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Energy security as a key factor in Ukrainian economic resilience in the time of war

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Abstract. The research aimed to evaluate the condition of the Ukrainian energy system amid the war, ascertain the degree of infrastructure damage, and estimate the potential for restoration and maintenance of a steady energy supply. The study during 2022-2024 was based on the analysis of official reports, satellite images and analytical materials on the damage and restoration of Ukrainian energy infrastructure. The financing of recovery and regulatory reforms in the energy sector was highlighted. The study established that the total financial losses of the energy sector amount to more than USD 33.8 billion. Of these, USD 11.4 billion were direct losses in the electricity sector. The analysis showed a significant debt burden on district heating companies (USD 2.6 billion) and the need for debt restructuring. The study characterised the indicators of the level of damage to the energy infrastructure, which is a critical stage in the analysis of Ukraine's energy security as a fundamental factor of national economic stability. The assessment of possible sources of financing for the industry's recovery, including international assistance, grant programmes and private sector investment, was emphasised. It was examined the role of international financial institutions, such as the European Bank for Reconstruction and Development, the World Bank and the European Investment Bank, which have already allocated more than USD 1.1 billion for emergency measures to restore Ukraine's energy infrastructure. Given the financial challenges, recommendations were developed to attract additional resources through investment insurance mechanisms, green bonds, and public-private partnerships. The study also addressed the issue of adapting tariff policy and introducing differentiated tariffs to cover the costs of infrastructure rehabilitation and encourage energy saving. This model integrates technical, financial and managerial solutions to ensure economic stability and attract the capital needed to modernise Ukraine's energy sector

Keywords: infrastructure challenges; decentralised generation; renewables; grid integration; innovative development

Introduction

Securing energy stability is a crucial aspect of national security, particularly in the context of violent conflicts that jeopardise governance and economic progress. The ongoing hostilities in Ukraine since 2014, which escalated significantly in 2022, have caused large-scale destruction of energy infrastructure, interruptions in supply and destabilisation of the energy system. In addition to physical losses, the country faced dependence on imported energy supplies, threats of energy blackmail, financial pressure on the industry and the need to urgently restore facilities. Systematic attacks on critical infrastructure, disruption of logistics chains and loss of control over energy-generating facilities have significantly complicated the country's stable energy supply. The destabilisation of the energy sector directly affects industry, agriculture, business and the daily lives of citizens, making energy security analysis essential to assess risks and develop stabilisation strategies. Ensuring energy security is the foundation for economic resilience, as a stable energy supply ensures the continuity of industrial production, the operation of small and medium-sized enterprises, and social facilities. Existing research in the context of armed conflict has largely focused on energy diversification, infrastructure rehabilitation, and adaptation of governance systems.

Author A. Lisovyi (2024) examined the issue of Ukrainian energy security in light of contemporary concerns stemming from geopolitical causes and the ramifications of the armed conflict. The author emphasizes the nation's reliance on imported resources, technological constraints, inadequate energy efficiency, and infrastructural degradation resulting from war actions. The document underscores the significance of diversifying energy suppliers, advancing renewable energy sources, and enhancing energy efficiency to bolster energy independence. Y. Kovalenko *et al.* (2024) examined the evolution of energy security measures, transitioning from conventional fuel supply to contemporary challenges arising from global conflicts and environmental issues. The research highlighted the necessity of incorporating innovative technology and alternative energy sources to guarantee the sustainability of energy supply, particularly in light of contemporary geopolitical issues.

A. Polukhin *et al.* (2023) examined the ramifications of the war on Ukraine's energy security, encompassing a reduction in production, increased energy prices, and infrastructure loss. The authors underscored the necessity of implementing measures for effective state support to maintain the stability of the energy sector during crises. A. Mazaraki & T. Melnyk (2024) delineated the present condition of Ukraine's energy system during military assault, highlighting the necessity of achieving energy independence and integration with the EU energy market. The study analyses the repercussions of the devastation of the energy infrastructure, encompassing the depletion of a substantial portion of renewable energy sources, as well as nuclear and thermal generating. Special emphasis is placed on the effective synchronisation of the Ukrainian power system with ENTSO-E and the initiation of electricity exports to European nations.

Researchers O. Malinovska & M. Vysochanska (2023) established the notion of energy security in Ukraine as a critical element for the effective operation of the national economy. The authors underscored the necessity of implementing competitive strategies in the electrical market, including contractual agreements, day-ahead market operations, and the utilisation of balancing devices to maintain the stability of the power system. V. Goryn (2024) underscored the necessity of advancing distributed generation, necessitating the elimination of legislative and organisational impediments, alongside the establishment of

financial incentives for investment in renewable energy sources. The author underscores the necessity of implementing energy efficiency programs via concessional lending and Energy Service Company funding, which will enhance the sustainability of the national energy system.

V. Vovk & A. Krasnoselska (2023) examined the environmental and economic dimensions of transformations in Ukraine's energy sector amid the war and subsequent recovery efforts. The authors analyse the trends toward the more vigorous use of renewable energy sources in Ukraine and the EU, highlighting the potential of biogas as a replacement for natural gas. The authors underscore the necessity of optimizing regulatory elements of biomethane characteristics for their incorporation into gas distribution and transmission networks, thereby facilitating domestic consumption, exports, and contributing to the nation's economic development. E. Lapenko (2023) examined critical facets of Ukrainian energy security, encompassing the influence of military activities on gas consumption and the national commitments under the Association Agreement with the EU to establish strategic reserves of oil and petroleum products. The author emphasized the particulars of establishing such reserves, including the criteria for their composition, storage, and the potential for their relocation overseas. The author analysed the fluctuations of fuel costs during the conflict, which were contingent upon inexpensive supply of Russian origin and reduced excise duties. The report emphasized the dangers presented by Russian activities at nuclear power plants and their effects on the energy stability of Ukraine and Europe.

Notwithstanding extensive research, unanswered concerns persist concerning the evaluation of the energy system's capacity to address wartime challenges and the energy crisis's effect on the nation's economic stability. Contemporary study necessitates a comprehensive examination of the correlation between energy security and economic resilience during conflict, with the exploration of creative strategies to enhance the robustness of the energy system.

The research aimed to examine the condition of Ukraine's energy system amid the war, identify principal issues and strategies for resolution, and evaluate the influence of energy security on national economic stability. The study objectives encompassed identifying primary issues in the energy system's operation resulting from military activities; evaluating the efficacy of diverse crisis response strategies; analysing the economic repercussions of energy instability; and formulating recommendations for innovative approaches to enhance the energy system's reliability.

Materials and Methods

In the period of 2022-2024 years, a study was conducted to assess the consequences of the armed conflict. The main data sources used were official documents prepared by national and international institutions, such as the Organisation for Economic Co-operation and Development (2023a; 2023b), United Nations Development Programme (2023), and analytical materials of ENTSO-E (2024). These sources provided important data on the state of the infrastructure, the extent of damage, and the scale of economic losses.

The study analysed data regarding the status and capacities of the energy system's generation facilities, heating networks, gas transmission infrastructure, and renewable energy sources. Information on damage to energy infrastructure facilities was obtained from reports and satellite images processed in Quantum geographic information system software.

The study analysed international experience in stabilising energy systems in crisis conditions. The reports of the International Energy Agency (2024) and ENTSO-E (2024) provided information on best practices for implementing decentralised generation systems, integrating alternative energy sources, and creating conditions for the long-term sustainability of energy systems. This information formed the basis for the development of scenarios for the restoration of the Ukrainian energy system. The indications of financial losses and rehabilitation requirements for the Ukrainian energy sector from 2022 to 2024 were studied. The primary focus was on examining the repercussions of the loss of critical infrastructure, including the Zaporizhzhia Nuclear Power Plant and thermal generation facilities. The primary elements of securing funding for the rehabilitation of Ukraine's energy infrastructure through diverse procedures that mitigate the particular risks linked to investment in the nation amid military aggression are defined.

The analysis confirmed the distinct characteristics of several regulatory and legal reforms designed to stabilise and expand Ukraine's energy industry throughout the wartime conflict. In particular, the authors provided a detailed description of the Law of Ukraine No. 3220-IX "On Amendments to Certain Laws of Ukraine on the Restoration and "Green" Transformation of the Energy System of Ukraine" (2023), the Resolution of the Cabinet of Ministers of Ukraine No. 227 "On the Introduction of Guarantees of Origin of Electricity Generated from Renewable Energy Sources" (2024a), and the National Renewable Energy Action Plan for the period up to 2030 (Resolution of the…, 2024b). The study analysed and processed data on sources of international financial support in 2023-2024 from the European Investment Bank, the World Bank, the European Bank for Reconstruction and Development, the EU and the United States.

The examination of an extensive model of energy system development, encompassing the interplay of financing, technology, legislative regulation, and international alliances, constituted a crucial component of the study. A specialised model was utilised to evaluate the impact of incorporating renewable energy sources on the stability of the energy system, emphasising responses to external challenges and energy efficiency. The model also incorporated regional peculiarities and specific risks for different sectors of the energy infrastructure, which was used to create adaptive recovery scenarios. The work with the documents included a review of reports from international do-

nors, such as the European Bank for Reconstruction and Development, which provided financial support for the restoration of critical energy facilities. The data was subjected to a thorough analysis, which determined the impact of innovative technologies on restoring the stability of the power system.

Results

The Ukrainian energy system is critically compromised due to extensive destruction from ongoing missile assaults and the takeover of regions housing essential energy infrastructure. Since the commencement of the large-scale invasion in 2022, over fifty percent of the nation's generating capacity has been impaired, obliterated, or appropriated, substantially constraining the country's energy supply alternatives. The loss of the Zaporizhzhia Nuclear Power Plant (6 GW) and the intense attacks of 2024, which additionally deprived Ukraine of 9 GW of capacity, created the conditions for a serious energy crisis (International Energy Agency, 2024). The situation is further complicated by the destruction of heating facilities, gas infrastructure and other key components of the energy system (Table 1).

Table 1. Analysis of key data on the state of Ukrainian heating networks (2022-2024)

Metric	Data
Number of households connected to district heating	More than a third
Share of heat generated by gas	70%
Share of combined heat and power production	30%
Destroyed or damaged facilities:	
Combined heat and power plants	18 units
Boiler houses	815 units
Central heating stations	152 units
Heating networks	354 km
Direct losses	USD 2.4 billion
Debts of heating companies to Naftogaz	UAH 95 billion (USD 2.6 billion)

Source: compiled by the authors based on International Energy Agency (2024)

An analysis of Table 1 demonstrates that Ukrainian district heating infrastructure, which supplies more than a third of households, has suffered significant damage. The critical dependence of heat supply on natural gas (70%) and combined heat and power plants (30%) significantly increases the system's vulnerability to external attacks and supply disruptions. The substantial subsidisation of heat tariffs has resulted in the buildup of loans within the sector, complicating its recovery. The Public Service Obligation mechanism introduced in 2022, which provides for the supply of gas at a reduced price compared to the market price, helped stabilise heat supply but also increased the financial burden on Naftogaz. As of October 2023, the debt of heating companies reached USD 2.6 billion, which required debt restructuring and the search for additional financial sources (World Bank, 2023). The electricity shortage was particularly acute in 2024 when generating capacity was unable to cover the peak demand of 12 GW, even with electricity imports from neighbouring countries. The most affected regions were forced to limit electricity supply to a few hours a day, which negatively affected economic activity and the basic needs of the population. During this period, international partners provided critical equipment to stabilise the power system.

Energy security is a key factor in Ukrainian economic resilience in times of war, as the destruction of critical infrastructure caused large-scale financial losses and significant challenges for the economy. The electricity sector suffered the greatest losses, with restoration needs estimated at USD 33.8 billion. This is estimated at USD 33.8 billion due to the destruction of electricity generation and distribution facilities. The oil and gas sector incurred substantial losses, requiring about USD 14.8 billion for restoration. The oil and gas industry, as well as the coal industry and the heating system, have also suffered significant losses. Funding for the reconstruction measures involves attracting international assistance from the EU, the World Bank, the International Monetary Fund and other donors, as well as reparations from Russia, which requires the development of appropriate legal mechanisms (Table 2).

Table 2. Financial losses and restoration needs in the energy sector of Ukraine (2022-2024)

Sector	Direct losses (million USD)	Indirect losses (million USD)	Recovery needs (million USD)	Possible sources of funding
Electricity sector	11,425	18,607	33,839	EU, World Bank, European Bank for Reconstruction and Development, state budget, private investors
Electricity generation	8,520	12,582	14,065	International Monetary Fund, Green Climate Fund, private investors
Oil and gas sector	3,331	1,387	14,812	World Bank, International Monetary Fund, European Bank for Reconstruction and Development, reparations from Russia

Table 2, Continued

Sector	Direct losses (million USD)	Indirect losses (million USD)	Recovery needs (million USD)	Possible sources of funding
Coal industry	840	676	521	European Bank for Reconstruction and Development, reparations from Russia, state budget
Heat supply	972	872	1,350	State subventions

Source: compiled by the authors based on Kyiv School of Economics (2024)

The Ukrainian gas supply system has sustained considerable damage due to fighting and assaults on essential infrastructure. In particular, the above-ground gas storage facilities were heavily damaged, while the underground ones remained largely intact, providing reserve capacity to meet domestic demand. However, the situation is exacerbated by a growing gas shortage due to the seasonal increase in demand in winter and the possible termination of Russian gas transit from January 2025. These developments pose significant risks to ensuring stable gas supplies, both for domestic consumption and for energy imports from the EU.

The winter period of 2024-2025 poses new challenges for the Ukrainian energy system, as the expected increase in energy demand and the high probability of new attacks on infrastructure could lead to a deepening of the crisis. In such circumstances, stabilising the energy system requires a comprehensive approach, including modernising grids and introducing decentralised generation technologies. Special emphasis must be placed on the implementation of alternative energy sources and the optimisation of energy consumption to diminish reliance on conventional energy supplies (International Energy Agency, 2024).

The Ukrainian energy system may develop under several scenarios in the period of 2025-2026 years, depending on the success of reforms, the foreign policy situation and the level of international support. A primary alternative entails the active integration of Ukraine into European energy markets, necessitating the modernisation of energy infrastructure, the adoption of European standards, and an augmentation of the proportion of renewable energy sources. According to the National Bank of Ukraine, the national electricity deficit is expected to decrease from 4% in 2025 to 2% in 2026, indicating a gradual improvement in the energy situation as reforms are implemented (Petrovsky, n.d.). The government intends to elevate the proportion of renewables in the energy mix to 27% by 2030, thereby diminishing reliance on conventional energy sources and enhancing the resilience of the energy system. A crucial measure is the complete integration of Ukraine's power and gas markets with the EU by 2025, which will enhance energy import prospects during crises and draw European investment (Order of the…, 2023).

Despite the significant pressure on the Ukrainian energy system, strategic planning and international support helped ensure the basic stability of energy supplies. At the initial stage, the Group managed to arrange electricity imports from the EU, which reached 1.7 GW to cover its needs. These actions were key in meeting the needs of the regions that suffered the most damage, where domestic generating capacities were partially or completely out of action. The stability of the energy system largely depends on the three operating nuclear power plants of Rivne, Khmelnytsky and South Ukrainian Nuclear Power Plants (Fig. 1).

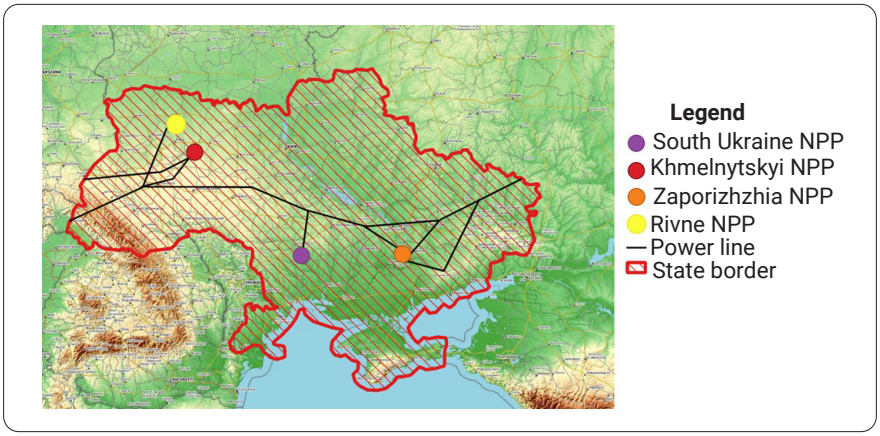

Figure 1. Map of locations of operating nuclear power plants in Ukraine

Source: compiled by the authors using Quantum geographic information system software tools based on the Quick Map Service and Open Topo Map software modules

Rivne Nuclear Power Plant, located in the northwestern part of the country, is one of the key sources of energy supply for the western regions. Its operation remains relatively stable due to its distance from active combat zones,

but the risks of attacks on transmission networks remain. Khmelnytskyi Nuclear Power Plant, located near the western border, is important not only for supplying energy to the central and western regions but also for establishing energy cooperation with the EU. The South Ukrainian Nuclear Power Plant supplies electricity to the southern and central regions, but its proximity to the war zone poses significant risks to stable operation. At the same time, the Zaporizhzhya Nuclear Power Plant, which provided about 25% of the national electricity before the war, remains under occupation by Russian troops, which significantly limits the possibilities of energy supply (Organisation for Economic Co-operation and Development, 2023a).

In the heating industry, there is an urgent necessity to formulate contingency plans for heat supply, particularly in major cities like Kyiv and in areas that have experienced substantial infrastructure damage. This includes the installation of supplementary mobile boiler houses, the implementation of decentralized heating systems, and the utilisation of cogeneration units. These efforts will somewhat offset the losses incurred from the demolition of central heating facilities and address the essential demands of the populace amid the energy crisis.

International assistance remains an important factor in stabilising the Ukrainian energy system. Integration into the European energy market through ENTSO-E (2024) is a significant achievement that provides Ukraine with access to alternative sources of electricity. However, further investments in infrastructure modernisation, energy efficiency and decentralisation of energy supply are needed to ensure long-term sustainability.

In light of the substantial risks associated with investing in the energy sector, the Ukrainian government is proactively enacting measures to decentralise generating. The emphasis is on the utilisation of tiny modular gas turbines with capacities ranging from 5 to 40 MW, rather than conventional huge power units, which are vulnerable targets. The emphasis is placed on the advancement of decentralized generation via the installation of rooftop solar panels equipped with energy storage systems in administrative buildings, hospitals, schools, residences, and enterprises. By early 2024, the total capacity of this generation approached 1.5 GW, and this number is steadily increasing thanks to the government's consistent support (Organisation for Economic Co-operation and Development, 2023a).

An evaluation of the damage to the energy infrastructure is crucial for assessing Ukrainian energy security, which is essential for economic sustainability. The persistent armed war, coupled with systematic assaults on energy infrastructure, severely restricts the state's capacity to fulfil the requirements of the populace, industry, and social sector. This analysis not only determined the extent of the destruction but also demonstrated which elements of the energy system need to be restored as a matter of priority. At the same time, an important challenge for the energy sector is the outflow of skilled personnel, which complicates the recovery process and requires the development of effective mechanisms for their retention, retraining and training. In addition, systematic data on damage serves as a basis for developing recovery strategies, attracting international financial support, and further modernising infrastructure (Fig. 2).

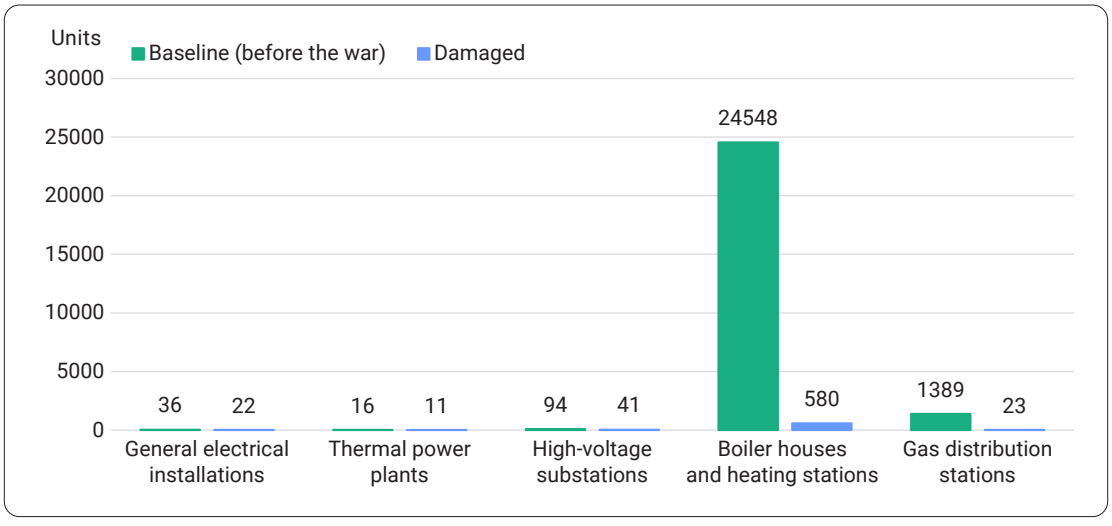

Figure 2. Assessment of damage to key energy assets in Ukraine

Source: compiled by the authors based on Organisation for Economic Co-operation and Development (2023a), International Energy Agency (2024)

The analysis of the data in Figure 2 shows significant losses in all sectors of energy infrastructure, which makes it difficult to ensure a stable energy supply in the context of the ongoing conflict. In the power generation sector, losses amount to 61.4% of the baseline. Out of a total installed capacity of 36 GW, only 14 GW remain available for use. Much of the capacity is located in the temporarily occupied territories, including the Zaporizhzhia nuclear

power plant (6 GW), depriving the country of a critical resource. The destruction of high-voltage grids further complicates the transmission of electricity between regions, which destabilises the power system. In the thermal power and combined heat and power plants sector, losses reached 71.5%. Only a third of the 16 GW of capacity is available (International Energy Agency, 2024). This poses significant risks to the district heating system, which meets the needs of large cities such as Kyiv, Kharkiv and other urbanised regions. These losses directly affect the national ability to provide heat in the winter.

The high-voltage infrastructure also suffered significant damage. Out of 94 critical high-voltage substations, 41 were damaged, or 43.6% of the baseline. Most of them have suffered repeated strikes, significantly reducing their reliability. The destruction of this infrastructure makes it impossible to effectively redistribute electricity in the grid and leads to energy shortages in some regions. Damage to heating networks and boiler houses is relatively less severe, but the impact on social stability is significant. Out of more than 24,500 units, 580 were damaged, or 2.4%. The bulk of the losses occurred in the regions of active hostilities, where district heating became unavailable to thousands of households (Trading Economics, 2024). The gas infrastructure suffered less damage compared to other sectors. Out of a total of 1,389 gas distribution stations, 23 were damaged, or 1.7% of the baseline. However, even these relatively minor losses significantly affected the gas supply to regions that depend on stable energy supplies.

The scale of the destruction in all sectors significantly increases the threat of an energy crisis, especially during the winter season and high energy consumption. The loss of 61.4% of generating capacities and 71.5% of thermal power plants and combined heat and power plants indicates a significant reduction in the ability of the energy supply system to meet the basic needs of the population and industry. This is especially critical for heating in urban agglomerations such as Kyiv and Kharkiv, where the district heating system is the main source of heat (United Nations Development Programme, 2023).

The destruction of 43.6% of high-voltage substations highlights the vulnerability of the electricity transmission system, which has caused a serious imbalance due to damage to key nodes. The inability to ensure efficient redistribution of energy between regions is leading to local energy shortages, especially in the eastern and southern regions, where the infrastructure has suffered the most damage. At the same time, even minor damage to the gas infrastructure (1.7%) significantly affected the stability of gas supplies in the affected regions. The hostilities make it difficult to quickly repair the damaged facilities, which increases the risk of prolonged disruptions in energy supplies.

The stability of the district heating system remains under threat due to significant losses in the combined heat and power plants and boiler house sector, which is critical for regions with severe winter conditions. Winter conditions in 2024 exacerbate these risks, given the projected increase in energy demand and the risk of repeated attacks on infrastructure. An analysis of the economic damage caused to the energy infrastructure as a result of hostilities highlights the urgent need to develop and implement solutions aimed not only at restoring but also at increasing the resilience of key energy facilities. Energy security is crucial in ensuring the economic stability of the state, as it directly affects the social sphere, industry and the ability of the economy to operate in crises (Order of the…, 2023).

Ukraine is actively implementing comprehensive measures to modernise its energy system, given the difficulties caused by the armed conflict. In 2024, the Energy Strategy of Ukraine until 2050 was approved, which envisages integration with the EU energy system, development of renewable energy sources, renovation of heating networks and buildings, and encouragement of private sector investment (Table 3).

Table 3. Key areas for modernising the Ukrainian energy system

Direction	Description	Expected effect
Strategic planning	Implementation of the plans of the Energy Strategy of Ukraine until 2050 and integration with the EU energy system	Ensuring long-term energy security
EU integration	New interconnectors with Romania and Slovakia by 2026	Increased exports and security of supply
Energy efficiency	Modernisation of buildings and heating networks through financial mechanisms	Reduced energy consumption by up to 50%
CEP development	Launch of biomethane plants and development of solar and wind power plants	Increase the share of renewable energy sources and reduce gas dependence
Tariff reform	Introduce differentiated tariffs to protect vulnerable consumers	Stimulating investment and optimising costs
“Smart” technologies	Implementation of smart meters and demand side management	Optimisation of energy consumption and reducing peak loads
Support for the private sector	Transparent rules and mechanisms for investment insurance	Raising capital to modernise the system
Integration of gas storage facilities	Provision of 10 billion cubic metres to European partners for gas storage	Additional revenues and enhanced security for Europe
Citizen engagement	Energy saving campaigns and public education	Increase efficiency and reduce costs

Source: compiled by the authors based on Organisation for Economic Co-operation and Development (2023a), United Nations Development Programme (2023), International Energy Agency (2024)

Considering the main directions of modernisation of the Ukrainian energy system, it should be emphasised that the creation of new energy connections is an important project within the framework of integration with the EU. In particular, it is planned to launch new 400 kV power lines between Ukraine and Romania by 2026, estimated at 300 million EUR, partially financed by the European Bank for Reconstruction and Development. The Hungarian route provided supplies of up to 9 million cubic metres of gas per day, but the agreement was only valid until January 2025, and its extension is critical (World Bank, 2023). Funding was made possible through initiatives such as the G7+ Energy Coordination Group, which provided 1.4 billion dollars in 2023 to restore critical infrastructure (European Commission, 2024). In addition, Ukraine used the AggregateEU platform to purchase an additional 0.6 billion cubic metres of gas from the EU in September-October 2024, with a total value of 250 million EUR.

Funding for the restoration of Ukrainian energy infrastructure is raised through various mechanisms that consider the specific risks associated with investing in a country under military aggression. One of the key sources of financing is international financial institutions, such as the European Bank for Reconstruction and Development and the International Finance Corporation. These institutions provide long-term loans and investments aimed at supporting Ukrainian enterprises, in the energy sector, agribusiness and infrastructure. In addition, export credit agencies, such as the U.S. Corporation for International Development and the UK Export Finance, are important. These institutions offer insurance and reinsurance of investments against political and military risks, which helps to attract private capital (Ministry of Economy of Ukraine, n.d.).

An additional mechanism of financial support is provided by the Multilateral Investment Guarantee Agency, a member of the World Bank Group that specialises in political risk insurance for foreign investors investing in the Ukrainian economy. In addition, some governments have created special investment funds to support projects in Ukraine. For instance, the Danish Government Investment Fund finances economically viable projects that promote a green transition and energy infrastructure development (Insurance of investments…, 2024).

However, investing in the energy sector of Ukraine is accompanied by significant risks. The most significant of these are military risks, as the ongoing aggression significantly increases the probability of damage or destruction of critical infrastructure, which could cause a loss of investment. Political risks also remain a serious factor, as the unstable situation in the country creates the possibility of changes in legislation that could affect investors' rights. In addition, there are economic risks associated with the volatility of macroeconomic indicators, which may affect the government's ability to meet its financial obligations to creditors. Operational risks, such as the destruction of infrastructure, logistical problems, and a shortage of qualified personnel, can complicate the implementation of investment projects. Several key mechanisms are used to minimise these risks. First, international financial institutions provide guarantees and insurance, which reduce the risks for private investors. Second, state guarantees and government participation in financing infrastructure projects increase confidence in investing in Ukraine.

The advancement of renewable energy sources is a specific emphasis. In 2024, Ukraine inaugurated 10 biomethane facilities with a combined capacity of 1.5 million cubic meters annually. This diminishes reliance on natural gas and aids in the attainment of sustainable development objectives. In the Mykolaiv region, a 200 MW wind farm was completed with a budget of 450 million USD, 70% of which was financed by the European Investment Bank. Tariff reform is also central to the development of the region. In 2024, differentiated electricity tariffs were introduced: basic household consumption is subsidised, while consumption above the standard is paid at market prices. This helps to stimulate energy saving and attract private investment (World Bank, 2023).

During the period of military operations, Ukraine implemented several regulatory reforms aimed at stabilising and developing the energy sector. One of the key changes was the implementation of European standards in the energy sector. The Law of Ukraine No. 3220-IX "On Amendments to Certain Laws of Ukraine on the Restoration and "Green" Transformation of the Energy System of Ukraine" (2023) introduced the concept of an "active consumer", which allowed citizens and businesses to install private generating units to produce electricity on their own and sell its surplus to the grid. In January 2024, the relevant amendments to the Distribution Systems Code enshrined the legal mechanisms for implementing this process (Resolution of the…, 2018).

The government has initiated a corporatisation process to enhance the transparency of state-owned energy company management. In February 2024, a resolution was enacted to convert the State Enterprise Guaranteed Buyer into a joint-stock corporation, retaining 100% of its shares under state ownership. This was intended to bolster confidence among foreign partners and investors (Petrov & Andarak, n.d.). The ratification of Cabinet of Ministers of Ukraine Resolution No. 227, titled "On the Introduction of Guarantees of Origin of Electricity Generated from Renewable Energy Sources," marked a pivotal advancement in renewable energy development (2024a). The program sought to entice international investment in the renewable energy sector, as assurances of origin offer the potential for enhanced tax incentives and advantageous financing conditions.

In August 2024, the government ratified the National Renewable Energy Action Plan for the period leading to 2030, which anticipates an augmentation of the renewable sources' participation in the energy consumption framework to 27% (Resolution of the…, 2024b). The proposed actions entail conducting auctions for the establishment of new renewable energy installations, thereby fostering advantageous conditions for industry advancement. A crucial

aspect was to promote the advancement of distributed generating. In response to the risks of physical destruction of centralized infrastructure, the government has formulated a strategy for the advancement of small-scale generation from renewable energy sources. This streamlines the processes for integrating such plants into the grid and offers them enhanced financial and regulatory incentives. This method facilitates the decentralisation of electricity generation and strengthens the resilience of the power system. Notably, a significant measure in enhancing state control over energy assets was the transfer of 27 gas distribution companies to state oversight in 2023. This method seeks to guarantee a continuous gas supply and mitigate the impact of oligarchic entities on the gas market (Scientific concept of…, 2024).

The implemented regulatory modifications enhanced the electricity system's resilience and its capacity to respond to wartime conditions. The incorporation of European standards guarantees market transparency and establishes the prerequisites for attracting investment. The advancement of renewable energy and distributed generation facilitates the decentralisation of electricity supply, hence mitigating the hazards linked to physical assaults on energy infrastructure. Strengthening state control over gas networks and implementing measures to develop nuclear power form the basis for ensuring long-term energy security.

To improve the efficiency of energy consumption in buildings, in 2023 the Energy Efficiency Fund of Ukraine provided grants totalling UAH 600 million, which covered the insulation of more than 500 apartment buildings. In 2024, this figure will be increased to UAH 1 billion, which will allow for the modernisation of about 1,200 more facilities (International Energy Agency, 2024). In addition, modernisation includes the active introduction of smart technologies. As of the end of 2024, more than 1.5 million smart electricity meters had been installed, funded by a USD 200 million loan from the World Bank (2023). Strategic measures focused on integration with the EU, tariff reform, and infrastructure development allow Ukraine to ensure not only energy security but also lay the foundation for economic sustainability.

Strategic planning to enhance Ukrainian energy security include many initiatives focused on modernizing infrastructure, diversifying energy sources, enhancing energy efficiency, and connecting with European energy networks. The execution of these efforts will guarantee the stability of the energy system and enhance the nation's economic resilience against military threats. The modernisation of Ukrainian energy infrastructure emphasizes sustainable outcomes. The utilisation of renewable energy sources, along with the incorporation of smart grids and energy storage systems, is essential for diminishing reliance on conventional energy resources and enhancing energy efficiency. Furthermore, these technologies generate new prospects for Ukrainian integration into the European energy sector, thereby enhancing energy independence and economic stability.

Implementing creative solutions can markedly diminish the dangers linked to external threats. These methodologies facilitate the establishment of local energy systems capable of guaranteeing a reliable energy supply for essential facilities, including medical institutions and industrial businesses. Special emphasis must be placed on the cybersecurity of energy systems, as contemporary digital threats considerably impact the security of energy infrastructure (Fig. 3).

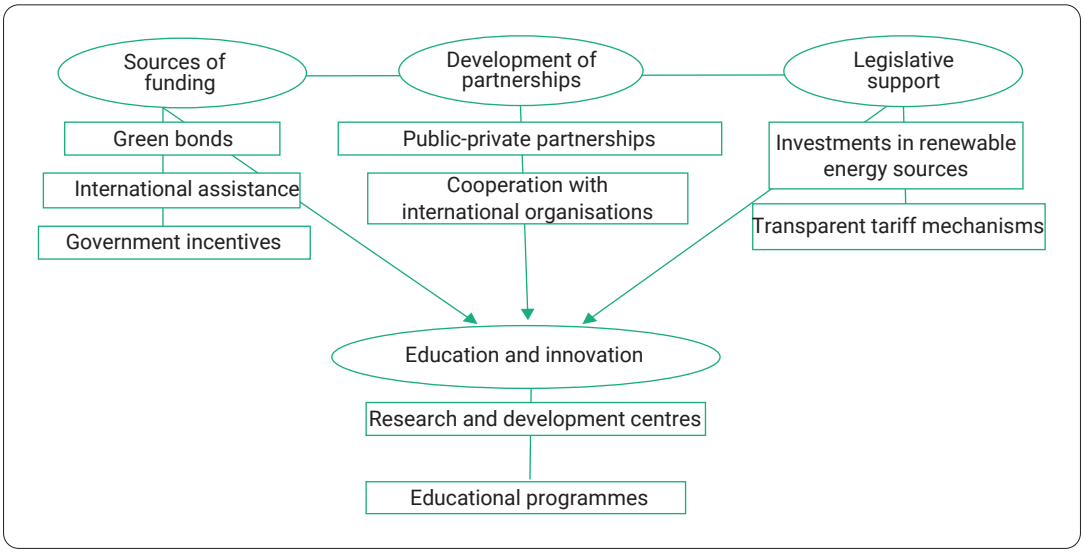

Figure 3. Model of integrated development of energy security in the country as a key to economic sustainability
Source: compiled by the authors

The model presented in Figure 3 is key to assessing Ukrainian energy infrastructure, focusing on the relationships between funding sources, partnerships, legislative support and innovation. It aims to identify vulnerabilities in the energy system and develop effective strategies to enhance energy security and economic resilience. Financing

sources such as green bonds, international aid, and government incentives form the basis for implementing renewable energy projects and infrastructure upgrades. For instance, the use of green bonds allows attracting investment in solar and wind energy projects, which reduces the country's carbon footprint. In 2023, such bonds provided more than EUR 500 million to finance energy initiatives (Organisation for Economic Co-operation and Development, 2023b). International support, in particular funding from the European Bank for Reconstruction and Development, has enabled Ukraine to implement urgent infrastructure rehabilitation projects. The development of cooperation through public-private partnerships and integration with international organisations, such as the Energy Community (2024), helps to attract investment and introduce innovative technologies. For instance, private investors, together with the state, are financing the construction of new wind farms with a capacity of 200 MW, which will ensure energy independence for certain regions. Cooperation with international organisations also allows Ukraine to adapt its legislation to European standards, creating preconditions for further integration into the EU energy market.

External financial assistance during the 2023-2024 period has been vital for Ukraine's energy sector, bolstering its resilience against the winter months and the impacts of the conflict. Financial assistance from the European Investment Bank, the World Bank, the European Bank for Reconstruction and Development, the European Union, and the United States facilitated the rapid restoration of damaged infrastructure, averted energy crises, and bolstered the transition to a more stable and autonomous energy system. Without this assistance, Ukraine would have faced large-scale power outages and critical disruptions in vital services (Table 4).

Table 4. Main sources of financing for the energy sector of Ukraine in 2023-2024

Sources of funding	Amount of funding	Usage	Period
World Bank	200 million USD	Repair of Ukrainian energy infrastructure, with the possibility of additional financing of up to 300 million USD	During March 2023
European Bank for Reconstruction and Development	300 million EUR	Repair of energy infrastructure before the winter season	August 2024
European Investment Bank	600 million EUR	Providing for the urgent heating and electricity needs of Ukraine during the war, as well as supporting green energy initiatives, including energy efficiency and renewable energy development	October 2024
European Commission and the US government	106.6 million EUR	Restoration of energy facilities damaged by Russian attacks	November 2024

Source: compiled by the authors based on Energy rescue plan approved to finance EU-backed emergency heating and power projects for Ukraine ahead of winter season (2024), BDO (2024), K. Strohecker & O. Harmash (2024), Ukraine's DTEK to receive 107 mln euros from EU, US to rebuild power facilities (2024)

Legislative support in Ukraine enhances transparency and creates conducive conditions for renewable energy investments, with initiatives such as the feed-in tariff and streamlined import procedures resulting in a 25% rise in investments. Education and innovation are emphasized via research institutions and specialized training, concentrating on technologies such as Smart Grids and energy storage systems. In 2024, three new research facilities were inaugurated, and instructional programs on cyber protection for the energy sector were instituted. This holistic strategy, encompassing financing, public-private collaboration, legal assistance, and innovation, fortifies energy system sustainability, diminishes import reliance, curtails CO2 emissions, and bolsters economic stability, establishing a foundation for sustainable development, particularly in response to external threats.

Discussion

The findings of this study are essential for developing strategies to rehabilitate and modernise the Ukrainian energy sector. The evaluation of the destruction underscored essential areas for intervention, with systemic reorganisation being of utmost importance. The recovery must prioritise decentralisation, including the promotion of distributed generation, the establishment of local energy sources, and the improvement of regional autonomy. This method will reduce the vulnerability of power networks to attacks and lessen dependence on large, centralised power plants, which are increasingly favoured targets for adversaries. To ensure energy security, it is imperative to diversify energy sources by increasing the share of renewables, establishing additional wind and solar power installations, and enhancing biomethane production facilities. This method will reduce dependence on fossil fuels and improve the energy system's adaptability and robustness against external threats. (Sirko *et al.*, 2023).

To avert such losses, it is essential to establish robust measures for safeguarding critical infrastructure. This encompasses the physical safeguarding of energy infrastructure, cybersecurity measures, and the advancement of smart grids that provide prompt threat response and load redistribution during energy shortages. A crucial element is the upgrading of power transmission networks and high-voltage infrastructure, which will reduce losses

during electricity transmission and guarantee the stability of energy supply to the regions most impacted by devastation (Hrytsiuk *et al.,* 2024).

The results align with the findings of J.D. Colgan *et al.* (2023), highlighting the necessity to modify energy systems for crisis conditions through the diversification of energy sources and enhancement of their resilience. The authors emphasise that countries which rapidly adopt renewable technology and establish distributed energy networks are more resilient to external threats. The conclusions are thoroughly substantiated by the findings of the current study, which indicate that the restoration of Ukraine's energy system should prioritise decentralisation, the advancement of renewable energy sources, and the enhancement of infrastructure resilience.

This study also corroborated D. Borozan's (2024) views regarding the necessity of technological modernisation to provide energy security. The research demonstrated that the implementation of intelligent technologies, including automated energy flow management, energy storage system development, and digital network monitoring, is essential for enhancing system resilience and optimising its performance.

Further development of the energy sector requires significant investment, which is consistent with the findings of G. Ofosu-Peasah *et al.* (2024), who emphasised the importance of investing in the modernisation of energy infrastructure to prevent future crises. In the Ukrainian context, this is especially relevant for the restoration of the destroyed heating system, which puts significant pressure on the government and international partners. To effectively address this problem, a well-coordinated approach to international assistance, government programmes, and private capital is needed. In addition, the study by H.H. Nguyen *et al.* (2024) proved that global geopolitical crises can boost the transition to renewable energy sources. For Ukraine, this conclusion is of strategic importance, as the energy crisis caused by the war accelerates the need to create local heating networks with high energy efficiency. The introduction of such systems will reduce the load on centralised heating networks, increase regional autonomy and create a more reliable energy supply system in an unstable environment.

In addition to restoring the destroyed infrastructure, an important strategic direction is the international integration of the Ukrainian energy system (Ostudimov & Kaminska, 2023). The concept of energy sovereignty, presented by M.C. LaBelle (2024), is key to defining the significance of Ukrainian accession to ENTSO-E. International cooperation, which enables the interconnection of energy systems, is an important step towards strengthening resilience. At the same time, Ukraine faces challenges in balancing its energy sovereignty and dependence on external partners. Implementing such a model of cooperation will allow Ukraine not only to strengthen its energy potential but also to gain access to stable reserve capacities, which is critical in the context of future crises.

The financial support provided by international partners, including a USD 1.4 billion loan from the G7+ Energy Coordination Group, is crucial to stabilising the situation. However, to ensure the effective use of these resources, Ukraine must ensure transparency and targeted use of financial assistanc (Berdar *et al*., 2024). This aspect becomes even more relevant given the development of the green bond market, which has already been successfully used by Ukraine. E. Akusta (2024) highlighted the potential of such instruments to finance sustainable energy development in crisis conditions. In addition, the introduction of financial aid monitoring systems can be a crucial factor in ensuring its effectiveness.

Ukraine is demonstrating an accelerated introduction of renewable energy sources, such as the construction of 10 biomethane plants and the installation of 200 MW of wind power in 2024 (Shahini *et al*., 2024). This reflects the trend described by B. Wang *et al.* (2024), emphasising the importance of renewables for ensuring both energy security and environmental sustainability. The financial challenges associated with infrastructure rehabilitation, such as debt in the district heating sector, indicate the need to use innovative financial instruments (Skochko *et al*., 2024).

In contrast to the more stable situation in the UK, where, according to M. Mersch *et al.* (2024), energy security can be combined with the transition to carbon neutrality, in Ukraine, long-term strategic planning often gives way to the need for immediate stabilisation measures. The destruction of Ukrainian energy infrastructure also confirms the need for decentralisation of energy systems, as discussed by J. Du *et al.* (2024). The authors emphasised that centralised energy systems are much less adaptive to crises, while decentralised energy supply models can respond more quickly to changes and function even in cases of destruction of part of the infrastructure. The current study confirms this conclusion, as the analysis of losses showed that centralised heating networks and large power plants were the most affected, while local generation facilities showed higher resilience.

The influence of natural resources on energy security stability, as observed by F. Ullah *et al.* (2024), highlighted the disparity between Ukraine and resource-abundant nations like the BRICS. Ukraine, constrained by its limited resources, heavily relies on international assistance to maintain the viability of its energy infrastructure. J. Kim *et al.* (2022) confirm the significance of global collaboration in enhancing energy security. The authors of the current study observed that nations with restricted access to indigenous energy resources require extensive international investment, technical support, and policy alignment to attain energy stability. In the Ukrainian context, limited resources include not only domestic energy capacities destroyed as a result of military operations but also insufficient financial capacities to restore energy infrastructure independently (Krawczyńska *et al*., 2024). The substantial financing of the sector's reconstruction by the EU, the World Bank, the foreign Monetary Fund, and other foreign partners confirms this assertion.

The Ukrainian experience also confirms the importance of a comprehensive risk assessment. At the same time, the predictive models developed by M. Tao *et al.* (2024) can predict and minimise the impact of future crises. The contribution of L. Tichý & Z. Dubský (2024), who emphasise the need to improve the mechanisms of international cooperation to prevent energy crises, is also substantial. Furthermore, the Ukrainian Energy Strategy until 2050 envisages large-scale integration with European energy markets, which is key to system stability. This plan, supported by international collaborations, aligns with global trends that underscore the significance of advancing renewable energy and innovative technologies for attaining energy sustainability, as articulated by M.F. Bashir *et al.* (2024). This underscores the necessity for tailored solutions to particular area concerns. The effective execution of this approach will substantially influence the economy by attracting investment, generating new employment opportunities, and enhancing energy independence. An auspicious domain for additional investigation is the examination of the effects of decentralised energy systems during crises. Y. Fan *et al.* (2024) assert that the diversification of energy sources is crucial for mitigating the risks linked to supply disruptions. In Ukraine, this can be implemented through the development of local networks and the introduction of microgrids.

The study emphasises the substantial destruction inflicted on Ukraine's energy infrastructure by the conflict, exacerbating financial burdens and social hazards owing to interruptions in heating and electricity provision, while highlighting the necessity for adaptive system management. Reconstruction initiatives necessitate a holistic strategy encompassing investments in physical security, digital transformation, tariff policy reform, and enhanced collaboration with foreign partners. This corresponds with the conclusions of A. Gatto & C. Drago (2020) regarding the multifaceted character of energy sustainability, encompassing economic, social, environmental, and governance dimensions. The research underscores the significance of decentralised generation in bolstering resilience against external threats, along with J. Jasiūnas *et al.* (2021) examination of the susceptibility of energy networks to extreme weather and cyber threats. The results necessitate a comprehensive strategy for Ukraine's energy security, tackling both technological and socio-economic issues.

The current study highlights the necessity of developing autonomous solutions to address the population's needs, including local heating systems, heat pumps, and cogeneration units. These results have certain parallels with the research by Y. Zou *et al.* (2023), who analysed the energy sustainability of the residential sector in China in the context of climate change. The authors argue that an increase in demand for energy for cooling is inevitable and puts an additional burden on the power system. In the case of Ukraine, a similar situation may occur due to the increased load on heating systems in winter, which once again proves the need to diversify energy consumption and develop autonomous solutions.

The energy crisis in Ukraine demonstrates the complex interplay between geopolitical risks, infrastructure vulnerabilities and the prospects for a transition to renewable energy sources. Incorporating the findings with international research facilitates the identification of appropriate strategies and policies to guarantee the long-term sustainability of Ukraine's energy system. At the same time, further research should address the adaptation of international experience to Ukraine's conditions, with a focus on decentralisation, renewable energy development and investment attraction. Successful implementation of such initiatives can significantly enhance economic stability, reduce dependence on energy imports, and increase the competitiveness of the national economy in the long run.

Conclusions

The research indicated that Ukrainian energy infrastructure is in a precarious state due to extensive damage inflicted by fighting and recurrent missile strikes. Since the comprehensive invasion in 2022, almost 61.4% of energy-generating facilities, encompassing 71.5% of thermal power plants and combined heat and power plants, have sustained damage or lost control. Such losses severely impede the delivery of essential services to the populace and the consistent functioning of industry, particularly during the winter months.

A critical analysis of the state of the heating networks revealed a dependence on the district heating system, which supplies more than a third of households. The main challenges are the high dependence on natural gas (70%) and the debt burden of district heating companies, which has reached USD 2.6 billion. The study also stated that the restoration of the system is complicated by the destruction of key facilities, such as boiler houses (815 units) and heating networks (354 km).

The total financial losses of the energy sector because of the destruction in 2022-2024 were estimated at USD 33.8 billion. The electricity sector suffered the largest losses (USD 11.4 billion in direct losses) and the oil and gas industry (USD 3.3 billion). The restoration of essential infrastructure necessitates substantial investments, particularly in renewable energy and the upgrading of heat supply systems.

The study period from 2022 to 2024 determined that financing was provided by international institutions, including the World Bank (USD 200 million), the European Bank for Reconstruction and Development (300 million EUR), the European Investment Bank (EUR 600 million), as well as assistance from the European Commission and the US government (EUR 106.6 million). In addition, private capital attraction is stimulated by the reform of the electricity market and the introduction of insurance mechanisms to reduce investment risks. Accordingly, in 2024, differentiated tariffs were introduced, which contributed to a 25% increase in renewable energy investments. Additional measures, such as integration with ENTSO-E, construction of new interconnectors and modernisation of high-voltage

infrastructure, will help reduce energy dependence and stability of Ukraine's power system.

Promising directions for future research encompass the examination of the effects of decentralised energy technologies on overall energy security, the development of models for climate change adaptation, and the enhancement of power grid resilience against cyber threats. The complete implementation of these solutions would enhance the stability and reliability of the energy system amidst present problems.

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None.

Conflict of Interest

None.

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Анотація. Метою дослідження було оцінити стан енергетичної системи України в умовах війни, визначити масштаби пошкодження інфраструктури та проаналізувати можливості відновлення і забезпечення стабільного енергопостачання. Дослідження протягом 2022-2024 років базувалося на аналізі офіційних звітів, супутникових знімків та аналітичних матеріалів щодо пошкоджень та відновлення енергетичної інфраструктури України. Особливу увагу було приділено фінансуванню відновлювальних робіт та регуляторним реформам в енергетичному секторі. Дослідження встановило, що загальні фінансові втрати енергетичного сектору становлять понад 33,8 млрд доларів США. З них 11,4 млрд доларів США – це прямі втрати в електроенергетиці. Аналіз показав значне боргове навантаження на підприємства теплокомуненерго (2,6 млрд. дол. США) та необхідність реструктуризації боргів. У дослідженні охарактеризовано показники рівня пошкодження енергетичної інфраструктури, що є важливим етапом аналізу енергетичної безпеки України як фундаментального фактору національної економічної стабільності. Наголошено на оцінці можливих джерел фінансування відновлення галузі, включаючи міжнародну допомогу, грантові програми та інвестиції приватного сектору. Розглянуо роль міжнародних фінансових інституцій, таких як Європейський банк реконструкції та розвитку, Світовий банк та Європейський інвестиційний банк, які вже виділили понад 1,1 мільярда доларів США на надзвичайні заходи з відновлення енергетичної інфраструктури України. З огляду на фінансові виклики, були розроблені рекомендації щодо залучення додаткових ресурсів через механізми страхування інвестицій, «зелені» облігації та державно-приватне партнерство. У дослідженні також розглянуто питання адаптації тарифної політики та запровадження диференційованих тарифів для покриття витрат на відновлення інфраструктури та стимулювання енергозбереження. Ця модель інтегрує технічні, фінансові та управлінські рішення для забезпечення економічної стабільності та залучення капіталу, необхідного для модернізації енергетичного сектору України

Ключові слова: інфраструктурні виклики; децентралізована генерація; відновлювані джерела енергії; мережева інтеграція; інноваційний розвиток