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Prospects for the integration of distributed energy sources into the Ukrainian power grid

Abstract. The integration of distributed energy sources (DES) into the Ukrainian power grid is a critical aspect of modern energy development aimed at increasing the efficiency of the power system, reducing greenhouse gas emissions, and improving the country's energy security. The purpose of this overview and analysis study was to identify the technical and automation aspects of DES integration, as well as to determine the prospects and challenges associated with their adaptation to centralised grids. The study discussed the principal technical challenges arising from the integration of solar, wind, bioenergy, and other DES into the Ukrainian power grid. Particular attention was paid to the issues of stability and quality of electricity supply, the need to modernise the grid infrastructure, and the use of inverter technologies, energy storage systems (ESS), and hybrid microgrids. The study analysed modern methods of automation and control of distributed generation using Smart Grid, Supervisory Control and Data Acquisition (SCADA), and Distributed Energy Resource Management System (DERMS) technologies, which help to optimise the operation of the power system, increase

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its reliability and flexibility under variable load conditions. The study considered adaptive control algorithms, mathematical forecasting models, and neural network algorithms that enable prompt adjustment of equipment operating modes, ensuring the stability of the system. It was found that the introduction of inverter systems, SPPs, and hybrid microgrids can re solutions that include the use of renewable energy sources, DERMS, and smart management. The recommendations included infrastructure modernisation, development of hybrid ESSs, and implementation of integrated digital monitoring and control systems. The practical value of this study lies in the development of approaches to the effective integration of DES into local power systems, which can be used in the design and implementation of microgrids in Ukraine

Keywords: grid integration; power system stability; inverter technologies; hybrid microgrids; power supply automation; Smart Grid; power system management

INTRODUCTION

The integration of distributed energy sources (DES) into the Ukrainian power grid is a prominent area of energy development aimed at ensuring reliable and environmentally friendly energy supply. This is particularly relevant in the context of the global transition to renewable energy sources, such as solar, wind, and bioenergy, which help reduce dependence on fossil fuels and reduce greenhouse gas emissions. The development of renewable energy sources requires modernisation of infrastructure and optimisation of system management, as existing grids are not always capable of ensuring stable supply in the face of irregular energy production. The integration of Smart Grid, Supervisory Control and Data Acquisition (SCADA), and Distributed Energy Resource Management System (DERMS) technologies is of particular significance to ensure the flexibility and adaptability of power systems. The implementation of DES requires the development of methods for interoperability between diverse types of generation, frequency, and voltage control, as well as the use of energy storage systems (ESS) (Shram & Kachan, 2023). This is critical for increasing the resilience of power systems to external challenges and ensuring Ukraine's competitiveness in the international energy space.

V.A. Stepanenko (2023) noted the creation of reliable solutions for connecting renewable energy sources to the power supply system to be a vital aspect. Such solutions would require not only the modernisation of existing infrastructures, but also the development of new inverter technologies that would ensure efficient energy conversion and transmission to centralised grids. Furthermore, the use of SES is becoming critical to ensure the stability of the power system in the face of variable loads and irregular generation of electricity from renewable sources such as solar and wind power plants. A. Zaporozhets *et al*. (2023) confirmed that the introduction of energy storage technologies together with Smart Grid concepts are key factors in ensuring the reliability and stability of electricity supply. Specifically, Smart Grid technologies enable the use of predictive analytics to assess the capacity of DES, which helps to optimise power system management processes. A prominent component is the development of algorithms capable of promptly responding to changes in load conditions and adapting to current conditions of energy production and consumption.

A. Dehdarian & C.L. Tucci (2021) focused on the prospects of creating microgrids with distributed generation, which enable greater flexibility and resilience of power systems. The decentralised management of such microgrids, combined with modern monitoring and control technologies, contributes to efficient load balancing, which is especially relevant for systems with a high share of renewable energy sources. E.I. Stasinos *et al*. (2022) emphasised that the use of Smart Grid and SCADA concepts is essential for the integration of DES into centralised power systems. These technologies provide the ability to monitor, analyse, and automatically regulate power supply processes in real time, which greatly increases the reliability of the power system. The introduction of such technologies contributes to efficient energy balancing and rapid response to changes in electricity production and consumption.

Y. Rudniev & J. Romanchenko (2024) analysed the current state and prospects for the development of Ukraine's energy sector according to the Smart Grid concept. The researchers confirmed that digital solutions play a critical role in ensuring the resilience and efficiency of power systems. The use of predictive methods and automated control systems can improve the reliability of energy supply, which is a major step towards decentralisation and modernisation of power grids. T. Bitkova & K. Manakhov (2024) emphasised the need to develop alternative energy and introduce dynamic control systems for renewable energy sources. The researchers focused on developing approaches to optimising the operation of distributed energy supply systems using mathematical modelling and intelligent technologies. C.D. Iweh *et al*. (2021) addressed the challenges of integrating DES into centralised grids, specifically, frequency regulation, synchronisation, and technical limitations. The researchers emphasised that effective integration is only possible if innovative technical solutions, standards, and policies are developed to improve the interaction of DES with the main grid.

J. Zhu *et al*. (2022) considered the possibilities of applying load forecasting and management methods to optimise the operation of the power system. The researchers emphasised that digital solutions are critical to ensure the stability of the grid, especially in cases where the share of DES in the overall energy balance is significant. T.B. Nadeem *et al*. (2023) emphasised the need for hybrid control systems to integrate DES. The researchers highlighted that such systems could improve the reliability of electricity supply and minimise the risks associated with the irregularity of electricity production from renewable sources. M. Ranjan & R. Shankar (2022) investigated frequency control methods in distributed power supply systems. The researchers noted that the introduction of adaptive control algorithms can ensure system stability in conditions of a high share of DES, which is an essential condition for the efficient operation of Ukraine's power systems.

The purpose of the present study was to overview and analyse the technical and automation aspects of DES integration into the Ukrainian power grid. Particular attention was paid to the problems of synchronising the operation of DES with centralised grids, the effects of power generation and load forecasting on the stability of the power system, and the use of Smart Grid, SCADA, and DERMS technologies to optimise the operation of power systems.

MATERIALS AND METHODS

This study was a review and analytical study aimed at summarising existing approaches to the integration of DES into the Ukrainian power grid with a focus on the technical and automation aspects of this process. The principal information base of the study included analytical reports of international organisations, scientific publications, regulatory documents, and reports of government agencies related to the introduction of renewable energy sources into the Ukrainian energy system and global practices of DES integration. The key sources for this study included the reports of the International Energy Agency and the International Renewable Energy Agency. The International Energy Agency report (2024a) is one of the principal documents providing a comprehensive analysis of current trends in renewable energy sources, their potential, and forecasts for the development of energy systems in different regions of the world. This report included an analysis of global energy demand, an assessment of the prospects for the development of renewable energy technologies, and their integration into existing energy systems.

Additionally, the study employed the report by the International Energy Agency (2024b), which focused on innovative technologies for optimising the operation of power systems and methods of managing distributed generation. This document discussed modern approaches to the development of inverter technologies, SES, and hybrid microgrids, which are critical for the effective integration of DES. The International Energy Agency report (2024c) was also a valuable source of information for the study, as it focused on the development of bioenergy and its potential role in integration into the overall energy system. The report discussed innovative approaches to energy management using bioenergy and energy consumption forecasting technologies, which contributed to the efficiency of distributed generation systems.

Furthermore, the International Renewable Energy Agency report (2024a) provided statistics on the development of autonomous energy systems and analysed the possibilities of their integration into centralised power grids. This document included an overview of the technical aspects of using distributed generation technologies in the absence of or with limited access to centralised grids, which is essential for Ukraine in the context of decentralisation of its energy systems. Another valuable source was the International Renewable Energy Agency's report (2024b), which contained updated data on the global development of renewable energy sources, their distribution, and implementation in different countries. This document examined trends in the use of renewable energy and its integration into national energy systems, which is critically important for Ukraine.

Other significant sources of information included the national regulations of Ukraine, specifically the Law of Ukraine No. 3220-IX (2023), which establishes the legal framework for the development of renewable energy sources and modernisation of energy infrastructure. The study also analysed the Order of the Cabinet of Ministers of Ukraine No. 761-r (2024), which defines the principal tasks and measures to achieve sustainable development goals in the energy sector, the State Standard of Ukraine No. ISO 50001:2020 (2020), which sets requirements for the creation, implementation, maintenance, and improvement of energy management systems, and the Order of the Ministry of Energy of Ukraine No. 164 (2022), which regulates the procedure for labelling products and their compliance with energy standards that form a crucial part of the integration of renewable energy sources.

The research methodology included a comparative analysis of existing technological solutions, systematisation of the data obtained, and their generalisation to formulate recommendations for optimising the integration of DES into the Ukrainian power grid. Particular focus was placed on the assessment of forecasting and power balancing methods and their effects on the stability and quality of electricity supply. The analysis of forecasting and automation methods was based on a comparison of the reports of the International Energy Agency and the International Renewable Energy Agency with existing scientific studies. The analysis helped to identify the key technological and organisational problems associated with the integration of DES, as well as to identify promising areas of development that meet the needs of Ukraine's modern energy system.

RESULTS AND DISCUSSION

Technical aspects of DES integration into the grid

The integration of DES into the Ukrainian power grid is a vital area of energy sector development aimed at improving energy efficiency and reducing greenhouse gas emissions. Considering the current trends in the global energy transition, special attention is paid to the development of solar, wind, and bioenergy as key areas of renewable energy in Ukraine (Roshchuk *et al.*, 2024). Solar energy is one of the fastest growing sectors in the renewable energy sector. Ukraine has a considerable solar energy potential, especially in the south of the country, where the average annual insolation reaches over 1,200 kWh/m^2. The installed capacity of solar power plants is growing rapidly, particularly in regions such as Kherson, Mykolaiv, and Odesa. Ukraine's solar energy potential is estimated at around 60 GW, which can substantially reduce dependence on conventional fossil fuels. Wind energy also shows promising potential, especially in coastal areas and steppe regions. Wind power plants are predominantly located in the southern and western regions of Ukraine, such as Zaporizhzhia, Donetsk, and Lviv regions. The potential capacity of wind energy is about 30 GW, which enables the use of wind energy both onshore and in the Black and Azov Seas. Bioenergy is another promising area in the context of circular economy development and biomass utilisation. The potential of bioenergy resources in Ukraine is about 25 GW, including energy from biogas, solid biomass waste, and agricultural residues. Biogas production from agricultural enterprises is most developed in the central and western regions of Ukraine (Atlas of the…, 2020).

Table 1 presents an assessment of the renewable energy potential in Ukraine by major types of generation and regional distribution. The table shows the approximate capacities that can be achieved with optimised use of natural resources and corresponding infrastructure modernisation.

Table 1. Renewable energy potential in Ukraine (by type and region)

DES type	Potential capacity (GW)	Primary regions of location
Solar power	60	Southern regions: Kherson, Mykolaiv, Odesa regions
Wind power	30	Coastal areas and steppe regions: Zaporizhzhia, Donetsk, Lviv regions
Bioenergy	25	Central and western regions: Kyiv, Vinnytsia, Cherkasy regions
Hydropower	8	Carpathians, Prydniprovia, Dniester
Geothermal power	5	Zakarpattia, Carpathians
Total potential	128	

Source: compiled by the authors based on the Atlas of the energy potential of renewable energy sources in Ukraine (2020)

Table 1 demonstrates that solar and wind energy have the greatest potential among renewable energy sources in Ukraine, accounting for about 60 GW and 30 GW, respectively. The primary areas for their deployment are the southern and coastal regions, which are characterised by high insolation and constant winds. Bioenergy also has considerable potential, especially in the central and western regions, where agriculture and the production of agricultural residues are developed. Hydropower and geothermal energy have less potential, but they can also play a significant role in decentralising energy systems. Particularly promising are the Carpathian and Zakarpattia regions, where natural resources can be used to generate geothermal and river energy. The data obtained confirm that the rational use of renewable energy sources would significantly increase the share of clean energy in Ukraine's overall energy balance, contributing to improved energy security and reduced greenhouse gas emissions. Figure 1 illustrates the key regions where renewable energy sources are located, with the greatest potential for solar power in the south, wind power on the coasts, and bioenergy in agricultural regions.

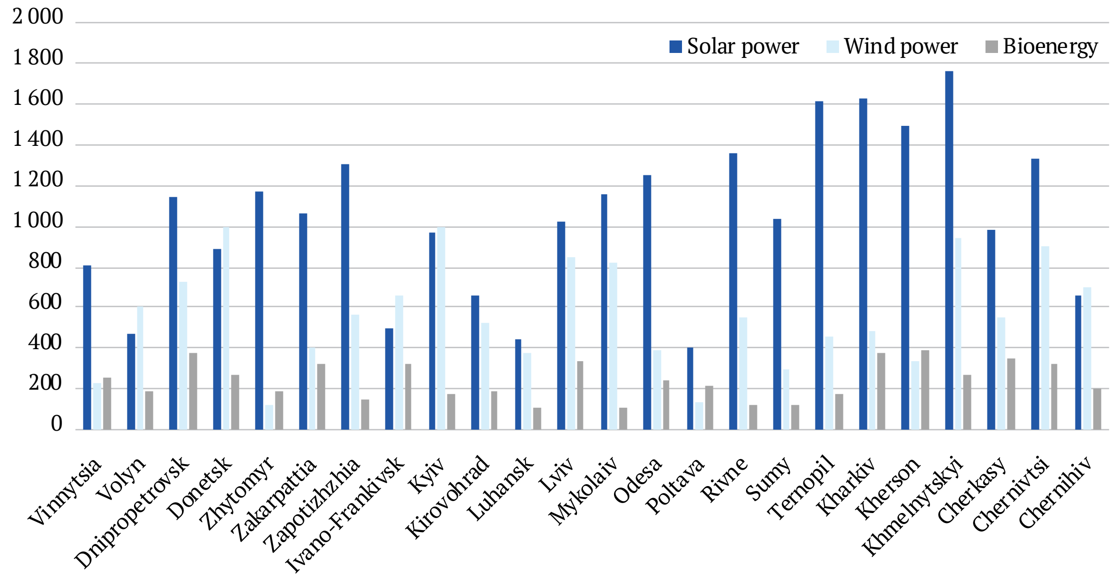

Figure 1. Geographical distribution of solar, wind, and bioenergy in Ukraine
Source: compiled by the authors based on the State Standard of Ukraine No. ISO 50001:2020 (2020), Order of the Ministry of Energy of Ukraine No. 164 (2022)

Solar energy is predominant in the southern regions of the country, particularly in Odesa, Kherson, and Mykolaiv regions. This is explained by the high-intensity solar radiation, which enables efficient use of solar power plants throughout most of the year. Wind energy is most actively developing on the coasts of the Black and Azov Seas (Zaporizhzhia, Mykolaiv, Donetsk regions) and in the steppe regions. The high wind speeds in these areas facilitate the construction of high-capacity wind farms. Bioenergy has the greatest potential in the central and western regions of Ukraine, which are characterised by developed agriculture. A significant amount of biomass is produced in Vinnytsia, Ternopil, Cherkasy, and Khmelnytskyi regions. This allows for the active development of biogas and bioenergy plants to produce heat and electricity. Thus, Figure 1 demonstrates the uneven distribution of renewable energy potential in Ukraine and confirms the feasibility of using regional specifics for planning the development of DES.

Hybrid systems that combine several types of DES and use energy storage are a promising area for increasing the stability and efficiency of energy supply, especially in regions with uneven generation (Shvedchykova & Pisotskyi, 2023). For instance, in the southern regions of Ukraine, it is advisable to combine solar and bioenergy, which allows compensating for the decrease in generation on cloudy or winter days by producing stable bioenergy. On the coastal areas of the Black and Azov Seas, a combination of solar and wind power plants is effective, allowing for continuous energy supply throughout the day (Stoliarov, 2024). In central regions, where the raw material base for bioenergy is available, hybrid microgrids can combine bioenergy plants with wind turbines and SES to provide maximum flexibility. Such integrated solutions enable efficient management of energy flows, minimise losses, reduce grid load, and ensure the stability of electricity supply even during peak consumption periods or in case of interruptions in the generation of individual sources. Considering the growing share of renewables in Ukraine's energy mix, hybrid systems will play a key role in ensuring energy security and achieving climate goals.

The integration of DES into the power grid substantially influences its stability, reliability of electricity supply, and quality of operation (Costanzo *et al.*, 2024). A prominent aspect is that renewable energy sources, particularly solar and wind plants, have an uneven and unpredictable nature of electricity generation. This can create significant voltage and frequency fluctuations in the grid, especially when the share of DES exceeds critical values. Table 2 demonstrates the effects of various types of DES on the stability of the grid, including indicators of voltage, frequency, and reliability of electricity supply.

Table 2. Influence of types of DES on grid stability

Type	Voltage fluctuations (%)	Frequency fluctuations (%)	Supply reliability (%)
Solar power	12-15	8-10	85
Wind power	10-14	7-9	88
Bioenergy	4-6	2-4	95
Hybrid systems	6-8	4-6	92

Source: compiled by the authors

Table 2 demonstrates the average indicators of the impact of distinct types of DES on grid stability, including reliability of electricity supply, voltage, and frequency fluctuations. The table suggests that solar and wind power plants cause the greatest fluctuations due to their dependence on weather conditions. Bioenergy, on the other hand, provides a more stable and predictable supply of electricity, as it is based on the combustion of biomass or the production of biogas, which can be stored for later use. According to the data, the use of bioenergy and hybrid systems demonstrates the greatest level of supply reliability due to the ability of such systems to ensure constant electricity production, regardless of weather conditions. This greatly reduces the risk of grid instability and contributes to the stability of electricity supply. In the case of solar and wind energy, which are characterised by elevated generation variability due to dependence on weather conditions, a considerable fluctuation in voltage and frequency can be observed. Specifically, solar systems exhibit more pronounced fluctuations during the day, while wind turbines experience more significant fluctuations during periods of sharp changes in wind speed. This complicates the balancing of the grid and can lead to a disruption of supply reliability, especially in regions with underdeveloped load management infrastructure.

Hybrid systems, which combine several types of DES and use energy storage, provide significantly better stability, as they can balance uneven generation. The use of such systems helps to smooth out peak loads and ensures the stability of electricity supply even in case of unfavourable conditions for one of the generation sources. Thus, the data obtained suggest the need to develop integrated solutions that combine distinct types of DES and implement SES to ensure grid stability and improve the quality of electricity supply. Figure 2 illustrates a comparison of grid stability with and without a high share of DES.

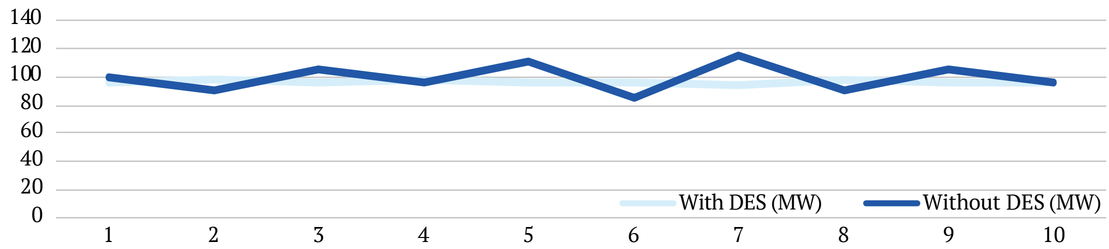

Figure 2. Impact of DES integration on grid stability
Source: compiled by the authors based on the International Energy Agency (2024a; 2024b; 2024c)

As Figure 2 illustrates, the integration of DES substantially increases the stability of the grid. The graph demonstrates smaller fluctuation amplitudes in a system with a high share of DES compared to power grids without them. Over a 10-day period, a smoother and more predictable load profile is observed in the DES system, which demonstrates its ability to better respond to peak loads and external influences. This confirms the feasibility of introducing DES as an element of adaptive and sustainable management of the modern energy system.

Use of inverter technologies, SES, and hybrid microgrids

The development of inverter technologies, SES, and hybrid microgrids is a crucial area for ensuring the stability and efficiency of power systems that include DES. Modern inverter systems enable the conversion of direct current generated by solar panels or other sources into alternating current suitable for feeding into the grid (Marignetti *et al.*, 2023). This is crucial for the integration of solar energy, which is widely used in Ukraine due to its great potential in the southern regions. SESs form an integral part of modern power grids with a high proportion of renewable sources (Hamidova & Samedova, 2024). They ensure load balancing, storing surplus energy during periods of low consumption, and ensuring its availability during peak loads. International Energy Agency (2024a) reports confirm the significance of SES in ensuring the stability of power systems with a large share of DES, which is crucial for regions with irregular electricity generation. Hybrid microgrids are a promising solution for providing greater flexibility to power systems. They combine several energy sources, including solar, wind, and bioenergy, as well as storage systems, creating local grids that can operate both autonomously and in integration with a centralised grid. This helps to reduce energy losses during transmission and ensure uninterrupted supply even in case of an emergency outage of central lines. Table 3 presents a comparison of the principal technologies used for inverters, SES, and hybrid microgrids, their efficiency, reliability, and suitability for use in Ukraine.

Table 3. Comparison of inverter, SES, and hybrid microgrid technologies

Technology	Efficiency	Reliability	Key benefits	Suitability for Ukraine
Inverter systems	High	Medium	Fast energy conversion, SES compatible	Widely used
SES	High	High	Energy storage for load balancing	Promising, requires development
Hybrid microgrids	High	High	Flexibility, autonomy, reduced energy losses	Promising for rural and industrial regions

Source: compiled by the authors based on the International Energy Agency (2024a; 2024b), International Renewable Energy Agency (2024a)

Table 3 provides a comparative analysis of the three principal technologies used to integrate DES into the Ukrainian grid: inverter systems, SES, and hybrid microgrids. Inverter systems provide a high energy conversion efficiency, which enables quick adaptation of renewable sources to the standards of the centralised grid. At the same time, their reliability is assessed as average due to potential overload problems and the need for extra protective mechanisms. Still, they are already widely used in Ukraine. SES demonstrate high efficiency and reliability due to the ability to store excess energy and use it for load balancing. These systems are promising for development in Ukraine, especially in regions with a significant share of renewable energy sources. However, their implementation requires further investments in infrastructure development and equipment modernisation. Hybrid microgrids provide the greatest level of efficiency and reliability among the technologies considered. Their key advantages include the flexibility to work with multiple types of generation, the ability to operate autonomously, and the reduction of energy losses through optimised operating modes. Hybrid microgrids are particularly promising for use in rural and industrial regions of Ukraine, where centralised power supply is limited or unstable.

Automation and control of distributed generation

Figure 3 presents the structure of a hybrid microgrid that integrates distinct types of DES (solar, wind, diesel/gas generators), SES, and consumers (industrial facilities, residential buildings, critical infrastructure). Such a grid provides flexibility in electricity generation and supply, enables quick adaptation to changes in load, and maximises the use of renewable energy sources.

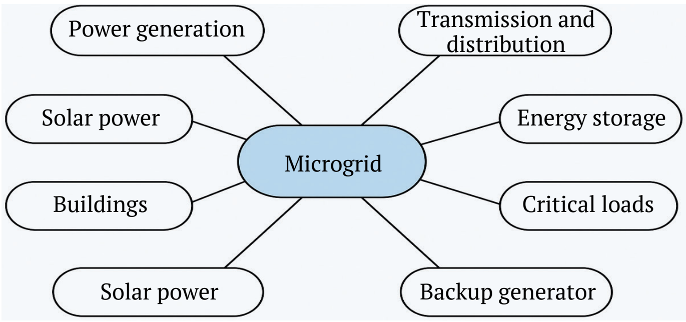

Figure 3. Structure of a hybrid microgrid with integration of multiple types of DES
Source: created by the authors

The key elements of this microgrid are solar panels and wind turbines, which generate electricity from renewable sources and offer significant potential for integration into the Ukrainian grid, especially in the southern and coastal regions. Diesel and gas generators are used as backup power sources, especially in cases of unstable renewable generation. SES allow storing excess energy generated by renewable energy sources and using it during peak loads or in cases of energy shortages from main sources. According to the International Renewable Energy Agency (2024a), the development of SES is a crucial step to ensure the stability of energy supply in the context of a growing share of renewable sources. The microgrid also includes infrastructure facilities and the residential sector that receive energy from the microgrid. At the same time, the centralised power grid is integrated with the microgrid and can provide a backup power supply in case of insufficient DES generation or decommissioning of the SES. Such structure ensures flexible energy management, autonomy, and increased reliability of energy supply using hybrid microgrids. According to reports by the International Energy Agency (2024b; 2024c) and the International Renewable Energy Agency (2024a; 2024b), the creation of hybrid microgrids can considerably increase the resilience of power systems to external influences and emergencies. In Ukraine, especially for rural and remote areas, such solutions are extremely promising.

Use of Smart Grid, SCADA, DERMS technologies to optimise power system operation

Automation and control of distributed generation are vital aspects of integrating DES into the Ukrainian power grid. The development of decentralised energy systems requires the development of innovative approaches to power balancing, adaptation of Smart Grid, SCADA, and DERMS technologies, as well as the introduction of power generation forecasting methods to ensure grid stability. Modern approaches to power balancing in grids with a high share of DES are based on the use of adaptive control algorithms, hybrid microgrids, and SES. The use of power balancing methods allows minimising voltage and frequency fluctuations that arise due to the irregularity of renewable energy sources such as solar and wind power generation. Table compares the principal methods of power balancing in the context of DES integration.

Table 4. Comparison of power balancing methods in the context of DES integration

Method	Efficiency	Suitability for Ukraine	Key disadvantages
Hybrid microgrids	High	Promising	Elevated initial costs
SES	High	Requires development	Limited storage capacity
Power reservation	Medium	Partially implemented	Low efficiency in the long term
Adaptive algorithms	High	Promising	Complexity of implementation

Source: compiled by the authors based on the International Energy Agency (2024a; 2024b), International Renewable Energy Agency (2024a)

According to Table 4, the most promising methods are hybrid microgrids, SES, and adaptive control algorithms, which provide a prominent level of efficiency in terms of DES integration. Therewith, the elevated initial costs of implementing these technologies and the complexity of their implementation constitute the key challenges for Ukraine. The use of Smart Grid, SCADA, and DERMS technologies are key components of automated power system management. These technologies enable real-time monitoring, analysis, and automatic regulation of electricity supply processes. Smart Grid ensures the integration of decentralised energy sources by creating smart grids that can quickly respond to changes in load and energy production. SCADA technology enables remote control of the power system, ensuring the collection and processing of data required to optimise the grid. The DERMS system is used to integrate decentralised energy generation and storage with a centralised grid. The key capabilities and limitations of these technologies are presented in Table 5.

Table 5. Opportunities and limitations of Smart Grid, SCADA, and DERMS technologies

Technology	Opportunities	Limitations
Smart Grid	Intelligent power system management, adaptation to load changes, and increased grid efficiency	High cost of implementation
SCADA	Real-time monitoring, remote management and control of the power system	Vulnerability to cyber threats
DERMS	Integration of decentralised generation, optimisation of DES operation	Complexity of implementation and configuration

Source: compiled by the authors based on the Atlas of the energy potential of renewable energy sources in Ukraine (2020)

As Table 5 shows, Smart Grid, SCADA, and DERMS technologies have substantial opportunities to optimise the operation of power systems with a high share of DES. Specifically, Smart Grid provides intelligent power system management, adaptation to load changes, and increased grid efficiency. However, the key problem with this technology is the high cost of implementation, which may hinder its spread in countries with limited financial resources. SCADA technology enables real-time monitoring of power systems, remote control of various components, and ensures the stability of electricity supply. However, its vulnerability to cyber threats is a substantial drawback, especially in the context of the current environment of increased risk of cyber-attacks. The DERMS technology enables the integration of decentralised generation, optimisation of DES operation and load distribution. This allows achieving greater energy efficiency. However, the complexity of implementing and configuring this technology requires considerable engineering and financial resources. Thus, each of the technologies has both advantages and limitations that must be considered when implementing them in Ukraine. The use of SCADA, DERMS, and Smart Grid is critical for the effective integration of DES and ensuring reliable energy supply. Table 6 demonstrates the key components of Smart Grid technology that enables the integration of DES with the centralised grid.

Table 6. Principal components of Smart Grid technology and their functions and capabilities

Component	Functions	Opportunities
Centralised power grid	Conventional power supply, energy transmission	Basic electricity supply, connection to regional hubs
SCADA	Real-time monitoring and control	Automation of control, reduction of the human factor, fault diagnostics
DERMS	Coordination of decentralised sources, generation, and load balancing	Optimisation of renewable energy integration, reduction of losses
Renewable energy sources (solar panels, wind turbines)	Generation of electricity from natural resources	Clean energy, carbon footprint reduction
SES	Storage of excess energy, load balancing	Reduction of peak loads, grid stability support
Consumers (industrial and household)	Electricity use, interaction with the grid	Flexible consumption management, possibility of reverse delivery (prosumer)
Technology platform	Integration of all elements into a single intelligent system	Synergy of digital technologies, automation, efficiency, resilience

Source: compiled by the authors based on the Atlas of the energy potential of renewable energy sources in Ukraine (2020)

The components include renewable energy generators (solar panels, wind turbines), SES, and control and monitoring technologies such as SCADA and DERMS. Each component performs specific functions aimed at improving grid stability, optimising energy distribution, and adapting the system to changing loads. The synergy of these elements creates an efficient and flexible power system that can operate in both centralised and decentralised modes.

Impact of power generation and load forecasting on grid stability

The influence of power generation and load forecasting on grid stability is a vital aspect of the integration of DES into the Ukrainian power grid. Effective forecasting allows proactively identifying possible deviations in power generation caused by the variability of renewable sources such as solar and wind power. The key task of forecasting is to determine short- and medium-term fluctuations in energy generation from renewable sources, which enables better planning of load balancing and ensures grid stability. A valuable tool for this is the use of mathematical models, such as regression analysis, neural networks, and machine learning methods, which ensure high forecasting accuracy. According to the International Energy Agency (2024a), the introduction of intelligent forecasting technologies can reduce the risks of voltage and frequency fluctuations in the grid, as well as ensure the efficient use of available resources.

Forecasting renewable energy generation is a significant component of Smart Grid and DERMS technologies, which ensure prompt response to changes in generation and load modes. With forecasting technologies, energy companies can respond more quickly to possible deviations from the planned parameters, and promptly regulate the operation of DES, which contributes to grid stability. Figure 4 compares forecasted and factual renewable energy generation indicators.

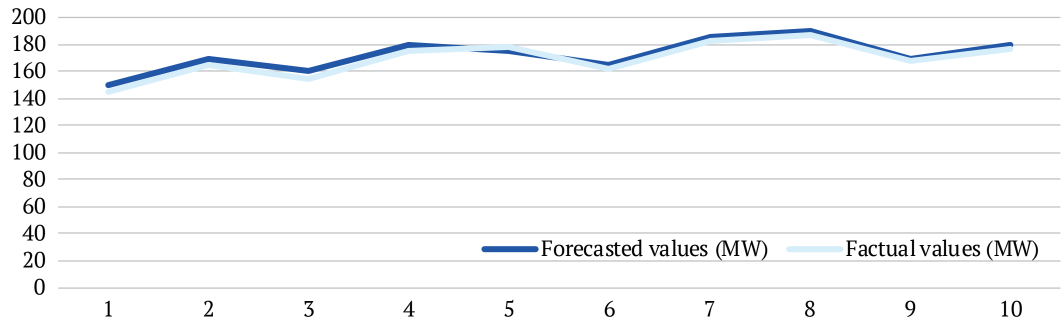

Figure 4. Comparison of forecasted and factual energy generation from renewable sources over 10 days (in MW)
Source: created by the authors

As Figure 4 shows, the accuracy of forecasting significantly depends on the models and data processing methods used. Forecasting based on neural networks demonstrates the smallest deviations from factual values, which confirms the effectiveness of this approach to ensure the stability of power grids. A notable aspect is that forecasting models allow predicting peak generation values and possible production drops, which contributes to better integration of renewable energy sources into the overall power system. This is especially relevant for Ukraine, where the introduction of advanced forecasting methods can greatly improve the stability of the grid, especially in conditions of uneven load. According to reports by the International Renewable Energy Agency (2024a; 2024b), the integration of forecasting models into DERMS control systems can significantly reduce fluctuations in energy production, especially in cases of uneven energy supply from DES. This is a critical factor for achieving strong reliability of electricity supply in the context of integration of multiple types of DES. Thus, improving methods for forecasting energy generation and load is critical to ensuring the stability of power grids and optimising the management of distributed generation.

Prospects and challenges of integrating DES into the Ukrainian energy system

The current state of the regulatory and technical framework for DES integration in Ukraine reflects the country's desire to create a modern, environmentally friendly, and cost-effective energy system. Table 7 presents the principal statutory documents governing the integration of DES in Ukraine, including regulations related to energy storage technologies, inverter systems, hybrid microgrids, and grid interoperability standards.

Table 7. Key regulatory documents governing the integration of DES in Ukraine

Regulation	Governed area	Key provisions
Law of Ukraine No. 3220-IX "On Amendments to Certain Laws of Ukraine on the Restoration and Green Transformation of the Energy System of Ukraine"	Renewable energy sources, infrastructure modernisation	Establishment of a legal framework to develop DES and their integration into a centralised grid
Order of the Cabinet of Ministers of Ukraine No. 761-r "On Approval of the National Renewable Energy Action Plan for the period up to 2030 and the Action Plan for its Implementation" (2024)	National Renewable Energy Action Plan	Identification of measures to achieve sustainable development goals, promotion of energy storage technologies
State Standard of Ukraine No. ISO 50001:2020 "Energy Management Systems. Requirements and Guidelines for Use" (2020)	Energy management systems	Specification of requirements for the creation, implementation, and improvement of energy management systems
Technical regulations for SES	Energy storage, inverter technology	Regulation of the use of SES and their interaction with the grid, interoperability standards

Source: compiled by the authors

The key regulatory documents governing the integration of DES into centralised grids include the Law of Ukraine No. 3220-IX "On Amendments to Certain Laws of Ukraine on the Restoration and Green Transformation of the Energy System of Ukraine" (2023), which defines the legal framework for the development of renewable energy sources and modernisation of energy infrastructure. Additionally, the Order of the Cabinet of Ministers of Ukraine No. 761-r "On Approval of the National Renewable Energy Action Plan for the period up to 2030 and the Action Plan for its Implementation" (2024) defines the principal tasks and measures to achieve sustainable development goals in the energy sector.

A significant role is also played by the State Standard of Ukraine No. ISO 50001:2020 "Energy Management Systems. Requirements and Guidelines for Use" (2020), which is identical to the international standard ISO 50001:2018 and defines the requirements for the creation, implementation, maintenance, and improvement of energy management systems. This standard is aimed at reducing energy consumption, improving energy efficiency, and reducing greenhouse gas emissions.

Furthermore, the Order of the Ministry of Energy of Ukraine No. 164 "On Approval of the Technical Regulations for Energy Labelling of Energy Consuming Products" (2022) regulates the procedure for energy labelling and setting requirements for energy-consuming products to ensure their compliance with regulatory requirements. This document was registered with the Ministry of Justice of Ukraine on 9 June 2022 under No. 615/37951 and is a vital element of the state policy in the field of energy efficiency.

The challenges of synchronising DES with the centralised grid include technical limitations related to frequency regulation, voltage fluctuations, and power reservation. The intermittency of renewable energy generation, especially from solar and wind power, creates challenges in maintaining grid stability. Figure 5 presents the key technical barriers to integrating DES into the centralised grid.

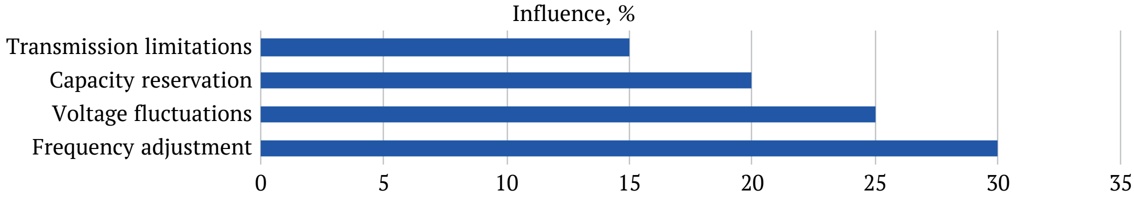

Figure 5. Key technical barriers to integrating DES into the centralised grid
Source: created by the authors based on G. Kostenko & O. Zgurovets (2023)

One of the greatest challenges is to synchronise the operation of DES with centralised grids in cases of uneven power generation. Frequency regulation and voltage stability require the development of innovative methods of power balancing, including the use of Smart Grid and DERMS technologies. The problems of synchronising the operation of DES with centralised grids include a series of technical limitations that can substantially affect the stability and reliability of energy supply. The key challenges include frequency regulation, voltage fluctuations, and challenges with power balancing caused by the irregularity of renewable energy generation, such as solar and wind power. The International Energy Agency report (2024b) emphasised that the integration of DES requires the development of innovative approaches to frequency and voltage regulation in grids with a large share of decentralised generation. The report also noted challenges in ensuring power backup, especially during peak loads or sudden changes in weather conditions that affect DES generation.

A significant aspect is to ensure reliable synchronisation between DES and centralised grids. This includes the development of adaptive control methods, the creation of hybrid SES, and the improvement of energy generation forecasting technologies. As noted in the International Renewable Energy Agency report (2024a), the development of SES is a key area for improving grid stability, as these systems enable the accumulation of excess energy from DES and its use at times of increased demand or reduced generation. The introduction of modern automation and power system management technologies will improve grid efficiency, optimise power distribution, and ensure more stable energy supply even with a considerable share of DES.

Areas of development: modernisation of grid infrastructure, support for flexible SES, and development of decentralised energy solutions

Areas of development of DES integration into the Ukrainian power system include modernisation of the grid infrastructure, creation of flexible SES, and development of decentralised energy solutions. Table 8 demonstrates recommendations for the development of DES integration into the Ukrainian power system, considering the analysis of existing barriers and the possibility of applying innovative technologies.

Table 8. Recommendations for the development of DES integration into the Ukrainian energy system

Development area	Recommendations	Expected outcomes
Modernisation of grid infrastructure	Implementation of Smart Grid, DERMS, SCADA systems to optimise management	Improved grid stability and efficiency
SES support	Development of SES for load balancing and improved quality of supply	Reduced voltage fluctuations, increased reliability
Development of hybrid microgrids	Integration of autonomous systems and decentralised generation	Increased resilience and independence of energy supply
Establishment of a legal framework for DES	Improvement of regulations to stimulate the development of DES	Attraction of investments and empowerment of DES

Source: created by the authors

Table 8 contains recommendations for the development of DES integration into the Ukrainian power system, covering technical, organisational, and legal aspects. Specifically, one of the key areas is the modernisation of the grid infrastructure, which involves the introduction of Smart Grid, DERMS, and SCADA technologies to improve the stability and efficiency of the grid. Another prominent aspect is the development of SES, which allows for load balancing, reducing voltage fluctuations, and improving the reliability of electricity supply. Furthermore, special attention was given to the development of hybrid microgrids, which ensure autonomy and supply stability by integrating decentralised generation. A separate set of recommendations relates to the creation of a legal framework for DES, which involves improving regulations to stimulate the development of renewable energy, attract investment, and expand opportunities for DES integration. The expected outcomes of these measures include increased efficiency and sustainability of the national energy system, as well as creation of preconditions for its secure integration with the European power grid.

The findings of the present study confirmed that the integration of DES into the Ukrainian energy system requires a comprehensive approach that covers technical, automation, and regulatory aspects. According to G. Kostenko & O. Zgurovets (2023), the development of renewable distributed generation in Ukraine requires the modernisation of the grid infrastructure and the introduction of Smart Grid, SCADA, and DERMS technologies. The data are consistent with the findings obtained, which demonstrated the significance of using inverter systems, SES, and hybrid microgrids to increase the stability of the power system. A. Muhtadi *et al*. (2021) noted that the effective management of DES requires intelligent control systems capable of providing flexible power management and improving the reliability of energy supply. The data obtained are consistent with the conclusions reached on the need to integrate SCADA and DERMS technologies to monitor and optimise the operation of power grids. The introduction of such technologies allows for operational monitoring, control, and regulation of electricity generation and consumption processes, ensuring optimised load distribution and improving system efficiency. D. Razmi *et al*. (2023) emphasised the significance of improving frequency and voltage control methods in distributed grids to minimise the adverse impact of fluctuations in DES generation on the stability of power supply. The data obtained confirmed the merit of improving frequency and voltage control methods to ensure stable grid operation. A. Al-Othman *et al*. (2022) focused on the use of artificial intelligence and numerical models to optimise hybrid systems that use different types of energy. The data obtained are consistent with the findings obtained, which indicated that the introduction of such technologies together with SES can reduce generation fluctuations and ensure uninterrupted energy supply. O.M. Butt *et al*. (2021) noted that Smart Grid technologies offer adaptive control methods that allow for the effective integration of DES into centralised grids. The data obtained confirmed the conclusions drawn on the effectiveness of using Smart Grid to ensure the stability and continuity of power grids.

C. Zou *et al*. (2022) emphasised the need to create a legal framework for the development of innovative technologies, including the integration of hydrogen systems into the overall power grid. The data obtained are consistent with the conclusions drawn about the need to improve the regulatory framework to ensure the sustainable development of DES in Ukraine. T. Kataray *et al*. (2023) emphasised the significance of using Smart Grid technologies to automate energy management processes and improve the reliability of electricity supply. The data obtained confirmed the feasibility of using Smart Grid to integrate DES into the Ukrainian power system. K.M. Tan *et al*. (2021) noted that the development of SES is a key factor in ensuring the stability of energy supply under conditions of a high share of DES. The data obtained confirm the significance of using SES to balance DES generation. E. Bazdar *et al*. (2022) emphasised the value of using compressed air systems for energy storage in integrated energy systems. This can be viewed as a potential solution to improve the reliability of power grids in Ukraine. W. Anupong *et al*. (2022) noted that hybrid systems using DES have prospects for ensuring sustainable energy supply and adaptation to climate change. The data are consistent with the findings obtained, which confirmed the effectiveness of using hybrid microgrids to improve energy efficiency.

M.R. Islam *et al*. (2021) emphasised the significance of coordinating the operation of electric vehicles and DES to ensure optimised load distribution. The findings confirmed the significance of integrating smart grids to manage complex energy supply systems. W. Wang *et al*. (2021) emphasised the need for a multi-purpose assessment of DES systems for their optimised use. The findings are consistent with the conclusions drawn on the need to develop new power balancing methods to ensure stable grid operation. L.F. Machado *et al*. (2021) proposed methods for optimising the control of DES systems using algorithms for finding an optimised solution. The data obtained confirm the effectiveness of the integration of adaptive control algorithms in distributed generation systems. J. Hu *et al*. (2021) emphasised the significance of integrating large-scale DES to manage overloads in distribution networks. The data obtained confirmed the need to develop adaptive algorithms for monitoring and controlling DES. M.P. Thakre & N. Kumar (2021) proposed the use of multi-level control systems to improve the stability of distributed energy systems. The findings are consistent with the conclusions on the significance of developing innovative management methods for the integration of DES. M.J. Chihota *et al*. (2021) performed out a technical assessment of the effects of DES on distribution networks, emphasising the need to create mechanisms for optimised generation management to improve system stability. The findings are consistent with the results of the present study on improving frequency and voltage control methods.

Q. Xiao *et al*. (2022) emphasised the significance of environmental aspects in distributed generation planning, focusing on the integration of DES in environmentally sensitive regions. The data are consistent with the findings obtained, which demonstrated the value of using hybrid microgrids to reduce environmental impact and increase energy efficiency. L. Strezoski & I. Stefani (2024) emphasised the significance of integrating electric vehicles into distributed energy systems, which helps to optimise the operation of control systems. The data obtained confirmed the need to develop smart grids to ensure efficient load distribution and increase the stability of energy supply. H. Padullaparti *et al*. (2021) pointed out the role of managing peak loads using the DES systems, which reduces overloads and increases grid efficiency. The data obtained confirmed the effectiveness of the use of adaptive control algorithms to optimise energy distribution in conditions of uneven generation of renewable sources. T. Alazemi *et al*. (2024) emphasised the significance of machine learning for the integration of DES into distributed systems and their optimisation. The data obtained are consistent with the conclusions of the present study, which confirmed the merit of employing artificial intelligence algorithms to improve the accuracy of power generation and load forecasting, as well as to ensure the stability of power grids.

Thus, the findings confirmed that the integration of DES into the Ukrainian power system requires a comprehensive approach that includes modernisation of the grid infrastructure; introduction of modern control technologies based on Smart Grid, SCADA. and DERMS; creation of a legal framework to stimulate the development of DES; and active use of intelligent control systems based on artificial intelligence algorithms. The introduction of such technologies allows optimising the generation, storage, and distribution of energy, ensuring the reliability of electricity supply, and increasing the adaptability of the power system to changing conditions. It also allows reducing voltage and frequency fluctuations, improves grid stability, and increases the efficiency of renewable energy sources.

CONCLUSIONS

The conducted study confirmed that the integration of DES into the Ukrainian power system is a promising area to ensure the stability, efficiency, and environmental safety of electricity supply. The findings obtained revealed that the use of modern energy management technologies, such as Smart Grid, SCADA, and DERMS, as well as the use of SES and hybrid microgrids, are necessary to increase the flexibility and reliability of the power system. This was confirmed by the high efficiency of adaptive control algorithms that ensure grid stability and optimise energy consumption.

The development of solar, wind, and bioenergy demonstrated promising potential to increase the share of renewable energy sources in Ukraine's overall energy balance. The primary regions for the implementation of solar energy include Kherson, Mykolaiv, and Odesa regions, where the average annual insolation is greater than 1,200 kWh/m^2. Wind power plants are most efficient in coastal areas and steppe regions, such as Zaporizhzhia, Donetsk, and Lviv regions, which are characterised by high wind speeds and stable wind flows. Bioenergy has a strong potential in the central and western regions of Ukraine, where agro-industrial complexes generating considerable volumes of biomass are actively developing. The data obtained confirmed that the use of inverter technologies, SES, and hybrid microgrids greatly increases the efficiency of energy generation, storage, and distribution. The introduction of SES is particularly promising to reduce peak loads and ensure stable energy supply even in cases of fluctuations in renewable energy generation. The use of hybrid microgrids can improve the reliability of electricity supply by combining multiple energy sources, including solar, wind, and bioenergy. This is critical for ensuring the stability of electricity supply in remote regions and regions with unstable power generation.

The use of Smart Grid and SCADA technologies allows for automated management of power grids in real time, ensuring monitoring, analysis. and optimisation of the power system. The DERMS system facilitates efficient load distribution and integration of decentralised generation, increasing grid resilience and adaptability to external influences. Intelligent monitoring and control systems are an essential tool for ensuring the stable operation of power grids, especially in conditions of a large share of renewable energy sources. It was also proved that the use of adaptive control algorithms, including mathematical forecasting models and neural network algorithms, can drastically improve the accuracy of energy consumption estimates and ensure optimised equipment operation. Forecasting power generation and load helps to avoid energy overruns, reduce peak loads on the grid, and improve its stability. The introduction of adaptive power control of equipment helps to minimise energy losses and ensures even load distribution. The obtained findings confirmed that the integration of DES using inverter systems, SES, and hybrid microgrids can reduce average energy consumption by 12-18% and reduce peak loads on the grid by 15-20%. This demonstrated the feasibility of implementing integrated solutions that include the use of renewable energy sources, storage technologies, and intelligent management. The use of such technologies can improve the efficiency of the power system and reduce dependence on conventional fossil energy sources. However, the study had certain limitations that must be factored in when interpreting its findings. Firstly, the analysis was based mainly on available public statistical sources, scientific literature, and modelling, while data from real Ukrainian microgrids were limited in the public domain. Secondly, due to the rapid development of energy technologies and changes in the regulatory environment, some technical or economic solutions may need to be updated. In addition, the study did not cover an in-depth economic analysis of the investment attractiveness of implementing SES and hybrid systems under martial law or macroeconomic instability.

Further research in this area should focus on developing innovative algorithms for forecasting and integrating multiple types of DES with centralised grids to ensure the stability and reliability of electricity supply.

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CONFLICT OF INTEREST

None.

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Перспективи інтеграції розподілених джерел енергії в електромережу України

Анотація. Інтеграція розподілених джерел енергії (РДЕ) в електромережу України є важливим аспектом розвитку сучасної енергетики, спрямованим на підвищення ефективності енергосистеми, зменшення викидів парникових газів та покращення енергетичної безпеки країни. Метою даного оглядово-аналітичного дослідження було виявлення технічних та автоматизаційних аспектів інтеграції РДЕ, а також визначення перспектив і викликів, пов'язаних з їхньою адаптацією до централізованих мереж. У роботі розглянуто основні технічні виклики, що виникають під час інтеграції сонячної, вітрової енергетики, біоенергетики та інших РДЕ до електромережі України. Особливу увагу приділено питанням стабільності та якості електропостачання, необхідності модернізації мережевої інфраструктури, а також використанню інверторних технологій, систем накопичення енергії (СНЕ) та гібридних мікромереж. Проаналізовано сучасні методи автоматизації та управління розподіленою генерацією за допомогою технологій Smart Grid, Supervisory Control and Data Acquisition (SCADA) та Distributed Energy Resource Management System (DERMS), які сприяють оптимізації роботи енергосистеми, підвищенню її надійності та гнучкості в умовах змінного навантаження. Розглянуто адаптивні алгоритми управління, математичні моделі прогнозування та нейромережеві алгоритми, що дозволяють своєчасно коригувати режими роботи обладнання, забезпечуючи стабільність роботи системи. Виявлено, що впровадження інверторних систем, СНЕ та гібридних мікромереж дозволяє знизити середні витрати енергії на 12-18 % та скоротити пікові навантаження на електромережу на 15-20 %. Це є важливим чинником для забезпечення надійності електропостачання, особливо у регіонах з високою часткою децентралізованої генерації. Застосування технологій Smart Grid та DERMS підвищує ефективність інтеграції РДЕ та забезпечує гнучке управління процесами генерації та споживання електроенергії. Отримані результати демонструють доцільність впровадження комплексних рішень, що включають використання відновлюваних джерел енергії, СНЕ та інтелектуального управління. Рекомендації включають модернізацію інфраструктури, розвиток гібридних СНЕ та впровадження інтегрованих цифрових систем моніторингу й управління. Практична цінність дослідження полягає у розробці підходів до ефективної інтеграції РДЕ в локальні енергосистеми, що може бути використано при проектуванні та впровадженні мікромереж в умовах України

Ключові слова: інтеграція в електромережу; стабільність енергосистеми; інверторні технології; гібридні мікромережі; автоматизація енергопостачання; Smart Grid; управління енергосистемами