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Technical solutions to prevent blackouts in order to provide the population with electricity: The case of Ukraine

Abstract. Due to the deteriorating condition of the power grids and the increasing number of power outages, research on technical solutions to prevent blackouts in the Ukrainian energy system is becoming an extremely relevant and necessary task. This study aims to analyse technical solutions aimed at increasing the resilience of Ukraine's energy system to prevent blackouts and ensure reliable electricity supply to the population. The methods used include the analytical method, classification method, functional method, statistical method, synthesis method, and others. The study analysed modern technical solutions to improve the resilience of the Ukrainian energy system. The study included a detailed analysis of innovative approaches to modernizing the energy infrastructure. The primary objective was to study and evaluate modern technologies for designing new power lines with improved transmission characteristics. The study emphasized the importance of expanding automation systems to effectively monitor and control the state of the power grid. The study

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also identified the importance of using energy storage, developing renewable energy sources and improving electricity consumption forecasting systems. Flexible load management measures and improved cybersecurity systems were identified as critical. It is noted that the implementation of the project to provide electricity to the conditional area will be a key step in improving the lives of the local population and providing the necessary conditions for the development of the area's infrastructure and economy. In addition, the operation of generators for electricity supply will help to reduce the feeling of lack of electricity among residents and ensure reliability in the use of electricity for all sectors of the district's economy. The overall conclusion is that the implementation of such technical solutions will significantly increase the resilience of Ukraine's energy system. The results obtained make it possible to effectively avoid blackouts and ensure a sustainable electricity supply to the population. This allows energy companies, government agencies and other stakeholders to optimize energy resource management and make informed decisions to ensure the sustainable and efficient operation of Ukraine's energy system in the face of a possible blackout risk

Keywords: power grids; infrastructure modernization; power automation system; renewable energy sources; flexible load management

INTRODUCTION

Against the backdrop of the war between Russia and Ukraine, the study of technical solutions to prevent blackouts and ensure the resilience of energy systems is becoming particularly important. The war reinforces the need to improve technical means for effective management and protection of power grids in the face of possible increased risk and challenges arising from martial law. Increased burden on power grids and possible attacks on infrastructure may pose serious challenges to Ukraine's energy security. Ensuring the stability and reliability of energy systems is becoming a strategic task to ensure the normal functioning of the economy and the living standards of the population in times of war. The study of technical aspects, such as protection against cyber threats, enhancing cybersecurity and emergency response, is becoming an important element of the strategy to ensure energy security in the face of a military threat.

The research is aimed at developing and implementing effective technical solutions to prevent blackouts in the power supply system, in particular, in the conditions specific to Ukraine. Ensuring a sustainable and reliable energy infrastructure is an important task, as blackouts can have serious consequences for society, the economy and vital infrastructure. The study aims to improve monitoring systems, demand management, renewable energy sources, backup power supply and other technical aspects to minimize the risks and consequences of energy accidents.

V. Shchelkunov *et al.* (2023) emphasize the critical need to introduce new technical solutions to increase the resilience of the Ukrainian energy system. The authors insist on the importance of modernizing infrastructure and applying innovative methods of automation and control. As noted, the study does not consider the impact of energy systems on environmental aspects and the possibility of improving energy efficiency, considering environmental requirements. V. Vashchenko & I. Korduba (2023) note that the efficiency of energy supply is of particular importance in the context of increasing load on the power grid and unpredictability of electricity consumption, which can lead to serious problems. It is important to note that the researcher did not consider the relationship between flexible load management and emissions reduction, which may prove to be key in measuring environmental impact.

In their work, P.P. Myrutenko & L.K. Listovshchik (2022) note that the use of energy storage and the promotion of renewable sources are key elements of a strategy to increase the resilience of the energy system. However, it should be noted that the study does not consider the possibilities of using hybrid energy systems to maximize the use of renewable sources and increase the resilience of energy infrastructure. Researchers S.M. Stezhko & V.M. Fitsa (2021) note the importance of implementing flexible load management and improvements in energy systems to ensure resilience and protect against potential cyber threats. However, it should be noted that the researcher's attention is not focused on specific cyber defence technologies and strategies, which may have an impact on the effectiveness of measures to counter cyber threats.

In the work by A.V. Polukhin *et al.* (2023), special attention is paid to the analysis of current technical solutions and their impact on increasing the resilience of the Ukrainian energy system. However, it is important to note that the study does not pay due attention to the dynamics of changes in electricity consumption and their possible impact on the stability of energy systems in the future. In the study by R. Hryshchenko (2022), the author raises an important issue of effective forecasting of electricity consumption, which is a key element in improving forecasting systems and optimizing resource use. It is worth noting that the study does not go into greater depth on the importance of introducing intelligent forecasting systems that consider socio-economic factors and changes in consumption.

The purpose of this study is to analyse technical solutions that can increase the resilience of Ukraine's energy system and prevent power outages.

MATERIALS AND METHODS

The analytical method helped to thoroughly analyse technical solutions aimed at improving the resilience of Ukraine's energy systems. The use of this method allowed for a detailed consideration of the effectiveness and possible limitations of each technical solution, which became the basis for further conclusions and recommendations for improving the energy infrastructure. The statistical method was used to study trends and patterns in the functioning of the energy system, which allowed for reliable forecasts of possible variations in electricity production and consumption. This method has proven to be an effective tool for formulating energy management strategies and identifying the best ways to improve system efficiency.

Using the functional method, the key functional components of the energy system and their interactions were identified. This method allowed understanding important aspects of the internal interaction of the system components, which is critical for optimizing the operation and ensuring the highest efficiency of energy processes. The results of the functional method serve as the basis for further recommendations to improve the system's operation.

The deduction method helped to study the cause-and-effect relationships between different elements of the energy system and identify the main factors that affect its sustainability. This method helped to identify the key aspects that determine the efficiency and reliability of the system. Based on the findings, sound strategies can be developed to further improve and optimize the energy infrastructure.

By applying the synthesis method, integrated concepts for improving the energy system were created. This method allowed combining various technical solutions and strategies into a single harmonious system aimed at increasing sustainability and efficiency. The synthesis method helped to find optimal combinations of technical solutions that can be implemented to achieve the goal of ensuring the stability of energy systems. The results of the synthesis identify practical steps for implementing innovations and optimizing system performance.

The classification method helped to structure various technical solutions and components of the energy system, identify their main characteristics and group them by common features. This method helped to systemize information and make the variety of available technical solutions clear. The classification method has become an important tool for selecting the optimal system components, which contributes to the goal of increasing the resilience and reliability of the energy infrastructure.

The induction method, in the context of this study, was used to investigate the collected facts and data to identify general trends and patterns in energy systems. This method helped to identify the internal relationships and dynamics of the system, considering various influences and factors. This method allowed considering the specific conditions and context of the Ukrainian energy system in order to develop balanced recommendations and strategies to improve its performance and reliability.

The synthesis method combined the findings and conclusions to provide an overall picture of the energy system. This method allowed abstracting from the details and identifying the main trends and key relationships, which is important for understanding the overall dynamics of energy processes. Summarizing the findings helped to identify strategic areas for further research and action to improve the efficiency and stability of the energy system.

RESULTS

The energy crisis in Ukraine is the result of a variety of factors. The crisis is driven by the difficult situation in the energy market, including insufficient infrastructure development, malfunctioning of the electricity supply system, and institutional weaknesses in the management of the energy sector. Not only socio-economic factors contributed to the energy crisis, but also political, institutional, environmental, and regional aspects. The threats in this context are the war on the part of Russia and the occupation of Donetsk, Luhansk, Kherson and Zaporizhzhia regions, where the main thermal coal production is located, which is used to generate electricity for thermal power plants (TPPs). Other challenges include the monopolization of the electricity market, high depreciation of power plants, the constant decommissioning of unprofitable coal mines, low penetration of alternative electricity sources, ongoing ambiguity over Energy Community reforms, reduced dependence on external supplies, institutional imbalances in the energy market, and others. As a result of these threats, a situation has arisen where energy demand has exceeded supply, which necessitates the creation of mechanisms to ensure Ukraine's energy security (Kulcsár *et al.*, 2021).

To ensure the stability of electricity supply, measures are taken to protect power grids from possible enemy attacks. Attacks can take many forms: physical (including bombings, shelling, and sabotage), cyber (such as hacking, viruses, and hacker attacks), and electromagnetic (high voltage or frequency pulses). A variety of strategies can be implemented to successfully defend against various attacks (Karako & Dahlgren, 2022). Physical protection includes strengthening the structures and materials of equipment and power transmission lines, installing barriers and fences, as well as using video surveillance and alarm systems, and organizing security and patrols.

Protection against cyber threats includes the use of encryption, authentication, and access control to information systems and networks. Equally important is the installation of antivirus and anti-spyware software, regular updates of software and operating systems, as well as data backup and the creation of alternative communication channels. Electromagnetic protection includes the use of means of filtering, stabilizing, and controlling the voltage and frequency of electrical energy. It is also essential to install protective devices against overloads, short circuits, and overvoltage, as well as to use shielded cables and equipment.

Ensuring the resilience of power supply in the face of a full-scale invasion and restoring years of experience in critical situations (the process of restoring and applying the experience of operating systems or technologies accumulated over many years in conditions of critical situations or emergencies) involves the use of a set of measures. For example, the creation of additional sources of electricity, such as diesel generators, batteries, and renewable energy sources, which can be switched on when the main sources fail. An important element is the use of automation, control, and protection systems for power grids that can respond quickly to changes in electricity parameters and the network situation, such as relay protection, automatic backup, and remote control. Also, important is the development of small distribution generating systems, such as microgrids, mini-hydroelectric power plants and solar panels, which can operate independently or in parallel with centralized grids, contributing to decentralization. This set of measures is aimed at guaranteeing the reliability, quality, and efficiency of electricity supply during wartime, as well as increasing the resilience of electricity grids to extreme impacts.

In addition to quality and reliability aspects, there is another important factor in the electricity supply sector – efficiency, which is determined by the ratio of the costs of electricity generation, transmission, and distribution to its efficient use (Butt *et al.*, 2021). The efficiency of electricity supply is determined by the choice of optimal schemes and designs of system elements, as well as the rational distribution of loads in accordance with different reliability categories. In addition, the efficiency of electricity supply is closely related to the reduction of electricity losses during transmission and distribution, as well as to the improvement of energy efficiency of consumers.

When considering the structure of electricity generation in the United Energetic System of Ukraine (UES), it is important to note that nuclear power plants (NPPs) account for more than half of the total, exceeding 50% (Fig. 1).

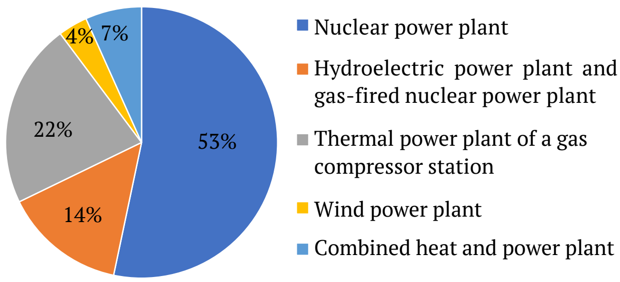

Figure 1. Ratio of electricity generation in UES of Ukraine during maximum load
Source: compiled by the authors based on M.P. Pablo-Romero *et al.* (2021)

The ratio of electricity generation in the UES of Ukraine during peak load determines an important aspect of the country's energy system. During this period, it is possible to note which energy sources provide the largest contribution to electricity generation. This information is important for planning and managing energy resources, allowing to optimize the use of different sources and ensure stable operation of the system during peak load. Analysing this ratio is an important step in improving generation strategies and ensuring the efficiency of Ukraine's energy system. The distribution of electricity consumption in Ukraine is shown in Figure 2.

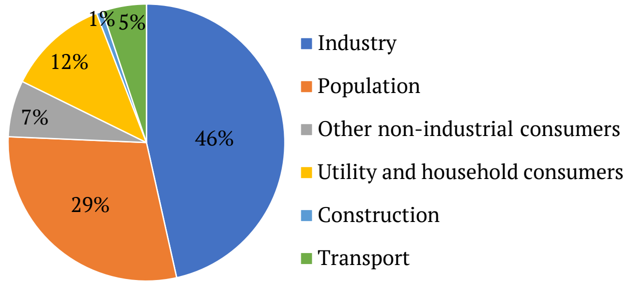

Figure 2. Distribution of electricity among different groups of consumers in Ukraine, except for temporarily occupied territories
Source: compiled by the authors based on A. Szeberényi & F. Bakó (2023)

The distribution of electricity among different consumer groups in Ukraine, excluding the temporarily occupied territories, is a key aspect of analysing the country's energy system. This structure determines how different sectors of the economy and the population use electricity and can indicate the needs and requirements of different industries. It is advisable to take this distribution into account when developing strategies to ensure the sustainability and reliability of energy supply, as different segments may have different requirements for power, quality, and reliability of electricity consumption. Such an analysis also helps to identify potential areas for improving and optimizing energy infrastructure, considering the needs of different sectors of the economy and the population.

It is worth considering a notional district with a population of 100,000 people that was left without electricity supply. The area of the district is 100 km². The total electricity demand for the district's population is about 10 MW. This electricity demand includes different areas of consumption, including housing, transport, trade, and public facilities. Residential use, which includes lighting, heating and household appliances, accounts for 7 MW. Transport infrastructure requires 1 MW of electricity, trade uses 1 MW, and public facilities require another 1 MW. In total, these sectors have a combined need for 10 MW of electricity. The total cost of purchasing and operating the generators to provide electricity to the district is estimated at approximately UAH 100 million. This financial amount includes an amount of UAH 50 million for the purchase of generators and an additional UAH 50 million to be spent on the purchase of fuel for the continuous operation of these generators.

Various technical solutions can be used to ensure the district's electricity supply. The most reliable solution is to install generators at critical infrastructure facilities. This option ensures uninterrupted power supply for vital facilities, but is costly due to the need to purchase and operate numerous generators. Installing generators at critical infrastructure facilities is the best solution in terms of reliability. However, this solution is also the most expensive. The distributed power generation option involves installing generators at every home or business. This approach is less reliable; as other generators may be overloaded if one of them fails. However, it is more cost-effective because it requires fewer generators. Distributed power generation is a less reliable solution, but it is also cheaper. This option may be acceptable for areas with limited financial resources.

The combined approach includes both the installation of generators at critical infrastructure facilities and distributed power generation. This option is the most optimal, as it ensures reliable power supply at relatively low costs. The combined option is the most optimal in terms of reliability and costs. This option may be acceptable for most areas. Within the combined option, different technical solutions can be used to provide electricity supply in different areas (Fig. 3). For the residential sector, solar power plants are an effective solution, providing clean and affordable energy. However, gas generators can be used for uninterrupted power supply at night.

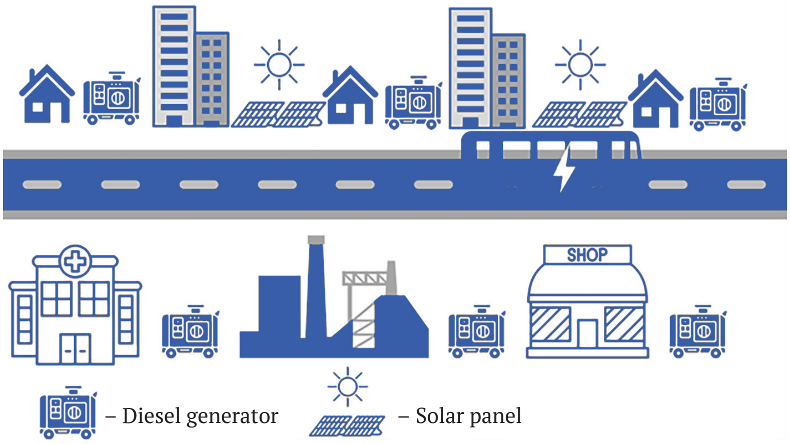

Figure 3. Scheme of an electro-dependent district during a power outage
Source: compiled by the authors

It is recommended to use electric buses for transport, which are more environmentally friendly than traditional diesel buses. However, due to the limited range of electric buses, charging stations can be used to ensure uninterrupted power supply at night. Diesel generators are recommended for use in retail and public facilities. Diesel fuel is more affordable, which can make diesel generators a cost-effective solution for providing power to these facilities. Implementation of the technical solutions described above could help ensure reliable power supply for the population of Ukraine even in the event of a power grid failure. These solutions will require significant investment, but they can bring significant social and economic benefits.

The current challenges in the energy sector require appropriate technical solutions and strategies, including infrastructure expansion and modernization. One of the key areas of this process is to increase the capacity of transmission lines. The installation of new transmission lines and the modernization of existing ones are critical elements for increasing the capacity and resilience of energy systems (Ghiasi *et al.*, 2023). New technologies and materials are enabling transmission lines to be built with high efficiency, ensuring optimal transmission of electricity over long distances without losses. In addition, the development of automation and control systems is a necessary step in the evolution of energy infrastructure. The introduction of modern automation systems allows grid operators to instantly interact with system components, monitor the status of grid elements in real time and respond effectively to any deviations or emergencies. This approach to infrastructure expansion and modernization not only improves the efficiency and resilience of the energy system, but also enables the integration of renewable energy sources, which contributes to sustainable development and reduces emissions. These measures set the right course for building a future energy landscape that meets the current and future needs of society.

The introduction of battery storage is an important step in improving grid resilience and reliability. These storages can effectively compensate for electricity losses, smooth out demand peaks and provide energy reserves in the event of accidents or grid failures. They allow for the accumulation of excess energy generated during periods of low consumption and its use during peak times, which is key to ensuring the resilience and efficiency of the system. The development of renewable energy sources, such as solar and wind power, is a strategic step towards sustainable development (Østergaard *et al.*, 2022). Increasing the share of renewable energy sources allows for decentralized electricity production, reduced dependence on traditional sources, and lower greenhouse gas emissions. In addition, it contributes to the creation of a sustainable energy system capable of addressing the challenges of climate change and ensuring a stable electricity supply in all conditions.

In general, increasing the efficiency of electricity supply through the use of energy storage and renewable sources is a key step towards a sustainable, efficient and environmentally friendly energy future. The development and implementation of energy efficiency systems includes the use of advanced technologies and energy saving systems in industry, businesses, and households. The use of energy-efficient technologies can significantly reduce energy consumption, ensuring optimal use of resources and thus reducing the negative impact on the environment.

The use of "flexible" control technologies allows for the regulation of electricity consumption depending on the needs of the system (Ma *et al.*, 2022). This means that the load can be adapted to changes in energy demand, reducing the risk of overloading and ensuring efficient energy use. Flexible control also makes it possible to use renewable energy sources in the most optimal way, helping to balance production and consumption. Load management and energy efficiency not only ensure the stability of energy systems, but are also strategic steps towards a sustainable, efficient, and environmentally friendly energy sector. This is an investment in the future, where modern technologies and innovative approaches define the path to an energy system that meets the current challenges and needs of society.

In today's world, where electricity is an integral part of life, improving forecasting systems is becoming a strategic task to ensure the sustainability and reliability of energy systems. It is important to improve electricity consumption forecasting systems. The use of modern algorithms and technologies allows accurately predicting peak loads and optimizing the operation of power supply systems. This is especially important in the context of growing demand and various factors that can affect the energy system. Accurate forecasts allow system operators to fine-tune the production and distribution of electricity, avoid congestion and ensure efficient use of resources. Improved forecasting systems are also a key element for the integration of renewable energy sources (Erdiwansyah *et al.*, 2021). With accurate forecasting of weather conditions and renewable energy production, systems can effectively account for fluctuations in production and align it with consumption. This enables optimal use of renewable sources and contributes to system resilience.

With rapid technological developments, improving forecasting systems is a strategic step in building the future of energy. Accurate and efficient forecasts not only ensure the sustainability of systems, but also lay the foundation for the development of intelligent energy systems that can meet the challenges of today and contribute to sustainable development. In the era of digital transformation and the growing number of connected systems, resilience to cyber threats is becoming an integral part of ensuring the security of energy networks. A key aspect is protection against cyber threats, which involves the development and implementation of effective cybersecurity measures. Energy infrastructure is becoming an attractive target for cybercriminals, and it is therefore important to develop and implement strategies and technologies that effectively protect systems from attacks and intrusions. This may include improving authentication systems, encrypting data, and even implementing artificial intelligence to detect and remediate threats in real time.

The knowledge and skills of cybersecurity personnel can be a key factor in preventing and detecting attacks (Zwilling *et al.*, 2022). Regular training, simulations and updates to security procedures can significantly increase the resilience of systems. Resilience to cyber threats is becoming a top priority in a world where technology is evolving rapidly and threats are becoming more sophisticated and complex. Protecting energy infrastructure from cyberattacks is not only a security measure, but also a guarantee of the stability of energy systems and protection against the negative impact of external factors.

Successful implementation of the above technical solutions opens up the prospect of ensuring the resilience of the power grid in Ukraine and effective prevention of possible blackouts. This will help to create a more reliable and resilient energy infrastructure, reducing the risks of situations that could lead to major power outages. Given the growing burden on the power grid and the threat of blackouts, the successful implementation of these solutions is key to ensuring uninterrupted and stable power supply for the population and various sectors of the economy. This step will help improve energy security and meet the requirements of the modern energy landscape.

DISCUSSION

Energy security is a critical aspect of any country's life, especially in times of geopolitical conflict and war. Ukraine, being at the centre of energy tensions due to the war with Russia, is studying and implementing technical solutions to prevent blackouts and ensure the resilience of the power grid. One of the key challenges for Ukraine is the need to increase the resilience of the energy system in the context of the escalating war. An important part of this process is the development and modernization of infrastructure. The installation of new power lines and the modernization of existing ones play a key role in increasing the capacity and resilience of the system.

Consideration and implementation of the latest automation and control technologies is another perspective. The use of systems that allow operators to monitor the grid in real time and respond effectively to deviations in power consumption can significantly improve the response to potential threats. Increasing the efficiency of electricity supply also requires the introduction of energy storage. Battery storage can compensate for power losses and ensure grid resilience. The development of renewable energy sources, such as solar and wind power plants, is also a key element of the energy security strategy (Sadykov *et al.*, 2023). However, all these technical solutions must be combined with cybersecurity considerations. In the face of cyber threats, it is important not only to develop the resilience of physical infrastructure elements, but also to implement effective cyber defence measures to prevent attacks on information systems and energy infrastructure management.

Ukraine has extensive experience of working in wartime, and studying its approaches to technical solutions can serve as an example for other countries that also face similar challenges in ensuring the resilience and security of their energy systems. According to the research by S.V. Kalantar *et al.* (2021), the study of consumer behavioural potential plays an important role in developing effective solutions to prevent a power outage crisis. Understanding and analysing electricity consumption patterns can identify consumer patterns and help develop strategies to optimize energy consumption. Applying artificial intelligence and data analytics technologies to study electricity consumption habits can provide valuable insights into how to effectively manage load and generation. The development and use of solar energy is also an important aspect in preventing an energy supply crisis. Increasing the capacity of solar power plants can make the energy system more resilient and less dependent on traditional sources. The use of solar technologies will not only reduce the responsibility for CO_2 emissions, but also ensure stability in energy supply, even in the event of a crisis (Rausch & Suchanek, 2021). These findings are in line with the theses presented in the previous section. The combination of behavioural potential analysis and active development of solar technologies can contribute to a more resilient and sustainable energy system, providing the necessary reserves and energy sources for unforeseen circumstances.

Referring to the definition of N. Sharma *et al.* (2021), large-scale power outages are a serious problem that can have a significant impact on society and the economy. One of the main reasons for such outages is the obsolescence of energy systems and infrastructure, which is not always able to withstand the load during rapid changes or emergencies. Technical failures, malfunctions in network equipment and insufficient preventive measures also contribute to the occurrence of major outages (Panov & Tymchuk, 2023). To prevent such situations, it is important to consider recommendations for modernizing energy systems. This may include infrastructure improvements, the use of new technologies such as monitoring and remote control systems, and increased maintenance activities. However, there are a number of challenges to improving energy resilience, such as the financial costs of modernization, difficulties in implementing new technologies, and coordination between different energy sector actors (Selvakumar *et al.*, 2023). It is worth noting that addressing the problem of large-scale power outages will require a comprehensive approach, combining technical innovations, modernization strategies and sound decisions to increase the resilience of energy systems.

Researchers D. Majchrzak *et al.* (2021) determined that the preparedness of the crisis management system in Poland plays a key role in addressing long-term and large-scale problems related to electricity shortages and possible power outages. This preparedness is determined by the effectiveness and coordination of measures aimed at ensuring the resilience of the energy system in times of great difficulty. An important aspect is the development of crisis management strategies that include large-scale power outages. This includes not only technical aspects, but also evacuation plans, ensuring the living environment for the population and maintaining critical infrastructures. Emergency response systems must be ready to take immediate action to prevent a humanitarian crisis and ensure the safety of citizens. In addition, the effectiveness of the crisis management system is determined by the level of interaction between different branches of government, local authorities, energy companies and other stakeholders (Ostudimov & Kaminska, 2023). It is important to have communication and information exchange mechanisms in place to respond quickly to any challenges that may arise as a result of a long-term electricity shortage. These results confirm the above study, as the Polish crisis management system should also consider supporting measures to increase the efficiency and flexibility of the energy infrastructure, such as the development of energy storage and the use of renewable energy sources. Taking these aspects into account, a more resilient and crisis-ready electricity supply system in Ukraine could be created.

G. Mutani *et al.* (2021) have shown through their work that the creation of energy communities is a strategic step to ensure territorial resilience and minimize the risks of power outages. One of the key advantages of energy communities is their ability to introduce innovative technologies and effectively coordinate the operation of the electricity supply system at the local level. This creates opportunities for load sharing and the use of local renewable energy sources. The measure of blackout risk is becoming an important tool for energy communities to define response strategies and plan for negative scenarios. Measuring this risk involves analysing factors such as the technical condition of the grid, the dynamics of electricity demand, the degree of renewable energy use, and the interaction with neighbouring power systems (Zhuravel *et al.*, 2023). This view can be agreed with, as the development of an effective load monitoring and forecasting system can be critical to reducing the risk of blackouts. These measures are aimed at ensuring the elasticity of power supply management to respond to changes in consumption, in particular, in blackouts and emergencies. Implementing smart solutions at the local level can help optimize system performance and ensure the sustainability of the electricity infrastructure, especially in the face of emergencies.

As noted by R. Bajo-Buenestado (2021), the power outages have a significant impact on household electrification, especially in countries where access to energy may be limited. In Kenya, for example, the electricity supply system has been challenged by numerous outages due to technical failures, inadequate infrastructure, and unstable power generation. Power outages in Kenya can have serious socio-economic impacts on households. Many homes and businesses may have limited access to lighting, communications, and electrical appliances, affecting the convenience and efficiency of their operations. This is especially true in rural areas, where a large proportion of the population may be dependent on electricity for agricultural activities. Analysing the results and conclusions obtained, we can assume that the results proposed by the authors in the analysed papers may be appropriate not only under normal conditions, but also in the context of emergency outages and blackouts. Adaptation to such challenges will require the implementation of technical and infrastructural solutions, such as the development of stable power supply systems, the use of alternative energy sources and effective crisis management strategies.

Researchers N. Fabra *et al.* (2022) identified that developing resilience strategies in electricity markets is important to ensure efficient and reliable electricity supply. Lessons that can be learnt from electricity markets can help develop effective strategies to ensure the resilience and reliability of energy systems. An important element is to understand the impact of market mechanisms on the resilience of electricity supply. For example, the introduction of electricity trading systems can create incentives for the development of new technologies and increase competition in the market. However, at the same time, it is necessary to avoid the "too much flexibility" effect, where a high dependence on market mechanisms can be vulnerable to extreme situations.

Considering the issue of blackouts and blackouts, it can be noted that the implementation of a resilience strategy in electricity markets requires a comprehensive approach that considers technical, economic, and environmental aspects. At the same time, it is important to assume that the results of the analysed work are applicable in situations of emergency outages, not just in normal conditions. Learning from the experience of other markets can be a valuable tool for developing effective strategies aimed at sustainable and resilient energy systems.

CONCLUSIONS

Infrastructure development and modernization is an important step in ensuring the resilience of the electricity supply system. Installing new transmission lines and improving the efficiency of existing structures is crucial to increase the capacity and reliability of the grid. Given the consideration of an off-grid scenario and the different consumption sectors, a combined approach is recommended to ensure reliable and cost-effective power supply, including the installation of generators at critical infrastructure and distributed power generation. The introduction of systems that allow operators to monitor the grid in real time and respond effectively to potential threats can significantly improve system resilience.

One of the key tasks was to research and evaluate the latest technologies for the installation of new power lines with improved transmission characteristics. The importance of expanding automation systems to effectively monitor and control the state of the power grid was noted. Increasing the efficiency of electricity supply in Ukraine is also driven by the development of energy storage and the use of renewable energy sources. Battery storage and renewable energy sources play a key role in ensuring grid stability and compensating for electricity losses. It is impossible to ignore the issue of cybersecurity in the context of technical solutions. The use of effective cyber defence measures to protect energy infrastructure from attacks and intrusions is an integral part of the strategy.

Ukraine, in the midst of a difficult military conflict, is studying and implementing these technical solutions to provide electricity to its population and maintain the stability of the energy system. The country's experience can serve as an important source of information for other countries facing similar challenges and create the basis for further development and improvement of technical aspects of energy security. Implementation of these technical solutions in Ukraine can significantly increase the resilience of the energy system, ensuring the efficiency and reliability of electricity supply. Optimization and modernization of infrastructure, use of innovative technologies and implementation of cybersecurity measures are key steps for Ukraine's modern energy sector.

In the future, for a more complete understanding and successful implementation of technical solutions to prevent blackouts in Ukraine, it is important to study in detail the interaction between these technological solutions, assess their cost and cost-effectiveness, and analyse potential challenges and limitations in their implementation in the Ukrainian context.

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CONFLICT OF INTEREST

None.

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Технічні рішення щодо запобігання блекауту задля забезпечення населення електроенергією: кейс України

Анотація. У зв'язку з погіршенням стану електромереж та збільшенням кількості відмов у постачанні електроенергії, проведення досліджень щодо технічних рішень для запобігання блекаутам українською енергетичною системою стає вкрай актуальним та необхідним завданням. Це дослідження має на меті аналіз технічних рішень, спрямованих на підвищення стійкості енергетичної системи України для запобігання блекаутам та забезпечення надійного електропостачання населенню. Серед використаних методів слід зазначити аналітичний метод, метод класифікації, функціональний метод, статистичний метод, метод синтезу та інші. У ході дослідження було проведено аналіз сучасних технічних рішень для підвищення стійкості української енергетичної системи. У рамках дослідження було здійснено докладний аналіз інноваційних підходів до модернізації енергетичної інфраструктури. Першочерговою задачею було вивчення та оцінка сучасних технологій проєктування нових ліній електропередачі з покращеними характеристиками передачі електроенергії. Підкреслено важливість розширення систем автоматизації для ефективного моніторингу та керування станом енергетичної мережі. Дослідження також визначило важливість використання сховищ енергії, розвитку відновлювальних джерел та удосконалення систем прогнозування споживання електроенергії. Заходи з гнучкого керування навантаженням та покращення систем кібербезпеки були визначені як критичні. Зазначено, що реалізація проєкту забезпечення електропостачання умовного району буде ключовим кроком у покращенні життя місцевого населення та забезпеченні необхідних умов для розвитку інфраструктури та економіки району. Крім того, експлуатація генераторів для електропостачання допоможе зменшити відчуття відсутності електроенергії серед мешканців та забезпечить надійність у використанні електричної енергії для всіх секторів господарства району. Загальним висновком є те, що впровадження таких технічних рішень дозволить значно підвищити стійкість енергетичної системи України. Отримані результати дозволяють ефективно уникати блекаутів та забезпечувати стале електропостачання населенню. Це дозволяє енергетичним компаніям, урядовим органам та іншим зацікавленим сторонам оптимізувати управління енергетичними ресурсами та приймати обґрунтовані рішення для забезпечення сталої та ефективної роботи енергетичної системи України в умовах можливого ризику блекаутів

Ключові слова: електромережі; модернізація інфраструктури; система автоматизації електроенергії; відновлювані джерела; гнучке керування навантаженням