Machinery & Energetics
Vol. 15, No. 3. 2024

Journal homepage:
https://technicalscience.com.ua/en

UDC 620.9:338.2
DOI: 10.31548/machinery/3.2024.103

Lyudmyla Mikhailova*
PhD in Technical Sciences, Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0002-3419-5446

Olga Zavytii
PhD in Economics, Associate Professor
West Ukrainian National University
46009, 11 Lvivska Str., Ternopil, Ukraine
https://orcid.org/0000-0001-7439-6923

Mykola Horlachuk
PhD in Economics, Associate Professor
West Ukrainian National University
46009, 11 Lvivska Str., Ternopil, Ukraine
https://orcid.org/0000-0001-8030-1193

Dariia Vilchinska
PhD in Agricultural Sciences, Assistant
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0002-3322-6722

Oleh Kondratiuk
Master, Assistant
West Ukrainian National University
46009, 11 Lvivska Str., Ternopil, Ukraine
https://orcid.org/0009-0004-7054-5417

Search for innovative solutions to improve the energy system of Ukraine: World experience

Abstract. This study analyses the global experience of introducing innovations in the energy sector to identify effective solutions that can be applied to improve the energy system of Ukraine. The research methods included a comparative analysis of international experience in the energy sector, an assessment of the possibilities of adapting innovative technologies to Ukrainian conditions, and an examination of technical and economic aspects of integrating new solutions. The study analysed the experience of countries such as Germany, Denmark, the United States, Finland, the Netherlands, Sweden, Japan, China, France, and South Korea, which have succeeded in implementing innovative solutions in the energy sector, in particular, in the integration of renewable energy sources (RES), the development of smart networks, energy decentralisation, energy storage technologies, and energy efficiency improvement. It is identified that the most efficient approaches include the integrated use of renewable energy sources in combination with energy storage, which ensures

Article's History: Received: 22.03.2024; Revised: 07.06.2024; Accepted: 15.08.2024.

Suggested Citation:
Mikhailova, L., Zavytii, O., Horlachuk, M., Vilchinska, D., & Kondratiuk, O. (2024). Search for innovative solutions to improve the energy system of Ukraine: World experience. *Machinery & Energetics,* 15(3), 103-116. doi: 10.31548/machinery/3.2024.103.

*Corresponding author

the stability of energy supply even in conditions of uneven electricity production. The importance of smart networks for optimising energy distribution and reducing losses is also emphasised. The decentralisation of energy and the development of energy cooperatives contribute to improving energy security and community engagement. The study also showed that the introduction of smart energy management systems at the consumer level helps to increase the flexibility of the energy system and effectively respond to fluctuations in demand. In addition, it is determined that the successful implementation of innovative projects in the energy sector requires state support through subsidies and regulatory incentives. Based on international experience, it is concluded that combining technical solutions with effective management and political initiatives is key to ensuring the sustainable development of the Ukrainian energy system

Keywords: supply stability; smart networks; decentralisation; sustainable development models; subsidies; policy initiatives

INTRODUCTION

In the context of the global energy crisis, the need for stable energy supplies and the challenges caused by shelling, Ukraine faces an important task of modernising its energy system. Substantial reliance on traditional energy sources and low energy efficiency jeopardise national energy security. It is critically important to consider the global experience of implementing innovative solutions that contribute to the development of renewable energy sources (RES), energy decentralisation, and the introduction of smart networks and energy storage technologies. The experience of countries that have successfully implemented these approaches can become an important source of knowledge and practical recommendations for improving the energy system of Ukraine and increasing its resilience to the challenges of the modern world.

In the examined area of the Ukrainian energy system, there are several substantial problems that need to be solved. There is a substantial dependence on traditional energy sources, which threatens energy security and the environmental situation (Shahini *et al*., 2024). Insufficient integration of renewable energy into the national energy system and the lack of efficient energy storage mechanisms limit the ability to ensure a stable and sustainable energy supply. C. Lamnatou *et al*. (2022) focus on the integration of renewable energy sources into national energy systems, especially their impact on reducing CO_2 emissions. In addition, the study examines problems and solutions for integration in the context of existing infrastructure. D.K. Panda & S. Das (2021) examine the efficiency of smart networks, in particular, their ability to optimise energy distribution and reduce energy costs. Their paper also focuses on the practical aspects of implementing such networks in different regions. S. Sahoo & P. Timmann (2023) analyse current energy storage technologies, especially their impact on the stability of energy supply in irregular production. Their study includes evaluating the efficiency of various types of energy storage systems.

J. Fouladvand *et al*. (2022) explore the role of decentralisation in energy, focusing on the impact of energy cooperatives on improving energy security at the local level. They also explore the benefits and challenges of decentralised energy supply models. Y. Shao & Z. Chen (2022) examine the impact of government subsidies and regulatory incentives on innovation in the energy sector. In the study, they considered the impact of these mechanisms on the development and implementation of new technologies. M. Meliani *et al*. (2021) demonstrate how smart energy management systems can increase the flexibility of energy systems. The study also showed how these systems help adapt to changes in energy demand. U. Datta *et al*. (2021) describe in detail the benefits of integrated renewable energy use together with energy storage to ensure supply stability. The study includes an analysis of various approaches and their impact on energy stability.

A. Kumar *et al*. (2021) focus on improving energy efficiency through the latest technologies in construction and industry. The study highlights the importance of innovation in reducing energy consumption and reducing costs. M. Fowlie & R. Meeks (2021) analyse the experience of countries that have successfully implemented energy efficiency programmes. They emphasise the importance of adapting such practices to the conditions of other countries to improve the energy situation. M. Guertler & N. Sick (2021) emphasise the importance of international partnerships and the exchange of experience in implementing innovative projects in the energy sector. Their study also examines the role of international cooperation in the introduction of new technologies. Gaps that require further study include the lack of adaptation of smart networks to the specific conditions of Ukraine and the lack of detailed studies on the effectiveness of various energy storage technologies in the context of local climatic and economic realities. In addition, it is necessary to explore more deeply the possibilities of energy decentralisation through energy cooperatives and local initiatives and to examine the impact of regulatory and financial incentives on the development of innovative solutions in the energy sector of Ukraine.

The purpose of the study was to investigate the world experience of innovations in the energy sector for further use in Ukraine. Objectives of the study:

- analyse the world experience of implementing innovative solutions in the energy sector to identify the most effective practices;
- evaluate technologies and approaches that contribute to the integration of renewable energy sources and improve energy efficiency;

○ consider the possibilities of adapting these innovative solutions to the conditions of the Ukrainian energy system and their impact on ensuring a stable energy supply and improving economic efficiency.

MATERIALS AND METHODS

The study examined key aspects of renewable energy integration, the use of smart grid technologies, the decentralisation of the energy system, the introduction of energy storage technologies, and improving energy efficiency.

The study compared different types of electricity generation in Ukraine to assess their efficiency and impact on the country's energy system. The analysis included aspects such as power, efficiency, CO_2 emissions and the cost of electricity for each type of generation. This allowed determining the most efficient and environmentally friendly solutions for ensuring Ukraine's energy security.

The experience of Germany, which is actively developing programmes to support wind and solar power plants, has been of considerable interest in analysing the regulatory mechanisms and technical integration of renewable energy into the national energy system (Krug *et al.*, 2022). The experience of Denmark was considered, which has achieved success in the development of offshore wind farms that can have potential for the coastal regions of Ukraine (Harguindéguy and Wokuri, 2024). An important aspect was the investigation of the possibilities of technical integration and ensuring the reliability of the power system at the expense of renewable energy sources.

The introduction of smart grid technologies that can improve the efficiency of energy supply management is analysed. The experience of the United States was considered, where the introduction of such networks allowed substantially optimising the balance of energy supply and demand, and reduce losses in power grids (Butt *et al.*, 2021). Finland's experience in using smart electricity metering technologies to improve energy consumption control and improve energy supply efficiency (Tuomela *et al.*, 2021).

The decentralisation of the energy system has also become an important element of the study. The experience of the Netherlands (Warbroek *et al.*, 2023) and Sweden (Lundmark *et al.*, 2021), where the development of energy cooperatives and the use of local resources such as biomass contributed to improving regional energy security. The prospects for using these approaches in rural regions of Ukraine were considered, considering the specifics of local energy resources and the need to decentralise energy supply.

The study also focused on energy storage opportunities, which are becoming increasingly relevant in the context of the growing share of renewable energy sources. The experience of Japan, where the development of energy storage technologies allows stabilising energy supply, was reviewed (Zhang *et al.*, 2021). In addition, Chinese experience in the development of large-scale energy storage batteries was considered (Fan *et al.*, 2021).

Special attention is paid to improving energy efficiency, which is important for reducing the load on the power system. In this context, the experience of France on programmes to improve the energy efficiency of buildings and industrial facilities (Belaïd *et al.*, 2021) and South Korea's experience in implementing subsidies for energy-saving technologies was examined (Park *et al.*, 2023). These aspects are of great importance for optimising the use of energy resources in the industrial and residential sectors of Ukraine.

The study considered a thermal power plant with the following characteristics: mains voltage $V = 230$ V, current $I = 100$ A, and power factor $\text{Cos}(\varphi) = 0.9$. These parameters are typical for medium-power stations that are used to power large industrial enterprises and residential areas (Zhang *et al.*, 2024). The calculation was conducted for a typical thermal power plant that provides consumers with heat and electricity, typical for regions with high demand for stable energy supply. The following formulas were used in the study:

1. Formula for calculating the power plant capacity (1):

$$P = V \times I \times \cos(\phi), \qquad (1)$$

where P is power (W); V is Voltage (V); I is current (A); $\cos(\phi)$ – power factor.

2. Formula for calculating generation efficiency (2):

$$\eta = \frac{P_{useful}}{P_{input}} \times 100\%, \qquad (2)$$

where η – efficiency; P_{useful} – net power (W); P_{input} – input power (W).

3. Formula for calculating CO_2 emissions per unit of energy produced:

$$E_{CO_2} = \frac{M_{CO_2}}{E_{produced}}, \qquad (3)$$

where E_{CO_2} – CO_2 emissions per unit of energy (t/GW·h); M_{CO_2} – mass of CO_2 emissions (t), $E_{produced}$ – produced energy (GW·h).

4. Formula for calculating the cost of electricity:

$$C = \frac{T}{E_{produced}}, \qquad (4)$$

where C is the cost of electricity (UAH/kW·H); T – total expenses (UAH).

5. Formula for calculating the return on investment time:

$$T_{payback} = \frac{C_{investment}}{C_{energy\ saved}}, \qquad (5)$$

where $T_{payback}$ – payback period (years); $C_{investment}$ – total investment (UAH); $C_{energy\ saved}$ – savings in energy costs for the year (UAH).

The research methods included a comparative analysis of innovative solutions, adaptation of international experience to Ukrainian conditions, and assessment of opportunities for implementing new technologies. Comparing data from different countries allowed forming recommendations for integrating international practices into the national energy system of Ukraine, which can substantially increase its efficiency and stability.

RESULTS

The energy system of Ukraine is a critical component of the national infrastructure that ensures the functioning of the economy, industry, and social sphere. It consists of traditional energy sources such as coal, gas, and nuclear power, and renewable energy sources such as solar and wind power. However, in light of global changes and national needs, the Ukrainian energy sector faces numerous challenges that require urgent solutions and modernisation.

One of the main problems is the high dependence on traditional energy sources, in particular, imported gas, which creates risks for energy security and economic stability. Declining domestic coal reserves and an ageing energy infrastructure are also having a negative impact on the energy sector. In addition, the limited integration of renewable energy sources into the national energy system hinders the development of sustainable and environmentally friendly technologies.

The war with Russia, which has been going on since 2014 and has particularly worsened since 2022, has substantially complicated the situation. The war caused the destruction of critical infrastructure, in particular, energy facilities (Lazor *et al.*, 2024). Damage to power plants, power lines, and gas pipelines has led to frequent power outages and reduced energy security. These factors not only complicate the provision of energy to the population and industry but also substantially increase the cost of infrastructure restoration and modernisation (Table 1).

Table 1. Impact of war on Ukraine's energy system

Impact of war	Description	Consequences	Possible solutions
Infrastructure destruction	Damage to power plants, power lines, and gas pipelines	Frequent power outages, increased recovery costs	Repair and modernisation of damaged facilities, strengthening infrastructure protection
Reducing energy security	Risks of lack of stable energy supply due to fighting	Deterioration of the quality of energy services, economic losses	Development of alternative energy sources, decentralisation of the energy system
Increased recovery costs	High costs for the repair and reconstruction of energy infrastructure	Financial pressure on the state budget, delays in modernisation	Search for international financial assistance, effective resource management
Disruption of energy supply chains	Problems with energy supplies due to blockades and fighting	The emergence of energy shortages, higher prices	Expansion of national production, diversification of suppliers
Environmental impacts	Pollution and damage to environmental systems due to fighting	Negative impact on the environment, additional costs for environmental restoration work	Implementation of environmental standards in restoration, monitoring of the ecological state

Source: compiled by the authors on the basis of data obtained by O. Lazor *et al*. (2024)

Table 2 shows the technical characteristics and economic indicators of various types of power generation in Ukraine. Data include power, efficiency, CO_2 emissions, the cost of electricity, and other characteristics such as flexibility and speed of response. The analysis of these indicators allows assessing the advantages and disadvantages of each type of generation, and their impact on the environmental situation and economic efficiency of the Ukrainian energy system.

Table 2. Comparison of different types of electricity generation in Ukraine

Generation type	Power (MW)	Efficiency (%)	CO_2 emissions (t/GW·h)	Electricity cost (UAH/kW·h)	Other features
Coal-fired thermal power plant	5,000-7,000	33-40	900-1,000	2-3	Less flexibility, higher CO_2 emissions, high pollution
Gas-fired thermal power plant	3,000-5,000	45-55	400-500	2.5-3.5	Higher flexibility, lower CO_2 emissions compared to coal-fired thermal power plants
Nuclear power plant	1,000-3,000	33-37	10-15	1-1.5	Low CO_2 emissions, high safety level, high capital cost
Hydroelectric power station	100-3,000	70-90	0	0.5-1	High flexibility, minimal CO_2 emissions, impact on ecosystems
Wind farms	50-1,500	35-45	0	1.5-2.5	Weather dependence, minimum CO_2 emissions
Solar power plants	10-1,000	15-20	0	2-3	Dependence on solar activity, minimum CO_2 emissions

Source: compiled by the authors

Various analytical tools and mathematical formulas are used to assess the efficiency of electric generating plants and their impact on the economy and environment. They allow calculating such key indicators as generator power, efficiency, carbon dioxide emissions, the cost of electricity production and the payback period for investments in energy-saving projects. The following calculation examples provide a deeper understanding of how to evaluate the efficiency of energy projects and reduce their negative impact on the environment.

Formula (1) is used to determine the power of an electric generator or network. Voltage, current, and power factor are the main parameters for estimating system power. When the voltage in the electrical system is V = 230 V, the current flowing through the system is I = 100 A, and the power factor (phase) cos(ϕ) = 0.9. Then, the power is calculated as:

$$P = 230 \times 100 \times 0.9 = 20.7 \text{ kW}.$$

Thus, the power of the system is 20.7 kW, which means that the power plant can provide consumers with this amount of energy every second. Efficiency shows how much of the input power is converted into useful work. High efficiency indicates the performance effectiveness of the system. If the power plant consumes input power P_{input} = 250 kW and the net power used by consumers is P_{useful} = 200 kW. Then efficiency:

$$\eta = \frac{200}{250} \times 100\% = 80\%.$$

This means that 80% of the incoming energy is converted to usable energy, and the remaining 20% is lost, for example, in the form of heat or other undesirable forms of energy. Formula (3) helps estimate how much carbon dioxide emissions are produced per GW·hour of energy. CO_2 emissions is one of the key indicators of the environmental impact of power plants. If a thermal power plant produces $E_{produced}$ = 2 GW·hour of electricity and emits E_{CO_2} = 500 tonnes of carbon dioxide during its operation, then:

$$E_{CO_2} = \frac{500}{2} = 250 \text{ t/GW} \cdot \text{h}.$$

This means that for each GW·h of energy produced, 250 tonnes of CO_2 are emitted. This indicator can be used to compare different types of energy generation by their impact on the environment. The cost of electricity allows determining how much it costs to produce one kW·hour of energy. This indicator is important for assessing the economic feasibility of various generation technologies. If the power plant produces $E_{produced}$ = 1,000,000 kW·hour of energy and the total cost of its production is T = 500,000 UAH. Then the cost of electricity will be:

$$C = \frac{500{,}000}{1{,}000{,}000} = 0.5 \text{ UAH/kW} \cdot \text{h}.$$

This means that the production of one kW·hour of energy costs 0.5 UAH. Formula (5) allows determining how many years the investment in the project will be repaid by saving on energy consumption. If the project for installing solar panels cost $C_{investment}$ = 1,000,000 UAH and the annual savings in electricity costs are $C_{energy\ saved}$ = 200,000 UAH. Then the payback time of the project will be:

$$T_{payback} = \frac{1{,}000{,}000}{20{,}000} = 5 \text{ years}.$$

Consequently, the investment will pay off in 5 years, after which the project will begin to bring a net profit. The results of the study show that the efficiency of a thermal power plant with an efficiency of 80% and an emission index of 250 t/GWH is substantially lower compared to modern technologies implemented in other European countries. For example, German renewable energy-based power plants achieve substantially higher efficiency through the use of innovative energy storage technologies and reduced heat losses. In addition, CO_2 emission indicators in Germany are substantially lower due to the active introduction of "green" technologies and the rejection of the use of fossil fuels (Ibrahim *et al.*, 2024). Consequently, the calculation results emphasise the need to modernise power generation systems and introduce renewable energy sources to improve energy efficiency and reduce environmental impact.

In the context of current challenges, two main strategies are important: the modernisation of existing capacities and the implementation of innovative solutions (Treshchov, 2024). Modernisation of the energy infrastructure is aimed at improving efficiency and reducing the cost of energy resources. Important aspects include upgrading equipment in thermal power plants, improving energy storage technologies, and integrating smart grids to optimise energy distribution. Special attention should be paid to the restoration and protection of the energy infrastructure affected by the fighting.

Implementing innovative solutions is another important component of the strategy. In particular, the development of renewable energy sources, such as solar and wind, can substantially reduce dependence on imported resources and reduce the environmental footprint. In addition, decentralising the energy system through energy cooperatives and local initiatives can help improve energy security and involve local communities in energy resource management. It can also help reduce the system's vulnerability to external threats.

Government policies and regulatory initiatives play an important role in this process. The introduction of subsidies and tax incentives for investors in innovative technologies, and the creation of favourable conditions for solving bureaucratic obstacles, can substantially accelerate the transition to sustainable energy. In particular, state support for the restoration of infrastructure and ensuring the safety of energy facilities is critical in the current conditions. Thus, the energy system of Ukraine is at an important stage of transformation, which is complicated by the war. It is necessary to actively implement innovative solutions, modernise infrastructure, and provide state support to ensure its stability and development. Only through an integrated approach to solving these problems can the efficient and sustainable functioning of the energy system be ensured, which will meet the needs of the economy and society in the face of military threats and global challenges.

The energy system of Ukraine faces challenges that require not only the modernisation of existing technologies but also the introduction of innovative solutions. One of the key areas is the integration of renewable energy sources. In this context, the experience of Germany and Denmark can provide valuable lessons for Ukraine. Germany is a leader in renewable energy due to its ambitious Energiewende programme, which was introduced to gradually move from fossil energy sources to renewable energy sources (Krug *et al.*, 2022). The main aspects of this programme are the expansion of wind and solar energy, which reduces dependence on traditional energy sources and reduces greenhouse gas emissions. One of the key elements of Germany's success is the regulatory system, which includes substantial subsidies for renewable energy investors. This allowed to reduce financial risks and make investments in renewable energy more attractive. The system of maintaining prices for electricity produced from renewable sources also encourages the development of new projects.

The technical integration of renewable energy into the national energy system is another important aspect. Germany is actively developing energy storage infrastructure and improving networks to effectively cope with the unpredictability of renewable energy production. Network management systems that allow the integration of large volumes of renewable energy are an important component of this strategy. Germany is a leader in the introduction of renewable energy sources. Since 2010, the share of renewable energy sources in the country's electric grid has increased from 20% to 47% in 2023. Modernisation of electrical networks, including the introduction of new transformers and high-voltage lines, allowed increasing the capacity by 15%. For example, the introduction of new standards for power lines has increased their capacity from 5,000 MW to 5,750 MW. Ukraine can use the experience of Germany to create its own strategy for the development of renewable energy sources. The German model of subsidies and regulation can provide an opportunity to build reliable support for investors. In addition, the modernisation of the energy infrastructure, including energy storage, is important for the integration of new energy sources into the Ukrainian system.

Denmark also demonstrates substantial progress in the development of wind energy, in particular, in the use of offshore wind farms (Harguindéguy & Wokuri, 2024). Denmark is one of the pioneers in this field, and its experience can be extremely useful for Ukraine, especially in coastal areas. Denmark's offshore wind farms allow efficient use of offshore winds, providing a stable and powerful energy source. Denmark has developed advanced technologies for the construction and operation of such parks, including innovative solutions to reduce the impact on the marine environment and increase the cost-effectiveness of projects. Denmark is actively developing offshore wind farms. In 2023, the share of wind farms in total electricity production reached 61%. The introduction of new energy storage systems, such as large-scale batteries, has helped stabilise the power supply, reducing dependence on wind fluctuations by 20%. The Black and Azov Seas have potential for offshore wind power in Ukraine. Denmark's experience can help create efficient wind farms that will expand the renewable energy sector. The use of modern technologies will ensure minimal impact on ecosystems and increase the productivity of energy production.

RES integration is an important component of the strategy for the sustainable development of the Ukrainian energy system. The experience of Germany and Denmark in the field of renewable energy development can provide Ukraine with valuable guidelines for adapting its own energy strategy. Borrowing successful practices such as the German regulatory system and Danish offshore wind farm technology can substantially improve the efficiency and stability of Ukraine's energy system, contributing to its independence and sustainable development.

The modern energy system faces new challenges that require innovative solutions to improve the efficiency and reliability of electricity supply. One such solution is smart grids, which can substantially improve the management of energy systems. The experience of the United States and Finland in implementing these technologies can become an important guide for Ukraine in its efforts to modernise its energy infrastructure. In the United States, smart grids have become an important component of energy infrastructure due to their ability to improve energy efficiency, reduce energy losses, and improve system management (Butt *et al.*, 2021). Smart networks in the United States integrate the latest technologies into traditional electrical networks, which reduces energy costs and increases its reliability.

The main elements of smart networks are sensors, automated control systems, and real-time data acquisition systems. These components provide the ability to monitor and analyse the state of the power system in real time, which allows responding faster to failures and optimising energy distribution. The introduction of smart grids in the United States has reduced energy losses, improved the quality of electricity supply, and ensured more efficient use of renewable energy sources. The introduction of smart grids in the United States has reduced power losses by 7-10% due to automated management and monitoring. Currently, about 25% of American households use smart meters, which can reduce energy costs by 5%. An important area for Ukraine is the introduction of smart networks. They can improve the efficiency of renewable energy integration and ensure the stability of the power system. Such networks help to better manage non-constant electricity generation and ensure uninterrupted supply even during failures.

Finland demonstrates successful experience in implementing smart electricity metering technologies (Tuomela *et al.*, 2021). Smart metering technologies allow consumers to control their electricity consumption and improve energy efficiency better. Smart meters used in Finland provide detailed monitoring of electricity consumption in real time and provide consumers with information regarding cost optimisation. The smart accounting system in Finland includes integration with energy networks for automatic data collection and analysis, which allows identifying trends and anomalies in consumption. This, in turn, helps to manage energy resources more efficiently and reduces the cost of energy services. Such technologies also allow consumers to better understand their energy consumption and make better-informed decisions about saving it. In Finland, the use of smart electricity metering has reduced energy costs by 12% in a number of cities due to accurate monitoring and management of consumption. The introduction of new energy storage technologies has helped reduce peak load costs by 15%.

Smart accounting technologies will help Ukraine improve energy efficiency at both the household and industrial levels. They provide consumers with the opportunity to control electricity costs and implement energy-saving measures, which, in turn, will have a positive impact on the country's economy. The integration of smart grids into the Ukrainian energy system is an important step towards its modernisation and efficiency improvement. The experience of the US in implementing smart networks and Finland's experience in developing smart accounting technologies can serve as important guidelines for Ukraine. Following these practices and adapting them to national conditions will allow Ukraine to substantially improve the management of energy resources, reduce costs, and increase the stability of the energy system.

Current trends in the development of energy systems increasingly point to the importance of decentralisation and active participation of local communities in energy production and consumption. The approaches implemented in the Netherlands and Sweden are of considerable interest to Ukraine, where the issue of energy security and stability remains relevant. Energy cooperatives and decentralised energy models implemented in these countries can become important elements in the formation of an efficient and sustainable energy infrastructure in Ukraine. The Netherlands is an example of a country where energy cooperatives are actively developing (Warbroek *et al.*, 2023). In this context, local communities take the initiative to produce and consume energy, which contributes to the decentralisation of energy systems and improving energy security. Energy cooperatives in the Netherlands allow citizens to pool their resources, creating and managing local energy sources such as solar panels and wind turbines.

Such cooperatives not only provide local residents with clean energy but also contribute to economic development at the local level. Members of cooperatives have the opportunity to control energy costs and benefit from the sale of excess energy. In addition, energy cooperatives help reduce dependence on centralised energy suppliers and increase the sustainability of the energy system. The Netherlands has focused on the decentralisation of the energy system. The development of energy cooperatives and the use of biomass allowed increasing the share of renewable energy sources to 20% in 2023. It also helped reduce energy security costs by 10%. Ukraine can borrow the experience of the Netherlands in creating energy cooperatives, which will help increase energy autonomy at the local level. This is especially important for regions where there is a need to reduce dependence on centralised suppliers and encourage local development.

Sweden has successfully applied models of decentralised energy, in particular, in the use of local resources such as biomass (Lundmark *et al.*, 2021). The Swedish model is based on the principle that local resources can meet the energy needs of regions, reducing dependence on external energy sources and increasing the sustainability of the system. The use of biomass, agricultural waste, and other local resources allows Sweden to create efficient energy supply systems that meet the specific conditions of each region. This not only helps reduce greenhouse gas emissions but also encourages rural development by creating new jobs and supporting local businesses. Sweden has made substantial strides in introducing biomass as an energy source, increasing its share to 35% in total production. The introduction of new biomass combustion technologies has reduced CO_2 emissions by 25% over the past 10 years. The use of Swedish practices in processing biomass and agricultural waste for energy production is a promising path for Ukraine. This can reduce emissions, increase energy efficiency, and boost economic development in rural areas.

Energy cooperatives and decentralised energy models implemented in the Netherlands and Sweden represent valuable experience for Ukraine. The integration of these approaches can substantially improve the efficiency and sustainability of energy systems in Ukraine, ensure a more even distribution of energy resources, and promote the development of local communities. The use of local resources and the participation of communities in energy production can be important factors in improving energy security and stability in Ukraine.

In the context of the global transition to renewable energy and the growing demand for energy stability, energy storage technologies have become an important component of modern energy systems (Shram & Kachan, 2023). Japan and China are leaders in this area, and their achievements can serve as a guide for Ukraine, which seeks to reduce its dependence on traditional energy sources and ensure the stability of its energy system. Japan is one of the leading countries in the development of energy storage technologies. Japanese companies are actively investing in the latest battery systems that allow efficient storage and use of energy from renewable energy sources (Zhang *et al.*, 2021). One of the key technologies is the use of lithium-ion batteries, which provide high energy density and long service life.

Japanese developments in this area not only improve the efficiency of renewable energy use but also contribute to the stability of the energy system. They allow storing energy during periods of low consumption or excessive production and using it when consumption exceeds production. This helps reduce dependence on traditional energy sources and ensures an uninterrupted power supply. Japan is actively developing energy storage technologies. Large-scale batteries introduced after Fukushima can store up to 10 GW·hour of energy that helps stabilise the energy system. This reduces fluctuations in energy supply by 30%. Japanese energy storage technologies can be useful for Ukraine in the context of improving the stability of the energy system. Considering the Japanese experience will help reduce the risks associated with fluctuations in energy production from renewable sources and ensure the smooth operation of networks.

China is also actively investing in developing and producing high-capacity batteries (Fan *et al.*, 2021). The Chinese approach focuses on large-scale production and improvement of energy storage technologies. Chinese company Contemporary Amperex Technology Co. Limited is a global leader in the production of lithium-ion batteries used in electric vehicles and energy storage systems. China is a world leader in the development of large-scale energy storage batteries. Investment in this area allowed the country to install 30 GW of energy storage capacity in 2023. This reduced energy infrastructure costs by 15%. With a large amount of investment and technological innovation, China has the ability to provide high-quality batteries at competitive prices. This makes energy storage technologies more accessible to developing countries, including Ukraine. The introduction of Chinese technologies can help Ukraine create energy storage systems that will ensure a stable supply of electricity even in conditions of uneven production from renewable energy sources.

Energy storage technologies developed in Japan and China can substantially affect Ukraine's energy infrastructure. Japanese experience in the development of high-efficiency batteries and Chinese achievements in large-scale production of high-capacity batteries represent a substantial potential for improving the stability and efficiency of the Ukrainian energy system. Adapting and implementing these technologies can reduce dependence on traditional energy sources, ensure reliable electricity supplies, and contribute to the sustainable development of the country's energy sector.

In today's world, the growing emphasis on sustainable development and energy security forces countries to look for ways to reduce energy consumption and improve energy efficiency. France and South Korea are prime examples of countries successfully implementing energy efficiency programmes, and their experience can serve as a valuable guide for Ukraine in this direction. France is one of the European countries that actively implements energy efficiency programmes in both the construction sector and industry (Belaïd *et al.*, 2021). The French approach to energy efficiency is based on an integrated approach that includes regulations, financial incentives, and technological innovations. One of the main initiatives is the Plan Bâtiment Durable programme, which aims to reduce energy consumption in buildings through the introduction of new construction standards, modernisation of existing buildings, and the use of energy-saving technologies.

France also implements support programmes that promote the energy modernisation of industrial facilities, through the provision of subsidies and tax incentives for enterprises implementing energy-saving technologies. These initiatives not only reduce energy consumption but also energy costs and the negative impact on the environment. In France, energy efficiency programmes for buildings have reduced energy consumption by 20% in a number of new projects. This was achieved by introducing the latest thermal modernisation technologies, such as energy-saving windows and insulation. Ukraine can use the French experience to develop energy-efficient regulations and support innovations in industry and the construction sector. This will reduce energy consumption and increase the overall efficiency of using energy resources.

South Korea is another example of a country that is actively developing energy efficiency programmes (Park *et al.*, 2023). An important part of the Korean strategy is to provide subsidies and encourage the introduction of energy-saving technologies through various financial instruments, such as compensation programmes and tax breaks for companies implementing energy projects. Korea is also actively implementing energy efficiency technologies in construction and industry. In particular, the programmes promote the use of highly efficient heating and cooling systems, the introduction of modern energy management systems, and infrastructure modernisation. This allows reducing energy consumption at all levels, reducing the load on the energy infrastructure and energy costs. South Korea has introduced subsidies for energy-saving technologies, which has reduced energy costs by 18% in the industrial sector. The introduction of new accounting technologies has reduced the cost of energy resources by 10%. Ukraine can consider the experience of South Korea, which has made substantial progress in improving energy efficiency through financial incentives and technological innovations. The introduction of subsidies and compensations for energy-saving technologies will contribute to improving energy efficiency at the national level.

Reducing energy consumption and improving energy efficiency are critical aspects of ensuring energy security and sustainable development. The experience of France and South Korea in implementing energy efficiency programmes provides Ukraine with the opportunity to implement proven practices to achieve these goals. Learning and adapting these approaches can substantially improve a country's energy efficiency, reduce the burden on energy infrastructure, and promote sustainable development. Thus, innovative solutions, such as the integration of renewable energy sources, the introduction of smart networks, the development of energy storage technologies, energy decentralisation, and energy efficiency improvement, are critical to improving the energy system of Ukraine (Table 3).

These solutions will not only help ensure the stability and efficiency of the energy system but also contribute to the economic and environmental development of the country in the face of modern challenges.

Table 3. Key innovative solutions for improving the energy system of Ukraine

Innovative solution	Description	Advantages
RES integration	Introduction of solar, wind, and hydroelectric power plants	Reducing dependence on imported energy carriers, reducing CO_2 emissions
Smart networks	The use of digital technologies for monitoring and managing the energy network	Optimising energy distribution, reducing losses, and improving efficiency
Energy storage technologies	Introduction of battery systems and other storage technologies	Ensuring the stability of power supply, supporting renewable energy sources
Energy decentralisation	Creation of local energy cooperatives and independent energy sources	Improving energy security, involving communities in management
Improving energy efficiency	Introduction of new technologies in construction and industry to reduce energy consumption	Reduce overall energy consumption, reduce costs

Source: compiled by the authors on the basis of L. Mykhailova & O. Dumanskyi (2024)

Adaptation and implementation of international experience in the energy system of Ukraine can be a crucial factor in ensuring its sustainability, efficiency, and independence. Innovative solutions, such as renewable energy integration, smart grid development, energy decentralisation, energy storage, and energy efficiency improvement, can substantially change the energy landscape of Ukraine, making it more adaptive to modern challenges.

DISCUSSION

As a result of the analysis of innovative solutions for improving the energy system, it was determined that the integration of renewable energy sources is a key aspect for ensuring energy stability. The identified data confirm that the use of solar and wind power plants contributes to reducing dependence on traditional, imported energy carriers, and substantially reducing greenhouse gas emissions. This approach allows for a more sustainable energy environment and meets international environmental standards. However, it is also necessary to consider potential risks, such as instability in renewable energy production, which may affect the reliability of energy supply. This was also investigated by M. Farghali *et al*. (2023), where the results confirmed that the integration of renewable energy sources, such as solar and wind energy, reduces the negative environmental impact of traditional fuels by reducing emissions of polluting gases. However, RES can affect local ecosystems, for example, wind turbines can harm birds, and hydroelectric power plants can alter river ecosystems. It is important to conduct environmental assessments and take measures to minimise negative impacts. A study by S. Erdoğan *et al*. (2021) also showed that switching to renewable energy can substantially reduce dependence on traditional energy resources such as oil, gas, and coal. This not only reduces greenhouse gas emissions but also the economic dependence on imported fuels, which can improve the country's energy security. Notably, this transition also has economic advantages since renewable energy sources often have reduced operating costs compared to traditional sources. Despite the advantages of renewable energy sources, their integration into energy systems requires careful planning and investment in new technologies. The effectiveness of renewable energy sources may depend on the geographical location, climatic conditions, and level of infrastructure development (Stoliarov, 2024). In addition, it is necessary to consider potential environmental impacts, such as the need for backup systems to ensure the stability of energy supplies. Existing challenges can be overcome through innovations in energy storage technologies and improved management practices.

The second important aspect is the introduction of smart networks, which has been confirmed by the results of the study. Smart grid technologies allow managing energy flows more efficiently, reducing energy losses, and increasing overall system efficiency (Selvakumar *et al*., 2024). However, the implementation of such systems requires substantial investment and adaptation to the specific conditions of the Ukrainian market, which can be a challenge for large-scale implementation. M. Judge *et al*. (2022) concluded that the introduction of smart grids ensures the integration of modern technologies into energy systems to improve their efficiency and reliability. Smart networks use sensors, automated systems, and data analytics to monitor and manage electrical networks in real time. This allows optimising energy distribution, reducing the likelihood of supply disruptions, and improving response to changing consumption conditions. Key benefits include increased fault tolerance, the ability to integrate renewable energy sources, and improved load management. T. Ahmad & D. Zhang (2021) established that smart grids show high efficiency in reducing energy costs by being able to accurately measure and monitor energy consumption. They provide more precise control of electrical loads, which reduces energy costs and optimises the operation of generators. The use of data analytics is used to predict demand and adjust energy generation in accordance with the needs of consumers, which reduces the cost of maintaining excess capacity. These results support the above study, as they demonstrate the benefits of smart grids in reducing energy costs and improving system efficiency. They show that such networks optimise energy distribution, reduce costs, and improve the reliability of energy supply, confirming their role in ensuring economic and energy efficiency.

Energy storage technologies have also demonstrated their importance. Battery systems ensure a stable power supply, compensating for periods of low renewable energy production (Amidu *et al.*, 2023). The study results showed that such systems were successfully implemented in the Kyiv region, where they helped to save excess energy and ensure its availability during peak periods. Therewith, the cost of implementing and maintaining battery systems remains high, which requires additional funding and support from the state. A paper of Q. Wu *et al.* (2021) is notable, who also determined that energy storage technologies such as batteries, pumped storage stations, and systems based on new materials play a vital role in ensuring the stability of energy systems. They provide for storing excess energy obtained during periods of high generation or low consumption and its usage at times of peak load or shortage. This helps equalise fluctuations in renewable energy generation, such as wind and sun, which can be unstable. In turn, M. Hannan *et al.* (2021) concluded that battery systems have a substantial impact on ensuring the stability of power supply since they provide the ability to store and distribute energy depending on needs. These systems allow reducing the load on the network during peak consumer periods and provide backup energy sources in the event of interruptions. Batteries also facilitate the integration of renewable energy sources by loading the network during periods of high generation and unloading it during periods of low generation. These data are consistent with the theses presented in the previous section, as they confirm the critical role of energy storage technologies in ensuring the stability of energy systems. In particular, it is shown that battery systems effectively smooth out fluctuations in energy supply and help maintain a balance between generation and consumption. This confirms that increased use of such technologies can reduce dependence on traditional, less stable energy sources and improve the overall reliability of energy infrastructure.

Energy decentralisation, which was analysed in detail, also proved to be an effective tool for improving energy security. The creation of energy cooperatives and the development of local energy sources reduces dependence on centralised suppliers and ensures greater participation of local communities in the management of energy resources (Stepanov *et al.*, 2023). For example, in the Cherkasy region, implemented projects on energy cooperatives have demonstrated a positive impact on the energy independence and economic development of local communities. However, scaling up such initiatives requires a comprehensive approach to state funding and support. A. Berka & M. Dreyfus (2021) also conducted a study that confirmed that energy decentralisation involves the transition from centralised power supply systems to distributed models where energy resources are produced and managed locally. This can have a substantial social impact, in particular, contribute to improving the energy independence of the community, creating new jobs, and developing local economies. However, decentralisation can also lead to uneven access to new technologies and resources, especially in remote or economically weaker regions. M. Rabbi *et al.* (2022) also established that energy cooperatives play an important role in improving energy security through collective ownership and management of energy resources at the local level. Such cooperatives allow communities to invest together in renewable energy sources, such as solar or wind installations, and provide reliable energy supplies, especially in remote or poorly connected areas. It also helps reduce energy costs and increase resilience to energy crises. Comparing the data obtained in the course of the study, it can be argued that the decentralisation of energy and energy cooperatives substantially increases social and economic sustainability. Decentralised systems provide greater energy independence and create new jobs, improving the social structure. Energy cooperatives increase energy security by reducing costs and stabilising supplies, especially in remote regions. Data confirm that these models effectively contribute to development and stability but their success depends on equal access to new technologies.

Improving energy efficiency, as the results of the study showed, is crucial for reducing overall energy consumption. Projects for the thermal modernisation of buildings in large cities, such as Kyiv and Kharkiv, have confirmed that the latest technologies can substantially reduce the cost of heating and air conditioning, which has a positive impact on the economic situation and environmental balance. However, the successful implementation of such projects requires ensuring the appropriate level of qualification of performers and compliance with high quality standards. H. Sun *et al.* (2021) concluded that the latest technologies, such as intelligent energy management systems, high-performance thermal insulation materials, and state-of-the-art automation systems, play an important role in improving the energy efficiency of buildings and industrial processes. In particular, the introduction of intelligent control technologies allows optimising energy consumption in real time, reducing costs, and improving the overall efficiency of energy systems. Highly efficient materials and automation systems provide a substantial reduction in energy consumption for heating and cooling, which also has a positive impact on economic performance. R. Blazy *et al.* (2021) note that thermal modernisation, which includes updating thermal insulation, replacing old windows and doors, and improving heating and ventilation systems, has a substantial impact on overall energy consumption. It reduces heat loss and the need for energy for heating or cooling buildings. This, in turn, helps reduce energy costs and improve living comfort. When analysing the results of the study, it is clear that the latest technologies and thermal modernisation substantially increase energy efficiency. Intelligent control systems and efficient materials reduce energy consumption, resulting in economic and environmental benefits. Thermal modernisation also substantially reduces overall energy consumption and reduces costs, confirming its effectiveness in reducing heat loss and improving comfort.

In general, the results obtained highlight the need to integrate innovative solutions into all aspects of the Ukrainian energy system. Despite the positive trends demonstrated by various innovative approaches, there are substantial challenges associated with financing, technological adaptation, and state support. In the future, to achieve sustainable development of the energy system, it is necessary to continue research, improve existing solutions, and adapt them to the specific conditions of Ukraine.

CONCLUSIONS

A comparative analysis of international experience shows that the introduction of innovative solutions in the energy sector can substantially improve the efficiency and stability of energy systems. For Ukraine, where modernisation of energy infrastructure is critical, it is advisable to adapt successful practices from other countries, in particular, optimise networks, integrate renewable energy sources, and use modern energy storage technologies. This will ensure the sustainability of energy supplies and reduce energy infrastructure costs.

The integration of renewable energy sources, such as solar and wind power plants, has demonstrated its effectiveness in reducing dependence on traditional energy resources and reducing greenhouse gas emissions. The introduction of such technologies ensures environmental stability and meets international standards.

The study also confirmed the importance of smart grids for optimising energy distribution, reducing costs, and improving overall system efficiency. Energy storage technologies, including battery systems, contribute to the stability of the energy supply and help compensate for periods of low renewable energy production.

Decentralisation of energy, including the creation of energy cooperatives and the introduction of innovative technologies, has proven to be an important factor in improving energy security and engaging local communities. Improving energy efficiency through the latest technologies, such as the thermal modernisation of buildings and the use of energy-saving materials, has shown a positive impact on the overall reduction of energy consumption and lower energy costs.

However, the implementation of these innovative solutions in Ukraine requires additional investment and state support. An assessment of international experience shows that success in implementing innovative projects is possible when combining technical solutions with effective management and political initiatives. Thus, to ensure the sustainable development of the Ukrainian energy system, it is important to adjust international practices to the specific conditions of the country and provide the necessary support for the implementation of these solutions.

It is necessary to examine the effectiveness of integrating new technologies in the specific conditions of the regions of Ukraine, including economic and social aspects, to ensure their scalability and sustainability at the national level. A limitation of this study is the lack of a detailed analysis of the economic and social impacts of implementing innovative solutions in different regions of Ukraine, which may affect the overall accuracy of recommendations.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Ahmad, T., & Zhang, D. (2021). Using the internet of things in smart energy systems and networks. *Sustainable Cities and Society*, 68, article number 102783. doi: 10.1016/j.scs.2021.102783.

[2] Amidu, M.A., Ali, M., Alkaabi, A.K., & Addad, Y. (2023). A critical assessment of nanoparticles enhanced phase change materials (NePCMs) for latent heat energy storage applications. *Scientific Reports*, 13(1), article number 7829. doi: 10.1038/s41598-023-34907-0.

[3] Belaïd, F., Ranjbar, Z., & Massié, C. (2021). Exploring the cost-effectiveness of energy efficiency implementation measures in the residential sector. *Energy Policy*, 150, article number 112122. doi: 10.1016/j.enpol.2020.112122.

[4] Berka, A., & Dreyfus, M. (2021). Decentralisation and inclusivity in the energy sector: Preconditions, impacts and avenues for further research. *Renewable and Sustainable Energy Reviews*, 138, article number 110663. doi: 10.1016/j.rser.2020.110663.

[5] Blazy, R., Błachut, J., Ciepiela, A., Łabuz, R., & Papież, R. (2021). Thermal modernization cost and the potential ecological effect – Scenario analysis for thermal modernization in Southern Poland. *Energies*, 14(8), article number 2033. doi: 10.3390/en14082033.

[6] Butt, O.M., Zulqarnain, M., & Butt, T.M. (2021). Recent advancement in smart grid technology: Future prospects in the electrical power network. *Ain Shams Engineering Journal*, 12(1), 687-695. doi: 10.1016/j.asej.2020.05.004.

[7] Datta, U., Kalam, A., & Shi, J. (2021). A review of key functionalities of battery energy storage system in renewable energy integrated power systems. *Energy Storage*, 3(5), article number e224. doi: 10.1002/est2.224.

[8] Erdoğan, S., Çakar, N.D., Ulucak, R., Danish, & Kassouri, Y. (2021). The role of natural resources abundance and dependence in achieving environmental sustainability: Evidence from resource-based economies. *Sustainable Development*, 29(1), 143-154. doi: 10.1002/sd.2137.

[9] Fan, B., Wu, T., Zhuang, Y., Peng, J., & Huang, K. (2021). The development of energy storage in China: Policy evolution and public attitude. *Frontiers in Energy Research*, 9, article number 797478. doi: 10.3389/fenrg.2021.797478.

[10] Farghali, M., Osman, A.I., Chen, Z., Abdelhaleem, A., Ihara, I., Mohamed, I.M., Yap, P.-S., & Rooney, D.W. (2023). Social, environmental, and economic consequences of integrating renewable energies in the electricity sector: A review. *Environmental Chemistry Letters*, 21(3), 1381-1418. doi: 10.1007/s10311-023-01587-1.

[11] Fouladvand, J., Ghorbani, A., Sarı, Y., Hoppe, T., Kunneke, R., & Herder, P. (2022). Energy security in community energy systems: An agent-based modelling approach. *Journal of Cleaner Production*, 366, article number 132765. doi: 10.1016/j.jclepro.2022.132765.

[12] Fowlie, M., & Meeks, R. (2021). The economics of energy efficiency in developing countries. *Review of Environmental Economics and Policy*, 15(2), 238-260. doi: 10.1086/715606.

[13] Guertler, M.R., & Sick, N. (2021). Exploring the enabling effects of project management for SMEs in adopting open innovation – a framework for partner search and selection in open innovation projects. *International Journal of Project Management*, 39(2), 102-114. doi: 10.1016/j.ijproman.2020.06.007.

[14] Hannan, M.A., Al-Shetwi, A.Q., Begum, R.A., Ker, P.J., Rahman, S.A., Mansor, M., Mia, M.S., Muttaqi, K.M., & Dong, Z.Y. (2021). Impact assessment of battery energy storage systems towards achieving sustainable development goals. *Journal of Energy Storage*, 42, article number 103040. doi: 10.1016/j.est.2021.103040.

[15] Harguindéguy, J.B., & Wokuri, P. (2024). When politics determines policy success and failure. A comparison of offshore wind power in Denmark and Spain. *Journal of Comparative Policy Analysis: Research and Practice*, 26(5), 511-529. doi: 10.1080/13876988.2024.2372617.

[16] Ibrahim, R.L., Adebayo, T.S., Awosusi, A.A., Ajide, K.B., Adewuyi, A.O., & Bolarinwa, F.O. (2024). Investigating the asymmetric effects of renewable energy-carbon neutrality nexus: Can technological innovation, trade openness, and transport services deliver the target for Germany? *Energy & Environment*, 35(1), 185-206. doi: 10.1177/0958305X221127020.

[17] Judge, M.A., Khan, A., Manzoor, A., & Khattak, H.A. (2022). Overview of smart grid implementation: Frameworks, impact, performance and challenges. *Journal of Energy Storage*, 49, article number 104056. doi: 10.1016/j.est.2022.104056.

[18] Krug, M., Di Nucci, M.R., Caldera, M., & De Luca, E. (2022). Mainstreaming community energy: Is the renewable energy directive a driver for renewable energy communities in Germany and Italy? *Sustainability*, 14(12), article number 7181. doi: 10.3390/su14127181.

[19] Kumar, A., Sharma, S., Goyal, N., Singh, A., Cheng, X., & Singh, P. (2021). Secure and energy-efficient smart building architecture with emerging technology IoT. *Computer Communications*, 176, 207-217. doi: 10.1016/j.comcom.2021.06.003.

[20] Lamnatou, C., Chemisana, D., & Cristofari, C. (2022). Smart grids and smart technologies in relation to photovoltaics, storage systems, buildings and the environment. *Renewable Energy*, 185, 1376-1391. doi: 10.1016/j.renene.2021.11.019.

[21] Lazor, O., Zabolotnyy, A., & Zubar, I. (2024). The role of critical infrastructure in ensuring the state policy of food security in Ukraine. *Current Issues in Modern Science*, 22(4), 393-408. doi: 10.52058/2786-6300-2024-4(22)-393-408.

[22] Lundmark, R., Anderson, S., Hjort, A., Lönnqvist, T., Ryding, S.O., & Söderholm, P. (2021). Establishing local biogas transport systems: Policy incentives and actor networks in Swedish regions. *Biomass and Bioenergy*, 145, article number 105953. doi: 10.1016/j.biombioe.2020.105953.

[23] Meliani, M., Barkany, A.E., Abbassi, I.E., Darcherif, A.M., & Mahmoudi, M. (2021). Energy management in the smart grid: State-of-the-art and future trends. *International Journal of Engineering Business Management*, 13. doi: 10.1177/18479790211032920.

[24] Mykhailova, L., & Dumanskyi, O. (2024). Innovative technologies in green energy: Prospects and challenges. *Science and Technology Today*, 30(2), 899-909. doi: 10.52058/2786-6025-2024-2(30)-899-909.

[25] Panda, D.K., & Das, S. (2021). Smart grid architecture model for control, optimization and data analytics of future power networks with more renewable energy. *Journal of Cleaner Production*, 301, article number 126877. doi: 10.1016/j.jclepro.2021.126877.

[26] Park, J., Woo, J., & Jin, T. (2023). Assessing electricity reduction program under the presence of the other energy saving programs using quasi-experimental design: A case study of South Korea. *Energy Efficiency*, 16(3), article number 9. doi: 10.1007/s12053-023-10094-9.

[27] Rabbi, M.F., Popp, J., Máté, D., & Kovács, S. (2022). Energy security and energy transition to achieve carbon neutrality. *Energies*, 15(21), article number 8126. doi: 10.3390/en15218126.

[28] Sahoo, S., & Timmann, P. (2023). Energy storage technologies for modern power systems: A detailed analysis of functionalities, potentials, and impacts. *IEEE Access*, 11, 49689-49729. doi: 10.1109/ACCESS.2023.3274504.

[29] Selvakumar, R.D., Wu, J., & Alkaabi, A.K. (2024). Electrohydrodynamic acceleration of charging process in a latent heat thermal energy storage module. *Applied Thermal Engineering*, 242, article number 122475. doi: 10.1016/j.applthermaleng.2024.122475.

[30] Shahini, E., Fedorchuk, M., Hruban, V., Fedorchuk, V., & Sadovoy, O. (2024). Renewable energy opportunities in Ukraine in the context of blackouts. *International Journal of Environmental Studies*, 81(1), 125-133. doi: 10.1080/00207233.2024.2320021.

[31] Shao, Y., & Chen, Z. (2022). Can government subsidies promote the green technology innovation transformation? Evidence from Chinese listed companies. *Economic Analysis and Policy*, 74, 716-727. doi: 10.1016/j.eap.2022.03.020.

[32] Shram, O., & Kachan, Yu. (2023). Determination of appropriate energy storage devices in the power grids of industrial enterprises. *Journal of Kryvyi Rih National University*, 21(2), 52-59. doi: 10.31721/2306-5451-2023-1-57-52-59.

[33] Stepanov, D., Stepanova, N., Onykiienko, S., & Martynenko, V. (2023). Indicators of energy efficiency of public building. *Modern Technologies, Materials and Structures in Construction*, 20(1), 134-139. doi: 10.31649/2311-1429-2023-1-134-139.

[34] Stoliarov, O. (2024). Efficient electricity generation forecasting from solar power plants using technology: Integration, benefits and prospects. *Bulletin of Cherkasy State Technological University*, 29(1), 73-85. doi: 10.62660/bcstu/1.2024.73.

[35] Sun, H., Edziah, B.K., Kporsu, A.K., Sarkodie, S.A., & Taghizadeh-Hesary, F. (2021). Energy efficiency: The role of technological innovation and knowledge spillover. *Technological Forecasting and Social Change*, 167, article number 120659. doi: 10.1016/j.techfore.2021.120659.

[36] Treshchov, M. (2024). Modernization of the energy sector as a priority direction of the post-war reconstruction of Ukraine. *Scientific Bulletin: State Administration*, 1(15), 28-45. doi: 10.33269/2618-0065-2024-1(15)-28-45.

[37] Tuomela, S., de Castro Tomé, M., Iivari, N., & Svento, R. (2021). Impacts of home energy management systems on electricity consumption. *Applied Energy*, 299, article number 117310. doi: 10.1016/j.apenergy.2021.117310.

[38] Warbroek, B., Holmatov, B., Vinke-de Kruijf, J., Arentsen, M., Shakeri, M., de Boer, C., Flacke, J., & Dorée, A. (2023). From sectoral to integrative action situations: An institutional perspective on the energy transition implementation in the Netherlands. *Sustainability Science*, 18(1), 97-114. doi: 10.1007/s11625-022-01272-2.

[39] Wu, Q., He, T., Zhang, Y., Zhang, J., Wang, Z., Liu, Y., Zhao, L., Wu, Y., & Ran, F. (2021). Cyclic stability of supercapacitors: Materials, energy storage mechanism, test methods, and device. *Journal of Materials Chemistry A*, 9(43), 24094-24147. doi: 10.1039/D1TA06815F.

[40] Zhang, C., Wang, Z., Su, W., & Dalia, S. (2024). Differentiated power rationing or seasonal power price? Optimal power allocation solution for Chinese industrial enterprises based on the CSW-DEA model. *Applied Energy*, 353, article number 122150. doi: 10.1016/j.apenergy.2023.122150.

[41] Zhang, Z., Ding, T., Zhou, Q., Sun, Y., Qu, M., Zeng, Z., Ju, Y., Li, L., Wang, K., & Chi, F. (2021). A review of technologies and applications on versatile energy storage systems. *Renewable and Sustainable Energy Reviews*, 148, article number 111263. doi: 10.1016/j.rser.2021.111263.

Людмила Михайлова
Кандидат технічних наук, професор
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-3419-5446

Ольга Завитій
Кандидат економічних наук, доцент
Західноукраїнський національний університет
46009, вул. Львівська, 11, м. Тернопіль, Україна
https://orcid.org/0000-0001-7439-6923

Микола Горлачук
Кандидат економічних наук, доцент
Західноукраїнський національний університет
46009, вул. Львівська, 11, м. Тернопіль, Україна
https://orcid.org/0000-0001-8030-1193

Дарія Вільчинська
Кандидат сільськогосподарських наук, асистент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-3322-6722

Олег Кондратюк
Магістр, асистент
Західноукраїнський національний університет
46009, вул. Львівська, 11, м. Тернопіль, Україна
https://orcid.org/0009-0004-7054-5417

Пошук інноваційних рішень для вдосконалення енергетичної системи України: світовий досвід

Анотація. Це дослідження аналізує світовий досвід впровадження інновацій в енергетичній сфері для виявлення ефективних рішень, які можуть бути застосовані для вдосконалення енергетичної системи України. Методи дослідження включали порівняльний аналіз міжнародного досвіду в енергетичному секторі, оцінку можливостей адаптації інноваційних технологій до українських умов, а також дослідження технічних і економічних аспектів інтеграції нових рішень. У дослідженні було проаналізовано досвід таких країн, як Німеччина, Данія, США, Фінляндія, Нідерланди, Швеція, Японія, Китай, Франція та Південна Корея, які досягли успіху у впровадженні інноваційних рішень в енергетичній сфері, зокрема в інтеграції відновлюваних джерел енергії (ВДЕ), розвитку розумних мереж, децентралізації енергетики, технологій зберігання енергії та підвищення енергоефективності. Виявлено, що найефективніші підходи включають комплексне використання ВДЕ у поєднанні зі зберіганням енергії, що забезпечує стабільність енергопостачання навіть за умови нерівномірного виробництва електроенергії. Також підкреслено важливість розумних мереж для оптимізації розподілу енергії та зниження втрат. Децентралізація енергетики та розвиток енергетичних кооперативів сприяють підвищенню енергетичної безпеки та залученню громад. Дослідження також показало, що впровадження розумних систем управління енергією на рівні споживачів сприяє підвищенню гнучкості енергосистеми та ефективному реагуванню на коливання попиту. Крім того, виявлено, що успішна реалізація інноваційних проектів у енергетиці потребує підтримки держави через субсидії та регуляторні стимули. На основі світового досвіду зроблено висновок, що поєднання технічних рішень з ефективним управлінням та політичними ініціативами є ключовим для забезпечення сталого розвитку енергетичної системи України

Ключові слова: стабільність постачання; розумні мережі; децентралізація; моделі сталого розвитку; субсидії; політичні ініціативи