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ADAPTIVE MANAGEMENT OF UKRAINE'S ENERGY DEVELOPMENT IN THE CONTEXT OF LOW-CARBON AND DIGITAL TRANSITION

АДАПТИВНИЙ МЕНЕДЖМЕНТ ЕНЕРГЕТИЧНОГО РОЗВИТКУ УКРАЇНИ В УМОВАХ НИЗЬКОВУГЛЕЦЕВОГО ТА ЦИФРОВОГО ПЕРЕХОДУ

Vavdiiuk Nataliia
Doctor of Economic Sciences, Professor,
Lutsk National Technical University
ORCID: https://orcid.org/0000-0001-9100-3722

Riznyk Dominika
Student,
Lutsk National Technical University
ORCID: https://orcid.org/0009-0001-1017-4544

Shovkalyuk Maryna
Candidate of Technical Sciences, Associate Professor,
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
ORCID: https://orcid.org/0000-0002-1898-3493

Вавдіюк Наталія Степанівна, Різник Домініка Романівна
Луцький національний технічний університет

Шовкалюк Марина Михайлівна
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»

The article is devoted to the development of an adaptive management system for Ukraine's energy sector based on the principles of a low-carbon economy. Current trends in energy development under conditions of decarbonization, post-war recovery, digital transformation, and European integration are analyzed. A system of indicators for adaptive energy development is proposed, integrating environmental, energy, digital, and socio-managerial components. The system includes indicators of decarbonization, energy security, renewable energy development, Smart Grid implementation, Internet of Things technologies, Artificial Intelligence applications, and information transparency. An adaptive management system based on continuous monitoring, forecasting, decision-making, and corrective actions is substantiated. The proposed approach contributes to improving energy security and supporting the low-carbon transformation of Ukraine's energy sector.

Keywords: adaptive management, low-carbon economy, decarbonization, energy security, Smart Grid, Internet of Things, Artificial Intelligence, energy efficiency.

Стаття присвячена формуванню адаптивної системи менеджменту енергетичного розвитку України на принципах низьковуглецевої економіки. Досліджено сучасні тенденції розвитку енергетичного сектору в умовах декарбонізації, післявоєнного відновлення, цифрової трансформації та європейської інтеграції. Проаналізовано показники низьковуглецевого розвитку, енергетичної безпеки, розвитку відновлюваних джерел енергії та цифровізації енергетичної галузі. Встановлено, що поряд із позитивними тенденціями щодо зниження вуглецевої інтенсивності виробництва електроенергії та розвитку відновлюваної енергетики зберігаються виклики, пов'язані зі скороченням внутрішньої генерації, зростанням імпорту електроенергії та недостатнім рівнем інформаційної прозорості галузі. Систематизовано ключові чинники, що впливають на адаптивність енергетичного сектору, та обґрунтовано необхідність переходу від традиційних підходів до управління до адаптивного менеджменту, орієнтованого на безперервний моніторинг, прогнозування та оперативне коригування управлінських рішень. Запропоновано систему індикаторів адаптивного енергетичного розвитку

України, яка інтегрує екологічні, енергетичні, цифрові та управлінські компоненти в єдину інформаційно-аналітичну основу для оцінювання. До системи включено індикатори декарбонізації, енергоефективності, розвитку відновлюваних джерел енергії, енергетичної безпеки, цифровізації, інформаційної прозорості, інноваційного розвитку та людського капіталу. Обґрунтовано адаптивну систему менеджменту енергетичного розвитку України, яка базується на безперервному циклі моніторингу, аналізу, прогнозування, ухвалення та коригування управлінських рішень відповідно до змін у внутрішньому й зовнішньому середовищі. Визначено роль цифрових технологій Smart Grid, Internet of Things, Artificial Intelligence, цифрової аналітики та інформаційних платформ у забезпеченні ефективності управління енергетичним розвитком. Запропонований підхід сприяє підвищенню обґрунтованості управлінських рішень, зміцненню енергетичної безпеки та досягненню цілей низьковуглецевого розвитку України.

Ключові слова: адаптивний менеджмент, низьковуглецева економіка, цифровізація, розумні мережі, Інтернет речей, штучний інтелект, енергоефективність.

Statement of the problem. In the current context of global climate change and the implementation of the Sustainable Development Goals, low-carbon development is becoming a key priority of the state's energy policy. Global trends indicate increased demand to reduce greenhouse gas emissions, improve energy efficiency, and introduce renewable energy sources. In accordance with the provisions of the European Green Deal and international climate commitments, the transformation of the energy sector involves not only technological modernization but also the improvement of energy development management mechanisms grounded in adaptability, innovation, and sustainability.

For Ukraine, the problem of developing an effective energy development management system has become especially relevant amid military challenges and post-war recovery. The destruction of energy infrastructure facilities, the growth of energy supply risks, the need to integrate into the European energy space, and the fulfillment of decarbonization obligations necessitate the introduction of new management approaches. At the same time, traditional energy development management systems are primarily focused on stable operating conditions and do not adequately account for high levels of uncertainty, rapid technological change, and the need for prompt responses to external challenges. Under such conditions, the formation of an adaptive management system capable of ensuring effective management of energy development processes, increasing energy efficiency, and achieving the goals of a low-carbon economy is particularly important.

Analysis of recent research and publications. The issues of low-carbon development, energy transition, and adaptive management of energy systems are at the center of contemporary scientific research. Significant contributions to the development of the theoretical and methodological foundations of low-carbon transformation have been made by both foreign and Ukrainian scholars, who investigate decarbonization processes, energy security, renewable energy development, and sustainable energy system management amid increasing uncertainty.

Theoretical and applied aspects of low-carbon transformation and adaptive management are reflected in the studies of D. Vovchuk [1, p. 61-68], O. Borysiak, V. Brych, V. Manzhula et al. [2], and I. Vakulenko, Y. Matvieieva, Y. Opanasiuk et al. [3, p. 54-62]. These authors substantiate the need to implement adaptive management mechanisms, integrate energy-efficient and low-carbon management approaches, and promote innovation transfer as a basis for the transition to a carbon-neutral economy. L. Proskuryakova [4] emphasizes the importance of low-carbon energy technologies for climate resilience and sustainable development.

A separate group of studies focuses on the post-war transformation and recovery of Ukraine's energy sector. O. Lukash and V. Namoniuk [5] examine scenarios for restoring the national energy system based on sustainable development and decarbonization principles. M. Yang, B. Cela, and F. Yang [6, p. 857-879] highlight the role of innovative energy policy in transforming Ukraine's energy system, while V. Denysov and T. Yevtukhova [7, p. 17-20] develop methodological approaches to scenario forecasting of energy sector development during the low-carbon transition. The interrelationship between environmental and energy security in Ukraine's post-war recovery is substantiated by S. Delehan and H. Melehanych [8].

An increasingly important area of research concerns the digitalization of monitoring processes and the application of digital technologies in energy management. M. Pavliuk, V. Fedoniuk et al. [9] demonstrate the potential of digital tools for processing climate-related data

and supporting decision-making by developing an automated application to determine the V. Boksha bioclimatic index. The results confirm the growing importance of digital technologies as a foundation for adaptive management in the context of environmental and climate change.

Highlighting previously unresolved parts of the overall problem. Despite the considerable number of studies devoted to decarbonization, renewable energy development, energy efficiency, and scenario forecasting of energy systems, insufficient attention has been paid to the formation of adaptive management systems capable of integrating environmental, energy, digital, and managerial components into a unified decision-making framework. In particular, the issues of combining digital monitoring technologies, performance assessment indicators, Artificial Intelligence tools, knowledge management mechanisms, and competency development within a comprehensive adaptive management system remain underexplored. Furthermore, existing studies rarely consider the interconnection among low-carbon transformation, digitalization, and adaptive managerial responses in the context of post-war recovery and increasing uncertainty. Therefore, the development of an adaptive management system for Ukraine's energy development, based on an integrated set of indicators and digital decision-support tools, represents a relevant and scientifically significant research direction.

Formation of the objectives of the article (task statement). The purpose of the article is to substantiate the theoretical foundations and develop an adaptive management system for Ukraine's energy development based on the principles of a low-carbon economy, while accounting for the challenges of decarbonization, post-war recovery, and European integration.

To achieve the stated purpose, the following tasks are defined:

– to identify the key trends and challenges of low-carbon energy development in Ukraine under conditions of post-war recovery and digital transformation;

– to analyze the current state of the energy sector using indicators of decarbonization, energy security, renewable energy development, and digitalization;

– to develop a system of indicators for assessing adaptive energy development based on environmental, energy, digital, and managerial components;

– to substantiate an adaptive management system for Ukraine's energy development based on continuous monitoring, forecasting, and flexible managerial response to changes in the internal and external environment.

Summary of the main research material. The transformation of the energy sector of Ukraine is under the influence of simultaneous economic, environmental, technological and security factors. One key indicator of low-carbon development is the coefficient of greenhouse gas emissions during electricity production, which characterizes the energy sector's carbon intensity. According to the Green Transition Office, during 2020–2023, the average emission factor decreased from 0.333 to 0.288 tons of CO_2 per MWh [10; 11], indicating Ukraine's gradual progress towards decarbonizing the energy sector. At the same time, in 2023, the indicator showed a slight increase compared to 2022, which may be due to changes in the generation structure and the impact of military factors on the energy system.

Positive changes in reducing carbon intensity are accompanied by significant structural challenges. As a result of the destruction of generating capacities and energy infrastructure, electricity production volumes have significantly decreased. If in 2021 the generation volume was 157.7 TWh, then in 2023 it decreased to 102.8 TWh, and in 2024 to 96.9 TWh [12].

At the same time, electricity imports in 2024 reached 4436.6 GWh, which was the highest figure in the last 11 years. This situation indicates an increase in dependence on external sources to cover the capacity deficit and actualizes the need to form mechanisms for adaptive energy resilience management. At the same time, synchronization of the Ukrainian energy system with the European ENTSO-E grid [13] opened up new opportunities for integration into the European energy space and increasing the resilience of the energy system. The implementation of the National Energy and Climate Plan provides for further reduction of greenhouse gas emissions, increasing energy efficiency, and achieving climate neutrality of the energy sector in the long term. In 2024, the share of electricity generated from RES was about 11%, which indicates a gradual recovery of the sector and the formation of prerequisites for further decarbonization of the economy [11]. At the same time, achieving the targets of the National Energy and Climate Plan will require accelerating the pace of development of renewable generation and introducing more flexible management mechanisms to support the energy transition.

The digital transformation of the energy industry requires special attention. Modern approaches to energy system management are based on the use of digital monitoring platforms, automated control systems, Smart Grid technologies, and data analytics of the International Energy Agency [14], NPC Ukrenergo [15]. In Ukraine, the development of Smart Grids is one of the priority areas of modernizing energy infrastructure and increasing the resilience of the energy system. The introduction of digital technologies provides an opportunity for prompt information collection and analysis, risk forecasting, and support for data-based decision-making. According to the Energy Transparency Index [16], in 2024, Ukraine received 44 points out of 100 possible, indicating an insufficient level of transparency. Although the index has increased by 3 points compared to 2023, it is still below the 2020-2021 level, when transparency was estimated at 58-63 points.

The analysis showed that assessing the effectiveness of low-carbon development in Ukraine's energy sector requires considering not only decarbonization indicators but also parameters of energy security, digital transformation, innovative development, and human capital. At the same time, the lack of completeness and consistency of statistical information on certain aspects of digitalization of the energy sector, the development of digital competencies, and the level of adaptability remains a significant limitation to management processes. This complicates the formation of a comprehensive evaluation system and the making of informed management decisions.

Thus, the analysis indicates that Ukraine's energy sector is developing amid the simultaneous impacts of decarbonization, post-war recovery, rising energy security requirements, and digital transformation. These trends require the introduction of new management approaches to ensure timely responses to external environmental changes, efficient resource use, and support for low-carbon development processes. Adaptive management, based on continuous monitoring, analysis, and adjustment of managerial decisions, is particularly relevant. To ensure its information and analytical support, it is advisable to establish an indicator system for adaptive energy development that integrates environmental, economic, technological, and digital parameters into a single basis for managerial decision-making.

A feature of the proposed system of indicators is the integration of environmental, energy, digital, and socio-managerial components into a single information and analytical system. Unlike traditional approaches to assessing energy development, the proposed system takes into account not only the results of the energy sector but also digital adaptation tools, in particular Smart Grid, Internet of Things, and Artificial Intelligence technologies, which provide the ability to monitor, forecast, and promptly adjust management decisions in the context of low-carbon transformation.

On the basis of the proposed system of indicators, an adaptive system of management of energy development of Ukraine based on the principles of a low-carbon economy, which is based on a continuous cycle of monitoring, analysis, forecasting, management decision-making, and their further adjustment in accordance with changes in the internal and external environment, has been formed. The first element of the system is the monitoring unit, which collects and aggregates information on key indicators of energy development. It includes indicators of decarbonization, development of renewable energy sources, energy security, energy efficiency, digitalization, and information transparency. Smart Grid technologies, IoT sensors, smart meters and digital data collection platforms play an important role in this phase, allowing real-time monitoring.

The second element is the analytical and prognostic block, which processes the data obtained, identifies trends, and assesses potential risks. Within this block, digital analytics tools, artificial intelligence technologies, scenario modeling, and forecasting methods are used. The use of AI enables forecasting the development of the energy sector, assessing the impact of external changes, and determining the most effective directions for management.

The third element is the block of managerial decision-making, within which priorities for the development of the energy sector are determined, measures are formed to improve energy efficiency, develop renewable energy, digitalize infrastructure, and strengthen energy security. The functioning of this block results in the development of strategic and operational decisions aimed at achieving the goals of low-carbon development.

The final element is the adaptation and feedback block, which ensures the assessment of the effectiveness of the implemented measures and the adjustment of management decisions. In the event of changes in external conditions, the emergence of new risks, or deviations between actual and planned results, the system

Table 1

Indicator System for Adaptive Energy Development in Ukraine Based on the Principles of a Low-Carbon Economy and Digitalization

Block	Indicator	Unit of Measurement	Assessment Method	Type of Adaptive Influence
Environmental Block				
Decarbonization	CO_2 emission factor in electricity generation	t CO_2/MWh	CO_2 emissions / electricity generation	Environmental adaptation
Renewable energy development	Share of renewable energy sources (RES) in electricity generation	%	RES generation / total electricity generation × 100	Structural adaptation
Energy efficiency	Energy intensity of GDP	kg of oil equivalent/1,000 USD GDP	Primary energy consumption / GDP	Resource adaptation
Energy Block				
Energy sustainability	Electricity generation volume	TWh	Actual electricity generation	System adaptation
Energy security	Electricity imports	GWh	Actual electricity imports	Security adaptation
Power system reliability	Duration and frequency of emergency outages	hours/year	System operator statistics	Operational adaptation
Digital Block				
Smart Grid	Smart Grid implementation level	% or index	Share of digitalized energy facilities	Technological adaptation
Internet of Things (IoT)	Deployment level of smart meters and IoT sensors	%	Share of facilities equipped with digital monitoring	Real-time adaptation
Artificial Intelligence (AI)	AI application in forecasting and decision support	% or index	Share of processes using AI solutions	Predictive adaptation
Digital analytics	Use of digital platforms and dashboards	Index	Expert assessment or usage statistics	Information adaptation
Information transparency	Energy Transparency Index	points (0–100)	DiXi Group methodology	Communication adaptation
Socio-Managerial Block				
Human capital	Development level of digital and green competencies	%	Share of personnel who completed relevant training	Human resource adaptation
Innovation development	Energy innovation implementation level	% or number of projects	Share of innovative solutions in the sector	Innovation adaptation
Management adaptability	Response time to changes in the external environment	Days	Time from problem identification to managerial decision	Managerial adaptation

Source: compiled by the authors based on [2; 4; 8-16]

initiates a new cycle of monitoring and analysis. This approach ensures the continuity of the management process and enhances the energy sector's ability to adapt to the challenges of low-carbon transformation.

Thus, the proposed adaptive management system integrates monitoring, forecasting, and management processes within a single digital environment, thereby improving decision-making efficiency, strengthening energy security, and advancing Ukraine's low-carbon development goals.

Conclusions. The study showed that Ukraine's energy sector is developing amid the simultaneous impacts of decarbonization, post-war recovery, rising energy security requirements, and digital transformation. The analysis of current trends showed a gradual decrease in the carbon intensity of electricity production, the development of renewable energy sources, and the introduction of digital technologies for energy infrastructure management. At the same time, the reduction in domestic generation, the growth of electricity imports, and the insufficient transparency of the energy sector create additional challenges to ensuring the sustainable development of the industry.

The expediency of using adaptive management as a tool for ensuring low-carbon development of Ukraine's energy sector in the context of the high dynamism of the external environment has been substantiated. It is determined that the effectiveness of managerial decisions largely depends on the timeliness of obtaining information, the ability to predict changes, and the prompt adjustment of managerial actions.

The main result of the study is the development of a system of indicators for adaptive energy development in Ukraine that integrates environmental, energy, digital, and socio-governance components. A feature of the proposed approach is the inclusion of digital indicators, in particular Smart Grid, Internet of Things, Artificial Intelligence, digital analytics, and the Energy Transparency Index, which allow for consideration of the energy sector's level of digital maturity and its ability to adapt in the context of low-carbon transformation.

The practical significance of the proposed system lies in its potential to serve as a basis for monitoring, evaluating, and supporting managerial decision-making in energy development. It is advisable to direct further research to the development of an integral index of adaptive energy development and the approval of the proposed system of indicators at the national and regional levels.

REFERENCES:

1. Vovchuk, D. (2024). Adaptive components of low-carbon development of enterprise. *Ekonomichnyy analiz*, *34*(1), 61-68. https://doi.org/10.35774/econa2024.01.061

2. Borysiak, O., Brych, V., Manzhula, V., Lechowicz, T., Dluhopolska, T., & Putsenteilo, P. (2025). Synergy of Energy-Efficient and Low-Carbon Management of the Logistics Chains Within Developing Distributed Generation of Electric Power: The EU Evidence for Ukraine. *Energies*, *18*(20), 5512. https://doi.org/10.3390/en18205512

3. Vakulenko, I., Matvieieva, Y., Opanasiuk, Y., Taraniuk, K., & Rosokhata, A. (2024). A road map for the transition to a carbon-free economy based on the energy innovations transfer. *Socio-economic relations in the digital society*, *3*(53), 54-67. https://doi.org/10.55643/ser.3.53.2024.568

4. Proskuryakova, L. (2023). The Contribution of Low-Carbon Energy Technologies to Climate Resilience. *Climate*, *11*(12), 231. https://doi.org/10.3390/cli11120231

5. Lukash, O., Namoniuk, V. (2024). Post-war Development Energy Scenarios for Ukraine. In: Tàbara, J.D., Flamos, A., Mangalagiu, D., Michas, S. (eds) Positive Tipping Points Towards Sustainability. Springer Climate. Springer, Cham. https://doi.org/10.1007/978-3-031-50762-5_6

6. Yang, M., Cela, B. & Yang, F. (2020). Innovative energy policy to transform energy systems in Ukraine. *Mitig Adapt Strateg Glob Change* 25, 857–879. https://doi.org/10.1007/s11027-019-09898-x

7. Denysov, V., & Eutukhova, T. (2024). Dynamic Models for Developing Reference Scenarios of Energy System in the Low-Carbon Transition. *System Research in Energy*, (1 (76), 17-26. https://doi.org/10.15407/srenergy2024.01.017

8. Delehan, S., & Melehanych, H. (2025). Environmental and energy security on the way to rebuilding Ukraine on the principle of zero carbon footprint. In S. Nate (Ed.), *Ukraine's journey to recovery, reform and post-war reconstruction* (Contributions to Security and Defence Studies). Springer. https://doi.org/10.1007/978-3-031-66434-2_14

9. Pavliuk, M., Fedoniuk, V., Vavdiiuk, N., & Fedoniuk, Yu. (2025). Distribution of V. Boksha's bioclimatic index in Ukraine and the development of an automated application for its determination. International Conference of Young

Professionals “GeoTerrace-2025”, 2025, 1–5. European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.202552084. https://doi.org/10.3997/2214-4609.202552084

10. Green Transition Office. URL: https://gto.dixigroup.org/en/ (accessed May 18, 2026).
11. Green Transition Office. (2024). *GHG emission factors for electricity generation and consumption in Ukraine: Analytical study and description of the methodological approach to the calculation*. DiXi Group. URL: https://gto.dixigroup.org/en/ (accessed May 18, 2026).
12. Ministry of Energy of Ukraine. URL: https://mev.gov.ua/en/home (accessed May 18, 2026).
13. ENTSO-E. URL: https://www.entsoe.eu/ (accessed May 18, 2026).
14. International Energy Agency. URL: https://www.iea.org/ (accessed May 20, 2026).
15. NPC Ukrenergo. URL: https://ua.energy/ (accessed May 20, 2026).
16. Energy Transparency Index. URL: https://index.dixigroup.org/ (accessed May 20, 2026).

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