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GLOBAL AND REGIONAL CHALLENGES AND INTERNAL RISKS FACING THE UKRAINIAN ELECTRIC POWER SECTOR

©2026 **KOSTENKO D. M., KALASHNIKOVA K. YU.**

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Kostenko D. M., Kalashnikova K. Yu. Global and Regional Challenges and Internal Risks Facing the Ukrainian Electric Power Sector

The article identifies and systematizes global and regional challenges and internal risks facing the Ukrainian electric power sector under the conditions of the full-scale war, accelerated integration with the European energy space and global technological transformation. The relevance of the research is due to the fact that russia's full-scale military aggression has led to the deliberate destruction of electricity generation, transmission, and distribution facilities, worsened the shortage of maneuverable capacities, increased dependence on imported equipment and electricity, and also revealed the structural vulnerability of the centralized energy system architecture. The aim of the article is to scientifically substantiate the system of global, regional, and internal risks in Ukraine's electric power sector and to determine the role of distributed energy systems as a tool to enhance its resilience. The methodological basis of the study includes systemic, structural-logical, comparative, and statistical analysis, SWOT analysis, cause-and-effect modeling, as well as a summary of data from international organizations, Ukraine and EU regulations, IRENA statistical profiles, and analytical materials from the IEA, World Bank, EIA, Energy Community Secretariat, and UNDP. It is substantiated that the main global challenges are climate change, decarbonization, digitalization, the development of distributed energy resources, storage systems, smart grids, virtual power plants, and active consumers. Regional threats are related to systematic attacks on electricity infrastructure, the integration into the EU electricity market, dependence on external aid and the need to combine short-term crisis response with long-term modernization. Internal risks include excessive centralization of generation, aging networks, shortage of flexible capacity, insufficient development of storage grids, poor digitalization and institutional fragmentation. The scientific novelty lies in systematizing the multi-level structure of risks in Ukraine's electric power sector and substantiating the cause-and-effect relationship between the identified vulnerabilities and the need to develop resilient distributed energy systems for local communities. The practical value of the results is in the possibility of using them when forming energy recovery strategies, community energy resilience plans, and distributed generation development programs.

Keywords: *electric power sector; energy resilience; distributed energy systems; distributed generation; microgrids; renewable energy sources; territorial communities.*
Fig.: *3.* ***Tabl.:*** *8.* ***Bibl.:*** *39.*

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Костенко Д. М., Калашнікова К. Ю. Глобальні та регіональні виклики та внутрішні ризики, з якими стикається українська енергетика

У статті ідентифіковано та систематизовано глобальні та регіональні виклики, а також внутрішні ризики, що визначають сучасний стан і перспективи трансформації електроенергетичного сектора України. Актуальність дослідження зумовлена тим, що повномасштабна воєнна агресія російської федерації призвела до цілеспрямованого руйнування об'єктів генерації, передачі та розподілу електроенергії, загострила дефіцит маневрових потужностей, посилила залежність від імпорту обладнання та електроенергії, а також виявила структурну вразливість централізованої архітектури енергосистеми. Метою статті є наукове обґрунтування системи глобальних, регіональних і внутрішніх ризиків електроенергетичного сектора України та визначення ролі розподілених енергетичних систем як інструменту підвищення його резильєнтності. Методологічну основу дослідження становлять системний, структурно-логічний, порівняльний і статистичний аналіз, SWOT-аналіз, причинно-наслідкове моделювання та узагальнення даних міжнародних організацій, нормативно-правових актів України та ЄС, статистичних профілів IRENA та аналітичних матеріалів МЕА, Світового банку, EIA, Energy Community Secretariat і UNDP. Обґрунтовано, що ключовими глобальними викликами є кліматичні зміни, декарбонізація, цифровізація, розвиток розподілених енергетичних ресурсів, систем накопичення, розумних мереж, віртуальних електростанцій та активних споживачів. Визначено, що регіональні загрози для України пов'язані насамперед із системними атаками на електроенергетичну інфраструктуру, інтеграцією до енергетичного ринку ЄС, залежністю від зовнішньої допомоги та необхідністю поєднання короткострокового кризового реагування з довгостроковою модернізацією. До внутрішніх ризиків віднесено: централізованість генерації, зношеність мереж, дефіцит гнучких потужностей, недостатній розвиток накопичувачів енергії, слабку цифровізацію та інституційну фрагментарність. Наукова новизна полягає в систематизації багаторівневої структури ризиків електроенергетичного сектора України та обґрунтуванні причинно-наслідкового зв'язку між виявленими вразливостями та потребою розвитку резильєнтних розподілених енергетичних систем територіальних громад. Практична цінність результатів полягає в можливості їх використання під час формування стратегій енергетичного відновлення, планів енергетичної резильєнтності громад і програм розвитку розподіленої генерації.

Ключові слова: *електроенергетичний сектор; енергетична резильєнтність; розподілені енергетичні системи; розподілена генерація; мікромережі; відновлювані джерела енергії; територіальні громади.*
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Ukraine's electric power sector operates under an unprecedented mix of global transformation processes, regional security threats, and internal structural vulnerabilities. Russia's full-scale military aggression against Ukraine has caused not only the physical destruction of generation, transmission, and distribution facilities but has also radically changed the understanding of what energy security means. Before the war, it was mostly seen in terms of the adequacy of generating capacity, availability of energy resources, and stability of centralized power supply. Now, resilience has become crucial – the ability of the energy system to anticipate threats, absorb shocks, maintain critical functions, adapt, and quickly recover from disruptions [1; 2].

For Ukraine, this issue is of an applied nature. According to international organizations, the energy sector is among the most affected areas of the economy, with damage covering generation, transmission networks, distribution infrastructure, combined heat and power plants, balancing facilities, and centralized heating supply [3; 4]. As a result, the electric power sector is simultaneously facing a power capacity deficit, rising costs for emergency recovery, the need to import electricity and equipment, risks to critical consumers, and the necessity to integrate into the European energy market.

What's special about the current situation is that electric power risks are multi-leveled. On a global level, the sector is influenced by climate change, decarbonization, technological transformation, the development of distributed energy resources, energy storage systems, and smart grids. At the regional level, the key factors are military attacks on energy infrastructure, commitments to European integration, and dependence on international aid. At the national level, the challenges include centralized architecture, worn-out main assets, a shortage of flexible capacity, and underdeveloped storage and smart grids. At the local level, risks show up as disruptions in electricity supply to hospitals, waterworks, schools, shelters, administrative buildings, and local businesses.

The regulatory framework for response is already partially in place. The strategy for the development of distributed generation up to 2035 outlines the need to create generating capacities closer to consumers [5]. The national energy and climate plan for the period up to 2030 sets goals for decarbonization, the development of renewable energy sources, and energy efficiency [6]. The conception of implementing “smart grids” in Ukraine by 2035 lays the infrastructure foundation for the digital transformation of the electric power sector [7]. The updated 2024 EU electricity market design reform strengthens the role of active consumers, energy sharing, energy communities, and the protection of vulnerable consumers during crises [8; 9].

ANALYSIS OF RECENT STUDIES AND PUBLICATIONS

The issue of energy system resilience is actively developing in global scientific literature. A. Sharifi and Y. Yamagata systematize the principles for assessing urban energy system resilience, highlighting the importance of flexibility, diversification, autonomy, and the ability to recover quickly [1]. The other reviews of contemporary research on energy system resilience stress the need to move from traditional reliability to the broader category of robustness against high-impact events, including physical attacks, cyberattacks, extreme weather events, and cascading failures [10; 11].

A separate area of literature is devoted to microgrids, energy storage, and distributed energy resources. Research by S. Mishra and co-authors shows that microgrids can be seen as a tool for threat detection, reducing vulnerabilities, and supporting critical loads when the main grid is damaged [12]. The MEA in the roadmap for Ukraine directly links the development of distributed energy resources with increasing the resilience of the electric power sector during wartime [13].

In the domestic scientific space, relevant studies for this research include works on regional resilience, the placement of renewable energy sources in distribution networks, bioenergy potential, and the transformation of Ukraine’s energy system [14–18]. They confirm the need to combine technical-energy, economic, and territorial approaches. At the same time, existing studies do not sufficiently reveal the systemic connection between global challenges, regional threats, internal risks in the electric power sector, and the need to develop resilient distributed energy systems for territorial communities.

Therefore, the scientific gap lies in the absence of a comprehensive analytical framework that allows for the simultaneous identification of external and internal risks in Ukraine’s electric power sector, assessment of their impact on generation, transmission, distribution, and consumption of electricity, and substantiation of the role of decentralization as a response to these risks.

RESEARCH AIM AND METHODOLOGY

The aim of the article is to identify and systematize the global and regional challenges, as well as internal risks of Ukraine’s electric power sector, with a substantiation of the role of resilient distributed energy systems as a strategic response to the identified vulnerabilities.

The methodological basis of the study combines general scientific and specialized methods. System analysis was used to consider the electric power sector as a multi-level socio-technical system, which includes generation, transmission, distribution, consumers, market institutions, and regulatory bodies. Structural-logical analysis was applied to differentiate global challenges, regional threats, national structural risks, and local risks of territorial communities. Comparative analysis allowed us to compare the traditional centralized model of electric power sector with the model of distributed energy systems. Statistical analysis was used to assess the dynamics of electricity production and the structure of generation. SWOT analysis and cause-and-effect modeling were applied to summarize the identified risks and determine possible responses through distributed energy.

The research information base consists of analytical materials from the IEA, the World Bank, IRENA, EIA, the Energy Community Secretariat, UNDP, Ukrainian and EU regulatory and legal acts, as well as scientific publications on energy system resilience, distributed generation, microgrids, cybersecurity, and regional development [2–13; 19–30].

RESULTS AND DISCUSSION

Global challenges in the transformation of the electric power sector. The first group of factors consists of global challenges that determine the long-term development trajectory of the power sector (*Tbl. 1*). These include climate change, decarbonization, technological transformation, digitalization, electrification of end-use, the growing role of renewable energy sources, energy storage systems, virtual power plants, active consumers, and microgrids. These processes are not just an external backdrop for Ukraine; they directly shape the parameters of the national postwar energy recovery.

Climate change affects the electric power sector by increasing the frequency of extreme weather events, raising summer peak loads, reducing the efficiency of

Table 1

Global challenges for Ukraine's electric power sector and their importance for distributed energy systems

Group of global challenges	Challenge content	Potential impact on Ukraine	Importance for distributed energy systems
Climate change	Extreme weather events, changing temperature patterns, infrastructure risks	Rising peak loads, risks for heating supply, hydropower, and networks	Need for local backup, micro-grids, adaptive management
Decarbonization	Cutting down on fossil fuel use, developing renewable	Need to modernize generation, industry, and heating supply	Development of local renewables, bioenergy, cogeneration
Technological transformation	Distributed energy resources, energy storage systems, smart grids, virtual power plants, and active consumers	The need for new market and technical models	Creating active consumers, aggregators, and energy communities
Market instability	Price volatility, logistics disruption, equipment shortages	Increasing restoration costs and the risk of energy dependency	Growing role of local resources and local energy production
Cyber threats	Attacks on digital energy management systems	Risks of disrupting dispatching, accounting, and market operations	Need for cyber-resilient local management systems
New energy security paradigm	Shift from reliability to resilience	Need to rethink energy planning principles	Development of modular, flexible, autonomous energy solutions

Source: developed by the authors based on [1; 2; 7; 8; 11–16].

power plant cooling systems, limiting the potential of hydropower, and increasing grid failures. For Ukraine, this challenge is further intensified by the fact that a significant part of the electricity networks and generating capacities was designed for different climatic and technological conditions [31].

Decarbonization and the European Green Deal form another global challenge. The shift to a low-carbon economy opens up access for Ukraine to "green" financing and investments in renewable energy, but at the same time, it raises demands for grid modernization, balancing unstable generation, developing storage, flexible capacities, and market mechanisms. Maintaining a high dependence on fossil fuels in electricity production can increase economic risks for export-oriented industries in the context of EU carbon regulations [32].

Technological transformation is the third challenge. In the global electric power sector, the role of distributed energy resources is growing: small and medium solar power plants, wind generation, bioenergy installations, small cogeneration systems, batteries, heat pumps, electric vehicles, demand management systems, virtual power plants, and microgrids. These technologies are changing the traditional logic of "generation – transmission – distribution – consumption", turning the consumer into an active market participant [13; 33].

The fourth challenge is cybersecurity. Automated dispatch systems, SCADA, smart metering, digital aggregator platforms, and flexibility management improve the efficiency of the electric power sector, but at the same time create new vulnerabilities. For Ukraine, which already has experience with cyberattacks on energy infrastructure, digitalization should be seen not only as technological progress but also as an area with increased security requirements [34].

Regional external threats to Ukraine's electric power sector. The second group of factors covers regional external threats, with the central focus on the military aggression of the russian federation and systematic attacks on electric power infrastructure. Power plants, substations, autotransformers, power lines, distribution nodes, and balancing facilities have become targeted objects. The aim of such attacks is not only to reduce generation volume but also to disrupt the controllability of the power system, complicate electricity transmission between regions, create shortages during peak periods, and exert socioeconomic pressure on the population.

According to RDNA4, in 2024, Ukraine's energy infrastructure suffered additional damage from 13 massive attacks, with damages recorded in thermal generation segments, large hydroelectric plants, combined heat and power plants, as well as in electricity transmission and distribution. The available installed capacity at the end of 2024 was lower than the winter peak demand, which created a risk of a power shortage [4]. The pre-winter IEA 2025 assessment confirms that the attacks remained intense and targeted facilities critical for the functioning of the electric power system [19].

The regional threat also has an integration aspect. Synchronization with ENTSO-E opened up opportunities for Ukraine to import, export, and receive technical support, but at the same time it set requirements for adapting the electricity market to the European acquis, transparency, market integrity, corporate governance, balancing, and regulatory stability. The EU Directive 2019/944, new 2024 acts, and the practice of the Energy Community Secretariat create a framework within which Ukraine has to combine wartime crisis management with market and integration commitments [8; 9; 20; 21].

Another threat is the dependence on external equipment supplies. Restoring the power sector requires transformers, cables, relay protection systems, distribution devices, gas turbine units, batteries, and power electronics. Limited capacity of global supply chains, a shortage of specialized equipment, and intense competition for critical components can slow down recovery, raise project costs, and increase reliance on donor assistance.

Internal structural risks of Ukraine's electric power sector. The internal risks of Ukraine's electric power sector have been developing over a long time, but it's the war that turned them into critical issues (*Tbl. 2*). The *first risk* is the excessive centralization of generation and dependence on large energy hubs. Historically, Ukraine's energy system has been focused on large nuclear, thermal, and hydro plants, main transmission lines, and centralized dispatch management. In peacetime, this model provided economies of scale, but in wartime, the concentration of capacity became a source of systemic vulnerability [17; 18].

The *second risk* is insufficient spatial and technological diversification of generation. Before the full-scale war, distributed generation, microgrids, storage systems, active consumers, and energy communities did not play a systemic role. As a result, many territorial communities remained dependent on external electricity supply and lacked their own resources to support critical loads.

The *third risk* is a shortage of maneuverable and reserve capacities. Damage to thermal power plants, combined heat and power plants, hydropower facilities, and transformer infrastructure has made it harder to cover morning and evening peaks, balance renewable energy sources, and maintain the standard frequency in the grid. That's why developing distributed flexible capacities, local cogeneration, and energy storage is becoming not just an auxiliary task but a strategic one [4; 19].

The *fourth risk* is the wear and tear of electrical networks, substations, and control systems. High

Table 2

Internal structural risks of Ukraine's electric power sector

Risk	Manifestation in the sector	Consequence	Response direction
Centralized architecture	Concentration of generation in large facilities	Cascading damage effects	Distributed generation and microgrids
Shortage of maneuverable	Damage to thermal power plants, combined heat and power, hydroelectric plants	Difficulty in balancing and peak periods	Cogeneration, BESS, demand response
Worn-out networks	Aging lines, substations, and protection systems	Accidents, losses, connection limitations	Network upgrades and smart grids
Insufficient storage	Small role of BESS and thermal storage	Low flexibility and weak backup	Development of storage
Insufficient digitalization	Limited smart metering and automation	Complex DER management	Digital platforms, SCADA, cybersecurity
Financial instability	Debts, tariff restrictions, expensive capital	Low investment capacity	Grants, PPPs, energy service models
Institutional fragmentation	Inconsistency of rules, roles, and authorities	Slow implementation of local projects	Legislation adaptation and municipal energy management

Source: developed by the authors based on [4–6; 20–30].

levels of physical wear and obsolescence increase accidents, technical losses, maintenance costs, and make it harder to integrate renewables, BESS, and active consumers.

The *fifth risk* is the insufficient development of energy storage systems, which in modern energy systems perform functions like balancing, backup, frequency support, integrating unstable generation, and supplying critical loads.

The *sixth risk* is insufficient digitalization. Without smart metering, generation and demand forecasting, automated management, cybersecurity, and aggregator platforms, distributed generation doesn't turn into a controllable system.

The *seventh risk* is the financial instability of the sector, aggravated by electricity market debts, tariff limits, and high capital costs.

The *eighth risk* is institutional fragmentation and insufficient integration of energy planning into community development strategies [22–36].

Statistical assessment of the transformation of the electric power sector. Statistical assessment of the transformation of the electric power sector. Quantitative indicators (*Fig. 1, Tbl. 3*) confirm the scale of structural changes. According to IRENA data, in 2018–2021, electricity production in Ukraine remained relatively stable, ranging between 150–161 TWh. After the start of the full-scale invasion, production fell from 158 TWh in 2021 to 109 TWh in 2022 and 98 TWh in 2024, which is about 38% of the prewar baseline year [27; 28].

The reduction in production is explained not only by the drop in industrial demand, population migration, and the overall economic downturn, but also by the occupation of some generating capacities, damage to power plants, substations, and the grid infrastructure. Losing access to the Zaporizhzhia NPP, the destruction of thermal generation, and damage to the networks have significantly reduced the available production volume and complicated the system's balancing.

The electricity production structure in 2024 (*Tbl. 4*) shows a dual-sided situation. According to the U.S. Energy Information Administration, Ukraine produced about 97.6 TWh of electricity: 52 TWh came from nuclear power, 19 TWh from coal, 10.5 TWh from natural gas and other gases, 9 TWh from hydropower, 7 TWh from other renewables, and 0.1 TWh from oil and petroleum products [27; 28] (*Fig. 2*).

A high share of nuclear power provides a relatively low-carbon electricity supply, but it doesn't remove the risks of a centralized setup. Even with baseload generation, damage to transmission networks, autotransformers, and substations can limit electricity delivery to consumers. This highlights the need to combine large generating facilities with local sources, storage, and microgrids.

Renewable energy sources (RES) play an important role in shaping distributed architecture. In 2024, electricity production from RES amounted to 15.7 TWh, of which 9.0 TWh came from hydropower, 4.6 TWh from solar energy, 1.1 TWh from wind energy, and 1.0 TWh from bioenergy [27; 28] (*Tbl. 5, Fig. 3*).

In 2025, the role of renewable energy continued to grow: according to the Ukrainian Institute for the Future, citing ExPro, electricity production from solar, wind, bioenergy, and small hydropower plants increased by 6.4% compared to 2023 and reached 11 million MWh, while the share of renewable energy in the energy balance was about 11% [29]. For resilient

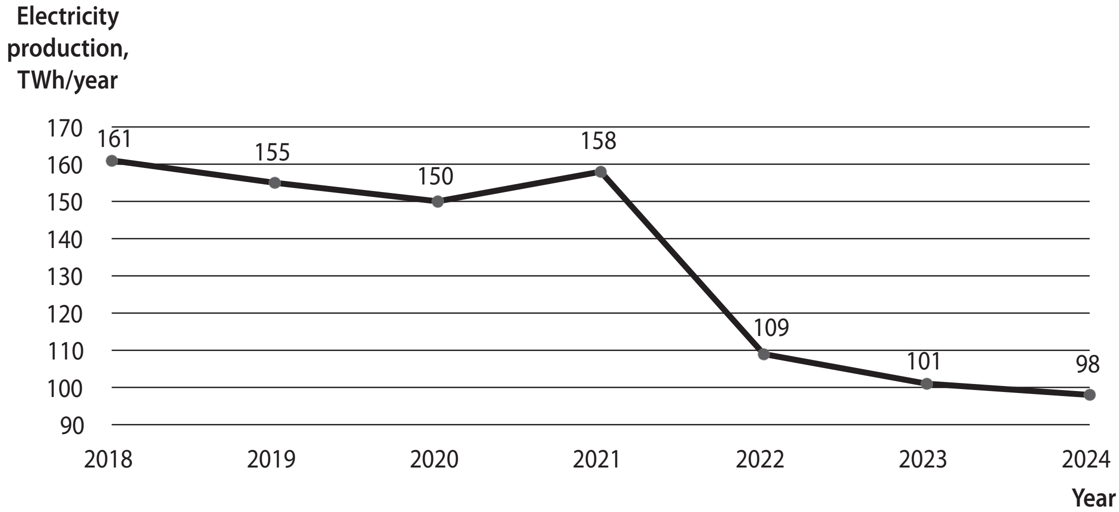

Fig. 1. Electricity production dynamics in Ukraine, 2018–2024

Source: composed by the authors based on the data [27; 28].

Table 3

Electric energy production dynamics in Ukraine in 2018–2024

Year	Production, TWh	Change compared to 2021, %	Analytical interpretation
2018	161	+1.9	Pre-war level of relative stability
2019	155	–1.9	Moderate decline in production
2020	150	–5.1	Impact of economic downturn and structural demand changes
2021	158	0	Baseline pre-war year
2022	109	–31.0	Sharp drop due to the full-scale war
2023	101	–36.1	Decrease in production due to loss of capacity and infrastructure destruction
2024	98	–38.0	Consolidation of lower production level due to loss of capacity and infrastructure destruction

Source: composed by the authors based on the data [27; 28].

Table 4

Structure of Ukraine's electricity production by source in 2024

Generation source	Volume, TWh	Share, %	Importance for resilience
Nuclear energy	52	53.28	Base low-carbon source, but highly dependent on network infrastructure
Coal	19	19.47	Maneuverable and thermal generation, vulnerable to attacks and fuel risks
Natural gas and other gases	10.5	10.76	Flexible source for backup and peak coverage
Hydropower	9	9.22	Important for balancing, but vulnerable to physical and hydrological risks
Other renewables	7	7.17	Promising base for decentralization, requires storage and flexibility
Natural oil/oil products	0.1	0.1	Marginal role
Total	97.6	100.0	–

Source: composed by the authors based on the data [27; 28].

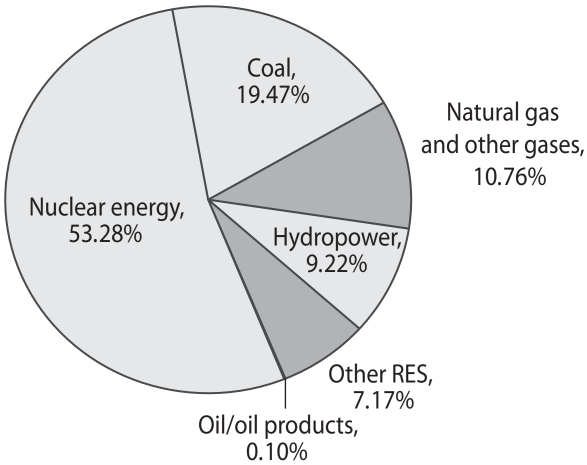

Fig. 2. Structure of electricity production in Ukraine by source in 2024

Source: composed by the authors based on the data [27; 28].

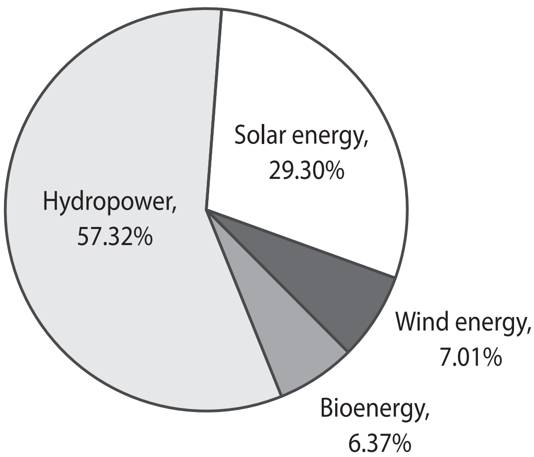

Fig. 3. Structure of electricity production from renewable energy in Ukraine in 2024

Source: composed by the authors based on the data [27; 28].

Table 5

Structure of electricity production from RES in Ukraine in 2024

RES Source	Volume, TWh	Share, %	Assessment from the perspective of distributed energy
Hydropower	9.0	57.32	Important for balancing, but geographically concentrated and vulnerable to attacks
Solar energy	4.6	29.3	Most suitable for local and community projects, but requires storage
Wind energy	1.1	7.01	Has significant potential, but some capacities are lost or unavailable due to the war
Bioenergy	1.0	6.37	Important for communities, as it can provide controllable generation and heat
Total	15.7	100.0	–

Source: composed by the authors based on the data [27; 28].

electric power systems, this means that renewables need to be developed not in isolation, but in combination with storage, demand management, flexible generation, and smart grids.

Risks for territorial communities as consumers and potential electric power industry stakeholders. At the local level, risks in the electric power sector show up as disruptions to specific vital functions (*Tbl. 6*). For territorial communities, a shortage or blackout of electricity means the risk of hospitals, water utilities, boiler houses, pumping stations, schools, shelters, administrative buildings, digital services, and local businesses shutting down. That's why communities should be seen not just as end-users, but also as potential players in building local energy resilience.

UNDP, within the Green Energy Recovery Programme, links the restoration of critical energy infrastructure with long-term green transformation, supporting local and regional energy stability, carrying out techno-economic studies at the regional and community levels, and ensuring the continuous operation of hospitals, water treatment facilities, and other basic services [30]. This shows why integrating energy projects into local strategic planning is necessary.

SWOT analysis and causal-risk map. To summarize the identified factors, a SWOT analysis was applied (*Tbl. 7*). Strengths include having a powerful integrated energy system, experience operating in isolation and synchronizing with ENTSO-E, significant renewable energy potential, developed gas transportation and distribution infrastructure, availability of bioenergy resources, engineering personnel, experience in emergency recovery, and increasing international support. Ukraine has already gained unique practical experience in maintaining the energy system during prolonged attacks, which the IEA considers a source of lessons for other countries on planning energy system resilience [2].

Weak points include high infrastructure wear and tear, centralized generation architecture, underdeveloped distributed generation, a limited number of storage systems, shortage of flexible capacities, financial instability of energy enterprises, institutional fragmentation, insufficient capacity of many communities to prepare quality energy projects, and underdeveloped energy communities.

Opportunities include postwar recovery following the build back better principle, integration into the EU energy market, attracting international financing, development of local generation, bioenergy, cogeneration, microgrids, smart grids, energy cooperatives, active consumers, storage systems, energy efficiency, and digital management. UNDP, in its green energy recovery program, emphasizes precisely the combination of immediate provision for critical infrastructure with a long-term transition to green, sustainable, and decentralized energy [39].

Threats include ongoing attacks on energy infrastructure, a shortage of generating capacity, winter period risks, rising equipment costs, dependence on external assistance, cyber threats, slow regulatory changes, energy poverty, inequality between communities, and the risk of returning to the old centralized model without considering new conditions.

Based on the SWOT analysis, four strategic conclusions can be drawn.

First, the strengths of Ukraine's energy sector – nuclear generation, engineering potential, international support, renewable energy resources, and crisis management experience – should be used not just to restore the pre-war system, but to create a more flexible and multi-level energy architecture.

Table 6

Risks to territorial communities in conditions of electric power sector instability

Risk group	Specific manifestation at the community level	Potential consequences	Priority response through distributed energy
Risk of power supply disruption	Power outages at critical facilities	Hospitals, schools, Centers for Administrative Services, shelters, pumping stations stopped	Local generation, batteries, microgrids for critical users
Risk of heat supply disruption	Boiler houses, CHP plants, pumping equipment stopped	Freezed out buildings, heat network accidents, humanitarian crisis	Cogeneration, bio-boilers, backup power for boiler houses
Risk of water supply and wastewater management disruption	No electricity for pumps	Water interruptions, sanitation risks	Solar plants with storage, diesel/biogas backup, water utility microgrid
Risk of dependence on natural gas	High share of gas boilers	Price risks, fuel shortage, dependence on imports	Biomass, energy crops, heat pumps, local cogeneration
Risk of financial incapacity	Limited community budget for energy projects	Lack of modernization, occasional generator purchases	ESCOs, grants, energy cooperatives, municipal energy service programs
Risk of managerial incapacity	No energy manager, no energy balance, no map of critical facilities	Chaotic crisis response	Municipal energy management, digital monitoring, local resilience plan
Risk of uneven resource potential	Different availability of biomass, sun, wind, and grid infrastructure	Unequal opportunities for communities	Typology of communities by energy potential
Risk of network damage	Destruction of lines, substations, transformers	Isolation of part of the community from energy supply	Network sectioning, local energy islands, microgrids
Risk of energy poverty	Households unable to pay for energy	Social tension, growing subsidies	Energy efficiency, rooftop solar panels, energy communities, targeted support
Risk of local business stoppage	Power outages for SMEs, agro-processing, services	Loss of jobs and budget revenue	Local energy hubs, shared reserves, RES for business clusters
Risk of weak public participation	Low trust in energy projects	Resistance to change, low investment activity	Energy cooperatives, community co-financing, transparent benefit models
Risk of lack of long-term planning	No emergency energy supply scenarios	Low readiness for future attacks or crises	Community energy resilience plan

Source: developed by the authors based on [17–19; 34].

Second, the weaknesses of Ukraine's energy system are mostly structural. They cannot be fixed simply by repairing damaged facilities. New technological and organizational solutions are needed: storage systems, microgrids, local generation, cogeneration, digital metering, energy communities, and municipal energy management.

Third, the biggest opportunities are at the level of territorial communities. It's the communities themselves that can combine local resources, critical needs, social participation, and spatial planning into a single model of energy resilience.

Fourth, the key threat lies not only in the continuation of attacks but also in the possibility of recreating the old centralized model without taking the lessons of the war into account. In that case, the rebuilt energy system would remain vulnerable to future physical, climate, market, and cyber shocks.

The cause-and-effect logic shows that distributed electricity is not an end in itself, but a response to specific vulnerabilities (*Tbl. 8*). Massive attacks on large power plants increase the need for spatially distributed generation. Damage to trans-

Table 7

SWOT matrix of Ukrainian energy sector in the context of building resilient distributed energy systems

S – strong points	W – weak points
High share of low-carbon generation thanks to nuclear energy	Excessive centralization of generating capacity
Experience of the energy system operating in isolation, synchronization with ENTSO-E, and during military attacks	Dependence of critical consumers on external electricity supply
Presence of extensive electrical, gas, and heat infrastructure	Significant wear and tear of electrical and heat networks
Significant potential of solar, wind, bioenergy, and small hydropower	Insufficient development of energy storage systems
Potential of biomass, agricultural waste, and energy crops in communities	Insufficient number of flexible and backup capacities
Presence of an engineering school and experience in emergency recovery	Financial instability of energy companies and the municipal sector
International support for Ukraine's energy recovery	Unclear legal status of microgrids, energy communities, and aggregators
Community experience in implementing energy efficiency and renewable energy projects	Low capacity of some communities to prepare investment projects
Opportunity to combine energy policy with postwar recovery	Insufficient digitalization of distribution networks and metering
O – opportunities	**T – threats**
Postwar reconstruction based on the «build back better» principle	Continued massive attacks on generation, networks and thermal infrastructure
Development of decentralized generation at the community level	Capacity shortages during winter peaks
Development of microgrids for critical infrastructure	Further destruction of maneuverable capacities
Scaling up bioenergy, cogeneration, and local heating supply	Dependence on imported equipment, transformers, batteries
Formation of energy cooperatives and communities	Cyber threats to digitalized energy
Integration with European energy markets	Regulatory lag compared to EU energy legislation
Attracting grants, loans, international technical assistance	Uneven community development and risk of energy inequality
Development of active consumers and aggregators	Energy poverty among the population
Using local resources to create jobs	Staff shortages in the energy sector and municipal management
Formation of local energy markets and energy hubs	The risk of reverting to the old centralized model without addressing vulnerabilities

Source: developed by the authors based on [2–8; 12; 20–38].

formers and substations justifies the development of microgrids and local energy islands. The shortage of maneuverable capacities requires cogeneration, BESS, and demand management. Cyber threats require cyber-resilient local control systems.

Role of distributed electric power systems in reducing identified risks. The challenges, threats, and risks identified indicate that one of the key directions for increasing the resilience of Ukraine's electric power sector is the development of distributed energy systems at the community level. Their role is not to completely replace the unified energy system, but to complement it with a new local layer of resilience capable of maintaining critical functions in case the main infrastructure goes down.

A territorial community's distributed electric power system can include local electricity sources, cogeneration units, bioenergy complexes, solar power plants, small wind turbines, battery systems, backup

Table 8

Map of cause-and-effect links between energy risks and responses through distributed energy

Threat	System vulnerability	Immediate consequence	Response through distributed energy
Massive attacks on large power plants	Concentration of generation in large facilities	Power shortages, emergency shutdowns	Distributed generation at the community level
Damage to substations and transformers	Consumer dependence on the main grid	Inability to deliver electricity even if generation exists	Microgrids, local energy islands
Destruction of thermal power plants and combined heat and power plants	Shortage of maneuverable capacity	Difficulty balancing the system	Cogeneration, bioenergy, gas engine plants
Damage to heating networks and boiler houses	Centralized dependence on heat supply	Risk of heating season disruption	Bio-boilers, local heat networks, heat storage systems
Electricity shortages during winter peaks	Low demand flexibility	Consumer blackouts	Demand management, batteries, energy efficiency
Climate extremes	Worn-out infrastructure and low adaptability	Network failures, system overloads	Decentralized backup sources, network sectionalization
Cyber threats	Dependence on centralized digital systems	Disruption of energy management	Cyber-resilient local control systems
Energy poverty	Low energy efficiency of buildings	Rising household costs	Energy efficiency, rooftop solar panels, energy communities
Weak community capacity	Lack of energy planning	Ad-hoc solutions without systemic effect	Community energy plans, municipal energy management
Uneven territorial development	Different resource bases and investment capacity	Deepening energy inequality	Community typology and differentiated energy system models
Loss of industrial load	Energy instability for businesses	Reduction of production and jobs	Local energy hubs for business

Source: authors' own development.

generators, microgrids, demand management systems, critical loads, control platforms, and organizational management structures. Overall, these elements can provide local autonomy, reduce the load on main networks, enable faster recovery after outages, save energy, and boost citizen and business participation in the energy transition [8; 9; 12; 13].

Microgrids are one of the most promising tools for local resilience. They allow you to connect distributed generation sources, storage, and consumers into a manageable system that can operate either in parallel with the main grid or in island mode. For territorial communities, this means being able to power critical facilities – hospitals, water utilities, boilers, schools, administrative buildings, shelters, and service centers – even if the external power supply is damaged [12].

Energy storage systems help reduce reliance on renewable generation schedules, support critical loads, provide backup power, smooth out consumption peaks, and improve power quality. Combined with local generation, they turn a community from a passive consumer into an active part of the electric power system [11; 26].

Bioenergy and cogeneration are especially important for Ukraine because they link electric power, heating, agricultural, municipal, and climate policies. Unlike solar and wind power, bioenergy and cogeneration plants can provide manageable electricity and heat generation. For communities with access to agricultural biomass, wood chips, energy crops, food industry waste, or biogas potential, this could form the foundation of a local energy system [16; 24].

Energy communities and cooperatives can provide an organizational mechanism for citizens and businesses to get involved in developing local generation. They allow pooling financial resources, increasing project acceptability, keeping some of the economic benefits in the community, and building a new culture of energy responsibility [8; 9].

Thus, distributed electric power systems are the answer to several groups of risks at once: physical – through the spread of generation; technological – through the use of smart grids, energy storage systems, and distributed energy resources; economic – through local use of resources; social – by supporting critical services; institutional – through new models of community participation; climate – through the development of RES, bioenergy, and energy efficiency.

Summing up the results of identifying challenges, threats, and risks. The carried out analysis allows us to conclude that the Ukrainian electric power sector is in the midst of a multi-level crisis, which is simultaneously a security, technological, economic, institutional, social, and climate crisis. Its peculiarity lies in the matter that short-term threats to the physical survival of the energy system are combined with long-term tasks of structural modernization, decarbonization, and European integration.

Global challenges are shaping the strategic context for the development of Ukraine's electric power sector. They require a move towards low-carbon, digital, flexible, and adaptive energy systems. Regional threats, primarily russian aggression and systematic attacks on energy infrastructure, create a direct need to enhance physical resilience, reserve capacity, decentralization, and local autonomy. National risks reveal the structural weaknesses of the current electric power model: centralization, aging infrastructure, lack of flexibility, insufficient digitalization, financial instability, and institutional fragmentation. Local risks show that territorial communities remain the most vulnerable and at the same time the most promising level for building energy resilience.

Statistical data confirm the depth of these changes. Electricity production dropped from 158 TWh in 2021 to 98 TWh in 2024, which is more than a third. At the same time, the structure of power generation remains dominated by nuclear energy, which provides a basic low-carbon output, but does not eliminate the risks associated with a centralized system, network vulnerabilities, and the underdevelopment of local backup sources [27; 28].

Under these conditions, developing resilient, distributed electric power systems for Ukraine's territorial communities should be seen as a strategic response to a multi-level risk system. Its essence is not to abandon the centralized energy system, but to create an additional local layer of energy resilience capable of supporting critical community functions if the main infrastructure is disrupted.

Therefore, the identified challenges and risks provide a scientific basis for further substantiation of transitioning from the traditional centralized electric power model to decentralized, distributed, and resilient energy systems. This directly corresponds to the logic of the study, within which identifying global, external regional threats and internal problems is the first stage of forming a conceptual model of resilient distributed energy systems for territorial communities.

Limitations of the study and prospects for further research. *First*, statistical data on Ukraine's electric power sector under wartime conditions are partially restricted for security reasons, and certain indicators may be revised after clarifying information about damages, recovery, and actual capacity availability. *Second,* risk assessment at the level of territorial communities requires detailed local energy balances, maps of critical consumers, and data on the technical condition of the distribution networks, which are not always publicly available or standardized. *Third,* the article is analytical and procedural in nature and does not claim to provide a complete quantitative model for assessing resilience.

It makes sense to link the prospects for further research with the development of an integrated resilience index for distributed energy systems in territorial communities, which would take into account technological, infrastructure, economic, institutional, and security parameters. This index could include indicators such as local generation, availability of storage, the share of critical loads with backup power, the level of network digitalization, the presence of energy management, the financial capacity of the community, and the potential of renewable energy sources.

Another direction for further research is the comparison of Ukrainian experience with EU country practices regarding local energy communities, microgrids, demand management, and storage systems. It is especially important to determine which elements of European experience can be adapted in the context of Ukraine's wartime and postwar recovery, and which require special models considering security threats, financial constraints, and uneven resource potential of the communities.

CONCLUSIONS

The conducted research allows us to conclude that Ukraine's electric power sector is simultaneously influenced by global transformational challenges, regional military-geopolitical threats, and internal structural risks. The global challenges are related to climate change, decarbonization, digitalization, the development of renewable energy sources, storage systems, smart grids, microgrids, and active consumers. Regional threats arise from systematic attacks on electric power infrastructure, integration into the European energy market, dependence on imported equipment, and the need to combine military crisis management with market obligations. Internal risks are determined by centralized generation architecture, aging networks, a lack of flexible capacities, insufficient development of storage systems, digitalization, and local energy planning.

Statistical analysis confirmed the scale of the transformation: electricity production fell from 158 TWh in 2021 to 98 TWh in 2024, which is more than a third. The generation structure shows the dominance of nuclear power, but at the same time highlights the system's reliance on the grid infrastructure and the limited role of distributed resources. The development of renewables, BESS, microgrids, local cogeneration, active consumers, and energy communities should be seen as a strategic direction for improving electric power system resilience.

The scientific novelty of the study lies in systematizing the multi-level structure of risks in Ukraine's electric power sector and substantiating the cause-and-effect relationship between the identified threats, structural vulnerabilities, and the need to develop resilient distributed energy systems for territorial communities. The practical value of the results lies in the possibility of using them to prepare energy recovery strategies, distributed generation development programs, local energy resilience plans, and prioritization of projects supporting the consumers of critical importance. ■

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