https://doi.org/10.31891/2307-5740-2026-350-1
UDC 338.242(477)
JEL Classification: Q40, Q42, Q43, Q48, O13

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ANALYSIS OF THE TRANSFORMATION OF THE ENERGY SYSTEM OF UKRAINE

The article analyzes the transformation of Ukraine's energy sector over the period 2000–2024 under the combined influence of structural economic changes, global energy transition trends, and military challenges. Particular attention is paid to the dynamics of the energy commodities trade balance, changes in the structure and volumes of electricity generation, generation intensity relative to economic output, and the emission intensity of the energy sector. The study shows that Ukraine's energy system has undergone a gradual shift from a carbon-intensive model dominated by coal-based generation toward a more diversified structure with a growing role of nuclear power and renewable energy sources. At the same time, the loss of generating capacities, disruption of energy infrastructure, and increased import dependence caused by military aggression have intensified structural imbalances and reduced system flexibility. The analysis of generation intensity indicates a decline in electricity production per unit of GDP, reflecting both economic contraction and changes in energy efficiency. Emission intensity trends demonstrate a long-term decrease driven by the reduction of coal generation and expansion of low-carbon sources, although short-term fluctuations remain sensitive to crisis conditions. Based on the results, the article emphasizes the need for realistic post-war recovery priorities focused on restoring flexible generation, expanding renewable energy, improving energy efficiency, and strengthening energy system resilience. The findings contribute to a comprehensive understanding of Ukraine's energy transformation and provide a basis for policy-oriented recommendations aligned with decarbonization and energy security goals.

Keywords: energy sector, energy system transformation, electricity generation structure, renewable energy sources, energy commodities trade balance, generation intensity, emission intensity, decarbonization, energy resilience

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АНАЛІЗ ТРАНСФОРМАЦІЇ ЕНЕРГЕТИЧНОЇ СИСТЕМИ УКРАЇНИ

У статті здійснено комплексний аналіз трансформації енергетичної системи України у 2000–2024 роках в умовах структурних економічних змін, глобального енергетичного переходу та збройної агресії. Дослідження базується на поєднанні макроекономічних, енергетичних та екологічних показників, що дозволяє оцінити системні зрушення у функціонуванні енергетичного сектору. Особливу увагу приділено динаміці торговельного балансу енергоносіїв, зміні обсягів і структури генерації електроенергії, показникам генераційної інтенсивності відносно валового внутрішнього продукту та інтенсивності викидів CO_2.

Встановлено, що енергетична система України поступово відходить від вуглецево-інтенсивної моделі, характерної для початку 2000-х років, у напрямі більш диверсифікованої структури з домінуванням атомної енергетики та зростаючою роллю відновлюваних джерел енергії. Показано, що після 2014 року, а особливо в умовах повномасштабної війни, суттєві втрати генеруючих потужностей та руйнування енергетичної інфраструктури призвели до посилення імпортної залежності та загострення структурних дисбалансів. Аналіз генераційної інтенсивності свідчить про зниження обсягів виробництва електроенергії на одиницю ВВП, що відображає як зміну економічної структури, так і скорочення промислової активності.

Виявлено довгострокову тенденцію до зменшення інтенсивності викидів у енергетичному секторі, зумовлену скороченням вугільної генерації та розширенням низьковуглецевих джерел, однак встановлено високу чутливість цього показника до кризових факторів. Обґрунтовано, що подальша трансформація енергетичної системи України має базуватися на поєднанні відновлення пошкодженої інфраструктури, розвитку маневрових і балансуючих потужностей, децентралізованої відновлюваної генерації та підвищення енергоефективності. Отримані результати формують аналітичне підґрунтя для розроблення політико-орієнтованих рішень у сфері декарбонізації та зміцнення енергетичної стійкості України.

Ключові слова: енергетичний сектор, трансформація енергосистеми, структура генерації електроенергії, відновлювані джерела енергії, торговельний баланс енергоносіїв, генеруюча інтенсивність, інтенсивність забруднення, декарбонізація, енергетична стійкість

Стаття надійшла до редакції / Received 17.12.2025
Прийнята до друку / Accepted 23.01.2026
Опубліковано / Published 29.01.2026

PROBLEM STATEMENT IN GENERAL TERMS AND ITS CONNECTION WITH IMPORTANT SCIENTIFIC OR PRACTICAL TASKS

At the current stage of development of Ukraine's energy sector, the transformation of the Unified Energy System has become critically important due to the combination of global energy transition trends and internal structural imbalances that have been intensified by external aggression. The loss of a significant share of generating

capacities, disruption of the territorial integrity of energy infrastructure, changes in the structure of electricity consumption, and the growing role of imports have exacerbated the problem of ensuring a sustainable balance between energy production and consumption. At the same time, Ukraine's integration into the European energy space and its decarbonization commitments require a gradual reduction in the share of fossil energy sources and the accelerated development of renewable generation. Under these conditions, the existing structure of the energy system, formed under the dominance of baseload capacities and a shortage of flexible generation, proves to be insufficiently adaptable and vulnerable to external and internal shocks. This necessitates a comprehensive analysis of the transformation of Ukraine's energy system, taking into account changes in the structure of generation, the trade balance of energy resources, the energy intensity of the economy, and the environmental characteristics of the energy sector.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

The issues surrounding the transformation of Ukraine's energy sector are widely addressed in academic research through the lenses of energy security, structural change, decarbonization, and the resilience of the energy system. A substantial body of scholarly work focuses on energy security as an integral component of national and economic security. In particular, V. Kuz [1] as well as M. Dykha and V. Dykha [2] emphasize the impact of geopolitical factors, import dependence, and transit risks on the stability of the energy sector, highlighting the urgent need for diversification of energy supply sources and the strengthening of state energy policy instruments. These studies underline that excessive reliance on external suppliers significantly increases vulnerability to political and military shocks, especially in periods of heightened geopolitical instability.

Within the context of the global energy transition, D. Tarasiuk [3] examines the transformation of Ukraine's energy industry under decarbonization imperatives, stressing the gradual reduction in the use of fossil fuels and the accelerated development of renewable energy sources (RES). Similar approaches are demonstrated by O. Verbova [4], who links the enhancement of the energy sector's competitiveness to technological innovation, improved energy efficiency, and deeper integration into global energy markets. These authors argue that structural modernization of the energy sector is not only an environmental necessity but also a key factor in ensuring long-term economic growth and international competitiveness.

The role of renewable energy in wartime conditions and post-war recovery is analyzed by L. Horoshkova and Yu. Korniichuk [5], who emphasize its importance in strengthening the resilience and decentralization of the energy system. According to their findings, distributed renewable generation can mitigate the risks associated with large-scale infrastructure damage and contribute to faster recovery of energy supply. At the same time, K. Predun, O. Kushnir, and O. Pochka [6] draw attention to the need to align energy transformations with environmental sustainability, stressing that the expansion of energy production must be accompanied by strict adherence to ecological standards and climate commitments. An engineering and technical analysis of the current state of Ukraine's energy system and the consequences of wartime destruction is presented in the work of Yu. Sirenko, S. Volvach, O. Savoiskyi, and V. Kozin [7], who provide a detailed assessment of infrastructure losses and the challenges of restoring system reliability.

A separate research direction is represented by studies employing mathematical modeling and scenario analysis. Ye. Shcherbyna [8] demonstrates that even under scenarios of active renewable energy development in the post-war period, a persistent deficit of balancing and flexible capacities remains. This, in turn, necessitates the comprehensive development of both baseload and flexible generation, including energy storage technologies and demand-side management mechanisms, to ensure system stability and operational flexibility.

Overall, the synthesis of existing research indicates that Ukraine's energy sector is undergoing a phase of profound transformation driven by the combined effects of military aggression and the global energy transition. The literature highlights that successful transformation requires an integrated approach encompassing energy security, technological modernization, diversification of generation sources, environmental responsibility, and institutional reforms. This creates a strong scientific and practical foundation for further research aimed at developing balanced strategies for the sustainable and resilient development of Ukraine's energy system.

HIGHLIGHTING PREVIOUSLY UNRESOLVED PARTS OF THE OVERALL PROBLEM

At the same time, existing research does not sufficiently combine the analysis of the structure of energy generation, the trade balance of energy resources, the energy intensity of the economy, and environmental indicators in an integrated manner. Most studies address these components separately, which limits the assessment of their interconnections and cumulative impact on the transformation of the energy sector. This gap determines the relevance of further research aimed at a more comprehensive and coordinated analysis of these dimensions in the context of Ukraine's energy system transformation.

FORMULATION OF THE ARTICLE'S GOALS (TASK STATEMENT)

The purpose of the article is to analyze the transformation of Ukraine's energy system under conditions of structural change and external challenges based on an assessment of the dynamics of the trade balance of energy resources, the structure of electricity generation, the energy efficiency of the economy, and the environmental

indicators of the energy sector, in order to substantiate directions for shaping a more resilient and adaptive model of energy system development.

PRESENTATIONOFTHEMAINRESEARCHMATERIAL

Under conditions of profound structural shifts in the energy system, the analysis of macro-level indicators that reflect changes in the role of the energy sector in the national economy and its interaction with the external environment becomes critically important. Changes in the generation structure, a decline in domestic production of certain energy resources, and a growing need for imports create new constraints on the functioning of the energy system and affect its resilience. In this context, it is appropriate to begin the analysis with indicators that comprehensively reflect these processes.

The transformation of Ukraine's energy system is manifested primarily in changes in the foreign economic parameters of the energy sector's operation. One of the key indicators of these changes is the trade balance of energy resources, which reflects the degree to which domestic demand is met by internal resources and the level of dependence on imported supplies. An analysis of the dynamics of the energy resources trade balance indicates a gradual deterioration of its balance, driven by declining extraction and exports of energy resources against the backdrop of a growing import component in the structure of energy consumption.

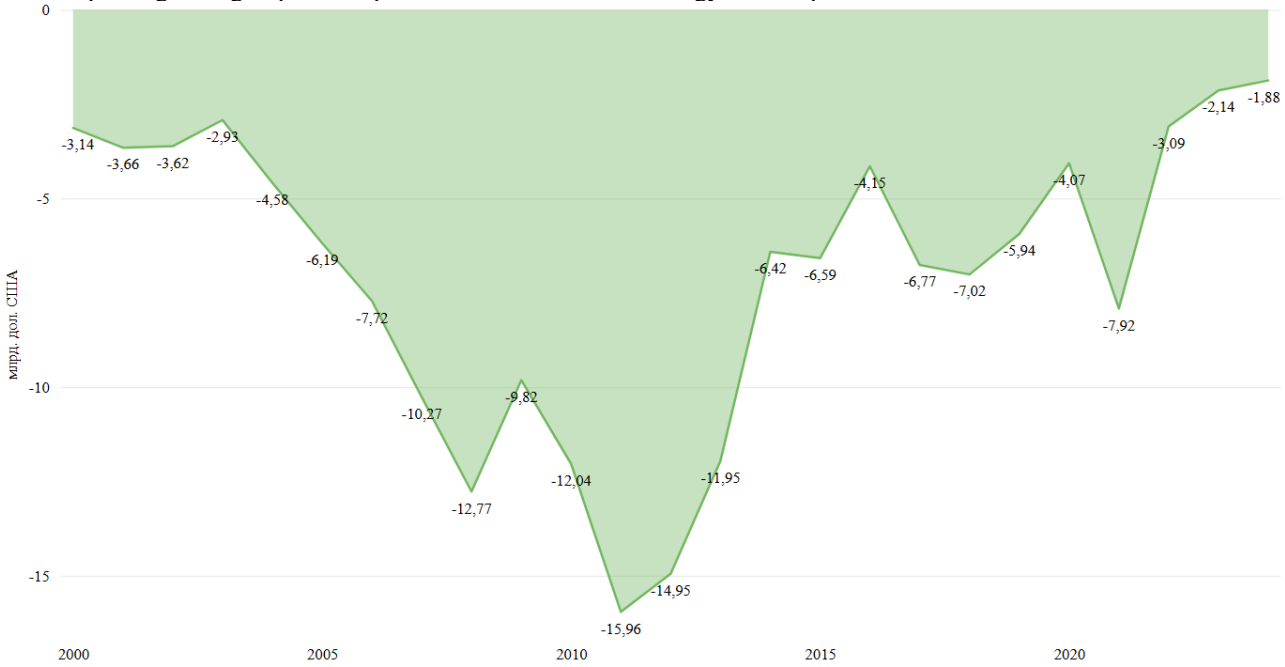

Fig. 1. Dynamics of Ukraine's energy resources trade balance in 2000–2024

Ukraine's energy resources trade balance in 2000–2024 remains persistently negative, reflecting the systemic import dependence of the energy sector and the limited capacity of domestic production to fully satisfy internal demand. The deepest deficit was recorded in 2009–2011, when it reached USD –15–16 billion, coinciding with high volumes of natural gas and oil imports amid elevated energy prices and the absence of sufficient domestic generation and resource alternatives capable of replacing imported supplies.

The outbreak of the war in 2014 became a structural turning point for the energy sector. A sharp decline in industrial production and overall energy consumption led to a reduction in the physical volumes of energy imports, as a result of which the trade deficit narrowed to USD –4–6 billion, despite the simultaneous loss of part of the generating capacities and resource base. This period illustrates that the improvement in the trade balance was driven primarily by demand contraction rather than by increased energy self-sufficiency.

The full-scale war caused renewed instability: in 2022, the deficit increased to USD –7.9 billion due to the destruction of energy and related infrastructure, disruptions in domestic production, and the need for emergency imports. At the same time, in 2023–2024 the deficit decreased to USD –2.1–1.9 billion, driven by a further decline in domestic demand and a shift in the generation structure in favor of nuclear energy and distributed renewable generation, which reduced the need for imported fossil fuels. Thus, the transformation of the electricity production structure is directly reflected in the dynamics of the energy resources trade balance, highlighting the close interdependence between structural changes in generation and external energy dependence.

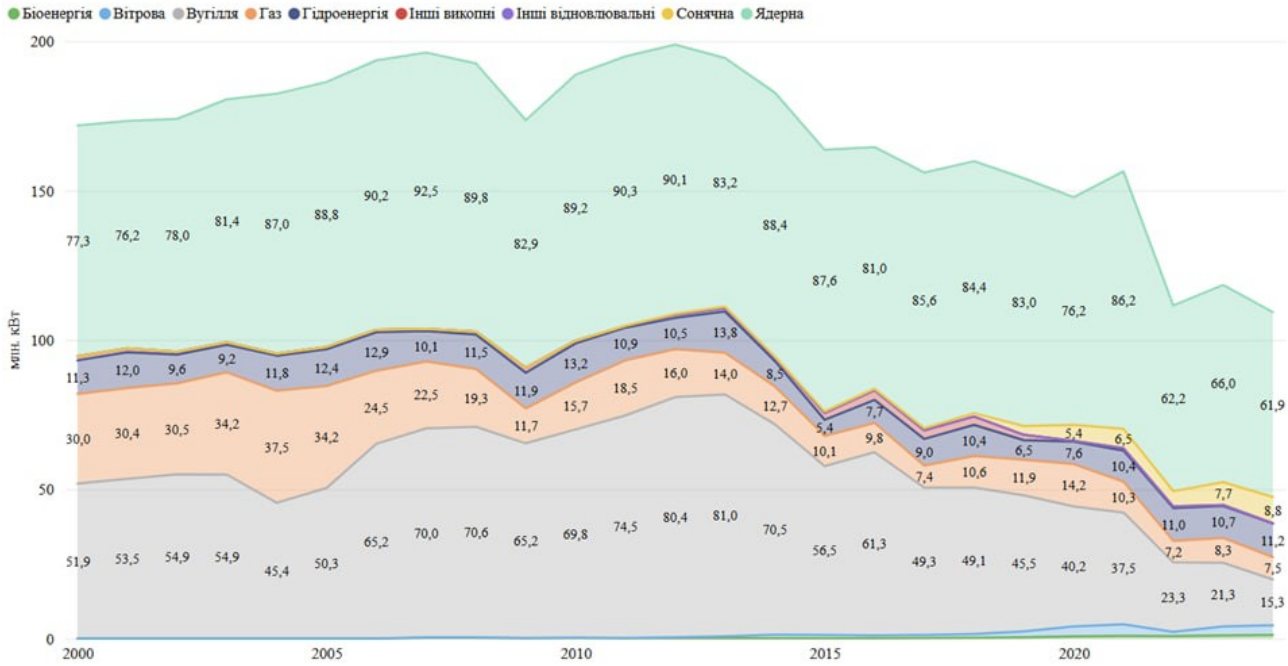

Fig. 2. Dynamics of electricity generation in Ukraine by type of generation in 2000–2024

The transformation of Ukraine's energy sector in 2000–2024 is characterized by a declining role of fossil fuel sources and the growing importance of nuclear and renewable generation, reflecting both long-term structural shifts and the impact of external shocks. In the 2000s, total electricity generation amounted to approximately 170–190 billion kWh per year, of which more than 75–85 billion kWh were produced by nuclear power plants (45–48%), while 70–80 billion kWh were generated by thermal power plants (40–45%). During this period, the share of renewable energy sources remained marginal and did not exceed 1–2 billion kWh, indicating the limited penetration of low-carbon alternatives.

After 2010, and especially with the onset of the war in 2014, coal-based generation began to decline rapidly—from more than 70 billion kWh to about 56 billion kWh in 2015, and after 2022 to approximately 15 billion kWh. As a result, the share of thermal generation fell to about 14% in 2024, reflecting both the loss of coal-fired capacities and deliberate shifts away from carbon-intensive production.

Nuclear energy has retained its role as a baseload source throughout the period, providing 55–60 billion kWh annually, which corresponds to 56–57% of total generation in 2023–2024. At the same time, electricity production from renewable sources increased steadily from less than 2 billion kWh in 2010 to more than 12–14 billion kWh in 2024, with their share exceeding 8%, demonstrating the gradual diversification of the generation mix.

Overall, the dynamics of generation volumes and structure indicate a reduction in carbon-intensive production, the preservation of nuclear generation as a core element of the energy system, and a growing role of renewable energy sources. At the same time, changes in the generation structure alone do not provide a complete picture of the efficiency of the energy sector, as they largely depend on fluctuations in economic activity and demand. Therefore, further analysis should focus on assessing generation efficiency, which reflects the relationship between electricity production volumes and GDP dynamics and allows for a more comprehensive evaluation of the sector's performance.

The dynamics of Ukraine's generation efficiency in 2000–2024 indicate a long-term decline in the energy intensity of the economy, reflecting not only changes in the energy sector itself but also broader transformations in the national economic structure. In the early 2000s, the indicator exceeded 4.0 kWh/USD, which signaled a strong dependence of economic growth on energy consumption, the dominance of energy-intensive industries, and a generally low level of technological efficiency and energy management.

During 2000–2008, a steady decrease in energy intensity to approximately 3.0 kWh/USD was observed. This trend was driven by structural shifts in the economy, including the gradual reduction of heavy and energy-intensive industrial output, improvements in production technologies, and initial measures aimed at enhancing energy efficiency. Economic growth in this period was increasingly supported by sectors with lower energy demand, which contributed to the observed decline in the indicator.

After the financial crisis of 2008–2009, and especially following the events of 2014, generation efficiency stabilized at the level of 2.6–2.8 kWh/USD. This stabilization indicates a relative decoupling of GDP dynamics from electricity generation volumes, suggesting that economic output became less directly tied to increases in electricity production. However, this decoupling was only partial and was influenced by both efficiency improvements and constraints on industrial activity.

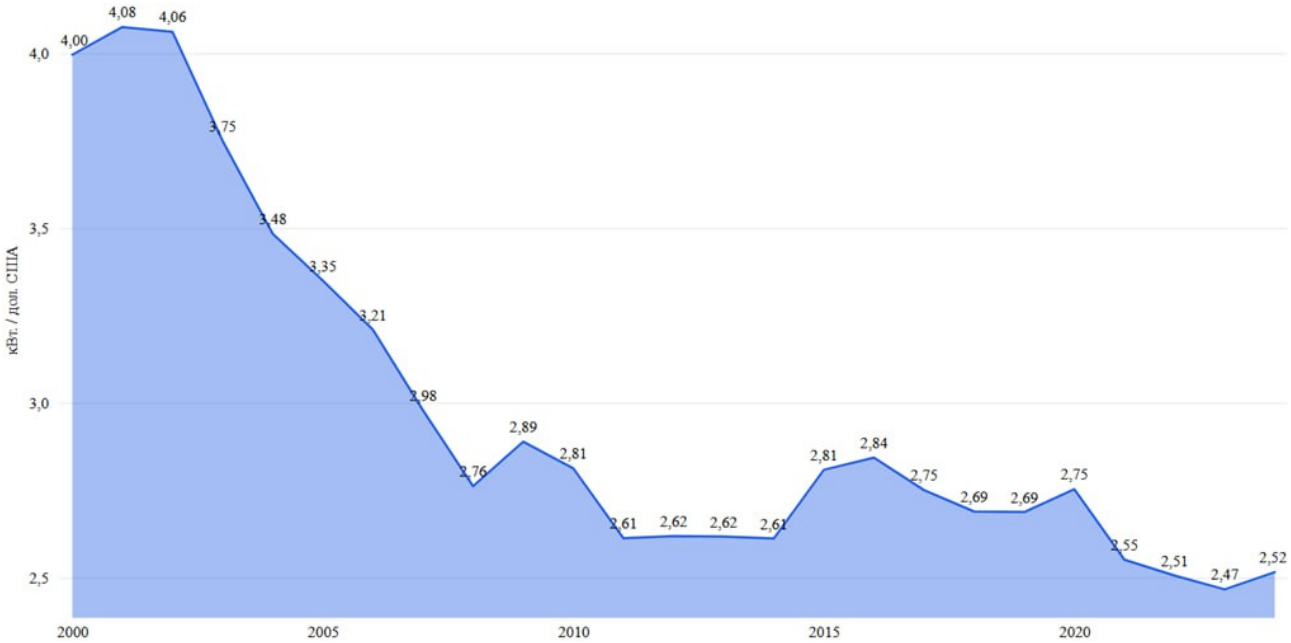

Fig. 3. Dynamics of Ukraine's GDP energy intensity in 2000–2024

The period after 2022 is characterized by a further decline in the indicator to about 2.5 kWh/USD, which was largely driven by a sharp contraction in industrial production and significant changes in the structure of the economy under wartime conditions, rather than solely by technological modernization or targeted energy efficiency policies. Overall, the recorded decline in generation efficiency points to a formal increase in the effectiveness of electricity use; however, it is largely the result of structural economic shifts and a reduction in energy-intensive activities rather than sustainable efficiency gains. At the same time, improvements or declines in energy efficiency are not always accompanied by a proportional reduction in environmental pressure. In this context, the analysis of pollution intensity in the energy sector becomes particularly important, as it allows an assessment of the extent to which changes in the structure and volumes of electricity generation are translated into actual reductions in emissions per unit of electricity produced.

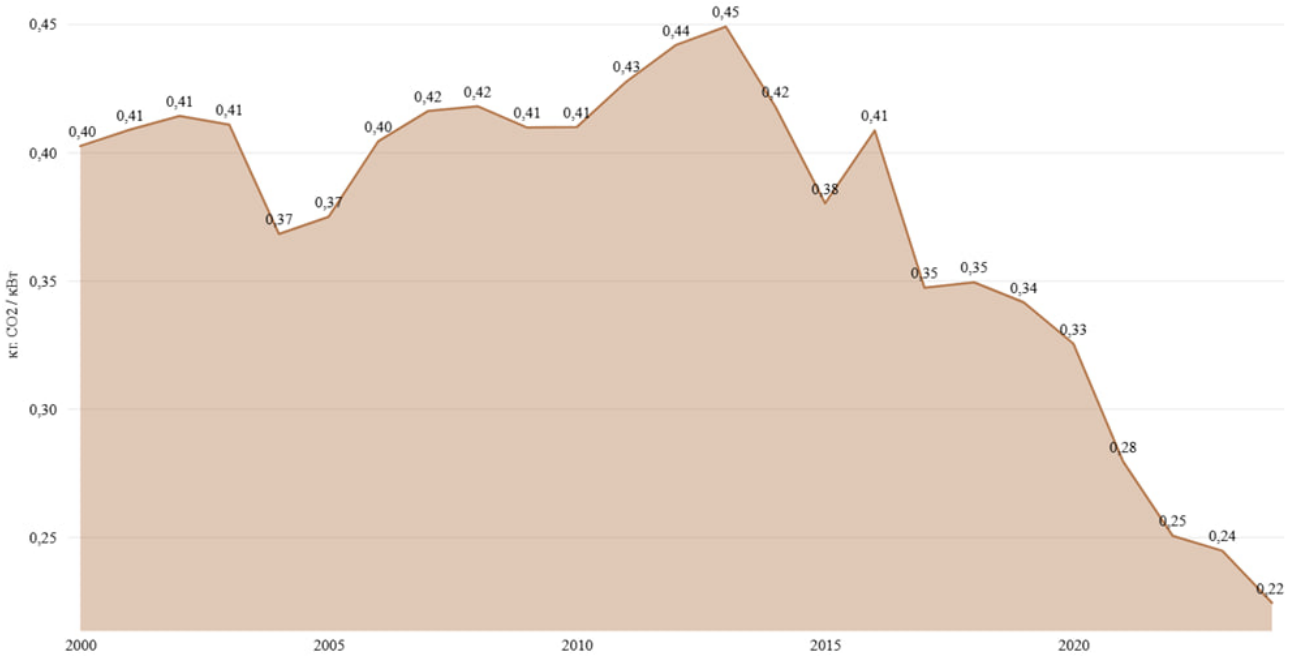

Fig. 4. Dynamics of pollution intensity of Ukraine's energy sector in 2000–2024

The pollution intensity of Ukraine's energy sector in 2000–2023 generally demonstrates a downward trend, albeit with clearly defined stages that reflect changes in the generation mix and external shocks. In the early 2000s, the indicator remained at 0.40–0.42 kg CO_2/kWh, corresponding to the dominance of thermal generation and the widespread use of fossil fuels, primarily coal and natural gas. In 2006–2013, pollution intensity increased to 0.44–

0.45 kg CO_2/kWh due to the intensive operation of coal-fired thermal power plants and the limited development of low-carbon and renewable energy sources, which constrained progress toward emission reduction.

After 2014, emission intensity gradually declined to 0.34–0.38 kg CO_2/kWh, driven by a significant reduction in coal-based generation and the growing role of nuclear energy and renewable sources in the electricity mix. This period reflects both structural adjustments in the energy sector and forced changes resulting from the loss of certain generating capacities. The most pronounced decrease was recorded in 2020–2023, when the indicator fell to 0.22–0.25 kg CO_2/kWh, mainly as a result of the loss of carbon-intensive capacities, reduced electricity generation volumes, and disruptions caused by the war. Overall, the observed decline has a structural character; however, it is largely driven by crisis-related factors rather than by a consistent and planned decarbonization policy.

The conducted analysis shows that further transformation of Ukraine's energy sector should be based on a combination of restoring damaged capacities and implementing gradual structural changes. Priority should be given to preserving nuclear generation as the baseload element of the energy system, as well as restoring hydropower and thermal power plants to ensure system reliability and effective balancing. The development of renewable energy should focus on distributed generation for self-consumption, which can reduce network loads, enhance local resilience, and lower the need for energy imports. Gas-fired generation should be used primarily as a flexible reserve to support system stability, while the reduction of coal-based generation should be gradual and targeted at the least efficient and most carbon-intensive capacities. Infrastructure reconstruction should focus on grid modernization and projects with rapid effects on the stability of energy supply, thereby creating a foundation for the further sustainable and resilient development of the energy system.

CONCLUSIONS OF THE STUDY AND PROSPECTS FOR FURTHER RESEARCH IN THIS FIELD

The study finds that Ukraine's energy sector is undergoing a profound transformation driven by a combination of accumulated structural imbalances and the direct consequences of military actions. The analysis of the energy resources trade balance revealed persistent import dependence and a high sensitivity of the energy system to external shocks, which intensified significantly after 2014 and during the period of full-scale war. This confirms the vulnerability of national energy security and the limited capacity of domestic resource and generation potential.

The examination of changes in the generation structure demonstrated a reduction in the share of carbon-intensive energy sources, the preservation of nuclear power as the baseload element of the energy system, and a gradual increase in the role of renewable energy sources. At the same time, these structural shifts are largely forced in nature, resulting from the loss of certain capacities and a decline in demand rather than solely from the implementation of a consistent energy transition strategy.

The assessment of generation efficiency revealed a close relationship between electricity production volumes and economic dynamics, which limits the effectiveness of technological changes in the absence of comprehensive structural and institutional reforms. The analysis of pollution intensity in the energy sector confirmed an overall downward trend, while also indicating a continued dependence of emission levels on the generation mix and the condition of flexible and balancing capacities.

The obtained results suggest that the further development of Ukraine's energy sector should be based on a combination of restoring damaged infrastructure, preserving low-carbon baseload generation, and accelerating the development of flexible and renewable capacities as a foundation for increasing system resilience and reducing environmental pressure.

Prospects for further research in this field include a deeper analysis of post-war energy system development scenarios, an assessment of the role of energy storage technologies and demand-side management mechanisms, as well as the study of economic and regulatory instruments to stimulate energy efficiency and decarbonization. Particular attention should be paid to the development of integrated models that combine economic, energy, and environmental indicators in order to substantiate long-term strategies for the sustainable development of Ukraine's energy sector.

References

1. Kuz V. Energy security of the state under conditions of intensified globalization processes // University Scientific Notes. – 2023. – No. 3–4 (93–94). – P. 18–29. – DOI: https://doi.org/10.37491/UNZ.93-94.2

2. Dykha M. V., Dykha V. V. Energy security of Ukraine in the context of threats related to the Nord Stream 2 launch // Scientific Works of Khmelnytskyi National University. – 2021. – Available at: https://elar.khmnu.edu.ua/bitstreams/46389090-c96f-4627-9375-65d587acc07c/download

3. Tarasiuk D. Transformation of Ukraine's energy sector under global decarbonization conditions [Electronic resource]. – 2023. – Available at: https://ela.kpi.ua/items/fdf2a806-c215-47f6-8339-02502e57945d

4. Verbova O. Enhancing the competitiveness of Ukraine's energy sector in the context of global transformations [Electronic resource]. – 2024. – Available at: https://ela.kpi.ua/items/cc5df18b-c040-403a-bd2e-388a9928bbf2

5. Horoshkova L. A., Korniichuk Yu. D. Renewable energy under wartime conditions and post-war recovery of Ukraine // Proceedings of the 3rd International Online Conference "Current Issues of Formal and Informal Education in Environmental Monitoring and Nature Conservation". – Kharkiv : V. N. Karazin Kharkiv National University, 2024. – P. 23–25. – Available at: https://www.researchgate.net/publication/393946291

6. Predun K., Kushnir O., Pochka O. Analysis of sectoral transformations as a prerequisite for the formation and development of biosphere compatibility in the energy sector // Efficient Economy. – 2024. – No. 8. – P. 137–140. – Available at: https://repositary.knuba.edu.ua/handle/123456789/13664
7. Sirenko Yu., Volvach S., Savoyskyi O., Kozin V. Analysis of the state of Ukraine's energy system and measures to improve the situation // Bulletin of Kherson National Technical University. – 2025. – Available at: https://www.researchgate.net/publication/394961246
8. Shcherbyna Ye. Modeling the structural transformation of the Integrated Power System of Ukraine during the post-war recovery period // Energy: Economics, Technology, Ecology. – 2025. – No. 2. – Available at: https://energy.kpi.ua/article/view/327484
9. Cabinet of Ministers of Ukraine. Energy Strategy of Ukraine until 2035: Security, energy efficiency, competitiveness : Order No. 605-r of August 18, 2017 [Electronic resource]. – Available at: https://zakon.rada.gov.ua/laws/show/605-2017-%D1%80#Text
10. Kovalenko Yu., Lazarenko D., Marchenko O. Energy security of the country during the war: Barriers and prospects for overcoming // Herald of Khmelnytskyi National University. Economic Sciences. – 2024. – No. 1 (326). – P. 262–266. – DOI: https://doi.org/10.31891/2307-5740-2024-326-41
11. EMBER. World electricity generation [Electronic resource]. – Available at: https://ember-energy.org/data/electricity-data-explorer/
12. ENTSO-E. Transparency Platform [Electronic resource]. – Available at: https://transparency.entsoe.eu/
13. ExPro Consulting. Special report: Five-year contract for the transit of Russian gas – results [Electronic resource]. – Available at: https://expro.com.ua/statti/specmateral-5-rchniy-dogovr-tranzitu-rosyskogo-gazu-pdsumki
14. International Trade Centre. Trade Map – trade statistics [Electronic resource]. – Available at: https://www.trademap.org/Index.aspx
15. World Bank. World Bank Open Data [Electronic resource]. – Available at: https://data.worldbank.org/