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Research Article

Role of distribution networks in rebuilding energy infrastructure in Ukraine

Yuliia Malohulko*, Olena Sikorska, Natalia Ostra, Vira Teptia

Department of Electrical Power Plants and Systems, Vinnytsia National Technical University, Vinnytsia, Ukraine

Abstract. The study aimed to justify technical, organizational and digital solutions for improving the stability and reliability of Ukraine's electricity distribution networks during recovery from large-scale war damage. A reconstruction-oriented analytical framework was applied that combined regional damage and network-loading indicators, System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) reliability metrics, renewable-energy integration, scenario-based assessment of energy storage systems (ESS), and quantitative international benchmarking of Smart Grid technologies. The analysis covered the Kyiv, Kharkiv and Lviv regions and used official regulatory data, distribution system operator materials and international reports for 2022-2025. Recorded damage to 0.4-10 kV power lines decreased from 7.8 thousand km in 2022 to 2.4 thousand km in 2025, while the number of damaged transformer substations declined from 340 to 120. Nevertheless, regional capacity utilization remained high, particularly in the Kyiv and Kharkiv regions. In 2022, SAIDI reached 1,200 min/consumer/year and SAIFI 4.1 outages/consumer/year, approximately 8.9 and 4.1 times the corresponding EU averages, respectively. By 2025, these indicators had declined to 850 min/consumer/year and 3.2 outages/consumer/year but remained approximately 7.1 and 3.6 times the corresponding EU averages. Scenario analysis showed that ESS support equivalent to 10% of regional load could reduce network utilization by approximately 8-9 percentage points in the most heavily loaded regions, while sensitivity analysis across the 5-15% support range confirmed the same direction of effect. International Smart Grid benchmarks indicated potential reductions in SAIDI of 29-38% and SAIFI of 18-28%, although these values were treated as comparative benchmarks rather than direct forecasts for Ukraine. The findings indicate that post-war reconstruction should combine physical restoration with increased redundancy, ESS deployment, automated control, secure digital monitoring and region-specific modernization priorities.

Keywords: Control automation; cyber protection; intelligent control systems; microgrids; power supply stability; renewable sources; technology flexibility.

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1. Introduction

As a result of the Russian full-scale invasion of Ukraine, distribution networks suffered extensive damage, leading to a decline in the reliability and stability of the electricity supply. The problem was caused by the high level of physical wear and tear of equipment, insufficient power reserves, dependence on centralised nodes and limited use of modern technologies, which exacerbated the negative consequences of the destruction. As a result, the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) significantly exceeded the European average, indicating the critical state of the network infrastructure. Eliminating these limitations creates opportunities to improve the stability and reliability of the system through the integration of renewable energy sources (RES), the introduction of energy storage systems (ESS) and smart grid technologies, which can ensure adaptability and reduce interruptions in electricity supply (Pavlovicova, 2015, Mitali *et al*., 2022, Escobar *et al*., 2021).

An analysis of scientific sources revealed that previous research on distribution networks has developed along several relatively separate trajectories. The first group of studies focuses on the technological transformation of distribution systems through smart grids, digitalisation, intelligent monitoring and cybersecure communication architectures (Escobar *et al*., 2021, Javid *et al*., 2024, Cao *et al*., 2022, Gönen *et al*., 2024, Rai *et al*., 2020, Hu *et al*., 2021). These works demonstrate the technical potential of decentralised sources, automated control, fault classification and advanced communication tools; however, they generally examine distribution networks under normal or planned modernisation conditions rather than under conditions of large-scale physical destruction. The second group of studies examines the integration of RES and ESS (Pavlovicova, 2015, Mitali *et al*., 2022, Li *et al*., 2021, Fatima *et al*., 2021). Their main contribution lies in assessing photovoltaic hosting capacity, storage dispatch and load-balancing mechanisms, but they usually treat RES and ESS integration as a technical or economic optimisation problem, without linking it to war-induced damage, uneven regional demand and emergency restoration priorities. The third group of studies addresses the Ukrainian post-war infrastructure context (Kosse, 2023, Popik, 2022, Aebi *et al*., 2024, Holovko & Haug, 2023). These works are important for understanding reconstruction principles, the need for green recovery and the interdependence of energy, transport and communication systems, yet they provide limited quantitative

* Corresponding author
Email: malohulkoo@ukr.net (Y. Malohulko)

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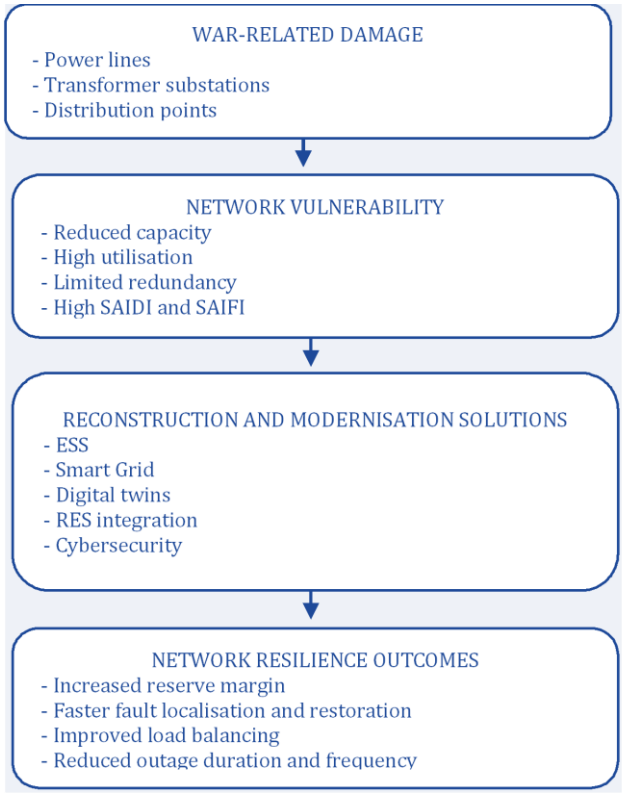


Fig. 1. Conceptual framework for resilience-oriented reconstruction of Ukraine's electricity distribution networks

assessment of distribution-network reliability and do not sufficiently connect reconstruction priorities with smart grid, ESS and digital twin technologies.

Despite these advances, the existing literature does not provide a structured analytical procedure for translating war-related distribution-network damage into technology-specific reconstruction priorities. The research gap therefore extends beyond the limited integration of smart grids, RES, ESS and digital twins in previous studies. It concerns the absence of an analytical framework that jointly considers physical infrastructure damage, operational reliability, regional loading constraints and the suitability of technological responses under conditions of large-scale destruction and incomplete recovery.

The present study addresses this gap by applying a reconstruction-oriented analytical framework consisting of three interconnected stages. First, regional network vulnerability is assessed using documented damage to distribution infrastructure, SAIDI and SAIFI reliability indicators, capacity-utilisation rates and reserve-capacity constraints. Second, the potential contribution of ESS and digitalisation is evaluated through scenario-based calculations and comparison with quantitative international benchmarks. Third, the identified mechanisms of vulnerability, including physical damage, overload, limited redundancy, restricted fault localisation and balancing constraints, are linked to specific technical and organisational responses, including ESS deployment, automated switching, Supervisory Control and Data Acquisition (SCADA)-based monitoring, smart grid technologies and digital twins. This approach differs from technology-centred reviews and policy-oriented reconstruction studies because it uses observed wartime network conditions as the basis for determining the applicability and priority of individual modernisation measures rather than treating these technologies as universally transferable solutions. The relationships among the diagnostic indicators, identified vulnerability mechanisms, technological responses and expected resilience outcomes are summarised in Fig. 1.

Within this framework, the study aimed to justify technical, organisational and digital solutions capable of improving the stability and reliability of Ukraine's electricity distribution networks in the context of post-war reconstruction. To achieve this aim, the study applied the integrated analytical framework to connect quantitative evidence on war-related infrastructure damage, regional network loading, SAIDI and SAIFI dynamics, renewable-energy integration and international technological benchmarks with specific reconstruction priorities. The scientific contribution therefore lies in converting these heterogeneous data into a structured and regionally differentiated assessment of which modernisation measures are most appropriate for particular vulnerability mechanisms and under which operational constraints their expected benefits should be interpreted.

2. Materials

The study was conducted between 2022 and 2025, covering periods of large-scale military destruction, partial reconstruction of energy infrastructure, and initial implementation of digital solutions. The object of analysis was Ukrainian power distribution networks, as they proved to be the most vulnerable to external influences and, at the same time, crucial for ensuring an uninterrupted power supply. The spatial scope of the study included the Kyiv, Kharkiv, and Lviv regions. These regions were selected not as a statistically exhaustive representation of the entire Ukrainian electricity distribution system, but as purposive comparative cases reflecting three contrasting operational conditions. The Kyiv region represented a central high-demand network with a large concentration of consumers and strategic significance for the national power

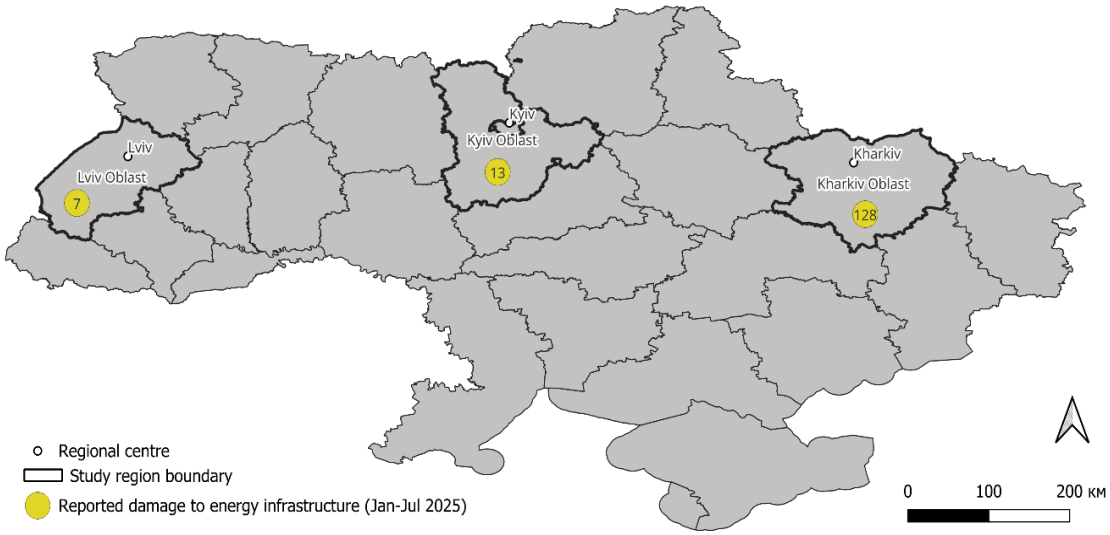


Fig. 2. Geographical location of the Kyiv, Kharkiv and Lviv study regions and reported damage to energy infrastructure in January-July 2025
Source: compiled by the authors based on data (Assessment Capacities Project (ACAPS), 2025a).

system. The Kharkiv region represented an eastern region exposed to extensive war-related damage and incomplete infrastructure recovery. The Lviv region represented a western region with relatively stable network operation and stronger potential for renewable energy integration. Together, these cases made it possible to compare high consumer concentration, severe physical damage and relatively stable post-crisis functioning within one analytical framework. National-level reports and consolidated regulatory data were used to contextualise these regional cases and avoid interpreting them as isolated examples. The geographical location of the three study regions and the reported damage to energy infrastructure in January-July 2025 are shown in Fig. 2.

For international comparison, several countries and regions with experience in integrating innovative technologies were selected: Germany (Bavaria, North Rhine-Westphalia, Berlin), Spain (Andalusia, Catalonia), Denmark (Fredericia), Italy (Lombardy), France (Hauts-de-France, Paris), Poland (Masovian Voivodeship), the Netherlands (Amsterdam), Australia (South Australia (Hornsdale)), and the United States (Texas, New York). These regions were selected due to their representativeness and the presence of large-scale projects that have been implemented. Bavaria, North Rhine-Westphalia and Berlin demonstrate different models of energy development in Germany, ranging from regions with a high concentration of renewable sources to centres of network digitalisation. In Spain, Andalusia and Catalonia have become pilot sites for the integration of solar and wind systems with storage facilities. Fredericia in Denmark was chosen due to the implementation of Ørsted's first large-scale project combining ESS and wind generation. Lombardy in Italy and Oise in France represent regions with high loads on the power system and a need to optimise distribution networks. The Mazovia Province in Poland is notable for its active development of SCADA and microgrids. Amsterdam in the Netherlands has become a key example of the use of digital twins for network modelling. In Australia, South Australia (Hornsdale) was selected as an example of one of the world's largest lithium-ion storage facilities, in the United States, Texas was chosen as a region with high peak loads and large-scale ESS projects (Gambit), and New York was chosen as a centre for the development of cybersecurity solutions and the digitalisation of energy infrastructure. These examples were chosen because of the large-scale projects that have been implemented there: Innovative Battery Park in Bavaria, Solar-ESS Integration Project in Andalusia, Ørsted Fredericia Battery Storage Project in Denmark, Hornsdale Power Reserve Extension in South Australia, Gambit Energy Storage Project in Texas, as well as the implementation of digital solutions in key European and American energy centres (Enkhardt & Siemer, 2024, REGlobal, 2024, Strategic Energy, 2025, Australian Renewable Energy Agency, 2024, Mathrani, 2025).

The key open sources included reports by the International Energy Agency (IEA, 2023), which documented the extent of damage to Ukraine's energy infrastructure in 2022-2023; a study by the Energy Charter Secretariat (2023) providing a quantitative assessment of losses in distribution networks and transformer substations; analytical materials from DTEK and the Kyiv School of Economics detailing the dynamics of facility restoration (Piddubnyi & Goriunov, 2024); and reports by the Assessment Capacities Project (ACAPS, 2024) on the consequences of attacks on energy facilities. For the international context, Institute of Electrical and Electronics Engineers (IEEE) standards and International Council on Large Electric Systems (CIGRE) technical brochures provided the methodological basis for damage classification.

Some of the quantitative indicators, in particular, detailed data for 2024-2025 on transmission capacity, utilisation rates, SAIDI and SAIFI reliability indicators, and installed renewable generation capacity, were based on reports, public and non-public materials, and open publications by distribution system operators. For DTEK Kyiv Electric Networks, the official company announcement "DTEK restores 1,441 energy facilities in first half of 2025" (DTEK, 2025), the agency publication "Restoration of networks after hostilities by DTEK companies in H1 2025 equals volumes for entire 2024" (Interfax-Ukraine, 2025), and the information "DTEK Kyiv Regional Grids restore over 3,000 energy facilities, 10,000 km of power lines in 1,000 days of war" (Interfax-Ukraine, 2023) were used. For Joint Stock Company (JSC) Kharkivoblenergo (2024), the Report of the executive body (Management) for 2024 was used. For Private Joint Stock Company (PJSC) Lvivoblenergo (2024a, 2024b, 2024c, 2024d), reports on electricity supply reliability (continuity) indicators were used: for Q1 2024, Q2 2024, Q3 2024 and Q4 2024. Additional verification was provided by the

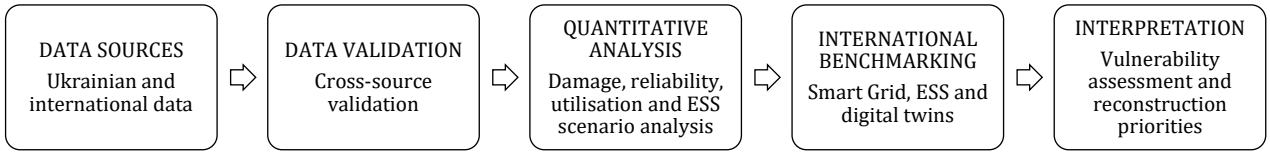


Fig. 3. Workflow of the analytical procedure used in the study. *Source: compiled by the authors.*

consolidated "Report on the quality of services provided by licensees in 2024" by the National Commission for State Regulation in Energy and Utilities (NKREKP) (2025) and the ACAPS (2025b) analytical study "Ukraine: Energy infrastructure attacks updated outlook and impact during the 2024-2025 cold season". This approach combined non-public materials with official open reports and communications, ensuring the representativeness and reliability of the assessment of distribution network operations during the war.

To improve data reliability and manage uncertainty, all quantitative indicators were subjected to cross-source validation. First, official regulatory and international reports were treated as primary verification sources, while operator communications and non-public materials were used only when they were consistent with these sources or provided more detailed regional information. Second, values on damaged power lines, transformer substations, capacity utilisation, SAIDI, SAIFI and renewable generation were compared across at least two available source categories whenever possible. Third, inconsistent values were checked against the reporting period, territorial coverage, measurement unit and object classification. When discrepancies could not be fully resolved, the more conservative value was retained, and the result was interpreted as an approximate estimate rather than an exact measurement. This procedure reduced the risk of overestimating restoration progress or digitalisation effects under conditions of incomplete wartime reporting.

The overall analytical workflow, from data collection and validation to quantitative analysis, international benchmarking and interpretation, is summarised in Fig. 3. A separate section analysed materials from international organisations and energy companies, regarding the implementation of smart grids in Germany, Italy, France, Spain and Poland, as well as initiatives to develop digital twin technology in the Netherlands, Germany, the EU and the US (Federal Ministry for Economic Affairs and Energy, 2025, Italy Tomorrow, 2022, French Energy Regulatory Commission, 2025, Iberdrola Spain, 2025, Electrum Poland, 2025, Digital Twin, 2025, Destination Earth, 2025, European Commission, 2024, Digital Twin Consortium US, 2025). These sources provided practical examples of the integration of digital solutions and RES in different regional conditions, which formed a representative international context for assessing the prospects for modernising Ukrainian distribution networks.

For digital twin technologies, the analysis considered not only expected reliability effects, but also practical implementation requirements. These included the availability of real-time network data, SCADA integration, smart meters, sensor coverage, geospatial models of network assets, secure communication channels, cloud or hybrid computing infrastructure, and qualified personnel for model calibration and interpretation. Since wartime damage limits data completeness and access to infrastructure, digital twin deployment was treated as a phased modernisation tool rather than an immediately scalable nationwide solution.

Statistical analysis combined descriptive statistics with exploratory trend and sensitivity analyses. For the annual series covering 2022-2025, linear trends were estimated for the principal damage and reliability indicators. The annual slope and coefficient of determination (R^2) were used as descriptive measures of the direction and consistency of change. Because each time series contained only four annual observations, the trend models were not used for formal hypothesis testing or causal inference. In addition, the robustness of the ESS scenario was assessed by varying dispatchable ESS support from 5% to 15% of actual regional load around the baseline 10% assumption and recalculating network utilisation and reserve-capacity margins. Given the incompleteness of wartime reporting, uncertainty was addressed through cross-source validation and scenario bounds rather than formal confidence intervals.

The prospects for modernising distribution networks were assessed by analysing the impact of introducing smart grids, ESS and digital twins, incorporating their effect on power supply reliability and system stability (Mitali *et al.,* 2022, Escobar *et al.,* 2021, Batty, 2018). Based on data from distribution system operators and international reports, the impact of digital technology integration on reducing the duration and frequency of outages, as well as on increasing the system's resilience to crises, was modelled. Cybersecurity was assessed as a cross-cutting factor affecting the reliability of digitalised distribution networks. The analysis considered the main vulnerability pathways relevant to Ukrainian conditions: SCADA and dispatching systems, remote access channels, smart meters, substation automation devices, digital twin data platforms and communication links between operators and field infrastructure. These pathways were evaluated in relation to three types of risk: loss of monitoring capability, manipulation of operational data, and disruption of automated control functions. Mitigation options were interpreted through technical and organisational measures, including information technology (IT) and operational technology (OT) network segmentation, multi-factor authentication, encryption of operational data, role-based access control, continuous event monitoring, backup communication channels and incident-response protocols. To assess the technical parameters of network throughput capacity, its utilisation coefficient was calculated using formula (1)

$$K = Pf/Pmax \times 100, \quad (1)$$

where Pf – actual network load, $Pmax$ – throughput capacity. This coefficient quantified the level of network loading, but it was not treated as a standalone indicator of wartime resilience. For a more comprehensive assessment, it was interpreted together with SAIDI and SAIFI reliability indicators, the number of damaged network elements, the availability of reserve capacity, the integration of ESS and RES, and the presence of digital monitoring and automated control tools. The reserve-capacity margin was calculated as the difference between available network capacity and actual or scenario-adjusted effective load; lower margins indicated weaker redundancy and a higher probability of cascading outages during external shocks. Since detailed node-level voltage and outage-probability datasets were not fully available under wartime conditions, voltage stability and probabilistic reliability were assessed indirectly through capacity utilisation,

outage duration, outage frequency and emergency shutdown dynamics. In addition to descriptive comparison, the study applied a scenario-based analytical interpretation of reliability dynamics. The expected effect of digitalisation was assessed by comparing the observed Ukrainian SAIDI and SAIFI values with international smart grid benchmarks, where automated switching, smart meters, SCADA systems and predictive analytics reduced outage duration and frequency. This approach made it possible to estimate the potential contribution of digitalisation measures to reliability improvement without presenting them as direct causal effects.

For quantitative international benchmarking, the 2025 Ukrainian SAIDI and SAIFI values were normalised relative to the corresponding EU averages. In addition, the percentage reductions reported for the international Smart Grid cases were applied to the Ukrainian 2025 baseline to estimate the remaining reliability gap under each benchmark scenario. The normalised benchmark ratio was calculated as follows (2):

$$N_{i,X} = \frac{X_{UA\left(1-\frac{r_{i,X}}{100}\right)}}{X_{EU}} \qquad (2)$$

where $N_{i,x}$ is the normalised benchmark ratio for SAIDI or SAIFI, X_{UA} is the observed Ukrainian value in 2025, X_{EU} is the corresponding EU average, and $r_{i,x}$ is the percentage reduction reported for the respective international Smart Grid case. For the observed Ukrainian baseline, r=0. A value of 1.0 represents the EU average, while values above 1.0 indicate a remaining reliability gap. The calculation was used for comparative benchmarking rather than forecasting or causal inference.

During the analysis of renewable energy integration, data from the State Agency on Energy Efficiency and Energy Saving of Ukraine (2024a, 2024b) on the installed capacity of solar and wind power plants were used. For the Ukrainian case, an ESS-support ratio was defined as the ratio of dispatchable ESS capacity to actual regional load. A 10% ESS-support scenario was used as the baseline assumption, with sensitivity analysis performed at 5%, 10% and 15% support levels. For each scenario, effective load was calculated by subtracting the assumed ESS-supported load from actual load. The adjusted utilisation rate was calculated as the ratio of effective load to available network capacity, while the reserve-capacity margin was calculated as the difference between available network capacity and effective load. These scenarios were treated as indicative estimates rather than forecasts because actual storage dispatch depends on technology, location, storage duration and operating conditions.

Uncertainty was managed by avoiding unsupported extrapolation from single operator reports to the entire national system. Regional data were interpreted together with national-level reports, while international cases were used as benchmarks rather than direct equivalents of Ukrainian conditions. A preliminary techno-economic interpretation was also applied to compare two reconstruction strategies: traditional replacement of damaged infrastructure and digitalised modernisation. The comparison considered investment requirements, expected operational savings, reduction of outage-related losses, maintenance efficiency, and the possibility of attracting mixed funding from public budgets, distribution system operators, international donors and green recovery programmes. This assessment was qualitative and scenario-based, as detailed project-level cost data were not fully available under wartime conditions. The results were interpreted by combining statistical analysis and comparison with international practice. Quantitative data were used to confirm trends, while analysis of practical experience in other countries provided conclusions regarding the possibilities for adapting digital and technical solutions to Ukrainian conditions. This yielded a comprehensive picture of the state, problems and prospects for the development of electricity distribution networks in the post-war period.

3. Results

3.1 The condition and vulnerability of electricity distribution networks in the context of war damage

The annual distribution of the data by asset category makes it possible to track changes in the recorded damage burden and identify the network elements most affected during 2022-2025. The temporal evolution of the main categories of damaged distribution-network assets is presented in Fig. 4. The figure shows changes in the recorded length of damaged power lines and the number of damaged transformer substations and distribution points, providing a basis for assessing the direction and consistency of wartime damage trends,

Exploratory linear trend analysis confirmed the direction of the changes shown in Fig. 4. Over 2022-2025, recorded damage to 0.4-10 kV lines decreased by approximately 1,780 km per year (R^2=0.969), while damage to 35-150 kV lines decreased by approximately 525 km per year (R^2=0.994). The corresponding annual declines were approximately 74.5 transformer substations (R^2=0.998) and 39 distribution points (R^2=0.984). These coefficients describe the consistency of the

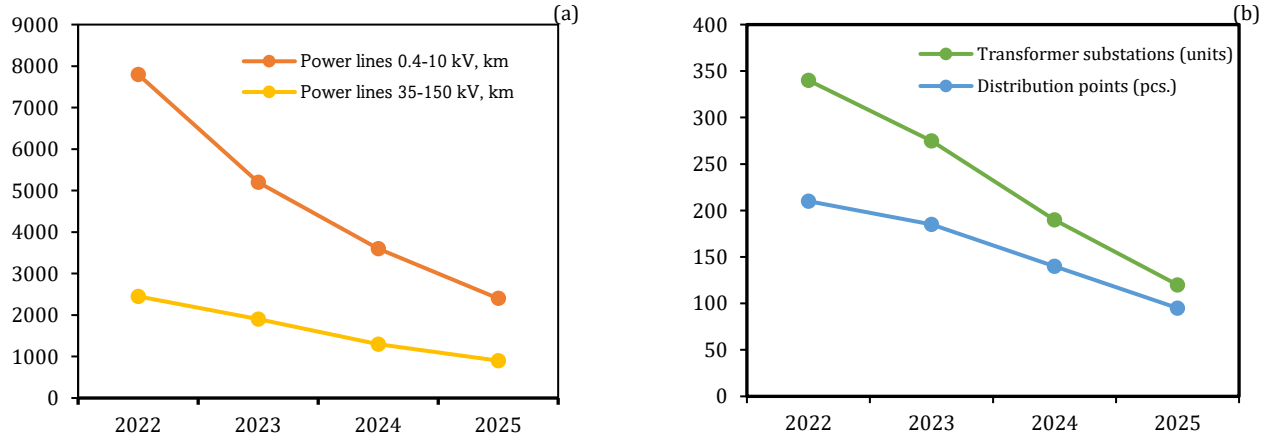


Fig. 4. Dynamics of damage to Ukraine's electricity distribution networks in 2022-2025: (a) damaged power lines; (b) damaged transformer substations and distribution points. Note: km – kilometres; kV – kilovolts; pcs. – units of objects. Source: compiled by the authors based on data (IEA, 2023; Energy Charter Secretariat, 2023; Piddubnyi & Goriunov, 2024; ACAPS, 2024, 2025b; DTEK, 2025; Interfax-Ukraine, 2023, 2025).

observed temporal decline but should not be interpreted as forecasts or causal estimates because the series contains only four annual observations and wartime reporting remains incomplete.

Analysis of the aggregated data shows a gradual decrease in the recorded damage burden after the peak level observed in 2022. However, this trend should not be interpreted as direct evidence of full infrastructure recovery. The reduction in recorded damage may reflect several simultaneous processes: partial restoration of damaged facilities, changes in the intensity and geography of attacks, reorientation of strikes toward other energy-system components, improved emergency localisation by operators, and incomplete wartime reporting. Therefore, the decline in damage to power lines, transformer substations and distribution points indicates a lower recorded damage burden, but it does not independently prove that the distribution network returned to a stable or pre-war condition.

The greatest losses were observed in the low- and medium-voltage power line segment (0.4-10 kV), due to its considerable length, high density and vulnerability to external influences. At the same time, the most critical cases remained the destruction of transformer substations and distribution points, since damage to even a limited number of these elements caused large-scale disruptions in local power systems. For this reason, the damage statistics were interpreted together with SAIDI, SAIFI and capacity-utilisation indicators. This combined interpretation showed that, despite the decline in recorded damage in 2024-2025, the system continued to operate under high technical stress and required reconstruction measures aimed at redundancy, automation and improved fault localisation.

For a systematic justification of the technical characteristics of damage, it is advisable to apply international classification approaches. IEEE and CIGRE standards provide a unified description of different types of damage, which can be used to compare Ukrainian observations with global practice. Applying these approaches to the 2022-2025 data provided a basis for interpreting the nature of damage and determining its effects on the technical parameters of power-system operation. Presenting classification approaches in tabular form (Table 1) makes it possible not only to systematise information, but also to develop practical recommendations on priorities for restoring critical infrastructure elements.

Analysis of the data in Table 1 shows that destruction and systemic failures are the most critical for the power system, as they lead to large-scale outages and require complete replacement of equipment, which involves significant time and financial costs. Partial damage and functional failures are less destructive, but their impact on grid stability is significant, as they increase the probability of cascading outages and reduce the reliability of the power supply. Secondary damage is complex in nature, arises from accompanying factors and complicates the localisation of accidents, which decelerates the recovery process. The application of international classification in accordance with IEEE and CIGRE standards can be used not only to systematise Ukrainian experience in the field of restoration, but also to integrate it into the global practice of technical damage analysis, forming the basis for further optimisation of decisions in the field of energy infrastructure.

The practical value of this classification was reflected in the prioritisation of restoration measures. In cases classified as complete failure, such as the destruction of transformer substations, restoration priority was given to equipment replacement and the creation of temporary supply routes, because such damage immediately caused large-area outages. In cases of partial damage to 35-150 kV lines, operational decisions focused on temporary repair, load limitation and phased restoration, since the damaged elements could still retain limited functionality. Functional failures, including switching-device malfunction caused by overload, required rapid diagnostics, remote monitoring and redistribution of load to prevent cascading outages. System disturbances caused by simultaneous damage to several lines were treated as high-priority emergency cases, where the main operational decision was to isolate the affected segment and restore supply through alternative network paths. Secondary damage, especially fires at distribution points after strikes on adjacent facilities, required safety localisation before technical repair could begin.

Thus, the IEEE/CIGRE-based classification was used not only as a descriptive tool. It helped distinguish between damage requiring immediate replacement, temporary repair, emergency isolation, load redistribution and safety-related intervention. For Ukrainian distribution networks, this approach supported more differentiated restoration logic: transformer substations and distribution points were prioritised when their failure affected large consumer groups, while line damage and functional failures were addressed through temporary switching, repair sequencing and automation-based fault localisation.

A systematic review of the data obtained confirms that the restoration of distribution networks cannot be limited to merely eliminating the consequences of war damage. The key factors remain internal technical limitations that were embedded in the

Table 1
Classification of damage to electrical distribution networks according to IEEE and CIGRE standards, with examples of application for Ukraine

Damage category (according to IEEE/CIGRE)	Damage characteristic	Typical cases for Ukraine (2022-2025)	Technical consequences
Complete failure	Complete loss of functionality of the element, need for replacement	Destruction of transformer substations in central and northern regions	Power outages affecting large areas, need to replace equipment
Partial damage	Damage to structural elements or insulation, possibility of repair	Insulation breaks and damage on 35-150 kV lines	Temporary reduction in throughput capacity, increase in accident rate
Functional failures	Violation of operating mode without visible mechanical damage	Failure of switching devices due to overload	Network instability, increased risk of cascading outages
System disturbances	Massive shutdown of elements due to external influences	Simultaneous damage to several lines as a result of heavy shelling	Destabilisation of local and regional energy systems
Secondary damage	Damage caused by indirect factors (fires, overloads)	Fires at distribution points after strikes on adjacent facilities	Additional equipment losses, complications in restoration work

Source: compiled by the authors based on data (IEA, 2023, Energy Charter Secretariat, 2023, Piddubnyi & Goriunov, 2024, ACAPS, 2024, IEEE Standards Association, 2025, CIGRE, 2025).

network structure even before the full-scale invasion began. The high level of physical wear and tear of equipment, limited bandwidth reserves, and high dependence on centralised nodes determine the need to review technical approaches to reconstruction and modernisation. These requirements form the basis for new reliability parameters and technical solutions that can increase the resilience of electricity distribution networks in the medium and long term. This approach can be used to view reconstruction not as a reproduction of the existing system, but as the creation of a more adaptive and technologically resilient infrastructure.

3.2. Technical parameters and modernisation needs of distribution networks

The dynamics of changes in the technical parameters of distribution electricity networks during 2022-2025 indicate a combination of several processes: a reduction in transmission capacity due to equipment damage, partial restoration of infrastructure in relatively safe regions, and the implementation of technical measures to increase network flexibility. In these conditions, the load-to-throughput ratio is an indicator that can be used to assess the stability of the system at the regional level and identify the most vulnerable segments. Table 2 contains data on the Kyiv, Kharkiv and Lviv regions, which reflect different conditions for the functioning of energy infrastructure and demonstrate the specifics of capacity utilisation in the context of its limitations. This regional comparison was used to illustrate three structurally different situations within the Ukrainian distribution system: a central overloaded network, a heavily damaged eastern network, and a relatively stable western network. Therefore, the analysis does not claim full statistical representativeness, but provides a differentiated basis for identifying the main types of vulnerability relevant to post-war reconstruction. This identifies critical areas where the utilisation rate remains consistently high, creating additional risks to system stability.

The consistently high utilisation rates have different engineering implications across the three regions. In the Kyiv region, the principal constraint is the concentration of demand relative to available network capacity, which reduces the reserve margin available for emergency switching and load redistribution. In the Kharkiv region, the problem is more directly associated with the loss of usable capacity caused by war damage and incomplete restoration, meaning that a comparable utilisation rate reflects a structurally weaker network with fewer alternative supply paths. The Lviv region retains a somewhat larger reserve margin, but utilisation above 84% still limits operational flexibility during peak demand or contingency conditions. These differences explain why similar utilisation percentages may represent different types of vulnerability and why reconstruction measures should be region-specific rather than based on a uniform national approach. Therefore, the utilisation coefficient was interpreted as a pressure indicator rather than as a complete resilience metric. Its consistently high values were combined with SAIDI, SAIFI and damage data to identify regions where limited redundancy, high load concentration and insufficient automation created the greatest risks for system stability.

In further analysis, SAIDI and SAIFI indicators, which are internationally recognised indicators of electricity supply reliability, are significant. In the context of military operations in Ukraine, these indicators showed substantial deviations from the corresponding EU averages, indicating a significant reliability gap. Tracking their dynamics in 2022-2025 (Table 3) quantified the magnitude of this gap and supported the need for accelerated modernisation, particularly through digital technologies and intelligent control systems.

The exploratory linear trend corresponded to an average annual decline of approximately 115 min/consumer/year for SAIDI (R^2=0.989) and 0.30 outages/consumer/year for SAIFI (R^2=1.000) over 2022-2025. Analysis of the data in the table shows that in 2022, Ukraine experienced a significant deterioration in the quality of electricity supply: SAIDI was approximately 8.9 times the EU average, while SAIFI was 4.1 times the EU average. The decline in SAIDI and SAIFI after 2022 suggests partial operational adaptation, but the persistence of values far above the EU benchmark indicates that restoration alone did not remove the structural causes of unreliability. The remaining gap can be explained by the interaction of physical damage, limited redundancy, high network loading and restricted fault-isolation capability, which prolong outages even when the number of newly damaged assets decreases.

A deeper interpretation of SAIDI and SAIFI indicates that outage dynamics were shaped by several groups of causes rather than by physical destruction alone. First, direct war-

Table 2
Transmission capacity and actual load of Ukraine's distribution networks in 2022-2025 (by region)

Year	Region	Capacity, MW	Actual average load, MW	Utilisation rate (%)
2022	Kyiv region	6,500	5,900	91
	Kharkiv region	5,200	4,650	89
	Lviv region	4,700	3,950	84
2023	Kyiv region	6,400	5,800	91
	Kharkiv region	4,800	4,350	91
	Lviv region	4,600	3,950	86
2024	Kyiv region	6,300	5,600	89
	Kharkiv region	4,500	4,050	90
	Lviv region	4,550	3,850	85
2025	Kyiv region	6,200	5,500	89
	Kharkiv region	4,400	3,950	90
	Lviv region	4,500	3,800	84

Note: to assess network congestion levels, a bandwidth utilisation coefficient was calculated (Formula 1), which was used to compare regions in terms of operational efficiency and identify critical areas of overload.
Source: compiled by the authors based on data (IEA, 2023, Energy Charter Secretariat, 2023, Piddubnyi & Goriunov, 2024, ACAPS, 2024, 2025b; Energy Community Secretariat, 2024, DTEK, 2025, Interfax-Ukraine, 2023, 2025, Kharkivoblenergo, 2024, Lvivoblenergo, 2024a, 2024b, 2024c, 2024d, National Commission for State Regulation in Energy and Utilities, 2025).

Table 3
Dynamics of SAIDI and SAIFI indicators in Ukraine in 2022-2025 compared to the average values for EU countries

Year	Ukraine: SAIDI (min/consumer/year)	Ukraine: SAIFI (outages/consumer/year)	Average EU metrics SAIDI (min/ consumer/year)	Average EU metrics SAIFI (outages/consumer/year)
2022	1,200	4.1	135	1.0
2023	1,050	3.8	130	1.0
2024	950	3.5	125	0.9
2025	850	3.2	120	0.9

Note: SAIDI – average duration of power outages per consumer per year; SAIFI – average number of outages per consumer per year; min – minutes.
Source: compiled by the authors based on data (IEA, 2023; World Bank, 2021; Energy Community Secretariat, 2024).

related damage to power lines, transformer substations and distribution points increased both the duration and frequency of outages, especially in regions where damaged elements could not be quickly replaced. Second, network overload intensified the effect of individual failures, since utilisation rates of 84-91% left limited reserve capacity for rerouting electricity supply. Third, maintenance-related failures became more probable under wartime conditions because emergency repair, shortage of spare equipment and restricted access to damaged facilities complicated preventive servicing. Fourth, cyber vulnerabilities and insufficient digital protection increased operational risks by limiting the reliability of monitoring, dispatching and automated response systems. Fifth, renewable intermittency did not act as the primary cause of outages, but it created additional balancing and voltage-stability requirements when RES integration was not supported by sufficient storage capacity and intelligent control systems.

The increased accident rate was reflected in the growing number of emergency shutdowns in 2022-2024, which demonstrated the instability of distribution networks during active military operations. However, these shutdowns should be interpreted as the result of interacting causes. Physical destruction created the initial loss of network functionality; overload reduced the possibility of safe redistribution of electricity flows; maintenance constraints delayed restoration; cyber vulnerabilities weakened monitoring and operational coordination; and renewable intermittency increased the need for balancing capacity. In these conditions, the modernisation of control and protection systems capable of detecting failures, redistributing load and supporting decentralised balance became a priority.

The technological foundation for further modernisation of distribution networks was the Smart Grid concept, which envisaged a transition to intelligently controlled systems. Such networks can balance loads in real time, integrating RES and storage systems, and ensuring coordinated interaction between different levels of energy infrastructure. International experience, in particular examples of smart grid implementation in Germany, Italy, France, Spain, Poland and the EU, has confirmed that the digitalisation of distribution networks contributes to a significant reduction in SAIDI and SAIFI indicators, increases the reliability of energy systems and improves the continuity of electricity supply (Federal Ministry for Economic Affairs and Energy, 2025, Italy Tomorrow, 2022, French Energy Regulatory Commission, 2025, Iberdrola Spain, 2025, Electrum Poland, 2025, European Commission, 2024). For Ukraine, the integration of these technologies is of strategic significance, as it both strengthens the stability of the networks and creates conditions for further integration into the European energy system.

The gradual introduction of digital management platforms, predictive analytics systems and the integration of local generation are creating the conditions for the transformation of the traditional model of distribution network operation. At the same time, consistently high network-utilisation rates confirm the need to increase the adaptability of networks to external threats and create conditions for the development of decentralised generation. Thus, research into technical parameters and the identification of modernisation needs confirms that the sustainable development of distribution networks is only possible with comprehensive digitalisation and the implementation of intelligent technological solutions.

3.3. Integration of RES and local generation into distribution networks

The development of RES is one of the key factors in the transformation of Ukraine's electricity distribution network architecture. The increase in the share of solar and wind power plants is changing not only the structure of generation but also the mode of operation of the infrastructure, creating new technical requirements for load balancing and voltage stability. The dynamics of the installed capacity of these facilities in 2022-2025 can be used to assess the scale of changes in the production sector and identify priority areas for the integration of renewable generation into distribution networks. During this period, the industry developed amid war damage, partial loss of infrastructure, and a gradual recovery of investment activity. The integration of distributed renewable generation into damaged distribution networks creates several technical constraints that cannot be reduced only to installed capacity growth. First, solar and wind generation may intensify voltage fluctuations, especially in radial low- and medium-voltage networks with limited reserve capacity. Second, the variability of renewable output increases the need for frequency regulation and balancing reserves, since damaged networks have fewer operational options for redistributing load. Third, high local generation during periods of low demand can cause reverse power flow, which complicates protection coordination and transformer operation. Fourth, intermittency requires short-term forecasting, storage support and automated dispatching to prevent rapid changes in power flows. Fifth, synchronization becomes more difficult when local generation, microgrids and restored network segments are reconnected after emergency shutdowns. Therefore, RES integration in Ukraine should be considered not only as a generation-expansion strategy, but also as a technical challenge requiring voltage control, adaptive protection, ESS deployment and intelligent network management.

Quantitative indicators of installed renewable-energy capacity were visualised to highlight the main trends in solar and wind generation during 2022-2025. Fig. 5 presents the dynamics of installed solar and wind power capacity in Ukraine and shows both the contribution of each generation type and the change in total renewable capacity over the study period.

Analysis of Fig. 5 shows that the installed capacity of both solar and wind power plants decreased between 2022 and 2023. This decline was associated with war-related damage to energy infrastructure and reduced investment activity, which resulted in the shutdown of some facilities and the postponement of new

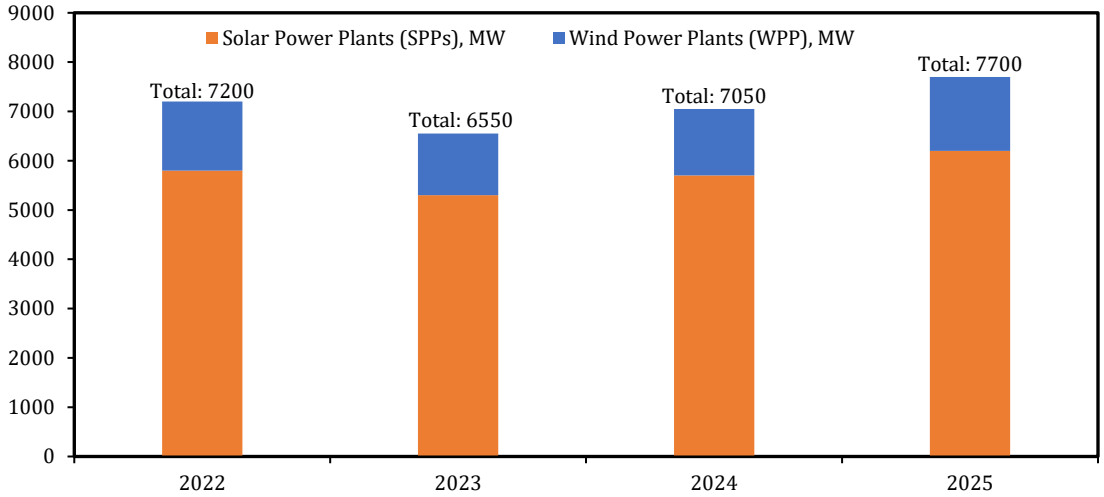


Fig. 5. Dynamics of installed solar and wind power capacity in Ukraine in 2022-2025. *Source: compiled by the authors based on data (Piddubnyi & Goriunov, 2024; State Agency on Energy Efficiency and Energy Saving of Ukraine, 2024a, 2024b, Ignatyev, 2024).*

projects. From 2024 onward, installed capacity began to recover, indicating a gradual restoration of the renewable generation sector despite continuing wartime constraints. A notable feature of this trend is that solar generation is recovering faster due to its lower capital intensity and shorter construction cycle compared to wind power. Additional growth in 2025 in both the solar and wind power segments indicates a gradual restoration of investor confidence and the formation of preconditions for the integration of a larger share of RES into distribution networks. The overall results confirm the potential for expanding decentralised generation and its key role in improving the resilience of the national energy system. At the same time, the increase in installed renewable capacity does not automatically improve distribution-network resilience. In regions with damaged lines, overloaded transformers and limited automation, distributed RES can increase operational complexity. Voltage deviations may arise when local generation exceeds local consumption; reverse power flow may affect protection settings; and rapid changes in solar or wind output may increase balancing pressure. These risks are especially important for Ukraine because the same networks that must integrate renewable generation also operate under war-related damage, high utilisation rates and restricted maintenance access. Consequently, the practical effect of RES depends on the simultaneous deployment of ESS, smart inverters, automated voltage regulation, real-time monitoring and coordinated dispatching. This asymmetric recovery also affects network planning because rapidly deployable solar capacity can grow faster than the reinforcement of distribution infrastructure required to accommodate bidirectional and variable power flows.

The further development of distribution networks is inextricably linked to the introduction of ESS, which are regarded as a key area for improving the reliability and flexibility of the energy sector. International experience shows that the use of ESS can smooth fluctuations in renewable energy production, reduce the number of outages and increase the stability of the power system (Mitali *et al.,* 2022). The most notable examples of large-scale ESS implementation have been in Germany, Spain, Denmark, Australia, and the United States, where significant results have been achieved in load balancing and network stability (Mitali *et al.,* 2022, Enkhardt & Siemer, 2024, REGlobal, 2024, Strategic Energy, 2025, Australian Renewable Energy Agency, 2024, Mathrani, 2025). The generalised parameters of these projects are presented in Table 4, which provides a practical guideline for adapting the experience to Ukrainian conditions. Various storage technologies, from lithium-ion batteries to supercapacitors and hybrid systems, demonstrate their effectiveness depending on regional conditions and the specifics of generation, which determines the need for a comprehensive approach to their integration into the process of modernising the domestic energy sector.

Analysis of the data in Table 4 shows that EU countries and the US apply different approaches to ESS implementation, adapted to the specifics of local energy systems. In Germany (Bavaria), the creation of Innovative Battery Park has reduced peak loads and enabled the effective integration of solar and wind generation into local grids, while the Spanish project in Andalusia has demonstrated the effectiveness of hybrid systems in smoothing daily fluctuations in SPP generation and reducing SAIDI. Denmark (Jutland) confirmed the feasibility of combining lithium-ion batteries with supercapacitors, which stabilised the frequency and increased the share of wind generation in the local balance to 45%. Outside the EU, Australia and the United States demonstrate different approaches: in Australia (Hornsdale Power Reserve Extension), lithium-ion storage facilities have become the basis for rapid reserve and reduction of emergency outages, while in Texas (ERCOT ESS Program), the main focus is on providing reserve capacity during peak demand. This variability confirms the flexibility of ESS and their ability to respond effectively to various challenges, from balancing generation to improving grid reliability. For Ukraine, the most relevant models are those focused on integrating solar and wind stations with local storage facilities, which can reduce SAIDI and SAIFI, increase grid resilience, and create a basis for the development of decentralised generation. A scenario-based estimate shows the possible Ukrainian effect more clearly. In 2025, the actual average load was 5,500 MW in the Kyiv region, 3,950 MW in the Kharkiv region and 3,800 MW in the Lviv region. If ESS provided dispatchable support equivalent to 10% of these loads during peak periods, the effective load would decrease by 550 MW, 395 MW and 380 MW, respectively. Under this scenario, utilisation would fall from approximately 89% to 80% in the Kyiv region, from 90% to 81% in the Kharkiv region, and from 84% to 76% in the Lviv region. The reserve margin would increase from 700 to 1,250 MW in the Kyiv region, from 450 to 845 MW in the Kharkiv region, and from 700 to 1,080 MW in the Lviv region. If the 15% SAIDI reduction observed in international

Table 4
Examples of ESS implementation in EU countries, Australia and the USA, with the possibility of adaptation for Ukraine

Country/Object	Year of launch	Power, MW	Technology	Achieved results	Adaptation potential in Ukraine
Germany, Bavaria (Innovative Battery Park)	2020	50	Lithium-ion	20% reduction in peak loads, integration of SPP and WPP into local networks	Use in communities with a high proportion of renewable sources
Spain, Andalusia (Solar-ESS Integration Project)	2021	30	Lithium-ion + hybrid system	Balancing daily fluctuations in solar generation output, reducing SAIDI by 15%	Relevant for the southern regions of Ukraine with high solar potential
Denmark, Jutland (Wind-ESS Hybrid System)	2022	40	Lithium-ion + supercapacitors	Frequency stabilisation, an increase in the share of RES in local generation to 45%	Relevant for the coastal and wind zones of Ukraine
Australia, South Australia (Hornsdale Power Reserve Extension)	2020	150	Lithium-ion (Tesla Powerpack)	Fast backup, reduction of emergency shutdowns by 35%	Suitable for regions with high network failure rates
USA, Texas (ERCOT/Gambit ESS Program)	2023	100	Lithium-ion + hybrid	Provision of reserve capacity during periods of peak demand, reducing emergency outages	Can be used to stabilise peak loads in industrial regions of Ukraine

Note: the table provides examples of projects from Germany, Spain, Denmark, Australia and the United States, as these countries have the most publicly documented experience of large-scale implementation of ESS systems in various regional conditions (from sunny and windy areas to industrial centres).
Source: compiled by the authors based on data (Enkhardt & Siemer, 2024, REGlobal, 2024, Strategic Energy, 2025, Australian Renewable Energy Agency, 2024, Mathrani, 2025).

ESS-supported cases were used only as a benchmark, Ukraine's 2025 SAIDI value of 850 min/consumer/year could be reduced by approximately 128 min/consumer/year under comparable operational conditions.

A sensitivity analysis was conducted to test whether this result depended on the assumed level of ESS support. At 5% ESS support, utilisation would decline to approximately 84.3% in Kyiv, 85.3% in Kharkiv and 80.2% in Lviv. Under the baseline 10% scenario, the corresponding values would be 79.8%, 80.8% and 76.0%, while at 15% support they would decrease further to 75.4%, 76.3% and 71.8%, respectively. The direction of the effect therefore remained consistent across the tested range, indicating that the conclusion regarding reduced peak-load pressure is robust to moderate variation in the ESS-support assumption. These scenarios remain indicative rather than predictive because actual storage dispatch depends on technology, location, duration and operating conditions. These calculations show that ESS deployment could reduce peak-load stress and reserve deficits and may contribute to shorter outage duration.

3.4. Prospects for digitalisation and improvement of the resilience of distribution networks

In the process of digitising energy systems, the introduction of smart grid technologies is primary, ensuring the integration of automated switching devices, remote monitoring systems and predictive analytics into a single managed structure (Escobar *et al.,* 2021). Reported applications of these technologies have been associated with shorter recovery times, more balanced load distribution and lower technical losses. EU cases indicate that Smart Grid deployment can contribute to improved distribution-network reliability and electricity-supply continuity. SAIDI and SAIFI are important indicators for assessing the effectiveness of these solutions because they quantify changes in outage duration and frequency.

Systematisation of international experience was conducted to generalise different models of smart grid implementation and compare their results using key reliability indicators (Escobar *et al*., 2021). The cases considered indicate that digital technologies in distribution networks can reduce the duration and frequency of power outages and facilitate the integration of RES. Table 5 summarises the reported effects of smart grid implementation on SAIDI and SAIFI in selected EU countries and provides a quantitative basis for comparison with Ukrainian conditions.

To quantify the magnitude of the reliability gap between Ukraine and the international benchmarks, the reported SAIDI and SAIFI improvements were applied to Ukraine's 2025 baseline and normalised relative to the corresponding EU averages. The resulting benchmark ratios are presented in Table 6.

Cases from Denmark, Australia and the United States reported non-equivalent quantitative outcomes, such as frequency stabilisation, emergency-shutdown reduction, ESS capacity, outage reduction or cyber-risk reduction. These indicators were therefore retained as technology-specific quantitative benchmarks and were not combined with SAIDI and SAIFI into a single normalised index, which would imply comparability between technically different performance measures.

The normalised comparison shows that Ukraine's 2025 SAIDI was approximately 7.1 times the EU average, while SAIFI was approximately 3.6 times. Applying the improvements reported for the international Smart Grid cases would reduce the normalised SAIDI ratio to approximately 4.4-5.0 and the SAIFI ratio to approximately 2.6-2.9. The Spanish case provides the strongest benchmark effect among the cases considered; however, even under this scenario, a substantial reliability gap relative to the EU average would remain. This indicates that digitalisation alone would be insufficient to close the gap and would need to be combined with physical reconstruction, increased redundancy and storage deployment.

The differences between the international cases indicate that reliability improvement depends on the function performed by the digital technology rather than on digitalisation alone. Automated switching primarily reduces outage duration by isolating damaged sections and restoring supply through alternative paths, while smart meters and remote monitoring improve fault detection and reduce diagnostic delays.

Table 5
Examples of Smart Grid technology implementation in EU countries and their impact on SAIDI and SAIFI indicators

Country/region	Year of introduction	Primary smart grid technologies	Reduction in SAIDI (%)	Reduction in SAIFI (%)	Key results
Germany (North Rhine-Westphalia)	2019	Smart meters, automated substations	35%	28%	Increased reliability, rapid recovery after failures
Italy (Lombardy)	2020	Smart meters, remote monitoring systems	32%	25%	Reduction in accidents and maintenance costs
France (Hauts-de-France)	2021	Automated load management systems	30%	20%	Optimisation of operating modes and integration of RES
Spain (Catalonia)	2022	Smart sensors, predictive analytics systems	38%	27%	Reduction of peak loads, reduction of accident response time
Poland (Masovian Voivodeship)	2022	Automated switching devices, SCADA	29%	18%	Improved network stability and microgrid integration

Note: the table provides examples from Germany, Italy, France, Spain and Poland, as these countries have the most representative experience in implementing smart grids in various regional conditions (from high-tech urbanised areas to areas with increased accident risks). Source: compiled by the authors based on data (Federal Ministry for Economic Affairs and Energy, 2025, Italy Tomorrow, 2022, French Energy Regulatory Commission, 2025, Iberdrola Spain, 2025, Electrum Poland, 2025).

Predictive analytics contributes by identifying emerging equipment problems before failure, whereas SCADA-based control improves real-time coordination and load redistribution. These mechanisms are particularly relevant to Ukraine because wartime outages are amplified by restricted physical access, limited redundancy and the need to isolate damaged network segments rapidly.

For Ukraine, the relevance of these technologies was assessed not by direct transfer of foreign results, but by matching smart grid functions with the failure mechanisms identified in Ukrainian distribution networks. Automated switching is relevant where physical damage requires rapid isolation of affected segments; SCADA and remote monitoring are relevant where access to damaged infrastructure is restricted; predictive analytics can support maintenance planning under equipment shortages; and real-time load management can reduce overload risks in regions where utilisation rates remain close to technical limits. Thus, international cases provide benchmark effects, while the Ukrainian data explain why these technologies are applicable under wartime reconstruction conditions.

The next step in the digital transformation of energy is the introduction of digital twin technology, which can be used to create virtual models of real objects and processes for comprehensive analysis (Batty, 2018). The use of such models creates opportunities for optimising operating modes, predicting potential failures and testing different scenarios without risk to physical infrastructure. Practice in the EU and the US confirms the effectiveness of digital twins in various areas, from the integration of RES to ensuring the cyber resilience of energy systems (Batty, 2018). Generalised examples are given in Table 7, which demonstrates the key results of the practical use of this technology in distribution networks and outlines the prospects for its adaptation in Ukraine.

The international cases indicate that the principal value of digital twins lies in reducing information and coordination delays rather than directly increasing physical network capacity. Their contribution to resilience arises from improved state estimation, faster fault localisation, predictive maintenance, scenario testing and optimisation of load flows. In wartime networks, these functions are particularly important because topology changes rapidly after damage and field access may be restricted. However, the effectiveness of digital twins depends on the availability and quality of real-time operational data; without sufficient sensor coverage, interoperable SCADA systems and secure communication channels, the model may reproduce incomplete or outdated network conditions and provide limited operational benefit.

For Ukraine, the practical implementation of digital twins would require several preconditions. At the infrastructure level, distribution system operators would need reliable asset inventories, smart meters, substations equipped with remote monitoring devices, SCADA-compatible data flows and updated geospatial models of damaged and restored network elements. At the computational level, the main challenges would involve processing incomplete wartime data, synchronising real-time and historical datasets, modelling rapidly changing network topology, and maintaining sufficient computing capacity for scenario testing. Cybersecurity is also critical, because a digital twin concentrates sensitive operational data and can become a target for cyberattacks; therefore, encryption, access control, network segmentation and continuous security monitoring should be included from the initial design stage. Financial feasibility depends on phased deployment: pilot digital twins should first be introduced in the most overloaded or repeatedly damaged regions, where faster fault localisation, improved maintenance planning and reduced outage duration can justify the initial investment. Thus, digital twins should be viewed not as an abstract digital solution, but as a technically demanding and financially staged instrument for post-war network reconstruction.

Research into the integration of RES has confirmed the potential for developing decentralised generation and the need to use ESS for load balancing. International experience with smart grids and digital twins in the EU and the US has shown a significant reduction in outages, increased cyber resilience and economic efficiency (Mitali *et al*., 2022, Escobar *et al*., 2021, Batty, 2018). However, their applicability in Ukraine depends on the gradual creation of data infrastructure, secure

Table 7
Examples of digital twin technology applications in EU countries and the US

Country/region	Year of introduction	Scope of use	Reached results
Netherlands	2020	Modelling the operation of distribution networks	25% reduction in accident response time, optimisation of load flows
Germany	2021	Integration of RES	20% increase in forecast accuracy for balances, reduction in overload incidents
France	2021	Infrastructure modernisation planning	15% reduction in maintenance costs, increased investment efficiency
USA (New York)	2022	Cyber defence scenario testing	40% reduction in the risk of successful attacks on critical infrastructure
USA (Texas)	2023	Optimisation of microgrid operation	Improved stability of local networks, reduction of outages by 18%

Source: compiled by the authors based on data (De Matos et al., 2022, Wynn & Irizar, 2023, Bonin & Frankhauser, 2025, Payne et al., 2025, Mandal et al., 2025).

communication systems, interoperable SCADA platforms, cybersecurity protocols and sustainable financing mechanisms. Without these conditions, digital twins would remain a modelling concept rather than an operational tool for improving reliability. The results indicate that digitalisation and the integration of renewable generation are key conditions for improving the resilience of Ukraine's electricity distribution networks in the medium and long term.

The combined results indicate that post-war network development can follow two distinct reconstruction pathways. Traditional reconstruction primarily restores damaged physical assets, whereas digitalised reconstruction combines physical reinforcement with automated monitoring, switching, storage and data-driven control. The principal differences between these approaches are summarised in Fig. 6. For Ukraine, the choice and sequencing of these measures should depend on regional damage intensity, network loading, infrastructure readiness and data availability rather than on a uniform reconstruction model.

4. Discussion

The results revealed that war damage to distribution networks led to a significant reduction in transmission capacity and an increase in the frequency of failures. Regional utilisation rates remained high throughout 2022-2025, indicating system overload. However, the utilisation coefficient alone cannot fully describe the resilience of wartime distribution networks. For this reason, the study interpreted it together with reliability indicators, redundancy constraints, damage intensity and the potential contribution of digital control systems. This broader interpretation showed that reliability improvement depended not only on reducing network load, but also on increasing reserve capacity, accelerating fault localisation, improving automated switching and strengthening the integration of local generation and storage systems. In 2022, the SAIDI indicator in Ukraine was 1,200 min/consumer/year, which was approximately 8.9 times the European average of 135 minutes/consumer/year, while the SAIFI reached 4.1 outages/consumer/year compared to the EU average of 1.0. Although their further decline showed positive dynamics, structural constraints remained unchanged. In this context, the integration of RES without sufficient ESS increased fluctuations in power flows, while international cases indicate that digital technologies such as smart grids and digital twins can contribute to reducing outage duration. These fluctuations were associated with voltage instability, reverse power flow, frequency-balancing pressure and synchronization risks during the reconnection of damaged or partially restored network segments. The root causes of these reliability problems were multidimensional. Physical destruction was the most visible driver of outages, but it interacted with pre-existing technical wear, insufficient redundancy and high capacity utilisation. Overload increased the probability that local failures would spread across connected network segments. Maintenance failures were linked not only to the age of equipment, but also to the limited availability of repair crews, spare parts and safe access to damaged infrastructure. Cyber vulnerabilities represented a separate operational risk because insufficiently protected digital systems could reduce the effectiveness of monitoring and dispatching. Finally, the growing role of renewable generation required storage and smart control technologies; without them, RES variability could increase balancing pressure rather than automatically improve resilience.

The analytical comparison indicates that reliability improvement was not only a result of physical restoration, but also depended on the gradual introduction of digital monitoring, automated control and decentralised balancing solutions. Therefore, the relationship between digitalisation and reliability should be interpreted as scenario-based and probabilistic: smart grid technologies can reduce outage duration and frequency, but their measurable effect in Ukraine depends on the scale of implementation, network damage intensity, regional load and the availability of storage systems.

The Ukrainian case differs from conventional grid-modernisation settings because network failures occur under repeated external damage rather than as isolated technical contingencies. Restoration therefore proceeds while network topology, available capacity and access to infrastructure continue to change. This explains why declining damage counts and improving SAIDI and SAIFI do not necessarily indicate a proportional recovery of resilience. The regional results also show that similar utilisation levels may reflect different vulnerability mechanisms: concentrated demand and limited redistribution capacity in the Kyiv region, loss of usable capacity and incomplete restoration in the Kharkiv region, and

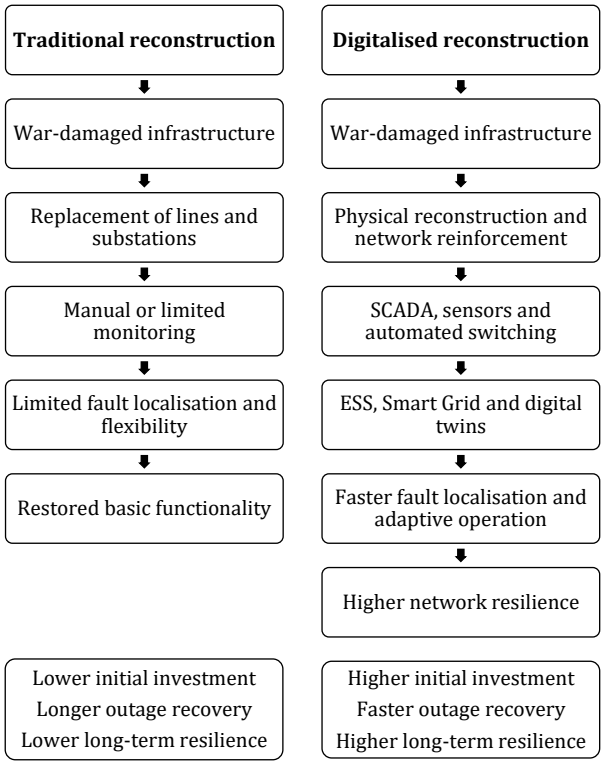


Fig. 6. Comparison of traditional and digitalised reconstruction pathways for electricity distribution networks.. *Source: compiled by the authors.*

comparatively greater reserve but increasing RES-integration requirements in the Lviv region. These findings support previous evidence that resilience depends on flexible network expansion and reconfiguration rather than on simple replacement of damaged assets (Fabra *et al*., 2022; Saberi *et al*., 2023; Sabouhi *et al*., 2021).

Under wartime conditions, the effect of an individual failure is amplified when neighbouring assets are unavailable, reserve capacity is limited or repair crews cannot rapidly access damaged infrastructure. This makes decentralised generation, storage and microgrids particularly important because they can maintain local supply when centralised network paths are disrupted. The Ukrainian results show that these findings acquire additional significance under conditions of repeated physical destruction and incomplete restoration (Kemabonta, 2021; Parast *et al*., 2021; Heffron *et al*., 2021).

The identified mechanisms also clarify why digital technologies should not be treated as a uniform modernisation package. Automated switching can isolate damaged sections and restore supply through alternative paths, SCADA and remote monitoring can reduce diagnostic delays when physical access is restricted, and coordinated digital control can improve load redistribution in highly utilised network segments. These functions are particularly important in Ukraine because system configuration may change rapidly after attacks and restoration measures must often be implemented before the wider network has returned to a stable condition. This interpretation is consistent with studies demonstrating the importance of integrated network redesign, prepared recovery procedures and digital control for resilience improvement (Wang *et al*., 2022; Fotis *et al*., 2022; Singh *et al*., 2022).

Cybersecurity represents a direct reliability constraint rather than a separate digital-policy issue, particularly under wartime conditions. Attacks on SCADA platforms, remote-access channels, smart meters, substation automation and communication links can delay fault localisation, distort operational data or disrupt automated switching, thereby increasing outage duration and the risk of cascading failures. The quantitative international case presented in Table 7 illustrates the potential value of cyber-resilience measures: cyber-defence scenario testing in New York was associated with a 40% reduction in the risk of successful attacks on critical infrastructure. For Ukrainian distribution networks, the most relevant mitigation measures therefore include IT/OT network segmentation, multi-factor authentication, encryption of operational data, role-based access control, continuous event monitoring and backup communication channels. These requirements are consistent with previous studies emphasising interoperability, secure digital infrastructure and coordinated control as essential conditions for energy-system digitalisation (Çelik *et al*., 2022; Aghahadi *et al*., 2024; Wu *et al*., 2020). Their importance is amplified in Ukraine because a cyber incident may coincide with physical infrastructure damage and further restrict the operator's ability to detect, isolate and restore affected network segments.

ESS addresses a different but complementary vulnerability mechanism by reducing peak-load pressure and increasing the operational reserve available during network contingencies. The scenario analysis in the present study showed that storage support equivalent to 10% of actual regional load would reduce utilisation by approximately 8-9 percentage points in the most heavily loaded regions, while the sensitivity analysis confirmed the same direction of effect across the 5-15% support range. This is especially relevant where physical damage and limited redundancy increase the probability that local failures will propagate to neighbouring network segments. Previous studies likewise identify energy storage as an important mechanism for balancing variable generation and improving network reliability (Worku, 2022; Tan *et al*., 2021).

To synthesise these comparisons and clarify the contribution of the present study relative to previous research, the main findings are summarised in Table 8.

Practical implementation should follow a phased roadmap reflecting both network vulnerability and investment intensity. In the short term (1-2 years), priority should be given to restoration of SCADA functionality, remote monitoring,

automated switching, backup communication channels and cybersecurity measures, as these interventions can improve fault detection and isolation without requiring complete network reconstruction. In the medium term (3-5 years), higher investment should be directed towards ESS deployment, smart meters, substation automation and communication infrastructure, particularly in highly loaded or repeatedly damaged regions. Longer-term implementation (>5 years) can include wider deployment of digital twins, microgrids and advanced coordinated control to support RES integration and system-wide optimisation. The main technical barriers are incomplete asset data, limited sensor coverage, damaged communication infrastructure, interoperability problems and shortages of specialised equipment and personnel. Institutional implementation will require coordination among distribution system operators, the national regulator, government authorities, local administrations and international donors, together with transparent procurement, common technical standards and stable financing mechanisms. Responsibility for implementation should also be differentiated by stakeholder. Government agencies and the national regulator should establish technical standards, cybersecurity requirements and funding priorities; transmission and distribution system operators should lead network automation, SCADA modernisation, substation upgrades and regional ESS integration; renewable energy developers should coordinate new generation projects with storage and grid-support requirements; and international funding organisations should prioritise concessional finance, grants and risk-sharing instruments for projects with high resilience and reconstruction value. These timelines should be interpreted as indicative planning horizons rather than fixed forecasts, because implementation speed will depend on security conditions, funding availability and the progress of physical reconstruction.

The findings therefore indicate that improving the resilience of Ukraine's distribution networks requires coordinated physical reconstruction, digital control, cybersecurity, storage deployment and decentralised generation. Unlike conventional modernisation programmes, these measures must be implemented under conditions of repeated infrastructure damage, restricted access and incomplete restoration, which limits the direct transferability of international solutions and requires their adaptation to regional vulnerability mechanisms.

5. Conclusions

The findings show that the reduction in recorded infrastructure damage during 2022-2025 should not be interpreted as equivalent to the restoration of distribution-network resilience. Despite improvements in damage and reliability indicators, regional capacity utilisation remained high, while Ukraine's 2025 SAIDI and SAIFI values were still approximately 7.1 and 3.6 times the corresponding EU averages. These results indicate that physical reconstruction alone does not eliminate the structural vulnerability created by limited redundancy, constrained reserve capacity, high loading and repeated external damage.

The broader scientific implication of the study is that reconstruction of conflict-affected distribution networks should be assessed as a combined problem of physical vulnerability, operational reliability and technological adaptability. The proposed reconstruction-oriented framework links observed infrastructure damage, regional loading conditions, reliability indicators and reserve constraints with the potential contribution of ESS, Smart Grid technologies and digital twins. Its practical engineering significance lies in identifying different technological responses for different vulnerability mechanisms rather than treating digitalisation or storage as universally applicable solutions. Automated switching and remote monitoring can improve fault localisation and network reconfiguration, ESS can increase operational reserve and reduce peak-load pressure, while digital twins can support state estimation, scenario testing and reconstruction planning under changing network conditions.

From a policy and implementation perspective, reconstruction should therefore prioritise measures according to both urgency and infrastructure readiness. Short-term priorities include restoration of monitoring and control functions, automated switching, secure communication channels and cybersecurity protection. Medium-term measures should focus on ESS deployment, smart metering, substation automation and strengthened communication infrastructure, while longer-term modernisation can include wider deployment of digital twins, microgrids and coordinated control systems supporting higher levels of renewable generation. The practical contribution of the framework is to provide a basis for aligning these measures with regional vulnerability rather than applying a uniform reconstruction model across Ukraine.

Several limitations should be considered when interpreting the results. Wartime datasets are inherently uncertain because damaged or temporarily inaccessible areas may be under-reported, reporting intensity may differ between regions and periods, and changes in source coverage may affect apparent temporal trends. The available data also do not provide complete asset-level information on network topology, individual substations, line condition or restoration status, which limits detailed spatial and causal interpretation. The ESS analysis is scenario-based and assumes dispatchable storage support equivalent to 5-15% of regional load; it does not incorporate site-specific storage efficiency, degradation, network constraints, installation costs or detailed dispatch optimisation. International benchmarking also has limitations because the selected cases differ from Ukraine in network structure, regulatory conditions, technology penetration and security environment. The reported Smart Grid improvements were therefore used as comparative performance benchmarks rather than as forecasts of equivalent effects in Ukraine. In addition, the regional analysis focuses on Kyiv, Kharkiv and Lviv and cannot represent the full diversity of operating conditions across the national distribution system.

Future research should consequently extend the framework to a larger number of regions and incorporate operator-level and asset-level data where security and data availability permit. Further work should also evaluate the combined technical and economic effects of Smart Grids, ESS, microgrids, digital twins and cybersecurity measures using network-specific optimisation and cost-benefit analysis. Such analysis would allow the indicative reconstruction priorities identified in this study to be converted into more detailed investment and implementation plans.

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