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IMPACT OF MARTIAL LAW ON THE ENERGY SECTOR OF UKRAINE: ECOLOGICAL AND ECONOMIC ASPECTS

The article examines the energy sector of Ukraine during the martial law. The dynamics of the share of business entities, involved in the supply of electricity, gas, steam, and air conditioning in 2019–2023, is reviewed. The distribution of the operating capacity of power generation facilities during the war is investigated. The consequences of martial law for the power system of Ukraine are considered. The losses of installed capacity after the season of massive Russian attacks on the national power system are examined. The main indicators of the energy sector are outlined. The consequences of the shelling for the Ukrainian energy system, which affect all spheres of the country's life, are determined. The main characteristics of the formation of the energy system of Ukraine are highlighted and its main sources are identified. The key challenges for the Ukrainian energy system are determined and characterized.

Keywords: energy sector; energy system; energy industry; martial law; electricity; electricity supply; transformation; restoration; energy infrastructure; environmental (ecological) and economic aspects (principles).

Relevance of the topic. The war in Ukraine has caused numerous energy and environmental problems. The constant bombardment and shelling have destroyed power plants, refineries and infrastructure, causing power outages and environmental pollution. The war has also led to a decline in the production and transportation of energy resources such as natural gas and oil. The environmental consequences of the war have also had a negative impact on natural resources, biodiversity, and the health of the local population.

2024 has become the most difficult year for the Ukrainian energy system, as it is taking place in conditions of constant hostile attacks on energy infrastructure facilities. Russia spent $5.6 billion on attacks on Ukraine's energy system in 2024, but never destroyed it. Ukraine's energy system suffered 12 massive attacks in 2024. Russia fired 708 missiles and 839 drones worth $5.6 billion at Ukrainian energy facilities, according to Forbes calculations

Electricity consumption restrictions for the population were applied in 2024 for a total of 1951 hours throughout the territory of Ukraine or in the vast majority of regions. This is 22% of the hours of the year. As of June 2024, the Ukrainian energy sector, according to the government, lost more than 9 GW of generation capacity as a result of Russian shelling. In particular, DTEK Group lost 80% of its generating capacity as a result of large-scale Russian attacks on March 22 and 29. According to the Verkhovna Rada Committee on Energy and Housing and Communal Services, as of early May, about 50% of Ukraine's energy infrastructure was affected by Russia. The above confirms the relevance of this study.

Analysis of recent research and publications. The problems of the power system under martial law were raised in the works of scientists, in particular, Kryzhnyi A. [1], Bredikhina H. [2], Albul S. [3], Yankovskyi O. [4], Marushchenko K. [7], Mykhailov D. [8], Oriekhova A., Kiiakh I. [9], Lisovyi A. [10], Stadzhy D. [11], Tkach D. [12]. Overcoming the unprofitability of the power system and energy market in the period of Ukraine's recovery is considered by Babak V. in his work [13]. At the Institute of General Energy of the National Academy of Sciences of Ukraine, scientists V. Babak, L. Shcherbak developed theoretical foundations for object-oriented identification of phenomena, processes and objects in the energy sector. This work is based on the study of an information resource, namely the characteristics of noise fields generated by energy facilities. The scientific research conducted at the Institute of General Energy of the National Academy of Sciences of Ukraine makes a significant contribution to the development of modern technologies in the energy sector. They relate to the theoretical foundations of object-oriented identification, the use of alternative energy sources, diagnostic methods and mathematical programming to optimize electricity and heat production. The results of these studies can be used to improve the efficiency and sustainability of energy systems, as well as to reduce the negative impact on the environment.

Scientist O. Novoseltsev proposed a new multilevel model of circulation-coordinated service-dominant transformation of the hybrid energy system structure based on the theory of fuzzy sets. The system includes equations and an organizational mechanism for the interaction of energy service market participants with energy and fuel markets. The use of this multi-level model makes it possible to determine the structure and volumes of optimal energy resources during the transformation of the energy system and the areas of cross-border assistance. This is in line with international standards and will be used in the transformation of the fuel and energy complex in the context of the country's post-war recovery [1].

The purpose of the study is to analyze the impact of martial law on the energy sector of Ukraine as well as to highlight the economic and ecological consequences.

Summary of the main material. The state of Ukraine's energy system during martial law is critical. The consequences of Russian attacks have led to significant damage and loss of capacity. The Ukrainian power system has lost more than 9.2 gigawatts of capacity, which equals more than a billion dollars. This amount is not yet finalized, as Russia continues to shell. After Russia's massive missile attacks, Ukraine's power grid still faces a significant deficit, and blackouts continue. Today, only a few units are operating, but they are only used for their own needs and partial heating of cities. There are also problems with gas supply, but energy reserves are generally sufficient [2]. In general, Ukraine's power system has been severely damaged, and restoring its performance will require significant efforts and investments [3].

In today's realities, when the world is facing various challenges, the country's energy system plays a key role in ensuring stability and development. Ukraine, like many other countries, is at risk due to geopolitical conflicts. The martial law in Ukraine has significant implications for its energy system, which affects all spheres of the country's life. One of the main challenges during martial law is ensuring energy security. Aggression and possible interference in the energy infrastructure lead to destruction and disruption of the energy system. For example, attacks on power plants, energy production facilities, and energy networks could lead to significant disruptions in the supply of electricity to households and industry. Another serious problem is the

reduced access to energy sources due to the loss of control over energy facilities. Blocked and damaged fuel delivery routes can cause energy crises and lead to energy shortages. This, in turn, affects the functioning of production, transportation, and the provision of energy for heating and lighting [3].

The energy sector is also becoming a target of cyberattacks, which is one of the main threats in the modern world. Martial law creates favorable conditions for cyberattacks on the control and monitoring systems of energy facilities. This can cause not only temporary power outages but also potentially damage or even destroy energy infrastructure. The loss of investment and opportunities for energy development is also a significant problem. The armed conflict creates uncertainty and risks for foreign investors, who may refrain from investing in projects to expand and modernize energy infrastructure. To overcome these challenges, Ukraine needs to improve its energy policy, taking into account the new conditions and challenges that arise during martial law. It is important to ensure that the energy infrastructure is reliably protected from physical and cyber-attacks, and to develop strategies to ensure sustainable energy supply for various sectors of the economy and the population. Ukraine should also actively cooperate with international partners, seeking support and technical assistance for the restoration and development of the energy system. Such measures will help to reduce the negative impact of martial law on the energy infrastructure and contribute to the country's sustainable development in the face of challenges and instability. Ukraine's energy system is protected from Russian shelling by both active and passive measures. In particular, it has emergency response systems, missile defense, recovery and backup systems [4].

The head of Ukrenergo noted that Ukraine's energy infrastructure will have three levels of protection against Russian attacks. The first level of protection involves the construction of gabions and big bags, the second – the installation of anti-missile systems, and the third – the creation of mobile generating capacities. The government and the General Staff of the Armed Forces of Ukraine have organized the creation of a three-level defense of energy infrastructure against Russian missiles and drones. Energy companies have created websites and bots to warn residents when the power goes out. Ukrainian energy facilities also have emergency response systems, recovery and backup systems. In addition, the authorities are considering options for

alternative mobile generation, such as gas turbine and gas piston power plants, as well as the construction and operation of small nuclear reactors. Ukraine's energy system is one of the most vulnerable sectors in a time of war. In the event of a military conflict, the energy system may be subject to various types of attacks, such as cyber-attacks, terrorist attacks, as well as physical destruction and destruction of infrastructure. The main sources of energy in Ukraine are thermal power plants fired by coal and gas, as well as nuclear power plants. In the event of war, these sources could be attacked, which could lead to a decrease in electricity production and disconnection of certain regions of the country from the grid. One possible solution is to develop alternative energy sources, such as solar and wind power. Ukraine has great potential for developing these energy sources, but unfortunately, the development of these industries is rather slow. It is also important to develop energy saving and energy efficiency. This can help reduce electricity consumption and ensure a more stable operation of the energy system in times of war.

For example, the introduction of energy-saving technologies in industry and housing and communal services can reduce electricity consumption by 20–30%. It is also important to develop a system of monitoring and management of energy consumption, which will allow for more efficient use of energy and ensure a more stable operation of the energy system in times of war. Thus, Ukraine's energy system is vulnerable in a time of war, but the development of alternative energy sources and energy saving and efficiency systems can help ensure a more resilient system in a time of war. In Ukraine, a significant number of entities provide electricity, gas, steam, and air conditioning services (Figure 1).

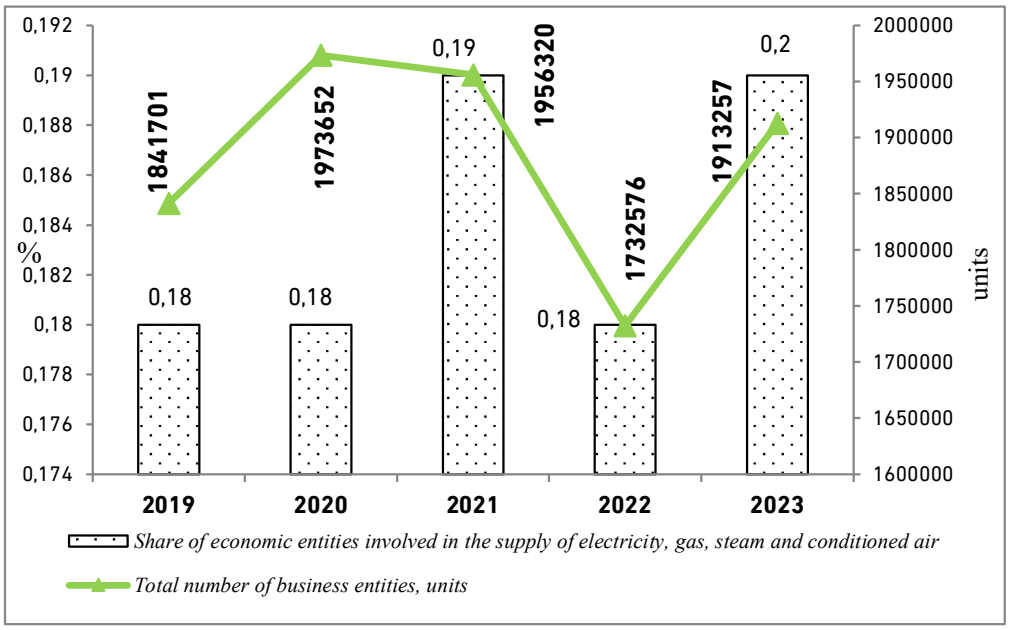

Fig. 1. Dynamics of the share of business entities involved in the supply of electricity, gas, steam and air conditioning in 2019–2023

Source: compiled by authors.

Thus, in the overall structure, the share of the studied entities is in the range of 0.18–0.2%. Ukraine's energy infrastructure is an important component of national security, especially in times of war. Currently, the Ukrainian energy system is being affected by the military conflict, in particular by Russian attacks on energy infrastructure. This jeopardizes the supply of electricity and other types of energy, and can lead to the destruction of energy facilities.

In order to protect the energy infrastructure from Russian attacks, Ukraine is developing and implementing measures to increase its resilience [5]. The plan to restore Ukraine's energy infrastructure also includes the production of solar panels, wind turbine equipment, inverter equipment, long-term energy storage systems, the introduction of smart grids, and the construction of green hydrogen production facilities. Despite the challenges faced by Ukraine's energy infrastructure, the country is working to identify the real state of the energy infrastructure after the devastating shelling. Work is also underway to prepare for possible Russian attacks during the next heating season. Thus, Ukraine's energy infrastructure is under increased scrutiny due to the military conflict, but the authorities are making efforts to ensure the security and resilience of the system.

One of the main consequences of martial law is physical damage to energy facilities. Power plants, substations, and networks become targets of possible military operations, which can lead to their

destruction and destruction. This disrupts the normal functioning of the system and leads to disruptions in electricity supply. Additionally, a military conflict may result in the cessation of electricity exports and imports. Stopping the flow of energy can lead to a shortage in the domestic market, which in turn affects the availability of electricity for households and businesses. In wartime, the infrastructure of gas pipelines used to transport natural gas may be affected. The destruction of gas pipelines and infrastructure may lead to problems with the supply of gas used for power generation and heating.

Another important aspect is the threat to energy security. Martial law can provoke attacks or sabotage of energy facilities, which leads to disruptions in normal operation and threats to energy supplies. The negative impact of a military conflict may also manifest itself in a decrease in energy production. Limited access to resources, loss of labor and equipment can lead to a decrease in electricity production capacity, which has serious consequences for the country. The loss of qualified personnel is another negative consequence of a military conflict. Evacuations or security threats at the workplace can lead to the loss of key specialists, making it difficult to restore energy systems. In addition, it is important to take into account the environmental aspects of military conflict. Fires, explosions, and other military activities can lead to serious pollution of water sources and air, disrupting the ecosystem and threatening public health. Overall, the consequences of martial law for Ukraine's energy system are a serious challenge that requires comprehensive measures to restore and ensure the sustainability of the country's energy sector. This also emphasizes the importance of international cooperation and support to restore the normal functioning of energy systems in wartime (Table 1).

Table 1

Consequences of martial law for Ukraine's energy system

No	Consequences of martial law for Ukraine's energy system	Characteristics
1.	Reduction of coal and other fuels production	National coal mines come under fire, which leads to a decrease in coal production
2.	Restrictions on energy supply	Martial law can lead to restrictions in the supply of electricity, especially in the conflict zone
3.	Damage to energy infrastructure	The shelling and hostilities may result in damage to power grids, power plants and other energy facilities
4.	Increase in energy costs	Due to limited access to some energy sources, dependence on imports may increase, leading to higher energy costs

Source: compiled by authors.

Ukraine's power system consists of various components, including electricity generation, transmission and consumption. The national energy company Ukrenergo is responsible for managing the power grids and ensuring the stability of the power system. Ukraine's energy management system is built in accordance with the EU's Third Energy Package. The Ukrainian energy system has been fully synchronized with the European system, which contributes to its reliability and efficiency. Ukraine's energy sector consists of various components, including electricity generation, transmission and consumption. The main sources of electricity include nuclear power, coal, fuel oil and gas combustion. Electricity production in the country is the backbone of the Ukrainian economy and is one of the oldest industries. The main indicators of Ukraine's energy sector are as follows. Electricity generation: nuclear power, coal, fuel oil and gas combustion. Electricity sources: solar, wind, organic mass gasification, waste gasification, geothermal power plants.

Electricity exports and imports: Ukraine's electricity exports exceeded imports by 4.5% over the week, while imports decreased by 9%. To ensure the stability of the power system, Ukrenergo has set up a headquarters for rapid response to power outages. As part of the reforms in Ukraine's energy sector, the government is focusing on diversifying the sources and routes of energy supplies to Ukraine. This includes receiving oil and gas from the Caspian Sea region, Central Asia and the Middle East, as well as preparing clean energy project proposals Ukraine has made significant progress in reforming its energy sector in line with EU legislation. In 2019–2021, the unbundling of the gas transmission network and transmission system operators was completed and certified. Key structural changes in the gas and electricity markets have been implemented, and corporate governance reform in state-owned energy companies is ongoing. The distribution of operating capacity of power generation facilities is shown in Table 2.

Table 2

The distribution of operating capacity of power generation facilities

Power generation facilities	**Facilities capacity, MW**	**Destroyed capacity, %**	**Capacity in the occupied territories, %**	**Available capacity, %**
Nuclear power plants	13940	-	43	57
Thermal power plants	5867	10	12	77
Combined heat and power plants	11197	4	50	46

Continuation of the table 2

Hydroelectric power plants	4837	-	7	93
Solar power plants	6067	14	18	69
Wind power plants	1583	-	94	6
Total	43491	4	35	61

Source: compiled by authors according to: [6].

The impact of the military conflict on the energy sector is negative. Energy infrastructure facilities are more often targeted by aggression. However, the Ukrainian energy system demonstrates resilience, and its specialists are highly professional, ensuring stable operation of the industry. As a result of hostilities, about 4% of generating capacity was destroyed, and another 35% is located in the occupied territories. This destructive effect covers 50% of thermal generation, 30% of solar generation and over 90% of wind generation. The losses are estimated at UAH 47 billion or $1.7 billion. Falling demand for energy (30-35% less than in 2021), the relocation of consumers to the western regions, and difficulties with the supply of petroleum products caused financial imbalances in the power system. Losses in the energy and oil and gas sector amounted to UAH 341.8 billion. Energy and fuel prices are rising, making it difficult to meet demand and causing a shortfall in the electricity market, amounting to about UAH 35 billion. As a result, it will be a challenge to ensure effective optimization of the energy system and ensure the solvency of the industry. The expected shortage of funds may lead to increased debts and financial problems for energy companies. This, in turn, puts additional pressure on the financial stability of the industry and may affect its ability to provide reliable and stable energy supplies to the national market and consumers. In addition, rising energy prices and tariffs in a situation of economic instability and military conflict may have a serious social impact on the population and businesses already experiencing difficulties. A large number of consumers left without access to energy or forced to pay higher tariffs could be a significant constraint on the country's economic recovery and stability. The losses of installed capacity after the season of massive Russian attacks on the Ukrainian energy system are shown in Table 3.

Table 3

Losses of installed capacity after the season of massive Russian attacks on the Ukrainian power system

Years	Information	Loss of installed power generation capacities (GW)
2021	In May 2021, there were 4 GW of installed capacity in the temporarily occupied territory, including the large Zuivska and Starobeshevska TPPs. They were occupied back in 2014	4
2022	A year later, in May 2022, due to Russia's full-scale invasion, 21 GW were already under occupation. This included Zaporizhzhia NPP, which provided about a fifth of electricity production	21
2023	In May 2023, after a season of massive attacks on the Ukrainian power grid, the loss of installed capacity increased to 27 GW	27
2024	A number of high-voltage transformers at the substations that transmit electricity were destroyed	35

Source: compiled by authors according to: [8].

Ukraine is implementing several projects to protect energy facilities, including passive and active protection [8]. Ukrenergo is focusing on passive and active protection of Ukraine's energy facilities from possible attacks by Russia. The National Security and Defense Council of Ukraine also approved a decision to strengthen the resilience of the country's energy system [8]. In addition, Ukraine is developing a nationwide investment project on an innovative basis to decarbonize the unified energy system. The key challenges for Ukraine's power system are presented in Table 4.

Table 4

The key challenges for Ukraine's power system

No	The key challenges	Characteristics
1.	Constant attacks on networks and transformers	Hostile attacks on substations, which play a key role in transmitting electricity to consumers, and cross-border networks for importing electricity from EU neighbors are extremely dangerous. This risks creating additional restrictions on the market. In addition to cross-border power lines and transformers, the aggressor's target is the infrastructure of extractive enterprises that supply the Ukrainian economy with natural gas, oil, and coal. Only nuclear power plants are operating stably. Their basic capacities remain capable of providing about 50% of the country's electricity

Continuation of the table 4

2.	Shortage of power equipment	During the war, Ukraine became the main buyer in Europe of cogeneration units, which provide for the simultaneous production of electricity and heat. In particular, the Energy Security Project, funded by the United States Agency for International Development (USAID), purchased more than 90 of them for the needs of communities. Now the problem is not only a lack of funding, but also a shortage of ready-to-sell equipment, including for urgent repairs after attacks. Its production may take longer than Ukrainian customers need
3.	Development of local and green generation	The development of renewable energy sources, in particular wind power, contributes to the sustainability and decarbonization of the Ukrainian energy system, and their support is a key priority for international partners
4.	Cyber threats and information terror	On average, hundreds of thousands of powerful cyberattacks on all energy companies are recorded two days before massive shelling. This shows that the enemy is acting systematically, combining physical and digital influence. At the same time, the presence of powerful professionals combined with unique experience during the war create the preconditions for Ukraine to lead the way in cybersecurity in Eastern Europe
5.	Stopping gas transit	Transportation of Russian gas through the Ukrainian gas transportation system has stopped. However, due to the suspension of Russian gas transit, «the risks of attacks» on the gas transportation system in Ukraine are "significantly increasing

Source: compiled by authors according to: [9; 10; 11; 12].

The destruction of public infrastructure and the potential threat of shelling of nuclear power plants increase the risk of environmental disaster in Ukraine. The shelling of oil depots and thermal power plants leads to air, soil and water pollution. In turn, continuous restoration requires additional resources. In addition, the tactic of repeated strikes means that fire brigades are more cautious. This affects the quality of extinguishing and response to calls. As for nuclear power plants, the greatest danger is posed by spent fuel storage facilities, which can become an accidental or special target during shelling. If the tactics of shelling large thermal power plants, hydroelectric power plants and other generation stations continue, Ukraine will obviously face a choice – to restore centralized carbon generation, which can be destroyed again, or to move to a decentralized energy system based on the principles of energy efficiency and the use of renewable energy sources. The benefits of modernizing the energy system and abandoning centralized, coal-based power hubs include energy security,

achieving sustainable development goals, mitigation/adaptation to climate change, and the development of new green technologies.

However, the development of a decentralized green energy system today requires capital investments. Ukraine needs 12 gigawatts of new installed capacity and $17.2 billion in investments to completely phase out coal-fired generation by 2034. For a country whose economy has suffered greatly from the military invasion, the implementation of such projects is possible only with the financial support of partners from other countries. Restoring Ukraine's energy system will require large investments in any case. The decision taken this year will determine whether the country's power system will be based on large thermal power plants, hydroelectric power plants and other nodes that can easily become targets of shelling, or whether the country will rely on a more extensive decentralized generation system that does not have critical facilities at all.

Conclusions. Consequently, Ukraine's energy sector has a significant impact on the country's economic development, ensuring its stability, determining the investment climate and the level of energy independence. The continuity of production processes in the economy depends on the stability of electricity supply, and the high quality of energy resources, in turn, makes it possible to increase labor productivity.

The power system of Ukraine is a set of nuclear, thermal, hydraulic and pumped storage power plants, combined heat and power plants and other power facilities united by a common mode of generation, transmission and distribution of electricity and heat under their centralized control. The IPS of Ukraine consists of 8 regional power systems interconnected by backbone and interstate high-voltage power lines.

A significant number of business entities are involved in the supply of electricity, gas, steam, and air conditioning. Their share in the overall structure of business entities is 0.18–0.2%. The main consequences of martial law for Ukraine's energy system are a decrease in coal and other fuels production; restrictions on energy supply; damage to energy infrastructure; and increased energy supply costs.

The article examines the distribution of operating capacity of power generation facilities during the war in terms of NPPs, CHPs, TPPs, HPPs, SPPs, and WPPs. The losses of installed capacity after the season of massive Russian attacks on the Ukrainian power system are reflected. It is determined that the loss of installed power generation capacities as of the end of 2024 amounted to 35 GW.

One of the ways to develop the energy sector is to modernize the energy system and abandon the centralized, coal-based power generation. The benefits of this implementation include energy security, achievement of sustainable development goals, climate change mitigation/adaptation, and development of new green technologies. The use of renewable energy sources such as wind, water, and solar can help reduce dependence on coal and natural gas imports and reduce the environmental impact of the energy system. The initiative to attract RES investments should come primarily from local governments to make decentralization in energy management a reality. However, the risks of investing in RES are exacerbated by the debt crisis in the electricity market. As of early November 2024, the debt of the national energy company Ukrenergo to RES producers exceeded UAH 32 billion. Continued integration of Ukraine's energy system with the European energy system ENTSO-E could help ensure greater stability and flexibility of energy suppliers. Thanks to "unprecedented assistance" from international partners, Ukraine's power system is now the most secure in the world in terms of engineering structures, air defense systems, available equipment reserves etc.

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ВПЛИВ ВОЄННОГО СТАНУ НА ЕНЕРГЕТИЧНУ ГАЛУЗЬ УКРАЇНИ: ЕКОЛОГО-ЕКОНОМІЧНІ АСПЕКТИ

У статті проаналізовано динаміку частки суб'єктів господарювання, залучених до постачання електроенергії, газу, пари та кондиційованого повітря за 2019–2023 рр. Встановлено, що в загальній структурі частка досліджуваних суб'єктів перебуває в межах 0,18–0,2%. Розглянуто наслідки воєнного стану для енергосистеми України. Виокремлено такі позиції, як: зниження видобутку вугілля та інших видів палива; обмеження енергопостачання; пошкодження енергетичної інфраструктури; збільшення витрат на енергозабезпечення.

Досліджено розподіл операційної потужності об'єктів електрогенерації у період війни в розрізі АЕС, ТЕЦ, ТЕС, ГЕС, СЕС, ВЕС. Відображено втрати встановленої потужності після сезону масованих атак РФ на українську енергосистему. Окреслено основні показники енергетики. Визначено наслідки обстрілів для енергосистеми України, що впливають на всі сфери життєдіяльності країни. Висвітлено основні характеристики формування енергосистеми України та визначено її основні джерела.

Ідентифіковано та охарактеризовано ключові виклики для енергосистеми України. Серед основних викликів виділено такі, як: постійні атаки на мережі і трансформатори; дефіцит енергетичного обладнання; розбудова локальної та зеленої генерації; кіберзагрози та інформаційний терор; зупинка газового транзиту. Виокремлено переваги модернізації енергетичної системи та відмови від централізованих, заснованих на вугільній енергетиці. Їх ідентифіковано у такому складі: енергетична безпека, досягнення цілей сталого розвитку, мітігація/адаптація до зміни клімату, розвиток нових «зелених» технологій. Встановлено, що продовження інтеграції енергосистеми України з європейською енергетичною системою ENTSO-E може допомогти забезпечити більшу стабільність та гнучкість енергопостачальників.

***Ключові слова**:* енергетична галузь; енергетична система; енергетика; воєнний стан; електроенергетика; електропостачання; трансформація; відновлення; енергетична інфраструктура; екологічні (екологічні) та економічні аспекти (принципи).

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