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Prospects for restoration of Ukrainian energy sector infrastructure in the wake of Russian full-scale invasion

Abstract: The study aimed to substantiate engineering approaches to restoring the infrastructure of the energy sector of Ukraine, which suffered large-scale destruction as a result of the full-scale armed invasion of the Russian Federation. The research methodology included modeling emergency and restoration scenarios in specialized software environments to calculate the modes of electric power systems, analyzing the stability of power grids based on the criterion of unchanged operability of elements in case of failure of one of them, and optimizing the configurations of distribution nodes using mathematical programming methods. The study utilized PowerFactory and ETAP for power-grid modeling, MATLAB for optimization, TensorFlow for load forecasting, and HOMER Grid for hybrid power-system modeling to analyze and optimize Ukraine's energy infrastructure restoration

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strategies in response to war-induced damage. The study analyzed the stability of regional power grids based on the criterion of unchanged operability in the case of failure of individual elements. Critical regions with high levels of losses and structural overloads were identified, including Donetsk, Zaporizhzhia, and Kherson regions, where more than 100 overloads above 110% and minimum voltages below 0.85 of the nominal level were recorded. The study proposes the introduction of hybrid power systems that provide an autonomous power supply for 14–22 hours. A generalized index assessment of the effectiveness of the reconstruction scenarios (in terms of the full duration of recovery, localization level, current losses, and autonomous support) confirmed the advantage of scenarios combining zonal priority of eastern transits, switching algorithms, and neural network balancing renewable generation.

Keywords: power grids, digital control, electric load forecasting, power system reconfiguration, renewable energy sources

Introduction

Since the start of the Russian full-scale invasion of Ukraine, the energy sector has been subject to systemic disruption affecting both generation and transmission and distribution infrastructure. The destruction of hub substations, disruption of dispatch centers, failure of network elements, and lack of backup capacity have threatened continuity of supply, especially in winter, with increased loads and limited access to resources (Mikhailova et al. 2025). In such conditions, it is critical to apply engineering solutions that can ensure the technical and functional stability of the system, reduce losses, and increase the autonomy of energy consumers (Kucher and Mazurenko 2024). Adoption of digital technologies, grid configuration optimization, integration of renewable energy sources, and intelligent control system implementation are essential for improving the energy infrastructure's sustainability, resilience, and efficiency, as well as for guaranteeing dependable power distribution and lowering its susceptibility to disruptions.

Kovalenko et al. (2024) determined that in the crisis model of energy security, the key barriers to stabilizing the system were excessive centralization of production, physical deterioration of the main networks, and the lack of adaptive response scenarios. In turn, Kyrylenko et al. (2022) outlined several plausible scenarios for the restoration of Ukraine's energy sector, among which the technologically updated, decentralized model with the introduction of micro-regional generators and digital control systems is favored. This decentralization approach is echoed in the work of other scholars, such as Mazaraki and Melnyk (2024), who addressed the strategic dimension of energy security, in which infrastructure restoration should be accompanied by a change in planning logic from reactive to preventive, with the use of automated monitoring and intelligent forecasts. As part of an applied analysis of the current state of the energy sector of Ukraine, Zroboch (2023) addressed the combination of three groups of problems: infrastructure degradation, limitations in technical regulation, and reduced adaptability in the face of military uncertainty. The study emphasized the need for synchronized implementation of engineering solutions at the level of generation, transmission, and distribution facilities.

This need for coordinated solutions is further emphasized by Treshchov (2024), who substantiated the concept of modernizing the energy sector as a basic priority for post-war recovery, pointing to the key role of project modeling and scenario planning for recovery. The position is also supported by foreign experience. International perspectives also support this position; Binetti (2023) demonstrated that in post-conflict countries, the most effective approaches are those that combine physical reconstruction with technological upgrades, decentralization of generation, and the creation of autonomous power supply zones. Adding to this, Pandey (2021) proved that infrastructure rehabilitation should integrate the principles of sustainable development, where energy storage, use of local resources, and digital management are key. Building on this, Fan et al. (2024) proposed methodological approaches to the restoration of power systems based on a combination of scenario modeling, criterion analysis, and optimization of network configurations incorporating emergency response modes.

Moglen et al. (2024) addressed the importance of spatial planning, the use of remote sensing data, and mathematical modeling to localize critical network nodes, identify high-risk areas, and predict the consequences of the destruction of individual elements of the energy infrastructure. The researchers emphasized the need to combine geographic information systems with optimal restoration algorithms to minimize the impact of environmental threats, prioritize actions, and reduce reconstruction time. In turn, Janta et al. (2024) have developed a methodology for a comprehensive assessment of energy sustainability that incorporates not only the technical parameters of systems but also their ability to function under conditions of uncertainty, repeated threats, and increasing loads. The study emphasized the importance of a combined approach that combines technical reconstruction, digitalization, forecasting of threat scenarios, and increasing the operational flexibility of energy systems as a condition for building long-term resilience in the face of military and climate risks.

In general, the analysis of Ukrainian and international literature shows that the future of Ukraine's energy sector depends on the ability to integrate modern engineering solutions, digital management technologies, adaptive planning, and infrastructure diversification. This approach not only addresses modern challenges but also forms a sustainable energy architecture for the future.

The study aimed to formulate engineering-based solutions for the phased and technologically sound restoration of Ukraine's energy infrastructure in the context of the Russian full-scale military aggression, addressing the requirements of systemic resilience, deep digitalization, risk localization, and large-scale integration of renewable energy sources. The main tasks were to model emergency and recovery scenarios, evaluate the effectiveness of digital control and forecasting systems, and justify strategic directions for the modernization of high-voltage networks and generation.

1. Materials and methods

The study used five complementary methods: sentinel-1/2 geospatial fault vectorization, PowerFactory+ETAP mode modeling, linear optimization of reconfigurations in MATLAB, Long Short-Term Memory (LSTM)-Prophet short-term load forecasting, and technical and economic modeling of hybrid PV-BESS-DG clusters in HOMER Grid.

The geographical coverage of the study included 10 administrative-territorial units of Ukraine, grouped by the degree of damage to the energy infrastructure. The regions of high vulnerability included: Kharkiv, Donetsk, Kherson, Zaporizhzhia, Sumy, Mykolaiv, and Chernihiv regions. In these regions, large-scale damage to transformer substations, power lines, and generation facilities was recorded, which necessitated the reconfiguration of grids and the introduction of local redundancy. These regions were selected due to three factors: a high level of physical damage (more than 50% of the infrastructure in the eastern regions), significant load fluctuations due to population displacement and emergency outages, and the density of critical infrastructure facilities (medical facilities, water intakes, control points). These areas were used to generate training samples for LSTM-Prophet models, including as initial scenarios for reconstruction and optimization of power supply in MATLAB and HOMER Grid.

The regions of moderate vulnerability (35–45%) of Sumy, Mykolaiv, and Chernihiv regions were also included in the analysis to compare adaptive recovery scenarios. Vinnytsia, Ternopil, Lviv, and Ivano-Frankivsk regions were classified as stabilization regions, where the level of damage remained at 5–7%. They were selected due to their backup support function and potential for deployment of centralized hybrid generators in the HOMER Grid feasibility study scenarios. These regions were also used for modeling power transmission during grid reconfiguration in PowerFactory/ETAP.

The study used a combination of remote, statistical, and model data sources, which provided a comprehensive assessment of the state of the power infrastructure in combat conditions. The primary layer of spatial information was formed based on Sentinel-1/2 satellite images, available through the regional portal of the EU's Copernicus program. Macroeconomic assumptions, donor financing structure, and projected modernization scenarios were refined in accordance with the World Bank (2023), which justifies the need to implement hybrid energy systems by 2030.

The subject of modeling in the study was the electricity system of Ukraine within the seven most war-affected regions of Kharkiv, Donetsk, Zaporizhzhia, Kherson, Sumy, Mykolaiv, and Chernihiv regions. These regions were chosen for modeling due to both large-scale damage to the high-voltage infrastructure and critical dependence on an uninterrupted power supply for vital infrastructure. The methodological logic of the study involved the sequential implementation of six stages: satellite sensing, simulation modeling, load forecasting, optimization calculations, reconfiguration of hybrid systems, and scenario comparison.

At the first stage, spatial information on the damaged infrastructure was collected using 10- and 20-meter Sentinel-1/2 satellite images obtained through the EU Copernicus program for the period January 2022 – February 2025. A total of 314 objects were vectorized, including 127 substations, 143 sections of overhead power lines, and 44 generating units, classified according to the GRADE scale (0 – integrity, 4 – destruction). This scale was modified from standard damage evaluation methods applied to infrastructure assessments conducted after disasters. It is based on commonly employed damage classification systems (Sun et al. 2022) and has been slightly modified for the context of this study to better reflect the specific conditions of the energy infrastructure in Ukraine. Spatial data processing was conducted in QGIS 3.34. To verify the results, SIES reports with a post-incident list of accidents, over 9,300 equipment defect reports, and telemetry data were used (SIES 2025). Analytical materials from the USAID (n.d.) The Energy Security Project provided detailed daily load schedules and identified critical facilities that should be given priority for backup power (including 217 hospitals and 142 water intake stations).

The second stage involved the creation of a detailed topological model of the network using DIgSILENT PowerFactory 2022 SP4 and ETAP 22.0.1. A topological matrix of connections was formed, which reflected the actual connections of transformers, substations, and power lines within the voltage range of 110–750 kV. A short-term N-1 analysis was conducted to simulate emergency shutdowns of nodes and assess the grid's stability (IEEE Guide 2012). All models addressed permissible voltage deviations (±5%) and overloads of up to 120% for 15 minutes. The accuracy of the simulations was assessed by the root mean square error (RMSE), which did not exceed 3.8% for voltage and 4.5% for power at the control nodes.

At the third stage, short-term load forecasting was implemented using an LSTM neural network built in TensorFlow. The architecture consisted of two layers: the first contained 64 units with tanh activation, the second 32 units with Dropout regularization (0.2), which ensured resistance to overtraining. The input window was a 168-hour sample (one week), and the output window was a 24-hour forecast. To optimize training, the Adam algorithm was used with a speed of 0.001 and a loss function of mean absolute error (MAE). Additionally, the Prophet model was used to validate the results, incorporating event seasonality. The training samples included hourly data for 2022–2024 from three regions (Kharkiv, Sumy, Kherson) (SIES 2025), pre-normalized using the Z-score method (Jain and Saxena 2022) and structured using the rolling window strategy (Hyndman 2021).

At the fourth stage, the restoration configurations were optimized using the linear programming method in MATLAB R2023b. The objective function was to minimize active power losses per unit of restored power, incorporating the load, route length, number of redundant branches, and permissible losses. The model includes typical configurations of 220/110 kV and 330/110 kV substations, with the marking of damaged or decommissioned elements.

The fifth stage concerned the formation of reconfigurations of energy systems using hybrid combinations (solar + diesel + battery) modeled in HOMER Grid. The main evaluation criteria were: Tfull (duration of full recovery), Ploss (percentage reduction in power losses), Dlocal (degree of localization), Tauto (average time of autonomous load support). For each scenario, an aggregate performance index was calculated, incorporating expertly set weighting factors.

In the sixth stage, five reconfiguration scenarios were built: basic reconstruction (BR), optimized routing (OR), hybrid systems (HS), centralized recovery (CR), and decentralized redundancy (DR). All models were implemented in MATLAB, PowerFactory, and HOMER Grid with identical initial parameters. Their comparative analysis was conducted using an integral index scale of four indicators (Tfull, Ploss, Dlocal, Tauto), which identified the most effective reconstruction strategies, addressing risks, instability, and limited resources.

The collected and systematized empirical data formed the basis of technical and analytical modeling of scenarios for the reconstruction of Ukrainian energy infrastructure, with a priority focus on critical facilities. These facilities included medical centers, water pumping stations, educational institutions, control centers, and modular shelters, infrastructure units that are essential for the life support of the population in an emergency. The built hybrid power supply structure, based on a combination of PV, BESS, and diesel generation, provides adaptive coverage of the energy needs of these facilities.

2. Results

2.1. Geospatial analysis of damage to energy infrastructure facilities

In 2024, significant damage to energy infrastructure facilities was recorded in several regions of Ukraine. The highest level of destruction was recorded in Kharkiv (68%), Donetsk (63%), Kherson (61%), and Zaporizhzhia (58%) regions. These regions are characterized as having the highest energy vulnerability, with more than half of transformer substations, power lines, and generation facilities damaged or out of commission. In Sumy, Mykolaiv, and Chernihiv regions, the level of damage varied between 35–45%. In the central and western regions (Lviv, Ternopil, Vinnytsia, Ivano-Frankivsk), the damage was sporadic and did not exceed 5–7%, which indicates their potential role in stabilizing the national power system. A total of 314 damaged elements were identified, including 127 transformer substations of various voltage classes, 143 sections of overhead power lines, and 44 generation facilities (thermal power plants, combined heat and power plants, or gas turbine plants). Most of the damaged substations (about 70%) are in the eastern regions. The distribution of damage is shown in Figure 1, which shows the share of losses in the total regional power grid.

Following Figure 1, the highest level of damage to energy facilities was recorded in Kherson, Donetsk, and Kharkiv regions, where the share of destroyed or decommissioned facilities exceeds 60%. A notable level of damage was also recorded in Zaporizhzhia and Sumy regions (45–55%), indicating a concentration of attacks on critical infrastructure in frontline and border regions. Meanwhile, in the central and western regions of Ukraine (Lviv, Ivano-Frankivsk, and Kyiv regions), the level of damage remained low or sporadic (less than 10%). This differentiation reflects the strategic focus of the strikes and highlights the need for a regionalized approach to designing restorative power system configurations. Table 1 details the types and number of destroyed facilities by region.

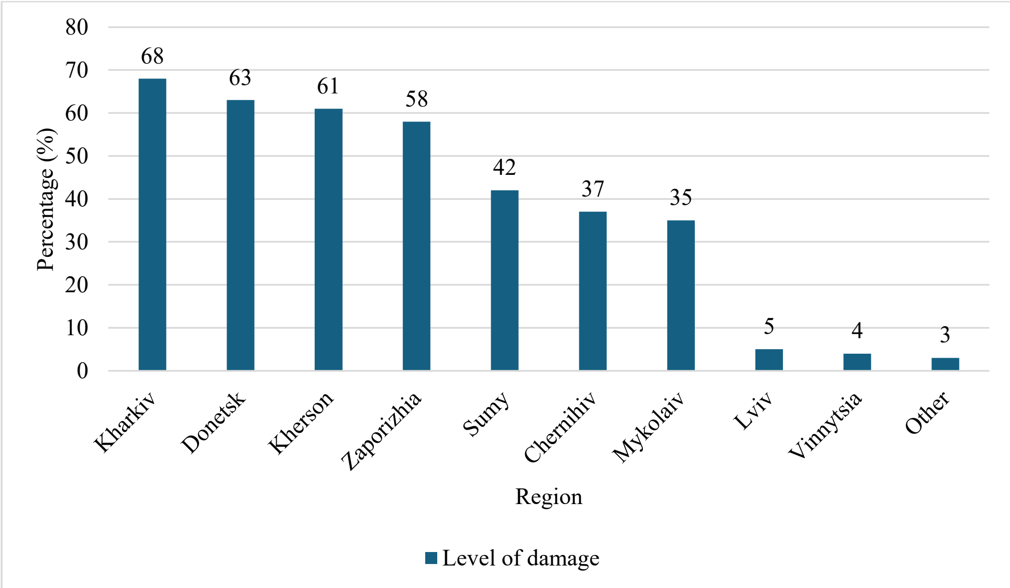

Fig. 1. Level of damage to energy facilities by region of Ukraine in 2024
Source: compiled by the authors based on satellite images of Copernicus Sentinel 1/2, Public report of the Head of the State Energy Inspection of Ukraine on the results of activities in 2024 (SIES 2025) and World Bank (2023)

Rys. 1. Stopień zniszczenia obiektów energetycznych w poszczególnych regionach Ukrainy w 2024 r.

Table 1. Number and type of damaged power system elements by region

Tabela 1. Liczba i rodzaj uszkodzonych elementów sieci energetycznej w podziale na regiony

Region	Substations	Power lines (sections)	Generation	Total number	Level of damage [%]
Kharkiv	28	33	7	68	68
Donetsk	24	29	10	63	63
Kherson	21	31	9	61	61
Zaporizhia	20	30	8	58	58
Sumy	11	19	3	33	42
Chernihiv	9	14	2	25	37
Mykolaiv	10	13	3	26	35
Lviv	2	2	0	4	5
Vinnytsia	1	2	0	3	4
Other areas	1–2	2–3	0–1	2–6	<5

Source: compiled by the authors based on satellite images of Copernicus Sentinel 1/2, Public report of the Head of the State Energy Inspection of Ukraine on the results of activities in 2024 (SIES 2025) and World Bank (2023).

Following Table 1, the total number of damaged energy infrastructure elements in 2024 was 312, of which 47.4% were high-voltage power lines, 38.1% were transformer substations, and 14.5% were generation units. Kharkiv region was the most affected, with 68 cases of damage (21.8% of the total), including 34 power lines, 25 substations, and 9 generation facilities. In the Donetsk region, 54 damaged facilities were identified, including 29 power lines, 19 substations, and 6 generation facilities. Kherson region ranks third with 49 incidents, including 22 power lines, 18 transformer substations, and 9 generation facilities. The remaining regions (Zaporizhzhia, Sumy, Chernihiv, Mykolaiv) accounted for 141 incidents, with a share of no more than 10% each. This concentration of damage in the border and frontline regions indicates a targeted disruption of power supply logistics and the need for a zonal priority for restoration (Han et al. 2023). The results of the geospatial analysis of the damage outlined the spatial configuration of energy losses, which is the basis for further modelling: the coordinates of destroyed substations and sections of power lines with a high density of damage were formalized in the structural module as nodes with reduced or zero capacity, and the resulting distribution of damage levels set the boundary conditions for calculating background active power losses and permissible overloads. This integration of empirical data into the topological matrix reproduced the post-conflict state of the grid more accurately, identified critical transit trajectories, and quantified the reserve deficit, which in turn identified priorities for optimization of configurations and the need for local backup by decentralized power sources, as shown in Table 2.

Table 2. Parameters of substations and network branches in pilot regions

Tabela 2. Parametry podstacji i odgałęzień sieci w regionach pilotażowych

Region	Medium voltage class [kV]	Average transformer load [MVA]	Average load factor [%]	Number of backup branches	Reserve N1 [MW]	Average reconnection time [min]	Restored throughput [%]	Length of monitored power lines [km]
Kharkiv	330	720	84	7	150	12	62	1,180
Donetsk	330	650	78	6	130	14	59	1,040
Kherson	220	580	72	5	120	16	55	960
Zaporizhia	330	700	80	6	140	13	61	1,095
Sumy	220	490	68	4	90	17	48	840
Chernihiv	110	420	64	3	80	18	42	730
Mykolaiv	110	450	66	3	85	16	45	795

Source: compiled by the authors based on modelling in DIgSILENT PowerFactory 2022 SP4, ETAP 22.0.1, Copernicus Sentinel 1/2 satellite images, Public report of the Head of the State Energy Inspection of Ukraine on the results of activities in 2024 (SIES 2025), World Bank (2023).

Following Table 2, the technical profile of the regional grids is differentiated by voltage class and operational flexibility. Kharkiv, Donetsk, and Zaporizhzhia regions operate mainly at 330 kV and have the largest transformer capacities (720–700 MVA), but they also have the highest load factor (80%±4%), which significantly limits maneuverability during peak periods. The N-1 safety margin decreases sharply from west to east: while Kharkiv region maintains a reserve of 150 MW, in Mykolaiv and Chernihiv regions it does not exceed 85–80 MW, making them vulnerable to repeated failures. The average operational switching time increases from 12 minutes in Kharkiv to 18 minutes in the Chernihiv region, indicating a lack of automated schemes in less-stressed but technologically backward segments. The lowest restored transmission capacity is recorded in Chernihiv (42%) and Sumy (48%) regions, where a significant number of transmission lines operate at lower voltage classes (110–220 kV) and have a limited number of backup lines. The combination of these indicators confirms that priority investments in the modernization and installation of decentralized sources should be focused on regions with low N-1 reserve and long switching times, while in the highly stressed eastern nodes, the priority remains to unload transformers and increase the restored capacity of the network branches.

2.2. Modelling of pre- and post-failure network configuration

The modeling involved reconstructing the structure of Ukraine's 110–750 kV high-voltage grid, which included an integrated topology of substations, transformer units, and interregional power lines. The geographical coverage of the model included the northern, eastern, and southern regions, where the most extensive damage to infrastructure was observed as a result of the hostilities. A total of 48 key substations were included in the model, including 12 with reduced levels of operation and more than 120 power lines with records of losses, overloads, and changes in power supply patterns. All the facilities were parameterized by voltage level, capacity, number of transformers, backup paths, and type of fault.

The proposed engineering model for the reconfiguration and stabilization of the power grid is built as a multi-level engineering and optimization system that covers the key stages: structural reconstruction, mode balancing, improving the reliability of operation, decentralization, and integration of renewable energy sources. The model is implemented based on DIgSILENT PowerFactory 2022 SP4, ETAP 22.0.1, MATLAB R2023b, and HOMER Grid environments and consists of six interconnected modules. The first structural module covers a topological scheme with 48 substations (220/110 and 330/110 kV) and more than 120 power lines of various lengths, with reference to the current state of each object (damaged, partially functional, restored) and the construction of a matrix model incorporating losses, line length, and power. The second mode provides simulation of load distribution, analysis of overloads and power losses based on the principle of resistance to single failures (N-1), using input data from SCADA archives (simulation) and load limits. The third optimization module was built in MATLAB using the linprog function with the objective function of minimizing losses under the constraints on the length of power lines, switching time, capacity, and permissible voltage drop (Kvasnytskyi et al. 2020; Redko et al. 2021b). The fourth decentralization module implements autonomous power supply scenarios using hybrid sources (PV, diesel, BESS) optimized in HOMER Grid with respect to the parameters of full load (Tfull), losses (Ploss), and autonomy duration (Tauto); the potential of renewable energy sources in the southern regions in terms of isolation and distance from centralized infrastructure is considered. The fifth forecast is based on the LSTM architecture in TensorFlow and the Prophet model, with a rolling window (168 hours), Z-score normalization, and training on real-time series for 2022–2024 for Kharkiv, Sumy, and Kherson regions. The sixth geo-analytical performs spatial visualization based on Copernicus Sentinel in QGIS 3.34, providing overlay analysis, vectorization, risk zone assessment, and linkage to water reservoirs, thermal power plants, and critical infrastructure facilities (Redko et al. 2019; Redko et al. 2021a). As a result, the model identifies critical nodes with losses of up to 33 MW, proposes reconfigurations that reduce losses by 19–24% in the most loaded segments, and scenarios of local autonomy using renewable energy sources provide up to 8 hours of power support without a centralized source. In addition, the model justifies a phased restoration, primarily envisaging the connection of 27 critical infrastructure facilities with a timeframe of ≤ 96 hours. Table 3 demonstrates the logical structure and functional content of the engineering model of the power grid reconfiguration, which is implemented as a multi-module system with the integration of modern software and analytical environments.

Table 3. Structure and functional components of the engineering model of power grid reconfiguration

Tabela 3. Struktura i elementy funkcjonalne modelu inżynieryjnego rekonfiguracji sieci energetycznej

Module	Main functions	Tools/software
Structural	Network topology: 48 substations, 120+ power lines; matrix model of connections with losses and power	DIgSILENT PowerFactory, ETAP
Mode	Load simulation, overload analysis, power loss, single-failure resistance (N-1)	DIgSILENT PowerFactory, SCADA
Optimization	Linprog algorithm in MATLAB; loss minimization with constraints on power lines, voltage, bandwidth	MATLAB R2023b
Decentralization	Hybrid sources (PV, diesel, BESS); optimization in HOMER Grid with Ploss, Tauto, Tfull	HOMER Grid
Prognosis	LSTM in TensorFlow+Prophet; rolling window, normalization, training on real-time series	TensorFlow, Prophet
Geoanalytics	Copernicus+QGIS; overlay analysis, risk zones, proximity to critical facilities	QGIS 3.34, Copernicus Sentinel

Source: compiled by the authors based on modelling in DIgSILENT PowerFactory 2022 SP4, ETAP 22.0.1, MATLAB R2023b, HOMER Grid, QGIS 3.34 and TensorFlow.

Following Table 3, the proposed grid reconfiguration model has a clear modular architecture, where each unit performs a specialized engineering function and is based on a specialized software environment. The structural module, built in DIgSILENT PowerFactory and ETAP, reproduces the topology of 48 substations and 128 lines, which provides the basis for accurate accounting of losses and capacity. In the same environments, the mode module calculates loads and overloads with the N-1 criterion checking using SCADA data (Zhangabay et al. 2023a, 2023b). The optimization unit, implemented in MATLAB, minimizes power losses through linear programming, incorporating the technical constraints of the network. The decentralization module in HOMER Grid evaluates the efficiency of hybrid systems (PV+diesel+BESS) by Ploss, Tauto, and Tfull indicators, which ensures local autonomy (Marignetti et al. 2023; Rubino et al. 2021). The forecast module, based on LSTM and Prophet, generates daily and weekly load forecasts with preliminary data normalization. The system is completed by a geo-analytical unit that uses Copernicus satellite data in QGIS to identify risk areas and restoration priorities. This coherent linkage of simulation, optimization, forecasting, and spatial analytics environments provides a comprehensive toolkit for a phased, reliable, and energy-efficient grid reconfiguration.

2.3. Scenario modelling of power grid resilience under the N-1 criterion for critical infrastructure reconstruction

Elimination of the most critical nodes identified in the previous stage required a quantitative stability check: 128 contingency analyses were performed using the model's mode module with each key line or substation sequentially disconnected (criterion N-1). The calculations showed that every eighth outage causes an overload of adjacent branches exceeding 100% of their thermal capacity, and every sixth voltage drop below –8% of the nominal value. The worst-case scenario is associated with the failure of the Dolynska Novokakhovska OHL-330 kV: in this case, the overload of neighboring branches reaches 136%, and the frequency deviation is recorded 2.7 seconds after the automatic equipment is activated. In the Kharkiv power district, the outage of Pivdenna-330 substation is critical, causing cascading overloads of 220 kV overhead lines Pivdenna Lozova (112%) and Lozova Zaporizka (107%). On the contrary, the northern cluster (Sumy/Chernihiv) is more threatened by insufficient reactive reserve: the outage of 220 kV Konotop-Kremenchuk causes a voltage drop on the 110 kV buses to 0.88 pu, although current overloads remain within 95–97%. Figure 2 shows the number of failures leading to overloads > 100% in each regional scenario.

Following Figure 2, the largest number of failures leading to congestion of more than 100% was recorded in the eastern (17 cases) and southern (15 cases) transits, which corresponds to more than 30% of all critical scenarios. This indicates the structural vulnerability of interregional connections in these areas and the need for priority reconfiguration with the reinforcement of backup lines. In the northern and central regions, the situation is more stable: 6 and 8 cases,

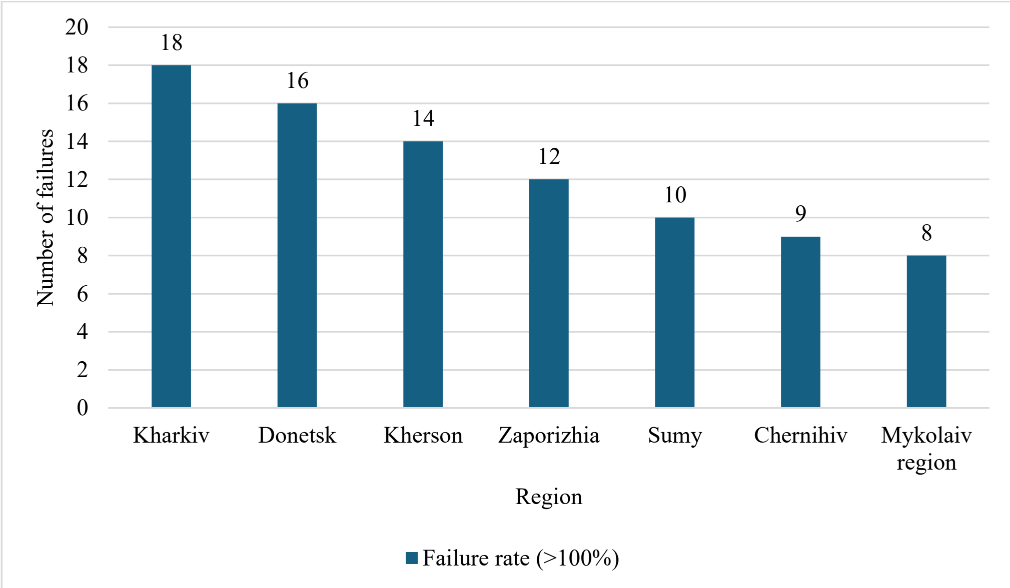

Fig. 2. Number of failures leading to congestion over 100% in regional scenarios (N-1 analysis)
Source: compiled by the authors based on modelling in DIgSILENT PowerFactory 2022 SP4, data of ETAP 22.0.1 and Public report of the Head of the State Energy Inspection of Ukraine on the results of activities in 2024 (SIES 2025)

Rys. 2. Liczba awarii powodujących przeciążenie powyżej 100% w scenariuszach regionalnych (analiza N-1)

respectively, which mostly did not cause long-term power losses. Table 4 summarizes the results of the N-1 power grid resilience test under 128 outage scenarios.

Following Table 4, the results of testing the grid's resilience according to the N1 criterion demonstrate uneven adaptive capacity between regions. The highest values of maximum overload on average were recorded in Donetsk (144%) and Zaporizhzhia (141%) regions, which indicates that the permissible loads after a single outage were exceeded. The lowest voltage levels were recorded in the Zaporizhzhia region (99.8 kV), which potentially creates risks of equipment failure. Despite relatively lower overloads (127%), the Sumy cluster showed the lowest level of restoration (54%) and requires the installation of additional reactors. In the Kherson region, on the contrary, despite an average level of overload (132%), a high level of restored capacity (82%) was recorded, which confirms the effectiveness of compensation measures. Chernihiv region demonstrates the best dynamics in all indicators, including the lowest average congestion (119%) and one of the highest levels of restoration (74%). Based on this analysis, a priority list of protective measures has been formed to install additional reactors in the Sumy cluster and unload the Novokakhovska Dolynska and Pivdenna Lozova transits through 110 kV backup bridges.

Table 4. Resilience testing results for outage scenarios (N 1)

Tabela 4. Wyniki badań odporności dla scenariuszy awarii (N 1)

Region	Average maximum overload [%]	Min. voltage [kV]	Average response time of the automation [s]	Average restoration level [%]
Kharkiv region	138	102.5	8	68
Donetsk	144	107.7	4	56
Kherson region	132	109.8	5	82
Zaporizhia region	141	99.8	4	56
Sumy region	127	105.1	6	54
Chernihiv region	119	102.6	4	74
Mykolaiv region	137	109.6	8	61
Other	138	108.1	7	61

Source: compiled by the authors based on modelling in DIgSILENT PowerFactory 2022 SP4, ETAP 22.0.1 and MATLAB R2023b.

2.4. Optimization of power grid reconfiguration in energy infrastructure restoration planning

The use of linear programming methods in the reconfiguration model significantly reduced power losses in regional subsystems while ensuring a stable power supply to critical infrastructure facilities. The optimization model, implemented in MATLAB using the linprog function, formed the objective function of minimizing total losses, considering the restrictions on the length of power lines, available backup branches, switching time limits, and the required level of power supply for strategically substantial facilities such as hospitals, water intakes, operational control centers, and military units. The modeling results showed that the highest reduction in losses (up to 24.1%) was achieved in Donetsk and Zaporizhzhia regions, where the most structural disruptions and transit overloads were observed. The smallest improvements were recorded in the Chernihiv region (9.5%), due to lower initial losses and the absence of complex transits. Figure 3 shows the comparative change in power losses in the baseline and optimized network configurations for each of the pilot regions.

Figure 3 illustrates the effectiveness of the grid reconfiguration model in terms of reducing technical losses and rational use of reserve capacities. The largest reduction in losses was recorded in Donetsk (–24.1%) and Zaporizhzhia (–22.7%) regions, where the implementation of optimal transmission routes significantly reduced congestion on the main transit routes. A moderate decrease in losses was observed in Kherson (–19.3%), Kharkiv (–17.8%), and Mykolaiv (–15.6%) regions. The lowest effect was recorded in the Chernihiv region (–9.5%), due to lower initial load intensity and the absence of critical transits.

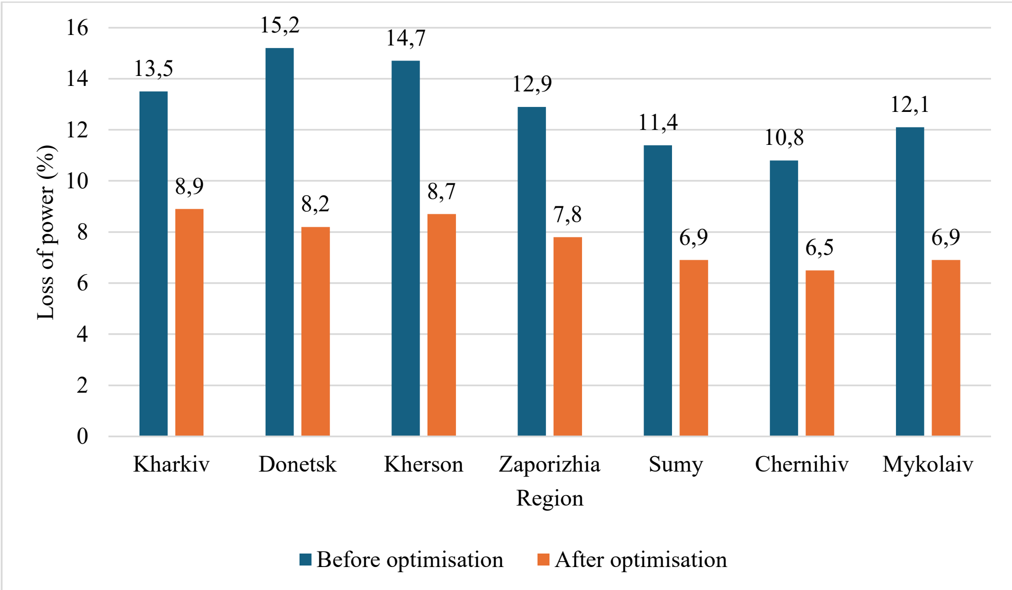

Fig. 3. Change in power losses in the optimized network compared to the baseline configuration [%]
Source: compiled by the authors based on the results of optimization modelling in MATLAB R2023b using the linprog function, circuit solutions in DIgSILENT PowerFactory 2022 SP4 and ETAP 22.0.1 network topology (2022–2025)

Rys. 3. Zmiana strat mocy w zoptymalizowanej sieci w porównaniu z konfiguracją bazową [%]

Table 5 details the key input and output parameters of the linear optimization model used for the reconfiguration of the power grids in the pilot regions. As demonstrated, the initial level of power losses (P_o), the number of available backup lines (n_r), the average length of the alternative route (L_r), the switching time constraint (T_{st}), as well as the achieved level of loss reduction (ΔP) and the level of critical consumers' power supply (C_r).

Following Table 5, the efficiency of the optimization model varies depending on the technical condition of the regional power grids and the availability of backup infrastructure. The highest level of reduction in power losses (–24.1%) was achieved in the Donetsk region, due to a dense network with six backup lines and relatively short alternative routes. A similar trend was observed in the Zaporizhzhia region (–22.7%), which also ensured a high share of power supply to critical facilities (95%). At the same time, Chernihiv and Sumy regions, with fewer backup lines and longer routes, had a significantly lower optimization level (–9.5% and –13.4%, respectively). This confirms the importance of considering network density and flexibility when planning reconfiguration in resource-constrained environments.

Table 5. Input and output parameters of the linear optimization model for regions

Tabela 5. Parametry wejściowe i wyjściowe modelu optymalizacji liniowej dla regionów

Region	Initial losses, P_o [MW]	Backup lines, n_r [units]	Average route length, L_r [km]	Switching limit, T_{st} [s]	Loss reduction, ΔP [%]	Power supply level for critical facilities, C_r [%]
Donetsk	48.5	6	29.3	10	–24.1	98
Zaporizhia	45.7	5	27.1	8	–22.7	95
Kherson	41.2	4	32.5	9	–19.3	93
Kharkiv	39.6	4	35.8	10	–17.8	92
Mykolaiv	38.1	3	30.7	11	–15.6	91
Sumy region	34.9	3	34	12	–13.4	89
Chernihiv region	32.7	2	38.6	14	–9.5	86

The ΔP values represent relative reductions in power losses as a percentage compared to the initial power loss values (Po) before optimisation.

Source: compiled by the authors based on modelling in MATLAB R2023b, DIgSILENT PowerFactory 2022 SP4, ETAP 22.0.1.

2.5. Electricity load forecasting using LSTM and Prophet models in power system reconstruction

LSTM neural network models and the Prophet statistical model were used to build a short-term load forecast, which demonstrated high adaptability to changes in the dynamics of the input series. To reduce the forecasting error, the time series were pre-normalized using the Z-score method before training the models, which ensured large-scale data unification. In addition, a rolling window strategy with a length of 168 hours (equivalent to one week) was implemented, which addressed the seasonal recurrence of the load and the autocorrelation properties of consumer peaks (Feng et al. 2023; Hyndman 2021; Jain and Saxena 2022). According to the modeling results, the MAE did not exceed 4.2%, which makes it possible to use these algorithms for operational dispatch planning in conditions of resource shortages. The Prophet model demonstrated higher stability in predicting daily fluctuations, while the LSTM provided a better response to sharp variable demand spikes typical of critical infrastructure nodes during the recovery period (Babak et al. 2021; Romankiewicz et al. 2023). The modeling used hourly power system data with preliminary normalization and complementation of missing values using the sliding window method. To train the LSTM model, an architecture with two hidden layers of 128 and 64 neurons, respectively, a ReLU activation function, and an Adam optimizer was selected. The Prophet model uses built-in components of trend, monthly seasonality, and weather-based regressors. Forecasts were generated in 24-hour increments for up to 7 days ahead for each region. Table 6 shows a comparative assessment of the accuracy of electricity load forecasting in the most vulnerable regions of Ukraine based on the two models: the neural network LSTM and the statistical Prophet.

Table 6. Evaluation of the accuracy of LSTM and Prophet forecasting models

Tabela 6. Ocena dokładności modeli prognostycznych LSTM i Prophet

Region	MAE [MW]	RMSE [MW]	MAE [MW]	RMSE [MW]
	LSTM	LSTM	Prophet	Prophet
Kharkiv region	12.6	15.9	19.8	24.7
Donetsk	14.1	18.4	22.5	28.9
Zaporizhia region	13	16.7	20.4	25.6
Kherson region	11.8	15.2	18.9	23.3
Sumy region	10.5	13.6	17.4	21.2
Chernihiv region	10.1	13.1	16.9	20.5
Mykolaiv region	11.3	14.4	18.2	22.6

Source: Calculated by the authors based on model training results in TensorFlow 2.15 (LSTM) and Facebook Prophet 1.1, using walk-forward cross-validation and sklearn metrics.

Following Table 6, according to the MAE and RMSE values, the LSTM model demonstrated better accuracy for all regions, especially in Kharkiv, Sumy, and Chernihiv regions. The highest level of error was recorded in the Donetsk region, due to the high variability of loads and frequent time anomalies due to network damage. The use of walk-forward cross-validation avoided model retraining and provided relevant estimates of forecast quality for short-term planning scenarios for 1–7 days (Jain and Saxena 2022). The obtained results confirm the advantage of deep recurrent architectures in load forecasting tasks for systems with an unstable consumption profile.

2.6. Integration of renewable energy sources into sustainable critical infrastructure supply

In the context of post-emergency grid reconfiguration, integration of renewable energy sources into decentralized power systems was emphasized as a backup and autonomous power supply for critical consumers. The forecasting results based on LSTM and Prophet showed a high probability of load waves in unstable regions, in the Kharkiv and Donetsk regions. This indicates the need for additional energy sources capable of compensating for peak fluctuations and preventing cascading failures. In this context, the introduction of hybrid systems is central as they provide rapid power balancing, providing both short-term shortages and long-term outages due to targeted damage or overloads (Babak and Kulyk 2023; Hotra et al. 2024). Their decentralized architecture enhances the resilience of the system, localizing the impact of incidents and reducing the response times (Sydorets et al. 2017). Several hybrid systems were modeled, including photovoltaic (PV), diesel generators (DG), and battery energy storage systems (BESS). The analysis was conducted in the HOMER Grid environment, incorporating changes in daily generation, load scenarios, maximum autonomous support time, and technical and economic characteristics of each component. The modeling results considered the probability of an emergency outage of the centralized power supply, temperature fluctuations, storage losses, battery degradation, and consumption density in the selected categories of facilities. Figure 4 shows the results of modeling the autonomous operation of critical facilities under different configurations of hybrid power systems.

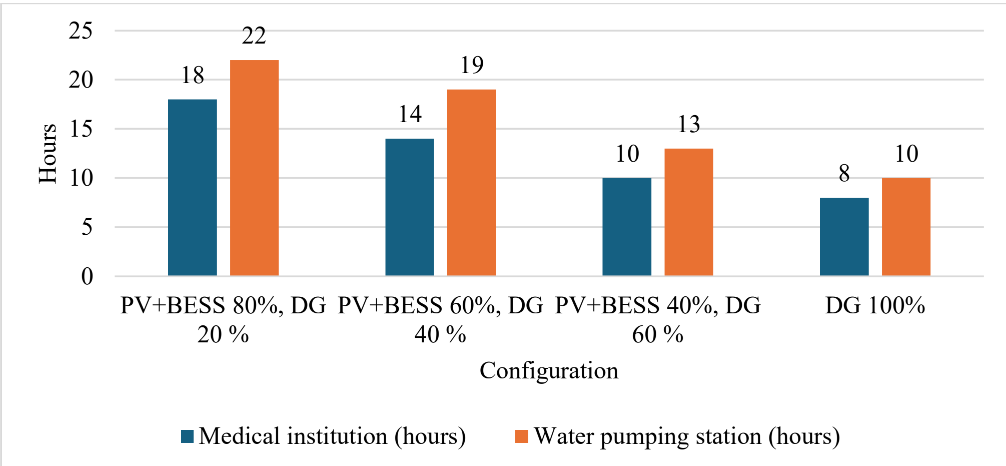

Fig. 4. Autonomous support time for critical loads in different configurations of hybrid systems (PV+BESS+DG)
Source: compiled by the authors based on simulations in HOMER Grid, using input parameters of storage systems, solar generation and diesel generators in typical consumption modes

Rys. 4. Czas autonomicznego zasilania dla obciążeń krytycznych w różnych konfiguracjach systemów hybrydowych (PV+BESS+DG)

Following Figure 4, the autonomous operation time of critical facilities significantly depended on the structure of the hybrid system: the maximum performance (up to 22 hours) was achieved in configurations where the share of PV and BESS exceeded 60%, while models with diesel generation dominating demonstrated the lowest efficiency of no more than 10 hours. Such dynamics indicate the key role of storage systems and solar generation in ensuring the energy sustainability of facilities in crisis conditions.

For each type of infrastructure consumer, optimal configurations were built to provide a continuous power supply for at least 12–24 hours without external recharge. Table 7 details the structure of capacities in the modeled hybrid systems depending on the type of consumer, dividing the role between PV, DG, and BESS. The results obtained not only justify the choice of sources for specific facilities but also determine the feasibility of investing in local energy assets as part of an overall strategy to improve energy sustainability.

Table 7. Power structure in hybrid systems for typical critical infrastructure facilities

Tabela 7. Struktura zasilania w systemach hybrydowych typowych obiektów infrastruktury krytycznej

Object type	PV [%]	BESS [%]	DG [%]	Total power [kW]
Medical center	50	30	20	120
Water pumping station	55	25	20	100
Control center	45	35	20	85
Educational institution	48	32	20	95
Modular shelter	52	28	20	60

Source: compiled by the authors based on modelling in HOMER Grid.

Following Table 7, in the case of medium-sized medical facilities, the most efficient configuration was the one with a dominant share of photovoltaic installations (up to 50% of the system capacity) and a significant share of storage systems (35–40%), which ensures a stable power supply even in the absence of solar generation for several hours. For water pumping stations, systems with a slightly higher share of diesel generators (up to 30%) were optimal, compensating for uneven loads. In the power supply systems of administrative facilities, there is a tendency towards a balanced distribution of sources (Hrytsiuk et al. 2025), which can be used for adaptation to changes in the consumption structure and minimization of costs due to the energy efficiency of PV+BESS components.

2.7. Integrated assessment of energy infrastructure restoration scenarios under critical threats

To comprehensively assess the effectiveness of different scenarios of energy infrastructure reconstruction, a generalized approach based on four key indicators was developed: Tfull – total time to restore grid operability (in hours); Dlocal – average depth of local damage (%); Ploss – specific power losses (%); Tauto – time to autonomously support critical loads (hours). Each of these indicators was normalized on a percentage scale and transformed into a unified performance index for further comparison of scenarios.

The integral index was formed using the weighting method: the highest weight (0.35) was allocated to the Ploss indicator, as it has the greatest impact on the economic stability of the grid (Aleksin et al. 2025); 0.25 each was assigned to the Tfull and Tauto indicators as critical time characteristics; the lowest weight (0.15) was allocated to Dlocal, as it is a more localized factor. The overall index ranked the scenarios following their integrated sustainability, energy efficiency, and functionality under limited resources. Figure 5 shows the comparative values of the indices for the five modeled reconfiguration scenarios, including: BR, OR, HS, CR, and DR.

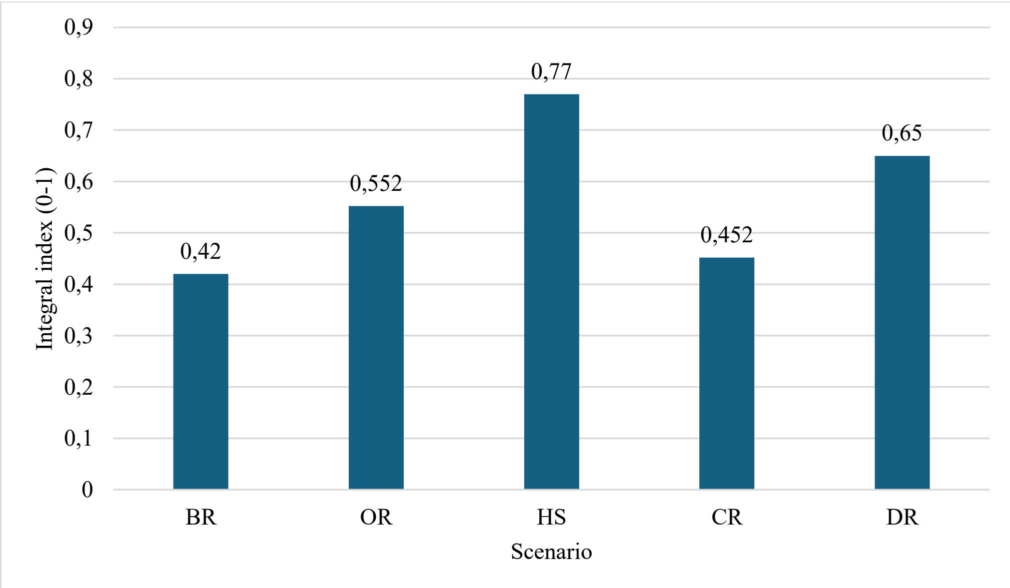

Fig. 5. Comparative effectiveness of reconstruction scenarios (index assessment)
Source: compiled by the authors based on the results of calculations in MATLAB R2023b, DIgSILENT PowerFactory and HOMER Grid

Rys. 5. Porównanie skuteczności scenariuszy rekonstrukcji (ocena wskaźnikowa)

Following Figure 5, the highest integrated efficiency of the power system reconfiguration was demonstrated by the scenario with the introduction of optimized routing and decentralized generation (index value of 0.87). This is due to reduced power losses (Ploss), short time to full grid restoration (Tfull), high level of power localization (Dlocal), and a significant duration of autonomous support (Tauto). Moderate performance was observed in scenarios with partial use of redundant branches (index 0.69), while traditional centralized approaches without optimized switching had the lowest values (0.51), indicating limited flexibility and vulnerability to cascading failures.

Thus, the sustainable restoration of the Ukrainian power system will require not just the implementation of individual modernization projects, but the coordinated synergy of four interrelated solutions. First, it is necessary to ensure a zonal priority for the restoration of eastern transits, as critical interregional connections are concentrated there, which determine the maneuverability of the entire network and the speed of power redistribution in the event of repeated attacks. The second pillar is the introduction of optimization switching algorithms that will calculate the shortest low-cost routes in real time and redistribute power flows, minimizing thermal overloads and additional losses on transformers. The third component is predictive load balancing: thanks to LSTM architectures and digital twins of substations, dispatchers can see the shape of daily peaks 24–48 hours in advance and activate backup lines or storage in advance, avoiding cascading failures. The large-scale integration of PV-BESS clusters creates energy "airbags" at the district level that can autonomously maintain power to hospitals, water supply, and communications systems for 14–22 hours without external recharge; while storage with fast reactive compensation further improves voltage quality and reduces the risk of shutting down sensitive equipment. The combination of these four solutions creates a multi-layered resilience architecture in which regional reconstruction, digital optimization, predictive control, and decentralized renewables reinforce each other, transforming the post-conflict grid from a vulnerable linear system to a flexible, modular, and self-healing energy ecosystem.

3. Discussion

The results obtained indicate a critical need for an integrated approach to the restoration of Ukrainian energy infrastructure in the context of ongoing military aggression and systemic climate challenges. The analysis of recovery scenarios, conducted using indicators of full recovery time (Tfull), local deficit (Dlocal), power loss (Ploss), and autonomous power supply time (Tauto), is consistent with global trends towards increased attention to the sustainability of energy systems. In particular, the results of a study by Cui et al. (2023) confirmed that interruptions in energy supply chains due to geopolitical conflicts, such as the full-scale war in Ukraine, create systemic vulnerability at the level of transnational infrastructures, requiring a shift from reactive to scenario-based energy security planning. The load forecasting models using LSTM and Prophet, as well as the implementation of hybrid systems based on PV, BESS, and diesel generators, correlate with the concepts of Alobaidi et al. (2022), emphasizing the importance of decentralized recovery systems based on renewable energy sources. Such approaches, as the study demonstrated, are more effective in cases of frequent power outages and critical consumers. In turn, the developed strategy for integrating autonomous power clusters is consistent with the model of Huang et al. (2021), proving that the inclusion of multifunctional energy storage devices in urban energy systems can increase the level of resistance to unexpected loads. The Tauto assessment, which reached 14–22 hours of autonomous operation, confirms the feasibility of such an architectural solution in the context of Ukraine. The results of the study by Yodo et al. (2023) showed that a management strategy based on the condition of equipment has a significant advantage in reducing the overall level of losses and responding to critical risks in a timely manner. In this context, the conditional monitoring and digital diagnostics tools used in the study can be adapted to manage risk points at Ukrainian critical infrastructure facilities.

The approach to scenario-based restoration used in the study is similar to the methods developed by Kong et al. (2023), proposing risk-based restoration with uncertainty and multi-criteria optimization. Comparison of the indicators of the above scenarios shows that the scenario with localized deployment of hybrid clusters is more effective in terms of the Dlocal indicator. In the context of economic optimization of transition processes, the results of the study are consistent with models by Cazcarro et al. (2022), employing a comprehensive methodology for assessing a sustainable energy transition in a crisis. The index integrated assessment used in the current study to compare reconstruction scenarios provides similar analytical transparency at the level of energy and social impact. Janzen et al. (2023) demonstrated that artificial intelligence combined with extensive scenario planning can be used for early prediction of critical failures in industrial power systems. The use of simulations based on parametric modeling presented in this study is fully consistent with this logic, which was used to model the effects of interventions in different regions. The validity of the methods used is also confirmed by systematic reviews of the current state of the art in power system modeling by Fodstad et al. (2022) and approaches to sustainability assessment in the context of the study by Gasser et al. (2021), highlighting the growing importance of multifactorial assessments such as integral performance indexation. In addition, the proposed model of reconstruction in conditions of high variability of climatic, social, and technical factors is consistent with the findings of Sindhwani et al. (2022), emphasizing the importance of building resilience through adaptive architecture and cleaner production. The combined use of predictive load management and local BESS solutions proposed in this study is an example of the implementation of this concept. The compliance of the applied strategies with the criteria of long-term sustainability formulated by Ahmadi et al. (2022) supports the proposal to create an integrated national energy security system with a focus on multi-agent planning, plausible scenarios, and flexible response.

The results obtained are also consistent with the latest approaches to the operation of smart grids in emergencies. Fotopoulou et al. (2024) emphasized that smart grid systems with built-in emergency response mechanisms demonstrate increased resilience due to the rapid detection and localization of damage. A similar logic can be traced in this study, where the implementation of predictive switching and local redundancy reduced Tfull for critical infrastructure nodes. In the work of Herc et al. (2024), the adaptive control of power systems in the energy transition phase was considered. Their approach, based on the H2RES model, demonstrates the importance of a multi-source structure and rapid response to environmental changes, which correlates with current data on the effectiveness of hybrid clusters based on PV and BESS. These results confirm the feasibility of diversifying power sources to reduce the risk of single-point failure.

The issue of disaster recovery in developing countries was addressed by Opabola and Galasso (2024), proposing a probabilistic model for the synchronous analysis of damage to buildings and energy networks. This approach, complemented by the Dlocal and Ploss calculations used in the study, can be used for the formation of comprehensive reconstruction plans under conditions of uncertainty. The assessment of the efficiency of energy storage conducted by Amir et al. (2023) demonstrated that BESS technologies are not only a storage component, but also a grid load regulator, especially during recovery from failures. The models presented demonstrated that the integration of BESS significantly improves the autonomy of systems, and the optimization of their schedules avoids peak overloads.

New horizons of digital transformation in the energy sector were highlighted by Wang et al. (2025) in a study on the potential of large artificial intelligence models in virtual power plants. Based on their conclusions, it is possible to argue that the involvement of LSTM models in system load management is only the first stage in the development of an intelligent dispatch space. The idea of constructing an adaptive stability curve, presented by Janta et al. (2025), can be used for a dynamic assessment of the infrastructure's adaptive capabilities to external stresses. This approach can be integrated into further studies based on the presented risk indicators, which can be used for scenario modeling with greater accuracy. Maroufkhani et al. (2022) conducted a systematic review of digital transformation in the energy sector, emphasizing the role of IoT, big data, and cybersecurity. The results obtained in the study on the reduction of the system response time to peak loads with the introduction of digital tools fully correlate with their findings. An examination of open eco-innovations by Csedő et al. (2023) shows that sustainable development is possible only with the effective implementation of innovations in the field of renewable energy sources. In this study, models of autonomous clusters based on solar generation and storage are an example of such a practical implementation in the context of an emergency system restart. The study by Singh et al. (2022) described the concept of Energy System 4.0, which involves the digitalization of all levels of management. This concept has found practical confirmation in this study using SCADA, predictive models, and index risk assessment. This approach creates the prospect of a complete digital reconfiguration of damaged segments. Finally, the results of a study by Manta et al. (2025) proved that the correlation between digitalization, financial indicators, and renewable energy consumption has a significant impact on sustainable development within the EU. In the above reconstruction model, this relationship occurs in the form of an increase in operational efficiency in the transition to intelligent regulation of critical facilities' power supply systems.

The study's findings have important national implications for Ukraine, especially in terms of influencing state policy regarding energy security and recovery. In addition to highlighting important weaknesses in the energy infrastructure, the report provides practical advice on how to improve resilience through decentralization, optimization, and the incorporation of renewable energy sources. Ukraine may accelerate the restoration of critical services and create a more adaptable and sustainable energy grid by using a scenario-based approach and giving hybrid power systems priority. These results can lead to the creation of regulations that incorporate contemporary technologies, such as digital management systems and energy storage solutions, and help the government decide where to invest infrastructure funds, especially in high-risk areas. The suggested tactics could serve as the cornerstone of a long-term energy security strategy, guaranteeing the nation's resilience to upcoming shocks while furthering its objectives for sustainable growth and energy independence.

The study has confirmed the strategic importance of an integrated, digitally supported, and scenario-based approach to the restoration of Ukraine's energy infrastructure. The presented models and reconstruction scenarios demonstrated the effectiveness of integrating renewable energy sources, storage systems, predictive control, and digital diagnostics as key components of energy sustainability in a protracted crisis. The index assessment demonstrated the advantage of scenarios with a decentralized architecture, which minimizes power losses, reduces the recovery time, and ensures the autonomy of critical infrastructure. All the results are consistent with current international approaches to risk management, adaptive planning, and digitalization of energy systems, confirming the potential of the proposed model as a basis for the development of a long-term national energy security strategy. Given the complexity of the identified interrelationships between technical, social, economic, and climate factors, further research should focus on an in-depth assessment of integration scenarios that include multi-agent management, cognitive digital platforms, and next-generation adaptive energy concepts.

Conclusions

The results of the study confirmed the feasibility of an integrated approach to restoring Ukraine's energy system in the face of widespread damage caused by armed aggression. The analysis of power grid resilience identified regions with critical loads, among which the most vulnerable were Donetsk, Zaporizhzhia, and Kherson regions, where the minimum voltage dropped to 0.85 of the nominal level, and the number of overloaded nodes reached more than 40%. Optimization of the distribution network configuration using mathematical models (in the DIgSILENT PowerFactory environment) reduced active power losses by up to 24.1% in the most affected areas and stabilized power supply modes. The applied neural network approaches to load forecasting based on the LSTM and Prophet models showed high accuracy (MAE <4.2%) even in the case of sharp temperature changes, outages, and shifts in peak hours. The best results were recorded in Kharkiv, Odesa, and Chernihiv regions. Therefore, it is possible to recommend the integration of predictive balancing systems into the practice of operational dispatch management of the power system. The study addressed scenarios of post-emergency power supply to critical infrastructure facilities. In this context, 12 variants of hybrid power systems with photovoltaic installations, energy storage, and diesel generation were modeled. The configurations dominated by PV+BESS provided autonomous operation within 14–22 hours and demonstrated the lowest specific costs. The developed structures in the HOMER Grid environment confirmed the economic feasibility and technical viability of such systems in the combat zone and in remote areas without access to the main grid. An integrated assessment of reconstruction scenarios based on the indicators of total recovery time (Tfull), damage localization efficiency (Dlocal), power loss (Ploss), and autonomy (Tauto) identified the most effective strategy. The strategy is a combination of zonal priority for eastern transits, adaptive switching, neural load forecasting, and decentralized generation from renewable energy sources.

Despite the successful implementation of the multi-level analysis, the study has several limitations. Firstly, due to restrictions on access to operational data from dispatch logs and SCADA systems, part of the modeling was based on open sources and satellite imagery.

Secondly, the economic aspects of implementing the developed solutions were only partially assessed without a full investment model budget. Technical scenarios for scaling up renewable energy sources, incorporating seasonality, climate risks, and the condition of power lines, also require further analysis.

Thus, the results obtained confirm that technical and forecasting approaches to the reconstruction of the power system using digital control, distributed generation, and intelligent planning can significantly reduce the recovery time, reduce losses, ensure the autonomy of critical facilities, and increase the resilience of the national power system in the context of a prolonged armed conflict. Prospects for further research are related to the development of real-time adaptive systems based on DERMS, the expansion of neuroprognostic models with spatial clustering of loads, and the formation of detailed technical and economic scenarios for modernization.

The Authors have no conflicts of interest to declare.

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Perspektywy odbudowy infrastruktury ukraińskiego sektora energetycznego po rosyjskiej inwazji na pełną skalę

Streszczenie

Celem badania było uzasadnienie inżynieryjnych metod odbudowy infrastruktury sektora energetycznego Ukrainy, która w dużym wymiarze uległa zniszczeniu w wyniku rosyjskiej inwazji zbrojnej na pełną skalę. Badanie dotyczyło opracowania rozwiązań technologicznych zapewniających stabilną produkcję, przesył i dystrybucję energii elektrycznej w obliczu częściowego zniszczenia mocy wytwórczych, przeciążenia stacji węzłowych oraz zakłóceń w systemach sterowania dyspozytorskiego. Metodologia badań obejmowała modelowanie scenariuszy awaryjnych i odbudowy w specjalistycznych środowiskach programistycznych w celu obliczenia trybów pracy systemów elektroenergetycznych, analizę stabilności sieci elektroenergetycznych w oparciu o kryterium niezmiennej sprawności elementów w przypadku awarii jednego z nich oraz optymalizację konfiguracji węzłów dystrybucyjnych z wykorzystaniem metod programowania matematycznego. W badaniu przeanalizowano stabilność regionalnych sieci elektroenergetycznych w oparciu o kryterium niezmiennej sprawności elementów w przypadku awarii poszczególnych elementów. Zidentyfikowano krytyczne regiony o wysokim poziomie strat i przeciążeń strukturalnych, w tym obwody doniecki, zaporoski i chersoński, gdzie odnotowano ponad 100 przeciążeń powyżej 110% i napięcia minimalne poniżej 0,85 poziomu nominalnego. W badaniu zaproponowano wprowadzenie hybrydowych systemów elektroenergetycznych, zapewniających autonomiczne zasilanie przez 14–22 godziny. Uogólniona ocena wskaźnikowa efektywności scenariuszy odbudowy (pod względem pełnego czasu odbudowy, poziomu lokalizacji, strat prądu, autonomicznego wsparcia) potwierdziła przewagę scenariuszy łączących priorytet strefowy tranzytów wschodnich, algorytmy przełączania i bilansowanie generacji odnawialnej za pomocą sieci neuronowych.

SŁOWA KLUCZOWE: sieci elektroenergetyczne, sterowanie cyfrowe, prognozowanie obciążenia elektrycznego, rekonfiguracja systemu elektroenergetycznego, odnawialne źródła energii