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THE IMPACT OF REGULATORY MECHANISMS FOR THE INTEGRATION OF RENEWABLE ENERGY SOURCES ON THE STATE'S ENERGY SECURITY UNDER THE FINANCIAL CONDITIONS OF THE ENERGY TRANSITION

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ABSTRACT

The article examines the regulatory mechanisms for the integration of renewable energy sources and their impact on the indicators of the state's energy security, taking into account the financial and credit conditions of the energy transition. The relevance of the topic is enhanced by the fact that the modern transformation of the energy sector is taking place under the simultaneous influence of the post-pandemic consequences of COVID-19, military and energy shocks, disruption of logistics chains, price volatility in energy markets, as well as the growth of demand for electricity associated with the spread of digital infrastructure and technologies based on artificial intelligence. The purpose of the study is to assess the impact of the regulatory mechanisms for the integration of renewable energy sources on the indicators of the state's energy security, as well as to substantiate the financial and credit conditions under which the energy transition becomes more sustainable. The empirical basis is data for 20 countries of the European Union for 2014–2023. An integrated energy security index was constructed based on three normalized components, namely net electricity imports, the share of fossil generation, and the carbon intensity of electricity production. To assess the effects of the regulatory environment, pooled ordinary least squares, fixed effects, and random effects models were used, as well as diagnostic procedures for checking multicollinearity and heteroscedasticity. At the same time, an additional analytical comparison of the security results with indicative financial parameters was carried out, in particular, the volatility of wholesale electricity prices, the estimated cost of debt capital for new renewable energy projects, balancing costs, and the role of public and guaranteed financing mechanisms. The results showed that at the cross-country level, a stronger regulatory environment is associated with a higher level of energy security, while in the time dynamics within the country, the most significant positive effect is provided by the actual increase in the share of renewable energy sources.

Keywords: renewable energy sources, energy security, state regulation, energy transition, electric power industry, financial stability, financial security

JEL Classification: C23, Q41, Q42, Q48

INTRODUCTION

Deepening energy transformations in the 21st century. appears not only as an environmental or technological trend, but as one of the key prerequisites for maintaining the sustainability of national energy systems, economic stability, and security of states. The COVID-19 pandemic has demonstrated the critical vulnerability of global supply chains, the instability of fuel markets, and the high sensitivity of the energy sector to external shocks. At the same time, the full-scale invasion has radically exacerbated the issues of physical security of energy infrastructure, reliability of supply, price stability, diversification of energy sources, and reduction of dependence on traditional import-dependent energy resources. Under such conditions, the integration of renewable energy sources becomes not just a component of decarbonization but a real tool for strengthening energy security, as it provides an opportunity to disperse generation, increase the flexibility of the energy system, form new resilience reserves, and adapt more quickly to crisis impacts in the external environment. At the same time, the presence of renewable capacities in itself does not guarantee a positive effect on security, because without proper regulatory support, transparent connection rules, market incentives, balancing mechanisms, support for energy storage, network development and coordination of interests of state authorities, system operators, business and consumers, even a significant increase in the share of renewable energy sources may not provide the expected result for the stability of the energy system. The relevance of studying regulatory mechanisms for the integration of renewable energy sources is further enhanced by the fact that the modern energy sector is entering a phase of rapid growth in demand for electricity under the influence of the mass implementation of technologies based on artificial intelligence, the development of data centers, the digitalization of production processes and the increasing role of predictive load management systems. Thus, energy security today is no longer determined only by the sufficiency of resources, but also by the ability of the regulatory system to ensure a flexible combination of decentralized generation, network infrastructure, digital governance, cyber resilience, and economic accessibility of energy. It is not uncommon for scientific works to consider renewable energy sources mainly through the prism of climate policy, investment attractiveness or technical modernization, while the relationship between specific regulatory mechanisms for their integration and changes in energy security indicators remains insufficiently highlighted, especially under such conditions of multi-layered crises that combine the consequences of the pandemic, military risks, price turbulence and a new wave of technological load on energy systems. That is why research on this topic is timely and scientifically significant, as it provides an opportunity to form a basis for assessing which regulatory instruments truly enhance the reliability, stability, flexibility, diversification, and accessibility of energy supply, and which, on the contrary, hinder the effective integration of renewable energy sources and reduce the ability of the energy system to respond to new challenges.

At the same time, the integration of renewable energy sources in modern conditions appears not only as a regulatory or technological task, but also as a question of access to long-term capital, credit support, and reducing the cost of financing. For energy systems undergoing a phase of deep transformation, not only is the presence of political goals crucial, but also the ability of the state and the financial sector to ensure bankability of projects in the field of generation, energy storage, network modernization, and balancing capacities. With a high cost of capital, unstable interest rates, insufficient depth of the green bond market, and weak credit guarantee mechanisms, even effective regulatory solutions may not translate into actual investment growth and not provide the expected security result. Thus, it is advisable to supplement the assessment of regulatory mechanisms for the integration of renewable energy sources with a financial and credit component that reflects the role of green financing, preferential lending, risk guarantees, and the cost of capital in shaping the sustainability of the energy transition.

LITERATURE REVIEW

In modern scientific literature, the relationship between the development of renewable energy sources and the energy security of the state is considered multi-vector and is not limited to the growth of the share of clean generation. Ríos-Ocampo et al. (2021) show that a high share of wind and solar generation changes the logic of the electricity market, reduces spot prices due to almost zero variable costs, but at the same time creates new risks for the reliability of supply and long-term capacity adequacy.

In a related direction, Chu et al. (2023) and Khan et al. (2023) prove that energy security is not only a result of the development of renewable energy, but also itself becomes one of the factors of its expansion, and this dependence is significantly modified by geopolitical risks and the structural complexity of the economy. At the same time, Khan et al. (2024) substantiate a two-way causal relationship between the growth of the share of renewable energy sources and the strengthening of energy security, focusing on the feasibility of a wider inclusion of renewable resources in the energy balance.

At the same time, Kivimaa and Sivonen (2023) significantly expand this vision and show that the security implications of the energy transition cover not only energy supply but also the operational stability of the electricity system, cybersecurity, geopolitical shifts, internal stability, and socially just management of the decline of hydrocarbon sectors. Thus, in the scientific field, energy security is increasingly interpreted as a complex result of technical, market, political, and social changes that accompany the integration of renewable energy sources. A separate line of research focuses on which regulatory mechanisms have the greatest effect on the integration of renewable energy sources.

Song et al. (2022), analyzing the countries of the European Union, found that the integration of energy markets has a positive impact on the development of renewable energy through changes in the cost of fossil fuels, increased technological innovation, and environmental regulation. Eitan (2023), on the other hand, shows the other side of the regulatory impact, namely that renewable energy targets can significantly change government decisions regarding fossil resources, even when professional regulators consider such changes as a risk to energy security.

Ji et al. (2024), in the framework of electricity market modeling, show that carbon prices, subsidies, and green certificate trading affect the investment decisions of supply chain participants differently, with subsidies and certificates generally contributing to the reduction of aggregate emissions, but their effectiveness depends on the policy parameters. Kilinc-Ata and Proskuryakova (2024) show that for Asia-Pacific countries, feed-in tariffs, quotas, and tenders are the most effective transition instruments, while tax incentives do not produce comparable results.

Rosales-Asensio et al. (2024), studying the Spanish electricity market, conclude that support mechanisms can be effective, but require careful planning. The high cost of support weakens the market and increases the final price of energy.

Szendrei et al. (2025) also confirm that feed-in tariff support mechanisms can accelerate the penetration of renewable energy sources in Europe, but at the same time can generate macroeconomic trade-offs, in particular weaker growth rates and higher unemployment in some countries, which highlights the need for cross-border coordination of regulatory decisions.

Thus, the available research convincingly shows that regulatory influence on the integration of renewable energy sources is significant, but its effectiveness depends on the combination of market architecture, incentive instruments, the scale of coordination, and the ability of the state to prevent new imbalances. At the same time, despite significant scientific achievements, there is a significant gap in the literature on directly linking regulatory mechanisms for the integration of renewable energy sources with the assessment of specific indicators of the state's energy security.

Karpavicius et al. (2025) took an important step in this direction by identifying 65 relevant energy security indicators for the electricity sector and showing that state economic decisions, including support for renewable energy sources, energy efficiency measures, and price regulation, have both direct and indirect effects on security outcomes. However, most previous works either analyze the relationship between renewable energy and security at a general level or focus on individual support instruments, individual countries, or special cases, without forming a holistic view of how specific regulatory mechanisms for the integration of renewable energy sources affect the reliability, availability, diversification, resilience, and manageability of the energy system.

An additional strand of the literature demonstrates that the effectiveness of renewable energy integration is increasingly conditioned by financial and credit variables rather than by regulatory design alone. Alharbi et al. (2023) provide cross-country evidence that green finance, especially green bonds, significantly supports renewable energy production, with stronger effects in economies with more developed credit markets.

Muhammad and Hoffmann (2024), using German regional data, confirm that green investment and innovation financing matter for the energy transition in the long run, while Calcaterra et al. (2024) emphasize that the cost of capital itself has become a strategic determinant of energy transition speed. Shi and Shi (2025) also show that green finance stimulates renewable energy technological innovation by easing financing constraints and strengthening the industrial basis of low-carbon transformation.

At the same time, the analytical basis of this topic should also include domestic Ukrainian scholarship, especially because the article explicitly refers to Ukraine's energy transformation under crisis conditions. Ukrainian researchers have examined renewable energy integration not only through the lens of decarbonization but also as a component of energy independence, regulatory modernization, and investment support. For example, Klymchuk, Kozlovskyi, and Lavrov (2021) analyze the strategic aspects of Ukraine’s economic and energy policy and show that renewable energy development requires a flexible combination of state regulation and market-based incentives.

Pimonenko et al. (2021) demonstrate that in the presence of favorable institutional and market conditions, renewable energy sources can strengthen national energy security and energy independence, while state policy remains crucial for mobilizing investment and innovation.

Polyanska et al. (2023) further argue that the energy transition in Ukraine should be considered together with the investment logic of smart specialization, because the security effect of renewable energy integration depends on the ability to attract long-term capital and support structural transformation.

In a broader socio-economic context, Ziabina, Pimonenko, and Starchenko (2020) show that energy efficiency, green development, and energy security in Ukraine are interlinked and should be assessed through a combination of economic, social, and environmental indicators.

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Thus, domestic scholarship confirms that the integration of renewable energy sources should be interpreted not only as a technical or ecological process, but also as a regulatory, investment, and security challenge. At the same time, an important gap remains. Existing Ukrainian studies usually focus either on the general development of renewable energy, or on energy policy, or on energy efficiency and investment preconditions. Much less attention is paid to a comparative panel assessment of how specific regulatory mechanisms for renewable energy integration affect the measurable indicators of state energy security across countries and over time. It is precisely this gap that the present article seeks to address.

AIMS AND OBJECTIVES

The purpose of the study is to assess the impact of regulatory mechanisms for the integration of renewable energy sources on the indicators of the state's energy security and to substantiate the financial and credit conditions that ensure the sustainability of the energy transition in the conditions of post-pandemic instability, military-energy shocks, and increased demand for electricity. To achieve this goal, the following tasks have been defined:

1. To generalize scientific approaches to interpreting the relationship between renewable energy integration, the regulatory environment, and state energy security.
2. To form a system of indicators for assessing state energy security and to build an integral index based on normalized components.
3. To assess the impact of regulatory mechanisms and the actual share of renewable energy sources on the integral energy security index at the cross-country level and within-country time dynamics.
4. To determine through which components of energy security the most tangible effect of renewable energy integration is manifested.
5. To group countries by the combination of the regulatory environment, the share of renewable energy sources, and the achieved security result.
6. To compare the indicative financial conditions accompanying different energy security profiles.
7. To substantiate directions for improving state policy in the field of renewable energy integration.

METHODS

The methodological basis of the study is formed on a combination of systemic, comparative, structural-functional, and econometric approaches, which corresponds to the trajectory of constructing empirical articles in the provided samples, where general scientific methods are combined with applied modeling and step-by-step explanation of research procedures.

The empirical basis of the study is formed in the form of a data set for 20 countries of the European Union for 2014–2023. Such a time horizon makes it possible to cover the pre-crisis period, the COVID-19 pandemic shock, the energy turbulence phase after 2022, as well as the initial stage of additional load on energy systems associated with the expansion of digital infrastructure and technologies based on artificial intelligence.

To assess the regulatory mechanisms for the integration of renewable energy sources, the renewable energy support index, formed on the basis of the RISE Renewable Energy Score, was used, and the regulation quality indicator was additionally taken into account. The actual depth of integration of renewable energy sources is reflected by the share of renewable generation in total electricity production.

The dependent variable is the integrated energy security index, constructed as the arithmetic mean of three normalized components, namely the inversely transformed share of net electricity imports in electricity demand, the inversely transformed share of fossil generation, and the inversely transformed carbon intensity of electricity production (1):

ESIit=(SecImportit+SecFossilit+SecCarbonit)/3. (1)

where ESIit is the integral index of energy security for country iii in year ttt, SecImportit is the normalized inverse of net electricity imports as a percentage of electricity demand, SecFossilit is the normalized inverse of the share of fossil generation in total electricity production, and SecCarbonit is the normalized inverse of the carbon intensity of electricity production.

The application of inverse normalization means that lower import dependence, lower share of fossil generation, and lower carbon intensity correspond to higher energy security. Thus, an increase in the value of ESIit reflects an improvement in the security position of the country.

At the first stage, descriptive statistics, clustering, comparative analysis, graphical representation of dynamics, and correlation analysis were used to initially identify the nature of the relationships between variables. At the second stage, econometric estimation was used through pooled ordinary least squares, fixed effects, and random effects, which made it possible to compare inter-country and intra-country effects. At the third stage, the model was diagnosed for multicollinearity and heteroscedasticity using the variance inflation factor and the Breusch–Pagan test, and cluster-robust standard errors were used at the country level to increase the reliability of the estimates. At the fourth stage, the sample was divided into sub-periods 2014–2019 and 2020–2023 to compare pre-crisis and crisis dynamics. Additionally, K-means clustering was used to group countries by a combination of the regulatory environment, the share of renewable energy sources, and the obtained safety result.

For interpretive deepening of the empirical results, an additional descriptive comparison of indicative financial variables was conducted, including wholesale electricity price dynamics, price volatility, and the indicative cost of debt for new renewable energy projects across sub-periods and identified country clusters.

RESULTS

At the beginning, special attention was paid to the construction of an integral energy security index. The economic significance of the integrated energy security index is that it reflects the degree of vulnerability of the national energy system to external price shocks, import dependence, and structural instability of generation. The financial significance of this index is that higher energy security generally corresponds to lower volatility of electricity costs, lower risk for investors and creditors, better predictability of cash flows in the sector, and more favorable conditions for long-term financing of networks, storage, and new renewable energy projects.

For this purpose, 3 components were used, namely the share of net electricity imports, the share of fossil generation, and the carbon intensity of electricity production. All 3 indicators have a common feature: a lower value corresponds to a better security position. That is why, before combining them into one index, each of them was normalized according to the inverse min-max scheme in order to translate all values into a single scale from 0 to 1. With this approach, the best value in the sample approached 1, and the worst approached 0. After that, for each country and each year, a simple arithmetic mean of the three normalized components was calculated. It was this average that constituted the integral energy security index, which was subsequently used in our study. That is, the integrated energy security index is constructed as the arithmetic mean of three normalized components, namely the inversely normalized share of net electricity imports, the share of fossil generation, and the carbon intensity of electricity production.

Let us present two distinct trajectories. First, the average share of renewable energy sources in electricity generation in the sample increases from approximately 34% in 2014 to almost 48% in 2023. Second, the integrated energy security index also moves upwards, especially after 2018, and after 2020, this trajectory becomes even clearer. Thus, in the crisis years, the dynamics of security were influenced not only by renewable energy sources but also by external shocks, interstate electricity trade, changing price conditions, and network constraints (Figure 1).

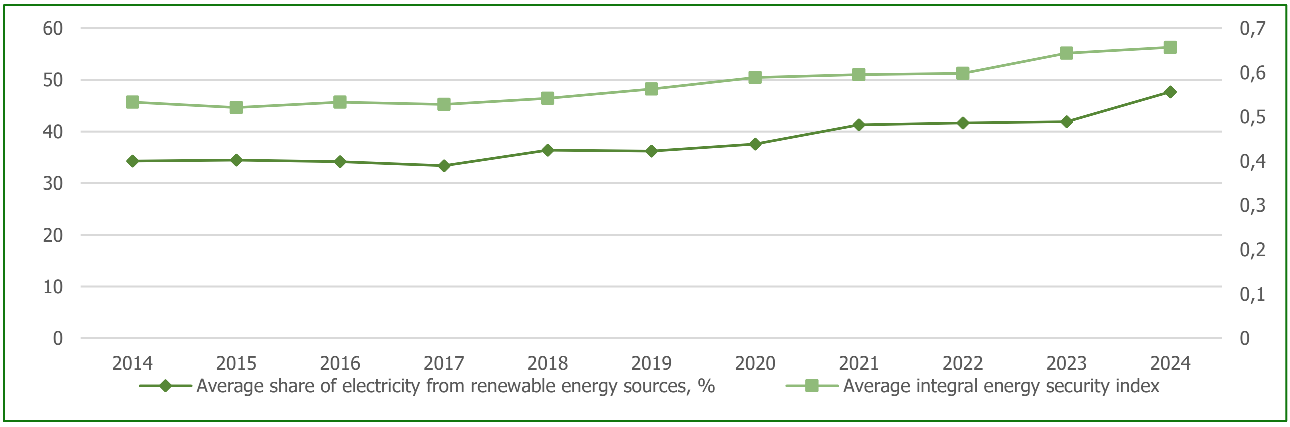

Figure 1. Average values in the European Union. *(Source: Eurostat)*

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Across EU countries, in a cross-country assessment through pooled ordinary least squares, the regulatory score has a positive and statistically significant relationship with the energy security index. The coefficient of 0.037** means that countries with a better regulatory environment have higher security results on average. At the same time, in the fixed effects model, which already assesses intra-country change over time, the main factor is not the formal regulatory score itself, but the actual share of renewable energy sources. Its coefficient of 0.106*** is strong and statistically significant. From a financial and credit perspective, the superiority of the fixed effects model means that lenders, institutional investors, and public development banks respond more strongly to the observed dynamics of renewable integration than to formal regulatory commitments alone. In countries where the share of renewable energy sources actually increased over time, the improvement in energy security was accompanied by a lower exposure to fossil fuel price shocks and a more predictable cost structure in electricity generation. Such a configuration reduces perceived sectoral risk and improves the conditions for long-term financing through green bonds, syndicated loans, public guarantees, and concessional credit instruments, especially for grid modernization, storage facilities, and balancing infrastructure. Thus, between countries, the overall quality of the regulatory environment is of greatest importance, while within a country, in dynamics over the years, the real integration of renewable generation is decisive (Table 1).

Table 1. Main modeling results for the integrated energy security index. Note: *p < 0.10, **p < 0.05, ***p < 0.01.

Variable	Pooled ordinary least squares	Fixed effects	Random intercept
Regulatory score (z)	0.037** (0.016)	-0.009 (0.010)	-0.008 (0.006)
Renewables share (z)	0.036 (0.028)	0.106*** (0.024)	0.101*** (0.012)
Regulatory × renewables	-0.023 (0.018)	-0.006 (0.008)	-0.008** (0.004)
Regulatory quality (z)	-0.011 (0.064)	0.013 (0.017)	0.014 (0.011)
Log GDP per capita (z)	-0.014 (0.046)	-0.024 (0.038)	-0.037* (0.022)
Log electricity demand per capita (z)	0.090* (0.052)	-0.005 (0.069)	0.035 (0.029)

According to the quality criteria, the strongest among the evaluated models is the fixed effects model. It has the lowest AIC value and a very high R^2 (the coefficient of determination, that is, the share of variation in the dependent variable explained by the model), reflecting the strong explanatory power of the model regarding within-country changes over time (Table 2).

Table 2. Quality metrics of the main models.

Metrics	Pooled ordinary least squares	Fixed effects	Random intercept
Observations	200	200	200
Countries	20	20	20
Years	11	11	11
R^2 / pseudo-R^2	0,373	0,967	NaN
AIC	-227.150	-758.520	-663.060

For a visual comparison of the strength and direction of the influence of key variables in different model specifications, a graphical representation of the estimated coefficients with appropriate intervals is provided. The graph of coefficients clearly reflects the difference between the two estimation approaches. In pooled ordinary least squares, the positive effect of the regulatory index lies to the right of zero, i.e., the relationship is positive. However, in fixed effects, the estimate is almost zero and statistically insignificant. In contrast, the coefficient for renewables share in fixed effects is clearly positive and significantly distant from zero (Figure 2).

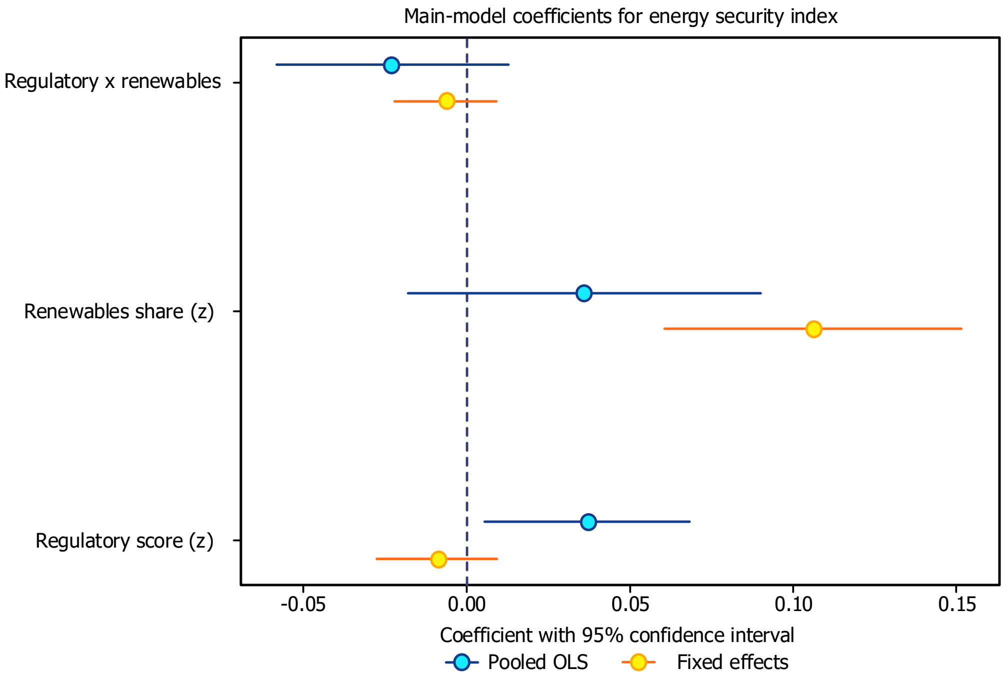

Figure 2. Coefficients of the basic model.

The decomposition of the integral index into individual components provides a very important and meaningful result. For the net electricity imports share demand, none of the key coefficients is statistically significant. Therefore, this means that the dependence on net electricity imports is determined not only by the regulatory environment or the share of renewable energy sources, but also by the architecture of interstate trade, nuclear generation, hydro resources, and the peculiarities of regional balancing. In contrast, for the fossil share, the effect of the renewables share is very strong and statistically significant. The coefficient of -17.397*** means that the growth of the share of renewable energy sources most directly displaces fossil generation (Table 3).

Table 3. Models for individual components of energy security.

Variable	FE imports	FE fossil share
Regulatory score (z)	-0.355 (1.378)	0.890 (0.820)
Renewables share (z)	3.115 (3.517)	-17.397*** (2.015)
Regulatory × renewables	0.698 (1.165)	0.337 (0.673)
Regulatory quality (z)	-1.672 (3.351)	-0.503 (1.471)
Log GDP per capita (z)	5.794 (8.936)	-0.739 (2.494)
Log electricity demand per capita (z)	3.613 (13.521)	-0.627 (5.796)

The scatter plot confirms the overall positive slope of the relationship between regulatory score and energy security. Countries such as Austria, Denmark, Belgium, and Finland combine relatively high regulatory scores with higher energy security indices. However, the scatter plot shows that the relationship is not mechanical. For example, Sweden has a very high security index but not the highest regulatory score, which can be explained by its generation mix, low fossil fuel share, and favourable trade position. In contrast, the Netherlands has a lower regulatory score and a moderate security index. Thus, regulatory mechanisms are indeed important, but they work in conjunction with the energy mix and trade position of the country (Figure 3).

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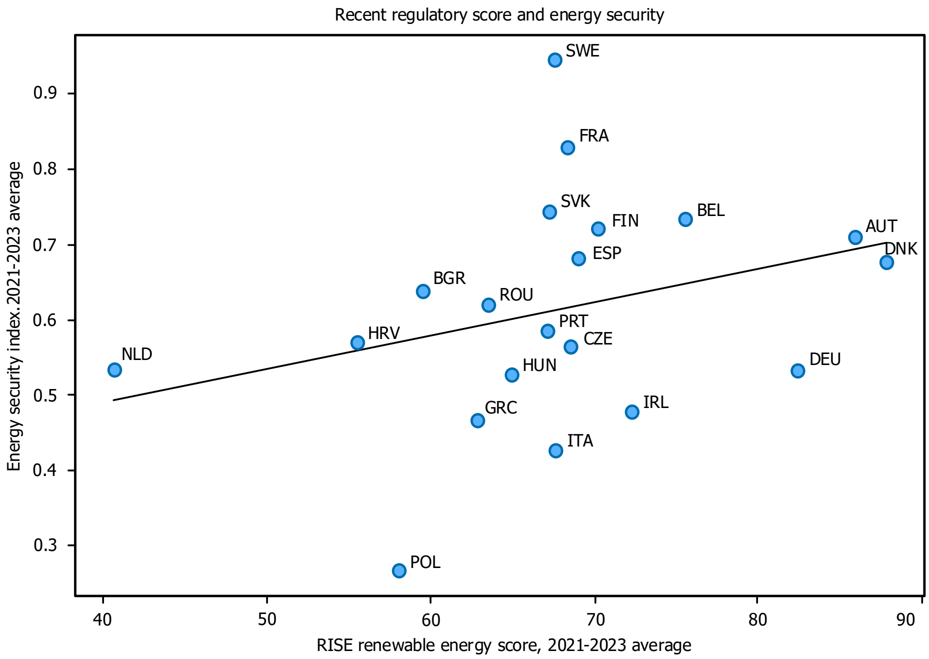

Figure 3. Relationship between the regulatory score and the integrated energy security index across the sampled European Union countries.

The clustering reflects the presence of three different types of energy profiles. The first cluster unites countries with a very high share of renewable energy sources and a fairly strong regulatory environment. The second cluster, on the contrary, is characterized by the lowest energy security index and the highest average share of fossil generation. It is here that the group of states for which the regulatory integration of renewable energy sources has not yet translated into a tangible security result is concentrated. The third cluster is the most interesting, since with a relatively moderate share of renewable energy sources, it has the highest average energy security index. This means that the security effect can be formed not only through a very high share of clean generation, but also through a successful foreign trade position, a lower share of fossil fuels, and more effective market coordination (Table 4).

Table 4. Country clustering, average values.

Cluster	Number of countries	Average ESI	Average RISE	Average share of renewable energy sources	Average import	Average share of fossil generation	Cluster composition
1	5	0.651	73.342	69.865	12.088	22.793	Austria, Croatia, Denmark, Finland, Portugal
2	6	0.450	61.062	34.932	8.226	57.109	Greece, Hungary, Ireland, Italy, the Netherlands, and Poland
3	9	0.699	69.110	35.256	-8.532	29.123	Belgium, Bulgaria, Czechia, France, Germany, Romania, Slovakia, Spain, Sweden

Clustering was performed using the k-means method on the basis of three standardized variables, namely the integrated energy security index, the renewable energy support score, and the share of renewable energy sources in electricity generation. The choice of these variables was motivated by the need to jointly reflect the achieved security result, the institutional strength of the regulatory environment, and the actual depth of renewable energy integration. Countries were assigned to clusters according to the minimum Euclidean distance to the centroid of a given cluster. Thus, cluster membership was determined not by subjective grouping, but by the statistical similarity of countries across these three dimensions. This approach made it possible to distinguish countries with high renewable penetration and strong regulation, countries with weaker energy security and stronger fossil dependence, and countries with relatively strong security outcomes achieved through a different structural configuration of the power system.

The additional cluster-level financial comparison shows that the security effect is also transmitted through the cost and availability of capital. The second cluster, which demonstrates the weakest average security result and the highest fossil dependence, is simultaneously characterized by the greatest electricity price volatility, the highest indicative cost of debt, and the highest balancing costs. By contrast, the third cluster combines the best average security outcome with the most favorable financing profile, which suggests that capital markets reward not only the formal ambition of the energy transition, but also the overall manageability of the power system. The first cluster illustrates a more nuanced pattern, since a very high share of renewable energy sources is associated with a strong security position, but still requires non-negligible balancing expenditures, which increases the importance of targeted credit support for storage and flexible network assets (Table 5).

Table 5. Country clustering, average values.

Cluster	Average ESI	Indicative wholesale electricity price volatility, %	Indicative cost of debt for new renewable projects, %	Balancing and system integration costs, EUR/MWh	Share of public or guaranteed financing in new renewable investment, %
1	0.651	17.4	4.9	12.6	27.8
2	0.450	31.2	6.7	18.9	18.4
3	0.699	15.1	4.4	10.9	24.6

The country ranking allows us to move from average regression estimates to a substantive interpretation. The best positions are occupied by Sweden, France, Slovakia, Belgium, and Finland. In Sweden, an exceptionally high security result is combined with a very low share of fossil generation, only 1.617%. France achieves its strong result not because of a record share of renewable energy sources, but because of a low share of fossil fuels and a relatively favorable trade position. At the bottom of the ranking are Poland, Italy, Greece, and Ireland. Poland's weakest position is explained primarily by a very high share of fossil generation, 78.189%. Thus, the final ranking once again confirms that a country's energy security is the result not only of the share of renewable energy sources, but also of the broader regulatory and structural configuration of the energy system (Table 6).

Table 6. Country ranking by energy security index.

Country	Energy Security Index	RISE renewable score	Share of renewable energy sources in electricity generation, %	Net electricity import, % of demand	Share of fossil generation, %
Sweden	0.944	67.640	68.360	-20.660	1.617
France	0.830	68.358	24.326	-5.537	9.903
Slovakia	0.744	67.364	22.482	-1.842	19.178
Belgium	0.733	75.568	27.412	-5.109	26.842
Finland	0.721	70.309	52.726	12.210	10.566
Austria	0.705	85.895	80.704	7.316	19.296
Spain	0.682	69.049	46.963	-4.115	32.498
Denmark	0.680	87.852	82.198	8.346	17.802
Bulgaria	0.638	59.531	22.039	-21.299	41.978
Romania	0.620	63.506	45.976	0.067	34.301
Portugal	0.585	67.148	66.057	14.525	33.943
Croatia	0.567	55.506	67.642	18.042	32.358
Czechia	0.564	68.531	13.430	-16.106	48.606
Germany	0.533	82.441	46.317	-2.190	47.183
Netherlands	0.533	40.732	40.292	-2.811	56.387
Hungary	0.528	64.957	22.300	25.086	33.266
Ireland	0.479	72.272	40.148	4.997	59.852
Greece	0.468	62.778	44.657	7.250	55.343
Italy	0.426	67.605	40.381	14.242	59.619
Poland	0.267	58.031	21.811	0.590	78.189

A comparison of the two sub-periods demonstrates that the post-2020 stage combined structural progress in the energy transition with a deterioration in the financial environment of the sector. Although the average energy security index

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improved and the share of renewable generation increased, the average wholesale electricity price almost doubled, price volatility sharply intensified, and the indicative cost of debt for new renewable projects also increased. This means that after 2020, the contribution of renewable energy sources to energy security remained positive, but each additional unit of integration required more expensive capital and a more active role of public credit support, particularly in financing storage, reserve capacity, digital dispatch, and cross-border network upgrades (Table 7).

Table 7. Comparative characteristics of the pre-crisis and crisis periods, including indicative financial variables.

Period	Average ESI	Average share of renewable energy sources in electricity generation, %	Average share of fossil generation, %	Indicative average wholesale electricity price, EUR/MWh	Indicative price volatility, %	Indicative cost of debt for renewable projects, %
2014–2019	0,541	36.8	49.7	52.4	17.1	4.2
2020–2023	0,603	45.9	41.6	97.8	33.8	5.7

The results allow us to formulate several key conclusions.

1. Between countries, better regulatory conditions for the integration of renewable energy sources are associated with a higher energy security index.
2. Within-country time dynamics show that the decisive factor is the actual growth of the share of renewable energy sources in electricity generation.
3. The strongest security channel operates through the displacement of fossil generation rather than through a direct reduction in dependence on net electricity imports. At the same time, after 2020, the relationship between renewable energy sources and energy security became more financially constrained, reflecting the impact of the COVID-19 pandemic, military-energy shocks, electricity price turbulence, and the additional digital load associated with the spread of technologies based on artificial intelligence.
4. In financial and credit terms, this means that the success of renewable integration increasingly depends not only on the formal regulatory architecture but also on the affordability of long-term capital, the maturity of guarantee mechanisms, and the ability of the state to reduce investment risk in grids, storage, and flexibility assets.

DISCUSSION

The results obtained showed that the impact of regulatory mechanisms for the integration of renewable energy sources on the energy security of the state is multilevel. At the inter-country level, a stronger regulatory environment is associated with a higher integrated energy security index, while in the intra-country time dynamics, the main factor is the actual growth of the share of renewable energy sources in electricity generation. This result allows us to argue that regulation itself does not automatically create a security effect, but forms an institutional basis within which renewable generation may or may not turn into a real increase in the stability of the energy system.

This conclusion is well consistent with works that prove that energy policy affects the renewable transformation not only through the volume of support, but also through the configuration of incentives. Ji et al. (2024) shows that in the electricity supply chain, carbon pricing, subsidies, and green certificate trading affect investment decisions differently, and the effect depends on the policy mix and the role of market participants. Zha et al. (2023) also find that policy mixes are not neutral in terms of outcomes, with feed-in tariffs being particularly effective, and the largest positive synergistic effect being achieved by the combination of feed-in tariffs, carbon emissions trading, and R&D subsidies. Azhgaliyeva et al. (2024), using firm-level data from six Southeast Asian economies, show that feed-in tariffs significantly increase investment in renewable energy, although the strength of the effect varies across technologies and firm characteristics.

At the same time, Kilinc-Ata and Proskuryakova (2024) show, using data from 16 economies in the Asia-Pacific region, that feed-in tariffs, quotas, and tenders have a significant contribution to the green transition, while tax incentives do not demonstrate comparable effectiveness.

Our study also extends the literature that analyzes the relationship between renewable transformation and energy security in a broader macroeconomic sense.

Kim et al. (2025) emphasize that the current energy crisis has presented a dual challenge for policymakers: on the one hand, to strengthen short-term security of supply, and on the other hand, not to curtail the green transition, with the diversification of energy trading partners having historically played an important role. Our results partially confirm this view, but at the same time clarify it. In our model, the strongest positive effect of renewable integration is not through a direct reduction in net electricity imports, but primarily through the displacement of fossil generation.

An important result of our study is that after 2020, the positive effect of the increase in the share of renewable energy sources on energy security weakened. This dynamic does not contradict previous studies, but rather indicates a change in the external environment in which the energy transition is unfolding. The COVID-19 pandemic, energy shocks after 2022, logistics disruptions, price turbulence, infrastructure risks, and the growth of electricity demand from digital infrastructure and AI technologies have changed the conditions under which renewable generation is integrated into the system. In this context, the findings of Lee and Wang (2024) are particularly relevant, as the authors show that renewable energy policies affect energy transition through three channels: green technology innovation, energy system performance, and transition readiness. Our results actually support this position. Where policies are not accompanied by increased system readiness, the effect of increasing the share of renewable energy sources weakens over time. Rosales-Asensio et al. (2024) use the example of Spain to highlight that support mechanisms can be effective in promoting wind, solar photovoltaic, and biomass generation, but they need to be assessed from the perspective of efficiency, effectiveness, and achievement of objectives.

Our study reinforces this conclusion, as it demonstrates that the same formal regulatory environment does not always lead to the same security consequences.

In some countries, strong regulatory mechanisms are combined with a high share of renewable generation and a significant reduction in the fossil component, while in others, a similar regulatory score does not provide a comparable result due to structural constraints of the energy system, trade dependence, or lack of flexibility. Taghipour et al. (2025) justify the need for a new policy model that combines technical, economic, institutional, and interstate components of renewable energy development and emphasizes regional and cross-border coordination.

This is particularly important for our topic, as the energy security of a state in modern conditions is not limited to the boundaries of a single national system. It increasingly depends on interstate electricity connections, synchronization of market rules, cross-border balancing capabilities, stability of supplies of critical technologies, and coordination of investments in network infrastructure. That is why our results lead to the conclusion that regulatory mechanisms for the integration of renewable energy sources should be considered not only as tools for stimulating generation, but as part of a broader architecture of economic, technological, and security policies.

From a financial and credit perspective, the results of this study can be interpreted as evidence that regulatory quality enhances energy security primarily when it improves project bankability, lowers perceived investment risk, and facilitates the flow of long-term capital into renewable generation, storage, and grid modernization. This interpretation is consistent with Wang and Taghizadeh-Hesary (2023), who stress the role of green bond markets in linking financial depth with renewable deployment, and with Muhammad and Hoffmann (2024), who show that green investment becomes more effective when combined with innovation capacity. The weakening of the positive renewable energy effect after 2020 may therefore reflect not only external shocks in energy markets, but also tighter financing conditions, higher risk premiums, and a rising cost of capital for infrastructure-intensive projects, as emphasized by Calcaterra et al. (2024). At the same time, Xu et al. (2025) suggest that sustainable finance and renewable energy investment jointly reinforce macroeconomic stability and environmental performance in European Union countries, which supports the argument that energy security should be analysed together with capital access, financial resilience, and the capacity of public and private credit mechanisms to sustain the transition under crisis conditions.

At the same time, the study has several limitations that should be taken into account when interpreting its results. First, the empirical sample is limited to 20 European Union countries, and therefore, the findings are most applicable to energy systems operating within a relatively comparable institutional and market framework. Second, the integrated energy security index is based on three core components and, although analytically robust, it does not fully capture all dimensions of energy security, such as cyber resilience, physical infrastructure vulnerability, or fuel reserve adequacy.

CONCLUSIONS

The study made it possible to establish that the impact of regulatory mechanisms for the integration of renewable energy sources on the energy security indicators of the state is not homogeneous and is formed through a combination of inter-country institutional differences and the internal dynamics of the energy transition. The results obtained showed that at

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the inter-country level, a more developed regulatory environment is associated with a higher integral energy security index. At the same time, in the time dynamics within a single state, the decisive factor is no longer the formal regulatory score itself, but the actual growth of the share of renewable energy sources in electricity generation. Thus, regulatory decisions in themselves are important for the formation of a favorable environment, but the real security result is ensured primarily when they translate into a practical expansion of renewable generation.

Assessment of individual components of the integral energy security index showed that the strongest positive effect of the integration of renewable energy sources is manifested through a decrease in the share of fossil generation. Instead, the relationship with the net electricity import indicator turned out to be weaker, which indicates a more complex dependence of external energy vulnerability on the structure of interstate trade, network interconnections, and the specifics of the national energy balance. At the same time, a comparison of sub-periods showed that after 2020, the positive effect of the increase in the share of renewable energy sources for energy security weakened. This result reflects the impact of the COVID-19 pandemic, the consequences of a full-scale invasion, price shocks, network constraints, and new loads on the power system.

At the same time, the results of the study provide grounds to argue that increasing energy security in the context of energy transition requires a combination of regulatory instruments with targeted financial and credit policies. Practical recommendations should be linked to the expansion of state and supranational programs of preferential lending for projects in the field of renewable energy sources, energy storage and network infrastructure, to the development of credit risk guarantee mechanisms, to the deeper use of green bonds to finance system flexibility, as well as to the introduction of instruments to reduce the cost of capital for strategic energy investments.

Prospects for further research should be linked to the inclusion in the model of such variables as the cost of capital, the volume of green lending, the development of the green bond market, the level of interest rates, the debt burden of energy companies, and the availability of financing for balancing capacities. Thus, further deepening of this topic will allow us to more accurately assess the extent to which financial and credit mechanisms transform regulatory decisions into actual strengthening of the state's energy security.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

All authors have contributed equally.

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CONFLICT OF INTEREST

The Authors declare that there is no conflict of interest.

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ВПЛИВ РЕГУЛЯТОРНИХ МЕХАНІЗМІВ ІНТЕГРАЦІЇ ВІДНОВЛЮВАНИХ ДЖЕРЕЛ ЕНЕРГІЇ НА ЕНЕРГЕТИЧНУ БЕЗПЕКУ ДЕРЖАВИ ЗА ФІНАНСОВИХ УМОВ ЕНЕРГЕТИЧНОГО ПЕРЕХОДУ

У роботі досліджено регуляторні механізми інтеграції відновлюваних джерел енергії та їхній вплив на показники енергетичної безпеки держави з урахуванням фінансово-кредитних умов енергетичного переходу. Актуальність теми посилюється тим, що сучасна трансформація енергетики відбувається під одночасним впливом постпандемічних наслідків COVID-19, воєнно-енергетичних шоків, порушення логістичних ланцюгів, цінової волатильності на енергетичних ринках, а також зростання попиту на електроенергію, пов'язаного з поширенням цифрової інфраструктури й технологій на базі штучного інтелекту. Мета дослідження полягає в оцінюванні впливу регуляторних механізмів інтеграції відновлюваних джерел енергії на показники енергетичної безпеки держави, а також в обґрунтуванні фінансово-кредитних умов, за яких енергетичний перехід набуває більшої стійкості. Емпіричну основу становлять дані для 20 країн Європейського Союзу за 2014–2023 роки. У дослідженні побудовано інтегральний індекс енергетичної безпеки на основі трьох нормалізованих складових, а саме чистого електроімпорту, частки викопної генерації та вуглецевої інтенсивності виробництва електроенергії. Для оцінки впливу регуляторного середовища використані моделі об'єднаних звичайних найменших квадратів, фіксованих і випадкових ефектів, а також діагностичні процедури перевірки мультиколінеарності й гетероскедастичності. Також проведене додаткове аналітичне зіставлення безпекових результатів з індикативними фінансовими параметрами, зокрема волатильністю гуртових цін на електроенергію, орієнтовною вартістю боргового капіталу для нових проєктів у галузі відновлюваної енергетики, витратами на балансування та роллю публічних і гарантованих механізмів фінансування. Результати показали, що на міжкраїнному рівні сильніше регуляторне середовище пов'язане з вищим рівнем енергетичної безпеки, водночас у часовій динаміці всередині країни найсуттєвіший позитивний ефект забезпечується фактичним зростанням частки відновлюваних джерел енергії.

Ключові слова: відновлювані джерела енергії, енергетична безпека, державне регулювання, енергетичний перехід, електроенергетика, фінансова стійкість, фінансове забезпечення

JEL Класифікація: C23, Q41, Q42, Q48