ECONOMICS OF DEVELOPMENT
Journal homepage: https://ecdev.com.ua/
Vol. 24, No. 2
2025

UDC 621.311:338.45
DOI: 10.63341/econ/2.2025.87

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Technical solutions for improving the sustainability of energy systems as a component of the state's economic sustainability

Abstract. The destruction of Ukraine's energy systems as a result of the fighting caused significant economic losses, which made it necessary to assess their impact on industry, the business environment and macroeconomic stability. The purpose of the study was to determine the main economic consequences of destabilisation of energy infrastructure and evaluate the effectiveness of technical measures for its restoration. It was found that power outages caused a 40% decrease in production capacity in metallurgy, 35% in the chemical industry, and 28% in mechanical engineering, which led to a reduction in exports, job losses, and a slowdown in economic growth. The increase in the cost of energy resources and logistics costs led to an increase in the cost of production by 10-15%, which negatively affected the competitiveness of enterprises. In 2022, the price of electricity reached 1,800 UAH/MWh, and in 2024 it increased to 3,100 UAH/MWh, which created an additional financial burden on the manufacturing sector and households. Analysis of investment flows showed

Article's History: Received: 29.01.2025; Revised: 28.04.2025; Accepted: 27.06.2025

Suggested Citation:
Semenenko, O., Movchan, O., Remez, A., Kliat, Yu., & Cherneha, T. (2025). Technical solutions for improving the sustainability of energy systems as a component of the state's economic sustainability. *Economics of Development*, 24(2), 87-102. doi: 10.63341/econ/2.2025.87.

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a reduction in foreign capital investment to USD 2 billion in 2022 and a partial recovery to USD 5.2 billion in 2024 due to international financial support. The economic benefits of implementing measures to modernise the energy system, in particular, the introduction of autonomous energy sources, the creation of microgrids and storage systems, which will reduce electricity losses by 15-20% and increase the stability of energy supply, were studied. The use of cost-benefit analysis confirmed the cost-effectiveness of such measures, since the cost-benefit ratio exceeded 1.6. Mechanisms for financing reconstruction, including state and international programmes, were proposed, which can cover up to 70% of the costs, which will help to stabilise the energy sector and restore economic activity

Keywords: military operations; financial costs; investment attractiveness; business environment; infrastructure modernisation

INTRODUCTION

The armed aggression against Ukraine caused a large-scale destruction of energy infrastructure facilities, which caused significant challenges for the functioning of the economy, in particular, in terms of providing industry, transport, utilities, and critical infrastructure facilities with stable energy supply. Energy destabilisation during the war period became a systemic threat to the economic security of the state, increased the dependence of production processes on external factors, and created barriers to investment activity. The problem of sustainability of energy systems in the context of armed conflict required quantitative substantiation and adaptation to the conditions of long-term economic recovery.

Within the framework of modern economic discourse, the concept of economic stability is defined as the ability of the national economy to adapt to shocks and ensure reproduction at the strategic level in the context of crisis impacts (Dykha *et al.*, 2024). One of the key prerequisites for such stability is the stability of the functioning of energy systems, in particular, their ability to maintain continuous power supply with partial or complete failure of individual generation, transmission, or distribution facilities. In this context, the categories of energy security, energy autonomy and technical stability of energy systems are used, which require a comprehensive economic analysis, considering the costs of modernisation, substantiation of investment decisions, and assessment of the benefits of implementing new technical solutions.

The analysis of scientific sources demonstrated the focus on the aspects of energy security, macroeconomic stability, and investment attractiveness of Ukraine in the context of armed conflict. The study by Y. Chen *et al*. (2024) investigated the importance of macroeconomic stability for sustainable development, with a focus on the relationship between energy policy and growth dynamics. However, this study did not provide an assessment of the economic impact of energy infrastructure disruptions on production activities and the business environment. The paper by O. Kubatko *et al*. (2023) focused on the threats to energy and economic security that arose as a result of military operations. Approaches to strengthening the sustainability of the energy sector have been developed, but no quantitative assessment of the economic losses caused by rising energy costs or the impact of these changes on investment activity in the generation sector, has been carried out. A. Yakymchuk *et al*. (2022) presented a conceptual model of energy security management in the face of threats, but did not cover the financial aspects of implementing technical solutions, in particular, the feasibility of various scenarios for the reconstruction of energy facilities from the standpoint of their economic efficiency was not evaluated.

Predictive modelling of the macroeconomic situation in Ukraine after the start of a full-scale invasion, carried out by O. Dobrovolska *et al*. (2024), covered the dynamics of the main economic indicators. However, the instability of energy supply as a separate factor affecting inflationary processes, employment, and investment inflows was not properly considered. The study by O. Kovalchuk *et al*. (2024) applied machine learning methods to model economic security, considering the interdependencies between key macroeconomic variables. However, the study did not consider the structural transformations caused by the disruption of energy systems, which limited the ability to interpret the results in an applied context. Comparative analysis of the levels of economic security in Ukraine and the countries of the European Union, conducted by V. Tokar (2024), provided an idea of key indicators of sustainability, but did not cover the specifics of the economic consequences of the destruction of energy infrastructure. The mechanisms used for its restoration in European countries were also insufficiently analysed.

The study by Y. Kuchmak *et al*. (2024) considered the regulatory and legal instruments for ensuring the economic security of Ukraine. However, the focus was not on the financial risks that arose as a result of energy instability or the effectiveness of state support for the energy sector. A. Kucher & V. Mazurenko (2024) analysed threats to industrial enterprises in the context of economic security, while the impact of power outages on the financial viability and competitiveness of producers, and adaptive strategies used to mitigate energy risks, remained outside the scope of the analysis. The study by V. Panchenko *et al*. (2024) concerned the macroeconomic impact of global financial crises, in particular in Ukraine. It did not consider the consequences of energy destabilisation as a factor that significantly affects the economic balance in emergency situations. V. Lytvynchuk & T.Y. Kolomiiets (2024) analysed macroeconomic indicators after the start of a full-scale invasion, but aspects of investment in the restoration of energy capacities and financial mechanisms for stimulating the modernisation of the energy sector remained out of consideration.

In general, the available research allowed forming an idea of the general macroeconomic and security contexts of the functioning of the energy sector of Ukraine in the context of the crisis. A number of gaps were identified, including the lack of a comprehensive approach to assessing economic losses caused by the destruction of energy infrastructure; insufficient analysis of the relationship between energy instability, investment activity and the business environment; limited coverage of the economic efficiency of technical solutions aimed at improving the stability of the energy system in the post-crisis period. The purpose of the study was to substantiate the economic feasibility of implementing technical solutions to improve the stability of Ukraine's energy systems in the context of their partial or complete destruction as a result of armed conflict.

MATERIALS AND METHODS

The study was of a complex applied nature and was based on a combination of macroeconomic analysis with an assessment of the technical and economic parameters of the functioning of the energy infrastructure. The time frame of the study covered the period before and after the outbreak of hostilities (2020-2024), which allowed tracking the dynamics of economic indicators and assessing the impact of energy supply instability on the macroeconomic situation. The analysis covered the assessment of production capacity losses in key industries, the dynamics of changes in electricity tariffs, and mechanisms for state and international financial support for the energy sector.

Data collection was carried out based on official statistical sources, financial reports of enterprises, and analytical studies of international organisations. Data from the State Statistics Service of Ukraine (n.d.), World Bank (n.d.), the Organisation for Economic Co-operation and Development (n.d.), the United Nations Development Programme (n.d.), European Bank for Reconstruction and Development (2024) and the National Bank of Ukraine (2025) were used. In addition, financial estimates and forecasts presented by the International Monetary Fund (n.d.) were considered, in particular, regarding the assessment of economic risks and macroeconomic adjustments in connection with energy crises. Analytical data from the International Energy Agency (n.d.) were used to assess the level of energy security and recommendations for the restoration of energy infrastructure.

The research methodology included the use of statistical and economic methods to assess the economic consequences of the destruction of energy systems and determine the effectiveness of modernisation measures. Variational statistics methods were used to estimate changes in production capacity in key industries, including determining arithmetic mean values, root-mean-square deviation, and average error of the arithmetic mean. The reliability of differences between economic indicators in different periods was checked using the Student's t test with an accuracy of 0.05.

To assess the financial impact of energy supply instability on industrial enterprises, a correlation analysis with a statistical significance level of $p \leq 0.05$ was used. The level of dependence between changes in the cost of electricity and the dynamics of production in metallurgy, chemical industry, and mechanical engineering was determined. In addition, an analysis of changes in investment activity in response to the destruction of energy infrastructure was carried out. To assess the economic efficiency of measures to improve the sustainability of energy systems, the cost-benefit analysis method was used. The ratio between the volume of investment in the modernisation of the energy system and the potential economic benefits from its stabilisation was determined. The analysis covered the financial costs of introducing autonomous energy sources, creating microgrids, and developing electricity storage systems. The payback rate of these measures and their potential effectiveness for reducing the risks of emergency shutdowns and stabilising industrial production were calculated.

Approaches to the interpretation of the results obtained included a comparative analysis of economic losses in regions with different levels of destruction of energy infrastructure. The influence of the increase in the cost of electricity on the production costs of enterprises is analysed and the consequences of the increase in tariffs on the competitiveness of the industrial sector were estimated. Changes in logistics costs due to energy instability and its impact on the cost of transportation of raw materials and finished products were analysed. The study also applied financial analysis methods to assess sources of financing for the modernisation of energy infrastructure. The effectiveness of state mechanisms for supporting the energy sector, in particular, international lending, grant financing and public-private partnership programmes, was evaluated. The level of financial burden on the state budget in the case of various reconstruction scenarios was determined. The results obtained helped to establish the relationship between the stability of energy supply and the level of industrial activity, assess the economic benefits of investment in the modernisation of the energy system, and determine effective financial mechanisms for its restoration.

RESULTS

Economic consequences of the destruction of energy systems and losses from power outages

The destruction of Ukraine's energy systems as a result of the fighting caused significant economic losses, which covered the industrial sector, transport, housing and utilities, and the business environment. Power outages caused by damage to the energy infrastructure as a result of Russian aggression led to large-scale interruptions in production processes, which affected the volume of output and efficiency of enterprises. A significant part of industrial facilities experienced a shutdown or reduction in production capacity, which led to a decrease in the level of exports and an increase in dependence on imported products. As a result, the structure of production chains has changed, which has further affected the country's economic stability.

Unstable power supply has created additional costs for businesses that have been forced to invest in backup energy sources, such as diesel generators and battery systems. This increased operating costs and the cost of final products, which in the long run reduced the competitiveness of manufacturers in the domestic and foreign markets. High energy costs have become particularly critical for energy-intensive industries, in particular, metallurgy, chemical industry, and mechanical engineering, which have experienced significant reductions in production volumes.

The dynamics of electricity prices is one of the key economic indicators that affects the cost of production, the competitiveness of enterprises, and the purchasing power of the population. Significant fluctuations in the cost of electricity have long-term consequences for the industrial sector, services, and housing and utilities. Changes in electricity tariffs in 2020-2024 reflect the impact of macroeconomic factors such as military operations, infrastructure destruction, restrictions on access to energy resources, and the need to attract additional financial resources to restore destroyed energy systems (Fig. 1).

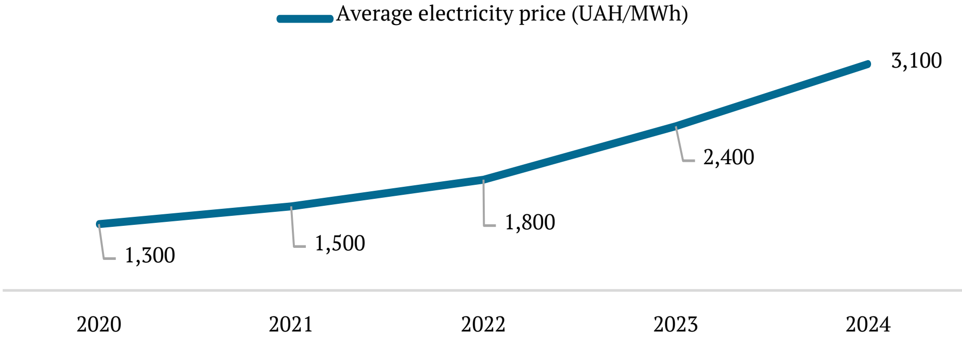

Figure 1. Electricity price dynamics (2020-2024)
Note: data reflects the average price of electricity for industrial consumers
Source: compiled by the authors based on State Statistics Service of Ukraine (n.d.)

In 2020-2021, the cost of electricity remained relatively stable, showing a moderate increase from 1,300 UAH/MWh in 2020 to 1,500 UAH/MWh in 2021. This was explained by the gradual transition to market pricing mechanisms, changes in tariff policy, and an increase in the cost of generation due to inflationary processes. Despite the increase in tariffs, the overall level of energy costs for industrial enterprises and the commercial sector remained acceptable, which contributed to the preservation of production activity. After the outbreak of hostilities in 2022, there was a sharp increase in the cost of electricity to 1,800 UAH/MWh, which was caused by the destruction of generating capacities, a reduction in supply in the energy market, and the need to import electricity. An additional factor was the increase in the cost of fuel, logistics, and disaster recovery of energy facilities. In the face of a shortage of electricity, enterprises were forced to increase the cost of backup energy sources, which additionally affected the total cost of products and services.

In 2023-2024, the cost of electricity continued to grow, reaching 2,400 UAH/MWh in 2023 and 3,100 UAH/MWh in 2024. This was conditioned by a further reduction in energy capacity, the need to attract significant investments in infrastructure restoration, and an increase in the cost of repairing and modernising the power system. High electricity prices created an additional burden on manufacturing enterprises, the transport sector, and utilities, which led to an increase in the overall level of inflation and a reduction in the solvency of businesses and the population. The transport sector has also been significantly affected by power outages. Electrified sections of railway transport suffered disruptions in operation, which led to delays in the transportation of critical goods, in particular, raw materials for industry and food products. Additional costs for diesel fuel and alternative routes increased logistics costs, which negatively affected the cost of transportation and final products for consumers. In the face of energy instability, transport companies were forced to reconsider their business models, which reduced the efficiency of logistics operations.

Housing and utilities faced rising costs to maintain energy infrastructure as networks suffered significant damage. Power outages in cities and villages led to interruptions in the operation of water supply, heat supply, and communications systems. This not only affected the quality of life of the population, but also required additional costs for emergency repairs and alternative means of energy supply. Budget expenditures of local communities to maintain the viability of critical infrastructure have increased accordingly, which has limited the ability to implement other social programmes.

The instability of energy supply has affected not only Ukraine's macroeconomic indicators, but also the global economy, in particular, the level of inflation, employment, and tax revenues. Increased spending on electricity and fuel has led to higher prices for goods and services, which has increased inflationary pressures in countries dependent on energy imports. Businesses that were unable to adapt to changes in energy supply were forced to cut staff or suspend operations, which led to an increase in the unemployment rate. The impact of the Russian-Ukrainian war on the global energy market was particularly felt by the countries of sub-Saharan Africa, where macroeconomic adjustments depended on the country's status as an exporter or importer of energy resources. Oil exporters, such as Nigeria and Angola, benefited in the short term from rising world prices, but the economic benefits were limited by structural problems and a lack of domestic refining infrastructure, while energy importers, such as Kenya and Senegal, faced significant increases in fuel and electricity costs, which worsened the state budget deficit and posed new challenges to fiscal policy (Taiwo *et al.*, 2024). Reduced production and reduced commercial activity as a result of energy crises in these countries have reduced tax revenues, created additional fiscal pressures and exacerbated socio-economic instability.

The destruction of industrial facilities and power outages has led to a significant reduction in production capacity in key sectors of the economy. The decline in output has negatively affected export capacity, employment, and overall economic stability. The largest losses were recorded in industries that depend on continuous power supply, such as metallurgy, chemical industry, mechanical engineering, and energy. Data analysis allows assessing the dynamics of capacity reduction in these sectors and identifying the main factors that affected their stability (Table 1).

Table 1. Loss of production capacity in key sectors of the economy (2020-2024)

Sector of economy	2020 (%)	2021 (%)	2022 (%)	2023 (%)	2024 (%)
Metallurgy	5	3	40	38	35
Chemical industry	3	4	35	30	28
Mechanical engineering	2	3	28	25	22
Energy	1	2	45	42	40

Source: developed by the authors based on State Statistics Service of Ukraine (n.d.), World Bank (n.d.), National Bank of Ukraine (2025)

In 2020-2021, production capacity in the main industries remained relatively stable, showing slight fluctuations, which was conditioned by both general economic instability and the consequences of the COVID-19 pandemic. Metallurgy lost 5% of its capacity in 2020 and 3% in 2021, due to reduced demand for steel products, disruption of logistics chains, and restrictions on production activities due to quarantine measures. The chemical, mechanical, and energy industries also suffered moderate losses, not exceeding 4%, as most businesses faced a shortage of raw materials, a slowdown in global trade, and an uneven recovery in economic activity. The main factors of influence during this period were changes in domestic consumption, gradual adjustment of the structure of industrial production in accordance with market conditions, and the adaptation of enterprises to new economic realities after the pandemic.

Since the outbreak of hostilities in 2022, capacity losses in all sectors have increased dramatically. The energy industry suffered the most, losing 45% of its capacity due to the destruction of power plants and substations. Metallurgy and the chemical industry also experienced significant reductions – 40% and 35%, respectively, which was caused by the destruction of factories, lack of raw materials, and logistical restrictions. In 2023-2024, there was a slight recovery, but the level of losses remained high: metallurgy – 35%, chemical industry – 28%, mechanical engineering – 22%, energy – 40%. This indicates difficulties in restoring industrial capacity, the need for large-scale investments, and the dependence on stable energy supply to restore production processes.

Special attention should be paid to assessing financial losses in the regions that have suffered the greatest destruction of energy infrastructure. Destroyed power plants, transformer substations, and power lines caused prolonged power outages, which made it impossible for enterprises in these regions to function normally. The need to restore energy infrastructure requires significant financial investments, which can be received both from the state budget and through international financial assistance and investment.

The short-term economic consequences of the destruction of energy systems include immediate loss of production capacity, increased costs of enterprises and the population for energy supply, and a decrease in the level of economic activity. The long-term consequences include changes in the structure of the country's energy balance, the need to modernise energy systems, the decline in the competitiveness of some sectors of the economy, and the transformation of the economic model towards decentralised energy sources. In the context of the need for economic recovery, an important task is to ensure stable energy supply, which directly affects the functioning of enterprises and the investment attractiveness of the country. Energy stability determines the future prospects for economic development and forms the basis for restoring production, stimulating business activities, and attracting investment.

Impact of energy system sustainability on business environment and investment climate

The sustainability of energy systems is a determining factor for the formation of a stable business environment, since the level of reliability of energy supply directly affects the operational activities of enterprises, product competitiveness and investment attractiveness of the country. The business environment largely depends on the availability and cost of electricity, which determines the cost of production, the consistency of logistics processes, and the efficiency of resource management. Disruptions in the functioning of the energy infrastructure led to an increase in enterprises' costs for backup power supply systems, which significantly affects financial results and long-term business development strategy.

The dynamics of foreign and domestic investment reflects the impact of economic and political factors on the country's investment climate. Domestic investment is higher due to government support programmes, critical infrastructure financing, and enterprise capital reinvestment, while foreign investment is more sensitive to macroeconomic risks. In the period 2020-2024, there were significant fluctuations in capital investment, in particular, due to the COVID-19 pandemic, the outbreak of full-scale hostilities, international financial assistance, and economic recovery measures. The data presented in Figure 2 allow assessing trends in attracting investment and the potential for financing energy infrastructure.

The data indicate significant fluctuations in the volume of foreign and domestic investment in the period 2020-2024. In 2020, investment activity was limited by the effects of the COVID-19 pandemic, which led to a low level of foreign investment of USD 3.1 billion, while domestic capital investment remained relatively stable at USD 11.56 billion. In 2021, there was an increase in both domestic and foreign investment due to the economic recovery after the pandemic, which is confirmed by an increase in foreign investment to USD 6.5 billion and domestic up to USD 15.07 billion. This indicates an improvement in the business climate, an increase in the economic activity of enterprises and the implementation of state programmes to stimulate production.

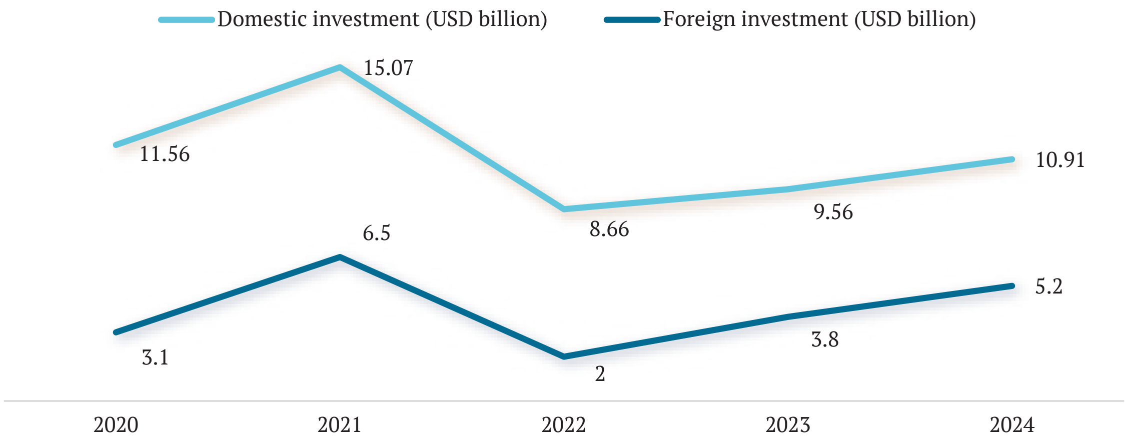

Figure 2. Comparative analysis of changes in foreign and domestic investment (2020-2024)

Note: domestic investment is higher than foreign investment due to the overwhelming share of government funding, business support programmes, and capital reinvestment of large enterprises. Foreign investment declined significantly in 2022 due to military action and increased risks to international investors, but in 2023-2024 there was a partial recovery due to international financial assistance and reconstruction support programmes. The difference between the indicators is also explained by the fact that domestic investments include financing critical infrastructure, restoring production and adapting businesses to new conditions

Source: compiled by the authors based on State Statistics Service of Ukraine (n.d.), World Bank (n.d.), Organisation for Economic Co-operation and Development (n.d.), European Bank for Reconstruction and Development (2024), National Bank of Ukraine (2025)

A sharp reduction in foreign investment in 2022 to USD 2 billion was conditioned by the high risks associated with military operations, infrastructure destruction, and the threat of capital loss, which forced international investors to reconsider their strategies. Simultaneously, domestic investment declined, but remained at USD 8.66 billion, since a significant part of the funds went to support critical industries and restore economic activity. In 2023-2024, there was a gradual increase in investment, in particular, due to international financial assistance, which contributed to an increase in foreign investment to USD 3.8 billion in 2023 and USD 5.2 billion in 2024. Domestic investment also showed positive dynamics, reflecting the adaptation of the economy to new conditions and the strengthening of the role of state mechanisms in the restoration of infrastructure and the energy sector.

Political instability significantly hinders the development of innovations in the field of renewable energy, which is confirmed by an analysis of data from 60 countries for 2002-2020 (Wang *et al.*, 2024a). It negatively affects investment in wind and solar energy, reducing government funding for research and access to international capital. The use of a two-way fixed effect model helped to minimise errors associated with endogenous factors and accurately assess the impact of political risks. The study by the International Energy Agency (n.d.) showed that this impact is amplified in countries with high levels of corruption and weak institutions, while high-quality public administration can partially compensate for the negative consequences.

Enterprises operating in conditions of unstable power supply are forced to adapt their production processes, which requires additional financial investments in the purchase and maintenance of autonomous energy sources. The cost of diesel generators, battery systems, and other backup mechanisms is increasing, which in the long run leads to an increase in the total cost of products and services (Borysiak *et al.*, 2022). This factor is especially critical for enterprises of the metallurgical, chemical, machine-building industries, and the food industry, where the continuity of the production cycle is a prerequisite for effective operation.

Instability in energy supply also leads to a reduction in investment in the real sector of the economy, as investors see the risks associated with unreliable energy supplies as one of the key barriers to long-term investment (Shahini & Shahini, 2024). The lack of guarantees of uninterrupted power supply makes it difficult to make decisions about opening new production facilities, which slows down economic development. Export-oriented business entities lose their competitive advantages due to the need to lay down additional costs for energy security, which makes it difficult for products to enter international markets.

Disruption of energy infrastructure also affects logistics processes, which is a critical factor for the functioning of industrial enterprises. Unstable power supply to railway transport and port infrastructure leads to disruptions in the supply of raw materials and exports of finished products. Additional costs for alternative routes and increased logistics risks negatively affect the efficiency of enterprises, which directly affects the level of business activity in the country. In the face of energy instability, businesses are forced to review their operating costs, increase funding for autonomous energy sources, and adapt their business models to new risks. Table 2 reflects the main factors influencing investment inflows and outflows, identifies the most affected sectors of the economy, and outlines possible mechanisms for restoring investor confidence through financial guarantees, infrastructure development, and alternative energy incentives.

Table 2. Analysis of the impact of energy infrastructure destruction on investment

Impact factor	Impact on investment	The most affected sectors	Mechanisms for restoring investor confidence
Destruction of energy infrastructure and power outages	Reduced capital investment in manufacturing industries, increased business costs	Metallurgy, chemical industry, mechanical engineering	Restoration of energy facilities, improvement of energy stability
Growth of enterprises' expenses for autonomous energy sources	Reduction of the profitability of enterprises, increasing the cost of production	Industrial enterprises, agricultural sector	Subsidising energy supply costs, supporting energy efficiency
Logistics instability and increased transportation costs	Falling investment attractiveness of the transport industry and logistics companies	Transport, logistics, trade	Investments in logistics infrastructure, compensation mechanisms
Declining confidence of foreign investors due to investment risks	Outflow of foreign capital, freezing of infrastructure projects	Financial sector, industry	Financial guarantees and insurance mechanisms for investors
Strengthening government programmes to support the energy sector	Increasing the investment attractiveness of the energy sector	Energy, manufacturing, infrastructure	State and international programmes for the development of the energy sector
Involvement of international financial institutions to restore infrastructure	Increased funding for reconstruction, improving the investment climate	Construction, industrial parks	Concessional lending and grant financing programmes
Renewable energy development as a risk reduction mechanism	Development of new investment directions, improvement of energy independence	Renewable energy, small businesses	Stimulating alternative energy, reducing the tax burden
Creating guarantees for businesses through energy risk insurance	Reducing risks to private capital, stimulating long-term investments	Industry, high-tech sectors	Ensuring the stability of the energy system and reducing investment risks

Source: developed by the authors based on V. Bohun *et al.* (2024), A. Hlushko (2024), L. Kvasnii *et al.* (2024)

The data presented in Table 2 show that the destruction of energy infrastructure has had a complex impact on the investment climate, in particular, due to a reduction in capital investment in manufacturing industries, an increase in business costs, and a decrease in the profitability of enterprises. The most vulnerable sectors were those that depend on uninterrupted power supply, in particular, metallurgy, chemical industry, mechanical engineering, and logistics. The outflow of foreign capital and the freezing of infrastructure projects further increased economic risks, which forced enterprises to adapt to new conditions due to reduced production volumes or the search for alternative energy sources.

Mechanisms for restoring investor confidence demonstrate potential opportunities for stabilising the economic situation. The implementation of state programmes to support the energy sector, attract international financing and develop renewable energy can become key tools for reducing investment risks. The country's investment attractiveness can be increased by introducing financial guarantees, insurance mechanisms for businesses, and stimulating alternative energy sources. Improving the stability of the energy system will not only contribute to the growth of domestic and external investment, but also create prerequisites for long-term economic recovery and expansion of production capacity.

Restoring the stability of the energy system is an important factor for attracting new investment, since reliable energy supply is one of the key conditions for the development of industrial parks, industrial clusters and technology parks. The stability of electricity supply contributes to the diversification of the economy, helping to expand production capacity and attract high-tech companies, for which the sustainability of energy supply is a critical factor in production efficiency. Mechanisms for reducing energy risks for businesses include the development of decentralised generation, the introduction of renewable energy sources, and the development of strategic electricity reserves. The use of solar and wind power plants allows enterprises to reduce their dependence on centralised supply, which improves the predictability of energy costs and increases the competitiveness of products.

Ensuring the stability of energy supply has long-term positive consequences for the economy, in particular, increasing employment, increasing investment activity and expanding the domestic market. Reducing energy risks creates prerequisites for restoring investor confidence, stimulating investment in industry, infrastructure, and the technology sector. Developing a sustainable energy system is an integral part of economic stability, as it provides predictable business conditions, helps to reduce risks, and improves overall resource efficiency. In this context, it is of key importance to estimate the financial costs of modernising the energy infrastructure and predict its economic benefits.

Financial costs of upgrading energy systems and potential economic benefits of improving their sustainability

Restoration and modernisation of energy systems requires significant financial resources, given the scale of destruction and the need to adapt infrastructure to modern challenges (Racek *et al.*, 2025). The main costs are related to the reconstruction of damaged generating capacities, the restoration of high-voltage networks, the construction of new substations, and the introduction of technological solutions to improve the stability of the power system. Investment needs include the purchase of new equipment, modernisation of energy management systems, and integration of digital technologies that automate processes and reduce electricity losses.

Modernisation of conventional power generating capacities is a key step in restoring the stability of the energy system and ensuring uninterrupted power supply. Significant destruction as a result of the fighting requires large-scale capital investments for the reconstruction of thermal, nuclear, and hydroelectric power plants, and the renewal of power grids. Investments in this sector are aimed not only at restoring lost capacity, but also at improving the efficiency of the power system, optimising fuel costs, and reducing accidents. Table 3 shows the main categories of expenditures, their projected volumes and expected economic benefits from the implementation of modernisation projects.

Table 3. Estimation of costs for reconstruction of conventional power generating capacities

Expense category	Estimated costs (USD billion)	Projected economic benefits
Restoration of thermal power plants	10.5	Increase in electricity production, reduce fuel costs
Reconstruction of hydroelectric power plants	3.2	Improvement of supply reliability, reduction of water resource losses
Restoration of nuclear power plants	8.7	Stability of the power system, reduction of dependence on imported fuel
Modernisation of coal generation	4.5	Optimisation of emissions, improvement of environmental indicators
Repair and strengthening of power grids	6.0	Reduction of emergency shutdowns, improvement of load regulation

Note: estimated costs for the reconstruction of conventional power generating capacities are calculated based on analytical estimates of international and Ukrainian organisations studying the energy sector. The data was generated considering the estimates of the World Bank, European Bank for Reconstruction and Development, International Monetary Fund, and International Energy Agency analytical reports. When determining the costs, the experience of reconstruction of energy infrastructure in countries that faced large-scale destruction (Iraq, Syria, the Balkans after the conflicts of the 1990s) was also taken into consideration. Additionally, the estimates of the Ministry of Energy of Ukraine regarding the necessary financial investments in the restoration of generation facilities and network infrastructure were used
Source: developed by the authors based on World Bank (n.d.), International Monetary Fund (n.d.), International Energy Agency (n.d.), European Bank for Reconstruction and Development (2024)

The data presented show that the largest investments are required for the restoration of thermal and nuclear power plants, since they provide the main share of electricity in the total energy balance. Investments in thermal generation are estimated at USD 10.5 billion, which is explained by significant damage and the need to introduce modern technologies to improve fuel efficiency. The restoration of nuclear power plants requires USD 8.7 billion, which is conditioned by the high safety requirements and complexity of reconstruction works. Smaller amounts of funding are provided for the modernisation of hydroelectric power plants and coal-fired capacities, but their importance in the stability of the energy system remains important.

Improving the state of the power grid also plays a key role in reducing power losses and improving supply reliability. The cost of repairing and strengthening networks is estimated at USD 6 billion, which will reduce the number of emergency shutdowns and improve load regulation. The implementation of modernisation measures will not only stabilise the energy system, but will also help to reduce the cost of electricity, increase the competitiveness of enterprises, and create prerequisites for attracting additional investment in the manufacturing sector.

One of the key aspects of modernisation is the introduction of distributed generation, which reduces the dependence of regions on centralised supply and increases the stability of the energy system to external risks. The use of decentralised energy sources, in particular, solar and wind stations, reduces the cost of infrastructure disaster recovery, since local power supply reduces the load on central networks and minimises the risks of large-scale outages (Tkachenko & Ismayilov, 2024). The economic benefits of developing distributed generation are to reduce the cost of maintaining traditional power systems and reduce losses during electricity transportation.

The introduction of energy-efficient technologies in the modernisation process can significantly reduce operating costs and increase resource efficiency. The use of the latest energy-saving systems, optimisation of transformer stations, and the introduction of "smart" power grids help to reduce electricity losses and ensure its rational distribution among consumers (Kubiczek *et al.*, 2023). The long-term economic effect of such measures is expressed in reducing the cost of electricity for enterprises and households, which increases the competitiveness of the economy and helps to attract additional investment.

Financing modernisation processes requires an integrated approach, including public investment, the involvement of international financial institutions, and the introduction of public-private partnership mechanisms. The estimate of the cost of necessary capital investments depends on the level of infrastructure destruction, but preliminary calculations indicate the need to attract multibillion-dollar investments for the reconstruction and renovation of energy facilities. An important factor is the support of international financing programmes that allow not only restoring destroyed facilities, but also introducing the latest technologies that meet modern energy security requirements.

Modernisation of energy systems is of strategic importance for reducing dependence on imported energy carriers and increasing the level of energy autonomy of the country. Investment in the development of renewable energy sources contributes to the diversification of the energy balance and reduces the need for fossil fuels, which reduces the economy's vulnerability to price fluctuations in international energy markets (Ismayilov *et al.*, 2023).

Switching to local energy sources ensures stable supply and allows for predictable planning of energy sector costs.

Assessment of the economic effect of modernisation of the energy system includes reducing the cost of electricity, improving the efficiency of enterprises and creating favourable conditions for the development of innovative technologies. Improving the quality of electricity supply contributes to increasing production productivity, which is an important factor for export growth and improving the overall economic balance. Additional benefits from modernisation are associated with the formation of new jobs in the energy sector, which has a positive impact on the level of employment and socio-economic stability.

The development of renewable energy sources and decentralised supply systems is a strategic area for modernising the energy infrastructure, which increases its sustainability and reduces dependence on fossil fuels. Investments in solar, wind, and energy storage systems help to reduce emergency shutdowns, optimise energy balance, and ensure greater regional autonomy. Such measures also reduce the environmental burden, which is an important factor in international climate commitments. The presented Table 4 contains an assessment of investments in key areas of renewable energy development and projected economic benefits from their implementation.

Table 4. Evaluation of investments in the development of renewable energy sources and decentralised systems

Investment category	Estimated costs (USD billion)	Projected economic benefits
Construction of solar power plants	7.8	Reduction of the cost of fossil fuels, reduction of CO_2 emissions
Development of wind generation	6.4	Improvement of the stability of the power system, reduction of dependence on centralised generation
Investment in energy storage systems	4.9	Network load stabilisation, ensuring uninterrupted supply
Creation of distributed microarrays	3.5	Reduction of accidents and increasing regional autonomy
Integration of bioenergy plants	2.7	Development of agricultural energy, improvement of energy balance

Note: assessment of investments in the development of renewable energy sources and decentralised systems is based on the average cost of implementing similar projects in countries with similar energy challenges. The data are based on analytical estimates of the International Energy Agency, the World Bank, the European Bank for Reconstruction and Development, and research by the Ministry of Energy of Ukraine on the potential development of alternative energy

Source: developed by the authors based on World Bank (n.d.) Organisation for Economic Co-operation and Development (n.d.), United Nations Development Programme (n.d.), International Monetary Fund (n.d.), International Energy Agency (n.d.), European Bank for Reconstruction and Development (2024)

The largest investments are provided for the construction of solar power plants and the development of wind generation, which is explained by their high efficiency and the possibility of rapid implementation in different regions. Investments in solar energy are planned at the level of USD 7.8 billion, which will help to reduce CO_2 emissions and reduce the cost of fossil fuels, while developing wind generation (USD 6.4 billion) will increase the stability of the power system and reduce dependence on centralised generation. Investments in energy storage systems amount to USD 4.9 billion, which is conditioned by the need to stabilise loads in networks and ensure uninterrupted power supply in conditions of fluctuations in electricity generation from renewable sources.

The creation of distributed micro-networks and the integration of bioenergy plants are less capital-intensive areas, but their implementation can significantly improve the energy balance. Investments in micro-networks are estimated at USD 3.5 billion, which will help to increase the autonomy of regions and reduce accidents. Investments in bioenergy plants (USD 2.7 billion) will support the development of agro-energy and promote the use of local resources for energy production. In general, investments in renewable energy sources can not only increase the stability of the energy system, but also create prerequisites for reducing the cost of emergency repairs and improving the country's energy independence.

The economic benefits of implementing new energy solutions become apparent on the long-term horizon, when the efficiency of investment begins to exceed the cost of modernisation. Reducing energy supply costs, reducing accidents, and improving the regulation of network loads create conditions for stable economic development and improving the quality of life of the population. Ensuring the stable operation of the energy system is an important factor for maintaining macroeconomic equilibrium, which avoids crisis situations associated with electricity shortages. The development of a sustainable and modernised energy infrastructure is a necessary condition for sustainable economic development. Investments in the restoration and improvement of the energy system have not only short-term effects in the form of restoring energy supply, but also long-term benefits in the form of improving the competitiveness of enterprises, reducing dependence on foreign energy markets and creating a favourable environment for further growth of economic activity.

Economic efficiency of measures to improve the sustainability of energy systems and the feasibility of attracting investment

Improving the sustainability of energy systems is an important factor for ensuring the smooth functioning of the economy, reducing risks to industrial production and minimising financial losses from power outages. Assessment of the economic efficiency of modernisation measures involves analysing the costs of implementing technological solutions and their impact on the stability of the energy system, the productivity of enterprises, and the overall competitiveness of the economy. Given the dependence of industrial enterprises on reliable electricity supply, special attention should be paid to measures that ensure energy autonomy and increase the efficiency of resource use.

Important areas for improving the sustainability of energy systems are the introduction of autonomous energy sources, in particular, solar and wind stations, which can reduce the load on centralised networks and reduce the likelihood of large-scale outages. The installation of microgrids, which combine local generation, energy storage systems and intelligent control systems, increases the flexibility of the energy infrastructure. The development of energy storage systems helps to reduce dependence on peak loads, ensure stable operation of enterprises, and increase the efficiency of using the generated electricity.

Assessing the economic efficiency of measures to improve the sustainability of energy systems is an important tool for determining optimal investment areas. Using the cost-benefit analysis method allows correlating the costs of implementing energy initiatives with the potential economic benefits achieved by reducing accidents, improving energy supply and energy efficiency. Table 5 provides an estimate of the financial costs of implementing various measures, projected economic benefits, and Cost Benefit Analysis, which demonstrates their long-term effectiveness.

Table 5. Economic efficiency assessment

Measures	Estimated costs (USD billion)	Projected economic benefits (USD billion)	Cost benefit analysis
Introduction of autonomous energy sources	7.5	12.3	1.64
Microgrid development	5.2	9.4	1.81
Energy storage systems	4.8	8.2	1.71
Increased capacity redundancy	3.6	6.5	1.81

Note: cost benefit analysis is used to evaluate the effectiveness of economic solutions by comparing the costs of their implementation and the projected benefits. In this case, the cost benefit analysis determines how profitable measures to modernise the energy infrastructure are by calculating the cost-benefit ratio. A value greater than one indicates that the economic benefits exceed the resources invested, which makes the corresponding measure economically feasible

Source: developed by the authors based on World Bank (n.d.), Organisation for Economic Co-operation and Development (n.d.), United Nations Development Programme (n.d.), International Monetary Fund (n.d.), International Energy Agency (n.d.), European Bank for Reconstruction and Development (2024)

The data in the table shows that all the measures considered are cost-effective, since the Cost Benefit Analysis exceeds 1. The highest indicator is the development of microgrids (1.81) and an increase in capacity redundancy (1.81), which indicates their high profitability in the long term. The introduction of autonomous energy sources and energy storage systems also has high cost-benefit analysis values (1.64 and 1.71, respectively), which confirms their effectiveness in stabilising the energy system and reducing the risk of emergency shutdowns.

Although the cost of implementing measures is significant, the projected benefits significantly exceed the invested funds, which indicates the feasibility of implementing them. The greatest economic benefits are expected from the introduction of autonomous energy sources (USD 12.3 billion), which is explained by their potential to reduce dependence on centralised energy networks and reduce fuel costs. Such measures can significantly improve the stability of energy supply, reduce electricity losses, and help to attract investment in the development of decentralised energy systems. Financing measures to modernise and improve the sustainability of energy systems requires an integrated approach, including government support, international financial assistance, and private investment. Attracting various financial mechanisms allows optimising costs and minimising risks for investors. The Table 6 shows the main sources of financing, their potential to attract investment, and the expected level of cost coverage.

Table 6. Opportunities to attract additional investment and mechanisms of state support

Financial mechanism	Assessment of the potential to attract investment (USD billion)	Expected cost coverage (%)
Government funding	6	40%
Grant programmes	3.8	25%
Public-private partnership	7.2	50%
Investment bonds	5.1	35%
International lending	10.4	70%

Note: assessment of the potential to attract investment is calculated based on historical data on the financing of energy projects, analytics of international financial organisations, and the capabilities of the state budget. The expected level of cost coverage is defined as the ratio of projected investments to the total financing needs for modernisation activities. The highest level of cost coverage is projected for international lending, while public-private partnerships and investment bonds have significant potential to raise funds, and government funding and grant programmes provide critical but limited support

Source: developed by the authors based on World Bank (n.d.), International Energy Agency (n.d.)

The Table 6 shows that international lending is the most promising source of financing for modernisation activities, as it allows attracting USD 10.4 billion, which covers 70% of the costs. This is conditioned by the significant efforts of international financial institutions, such as the World Bank, the International Monetary Fund, and the European Bank for Reconstruction and Development, to support the restoration of energy infrastructure. However, credit funds require careful planning for their repayment, which requires additional guarantees of financial stability.

Public-private partnerships and public financing are also important mechanisms for raising USD 7.2 billion and USD 6.0 billion, respectively, covering 50% and 40% of expenses. This indicates the need to actively attract private capital and create favourable conditions for investors. Grant programmes provide USD 3.8 billion (covering 25% of expenses), which is an important additional source of funding, since it does not require a refund. Investment bonds can raise USD 5.1 billion, which is 35% of the funding, providing the possibility of long-term attraction of private funds.

The development of sustainable energy systems has a significant impact on economic growth, as it ensures the continuity of production processes, creates new jobs in the field of renewable energy, and encourages the development of technological innovations. Investments in the modernisation of energy systems contribute to increasing the competitiveness of the industrial sector, since stable electricity supply is a critical factor for the smooth operation of enterprises and maintaining the country's export potential. The introduction of modern energy resource management technologies allows optimising electricity consumption and reducing production costs.

One of the key economic effects is the reduction of electricity losses in the networks, which reduces the cost of energy supply and reduces the burden on the budget due to the need for emergency infrastructure repairs. In addition, improving the efficiency of electricity generation and distribution contributes to reducing tariffs for industrial consumers, which is an important factor for the development of the manufacturing sector and attracting investment. Economic benefits include increasing the profitability of energy companies, which allows them to reinvest in further modernisation of the system.

The long-term effects of increasing the sustainability of energy systems are manifested in an increase in the share of renewable energy in the energy balance, reducing the impact of fluctuations in market prices for fuel and improving the environmental situation. Ensuring stable energy supply contributes to the growth of business activity, encourages the development of new technologies, and creates attractive conditions for external investment. As a result, measures to improve the stability of the energy system ensure macroeconomic stability, reduce dependence on crisis factors and create prerequisites for sustainable economic development.

The destruction of the energy infrastructure as a result of the fighting caused significant economic losses, manifested in a reduction in production capacity, a decrease in export potential, and an increase in the costs of enterprises for backup energy sources. Unstable energy supply led to an increase in the cost of electricity, which negatively affected the competitiveness of products and overall economic activity. The greatest losses were recorded in industrial sectors that are critically dependent on continuous energy supply, in particular, in metallurgy, chemical industry, and mechanical engineering. Significant fluctuations in the cost of electricity and rising costs for its emergency supply have increased inflationary pressures and created additional risks for businesses and households.

Instability in the energy supply has significantly affected the business environment and investment climate, leading to a reduction in foreign capital investment and an increase in the cost of operating activities of enterprises. The cost of autonomous power supply systems has become a significant financial burden, especially for industrial and transport enterprises. However, state programmes to support the energy sector and international investment have contributed to a partial recovery in the investment attractiveness of the economy. Financial support mechanisms, including international lending, public-private partnerships, and investment bonds, allow attracting significant resources for the reconstruction of energy infrastructure and stabilisation of the business environment.

Evaluation of the economic efficiency of measures to improve the sustainability of energy systems has shown the feasibility of investing in renewable energy sources, microgrids, and electricity storage systems. The implementation of such measures reduces electricity losses, reduces the cost of emergency repairs and improves the balance of the energy system. Modernisation of the grid infrastructure and optimisation of electricity generation contribute to improving energy efficiency, which is an important factor for economic growth and attracting long-term investment. Increasing the stability of the energy system creates prerequisites for macroeconomic stability and creates conditions for further economic development of the country.

DISCUSSION

The results obtained confirmed the significant impact of the destruction of energy infrastructure on the economic stability and investment attractiveness of the industrial sector. It was established that interruptions in energy supply caused significant losses in production, which led to a reduction in exports, an increase in the unemployment rate, and a slowdown in macroeconomic development. The analysis of the cost of modernisation of energy systems showed the high economic efficiency of the introduction of autonomous and renewable energy sources, which helped to reduce dependence on centralised supply and minimise the risks of emergency shutdowns. The study of investment flows showed that international financial support and reconstruction programmes played a crucial role in the partial recovery of capital investment, but the instability of the energy system continues to be a deterrent to attracting new investment. In addition, the simulation results confirmed the feasibility of using cost-benefit analysis to assess the effectiveness of modernisation measures, which helped to determine the most profitable areas of capital investment.

Analysis of the impact of the energy crisis in Ukraine has shown its direct relationship with the overall level of economic security of the state. The study by S. Ullah *et al*. (2024) demonstrated that internal and external conflicts cause short-term growth of energy security risks, while long-term consequences largely depend on the level of financial development and technological innovation. The results obtained confirm that the stability of energy supply is a critical factor in macroeconomic dynamics, the level of inflation, and investment attractiveness. In contrast to the global approach of S. Ullah *et al*. (2024), the direct economic effect of the destruction of energy infrastructure and possible directions of its restoration were studied. The problem of energy shocks caused by the conflict between Russia and Ukraine was considered in the study by Y. He (2024), where their impact on South Korea's macroeconomic stability was analysed. The use of Bayesian estimation methods established that the increase in the cost of energy carriers led to a decrease in production volumes, a reduction in investment, and a drop in the consumption of petroleum products. Similar trends can be traced in Ukraine, as the rise in the price of electricity in 2022-2024 negatively affected the competitiveness of the industrial sector.

The global macroeconomic implications of the war between Russia and Ukraine, including its impact on energy security, food chains, and post-pandemic recovery, were highlighted in the study by G.M. Noorani *et al*. (2024). It was revealed that geopolitical instability was a factor of significant changes in energy supplies, which forced countries to actively develop alternative energy sources. In contrast to the global context covered by G.M. Noorani *et al*. (2024), the analysis considered national economic consequences with reference to the structural characteristics of the energy sector of Ukraine. H.H. Nguyen *et al*. (2024) analysed the impact of sanctions against Russia in 2022 on the energy markets of 57 countries. It was found that the sanctions pressure caused a significant increase in the value of energy assets in countries dependent on oil imports, while enterprises operating in the field of renewable energy received economic advantages. Compared to the focus of H.H. Nguyen *et al*. (2024) on the financial aspects of the global energy market, this study evaluated the cost-effectiveness of solutions within the national energy system.

The increase in the cost of energy carriers in 2021-2022 and its consequences for inflation, financial stability of households and industrial enterprises were analysed by B. Gajdzik *et al*. (2021). The researchers concluded that such crises accelerate the introduction of energy-efficient technologies and encourage states to step up investment in renewable energy. The analysis confirms this pattern: autonomous energy sources can reduce electricity losses by 15-20%. The study by E.H. Ateed (2024) analysed the multidimensional impact of the war between Russia and Ukraine on the global energy crisis, in particular, changes in the supply of natural gas to Europe. It was found that energy instability stimulated countries to expand domestic electricity production and develop renewable energy sources. Similar processes can be traced in Ukraine, where the destruction of energy sector facilities has led to the need to introduce microgrids and energy storage systems to increase the sustainability of the energy system.

Research by U. Kayani *et al*. (2024) was devoted to the analysis of reverse overflow mechanisms in the energy market in the context of military conflict. The use of the E-GARCH model helped to determine that the largest fluctuations were recorded in the Brent Oil market, while changes in the cost of natural gas and CO_2 emissions had a less pronounced effect. The data obtained confirm significant structural changes in the energy market. This led to an increased financial burden on industrial enterprises and a decrease in the investment attractiveness of the energy sector. The macroeconomic consequences of a sharp increase in energy prices in 2022 were discussed in the paper by M. Sun *et al*. (2024). The use of the CGE model established that sanctions against Russia led to a reduction in its gross domestic product by 5.5%, a decrease in household income by 4%, and a decrease in domestic investment by 6%. For energy-independent countries, these changes had potential economic benefits, while other economies were negatively affected.

The relationship between the markets of energy and agricultural goods during the conflict between Russia and Ukraine was analysed by N. Kutsmus *et al*. (2024) and D.H. Vo & M.P. Tran (2024). Using the TVP-VAR model and analysing data from Google Trends revealed that instability in energy markets caused significant fluctuations in prices for agricultural products. The intersectoral nature of the previously performed analysis was replaced by an emphasis on internal structural changes in production costs caused by energy instability in Ukraine. The issue of transformation of European energy policy after the outbreak of war between Russia and Ukraine was considered in the study by M.C. LaBelle (2024). It was established that the strategy of energy interdependence gave way to the concept of energy sovereignty, which led to a strengthening of the policy of energy solidarity and expansion of independent sources of supply. The study confirmed the need to reduce Ukraine's dependence on centralised energy systems and develop renewable energy as a key area for improving the sustainability of the energy system.

The study by R. Yasmeen & W.U. Shah (2024) focused on investigating the relationship between energy uncertainty, geopolitical conflicts, and the level of militarisation in the G7 countries. The use of the moment quantitative regression method helped to establish that the growth of energy uncertainty has a positive impact on the development of renewable energy, but at the same time complicates the stable expansion of both renewable and conventional energy sources. The main difference is the scale of the analysis: R. Yasmeen & W.U. Shah (2024) considered the G7 countries, while this study focused on the economic consequences of the energy crisis in Ukraine. Research by Q. Wang *et al*. (2024b) was devoted to a comprehensive analysis of evolution, areas of cooperation and promising trends in the field of geopolitics and energy security. The use of bibliometric analysis methods helped to identify three main stages of the development of this scientific area, emphasising the gradual shift of researchers' attention from the stability of energy markets to the problem of energy transition. The results obtained confirmed the need to find new technological solutions to strengthen the sustainability of the energy infrastructure.

The impact of the COVID-19 pandemic and the war between Russia and Ukraine on the energy security of Organisation for Economic Co-operation and Development countries was discussed in the paper by S. Yildirim *et al*. (2024). The analysis showed that global crises significantly increase the dependence of economies on energy imports, creating additional risks of instability. The consequences of the destruction of Ukraine's energy infrastructure also confirm these trends, as they led to an increase in the cost of electricity and negatively affected industrial production. Strategies for ensuring energy security, considering geopolitical changes and policy measures to reduce dependence on conventional energy resources, were investigated by K.I. Ibekwe *et al*. (2024). The effectiveness of mechanisms of energy diversification and international cooperation in strengthening the sustainability of national energy systems was analysed. The transition to autonomous energy sources and decentralised systems was seen as an effective tool for minimising energy risks. The difference between the studies lies in the focus of the analysis: K.I. Ibekwe *et al*. (2024) considered the problem at the global level, while this study assessed the specific economic consequences of the energy crisis in Ukraine and possible ways to overcome them.

A comprehensive analysis of current research confirms that energy security is a key factor in macroeconomic stability and investment attractiveness of the industrial sector. It was established that the destruction of Ukraine's energy infrastructure has led to significant negative consequences, including a reduction in production volumes, a decrease in export potential, and an increase in the cost of electricity. The introduction of autonomous and renewable energy sources is seen as an effective tool for minimising the risks of emergency shutdowns and improving the sustainability of the power system. A comparative analysis of the literature showed that diversification of energy resources and modernisation of infrastructure remain the main areas for overcoming energy crises.

CONCLUSIONS

As a result of this study, a detailed assessment of losses in key sectors of the economy was carried out, in particular, in metallurgy, chemical industry, and mechanical engineering, which suffered a reduction in production capacity by 35-45% in 2022-2024. A comparative analysis of changes in the volume of domestic and foreign investment was carried out, which helped to identify the main risks for the recovery of the energy sector and identify effective mechanisms for attracting financing. It was found that the instability of energy supply caused an increase in logistics costs by 10-15% in the most affected regions, and also significantly affected the cost of industrial products.

Analysis of the sustainability of energy systems showed that prolonged power outages and a 139% increase in tariffs in 2020-2024 led to a reduction in the competitiveness of Ukrainian enterprises, a slowdown in economic recovery, and a decrease in the country's investment attractiveness. It was revealed that the development of autonomous energy sources, microgrids, and energy storage systems has a high economic potential, as it reduces electricity losses by 15-20% and increases the reliability of energy supply in crisis situations. The use of cost-benefit analysis determined that the introduction of modern energy technologies has a high cost-benefit ratio (from 1.64 to 1.81), which confirms the economic efficiency of measures to improve energy security.

Financial mechanisms for restoring energy infrastructure were considered and their effectiveness in the long term was evaluated. It was established that international lending can provide up to 70% of the necessary investments, while public-private partnerships can attract a significant amount of capital for the modernisation of critical energy facilities. Financing mechanisms were proposed, including government subsidies, international grant programmes, and the use of investment bonds for long-term capital raising. It was determined that state support for renewable energy sources is a key factor in stabilising the energy market and increasing its attractiveness for investors.

It is recommended to strengthen the state policy in the field of energy security by developing programmes of financial support for enterprises implementing autonomous energy sources and energy efficiency technologies. It is advisable to improve the mechanisms of energy risk insurance, which will help to reduce the level of investment uncertainty and attract additional capital to the energy sector. It is proposed to expand cooperation with international financial institutions and donors to finance the reconstruction of energy infrastructure and the implementation of strategic projects in the field of renewable energy. Further research may be aimed at analysing the long-term impact of energy system modernisation measures on the economic stability and competitiveness of industry. A promising area is to assess the effectiveness of the development of decentralised energy systems in the regional context, and to investigate the impact of renewable energy sources on the balance of energy markets.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Ateed, E.H. (2024). The impact of Russia-Ukraine war on the global energy crisis. In M.S. Özcan (Ed.), *Analyzing energy crises and the impact of country policies on the world* (pp. 119-138). London: IGI Global Scientific Publishing. doi: 10.4018/979-8-3693-0440-2.ch007.

[2] Bohun, V., Magomedov, A., Hromyka, O., Kovshun, N., & Fedorchuk, Y. (2024). Assessing the impact of infrastructure damage on national investment attractiveness during martial law. *Pakistan Journal of Life and Social Sciences*, 22(2), 10379-10385. doi: 10.57239/PJLSS-2024-22.2.00784.

[3] Borysiak, O., Skowron, Ł., Brych, V., Manzhula, V., Dluhopolskyi, O., Sak-Skowron, M., & Wołowiec, T. (2022). Towards climate management of district heating enterprises' innovative resources. *Energies*, 15(21), article number 7841. doi: 10.3390/en15217841.

[4] Chen, Y., Lyulyov, O., Pimonenko, T., & Kwilinski, A. (2024). Green development of the country: Role of macroeconomic stability. *Energy & Environment*, 35(5), 2273-2295. doi: 10.1177/0958305X231151679.

[5] Dobrovolska, O., Kolotilina, O., & Ostapenko, M. (2024). Forecasting macroeconomic dynamics in Ukraine: The impact of a full-scale war. *SocioEconomic Challenges*, 8(3), 211-237. doi: 10.61093/sec.8(3).211-237.2024.

[6] Dykha, M., Lukianova, V., Polozova, V., Pylypiak, O., & Ivanov, M. (2024). Transformation of Ukraine's socio-economic development in the context of global turbulence and war: Challenges and opportunities. *Scientific Bulletin of Mukachevo State University. Series "Economics"*, 11(2), 30-41. doi: 10.52566/msu-econ2.2024.30.

[7] European Bank for Reconstruction and Development. (2024). *Draft strategy for the infrastructure sector (v10.0) 2025-2029*. Retrieved from https://www.ebrd.com/infrastructure-sector-strategy-ukrainian.pdf.

[8] Gajdzik, B., Wolniak, R., Nagaj, R., Žuromskaitė-Nagaj, B., & Grebski, W.W. (2021). The influence of the global energy crisis on energy efficiency: A comprehensive analysis. *Energies*, 17(4), article number 947. doi: 10.3390/en17040947.

[9] He, Y. (2024). Unraveling the economic echoes: The Russo-Ukrainian conflict's influence on South Korean macroeconomic stability – insights from the energy sector. *SAGE Open*, 14(4). doi: 10.1177/21582440241287296.

[10] Hlushko, A. (2024). Strengthening energy security of Ukraine. *Economy and Region*, 94(3), 157-163. doi: 10.26906/EiR.2024.3(94).3494.

[11] Ibekwe, K.I., Etukudoh, E.A., Nwokediegwu, Z.Q., Umoh, A.A., Adefemi, A., & Ilojianya, V.I. (2024). Energy security in the global context: A comprehensive review of geopolitical dynamics and policies. *Engineering Science & Technology Journal*, 5(1), 152-168. doi: 10.51594/estj.v5i1.741.

[12] International Energy Agency. (n.d.). *Energy security in Ukraine*. Retrieved from https://www.iea.org/reports/ukraine-energy-profile/energy-security.

[13] International Monetary Fund. (n.d.). *Ukraine*. Retrieved from https://www.imf.org/en/Countries/UKR.

[14] Ismayilov, V., Mammadov, S., Abbasova, N., Babayeva, V., & Sadigova, S. (2023). The current state and prospects for further development in the energy sector in Australia: Reforms, foreign economic relations, investment climate. *Polityka Energetyczna*, 26(2), 105-120. doi: 10.33223/epj/163451.

[15] Kayani, U., Hasnaoui, A., Khan, M., Zahoor, N., & Nawaz, F. (2024). Analyzing fossil fuel commodities' return spillovers during the Russia and Ukraine crisis in the energy market. *Energy Economics*, 135, article number 107651. doi: 10.1016/j.eneco.2024.107651.

[16] Kovalchuk, O., Berezka, K., Babala, L., Ivanytskyy, R., Karpyshyn, N., & Zhuk, N. (2024). Modeling country economic security: A machine learning approach. In *Proceedings of the 14th international conference on advanced computer information technologies* (pp. 370-375). Ceske Budejovice: IEEE. doi: 10.1109/ACIT62333.2024.10712462.

[17] Kubatko, O., Kovalov, B., Yaremenko, A., & Piven, V. (2023). Economic and energy security of Ukraine in conditions of war. *Bulletin of Sumy National Agrarian University*, 96(4), 39-47. doi: 10.32782/bsnau.2023.4.7.

[18] Kubiczek, J., Hadasik, B., Krawczyńska, D., Przedworska, K., & Ryczko, A. (2023). Going beyond frontiers in household energy transition in Poland – a perspective. *Frontiers in Energy Research*, 11, article number 1239115. doi: 10.3389/fenrg.2023.1239115.

[19] Kucher, A., & Mazurenko, V. (2024). Essence and features of economic security of the industry sector. *Development Management*, 23(2), 16-24. doi: 10.57111/devt/2.2024.16.

[20] Kuchmak, Y., Litovchenko, V., Zarichnyi, R., Uskyi, M., Muzyka, Y., Mylyanyk, Z., Mazur, Yu., & Mylianyk, T. (2024). Economic security of Ukraine and its structural components: Economic and legal aspects. *Path of Science*, 10(5), 1008-1012. doi: 10.22178/pos.104-25.

[21] Kutsmus, N., Zinchuk, T., Usiuk, T., Prokopchuk, O., & Palamarchuk, T. (2024). War in Ukraine: Impact on global agri-food trade. *Scientific Horizons*, 27(3), 130-142. doi: 10.48077/scihor3.2024.130.

[22] Kvasnii, L., Malyk, L., Scherban, O., & Soltysik, O. (2024). Ensuring energy efficiency of the economy: Possibilities of implementation of foreign experience. *Academy Review*, 60(1), 20-35. doi: 10.32342/2074-5354-2024-1-60-2.

[23] LaBelle, M.C. (2024). Breaking the era of energy interdependence in Europe: A multidimensional reframing of energy security, sovereignty, and solidarity. *Energy Strategy Reviews*, 52, article number 101314. doi: 10.1016/j.esr.2024.101314.

[24] Lytvynchuk, V., & Kolomiiets, T.Y. (2024). Analysis of the main macroeconomic indicators of Ukraine after the full-scale invasion (2022-2023). In *Abstracts of XXIII international scientific and practical conference "The current state of the organization of scientific activity in the world"* (pp. 63-67). Madrid: European Conference.

[25] National Bank of Ukraine. (2025). *Inflation report*. Retrieved from https://bank.gov.ua/admin_uploads/article/IR_2025-Q2.pdf?v=13.

[26] Nguyen, H.H., Van Nguyen, P., & Ngo, V.M. (2024). Energy security and the shift to renewable resources: The case of Russia-Ukraine war. *Extractive Industries and Society*, 17, article number 101442. doi: 10.1016/j.exis.2024.101442.

[27] Noorani, G.M., Khan, M.T., & Khan, H.U. (2024). The global economic consequences of the Russia-Ukraine War: Implications for energy, food security, post-covid recovery, and regional economic stability. *Policy Research Journal*, 2(4), 380-390.

[28] Organisation for Economic Co-operation and Development. (n.d.). *Ukraine*. Retrieved from https://www.oecd.org/en/countries/ukraine.html.

[29] Panchenko, V., Yatsenko, O., Tetiana, M., Zinchenko, F., & Aleksandrova, M. (2024). Global financial crises and their macroeconomic consequences for national economies: The case of Ukraine. *Financial and Credit Activity Problems of Theory and Practice*, 6(59), 336-352. doi: 10.55643/fcaptp.6.59.2024.4552.

[30] Racek, D., Zhang, Q., Thurner, P., Zhu, X.X., & Kauermann, G. (2025). *Detection of building destruction in armed conflict from publicly available satellite imagery*. doi: 10.31219/osf.io/86t3g_v1.

[31] Shahini, E., & Shahini, E. (2024). Analysis of current investment projects and their economic justification. *Economic Forum*, 14(2), 38-50. doi: 10.62763/cb/2.2024.38.
[32] State Statistics Service of Ukraine. (n.d.). *Energy*. Retrieved from https://stat.gov.ua/uk/topics/enerhetyka.
[33] Sun, M., Cao, X., Liu, X., Cao, T., & Zhu, Q. (2024). The Russia-Ukraine conflict, soaring international energy prices, and implications for global economic policies. *Heliyon*, 10(16), article number e34712. doi: 10.1016/j.heliyon.2024.e34712.
[34] Taiwo, S., Uwilingiye, J., & Osei-Assibey, K. (2024). Macroeconomic adjustments to Russia-Ukraine war-induced energy prices shocks in sub-Saharan Africa: Effects based on countries' resource status. *African Development Review*, 36(1), S59-S74. doi: 10.1111/1467-8268.12783.
[35] Tkachenko, A., & Ismayilov, V. (2024). Renewable energy innovations: Synergy of technology and sustainable development. *Management and Business*, 2(2), 43-51. doi: 10.59214/mb/2.2024.43.
[36] Tokar, V. (2024). Ensuring economic security: Comparison of EU member states and Ukraine. *Baltic Journal of Economic Studies*, 10(3), 332-339. doi: 10.30525/2256-0742/2024-10-3-332-339.
[37] Ullah, S., Gozgor, G., & Lu, Z. (2024). How do conflicts affect energy security risk? Evidence from major energy-consuming economies. *Economic Analysis and Policy*, 82, 175-187. doi: 10.1016/j.eap.2024.02.039.
[38] United Nations Development Programme. (n.d.). *Ukraine*. Retrieved from https://www.undp.org/ukraine.
[39] Vo, D.H., & Tran, M.P. (2024). Volatility spillovers between energy and agriculture markets during the ongoing food & energy crisis: Does uncertainty from the Russo-Ukrainian conflict matter? *Technological Forecasting and Social Change*, 208, article number 123723. doi: 10.1016/j.techfore.2024.123723.
[40] Wang, J.Z., Feng, G.F., & Chang, C.P. (2024a). How does political instability affect renewable energy innovation? *Renewable Energy*, 230, article number 120800. doi: 10.1016/j.renene.2024.120800.
[41] Wang, Q., Ren, F., & Li, R. (2024b). Geopolitics and energy security: A comprehensive exploration of evolution, collaborations, and future directions. *Humanities and Social Sciences Communications*, 11(1), article number 1071. doi: 10.1057/s41599-024-03507-2.
[42] World Bank. (n.d.). *The World Bank in Ukraine*. Retrieved from https://www.worldbank.org/en/country/ukraine.
[43] Yakymchuk, A., Kardash, O., Popadynets, N., Yakubiv, V., Maksymiv, Y., Hryhoruk, I., & Kotsko, T. (2022). Modeling and governance of the country's energy security: The example of Ukraine. *International Journal of Energy Economics and Policy*, 12(5), 280-286. doi: 10.32479/ijeep.13397.
[44] Yasmeen, R., & Shah, W.U. (2024). Energy uncertainty, geopolitical conflict, and militarization matters for renewable and non-renewable energy development: Perspectives from G7 economies. *Energy*, 306, article number 132480. doi: 10.1016/j.energy.2024.132480.
[45] Yildirim, S., Yildirim, D.C., & Erdogan, S. (2024). Energy security dilemma in OECD countries: The COVID-19 pandemic, Russia-Ukraine War, and energy issues. In R.A. Castanho (Ed.), *Green economy and renewable energy transitions for sustainable development* (pp. 83-105). London: IGI Global. doi: 10.4018/979-8-3693-1297-1.ch005.

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Технічні рішення для підвищення стійкості енергетичних систем як складової економічної стійкості держави

Анотація. Руйнування енергетичних систем України внаслідок бойових дій призвело до значних економічних втрат, що зумовило необхідність оцінки їх впливу на промисловість, бізнес-середовище та макроекономічну стабільність. Метою дослідження було визначення основних економічних наслідків дестабілізації енергетичної інфраструктури та оцінка ефективності технічних заходів для її відновлення. Встановлено, що перебої в електропостачанні спричинили зниження виробничих потужностей у металургії на 40 %, у хімічній промисловості – на 35 %, у машинобудуванні – на 28 %, що призвело до скорочення експорту, втрати робочих місць та сповільнення економічного зростання. Зростання вартості енергоресурсів та логістичних витрат призвело до збільшення собівартості продукції на 10-15 %, що негативно вплинуло на конкурентоспроможність підприємств. У 2022 році ціна на електроенергію досягла 1 800 грн/МВт-год, а у 2024 році зросла до 3 100 грн/МВт-год, що створило додаткове фінансове навантаження на виробничий сектор та домогосподарства. Аналіз інвестиційних потоків показав скорочення іноземних капітальних інвестицій до 2 млрд доларів США у 2022 році та часткове відновлення до 5,2 млрд доларів США у 2024 році завдяки міжнародній фінансовій підтримці. Досліджено економічні вигоди від впровадження заходів із модернізації енергосистеми, зокрема, впровадження автономних джерел енергії, створення мікромереж та систем акумулювання, які дозволять зменшити втрати електроенергії на 15-20 % та підвищити стабільність енергопостачання. Використання аналізу «витрати-вигоди» підтвердило економічну ефективність таких заходів, оскільки співвідношення «витрати-вигоди» перевищило 1,6. Запропоновано механізми фінансування реконструкції, включаючи державні та міжнародні програми, які можуть покрити до 70 % витрат, що сприятиме стабілізації енергетичного сектору та відновленню економічної активності

Ключові слова: військові дії; фінансові витрати; інвестиційна привабливість; бізнес-середовище; модернізація інфраструктури