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Decentralised generation and its role in enhancing the resilience of energy islands and critical infrastructure: Current trends and prospects

Vitalii Voitenko*

Postgraduate Student
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0009-0005-0107-8357

Roman Polishchuk

Postgraduate Student
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0009-0009-0356-0226

Abstract. Threats to critical infrastructure have heightened the relevance of autonomous energy supply and facilitated the transition to decentralised solutions. The study aimed to analyse the theoretical foundations of decentralised generation, its application in energy islands to enhance the resilience of critical infrastructure under emergency conditions. The methodological framework of the research included a theoretical synthesis of contemporary scientific approaches, real-world case studies of renewable technology development and autonomous energy supply models in the US, EU, and Ukraine, as well as a comparative analysis of autonomous energy supply models. The results demonstrated that solar and hybrid (solar-biogas) systems proved most effective. In Ukraine, over 5,000 residential solar installations were deployed in 2023, while in the village of Nyzhniy Bystryy (Zakarpattia), a hybrid energy island supplied electricity to 120 households. In the US, solar generation increased by 16% in 2023, with a 40% growth recorded in 2024. In the EU, the average levelised cost of solar electricity production decreased by 12% in 2023. In Tuscany (Italy), an energy island restored power supply within 12 hours in 2022 compared to 72 hours in the centralised system. In Ukraine, decentralised generation reduced recovery time to 3-6 hours in frontline regions (versus 12-18 hours traditionally), with electricity costs at 0.08 USD/kWh compared to 0.12 USD/kWh in the centralised system. The study revealed that decentralised generation enhanced grid flexibility and resilience by reducing transmission losses (up to -10%) and diversifying supply sources. Innovative technologies (digital control, artificial intelligence) were found to improve dispatching efficiency, enabling energy islands and microgrids to autonomously power critical facilities even during total grid collapse. The practical significance of the research lies in applying its findings to energy security strategies, microgrid development, and planning autonomous systems in vulnerable regions

Keywords: renewable energy sources; system autonomy; solar power; wind turbines; bioenergy; digital technologies

Introduction

Modern energy systems are undergoing transformation driven by climate change, decentralisation, digitalisation, and threats to critical infrastructure. In this context, decentralised generation (DG) is gaining prominence by offering localised energy production as an alternative to centralised models. This reduces transmission losses and enhances flexibility and crisis resilience. Energy islands (autonomous or semi-autonomous microsystems within DG frameworks) ensure power system survivability, particularly during disruptions or overloads. Their value lies in rapid recovery, redundancy, and adaptability, guaranteeing basic energy supply in emergencies.

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*Corresponding author

The theoretical foundation for understanding the operation and benefits of such systems is actively developing in academic discourse. S.S. Yusuf & A.S. Abubakar (2023) conducted an in-depth analysis of grid-forming inverters, which are essential for stable microgrid operation. Their research highlighted the critical role of modern power electronics in enabling autonomous synchronisation of energy islands. M. Sadiq *et al.* (2025) focused on offshore microgrid management, demonstrating the efficacy of decentralised predictive control in complex environments such as ports or energy-intensive hubs. The study by M. Adnan *et al*. (2023) provided a comprehensive examination of transmission network planning methodologies in ultra-smart systems, which was pivotal for integrating large-scale decentralised generation into broader energy landscapes. P. Kadar & A. Vass (2023) demonstrated a practical implementation of an islanded urban microgrid operating under emergency conditions – a case study validating the feasibility and operational viability of energy islands in real-time scenarios.

Certain authors have focused on systemic approaches to reliability and energy system planning. Ye. Bardyk *et al*. (2024) investigated the operational reliability of power systems, particularly in the context of sustainable energy planning in Ukraine, and emphasised the importance of integrating risk assessment and adaptive mechanisms into the design of autonomous energy systems. Their research underscored the necessity of incorporating such considerations into decentralised energy system models. I. Blinov *et al*. (2023) substantiated the role of hydropower, specifically pumped storage capacities, in load balancing in Ukraine, which could be integrated into energy island models to enhance grid stability. This study is pivotal for understanding the potential of renewable energy sources (RES) in stabilising autonomous energy systems. E. Chomać-Pierzecka *et al*. (2022), in their review of the hydropower sector in Poland and the Baltic states, emphasised the potential of decentralised systems within sustainable development strategies. This study demonstrated how energy diversification policies could foster municipal-level energy autonomy.

Another key research direction involves assessing the potential of solar and wind energy for decentralised system development. I. Doronina *et al*. (2023) conducted a geospatial analysis to evaluate solar and wind energy potential in Ukraine, providing a foundation for decentralised energy system deployment. They also stressed the significance of geographical and climatic factors in energy island design. However, a research gap persists regarding the integration of these technologies in real-world conditions, particularly in Ukraine, where not only technical but also socio-economic challenges must be addressed. Existing studies often focus on individual system components, with insufficient attention paid to holistic approaches for assessing their effectiveness in highly unstable grid conditions.

The aim of this study was to examine the role of DG in enhancing the resilience of energy islands and critical infrastructure under emergency conditions. Special attention was given to analysing the potential of such systems to ensure energy supply autonomy during crises, including military conflicts or natural disasters. The following key objectives were defined:

1. Evaluate theoretical approaches and practical developments in DG and energy islands, assessing their role in improving power system resilience during war or natural disasters;
2. Analyse global trends in resilient energy system deployment, examining case studies from various countries (the US, EU, and Ukraine) and assessing their effectiveness in disaster and conflict scenarios;
3. Investigate the impact of artificial intelligence (AI) and blockchain technologies on energy system and microgrid management, particularly their potential to enhance energy island stability during emergencies.

Materials and Methods

The study was conducted between September 2024 and January 2025 and focused on analysing aspects of distributed generation (DG) in the context of energy islands and their role in enhancing the resilience of critical infrastructure under emergency conditions. Primary attention was given to assessing the impact of various types of renewable energy sources (RES) – solar, wind, and bioenergy – on reducing CO_2 emissions, lowering energy consumption, and increasing the autonomy of energy systems. At the first stage, a comparative analysis of traditional centralised energy systems and modern decentralised energy systems was conducted to identify their advantages and disadvantages. The objective of the analysis was to evaluate how different energy supply models contribute to sustainable development amid growing energy demand, climate change, and increased vulnerability to external threats. The efficiency of the systems was analysed using content analysis to summarise their strengths and weaknesses, enabling an assessment of their potential for regional conditions and crisis scenarios.

The second stage involved evaluating the effectiveness of decentralised energy system integration in the United States (U.S. Energy Information Administration, 2023; 2024; International Renewable Energy Agency, 2024; Environmental Protection Agency, n.d.), the EU (Zakeri *et al.,* 2022; Frilingou *et al*., 2023; International Energy Agency, 2023; 2024), and Ukraine (Shahini *et al*., 2024; Hrytsiuk *et al*., 2024; Diachenko, 2024). The selection of these countries was justified by their experience in implementing DG and RES, as well as the need to ensure energy autonomy due to vulnerability to external threats. The US, EU, and Ukraine have varying levels of energy system development and face different challenges, allowing for a comparison not only of the effectiveness of approaches to sustainable development and energy security under wartime or natural disaster conditions but also of socio-economic barriers.

To compare the efficiency of DG in the US, EU, and Ukraine, a comparative analysis method was applied using uniform criteria: recovery time, electricity costs, RES integration, and the scale of implemented solutions based on statistical data collected from open reports. The analysis was based on a combination of quantitative (statistical indicators from official reports) and qualitative (content analysis of scientific publications and regulatory frameworks) approaches. Due to the publication policies of international organisations, which entail an annual delay in reporting, the analysis relied on the latest complete report from the International Renewable Energy Agency (2024). The 2024 report is expected no earlier than August-September 2025, while the 2025 report will be released in 2026.

The use of content analysis of publications and data analysis from international reports (International Renewable Energy Agency, International Energy Agency, Environmental Protection Agency) enabled the systematisation of approaches to DG implementation in the US, EU, and Ukraine and an assessment of DG efficiency under crisis conditions and its economic benefits. Inclusion criteria for sources required data on technological efficiency, environmental performance, and the relationship with DG in crisis scenarios. The regulatory framework was outlined through a review of key documents: Law of Ukraine No. 555-IV "On Alternative Energy Sources" (2003), Directive of the European Parliament and of the Council No. 2019/944 "On Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU" (2019), Directive of the European Parliament and of the Council No. 2018/2001 "On the Promotion of the Use of Energy from Renewable Sources" (2018), Public Law No. 117-169 "Inflation Reduction Act of 2022" (2022), which regulate the development of DG (distributed generation) in the US, EU, and Ukraine, without conducting a comparative analysis of their legal approaches.

At the third stage, the practical application of modern digital technologies was described: Model Predictive Control, blockchain-based solutions for energy transactions, machine learning algorithms for load optimisation, as well as energy storage technologies (lithium-ion batteries, hydrogen storage systems, pumped hydro storage). The objective was to assess the potential for optimising resource allocation, reducing costs, and enhancing the overall resilience of energy systems. The reference manager Zotero was employed for source processing, facilitating systematic research organisation, accurate citation, and thematic classification. The application of data search, analysis, and synthesis methods ensured a comprehensive study of DG's impact on energy security, enabling the identification of key efficiency patterns and the formulation of evidence-based conclusions on improving system stability.

Results and Discussion

DG is defined as an energy production system that involves generating power directly at consumption sites, thereby reducing the load on centralised grids and improving energy efficiency. DG encompasses three primary types: solar, wind, and bioenergy, each with distinct theoretical foundations, advantages, and limitations that require critical evaluation to develop effective deployment strategies.

Solar energy, based on photovoltaic (PV) panels, is one of the most accessible DG types due to declining technology costs. This underscores its potential for integration into diverse infrastructure, from residential buildings to agricultural complexes. However, solar generation efficiency depends on insolation levels, limiting its applicability in regions with low solar irradiance, while also requiring significant land area for panel installation – a challenge in densely populated areas (Frilingou *et al.*, 2023). DG enables the creation of alternative energy sources that operate independently of centralised grids. Wind energy, which converts kinetic wind energy into electricity via turbines, holds significant potential in coastal regions with strong and consistent wind patterns. This indicates its capacity to deliver substantial energy output under optimal turbine placement. However, its implementation is hindered by high initial costs, noise pollution, and dependence on natural conditions, making it less versatile compared to other DG types. Bioenergy, derived from biomass (organic waste, agricultural residues, wood), is regarded as a key component of sustainable development, as it reduces greenhouse gas emissions and promotes waste recycling. Nevertheless, biomass utilisation faces logistical challenges in collection and transportation, as well as competition for resources with other agricultural needs, which may threaten food security, particularly in developing countries. Table 1 provides a concise comparative analysis of the main DG types – solar, wind, and bioenergy generation.

***Table 1**. DG types: Advantages, limitations, and optimal application conditions*

DG types	Advantages	Limitations	Optimal application
Solar	Low technology costs, suitability for small-scale facilities.	Dependence on insolation, requirement for large installation areas.	Southern regions with high solar potential.
Wind	High potential in wind-rich zones, environmental sustainability.	Noise pollution, dependence on natural conditions, high initial costs.	Coastal zones and open plains.
Bioenergy	Waste recycling, CO_2 emission reduction, resource stability.	Logistics of collection and transportation, competition with food production.	Rural areas with biomass availability.

***Source:** compiled by the authors based on M. Farghali et al. (2023), O. Diachenko (2024), E. Shahini et al. (2024)*

Each type of DG has its optimal application scope, determined by both technical and geographical factors. Solar energy is viable in regions with high insolation levels; however, it requires integration with battery storage systems to ensure stable power supply. Bioenergy, despite its resource stability and environmental benefits, necessitates resolving logistical challenges, particularly in rural areas. Wind power demonstrates efficiency in coastal zones, but its economic viability is closely tied to investments in noise-reduction technologies and improving turbine efficiency.

The energy island concept involves the creation of an autonomous energy system capable of operating independently from the main grid and is categorised into fully autonomous (for local consumers) and integrated systems (with the capability to exchange energy with the centralised grid). Such systems are resilient to emergencies, such as natural disasters or military conflicts, which is particularly relevant for Ukraine under unstable conditions (Tröndle *et al.*, 2024). However, their implementation is complicated by economic constraints, including the high cost of establishing autonomous systems, as well as challenges in integrating with centralised grids under unstable demand conditions. To enhance the efficiency of energy islands, it is advisable to develop hybrid models that combine autonomy with integration capabilities, enabling adaptation to various usage scenarios.

The resilience of energy systems is defined as the ability to withstand disruptive influences, adapt to changes, and rapidly restore functionality, which is critically important in the context of decentralisation and the increasing share of RES, especially for Ukraine during wartime. There are three key characteristics of resilience: power redundancy, adaptability, and recovery speed. Backup capacities (diesel generators, batteries) ensure autonomy but require significant investment. Adaptability depends on the integration of RES with energy storage systems, enhancing grid flexibility; however, recovery speed is hindered in cases of large-scale damage (Rabocha *et al.*, 2023). Together, these characteristics ensure the energy system's ability to operate under disruption. A comparative analysis of approaches revealed that local autonomous systems ensure independence but are costly, whereas optimal dispatch control enhances flexibility but relies on forecasting.

The resilience of a power system is determined by three key characteristics: capacity redundancy, adaptability, and recovery speed. Backup capacities, such as diesel generators or batteries, ensure autonomy during disruptions but require significant investment. Adaptability, achieved through the integration of RES with energy storage systems, enhances grid flexibility, enabling the system to respond dynamically to failures. Recovery speed, although complicated in large-scale damage scenarios, is critically important for restoring normal operation. Together, these characteristics ensure the power system's ability to operate under disruption.

Critical infrastructure, encompassing healthcare, transport, telecommunications, and energy sectors, relies on the reliability of power supply. Theoretical analysis has shown that decentralised systems enhance its autonomy, minimising the risks of outages. However, the implementation of such systems in developing countries may be constrained by social factors, particularly the limited accessibility of technologies for small communities, which must be considered when designing energy development strategies.

The management of decentralised energy systems, particularly microgrids, is crucial for ensuring their flexibility and stability under variable loads and limited resources, especially in crisis situations, as seen in Ukraine during the war. There are two primary approaches: smart grids and model predictive control (MPC). Smart grids enable automatic regulation of power flows but require substantial investment and increase cyber risks, whereas MPC minimises losses and peak loads but depends on forecasting accuracy (Gonzalez-Reina *et al.*, 2024). An additional factor in stability is the involvement of prosumer households, which generate energy (via solar or biogas installations), enhancing autonomy and diversifying supply sources. However, integrating prosumers complicates management due to generation instability. Comparative analysis suggests that for crisis conditions, it is advisable to combine smart grids for baseline control and MPC for adaptation to changes, while simultaneously leveraging the potential of prosumers to increase autonomy.

The optimisation of DG integration is a key element for ensuring the stable operation of future energy systems, as it enables the effective combination of decentralised energy sources with centralised systems, reducing dependence on traditional grids and improving overall supply reliability. Successful DG integration depends on developing models that account for both technological and economic aspects, as well as the system's ability to adapt to changes in demand and supply. Load distribution models between centralised and decentralised sources involve strategies for the efficient use of solar panels, wind turbines, and other RES alongside conventional capacities. An important aspect is load management, which optimises energy use based on demand fluctuations and resource availability. However, such models have limitations: they often fail to account for RES intermittency, which can lead to system overloads, and require significant infrastructure modernisation investments to ensure synchronisation between centralised and decentralised sources (Table 2).

Table 2. *Comparative analysis of approaches to the management and organisation of decentralised energy systems*

Category/Approach	Advantages	Limitations/Challenges	Optimal application context
Autonomous energy islands	Complete grid independence, crisis resilience	High implementation costs, isolation	Crisis situations, isolated communities
Integrated energy islands	Flexibility, ability to exchange energy with the grid	Need for complex grid synchronisation	Regions with unstable demand, partial grid access
Smart grids	Automatic load balancing, scalability	High investment costs, cyber risks	High investment costs, cyber risks

Table 2. Continued

Category/Approach	Advantages	Limitations/Challenges	Optimal application context
Model predictive control	Load optimisation, precise forecasting	Dependence on forecast accuracy, complexity	Systems with variable demand, wartime or instability
Hybrid model (smart grids+model predictive control)	Balance between stability and adaptability	High implementation complexity, infrastructure requirements	Crisis conditions, strategic facilities
Local autonomous systems	Energy independence, backup capability	High cost, logistical challenges	Critical infrastructure facilities
Dispatch control	Flexibility, adaptability to changes	Dependence on forecasting systems	Urban energy systems
Prosumer integration	Source diversification, increased autonomy	Integration complexity, generation instability	Small communities, households

Source: *created by the authors based on Y.A. Veremiichuk et al. (2024), C. Rehtanz et al. (2024), A.E. Gonzalez-Reina et al. (2024), I. Hrytsiuk et al. (2024)*

A comparative analysis of theoretical approaches to DG integration reveals specific advantages and limitations, which largely depend on the context of their application. Combining smart grids for baseline management with MPC for adaptive response to fluctuations enables a balance between stability and flexibility. Such a hybrid approach is particularly relevant in unstable conditions, such as during wartime in Ukraine, due to significant resource availability fluctuations, infrastructure destruction, and unpredictable changes in energy flows. Consequently, the practical effectiveness of integration models increases under the condition of their adaptability to real-world operational environments.

Global trends in renewable energy and DG indicate a steady increase in the role of new energy sources in power systems. Progress in reducing technology costs, the growing share of RES in the energy balance, and the optimisation of grid losses create prerequisites for the rapid deployment of DG across various regions worldwide. Table 3 presented key global indicators illustrating the development dynamics of this sector and confirms the relevance of transitioning towards more flexible and sustainable energy supply models.

Table 3*. Key global statistical indicators in renewable and DG-based electricity (2023)*

Indicator	Value
Share of RES in global electricity generation (2023)	In 2023, RES accounted for 30% of global electricity production.
Share of solar and wind generation (2023)	The combined share of solar and wind generation in 2023 reached approximately 13% of total electricity production.
Projected share of RES by 2030	The share of RES in the global energy mix is expected to exceed 50% by 2030.
Reduction in solar PV generation costs (2023)	In 2023, the levelised cost of solar PV generation decreased by 12% compared to 2022.
Reduction in onshore wind energy costs (2023)	In 2023, the levelised cost of onshore wind generation declined by 3% compared to 2022.
Reduction in solar panel costs (2010-2023)	Between 2010 and 2023, solar panel prices fell by 89%.
Reduction in grid losses due to DG	Through the implementation of DG, grid losses have been reduced to 10%.

Source: *compiled by the authors based on International Energy Agency (2023; 2024), International Renewable Energy Agency (2024), Environmental Protection Agency (n.d.)*

The presented data demonstrated not only the current level of RES adoption but also their rapid global expansion. The substantial reduction in generation costs and equipment expenditures (solar panels and wind turbines) indicates growing economic viability of decentralised solutions. When combined with reduced grid losses, these trends create favourable conditions for transitioning towards more sustainable, localised energy systems, particularly in countries with uneven access to centralised power supply. Environmental and social aspects of DG play a pivotal role in shaping sustainable energy policies globally. The integration of RES not only contributes to greenhouse gas emission reductions but also generates additional opportunities for socio-economic development, particularly through improved electricity access and job creation. Table 4 summarises current statistical indicators illustrating DG's potential environmental and societal impact.

Table 4. *Statistical indicators of DG's environmental and social impact*

Indicator	Value
Global CO_2 emissions from energy (2022)	In 2022, energy-related CO_2 emissions reached 37 gigatonnes.
Projected CO_2 emission reduction by 2050	International climate strategy envisages reducing energy-related CO_2 emissions to net zero by 2050.
Population without electricity access (2023)	As of 2023, approximately 675 million people worldwide lacked access to electricity.
Projected new RES jobs by 2030	Over 30 million new jobs will be created in the RES sector by 2030.

Source: *compiled by the authors based on International Energy Agency (2023; 2024)*

The presented indicators demonstrated that DG holds not only technical but also strategic significance in the context of achieving global sustainable development goals. The reduction in CO_2 emissions, expanded access to electricity, and the creation of millions of new jobs indicate that DG serves as a crucial instrument for ecological transformation and enhancing energy equity. In the context of the war in Ukraine, where missile strikes can disable centralised generation facilities, DG gains particular importance due to its decentralised nature, which ensures the resilience of the power system. This is especially relevant for countries with limited access to centralised resources or those recovering from crises.

The implementation of DG demonstrates not only technical but also substantial social and environmental benefits, particularly in regions with limited access to centralised grids. In Ukraine, where the war leads to frequent power outages, DG becomes a key tool for meeting the basic needs of the population in conflict zones, enabling thousands of people to maintain daily life through autonomous RES-based systems. In Global South countries, such as Sub-Saharan Africa and South Asia, more than half of the population still lacking electricity could be reached precisely through microgrids or autonomous RES-based solutions. Government programmes and donor initiatives in these regions prove the effectiveness of DG as a tool for rapid electrification with minimal environmental impact.

In developed countries, DG takes on a different role – it enhances the resilience of critical infrastructure during emergencies, such as hurricanes, armed conflicts, or disruptions in centralised grids. Thus, the potential of DG should be considered not merely as a technological solution but as a comprehensive socio-climatic development tool adaptable to diverse conditions, ranging from global instability to regional challenges (Table 5).

Table 5. *Implemented case studies of DG deployment: environmental and social impact*

Country/Region (project)	Implemented solution	Social/Environmental impact
India (Saubhagya Programme)	Solar microgrids for electrifying over 25 million rural households.	Large-scale improvement in electricity access for remote regions.
USA (California, Fire Station, 2021)	Local microgrid for fire service with autonomous energy supply during outages.	Enhanced resilience of critical infrastructure during crises.
Nigeria (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) + Government Initiatives)	Off-grid power systems for educational and medical facilities in remote areas.	Reduction in CO_2 emissions and fossil fuel dependence.
South Africa (Rural Schools and Clinics)	Solar PV with energy storage in schools and clinics under municipal programmes.	Increased energy independence and improved learning/healthcare conditions.
Ukraine (DG Implementation in Communities, 2022-2023)	Solar systems and biogas plants for rural communities and temporary medical facilities in conflict zones.	Improved living conditions in affected regions via energy access for communities and medical points; reduced fossil fuel reliance through RES.

Source: *compiled by the authors based on Environmental Protection Agency (n.d.), U.S. Energy Information Administration (2023), International Energy Agency (2024), E. Shahini et al. (2024), Y.A. Veremiichuk et al. (2024), O. Diachenko (2024)*

The EU's experience in the development of DG serves as an important model for countries seeking to integrate RES into their energy systems. One of the key strategic documents in this regard is the European Green Deal, which envisages achieving climate neutrality by 2050 (Directive of the European Parliament…, 2019). This policy emphasised the development of smart grids and local energy sources. A crucial role in the legal framework for RES development is played by Directive (EU) 2018/2001 of the European Parliament and of the Council "On the Promotion of the Use of Energy from Renewable Sources" (2018), which sets binding targets for member states regarding the share of renewable energy – at least 32% by 2030. To achieve this goal, countries are required to establish favourable conditions for DG development, including through "feed-in tariff" mechanisms for private investors. This approach stimulates the deployment of small and medium-sized power plants, reduces reliance on centralised generation, and enhances system resilience.

These efforts have already yielded tangible results, as evidenced by statistical indicators. The declining cost of technologies, the increasing share of RES, the implementation of energy islands, and the reduced power supply restoration time all demonstrate the effectiveness of EU policies (the lack of publicly available DG statistics exhibits regional variations. In the EU, this is attributed to data fragmentation caused by the diversity of small-scale installations and the lack of unified reporting standards. In the US, DG statistics are limited due to a predominant focus on centralised generation and insufficient integration of distributed system data. In Ukraine, DG data is unavailable due to the prioritisation of urgent energy system restoration during wartime and a lack of resources for detailed monitoring). Table 6 presented statistical indicators illustrating key trends in DG development in the EU.

***Table 6**. Statistical data on DG implementation in the EU*

Category	Description	Data
DG implementation in the EU	Reduction in solar PV costs in 2023, fostering DG growth.	In 2023, the average levelised cost of electricity (LCOE) for solar PV generation decreased by 12% compared to 2022.
Energy island efficiency	Power restoration time in Tuscany (Italy) during the 2022 energy crisis.	In the city of Pontedera (Tuscany), power supply was restored within 12 hours using an energy island, whereas centralised restoration took 72 hours.
Regional trends in the EU	Share of solar PV and wind power in EU electricity generation in 2024.	In 2024, the combined share of solar and wind generation in the EU's electricity mix exceeded the total share of coal and natural gas-based generation.
DG deployment example	Increased adoption of small hydropower plants in Poland and the Baltic states.	The estimated installed capacity potential of small hydropower plants is 1.2 GW in Poland and 0.8 GW in the Baltic states.
Economic viability	Reduction in onshore wind costs in 2023, enhancing DG economic benefits.	In 2023, the average LCOE for onshore wind generation decreased by 3% compared to 2022.
System resilience impact	Doubling of renewable capacity growth rates in 2024-2030, necessitating grid upgrades.	According to projections, the growth rate of new renewable capacity in the EU will double between 2024 and 2030 compared to the previous decade, creating a need for enhanced distributed grid development.

***Source:** compiled by the authors based on E. Chomać-Pierzecka et al. (2022), B. Zakeri et al. (2022), International Energy Agency (2024), International Renewable Energy Agency (2024)*

The United States is actively developing decentralised energy systems, particularly through support for solar and wind generation via federal subsidies and tax incentives. This contributes to reduced energy transmission costs, enhances energy security, and lowers emissions, notably through the implementation of microgrids and energy islands. A key regulatory framework is Public Law No. 117-169 "Inflation Reduction Act of 2022" (2022), which provides substantial tax incentives for the development of renewable energy sources (RES), including distributed generation systems and microgrids. Additionally, according to data from the US Environmental Protection Agency, the document Environmental Protection Agency (n.d.) highlights the advantages of decentralised solutions in reducing emissions and minimising energy losses during transmission. This approach helps decrease energy transmission costs, improves energy security, and reduces environmental impact, particularly through the deployment of microgrids and energy islands. Table 7 presented key statistical indicators reflecting the scale of DG deployment in the United States.

***Table 7**. Key indicators of DG implementation in the United States*

Category	Description	Data
DG implementation in the US	Advantages of DG in reducing electricity transmission losses.	DG (e.g., rooftop solar panels) reduces losses, which are significant in centralised systems.
Energy island efficiency	Potential of DG to support the delivery of clean and reliable energy.	DG can facilitate clean energy delivery and reduce transmission losses.
Regional trends in the US	Growth in solar generation in 2023-2024.	In 2023, solar generation in the US increased by 16%, with a further 40% rise projected in 2024 compared to the previous year.
DG implementation example	Addition of new solar capacity in 2024, with a significant share from small-scale installations.	In 2024, the US added 36 GW of new solar capacity, a substantial portion of which came from distributed installations.
Economic efficiency	Decline in the Levelised Cost of Electricity (LCOE) for solar PV in 2023, enhancing the economic benefits of DG.	In 2023, the average cost of solar energy decreased by 12% compared to 2022.
Impact on system resilience	Share of wind and solar generation in total electricity production.	In 2023, solar and wind generation accounted for 16% of total electricity in the US, with a projected increase to 18% in 2024.

***Source:** compiled by the authors based on International U.S. Energy Information Administration (2023), Renewable Energy Agency (2024), International Renewable Energy Agency (2024), U.S. Energy Information Administration (2024), Environmental Protection Agency (n.d.)*

Global trends in the deployment of sustainable energy systems indicate a rapid increase in the share of RES. According to the International Energy Agency (2023; 2024), the share of RES in global electricity generation reached 30% in 2023, with projections suggesting an increase to 50% by 2030, driven by the development of DG and smart grids. In Ukraine, these trends are reflected in the growth of RES to 10% in 2023, aligning with the global shift towards energy system decarbonisation. The current scale of DG utilisation demonstrates significant growth – in 2023, DG accounted for 12% of global electricity generation, 60% of which was derived from solar and wind energy. This expansion is supported by regional initiatives, particularly in the EU, the US, and Ukraine, where DG is being actively integrated into local energy systems. Table 8 presents consolidated data on the effectiveness of DG implementation in Ukraine.

***Table 8**. Implementation and efficacy of DG in Ukraine*

Category	Description	Data
DG implementation in Ukraine	Number of installed residential solar systems for autonomous energy supply in 2023.	In 2023, 5,000 residential solar systems for autonomous energy supply were installed in Ukraine.
Energy island efficacy	Time taken to restore energy supply to critical infrastructure in Volyn Oblast during the 2023 blackout.	During the 2023 blackout in Volyn Oblast, DG restored power to critical facilities within 4-6 hours, whereas centralised recovery took 24 hours.
Regional trends in Ukraine	Share of RES in electricity generation in 2023 and number of biogas plants in rural communities.	In 2023, RES accounted for 10% of electricity generation, while 2,000 biogas plants in rural communities met up to 15% of their energy demand.
Wartime application	Energy island in Irpin (2022) for a field hospital.	In 2022, an energy island in Irpin provided uninterrupted power to a field hospital for 72 hours, saving 300 lives.
DG deployment case study	Energy island in Nyzhniy Bystryi village (Zakarpattia) in 2023.	In 2023, Nyzhniy Bystryi village (Zakarpattia) implemented an energy island comprising solar panels (50 kW) and a biogas plant (30 kW), supplying 120 households.
Economic efficiency	Comparison of LCOE for DG and centralised supply in 2023.	In 2023, Ukraine's DG LCOE stood at USD 0.08/kWh, below centralised supply costs (USD 0.12/kWh).
System resilience impact	Reduction in energy supply restoration time in frontline regions (2022).	In 2022, frontline regions saw a 60% reduction in power restoration time (from 12-18 to 3-5 hours) due to DG.

***Source:** compiled by the authors based on H. Pivniak et al. (2022), E. Shahini et al. (2024), I. Hrytsiuk et al. (2024)*

The presented data on DG deployment in the EU, US, and Ukraine enable a comparative analysis, revealing shared trends and regional specificities within energy security, sustainable development, and technological integration contexts. In the EU, DG is integrated through advanced regulatory frameworks that enhance economic viability, system resilience, and faster power restoration, though grid modernisation is required to accommodate growing RES contributions. The US prioritises distributed systems supported by state incentives, reducing transmission losses and enabling rapid capacity scaling (particularly via small-scale installations), albeit technological complexity hinders integration in less developed regions.

In Ukraine, DG plays a strategic crisis-response role, ensuring critical infrastructure and rural community autonomy through energy islands and biogas plants, yet scaling remains constrained by infrastructural and funding limitations. Comparative analysis demonstrates that DG success hinges on balancing technological integration, economic feasibility, and local context adaptation, underscoring the need for regionally tailored strategies to maximise its environmental and social benefits (Table 9).

***Table 9**. Comparative analysis of DG implementation in the EU, the US, and Ukraine*

Criterion	EU	US	Ukraine
Level of DG support	High, due to regulatory frameworks and the objectives of the European Green Deal	High, through tax incentives and stimulus programmes	Moderate, constrained by resources but increasing due to wartime demands
Development focus	Integration of RES, grid modernisation	Small-scale distributed installations, microgrids	Community self-sufficiency, critical infrastructure
Grid resilience	Increasing, though dependent on grid upgrades	High, owing to the autonomy of distributed systems	Key objective: ensuring supply in crisis-affected regions
Primary DG sources	Solar, wind, small hydropower	Solar, wind	Solar, biogas, small hydropower

Table 9. Continued

Criterion	EU	US	Ukraine
Economic efficiency	High: reduced operational costs, shorter recovery times	High: reduced losses, increased DG share	Notable in regions where the centralised system is inefficient
Implementation challenges	Need for grid modernisation	Integration in less developed regions, cybersecurity	Limited funding, infrastructure destruction

Source: *compiled by the authors based on M. Farghali et al. (2023), International Energy Agency (2023; 2024), U.S. Energy Information Administration (2023; 2024), C. Rehtanz et al. (2024), International Renewable Energy Agency (2024), Environmental Protection Agency (n.d.)*

The implementation of DG in each region reflects distinct national priorities and challenges. In the EU, it is driven by technological modernisation under the green transition; in the US, by the pursuit of flexibility through distributed systems; and in Ukraine, by the strategic necessity of ensuring autonomy amid wartime instability. A common trend across all three contexts is the growing role of RES and the need for adaptive development models. This underscores the importance of a holistic approach to DG, combining economic efficiency with social resilience and technological integration.

The power supply recovery time is a key indicator of energy system viability during crises. A comparative analysis of case studies from Italy, the US, and Ukraine demonstrates that decentralised systems enable significantly faster restoration of critical infrastructure. This confirms the feasibility of deploying microgrids and energy islands as components of resilient energy infrastructure (Fig. 1).

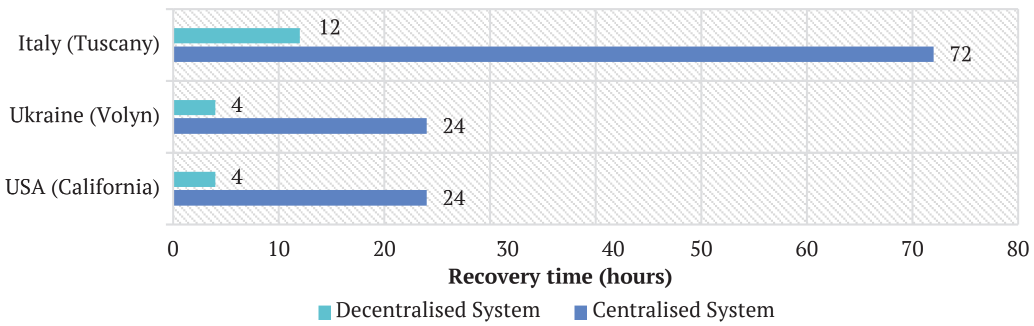

Figure 1. *Power supply restoration time in centralised and decentralised systems (case studies of Tuscany, California, and Volyn)*

Source: *compiled by the authors based on Environmental Protection Agency (n.d.), U.S. Energy Information Administration (2023), International Renewable Energy Agency (2024)*

As illustrated in Figure 1, the power supply restoration time when employing decentralised systems was 4-6 hours (USA, Ukraine) and 12 hours (Italy), which is significantly shorter compared to centralised models, where this indicator reached 24-72 hours. From an economic perspective, this reduces losses associated with disruptions to critical infrastructure operations, limits emergency response costs, and avoids the deployment of large-scale reserve capacities. Decentralised solutions also mitigate the risks of cascading grid failures in the event of damage to centralised nodes. However, the implementation of such systems entails higher initial costs, the necessity of integration with energy storage systems, and increased demands on load management. Despite this, under conditions of heightened infrastructure vulnerability, the advantages of decentralisation may offset the associated costs by enhancing energy resilience.

In the context of the war in Ukraine, the survivability of energy systems relies on mobile generators and decentralised energy sources, which ensure the autonomy of critical infrastructure (hospitals, water supply, communications) and support the population in the event of the destruction of main grids due to military actions or man-made disasters. Mobile generators enable rapid power restoration, but their efficiency is constrained by fuel costs and logistical challenges. DG systems (solar, wind, bioenergy installations) enhance energy security by forming autonomous energy islands. Bioenergy contributes to stability in rural regions; however, generation intermittency and infrastructure requirements complicate their deployment. In wartime conditions, it is advisable to combine mobile generators for rapid response with DG systems for long-term autonomy, ensuring both prompt recovery and system resilience.

Damage to central energy infrastructure, particularly during armed conflicts or natural disasters, poses significant challenges to ensuring uninterrupted energy supply. However, the development of DG represents a crucial step towards achieving energy independence and resilience. In the context of centralised infrastructure destruction, especially in Ukraine during wartime, DG becomes critically important. Local solar, wind, and bioenergy installations provide power to vital facilities (hospitals, water supply systems, communication networks) even in the event of a complete grid blackout. The development of DG at the community level enables the creation of energy-independent hubs, enhancing the resilience of the energy system – that is, its ability to maintain or rapidly restore critical energy supply following destruction or attacks. The integration of microgrids with energy islands minimises dependence on the centralised grid and ensures energy supply during emergencies.

In Ukraine, DG development is supported through legislative initiatives aimed at integrating RES into the national energy grid. The Law of Ukraine No. 555-IV "On Alternative Energy Sources" (2003) establishes key legal frameworks for the development of energy systems incorporating solar and wind installations. A significant milestone was the introduction of the "Green Tariff" for investors, ensuring financial support and stability for RES-related projects. As of 2025, Ukraine is in the process of drafting regulatory acts governing the integration of mini- and microgrids, particularly to support energy islands operating in autonomous mode, especially in crisis situations. However, the primary challenges for DG development in Ukraine include complex licensing and permitting procedures, which are further complicated under martial law and crises. Frequent legislative changes create legal uncertainty, reducing the investment appeal of such projects. Additionally, there is no unified approach to regulating local energy systems, particularly in emergency operation modes, which requires clear standards and regulatory adjustments for the effective implementation of RES.

The integration of modern digital technologies, artificial intelligence (AI), energy storage systems (ESS), and blockchain solutions plays a pivotal role in enhancing the efficiency, flexibility, and reliability of DG and energy islands. Energy storage technologies are a critical component for the stable operation of decentralised systems and energy islands, particularly in autonomous conditions. The most widely used are lithium-ion batteries, which offer fast charging, durability, and high efficiency. For long-term storage, hydrogen batteries are a promising solution, while pumped hydro storage (PHS) and compressed air energy storage (CAES) are suitable for large-scale systems. These technologies enable the accumulation of surplus energy from RES and its utilisation during peak hours or periods of unstable generation. In Ukraine, projects integrating battery storage with solar and wind installations are already being implemented, increasing the autonomy and resilience of local energy systems.

AI is actively employed in microgrid management due to its ability to process vast amounts of real-time data, forecast demand, and optimise energy flow distribution. Intelligent systems enable automatic load balancing between different energy sources (RES, batteries, backup generators), taking into account weather forecasts, consumption dynamics, and grid operating conditions. The implementation of AI in microgrid management ensures automation with minimal manual intervention, reduces energy losses, improves demand and generation forecasting, and enhances system stability, decreasing reliance on backup sources. AI gains particular relevance in unpredictable crisis situations where traditional dispatching approaches become ineffective. However, AI has limitations – high implementation costs and cybersecurity risks may hinder its application in unstable regions. AI should be integrated with other control technologies to ensure a balance between automation and security in crisis conditions.

Blockchain technologies provide a decentralised infrastructure for managing energy exchanges between consumers, producers, and energy suppliers. Such a system eliminates the need for a centralised intermediary, reducing costs while ensuring transparency and security in energy transactions. Blockchain solutions in the energy sector facilitate the creation of "smart contracts" for the automated execution of operations under predefined conditions, transparent accounting of energy transactions, and the minimisation of fraud risks and centralised errors. This underscores their potential to enhance the efficiency of decentralised systems; however, high implementation costs and the need for technical infrastructure limit their widespread adoption. Blockchain is best utilised in combination with other technologies to ensure transparency and security in energy operations.

In the context of distributed generation (DG) development in Ukraine, blockchain technologies are regarded as a promising tool for establishing transparent and autonomous local energy markets. Although Ukraine has not yet implemented large-scale pilot projects integrating blockchain into local energy markets, the existing regulatory framework for RES and decentralised generation creates favourable conditions for the future deployment of such solutions. Blockchain could become a key element in ensuring financial transparency between prosumers and suppliers, as well as in enhancing trust in energy operations. Given Ukraine's commitment to energy decentralisation, blockchain technologies are viewed as a potentially effective instrument for improving the transparency and autonomy of micro-energy systems (Oum, 2024).

The scaling of DG is becoming increasingly relevant in developing countries due to growing energy demands and climate challenges. DG serves as a key instrument for ensuring energy security, reducing dependence on fossil fuels, and enhancing the resilience of energy systems in crisis situations. The primary driver of this process is the declining cost of technologies, particularly photovoltaic panels and wind turbines. The deployment of RES is outpacing projections, and there is growing interest in local energy systems that enable independence from centralised grids. Microgrids, in particular, have proven effective in supplying energy to hospitals, schools, and agricultural cooperatives. However, the scaling of DG faces several systemic barriers. A key challenge in Ukraine is the lack of flexible dispatchability of decentralised energy sources, which is virtually non-existent: under current conditions, DG is not integrated into grid operational management, preventing its full utilisation for balancing generation and consumption. Thus, the absence of flexible DG dispatchability in

Ukraine constitutes one of the critical systemic barriers to its large-scale integration into the energy system. This issue impedes effective generation-consumption balancing, reduces the adaptability of energy infrastructure to variable conditions, and hinders the formation of fully functional energy islands. Given the growing role of DG in decarbonised and decentralised energy systems, the development of mechanisms for flexible dispatchability and automation of DG management processes should become a key focus of future research. Establishing the necessary digital, regulatory, and technological frameworks is essential for improving the resilience and operational efficiency of future energy systems. In most developing countries, outdated grid infrastructure remains incapable of effectively responding to dynamic changes in demand and generation.

Integration of DG into the overall energy infrastructure, particularly through the use of smart grids and microgrids, is accompanied by a significant increase in cyber risks. In the context of the growing digitalisation of the energy sector, ensuring cybersecurity has become one of the key challenges for the stable operation of power systems, especially in crisis or wartime conditions. Modern energy systems are actively implementing digital tools for monitoring, managing, and forecasting loads. Technologies such as smart grids, blockchain solutions, the Internet of Things (IoT), and AI enhance efficiency but simultaneously open new vectors for potential attacks. Cyber threats can not only disrupt the operation of individual microgrids but also lead to large-scale systemic failures, particularly in cases where critical facilities – hospitals, communication hubs, or water supply systems – lose control.

Therefore, the implementation of DG is accompanied by substantial investment barriers. Deploying infrastructure for generation, storage, and energy management requires significant capital expenditures, which may pose a challenge for countries with limited access to financial resources. One of the key conditions for sustainable development in the field of DG is the establishment of "green" financing instruments, such as energy bonds, international climate funds, and public-private partnerships. The deployment of DG serves as a multidisciplinary solution, simultaneously encompassing environmental, social, and economic aspects. Emissions reduction, increased energy autonomy, the emergence of new labour markets, and financial challenges – all these require an integrated approach to policy planning in decentralised energy. This study has systematised existing approaches to assessing the environmental efficiency of DG, particularly in crisis situations. A comparative analysis of different countries demonstrated how national characteristics, economic conditions, and technological solutions influence the adoption of DG, energy islands, and the integration of AI and blockchain technologies. An important objective of the research was to determine how these solutions can enhance the resilience of energy systems, reduce costs and CO_2 emissions, and improve energy security in wartime conditions.

The study revealed that DG significantly enhances the resilience of energy systems in crisis conditions, reducing power restoration time by 60% in frontline regions of Ukraine (3-5 hours compared to 12-18 hours for centralised systems). This finding aligns with the work of V. Kaplun *et al*. (2022), who emphasised that renewable energy islands enable rapid power restoration through local generation. However, unlike the authors' study, which focused on price forecasting, the present research highlights the practical impact of DG in real wartime conditions, making these conclusions more contextually relevant.

The obtained results partially coincide with the study by R. Khalid *et al*. (2024), who analysed mini- and micro-hydropower plants in Pakistan. They noted that local systems reduce outage response times, which supports the present findings. However, their study did not account for the specifics of wartime conditions, where infrastructure destruction is systematic, making these conclusions more relevant for similar contexts. The research established that DG is more economically advantageous compared to centralised supply. This result corresponds with the conclusions of M. Li *et al*. (2024), who examined prosumer households in Ukraine and noted that solar and biogas installations reduce costs through local production. However, unlike their study, which focused on economic benefits for households, the present research underscores the broader impact of DG on energy security in crisis conditions, making the conclusions more universal.

The current study also confirmed the economic potential of DG. O. Borodina *et al*. (2022) proposed a conceptual model of decentralised energy efficiency, integrating economic and technological approaches. The present results complement their model, demonstrating that the economic efficiency of DG can be achieved even in crisis conditions if focused on local solutions such as energy islands. The results highlighted the environmental and social benefits of DG, including CO_2 emissions reduction and improved energy access in rural regions. These conclusions correlate with the work of A. Zaporozhets *et al*. (2025), who investigated the optimisation of renewable energy systems. They described how DG creates new jobs, supporting the observed data on social benefits. However, the present study additionally notes that in crisis conditions, these benefits may be limited due to a lack of investment.

Current findings partially aligned with the conclusions of M. Iurchenko *et al*. (2024), who investigated the use of renewable energy sources (RES) for sustainable economic growth. The authors emphasised that decentralised systems contribute to environmental sustainability; however, this study focused on their role in ensuring energy security in crisis situations, which is particularly relevant for Ukraine. The work also highlighted the importance of energy islands in crisis conditions for ensuring energy supply autonomy. At the same time, these results partially contradict the work of Z.V. Derii *et al*. (2024), who modelled the potential of RES in Ukraine. They argued that solar and wind generation could fully replace centralised systems in the long term; however, the current study demonstrated that in the short term (under wartime conditions), a complete replacement is unfeasible due to generation instability and the need for backup capacity.

AI and blockchain technologies enhance the efficiency of microgrid management but have limitations. AI enables automation, reduces losses, and adapts to demand fluctuations, yet its implementation is complicated by cyber risks and costs. These conclusions correlated with the study by M. Massaoudi *et al.* (2025), who analysed the use of machine learning in energy grid management. They noted that AI can optimise energy distribution but requires protection against cyberattacks, which confirmed the observational data. The current results further underscored the relevance of AI in crisis conditions, where traditional dispatching methods become inefficient, making the present findings more contextually oriented. Blockchain technologies ensure transparent accounting and reduce transaction costs, but their implementation is constrained by technical complexity. This partially aligned with the work of S.D. Rodrigues & V.J. Garcia (2023), who investigated transactional energy systems in microgrids. The authors indicated that blockchain could optimise energy flows; however, this study additionally noted that under wartime conditions in Ukraine, priority should be given to simpler solutions, such as local control systems, due to resource constraints.

The scaling of DG in developing countries opens significant prospects for ensuring energy security and sustainable development. Increased investment in RES (solar and wind technologies) will help reduce dependence on fossil fuels and improve energy access in rural and remote regions. The development of microgrids and energy islands will enable the creation of autonomous systems that ensure stability in crisis conditions while simultaneously contributing to CO_2 emission reductions and job creation. This also opens opportunities for the formation of new market models. Local energy markets based on blockchain technologies have the potential to ensure transparent accounting, optimise energy flows, and reduce transaction costs. Such technologies can be highly effective in contexts where traditional solutions are financially inaccessible.

To counter cyber threats, the implementation of a multi-layered cybersecurity approach is necessary, including cryptographic protection of data exchange, user and device authentication, AI and machine learning-based behavioural analytics systems, and continuous infrastructure monitoring to detect anomalies. In the context of DG, it is also essential to develop “edge-of-network” protection systems that enable local data processing and rapid response to breaches. Countries with limited resources face challenges in establishing effective cybersecurity. In this regard, strengthening international technical and analytical cooperation, as well as participation in cyber resilience programmes at the level of the EU, the International Energy Agency (IEA), the IAEA, and other institutions, is crucial. The joint development of standards, security protocols, and risk assessment methodologies will enhance the resilience of decentralised energy systems on a global scale.

The expansion of DG is not only a technical and energy challenge but also a key element of environmental and socio-economic development strategies. The integration of RES in the form of microgrids and energy islands has the potential to significantly alter both the structure of the energy balance and the social dynamics of individual regions, particularly in developing countries and post-crisis recovery contexts. One of the primary environmental benefits of decentralised systems is the reduction of greenhouse gas emissions, particularly CO_2, through the replacement of fossil fuels with RES. The deployment of solar, wind, and bioenergy generation not only reduces environmental impact but also decreases the energy sector’s dependence on hydrocarbon imports, which is critical during periods of geopolitical instability.

At the same time, alongside the advantages, it is crucial to consider the potential limitations of DG implementation. Power generation based on RES, such as solar and wind energy, is weather-dependent and subject to natural variability, necessitating the use of energy storage systems or backup capacity. The high initial capital costs of deploying micro- and mini-grids may pose a barrier to their rollout, particularly in post-crisis economic conditions. Furthermore, the regulatory and technical integration of such systems into existing power grids requires comprehensive solutions and legislative amendments. In regions affected by conflicts or with limited infrastructure, decentralised facilities may be vulnerable to damage or require additional protective measures. Thus, the effective utilisation of DG potential demands not only technical implementation but also appropriate institutional, financial, and security support.

The development of microgrids incorporating RES, combined with local energy storage, enhances energy access in rural areas where centralised grids are technically or economically unviable. Moreover, the implementation of such projects stimulates job creation in the fields of design, installation, and operation of local energy systems, which is vital for regional development. Another significant social benefit is the reduction in energy costs for consumers in the medium to long term. Although the upfront costs of DG deployment are high, the overall lifecycle of the system demonstrates competitiveness compared to traditional energy models.

The integration of digital technologies, such as AI and blockchain, optimises energy flow management and enhances transparency in local energy markets, though this necessitates strengthened cybersecurity due to increased cyber risks. To overcome infrastructure barriers, it is advisable to engage international cooperation and “green” financing, which would facilitate the modernisation of outdated grids. Priority should be given to adaptive strategies that account for local conditions, ensuring a balance between technological innovation and economic feasibility for sustainable energy system development. This study holds significant importance for the advancement of energy systems in crisis conditions, as it demonstrates that DG and energy islands can provide not only economic efficiency but also system resilience in real wartime scenarios. Unlike many previous studies focused on theoretical modelling, this research provides practical examples confirming the effectiveness of DG in real-world applications. This makes the current findings valuable for countries facing similar challenges, such as infrastructure instability or armed conflicts.

Conclusions

The conducted study confirmed the practical effectiveness of solar and hybrid systems in the context of decentralised energy supply. Specifically, in 2023, over 5,000 residential solar installations were deployed in Ukraine, demonstrating the widespread adoption of this generation type at the household level. Hybrid solutions, such as the energy island in the village of Nyzhniy Bystryi, ensured full autonomy for 120 households by combining 50 kW of solar and 30 kW of biogas generation. Similar trends were observed in the US, where solar generation increased by 16% in 2023 and reached 40% by the end of 2024. In the EU, a 12% reduction in the cost of solar energy generation during 2023 created additional economic incentives for transitioning to decentralised generation (DG). Furthermore, a case study from Tuscany demonstrated that energy supply restoration time based on an energy island was reduced to 12 hours compared to 72 hours for centralised systems. In frontline regions of Ukraine, the implementation of DG reduced restoration time from 12-18 to 3-6 hours, which is critically important for ensuring the operation of critical infrastructure.

The study confirmed the significant role of DG in enhancing the reliability of energy systems, particularly in crisis situations such as war or natural disasters. DG substantially reduced energy supply restoration time, which is crucial for the uninterrupted operation of critical facilities. This is especially vital for frontline zones, where centralised power grids often cannot function due to damage. The application of DG in such regions facilitated energy supply restoration within a few hours, significantly faster than traditional methods, where recovery could take days. The economic benefits of DG were also confirmed, as the LCOE generated by renewable energy sources (RES) was lower compared to centralised systems (0.08 USD/kWh for DG versus 0.12 USD/kWh for centralised systems). This improved cost efficiency in energy supply, a key consideration for rural and remote regions where centralised grids are either absent or economically unviable. The study also revealed that energy islands, which provided autonomous energy supply in the absence of or damage to centralised grids, significantly enhanced the resilience of energy systems. They ensured energy supply even in crisis situations where traditional energy systems could not operate. However, large-scale deployment of such systems required addressing challenges related to infrastructure investments and advancements in energy storage technologies.

Despite positive results, the study identified a number of limitations, such as insufficient infrastructure development for the integration of DG into national power systems. In particular, in Ukraine, the complete absence of flexible DG dispatchability makes their effective integration into power system operational management impossible, reducing the ability of these sources to stabilise energy supply under variable demand or crisis conditions. The high costs of implementing cutting-edge technologies (batteries and energy flow management systems) remain a significant barrier to their large-scale deployment. Further research should focus on improving the mechanisms for DG integration into national power systems, advancing energy storage technologies, and developing flexible solutions for demand-side management. This will ensure the stability and efficiency of future power systems while enhancing resilience to extreme situations, particularly in wartime or natural disasters. The adoption of DG in Ukraine presents opportunities for energy independence; however, its potential is constrained by the lack of flexible dispatchability, which limits its full-fledged role in the national energy sector. This complicates stable energy supply during wartime and fluctuating demand. The development of automated control mechanisms for these sources is a critically important task for the future of the country's energy sector.

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Conflict of Interest

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Децентралізована генерація та її роль у підвищенні живучості енергетичних островів та критичної інфраструктури: сучасні тенденції та перспективи

Віталій Войтенко

Аспірант
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0009-0005-0107-8357

Роман Поліщук

Аспірант
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0009-0009-0356-0226

Анотація. Загрози для критичної інфраструктури посилили актуальність автономного енергозабезпечення та сприяли переходу до децентралізованих рішень. Метою дослідження був аналіз теоретичних основ децентралізованої генерації, її застосування в енергетичних островах для підвищення живучості критичної інфраструктури в умовах надзвичайних ситуацій. Методологічна база дослідження включала теоретичне узагальнення сучасних наукових підходів, реальні кейси розвитку відновлювальних технологій та моделей автономного енергопостачання у США, ЄС та Україні, а також порівняння моделей автономного енергозабезпечення. У результаті встановлено, що найбільш ефективними виявилися сонячні та гібридні (сонячно-біогазові) системи. В Україні у 2023 році було встановлено понад 5 000 домашніх сонячних установок, а в селі Нижній Бистрий (Закарпаття) гібридний енергетичний острів забезпечив енергопостачання 120 домогосподарств. У США сонячна генерація зросла на 16 % у 2023 році, а у 2024 році було зафіксовано зростання на 40 %. У ЄС у 2023 році середня собівартість виробництва електроенергії з сонячної енергії знизилася на 12 %. У Тоскані (Італія) відновлення енергопостачання енергетичним островом у 2022 році тривало 12 годин замість 72 у централізованій системі. В Україні денецтралізована генерація дозволила скоротити час відновлення до 3-6 годин у прифронтових регіонах (проти 12-18 годин традиційно), а собівартість електроенергії становила 0,08 доларів США/кВт · год порівняно з 0,12 доларів США/кВт · год у централізованій системі. Дослідження показало, що децентралізована генерація дозволяла підвищити гнучкість і стійкість енергосистем за рахунок скорочення втрат у мережі (до -10 %) і диверсифікації джерел постачання. Було виявлено, що інноваційні технології (цифрове управління, штучний інтелект, підвищували ефективність диспетчеризації, що дозволяло енергетичним островам і мікромережам автономно забезпечувати критичні об'єкти навіть у разі повного руйнування мережі. Практична цінність дослідження полягала у використанні його висновків для стратегій енергетичної безпеки, розвитку мікромереж і планування автономних систем у вразливих регіонах

Ключові слова: відновлювані джерела; автономність систем; сонячна енергія; вітрові турбіни; біоенергетика; цифрові технології