were grouped into three clusters: 'Leaders,' 'Transit Hubs,' and 'Vulnerable Markets.' The number of vulnerable countries is gradually decreasing. Regulators can use the results received to prioritize investments in interconnectors and system flexibility. They will also help shape the future trajectory of Ukraine's power system synchronization with the EU market.*

Keywords: EU Energy Union; ENTSO-E; energy market resilience; econometric modelling; electricity price convergence; Herfindahl–Hirschmann Index; synthetic stability index; cluster analysis; energy security.

Анотація. *Стаття розглядає Енергетичний союз ЄС як стратегічний механізм посилення стійкості європейських енергетичних ринків в умовах геополітичної нестабільності та енергетичного переходу. Стійкість оцінюється у трьох вимірах: цінова стабільність, ринкова інтеграція, безпека постачання через диверсифікацію, а також стійкість до ризиків енергетичного переходу. Для оцінки використовувалися σ- та β-*

конвергенція цін на електроенергію для домогосподарств і промисловості (2013–2024), індекс Герфіндаля–Гіршмана (HHI) для торгівлі електроенергією (2010–2023), а також синтетичний індекс стабільності з кластеризацією k-means. Результати показують виразну сегментацію: β-конвергенцію підтверджено для промислових цін, тоді як кінцеві ціни для домогосподарств не зближуються, а їхня дисперсія різко зростає у кризові роки. Концентрація торговельних партнерів у торгівлі електроенергією в середньому знижується після 2015 року, що свідчить про ширшу географію перетоків. Країни згруповано у три кластери: «Лідери», «Транзитні хаби» та «Вразливі ринки». Кількість вразливих країн поступово скорочується. Регулятори можуть використати отримані результати для пріоритизації інвестицій у інтерконектори та гнучкість енергосистеми. Вони також сприятимуть формуванню подальшої траєкторії синхронізації енергосистеми України з ринком ЄС.

Ключові слова: *Енергетичний союз ЄС; ENTSO-E; стійкість енергетичного ринку; економетричне моделювання; конвергенція цін на електроенергію; індекс Герфіндаля-Гіршмана; синтетичний індекс стабільності; кластерний аналіз; енергетична безпека.*

Introduction. EU-wide stability has emerged as a central focus of European Union policy, reflecting a shift from prioritizing market efficiency to establishing robust market structures capable of withstanding extreme price volatility, geopolitical crises, and supply disruptions associated with war. The energy price shocks experienced by numerous member states during 2022-23 highlighted how the interconnectedness of EU electricity markets can transmit stress unevenly across countries and consumer groups. While wholesale electricity markets in the EU are extensively coupled, retail tariffs often remain fragmented due to nationally determined taxes, network charges, and emergency support measures. This article defines "market stability" through the lens of three separate factors: (i) price stability and integration, (ii) diversifying supply to ensure security of supply, and (iii) the resilience to transition-related risks.

Although numerous academic papers have explored issues of either integration or security in isolation, very few have compared the multiple indicators of stability both cross-nationally and over time. The existing body of research has identified limited convergence in wholesale markets and significant divergence in retail prices, consistent with the idea of "convergence clubs" rather than a single unified market. To address this empirical and analytical gap, this paper applies a multi-indicator econometric framework to link EU-wide instruments for energy union to observable market outcomes and provides an additional layer of analysis regarding the overall resilience of energy markets in Europe. The central theoretical assumption underlying the paper is that further regulatory integration (achieved through a series of regulatory packages implemented by the EU since 2015) will lead to greater price convergence and supply diversification, resulting in a more uniform and resilient European energy system.

The purpose of the article. In particular, the study investigates whether electricity prices have become more similar between member states; whether the diversity of cross-border trade in electricity has increased; and whether, when examining each indicator together, countries can be divided into three or more stable subgroups. The findings deliver practical guidance for policy officials on where to focus efforts, particularly on strengthening interconnectors and investing in system flexibility, and are especially relevant for Ukraine as it continues to align its power system with the EU market under sustained geopolitical pressure. The emergency synchronization of the Ukrainian and Moldovan power systems in March 2022 serves as a real-world stress test, underscoring how physical infrastructure and coordinated governance shape resilience under extreme conditions.

Literature review. Research on EU electricity market integration primarily focuses on price convergence and structural market coupling. Zachmann (2008) identifies only partial wholesale price convergence and ongoing regional segmentation resulting from congestion and limited cross-border capacity. Market Monitoring Report confirms progress in integration but also draws attention to persistent structural bottlenecks and uneven cross-zonal capacity allocation *(ACER, 2024)*. Analyses of retail prices reveal even greater heterogeneity, demonstrating that EU countries frequently converge in "clubs," with household prices remaining structurally divergent *(Cassetta et al., 2022).*

The literature on the 2022–2024 energy crisis spotlights the effects of systemic shocks on EU integration in the energy sphere. North Sea electricity studies report heightened volatility and temporary fragmentation *(Sæther and Neumann, 2024).* Gas supply analyses document faster diversification and demand adaptation from 2022 to 2024 *(Zhou et al., 2025).* Post-crisis reforms address institutional challenges *(SIEPS, 2024),* while Commission reports note stabilization via lower wholesale prices and reduced Russian gas reliance *(European Commission, 2024).*

Ukrainian academic and policy literature mainly addresses the prospects for national integration. The DiXi Group and the Clingendael Institute (2024) present a policy-oriented roadmap for Ukraine's energy integration into the EU, while ExPro Consulting's White Paper outlines challenges related to electricity market synchronization and cross-border trade. Whereas academic work on "SMART integration" emphasizes regulatory harmonization and infrastructure stability *(Lutsenko, 2025; Zvarych and Kharkovskyi, 2025).* Nevertheless, the majority of Ukrainian sources remain descriptive and focused on national issues.

In contrast, this article adopts a more extensive EU-Ukraine perspective. It assesses EU-wide market resilience using harmonized econometric tools and situates Ukraine's trajectory within the overall European energy architecture. The study fills a methodological gap between policy discourse and empirical resilience assessment.

Methodology. This study uses econometric methods to examine the resilience of the European Union (EU) energy market amid geopolitical instability and the ongoing energy transition. The empirical analysis follows a quantitative approach and draws on secondary data from official sources, primarily Eurostat and the World Bank.

The dataset features: (1) annual electricity prices for households and industrial consumers for 2013–2024 (Eurostat); (2) cross-border electricity trade volumes by partner countries for 2010–2023 (Eurostat); and (3) a set of structural indicators used to construct a synthetic resilience index for 2010–2022, namely energy import dependency (Eurostat), the share of renewables in gross final energy consumption (Eurostat), energy intensity (World Bank), CO_2 emissions per capita (World Bank), and diversification of the energy mix (Eurostat).

To achieve the research's purpose, a comprehensive set of methods is applied. Price stability and market integration are assessed using standard econometric tests of σ- and β-convergence for both household and industrial electricity prices: σ-convergence is measured through the cross-country dispersion/standard deviation of prices over time, while β-convergence is tested via regression analysis of the convergence hypothesis (the relationship between the initial price level and subsequent price changes). The degree of diversification in external electricity trade is measured using the Herfindahl–Hirschman Index (HHI), calculated from import and export shares across trading partners (higher HHI values indicate greater concentration and, consequently, lower diversification). To examine structural resilience and develop a country typology, a Synthetic Market Stability Index is constructed: all five components are first standardized (z-scores), and the index is then computed as the arithmetic mean of the standardized indicators. Next, k-means clustering with a fixed number of clusters (K = 3) is applied to identify "leaders", "transit hubs", and "vulnerable" markets based on their resilience profiles. Overall, the selected methodology delivers a comprehensive (multidimensional) measurement of EU energy-market resilience: combining convergence assessments, concentration indicators (HHI), and an integral index based on standardized components makes it possible to assess integration dynamics simultaneously, changes in vulnerabilities under external shocks, and structural cross-country differences, as well as to develop a comparative market typology to support further applied conclusions and policy recommendations.

Main results of the research. Given that the EU energy market plays a crucial role in ensuring regional stability and integration, the following analysis examines empirical evidence of its resilience, focusing on price convergence, trade diversification, and structural transformation.

Econometric analysis exhibits statistically significant β-convergence of electricity prices for industrial end-users ($\beta = -0.138$; $R^2 = 0.153$). In member states where industrial electricity prices were initially elevated, price adjustments occurred more rapidly, showing a gradual alignment within the internal electricity market. This outcome corroborates previous findings of partial convergence in European wholesale markets and is in line with institutional reports that document deeper integration in competitive segments *(Zachmann, 2008; ACER, 2024).*

Household electricity costs, on the other hand, do not show statistically significant evidence of β-convergence. Retail markets remain structurally segmented. Household tariffs, unlike industrial rates, are still set by national regulatory bodies, such as taxes, network fees, and social compensation plans. Such elements weaken wholesale-to-retail price transmission and limit the integrative effects observed in industrial segments, which is consistent with research documenting "club convergence" rather than uniform retail harmonization *(Cassetta et al., 2022).*

The σ-analysis reveals that cross-country dispersion in household electricity prices consistently exceeds that observed for industrial tariffs over the period 2013–2024. This structural disparity underscores the ongoing segmentation between competitive and regulated markets.

The 2022–2023 energy crisis intensified dispersion across both segments, with the largest increase observed in the household sector. Countries that faced strong gas price shocks and had limited fiscal space saw greater price volatility *(Sæther and Neumann, 2024).* Governments with extensive support measures, by contrast, temporarily restrained retail price increases *(SIEPS, 2024).*

These patterns show that crisis conditions amplify structural asymmetries: integration mechanisms remain operative, but national policy space and fiscal capacity increasingly determine retail outcomes under stress.

The partner Herfindahl–Hirschman Index (HHI) shows that imports relied on a relatively concentrated set of trading partners in 2010–2014 (average import HHI ≈ 0.63). From 2015 onward, the index steadily fell, reaching about 0.54 over 2015–2023. This reduction demonstrates a broadening of cross-border electricity flows, reflecting a wider geography of interconnections and greater use of interconnections.

However, Member States diversified at varying rates. Highly interconnected systems in Western and Northern Europe maintained lower and more stable HHI values. In contrast, structurally limited systems, particularly peripheral markets or those with limited interconnection, sustained higher concentration levels and experienced greater HHI fluctuations during periods of stress.

Some national systems reduced their diversification under stress by reconcentrating their trade flows during the crisis. Where interconnector capacity or alternative corridors remain limited, market rules alone cannot prevent trade concentration under stress. These findings show that both physical infrastructure and regulatory integration are necessary for diversification.

Using the Synthetic Market Stability Index (constructed from standardised indicators of import dependence, renewable penetration, energy intensity, CO_2 emissions per capita, and trade diversification), the k-means clustering procedure identifies three structural groups:

- **Leaders:** systems distinguished by strong diversification, minimal import dependence, and advanced renewable energy penetration, mainly situated in Northern and Western Europe;
- **Transit Hubs:** intermediate systems presenting mixed structural characteristics and serving strategic cross-border roles, notably encompassing several Central European markets;
- **Vulnerable Markets:** systems characterized by high import dependence, limited diversification, and weaker transition indicators, typically corresponding to peripheral or isolated markets.

Over time, the number of countries classified as "vulnerable" declines modestly, while the intermediate cluster expands. This trend reveals gradual structural improvement and partial convergence of transition-related parameters.

For 2022, the clustering reveals a clear regional pattern: leaders are concentrated mainly in Northern and Western Europe, many Central European systems fall into the middle cluster, and several island (Cyprus, etc.) systems remain vulnerable.

Nonetheless, there is a lasting gap between structurally advanced Northern and Western systems and more constrained peripheral markets, showing the multidimensional nature of resilience: progress

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along a single dimension (for instance, renewable penetration) does not automatically compensate for weaknesses in diversification or import dependence.

Table 1

EU energy market stability indicators

Indicator	Method	Key result of the author's research	EU policy linkage	Target result 2030/2040	Status
Price dispersion (σ) of end-user electricity prices (households vs industry, 2013–2024)	Cross-country standard deviation (σ) of end-user prices	σ, €/kWh **Households:** 2013=0.0584 2016=0.0595 2020=0.0593 2022=0.0899 2023=0.1019 2024=0.0910 **Industry:** 2013=0.0309 2016=0.0187 2020=0.0180 2022=0.0477 2023=0.0580 2024=0.0435	Internal electricity market rules (Directive (EU) 2019/944; Regulation (EU) 2019/943)	No binding EU-wide numeric "σ target"; tracked in market monitoring	-
Price convergence (β) (households vs industry, 2013–2024)	β-regression on log(price)	**Households: no convergence** $\beta = 0.0010$ $p = 0.905$ $R^2 = 0.00006$ **Industrial β-convergence confirmed:** $\beta = -0.1375$ $p = 0.0000000007$ $R^2 = 0.153$	Internal electricity market rules (Directive (EU) 2019/944; Regulation (EU) 2019/943)	No binding EU-wide numeric "β target"; convergence is an expected outcome of deeper integration and grid reinforcement and is tracked by regulators	-
Electricity trade partner diversification (HHI) (imports/exports, 2010–2014 vs 2015–2023)	Partner-share HHI (imports and exports)	**Import HHI:** 0.63 → 0.54 **Export HHI:** 0.62 → 0.57	Infrastructure and interconnection framework (TEN-E Regulation (EU) 2022/869) + market integrity/transparency (REMIT Regulation (EU) No 1227/2011)	**2030:** Electricity interconnection target **15% by 2030** (enables substitution/diversification).	Progress differs by Member States
RES share in gross final energy consumption	Cross-country descriptive	**EU-27: 24.5% (2023)**	Renewable Energy Directive as revised in 2023/2413)	**2030:** EU binding renewables target **≥42.5%** (with ambition toward 45%).	-

(EU-27)	comparison				
Synthetic “Market Stability Index” + clustering	z-score standardisation of 5 indicators + composite index + k-means (K=3)	Three clusters were identified: Leaders (C1), Middle (C2), and Vulnerable Markets (C3). Over time, the number of “vulnerable” countries declines, and the middle cluster strengthens, indicating gradual convergence; however, a durable gap persists between leading systems and laggards.	Energy Union governance & comparability (Regulation (EU) 2018/1999) + risk-preparedness (Regulation (EU) 2019/941) + climate framework (Regulation (EU) 2021/1119)	**2030:** **≥55% net GHG reduction by 2030**; **≥42.5% RES, 11.7% energy efficiency improvement** (binding). **2040: 90% net GHG reduction** target under the EU’s 2040 climate-target process.	-

Note. Created by the author based on data from (EuroSat, World Bank, n.d.)

Place of Ukraine within the Energy Union framework. Ukraine occupies a strategic position within the Energy Union architecture, serving both as a frontline test of energy resilience under wartime conditions and as the frontier for extending the Eastern European market.

A turning point was the synchronization of Ukraine’s power system with continental Europe on March 16, 2022. Although originally scheduled as a gradual technical process, synchronization was completed under emergency conditions and established a stable operational connection with the continental grid. This physical interconnection demonstrated how infrastructure coupling can expand diversification options during crises.

The connection improved system stability and allowed the shift from emergency technical support to commercial operation. Cross-border electricity trade with EU Member States began later in 2022, transforming grid linkage into a practical instrument for diversification of supply and balancing resources at a time of severe domestic constraints.

Legal and institutional adjustments accompanied this process. As an EU candidate country and a Contracting Party to the Energy Community, Ukraine continues to align its energy legislation with the EU acquis. It has incorporated European market governance principles, strengthened transparency requirements, and introduced compatible monitoring and reporting procedures. These steps give interconnection a regulatory foundation, embedding it within the rules and practices of the EU internal energy market rather than leaving it as a purely technical arrangement.

Policy planning has advanced in parallel. The EU–Ukraine Association Agreement provides the legal framework for alignment, while national instruments translate commitments into concrete targets. Ukraine’s National Energy and Climate Plan (NECP) for 2030 introduces structured target-setting and control mechanisms for implementation. The National Renewable Energy Action Plan sets a 27% target for renewables in gross final energy consumption by 2030. Longer-term priorities are outlined in the Energy Strategy of Ukraine to 2050 and the Low Emission Development Strategy 2050, both of which define pathways for decarbonization and system modernization that are consistent with broader European climate objectives.

Integration also moves beyond the electricity sector. The EU–Ukraine Memorandum of Understanding on biomethane, hydrogen, and other renewable gases, signed on February 2, 2023, established cooperation on certification standards, market rules, and future cross-border trade in renewable gases. By extending cooperation to emerging energy carriers, this system deepens compatibility with the developing EU internal market and fortifies Ukraine's role in the wider regional transition.

Future research may examine modelling the impact of new market flexibility technologies or long-term resilience under 2030–2040 decarbonization trajectories.

Conclusions. The findings prove that the resilience of the EU energy market is multidimensional, structurally differentiated, and segment specific. Integration advances through distinct channels, such as price convergence, trade diversification, and structural transformation. These processes, however, develop unevenly across consumer groups and national systems. Empirical evidence shows that market mechanisms boost resilience when competitive structures are present, whereas institutional design and infrastructure lead to fragmentation.

Price Dimension. Industrial electricity prices show statistically significant β-convergence ($\beta = -0.1375$; $R^2 = 0.153$) and consistently lower σ-dispersion than household tariffs. Competitive segments respond to internal market instruments, including wholesale market coupling and cross-border exchanges, confirming that integration promotes gradual price alignment. By contrast, household prices show no statistically significant convergence and display heightened dispersion during the 2022–2023 crisis. National tax regimes, regulated network charges, public service obligations, and emergency interventions weaken the transmission of wholesale signals to final consumers. These results support the need for a differentiated resilience agenda. Where household segmentation persists, market integration reforms should be evaluated alongside national tariff structures and consumer protection mechanisms to ensure that wholesale integration translates into stable, predictable retail outcomes.

Security of Supply and Diversification. Partner-based Herfindahl–Hirschman Index (HHI) calculations show high concentration levels in 2010–2014 (approximately 0.63), followed by gradual diversification in 2015–2023 (around 0.54). This decline represents the expansion of cross-border electricity flows and partial strengthening of supply resilience. However, the 2022–2023 shock demonstrates that reconcentration can re-emerge quickly when interconnection capacity, internal grid reinforcement, or alternative trade corridors remain insufficient. Diversification depends not only on regulatory coordination but also on tangible infrastructure, balancing capacity, and storage availability. Where physical connections remain weak, particularly in island systems and structurally vulnerable markets, priority should be assigned to interconnector construction, network reinforcement, and system flexibility, including storage deployment.

Structural Resilience. The Synthetic Market Stability Index distinguishes three structural profiles: Leaders, characterized by diversified supply structures and stronger transition performance; heterogeneous Transit Hubs undergoing gradual improvement; and Vulnerable markets defined by high import dependence and limited diversification. Although the share of vulnerable systems declines over time and the intermediate group expands, structural asymmetries persist. Resilience increasingly depends on flexibility technologies, cross-border capacity expansion, and diversification embedded within decarbonization pathways.

These structural differences carry direct **policy implications**. Vulnerable systems require accelerated grid expansion, enhanced balancing resources, and storage integration. Transit Hub systems benefit from improved congestion management and deeper regional coordination. Leader systems may focus on regulatory refinement and market design optimization. A uniform integration approach cannot adequately address structurally asymmetric risk patterns throughout the Union.

The results also highlight **wider strategic opportunities**. Further synchronization and deeper market coupling with Ukraine enlarge the regional diversification set. Ukraine's integration serves not only as a national resilience strategy but also as a mechanism for extending Energy Union stability eastward, notably under stress, when alternative corridors and trading options become critical.

The Ukrainian case reinforces the central conclusion of this study: resilience strengthens most effectively when regulatory integration, infrastructure interconnection, and long-term transition policy evolve in a coordinated and mutually reinforcing manner rather than as isolated initiatives.

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