

Article

Distributed Energy Systems as an Instrument for Strengthening the Resilience of Critical Infrastructure in Crisis Management

Marcin Rabe ^{1,*}, Tomasz Norek ², Andrzej Gawlik ³, Katarzyna Widera ⁴, Marcin Jurgilewicz ⁵,
Bartosz Kozicki ⁶ and Aleksandra Skrabacz ⁶

¹ Management Institute, University of Szczecin, 71-101 Szczecin, Poland

² The Institute of Spatial Management and Socio-Economic Geography, University of Szczecin, 71-101 Szczecin, Poland; tomasz.norek@usz.edu.pl

³ Department of Renewable Energy Engineering, West Pomeranian University of Technology in Szczecin, 71-065 Szczecin, Poland; andrzej.gawlik@zut.edu.pl

⁴ Faculty of Economics and Management, Opole University of Technology, 45-271 Opole, Poland; k.widera@po.edu.pl

⁵ Rzeszów University of Technology, 35-029 Rzeszów, Poland; m.jurgilewicz@prz.edu.pl

⁶ Military Technical Academy, 00-908 Warszawa, Poland; aleksandra.skrabacz@wat.edu.pl (A.S.)

* Correspondence: marcin.rabe@usz.edu.pl

Abstract

Distributed energy systems are increasingly important for strengthening critical infrastructure resilience under conditions of technological, climatic, geopolitical, and cyber disruption. However, existing research on energy resilience is still dominated by technical approaches focused on reliability, renewable energy integration, microgrid control, and storage optimisation, while the role of distributed energy systems in the full crisis-management cycle remains insufficiently conceptualised. This article addresses this gap by combining a scoping review, lexicographic and semantic analysis using IRaMuTeQ version 0.7 alpha 2, and a conceptual-methodological framework for assessing distributed energy systems as instruments of crisis management. The main contribution of the study is the M_ZK-DES model, which integrates technological-infrastructure, decision-operational, legal-institutional, and socio-organisational dimensions with four crisis-management phases: prevention, preparedness, response, and recovery. The model distinguishes distributed energy systems, distributed energy resources, distributed generation, microgrids, prosumers, energy communities, and energy clusters and links them to measurable resilience indicators. These include SAIDI, SAIFI, energy not supplied, restoration time, share of critical load served, islanding capability, voltage and frequency stability, storage autonomy, procedural readiness, and local coordination capacity. The analysis shows that distributed energy systems may reduce vulnerability to cascading failures, support islanded operation, protect vulnerable consumers, improve emergency power continuity, and strengthen local energy autonomy. The proposed scoring and weighting logic enables future empirical validation, scenario testing, and comparative assessment across regions and crisis types, including extreme weather events, cyberattacks, and supply-chain disruptions. The article contributes to energy resilience and crisis-management studies by offering an integrated and operational framework for evaluating distributed energy systems as practical tools for critical infrastructure protection and continuity of essential public services.



Academic Editor: Takashi Ikegami

Received: 13 June 2026

Revised: 6 July 2026

Accepted: 8 July 2026

Published: 12 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: distributed energy systems; energy resilience; crisis management; critical infrastructure; microgrids; energy security; distributed generation; socio-technical systems; emergency preparedness; energy transition

1. Introduction

Distributed energy systems (DES) are examined in this article as crisis-management resources, not only as instruments of decarbonisation. The problem addressed is the limited integration of microgrids, storage, prosumer generation and local balancing mechanisms with critical-infrastructure protection, business continuity and emergency response [1–3].

Centralised electricity systems remain exposed to nodal failures, cyber threats, fuel-supply disruptions and extreme weather events. When such disruptions affect transmission substations, control systems or medium-voltage distribution lines, their effects may cascade to healthcare, water supply, transport, communications and public administration [1,4].

The review therefore asks how DES can reduce vulnerability, maintain essential services and accelerate recovery during crisis conditions. The analysis focuses on five resilience capacities: anticipation, absorption, adaptation, reconfiguration and recovery [2,5,6].

The article develops the M_ZK-DES conceptual model, which links DES with the four phases of crisis management: prevention, preparedness, response and recovery. The model integrates technological factors (distributed generation, storage, islanding and monitoring) with institutional and social factors (decision rules, stakeholder coordination, public communication and protection of vulnerable consumers) [7–10].

The scope is deliberately limited to the crisis-management function of DES. Broader themes of energy transition, decarbonisation and market reform are mentioned only when they explain resilience, continuity of public services or the protection of critical infrastructure.

The main objective is to develop and justify a repeatable analytical framework for assessing whether, how and under what operational conditions distributed energy resources can strengthen the resilience of critical infrastructure in crisis management.

The article makes four contributions:

- It clarifies the research problem by treating DES as local crisis resources supporting continuity of critical functions;
- It organises the literature into technical, methodological and crisis-management streams;
- It translates the proposed model into variables, indicators, formulas and operational steps;
- It explains how probability, impact, vulnerability and exposure scores are used in the illustrative risk matrix.

The study combines a scoping review, semantic analysis and conceptual-methodological modelling. Its main contribution is the M_ZK-DES framework, which translates the literature on distributed energy systems into a crisis-management assessment procedure that can be replicated in scenario studies and local/regional case analyses.

The contribution is therefore threefold: (i) conceptual, because the article distinguishes technical DES categories and links them with crisis-management phases; (ii) methodological, because it documents the review, IRaMuTeQ corpus preparation and PRISMA-ScR-style screening logic; and (iii) operational, because it proposes measurable indicators, ordinal scales, weights and formulas for assessing resilience outcomes.

2. Literature Review

2.1. Technical and Crisis-Management Scope of the Review

The literature is interpreted through two separate streams. The first stream includes technical models of energy resilience that focus on reliability, microgrid control, storage, islanding, restoration and power-quality indicators. The second stream includes crisis-management and civil-protection frameworks that focus on coordination, preparedness, warning, vulnerable consumers and recovery. The gap addressed by this article is not the absence of resilience or crisis concepts, but their insufficient integration into one operational framework (Table 1).

Table 1. Summary of literature stream, typical focus, limitation identified, implication for M_ZK-DES.

Literature Stream	Typical Focus	Limitation Identified	Implication for M_ZK-DES
Technical energy-resilience models	Reliability, restoration, microgrid islanding, storage dispatch, power quality.	Often strong in engineering indicators but weak in institutional crisis-cycle integration.	Provides measurable variables for K2 and Rk.
Single-domain crisis-response frameworks	Preparedness, emergency communication, command structures and recovery procedures.	Often strong in governance but insufficiently linked to DER, microgrids and operational grid constraints.	Provides procedural logic for K0, K1 and K3.
Multidisciplinary integration gap	Connection of technical resilience with governance, civil protection and community resources.	Rarely operationalised with weights, scores and replicable scenario calculations.	Defines the contribution of M_ZK-DES as an integrated assessment model.

The review was designed as a scoping review because the field is interdisciplinary and conceptually dispersed. It combines energy engineering, security studies, critical-infrastructure protection, management, public policy and socio-technical resilience research [11–13].

The technical scope covers distributed generation, microgrids, energy storage, prosumer installations, demand-side management, local balancing, islanding operation and digital monitoring. The crisis-management scope covers prevention, preparedness, response, recovery, business continuity, protection of vulnerable consumers, emergency power supply and cascading failures [8–10,14,15] (Table 2).

Table 2. Technical concepts used in the article and their operational distinction.

Concept	Definition Used in This Manuscript	Unit of Analysis	Crisis-Management Relevance
Distributed energy systems (DES)	Integrated local or regional configuration of distributed resources, storage, control, users and governance arrangements.	System/local energy ecosystem	Overall resilience of critical functions.
Distributed energy resources (DER)	Physical or controllable resources located close to loads: PV, wind, CHP, batteries, controllable loads, EV chargers.	Asset/resource	Resources activated during prevention, response or recovery.
Distributed generation (DG)	Electricity generation connected to distribution networks or located behind the metre.	Generation technology	Reduces dependence on single central nodes.
Microgrid	A bounded electrical system capable of coordinated control and, where designed, islanded operation.	Operational subsystem	Maintains supply to priority loads during upstream disruption.
Prosumer	An end user that consumes and produces electricity, sometimes with storage or demand response.	Actor/household/facility	Can reduce demand or provide a local supply in a crisis.
Energy community	Collective legal or organisational form for shared energy generation, use or governance.	Institutional actor	Supports local coordination and social acceptance.
Energy cluster	Territorial cooperation arrangement among generators, consumers, local authorities and firms.	Regional coordination structure	Provides a platform for crisis planning and resource pooling.

In this article, DES denotes the whole socio-technical system; DER and DG denote resources or generation assets; microgrid denotes an operational configuration; and prosumers, energy communities and clusters denote actors or governance structures.

2.2. Search Strategy and Keywords

The search was conducted in the Web of Science Core Collection. The database was selected because it indexes peer-reviewed publications and allows structured searches across interdisciplinary fields. The corpus was updated to include records available in 2025; publications after 2024 were screened when they met the inclusion criteria and were indexed in the database (Tables 3 and 4).

Table 3. Web of Science search protocol documented for replication.

Element	Specification in the Revised Manuscript
Database	Web of Science Core Collection.
Search date	24 June 2026 revision protocol; corpus records indexed up to the end of 2025 were screened where available.
Fields	Topic field (TS), including title, abstract, author keywords and keywords plus.
Document types	Article, review article and early access article; review articles were prioritised for the in-depth semantic corpus.
Language	English.
Search string A—DES	TS = (“distributed energy system*” OR “distributed energy resource*” OR “distributed generation” OR “decentralized energy system*” OR “decentralised energy system*” OR microgrid* OR “energy storage”).
Search string B—local actors	TS = (prosumer* OR “energy communit*” OR “community energy” OR “energy cooperative*” OR “energy cluster*” OR “local energy governance”).
Search string C—crisis/resilience	TS = (resilien* OR “critical infrastructure” OR “crisis management” OR “emergency management” OR “emergency response” OR “disaster recovery” OR “business continuity” OR blackout* OR islanding OR “security of supply”).
Combined logic	A AND (B OR C), followed by snowballing of highly relevant review papers already present in the corpus.
Inclusion criteria	Peer-reviewed; abstract available; directly related to DES/DER/microgrids/storage/prosumers and at least one resilience, security, reliability, governance or crisis-management category.
Exclusion criteria	Component-level technical studies without system implications; non-peer-reviewed documents; texts without abstracts; studies outside energy/crisis scope; duplicates; non-English records.

Table 4. Search blocks used in the scoping review.

Search Block	Examples of Keywords	Purpose
Distributed energy systems	“distributed energy systems”; “distributed generation”; “decentralised energy systems”; “renewable distributed generation”	Identify the core technological literature
Local actors and governance	“prosumer”; “energy communities”; “local energy governance”; “energy cooperatives”; “community energy”	Capture social, institutional and local-governance aspects
Crisis and resilience	“energy resilience”; “critical infrastructure resilience”; “crisis management”; “emergency response”; “disaster recovery”; “business continuity”	Identify publications linking DES with crisis management and continuity of operations
Operational resilience	“microgrid resilience”; “islanding operation”; “blackout response”; “emergency power supply”; “energy system recovery”	Capture operational mechanisms relevant to response and recovery

2.3. Screening Procedure and Corpus Construction

The screening procedure followed a transparent sequence: identification of records, removal of irrelevant records, eligibility assessment, and final qualitative and textual analysis. The initial search identified 2154 records. Additional crisis-resilience terms produced 46 highly relevant records. The final in-depth corpus consisted of 21 review articles published between 2016 and 2025 (Table 5).

Table 5. PRISMA-ScR-style screening flow used in the scoping review.

Identification	Records Identified in WoS Core Collection: <i>n</i> = 2154	Additional Crisis/Resilience Records Identified by Targeted Terms: <i>n</i> = 46
Screening	Records screened by title, abstract and keywords for DES/resilience/crisis relevance	Duplicates, non-English texts and off-topic records removed
Eligibility	Full-text or extended abstract eligibility assessed against inclusion/exclusion criteria	Purely component-level or non-systemic technical papers excluded
Included	Final in-depth corpus for IRaMuTeQ and qualitative synthesis: <i>n</i> = 21 review/framework articles	Corpus used to identify semantic clusters and research gaps

The numerical values in the flow diagram represent screening counts for the review process. They do not represent effect sizes or empirical results from energy-system operation (Table 6).

Table 6. Screening logic used in the review.

Step	Operation	Outcome Used in the Article
1	Broad search on distributed energy and decentralised generation	2154 records identified
2	Topic narrowing to local governance, prosumers, microgrids and resilience	Records screened for relevance to DES and crisis-management categories
3	Additional search using crisis, emergency, recovery and critical-infrastructure terms	46 records identified as particularly relevant to resilience and emergency management
4	Eligibility assessment using inclusion and exclusion criteria	Peer-reviewed English-language records with abstracts retained
5	In-depth synthesis and IRaMuTeQ analysis	21 review articles selected for semantic and lexicographic analysis

Inclusion criteria were: peer-reviewed publication, abstract availability, English language, and relevance to at least one of the following areas: distributed energy, microgrids, storage, prosumption, energy security, infrastructure resilience, risk management, business continuity or local governance. Exclusion criteria were: purely component-level engineering papers without system, organisational or crisis implications; non-peer-reviewed publications; records without abstracts; and publications outside the thematic scope.

The 2023–2025 literature stream includes recent studies on resilient community microgrids, black-start service restoration, resilient microgrid control, distributed energy system reviews and value-of-resilience assessment for DER. These sources confirm that current research increasingly reports measurable indicators, operational strategies and resilience valuation, but still rarely integrates these with crisis-management procedures and local governance [16–20].

The literature review has been further expanded with influential 2023–2025 sources on power-system resilience, DER management, islanding detection and the valuation of

resilient DER. Recent reviews emphasise that resilience is now assessed not only through classical reliability indices but also through restoration time, critical-load service, microgrid-forming capability, islanding-detection performance, cybersecurity exposure, and the economic value of avoided interruptions [21–26]. This strengthens the justification for treating DES as crisis-management instruments and for linking technical indicators with institutional readiness, stakeholder coordination and continuity of essential public services (Table 7).

Table 7. Twenty-one review/framework articles included in the in-depth analytical corpus.

No.	Authors/Year/Journal	Objective	Main Theme	Link with DES/Resilience/Crisis Management
1	Hirsch, Parag & Guerrero, 2018, Renewable and Sustainable Energy Reviews [9]	Review microgrid technologies and drivers.	Microgrids and deployment barriers.	Directly supports the microgrid component of DES resilience.
2	Koirala et al., 2016, Renewable and Sustainable Energy Reviews [27]	Review integrated community energy systems.	Energy communities and local systems.	Explains collective governance resources for local resilience.
3	Barabino et al., 2023, Sustainable Energy, Grids and Networks [28]	Review modelling and optimisation in energy communities.	Energy communities and optimisation.	Links local coordination with DES planning.
4	Akinyele, Belikov & Levron, 2017, Energies [29]	Review battery storage for electrical applications.	Storage technologies.	Supports storage autonomy and backup indicators.
5	Mishra et al., 2020, Applied Energy [30]	Assess microgrid resilience holistically.	Threats, vulnerabilities and mitigation.	Directly informs crisis-oriented microgrid assessment.
6	Wang, Rousis & Strbac, 2020, Renewable and Sustainable Energy Reviews [31]	Review microgrid modelling and operations for resilience.	Modelling and operational strategies.	Supports operationalisation and scenario analysis.
7	Wang et al., 2016, IEEE Transactions on Power Systems [32]	Review power-system resilience under natural disasters.	Resilience metrics and disasters.	Provides basis for measurable crisis indicators.
8	Jasiunas, Lund & Mikkola, 2021, Renewable and Sustainable Energy Reviews [33]	Review energy system resilience.	Energy resilience concepts.	Clarifies resilience as more than reliability.
9	Bhusal et al., 2020, IEEE Access [3]	Review practices and challenges in power-system resilience.	Current resilience practices.	Supports system-level risk and recovery framing.
10	Guo et al., 2017, Renewable and Sustainable Energy Reviews [4]	Review cascading failure analysis and modelling.	Cascading failures.	Supports vulnerability and interdependency analysis.
11	Siano, 2014, Renewable and Sustainable Energy Reviews [34]	Survey demand response and smart grids.	Demand-side management.	Informs load reduction in crisis response.
12	O’Connell et al., 2014, Renewable and Sustainable Energy Reviews [35]	Review demand response benefits and challenges.	Demand response.	Supports critical-load prioritisation.
13	Ines et al., 2020, Energy Policy [10]	Review regulatory challenges for collective prosumers.	Collective prosumers.	Links prosumer governance with local resilience.

Table 7. *Cont.*

No.	Authors/Year/Journal	Objective	Main Theme	Link with DES/Resilience/Crisis Management
14	Ouyang, 2014, Reliability Engineering & System Safety [15]	Review interdependent critical infrastructure modelling.	Infrastructure interdependencies.	Supports cascading-effects analysis across sectors.
15	Ackermann, Andersson & Soder, 2001, Electric Power Systems Research [36]	Define distributed generation.	Technical definition of DG.	Improves terminological precision.
16	Lund et al., 2017, Energy [37]	Define smart energy systems.	Smart energy integration.	Supports DES as integrated socio-technical system.
17	Cherp et al., 2018, Energy Research & Social Science [38]	Integrate transition perspectives.	Energy transitions.	Explains institutional and political context of DES.
18	Markolf et al., 2018, Earth's Future [39]	Frame infrastructure as social-ecological-technical systems.	SETS resilience.	Supports socio-technical resilience framing.
19	Martisauskas et al., 2022, Energies [40]	Propose quantitative indicators for energy-system resilience.	Quantitative resilience indicators.	Supports SAIDI, SAIFI, ENS and recovery metrics.
20	Wang et al., 2009, Renewable and Sustainable Energy Reviews [41]	Review MCDA in sustainable energy decisions.	Multi-criteria decision analysis.	Supports weighted indicator aggregation.
21	Gungor et al., 2011, IEEE Transactions on Industrial Informatics [42]	Review smart-grid communication technologies.	Communication and standards.	Supports monitoring and crisis communication variables.

2.4. Text Preparation and Analytical Procedure

The selected corpus was prepared by removing non-narrative elements, standardising terminology, lemmatising the text and dividing it into contextual units. IRaMuTeQ was then used for classical lexicographic analysis and similarity analysis. Nodes in the similarity graph represented lemmatised terms, and edges represented co-occurrence within contextual units [31] (Tables 8 and 9).

Table 8. IRaMuTeQ corpus preparation and reproducibility parameters.

Parameter	Specification
Corpus content	Titles, abstracts, keywords and conclusion/review-summary sections of the 21 selected review/framework articles.
Unit of analysis	Text segments generated after standard IRaMuTeQ segmentation of the cleaned corpus.
Pre-processing	Removal of references, author affiliations, tables, formulas and non-narrative captions; lower-case conversion; spelling harmonisation of decentralised/decentralised; lemmatisation; merging of multiword expressions such as critical_infrastructure and energy_storage.
Stop words	General English stop words, journal boilerplate, copyright statements and database export fields removed.
Analyses	Classical lexicographic statistics, similarity analysis based on co-occurrence, and cluster interpretation of technological and crisis-management terms.
Reported outputs	2876 unique terms; 852 DES-related terms; dominant technological cluster around energy, system, storage, microgrid and integration; weaker peripheral links around crisis, emergency, recovery and business_continuity.

Table 9. Lexical and semantic outputs reported from the IRaMuTeQ analysis.

Output Group	Main Terms or Relations	Interpretation for the Review
Core technological lexicon	energy; system; distributed; storage; microgrid; renewable; integration; control	Technological integration dominates the corpus.
Operational-resilience lexicon	reliability; flexibility; islanding; restoration; load; backup; automation	Operational resilience is present but usually technical.
Crisis-management lexicon	crisis; emergency; recovery; continuity; vulnerable_consumers; public_services	Crisis terms are less frequent and more peripheral.
Institutional lexicon	governance; regulation; community; prosumer; coordination; stakeholder	Governance appears mainly in community-energy studies.
Strong semantic relations	microgrid-storage; distributed-generation; renewable-integration; resilience-reliability	The field is structured around technical DES functionality.
Weak semantic relations	DES-crisis_management; storage-business_continuity; prosumer-emergency_response	These weak links justify the proposed M_ZK-DES model.

The similarity graph is presented together with tabular semantic relations so that the analytical interpretation remains readable and reproducible. For reproducibility, the semantic analysis reports the corpus structure, preprocessing criteria, lexical-frequency output, key terms, semantic-cluster relations, and visual outputs in the form of a word-cloud representation, similarity graph and cluster map. These elements document the analytical path from the textual corpus to the interpretation of the position of crisis-management concepts in the DES literature (Tables 10 and 11).

Table 10. IRaMuTeQ semantic-cluster visualisation.

Cluster A: Technology Core	Cluster B: Crisis Cycle	Cluster C: Governance and Users
DES/DER/microgrid/storage/control	risk/emergency/preparedness/response/recovery	operator/municipality/prosumer/community/vulnerable consumer
Main bridge terms: resilience, continuity, islanding, restoration, critical load	Interpretation: resilience and continuity form the lexical bridge between technical and crisis-management vocabularies	Reporting requirement: export similarity graph, cloud and cluster map from IRaMuTeQ in the final layout

Table 11. Summary of rank, term group, representative terms, and interpretive role in the corpus.

Rank	Term Group	Representative Terms	Interpretive Role in the Corpus
1	Core energy system	energy, system, distributed, generation, resource, network	Defines the technological centre of the review corpus.
2	Microgrid operation	microgrid, islanding, storage, control, load, frequency, voltage	Represents the operational-resilience and power-quality cluster.
3	Resilience and reliability	resilience, reliability, restoration, recovery, redundancy, vulnerability	Connects engineering performance with crisis outcomes.
4	Crisis management	crisis, emergency, preparedness, response, continuity, coordination	Shows the underdeveloped crisis-management cluster.
5	Institutional/community layer	prosumer, community, local, governance, operator, authority	Identifies actors required for practical implementation.

This procedure was used to determine whether crisis-management terms occupied central or peripheral positions in the DES literature. Particular attention was given to the terms resilience, risk, crisis, emergency, critical infrastructure, vulnerability, continuity, recovery, adaptation and response [32,43].

2.5. Main Findings of the Review

The review shows that technological clusters dominate the discourse. The strongest links concern renewable energy sources, energy storage, microgrids, integration, control optimisation and operational flexibility. Crisis-management terms appear less frequently and are usually weakly connected with the central technological categories [15,32,44].

This means that the literature provides many technical premises for resilience, but it rarely explains how DES should be embedded in crisis procedures, local response plans, emergency communication, business-continuity planning and the protection of vulnerable consumers [33,45].

2.6. Research Gaps

Three gaps follow from the review. First, the theoretical gap concerns the absence of a coherent model linking energy decentralisation with the crisis-management cycle. Second, the methodological gap concerns the limited integration of technical modelling with risk analysis, scenario analysis and socio-institutional assessment. Third, the practical gap concerns the unclear role of local governments, operators, emergency services, prosumers and energy communities in using distributed resources during crises [33,45,46].

These gaps justify the M_ZK-DES model developed in the following sections. The model is designed to be operational: it defines variables, steps, formulas and evaluation criteria that can be used in case studies, simulations and expert validation.

3. Selection and Description of the Research Method

The method is designed to be repeatable and operational. It consists of a model-based procedure that links the literature review with risk assessment, scenario analysis, indicator selection and validation. The aim is not only to describe DES but to show how the proposed framework can be applied by researchers, local authorities and energy-system operators (Table 12).

Table 12. Research procedure used to build and apply the M_ZK-DES model.

Step	Action	Output
1	Define the crisis-management problem and critical functions	List of facilities, services and consumers requiring continuity of supply.
2	Identify DES resources and vulnerabilities	Inventory of generation, storage, microgrids, control systems and exposed nodes.
3	Assess risk using P_i , S_i , V_i and E_i	Risk matrix and priority threats.
4	Map institutions and decision rules	Allocation of responsibilities and escalation paths.
5	Select operational response options	Islanding, reserve power, storage dispatch, demand reduction and consumer prioritisation.
6	Evaluate crisis outcomes R_k	Assessment of continuity, recovery time, coordination and social protection.
7	Validate and update the model	Expert review, scenario tests, case-study comparison and lessons learned.

3.1. Research Design

The study uses a combined interpretive and model-based design. The interpretive part identifies how the literature defines resilience, vulnerability, preparedness and recovery. The model-based part translates these categories into measurable variables and decision steps. This combination is appropriate because crisis resilience depends simultaneously on infrastructure, institutions, information and social behaviour [40,47–51].

3.2. Operational Sequence

The procedure follows the sequence: antecedent conditions—crisis process—resilience outcome. Antecedent conditions describe the state of the system before disruption. The crisis process describes detection, coordination and response. The resilience outcome describes the ability to maintain or restore critical functions (Table 13).

Table 13. Operational variables used in the model.

Stage	Variables	Examples of Indicators
Antecedent conditions	decentralisation, redundancy, storage, cybersecurity, institutional preparedness	share of local supply; storage autonomy in hours; number of backup sources; existence of continuity plans
Crisis process	detection, escalation, coordination, prioritisation, islanding, communication	detection time; procedure activation time; number of coordinated actors; availability of public messages
Resilience outcome	continuity, recovery, cascading effects, protection of vulnerable consumers, learning	duration of critical-function supply; restoration time; number of affected consumers; post-crisis updates

3.3. Risk Scoring and Formulas

To make the model repeatable, the risk of each threat i is calculated as an ordinal product: $R_i = P_i \times S_i \times V_i \times E_i$. P_i is probability, S_i is impact severity, V_i is system vulnerability and E_i is exposure of critical functions. Each variable is assessed on a 1–5 scale, where 1 means very low and 5 means very high. This explains how values such as $P_i = 4$ for medium-voltage line failure are obtained: they represent expert- or data-based ordinal assessments, not percentages.

The methodological sequence has been made more explicit: the scoping review defines the evidence boundary, the IRaMuTeQ analysis identifies the semantic separation between technical DES terms and crisis-management terms, and the M_ZK-DES model translates this gap into auditable variables. In application, each component score should be documented in a data sheet indicating the data source, expert judgement rule, normalisation method, weight, and uncertainty note. This improves transparency and makes the model suitable for replication across municipalities, distribution-system operators, critical facilities and crisis scenarios (Table 14).

The default weights are proposed for the conceptual version of the model and are treated as starting values. In empirical research they can be validated through expert elicitation, analytic hierarchy process, sensitivity analysis or calibration against outage and recovery data.

The decision component is expressed as $D_k = f(R_i, Z_a, C_t, I_s, P_r)$, where Z_a denotes available resources, C_t time pressure, I_s information quality and P_r response priorities. The operational component is expressed as $O_s = f(R_d, D_y, M_g, E_l, T_o)$, where R_d is redundancy, D_y is dispatchability, M_g is storage capacity, E_l is islanding capability and T_o is restoration time. The communication component is expressed as $C_k = f(A_i, W_i, Z_s, K_p, U_m)$, where the variables describe information availability, reliability, stakeholder trust, communication channels and public understanding.

Table 14. Scales, weights and formulas for operationalising M_ZK-DES.

Construct	Variables	Scale	Default Weight	Replicable Calculation
Threat risk R_i	P_i probability; S_i impact; V_i vulnerability; E_i exposure	1–5 ordinal scale for each variable	Equal weights unless justified otherwise	$R_i = P_i \times S_i \times V_i \times E_i$; classify 1–25 low, 26–125 medium, 126–625 high
Technical-operational capacity K_T	redundancy; storage autonomy; islanding; automation; restoration time	0–1 normalised or 1–5 ordinal	0.35	K_T = weighted mean of normalised technical indicators
Institutional-decision capacity K_I	procedures; coordination; roles; exercises; escalation paths	0–1 normalised or 1–5 ordinal	0.25	K_I = weighted mean of institutional preparedness indicators
Information-communication capacity K_C	monitoring; warning; data quality; public communication; stakeholder channels	0–1 normalised or 1–5 ordinal	0.20	K_C = weighted mean of information indicators
Social-continuity capacity K_S	critical load served; vulnerable consumers protected; community participation	0–1 normalised or 1–5 ordinal	0.20	K_S = weighted mean of social-continuity indicators
Overall resilience outcome R_K	K_T, K_I, K_C, K_S adjusted by risk level	0–100 points	sum = 1.00	$R_K = 100 \times (0.35K_T + 0.25K_I + 0.20K_C + 0.20K_S) \times (1 - \text{normalised residual risk})$

3.4. Scenario Application

The method can be applied through crisis scenarios. A scenario should specify the initiating event, affected assets, expected cascading effects, available DES resources, priority consumers, communication constraints and target recovery level. The scenario is then evaluated twice: under a baseline approach focused on technical restoration and under the M_ZK-DES approach focused on maintaining critical functions.

3.5. Validation

Validation combines parameter calibration, scenario validation, expert validation and case-study comparison. Empirical inputs may include outage statistics, distribution-system data, local energy plans, crisis-management plans, inventories of critical facilities, storage parameters and records from exercises or real disruptions [52–56].

4. Operationalization of Dimensions and Determinants in the Research Model of Crisis Management of Distributed Energy Systems

Each institutional dimension is scored on a 0–5 scale, where 0 means absent, 1 means formally mentioned, 2 means partially defined, 3 means implemented but not tested, 4 means implemented and periodically tested, and 5 means implemented, tested, updated and integrated with DSO/local-government/critical-facility procedures. This scale allows the model to be used in audits and case comparisons rather than only as a descriptive framework (Table 15).

The operationalisation links each dimension to measurable indicators and crisis-management phases. The following dimensions constitute an evaluation checklist for local or regional DES resilience.

The operationalization of dimensions and determinants in the research model of crisis management of distributed energy systems constitutes a fundamental stage of the research process, as it enables the translation of abstract theoretical categories into empirically verifiable variables, indicators, and evaluation criteria. From the perspective of crisis management, particular importance is attached to identifying those properties of the energy system that determine its capacity to anticipate threats, reduce vulnerability,

absorb disruptions, maintain continuity of operation, and restore critical functions after the occurrence of a crisis situation. Thus, operationalization does not refer solely to the description of the system's structure but includes an analysis of its functioning under conditions of uncertainty, time pressure, resource deficit, infrastructural interdependencies, and multi-actor decision-making responsibility [57–61].

Table 15. Summary of dimension, observable indicator, 0–5 scoring rule, suggested weight.

Dimension	Observable Indicator	0–5 Scoring Rule	Suggested Weight
Legal regulations	Clear division of responsibility; emergency-power obligations; CI protection duties.	0 absent; 5 binding, coherent and tested through procedures.	0.20
Policy and planning	Presence of DES, resilience and crisis scenarios in local/regional plans.	0 absent; 5 integrated with measurable targets and update cycle.	0.20
Local crisis governance	Crisis team capacity, DSO coordination and vulnerable-consumer registry.	0 absent; 5 operating, trained and exercised with partners.	0.25
Operational procedures	Islanded operation, load prioritisation, backup supply and communication protocols.	0 absent; 5 tested in exercises and linked to real assets.	0.25
Stakeholder participation	Role of prosumers, energy communities, service providers and critical facilities.	0 absent; 5 formalised and included in drills/data exchange.	0.10

Crisis management in distributed energy systems should be understood as a complex, multi-stage, and multi-level process encompassing prevention, preparedness, response, and recovery. This process requires the coordination of actions undertaken by public administration, energy system operators, business entities, security services, local government units, and end users. In this approach, the research model should make it possible to assess not only the formal existence of management procedures and instruments but also their actual operational effectiveness under conditions of disruptions, failures, supply constraints, extreme weather events, cyberattacks, geopolitical crises, and other events threatening energy security [62–67].

The conceptualization and operationalization of research constructs constitute a methodological bridge between the theoretical and empirical levels. Constructs such as systemic resilience, continuity of operation, crisis preparedness, infrastructural redundancy, adaptive capacity, institutional interoperability, crisis communication effectiveness, or the level of inter-organisational coordination require the assignment of clear operational definitions. These definitions should indicate which features of the system are subject to measurement, which indicators are used to assess them, and how their empirical verification is possible. In this sense, operationalization determines the validity, reliability, and repeatability of research on crisis management in the energy sector [68,69].

In this research model, the operationalization of constructs involves assigning clearly defined measurement attributes to individual dimensions, based on a critical analysis of the literature on crisis management, energy security, critical infrastructure protection, public policy, and risk management. This process includes identifying the key features of the analysed dimensions, determining their functional scope, indicating cause-and-effect relationships, and selecting appropriate empirical indicators. Validation procedures are of particular importance here, including content validity, construct validity, and measurement reliability, because the phenomena under study are dynamic, contextual, and

strongly dependent on changes in the legal, technological, social, and environmental environment [41,70].

The proposed research model distinguishes six basic dimensions for assessing crisis management in distributed energy systems:

(a) Legal regulations concerning security and crisis management, (b) strategic frameworks of policy, planning, and systemic resilience, (c) local authorities responsible for crisis management, (d) crisis-management instruments and procedures, (e) areas affected by the crisis-management system, (f) stakeholders of the crisis-management system in the energy sector [71,72].

The indicated dimensions form a logically interconnected analytical framework that allows for assessing the capacity of a distributed energy system to function under crisis conditions. Each dimension refers to a different aspect of system resilience: normative, strategic, institutional, instrumental, operational, and socio-organisational. The model assumes that the effectiveness of crisis management depends not on a single element but on the coherence and mutual alignment of all dimensions. This means that even a high level of technological development of the energy system does not guarantee security if it is not accompanied by adequate regulations, efficient decision-making procedures, effective crisis communication, resource availability, and the capacity to coordinate the actions of multiple entities.

The research model is based on a systemic and decision-making approach. It combines institutional and legal analysis with risk analysis, multi-criteria decision analysis, and participatory methods. Such an approach makes it possible to identify both the formal conditions of crisis management and the practical capacity of the system to respond to disruptions. The inclusion of modern technologies in the model, such as energy storage facilities, microgrids, digital monitoring systems, grid automation, and small modular reactors, enables the assessment of their potential for strengthening energy resilience. At the same time, these technologies should also be analysed as potential sources of new risks, including cyber, regulatory, organisational, environmental, and social risks [73].

4.1. Legal Regulations Concerning Security and Crisis Management

Legal regulations constitute the basic normative dimension of crisis management in distributed energy systems. They define the scope of responsibility of public authorities, energy system operators, business entities, and other participants in the process of energy security management. In this context, law performs not only a regulatory function but also preventive, coordination, and control functions. It defines obligations related to emergency planning, critical infrastructure protection, ensuring continuity of energy supply, responding to extraordinary situations, and restoring system functions after the occurrence of a disruption.

At the European Union level, regulations concerning the security of energy supply, critical infrastructure resilience, the energy transition, energy efficiency, and counteracting the effects of climate change are of significant importance. They influence the way threats are defined, risk management standards, and the scope of obligations imposed on Member States. At the national level, the coherence of sectoral regulations is crucial, including energy law, the Act on Renewable Energy Sources, the Act on Energy Efficiency, regulations concerning crisis management, and provisions relating to critical infrastructure protection. A lack of coherence between these legal acts may lead to a dispersion of responsibility, decision-making delays, and reduced effectiveness of crisis response.

The operationalization of this dimension may include indicators such as: the degree of compliance of local regulations with national and EU legal acts, clarity of the division of competences, the presence of emergency procedures in legal documents, the level of

integration of energy regulations with crisis-management regulations, the scope of requirements concerning critical infrastructure protection, and the existence of accountability and control mechanisms [74].

4.2. Strategic Frameworks of Policy, Planning, and Systemic Resilience

Strategic frameworks of policy and planning constitute the second dimension of the model, referring to the system's capacity for long-term preparation for crises. Strategic documents, such as energy policies, national and local energy and climate plans, security strategies, crisis-management plans, critical infrastructure protection plans, and climate change adaptation strategies, define directions of action aimed at reducing risk and strengthening the resilience of the energy system.

In crisis management, it is particularly important that these documents should not be merely declarative but should include measurable objectives, assigned responsibilities, implementation schedules, monitoring procedures, and update mechanisms. The effectiveness of planning depends on whether strategies take into account disruption scenarios, vulnerability analysis, risk assessment, resource needs, communication procedures, and principles of inter-institutional cooperation. The absence of such elements limits the possibility of moving from strategic planning to real operational action in a crisis situation.

The operationalization of this dimension may include indicators such as: the presence of crisis scenarios in planning documents, frequency of plan updates, the extent to which climate, technological, and geopolitical risks are included, measurability of strategic objectives, the existence of business continuity procedures, the level of integration of energy plans with crisis-management plans, and the extent of stakeholder participation in the planning process [75].

4.3. Local Authorities Responsible for Crisis Management

Local public administration bodies play a central role in the practical implementation of crisis management because it is at the local level that the direct effects of disruptions in energy supply become visible. Local government units are responsible for organising preventive, preparedness, response, and recovery activities, as well as for cooperating with energy system operators, rescue services, municipal enterprises, residents, and entities responsible for maintaining critical infrastructure.

At the local level, crisis management requires the ability to quickly diagnose a situation, make decisions under time pressure, activate emergency procedures, allocate resources, conduct crisis communication, and coordinate the actions of multiple entities. The effectiveness of local authorities therefore depends not only on formal competencies but also on organisational resources, quality of information, staff experience, level of procedural preparedness, and the ability to cooperate with the private sector and the local community.

The operationalization of this dimension may include: the level of preparedness of local crisis-management structures, the number and timeliness of local emergency plans, the frequency of crisis exercises and simulations, the availability of technical and human resources, the effectiveness of communication channels with residents, the degree of cooperation with energy infrastructure operators, and response time to events disrupting system functioning [76].

4.4. Crisis-Management Instruments and Procedures

Crisis management instruments and procedures constitute the operational dimension of the model. They include a set of tools used to identify threats, reduce risk, prepare resources, respond to crisis events, and restore system functionality. With regard to distributed energy systems, particular importance is attached to business continuity procedures, emergency power supply plans, early warning systems, infrastructure moni-

toring mechanisms, crisis communication procedures, information management systems, inter-institutional cooperation agreements, and instruments for financing preventive and recovery actions.

From a scientific point of view, these instruments should be assessed not only in terms of their formal presence but above all in terms of their functionality, effectiveness, and adequacy to the identified threats. It is therefore important to examine whether procedures are updated, tested, known to system participants, capable of being activated under conditions of limited access to information, and compatible with the procedures of other entities. Organisational and technical interoperability is of particular importance since the lack of procedural compatibility may lead to fragmentation of actions and intensification of the consequences of a crisis.

The operationalization of this dimension may include indicators such as: the number and quality of emergency procedures, the presence of business continuity plans, availability of alternative power sources, level of infrastructural redundancy, frequency of procedure testing, time required to restore basic system functions, effectiveness of warning systems, level of digitalization of monitoring, and availability of financial resources for crisis-related actions [42].

4.5. Areas Affected by the Crisis-Management System

The areas affected by the crisis-management system include those elements of the energy and socio-economic system that are influenced by planning, preventive, operational, and recovery activities. In distributed energy systems, the objects of impact include both technical infrastructure—such as generation sources, distribution networks, energy storage facilities, and control systems—as well as institutional entities, enterprises, households, public utility facilities, and groups particularly vulnerable to interruptions in energy supply.

From the perspective of crisis management, particular importance is attached to identifying critical functions whose maintenance is necessary for the security of the local community. This concerns, among others, the power supply of healthcare facilities, water supply systems, communication infrastructure, communication systems, rescue services, care facilities, and public administration facilities. The assessment of affected areas should take into account both the direct consequences of energy disruptions and the cascading effects resulting from the interdependence between the energy system and other critical infrastructure sectors.

The operationalization of this dimension may include: the number of identified critical facilities, the level of energy protection of these facilities, availability of emergency power sources, degree of consumer vulnerability to energy supply interruptions, scope of protection plans for vulnerable groups, level of integration of the energy system with other critical infrastructure sectors, and capacity to reduce cascading effects [77].

4.6. Stakeholders of the Crisis-Management System in the Energy Sector

Stakeholders constitute one of the key determinants of the effectiveness of crisis management because the system's capacity to respond to a crisis depends on the quality of cooperation among many actors. The most important stakeholders include public administration bodies, crisis-management centres, energy system operators, energy companies, entities responsible for critical infrastructure, rescue services, social organisations, the scientific community, entrepreneurs, and residents.

Under crisis conditions, the importance of stakeholders results from the need for rapid information exchange, agreement on priorities, coordination of resources, division of responsibility, and ensuring public trust. Insufficient communication between stakeholders may lead to information chaos, duplication of actions, decision-making delays, and a

decline in social acceptance of the interventions undertaken. For this reason, stakeholder management should include not only their identification but also the analysis of their influence, resources, responsibilities, communication channels, and level of involvement in individual phases of the crisis-management cycle.

The operationalization of this dimension may include: the number and types of stakeholders involved, formalisation of cooperation rules, frequency of coordination meetings, level of information exchange, existence of joint operating procedures, stakeholder participation in crisis exercises, level of inter-institutional trust, and effectiveness of communication with residents and end users [78].

5. Conceptual Model of Crisis Management of Distributed Energy Systems

The proposed research model is embedded in the perspective of crisis management of distributed energy systems, understood as complex technical and organisational arrangements whose functioning determines energy security, the continuity of public service provision, and the socio-economic resilience of territorial units [79,80]. Unlike classical models of energy planning, which focus primarily on technological efficiency, supply and demand balancing, and cost optimisation, the presented model frames the distributed energy system as an element of critical infrastructure exposed to multidimensional threats: technical, climatic, cyber, regulatory, economic, geopolitical, and social [81–84].

The fundamental objective of the model is to identify and analyse the mechanisms that enable the energy system to maintain critical functions under conditions of disruption, limit the scale of losses, ensure continuity of energy supply, coordinate the actions of multiple actors, and restore operational capacities after the occurrence of a crisis situation [85,86]. The model is therefore not limited to describing the structure of distributed energy sources but focuses on the system's capacity to move through successive phases of crisis management: prevention, preparedness, response, and recovery [87,88]. In this approach, distributed energy systems are analysed as dynamic adaptive systems whose effectiveness depends on the interaction of legal, institutional, technological, informational, and social components [89,90].

The decentralised nature of distributed energy systems means that crisis management requires not only technological modernisation, but also the transformation of regulatory frameworks, decision-making procedures, and coordination mechanisms [91,92]. Under crisis conditions, what matters is not merely the number of distributed energy sources, but their capacity to sustain local critical functions, cooperate with system operators, provide emergency power supply, and limit cascading effects [93–95]. This implies the need to integrate local energy initiatives with the crisis-management system, critical infrastructure protection, business continuity planning, and strategies of territorial resilience [96–98].

The analysis of the literature and the premises derived from crisis-management theory make it possible to formulate the following synthetic conclusions, which constitute the conceptual basis of the model:

From the perspective of the risk and systemic vulnerability paradigm:

- Distributed energy systems should be analysed through the lens of exposure to threats, the sensitivity of infrastructural components, and the capacity to absorb disruptions [99].
- It is crucial to identify critical points whose failure may lead to a loss of operational continuity or the emergence of cascading effects in other critical infrastructure sectors [100].

- Risk assessment should include both the probability of a crisis event and the scale of its potential consequences for consumers, operators, public administration, and the local economy [101].
- Managing system vulnerability requires continuous threat monitoring, updating crisis scenarios, and adapting response procedures to the changing security environment [102].

From the perspective of the systemic resilience paradigm:

- Energy system resilience means the capacity to maintain basic functions despite disruptions and then rapidly restore full operational efficiency.
- A high level of resilience requires infrastructural redundancy, diversification of energy sources, availability of energy storage, control flexibility, and the capacity for islanded or partially autonomous operation.
- Resilience is not solely a technological property but the result of the interaction of legal regulations, organisational procedures, human resources, information systems, and inter-institutional trust.
- A resilient system should be capable of learning from previous disruptions, tests, exercises, and crisis simulations.

From the perspective of the institutional coordination paradigm:

- Effective crisis management requires the cooperation of multiple actors: central and local government administrations, energy system operators, enterprises, rescue services, regulators, prosumers, and end users.
- Clear division of competences, rapid information exchange, procedural interoperability, and the capacity to make decisions under time pressure are key factors of effectiveness.
- A lack of institutional coordination increases the risk of decision-making delays, duplication of actions, information chaos, and the worsening of crisis consequences.
- Crisis management in distributed systems requires mechanisms of horizontal and vertical coordination between the local, regional, national, and European Union levels.

From the perspective of the digitalization and situational awareness paradigm:

- Virtualization, digital twins, real-time monitoring systems, and predictive tools increase the system's capacity for early threat detection and support crisis decision-making.
- Information management becomes one of the central elements of system resilience because the quality of decisions depends on the timeliness, completeness, and reliability of data.
- Digitalization increases the possibilities of system control but at the same time generates new categories of risk, especially in the areas of cybersecurity, dependence on ICT systems, and protection of operational data.
- Situational awareness should be treated as a dynamic organisational capability that enables the interpretation of events, forecasting of their consequences, and selection of adequate action strategies.

From the perspective of the socio-prosumer paradigm:

- Under crisis conditions, the prosumer is not merely a micro-producer of energy but may function as an active participant in local energy resilience.
- The involvement of local communities increases the system's capacity for self-organisation, limiting the consequences of energy supply interruptions and supporting particularly vulnerable groups.
- Social participation strengthens the legitimacy of crisis actions, improves the flow of information, and contributes to building a culture of energy security.

- At the same time, prosumer participation requires appropriate legal frameworks, technical standards, coordination mechanisms, and security procedures.

The analysis of the above paradigms indicates that crisis management of distributed energy systems requires a holistic approach that integrates the dimensions of risk, resilience, coordination, technology, information, and social participation. Each of the paradigms mentioned contributes distinct cognitive and practical value; however, only their combined application makes it possible to explain the system's capacity to function under conditions of disruption. The model should therefore be treated as an analytical framework for examining how the energy system identifies threats, prepares for crises, responds to disruptions, and restores operational capacity (Tables 16 and 17).

Table 16. Conceptual model of crisis management of distributed energy systems.

Prevention	Preparedness	Response	Recovery and Learning
K0: risk and vulnerability diagnosis -> identify hazards, exposed assets and cascading pathways	K1: institutional decision rules -> assign roles, thresholds, priorities and communication channels	K2: technical DES operation -> islanding, storage dispatch, DER activation and load prioritisation	K3/Rk: social-information feedback -> consumer protection, reporting, recovery metrics and plan updates
Feedback loop F1: post-event indicators update K0 risk assumptions	Feedback loop F2: exercises and audits update K1 procedures	Feedback loop F3: operational data update K2 resource settings	Feedback loop F4: lessons learned and public communication update K3 readiness

Table 17. Summary of inputs, model components, crisis-management phases, outputs.

Inputs	Model Components	Crisis-Management Phases	Outputs
Threats: blackout, cyberattack, extreme weather, fuel shortage	K0—risk and vulnerability diagnosis	Prevention	Reduced exposure and prioritised risk list
Resources: DG, storage, microgrids, prosumers, DSM	K1—decision and coordination rules	Preparedness	Procedures, roles, reserve resources and exercises
Data: monitoring, forecasts, operator and local authority information	K2—operational response and technical reconfiguration	Response	Critical-load supply, islanding, storage dispatch and demand reduction
Stakeholders: operators, local government, emergency services, communities	K3—communication, learning and social protection	Recovery	Shorter restoration time, lessons learned and updated plans

The proposed research model is based on the assumption that effective crisis management of distributed energy systems requires the integration of four fundamental components: the risk component, the institutional and decision-making component, the technological and operational component, and the social and informational component. These components are interconnected through feedback relations, forming a dynamic adaptive system capable of responding to changing environmental conditions.

From an epistemological point of view, the model assumes the transdisciplinarity of knowledge, since crisis management in the energy sector requires the simultaneous use of the achievements of management sciences, security studies, energy engineering, law, economics, cybernetics, complex systems theory, and social sciences. This means that the analysed system cannot be reduced solely to technical infrastructure. Rather, it is a socio-technical system whose functioning depends on the relationships between technology, regulations, decisions, information, and the behaviour of actors.

The model may be formally defined as an ordered structure:

$$M_ZK-DES = \{K_0, K_1, K_2, K_3, R_k\} \quad (1)$$

The default weights are not normative constants. They are starting values for transparent scenario testing. They may be modified by expert elicitation, the analytic hierarchy process, entropy weighting or regression/validation against historical outage data. For replication, all component scores are first normalised to the interval [0, 1], then multiplied by weights that sum to 1. The same weights must be reported for every scenario in a comparative study.

Example calculation: if $K_0 = 0.70$, $K_1 = 0.60$, $K_2 = 0.80$ and $K_3 = 0.50$, then $R_k = (0.25 \times 0.70) + (0.25 \times 0.60) + (0.35 \times 0.80) + (0.15 \times 0.50) = 0.68$. In this interpretation, a score below 0.40 indicates low resilience, 0.40–0.69 moderate resilience and 0.70–1.00 high resilience. Sensitivity testing can report how R_k changes when K_2 or K_1 weights are increased by $\pm 10\%$ (Table 18).

Table 18. Summary of component, normalised variables, default weight, calculation rule.

Component	Normalised Variables	Default Weight	Calculation Rule
K0 risk diagnosis	hazard probability, exposure, vulnerability, cascading potential	0.25	K_0 = weighted mean of normalised risk-diagnosis variables
K1 institutional decision capacity	legal clarity, plan quality, coordination, communication	0.25	K_1 = weighted mean of institutional variables
K2 technical-operational capacity	SAIDI/SAIFI improvement, ENS reduction, storage autonomy, islanding, stability	0.35	K_2 = weighted mean of technical indicators
K3 social-information capacity	warning reach, prosumer participation, vulnerable-consumer protection	0.15	K_3 = weighted mean of social-information variables
R_k resilience outcome	critical load served, time to recovery, service continuity, learning update	1.00	$R_k = 0.25K_0 + 0.25K_1 + 0.35K_2 + 0.15K_3$

where

K_0 —the component of risk and systemic vulnerability;

K_1 —the institutional and decision-making component of crisis management;

K_2 —the technological and operational component of energy resilience;

K_3 —the social and informational component and crisis communication;

R_k —crisis-management outcomes.

Each component includes a set of sub-nodes representing institutions, technologies, procedures, resources, information, and system participants. Relations occur between the sub-nodes, including flows of energy, information, decisions, resources, and responsibility. Unlike the classical DES model, in which the optimisation of the functioning of the energy system occupies the central position, in the crisis-management model the main objective is to maintain critical functions and minimise the consequences of disruptions.

5.1. Component K_0 : Risk and Systemic Vulnerability

Component K_0 is responsible for the identification, analysis, and assessment of threats affecting the distributed energy system. It includes technical, environmental, climatic, cyber, economic, regulatory, and social threats. This component also analyzes infrastructure vulnerability, consumer exposure, the probability of crisis events, and the potential scale of their consequences.

Systemic risk may be represented as a function:

$$R_i = f(P_i, S_i, V_i, E_i) \quad (2)$$

where

P_i —the probability of occurrence of a given threat;
 S_i —the scale of potential consequences;
 V_i —the system's vulnerability to a given disruption;
 E_i —the exposure of consumers and infrastructure.

A high-risk value indicates the need to apply preventive instruments that reduce system vulnerability and increase its resilience. Component K_0 therefore performs a diagnostic and prognostic function, serving as the starting point for the remaining components of the model.

5.2. Component K_1 : Institutional and Decision-Making Dimension of Crisis Management

Component K_1 includes the structures, procedures, and decision-making mechanisms responsible for crisis management. It comprises public administration bodies, crisis-management centres, energy system operators, regulators, local government units, and other entities participating in the decision-making process.

A crisis decision may be expressed as a function:

$$D_k = f(R_i, Z_a, C_t, I_s, P_r) \quad (3)$$

where

R_i —the level of identified risk;
 Z_a —availability of resources;
 C_t —time pressure;
 I_s —quality of situational information;
 P_r —applicable response procedures.

Component K_1 is responsible for selecting action strategies, activating emergency procedures, allocating resources, determining power supply priorities, and coordinating inter-institutional actions. Its effectiveness depends on the clarity of competencies, the timeliness of crisis plans, communication efficiency, and the capacity to make decisions under conditions of uncertainty.

5.3. Component K_2 : Technological and Operational Dimension of Energy Resilience

Component K_2 includes the material and operational basis of energy system resilience. It comprises distributed energy sources, energy storage facilities, microgrids, control systems, distribution infrastructure, backup devices, emergency power supply systems, and digital monitoring technologies.

The operational resilience of the system may be represented as a function:

$$O_s = f(R_d, D_y, M_g, E_l, T_o) \quad (4)$$

where

R_d —infrastructural redundancy;
 D_y —diversification of energy sources;
 M_g —availability of energy storage;
 E_l —control flexibility;
 T_o —technical recovery capability.

Component K_2 is responsible for the system's capacity to absorb disruptions, maintain a minimum level of power supply, switch between energy sources, operate in emergency mode, and restore functionality after a crisis event. In this approach, energy technologies are not assessed solely through the lens of economic efficiency, but above all through their contribution to continuity of operation and the resilience of critical infrastructure.

5.4. Component K_3 : Social, Informational, and Communication Dimension of Crisis Management

Component K_3 refers to the role of information, communication, social participation, and user behaviour under conditions of an energy crisis. It includes prosumers, end users, local communities, social organisations, the media, educational institutions, and crisis communication channels.

The effectiveness of crisis communication may be expressed as a function:

$$C_k = f(A_i, W_i, Z_s, K_p, U_m) \quad (5)$$

where

A_i —timeliness of information;

W_i —credibility of information;

Z_s —social trust;

K_p —capacity of communication channels;

U_m —recipients' ability to respond to crisis messages.

Component K_3 performs the function of integrating the social dimension with the operational dimension. In crisis situations, proper communication reduces uncertainty, limits chaotic behaviour, facilitates the protection of vulnerable groups, and increases the effectiveness of institutional actions. The participation of prosumers and local communities may strengthen system resilience, provided that it is embedded in clear cooperation and security procedures.

5.5. Crisis-Management Outcomes R_k

Crisis-management outcomes are defined as a multidimensional vector:

$$R_k = [B_e, C^d, O_r, K_i, A_s, S_p] \quad (6)$$

where

B_e —level of energy security;

C^d —continuity of energy supply;

O_r —system resilience to disruptions;

K_i —effectiveness of institutional coordination;

A_s —system adaptability;

S_p —social acceptance and participation.

The vector R_k makes it possible to assess whether the system achieves the desired crisis-management outcomes. It includes both technical effects, such as continuity of supply and the time required to restore system functions, as well as organisational and social effects, such as the quality of coordination, communication efficiency, and the level of stakeholder trust.

The integrated effectiveness of crisis management may be represented as a function:

$$E_{ZK} = \varphi(K_0, K_1, K_2, K_3) = \int_0^T [\alpha_1 O_s + \alpha_2 D_k + \alpha_3 C_k - \alpha_4 R_i] dt \quad (7)$$

where

E_{ZK} —integrated effectiveness of crisis management;

O_s —operational resilience;

D_k —effectiveness of crisis decisions;

C_k —effectiveness of crisis communication;

R_i —level of systemic risk;

α_1 – α_4 —weighting coefficients determining the significance of individual components.

Maximising the function E_{ZK} means striving to increase operational resilience, improve the quality of decisions, enhance communication, and reduce the level of risk. This

function does not constitute a complete computational model but rather a formal representation of cause-and-effect relationships between the basic components of crisis management.

The relationships between components K_0 – K_3 are recursive and organised as feedback loops. Risk identification in component K_0 influences the decisions made in component K_1 . These decisions activate technological and operational actions in component K_2 , the outcomes of which generate feedback data on system effectiveness. These data are then processed in component K_3 through mechanisms of information, communication, and social learning. As a consequence, the system updates its procedures, scenarios, and response strategies.

This architecture of the model allows crisis management to be interpreted as a process of continuous system learning. A crisis is not merely a disruptive event but also a source of information about the system's actual vulnerability, the effectiveness of procedures, the adequacy of technologies, and the quality of inter-institutional cooperation. The model therefore assumes that system resilience increases when information obtained from exercises, simulations, and real events is used to modify plans, investments, and procedures.

5.6. Illustrative Application of the Model and Comparison with the Baseline Approach

In order to demonstrate the practical usefulness of the proposed M_ZK-DES model, its illustrative application is presented using the example of a local distributed energy system operating within a municipality or a group of municipalities. The analysed system includes prosumer photovoltaic installations, local cogeneration sources, energy storage facilities, medium- and low-voltage distribution infrastructure, critical infrastructure facilities such as a hospital, water treatment station, municipal office and crisis-management centre, as well as individual consumers and local enterprises.

The crisis scenario under consideration assumes the occurrence of an extreme weather event combined with a failure of part of the distribution network and disruptions in digital communication. In the baseline approach, the system response focuses primarily on restoring electricity supply by the network operator, without fully using local distributed resources, prosumers, energy storage systems and crisis coordination mechanisms. In the approach based on the M_ZK-DES model, actions are initiated in a multidimensional manner: critical points are identified, power supply priorities are defined, local resources are activated, crisis communication is launched, and after the event the procedures are updated.

The illustrative application of the model may be presented as a sequence of four inter-related stages: risk diagnosis, crisis decision-making, operational response and feedback. Each stage corresponds to one of the K_0 – K_3 components of the model (Tables 19 and 20).

Table 19. Logic of applying the M_ZK-DES model in a crisis situation.

Start	1. Detect Disruption	2. Classify Risk	3. Select Response	4. Activate DES	5. Evaluate Outcome	End
Normal monitoring	Alarm from operator/local authority/prosumer	$R_i = P_i \times S_i \times V_i \times E_i$	Priority supply, islanding, storage dispatch, demand reduction	Microgrid/DER/backup resources activated	SAIDI, SAIFI, ENS, TTR, critical-load served, stability indicators measured	Plans updated after recovery

The following examples clarify that the numerical values are hypothetical expert-assigned scores used only to demonstrate model operation. They are not measured values from a real distribution operator. A real case study should replace these scores with outage records, operator logs, SCADA/AMI data, weather data, cyber-incident reports and critical-facility inventories.

Table 20. Summary of sequence, model component, operational question.

Sequence	Model Component	Operational Question
1	Crisis event	What disruption occurred and which critical functions are threatened?
2	K_0 : risk and vulnerability	Which assets, consumers and services are exposed?
3	K_1 : decisions and coordination	Who decides, with what data and under which priority rules?
4	K_2 : operational response	Which DES resources, storage, islanding and demand-side measures are activated?
5	K_3 : information and society	How are stakeholders and residents informed and coordinated?
6	R_k : outcomes and learning	What level of continuity, recovery and institutional learning is achieved?

The probabilities and other scores in Table 21 are ordinal expert-assessment values on a 1–5 scale. A score of 4 for medium-voltage line failure means “high probability” based on the assumed local exposure and historical/technical vulnerability; it is not a 4% probability (Tables 21 and 22).

Table 21. Example risk matrix for a distributed energy system.

Scenario	P	S	V	E	$R = P \times S \times V \times E$	DES Response Tested
Extreme weather: wind/flood damage to MV feeders	4	5	4	5	400	Islanding of critical microgrid; battery dispatch; priority supply for water/healthcare.
Cyberattack on distribution monitoring/communication	3	5	5	4	300	Manual fallback procedures; segmented control; emergency communication with local authority.
Supply-chain disruption: fuel/transformer replacement delay	3	4	4	4	192	Storage autonomy, demand reduction and reserve-sharing among local assets.
Combined event: storm plus communication outage	3	5	5	5	375	Local command cell, predefined load priorities and autonomous microgrid mode.

Table 22. Summary of threat, probability P_i , impact S_i , and vulnerability V_i .

Threat	Probability P_i	Impact S_i	Vulnerability V_i	Exposure E_i	Risk Level R_i	Assessment
Medium-voltage line failure	4	5	4	5	80	Very high
Extreme weather event	4	4	4	4	64	High
Cyberattack on the control system	3	5	3	4	60	High
Lack of institutional coordination	3	4	4	4	48	Elevated
Disinformation among consumers	3	3	3	4	36	Moderate
Unavailability of energy storage	2	4	3	4	24	Moderate

In the analysed example, the highest risk levels relate to medium-voltage line failure, an extreme weather event and a cyberattack on the control system. This means that preventive and preparedness measures should primarily include power supply redundancy, the possibility of island operation, cybersecurity safeguards, the availability of energy storage and procedures for priority power supply to critical facilities.

The M_ZK-DES model assumes that components K_0 – K_3 do not operate independently but form a system of mutual interdependencies. These relationships can be presented in the form of an influence matrix (Table 23).

Table 23. Matrix of relationships between the components of the M_ZK-DES model.

Influencing Component/Dependent Component	K ₀ Risk	K ₁ Decisions	K ₂ Operations	K ₃ Information and Society	R _k Outcomes
K ₀ Risk and Vulnerability	—	Strong	Medium	Medium	Strong
K ₁ Institutions and Decisions	Medium	—	Strong	Strong	Strong
K ₂ Technology and Operations	Medium	Medium	—	Medium	Strong
K ₃ Information and Communication	Strong	Strong	Medium	—	Strong
R _k Outcomes	Strong	Medium	Medium	Strong	—

The matrix indicates that the relationships between risk and crisis decisions, between decisions and operational activities, and between communication and crisis-management outcomes are particularly important. In practice, this means that even a high level of technological preparedness may fail to produce the expected results if efficient institutional coordination and reliable communication with consumers are lacking.

The added value of the M_ZK-DES model is assessed by comparison with the baseline approach. The baseline approach refers to traditional management of an energy failure, focused mainly on the technical removal of the disruption and restoration of the electricity supply by the operator. The model-based approach, by contrast, takes into account the full crisis-management cycle, coordination of multiple stakeholders, social communication, local energy resources and the post-crisis learning process (Table 24).

Table 24. Comparison of the baseline approach and the M_ZK-DES approach.

Criterion	Baseline Approach	M_ZK-DES Approach
Main objective	Restoration of electricity supply	Maintenance of critical functions and reduction in crisis impacts
Dominant actor	Energy system operator	Operator, administration, emergency services, prosumers and local community
Scope of analysis	Technical failure	Technical, climatic, cyber, social and institutional risk
System response	Repair of the damaged element	Prioritisation, source switching, emergency operation, communication and coordination
Role of prosumers	Limited	Active element of local energy resilience
Crisis communication	Additional and often reactive	Integral part of crisis management
Post-crisis learning	Limited	Systematic updating of procedures, scenarios and investments
Expected outcome	Restoration of the pre-failure state	Increased resilience and adaptability of the system

The comparison shows that the M_ZK-DES model extends the classical technical approach by adding organisational, social, informational and adaptive dimensions. As a result, an energy crisis is not perceived solely as an infrastructural problem but as a test of the capacity of the entire socio-technical system to maintain critical functions.

Table 25 compares the system response trajectory in the baseline approach and the M_ZK-DES model-based approach. The rows present successive phases of the crisis, while the columns indicate differences in system performance, restoration logic and resilience outcomes.

Table 25. Summary of phase, baseline approach, M_ZK-DES approach.

Phase	Baseline Approach	M_ZK-DES Approach
Normal state	100% functional level assumed	100% functional level assumed
Disruption	Steeper loss of performance due to centralised failure response	Smaller loss due to redundancy, storage and local resources
Response	Operator-focused restoration; limited social and institutional coordination	Coordinated response using priority supply, islanding and crisis communication
Recovery	Longer restoration and weaker learning loop	Faster stabilisation and explicit update of procedures, scenarios and investments

In the baseline approach, the decline in system performance is deeper and the recovery period is longer. This results from a focus on infrastructure repair without full use of local resilience mechanisms. In the M_ZK-DES approach, the decline in performance is limited by source redundancy, energy storage, priority power supply to critical facilities, and effective coordination and communication with consumers.

Crisis-management outcomes are presented as a multidimensional profile. For this purpose, the Rk vector = [Be, Cd, Or, Ki, As, Sp] is used, covering energy security, continuity of supply, resilience, coordination, adaptability and social participation. The outcome profile compares the same six indicators directly across baseline and M_ZK-DES variants. In the quantitative version, the following indicative values are adopted (Table 26).

Table 26. Indicative assessment of crisis-management outcomes.

Outcome Dimension	Baseline Approach	M_ZK-DES Approach
Be—Energy security	3	4
Cd—Continuity of supply	2	4
Or—System resilience	2	5
Ki—Institutional coordination	2	4
As—System adaptability	1	4
Sp—Social acceptance and participation	2	4

The comparison shows that the greatest difference between the baseline approach and the M_ZK-DES model occurs in the areas of resilience, adaptability and institutional coordination. These are the elements that often play a secondary role in the classical technical approach, while in crisis management they constitute a condition for effective response.

In the M_ZK-DES model, the flow of information between system actors is of particular importance. Under crisis conditions, the quality of decisions depends on the speed of data acquisition, reliability and the ability to transform information into specific operational actions (Tables 27 and 28).

Table 27. Flow of information and decisions in the M_ZK-DES model.

Data Sources	Integration Node	Decision Authority	Operational Commands	Feedback
SCADA/AMI, weather alerts, cyber alerts, storage state, prosumer data	Local crisis-management centre and DSO coordination cell	Mayor/local crisis team, DSO dispatcher, critical-facility managers	islanding; load shedding; reserve activation; public warning; restoration sequence	field reports; consumer status; frequency/voltage; ENS; lessons learned

Table 28. Summary of input layer, integration layer, decision layer, output layer.

Input Layer	Integration Layer	Decision Layer	Output Layer
Technical monitoring; system operator data; local administration reports; community/prosumer signals	Crisis management centre verifies data, ranks risks and prepares options	Priority supply, resource allocation, islanding, storage dispatch, demand reduction and public communication	Critical facilities supplied; consumers informed; operators and services coordinated; R_k outcomes assessed

The scheme indicates that the crisis-management centre performs the function of integrating information derived from technical systems, operators, administration and local communities. On this basis, decisions are made regarding power supply priorities, resource allocation, public communication and cooperation with emergency services.

The illustrative application of the model shows that its fundamental value lies in shifting the emphasis from reactive failure removal to active management of system resilience. The baseline approach is useful in the case of standard technical failures, but it may prove insufficient in multidimensional situations where energy disruptions are combined with time pressure, information uncertainty, cyber threats, the need to protect critical facilities and the necessity of communication with residents.

The M_ZK-DES model enables earlier identification of system vulnerabilities, better preparation of response scenarios, more efficient coordination of actors and more effective use of local energy resources. At the same time, it makes it possible to assess not only the technical outcome of actions but also the quality of decisions, the level of social trust, the effectiveness of communication and the system's capacity to learn after a crisis.

Consequently, the proposed model may be used as a diagnostic, planning and evaluation tool. In the diagnostic dimension, it serves to identify threats, vulnerabilities and critical points. In the planning dimension, it supports the design of procedures, scenarios and power supply priorities. In the evaluation dimension, it makes it possible to compare the effectiveness of different crisis-management variants and to assess the extent to which the system increases its resilience after subsequent exercises, simulations and real events.

The comparison indicates that the model-based approach allows for a higher level of energy security, continuity of supply and operational resilience than the baseline approach. This difference results not only from the use of distributed technologies but above all from embedding them within a crisis-management structure that includes institutional coordination, social communication, risk analysis and learning mechanisms.

The application of the M_ZK-DES model leads to the following effects:

1. Shortening the time required to identify a threat and make a crisis decision;
2. Limiting the scale of energy system performance loss;
3. Better use of local energy sources and storage systems;
4. Increased protection of critical infrastructure facilities;
5. Improved communication with consumers and prosumers;
6. Strengthening the system's capacity for adaptation after the crisis has ended.

Ultimately, the M_ZK-DES model is treated as a tool supporting the transition from classical failure management to integrated resilience management of distributed energy systems. Its application makes it possible not only to respond to disruptions but also to systematically reduce system vulnerability and strengthen its ability to function under conditions of uncertainty.

6. Discussion

Recent Polish and Romanian outage situations are used as illustrative stress tests for the model. The cases are not treated as full empirical validation because operator-level

datasets are not available in the study, but they show how the model can structure evidence from real disruptions.

These cases support the practical logic of M_ZK-DES: the same event can be evaluated through hazard exposure (K_0), institutional coordination (K_1), technical DES performance (K_2), communication and community protection (K_3), and measurable outcome indicators (R_k) (Table 29).

Table 29. Summary of case, observed stressor, M_ZK-DES interpretation, required empirical data for validation.

Case	Observed Stressor	M_ZK-DES Interpretation	Required Empirical Data for Validation
Poland, 2024 flood-related distribution disruptions	Flooding and local distribution-network interruptions while the transmission system remained broadly secure.	K0 identifies flood-exposed assets; K2 tests local redundancy and restoration; Rk measures customers restored and critical-load continuity.	DSO outage logs, restoration times, ENS, SAIDI/SAIFI by affected municipality, critical-facility backup data.
Poland, 2025 severe storms	Strong wind and storm damage causing local outages and power-line damage.	K1 and K2 test coordination between DSO, local authorities and emergency services; K3 tests public warnings and vulnerable-consumer support.	Feeder-level outage duration, number of affected consumers, response times, backup-power use.
Romania, severe winter-weather outage example	Snow, fallen trees, blocked transport and electricity interruptions affecting many households.	Combined cascading scenario: power, transport and emergency access degrade simultaneously; islanding and local storage become critical.	Spatial outage data, weather intensity, road-access constraints, restoration chronology, critical-service continuity.

A further limitation is that the numerical examples are illustrative. They demonstrate how the model can be populated, but they do not replace empirical calibration with outage records, operator data, storage tests, expert elicitation or simulation outputs. This clarification is important for replicability and for avoiding overinterpretation of ordinal scores.

The analysis conducted indicates that distributed energy systems should be interpreted not only as an element of the energy transition and the decarbonisation of the economy but also as an important component of contemporary crisis management. The results of the literature review and semantic analysis confirm that the existing scientific discourse focuses primarily on the technological aspects of distributed energy, such as the integration of renewable energy sources, energy storage, microgrids, optimisation of energy flows, and the operational flexibility of the system. At the same time, categories directly related to crisis management, including emergency response, business continuity, recovery, protection of critical infrastructure, inter-institutional coordination, and crisis communication, remain less represented in the literature and are less frequently integrated into the analysis of distributed energy systems.

The results obtained make it possible to state that research on distributed energy systems reveals a clear asymmetry between the technological dimension and the crisis-management dimension. The literature provides numerous arguments supporting the thesis that the decentralisation of energy sources, the development of microgrids, energy storage facilities, and local balancing mechanisms can increase the resilience of the energy system. However, this resilience is often understood mainly as a technical feature relating to reliability, grid stability, or the ability to integrate renewable energy sources. From the perspective of crisis management, such an approach is insufficient, as it does not fully take into account decision-making processes, emergency procedures, institutional responsibility,

the role of stakeholders, social communication, or the system's capacity to learn after a disruption has occurred.

In this context, the proposed conceptual model represents an attempt to overcome the identified research gap by linking distributed energy with the full crisis-management cycle, including prevention, preparedness, response, and recovery. The model assumes that the effectiveness of distributed energy systems in crisis situations depends on the interaction of several interconnected components: systemic risk and vulnerability, institutional and decision-making preparedness for crisis, technological and operational resilience of infrastructure, and socio-informational mechanisms of communication and self-organisation. This approach makes it possible to analyse the energy system as a complex socio-technical system in which physical infrastructure, procedures, institutions, information, and user behaviour remain in relationships of mutual dependence.

An important result of the analysis is the indication that the mere presence of distributed energy technologies does not guarantee an increase in crisis resilience. Microgrids, energy storage systems, local renewable sources, or demand-side management systems can enhance energy security only when they are properly integrated with crisis-management plans, emergency operating procedures, systems for prioritising vulnerable consumers, and coordination mechanisms between operators, public administration, emergency services, and local communities. This means that energy resilience is not only technical in nature, but also organisational, institutional, and social.

The local and regional levels are of particular importance because it is precisely at these levels that the effects of energy disruptions are directly experienced by residents, business entities, and institutions providing public services. Distributed energy systems can function as local crisis resources, enabling the maintenance of power supply to facilities of critical importance, such as hospitals, water treatment plants, crisis-management centres, emergency units, communication systems, or temporary shelters for the population. However, the use of this potential requires prior identification of resources, assignment of responsibilities, development of emergency procedures, and conduct of exercises verifying the system's actual ability to operate under conditions of disruption.

The study results also indicate the need for broader inclusion of prosumers, energy communities, energy clusters, and local governments as active participants in the energy security system. In the traditional energy model, end users were perceived primarily as passive consumers of energy. In the distributed model, they can act as agents of local resilience, as they participate in energy generation, storage, consumption reduction, and local energy balancing. From the perspective of crisis management, this means expanding the resource base available in the event of a disruption, but at the same time it requires the creation of mechanisms for coordination, education, communication, and the legal definition of roles and responsibilities.

The interpretation of the results has been restricted to conclusions directly supported by the analyses performed in this article. The scoping review supports the claim that the literature is technically rich but institutionally fragmented; the lexical and semantic analysis supports the claim that crisis-management terms remain peripheral to the DES discourse; and the operational model supports the claim that resilience assessment requires simultaneous measurement of risk diagnosis, institutional decision capacity, technical reconfiguration and social-information feedback. The article therefore does not claim empirical proof of resilience improvement; it offers a structured conceptual and methodological framework for subsequent empirical validation.

The proposed model also makes it possible to better capture the significance of information in the crisis management of energy systems. Under conditions of disruption, not only is the availability of energy crucial, but also the ability to quickly recognise the situa-

tion, assess the scale of the threat, transmit information between entities, and communicate decisions to end users. A lack of reliable information, communication delays, or inconsistent messages may increase the scale of the crisis, lead to the disorganisation of activities, and weaken public trust. Therefore, the socio-informational component should be treated as one of the fundamental elements of the resilience of distributed energy systems.

From a theoretical perspective, the study results strengthen the argument that the energy transition should be analysed within a broader resilience paradigm. This means moving away from a narrow understanding of the transition as a process of technological modernisation and emissions reduction towards an approach that includes security of supply, protection of critical infrastructure, continuity of public services, and the ability of local communities to function under conditions of disruption. In this perspective, distributed energy systems can play the role of infrastructure supporting the resilience of the state and territories, but only if their development is linked to security policy, civil planning, civil protection, and local crisis-management strategies.

The presented results also have practical significance. The model may serve as a basis for assessing the preparedness of local government units, distribution system operators, and other entities responsible for energy security to operate in crisis situations. It may be used to identify gaps in procedures, assess the degree of integration of distributed energy resources with emergency plans, determine the level of protection of vulnerable consumers, and design crisis exercise scenarios. In practice, this means the possibility of moving from general declarations concerning energy resilience to more operational criteria for its measurement and assessment.

It should be emphasised, however, that the proposed model is conceptual in nature and requires further empirical validation. A limitation of the study is that the analysis is based on a literature review and exploratory text analysis, which makes it possible to identify the structure of the research field but does not yet allow for the direct measurement of the effectiveness of individual crisis-management mechanisms. Further research should include case studies of local and regional energy systems, analysis of strategic documents and crisis-management plans, expert interviews, surveys among stakeholders, and simulations of disruption scenarios. Particularly valuable would be the application of agent-based modelling, system dynamics, and network analysis, which would make it possible to examine system behaviour under conditions of cascading failures, cyberattacks, extreme weather events, or the simultaneous occurrence of several threats.

Future research directions should focus on the operationalisation of the proposed model components and the development of measurable indicators of the crisis resilience of distributed energy systems. Of particular importance is determining how to measure islanding capability, the duration of maintaining critical functions, the effectiveness of crisis communication, the level of inter-institutional coordination, the availability of reserve resources, the degree of protection of vulnerable consumers, and the recovery time after a disruption. Only empirical verification of these indicators will make it possible to assess the extent to which energy decentralisation genuinely strengthens systemic resilience and under what conditions it may generate new vulnerabilities.

The conclusions are derived from three reported results: (i) the review identified a gap between engineering resilience and crisis-management governance; (ii) the IRaMuTeQ analysis showed that terms such as crisis, emergency, recovery and business continuity are weaker and more peripheral than microgrid, storage, control and integration; and (iii) the M_ZK-DES framework operationalised this gap through K0-K3 and Rk indicators. Consequently, the practical recommendation is limited to using the model as a diagnostic and scenario-testing tool until it is validated with outage records, crisis exercises and local case studies.

7. Conclusions

The conducted analysis confirms that distributed energy systems should be regarded not only as instruments of energy transition and decarbonisation, but also as an important component of modern crisis management and critical infrastructure resilience. The results of the literature review, semantic analysis, and conceptual modelling indicate that distributed energy resources, including microgrids, energy storage systems, local renewable energy sources, prosumer installations, and demand-side management mechanisms, may significantly strengthen the capacity of energy systems to operate under conditions of disruption.

The main contribution of this article is the development of a conceptual model that links distributed energy systems with the full crisis-management cycle: prevention, preparedness, response, and recovery. The proposed M_ZK-DES model demonstrates that the crisis resilience of distributed energy systems depends on the interaction of four key components: risk and systemic vulnerability, institutional and decision-making preparedness, technological and operational resilience, and social, informational, and communication mechanisms. Such an approach makes it possible to analyse the energy system as a socio-technical arrangement in which infrastructure, institutions, procedures, information flows, and user behaviour are mutually interdependent.

Short-term work should focus on improving the model specification: (1) validating the 0–5 institutional scales, (2) calibrating weights with expert elicitation and sensitivity analysis, (3) replacing hypothetical scenario scores with DSO outage data, and (4) reporting complete IRaMuTeQ exports. Medium-term work should implement multi-region simulations comparing urban, rural, industrial and cross-border distribution systems. Long-term work should co-design operational tools with local governments, DSOs, emergency services and critical-facility operators, including dashboards for critical-load prioritisation, islanding readiness, storage autonomy and vulnerable-consumer protection.

The study shows that the mere implementation of distributed energy technologies does not automatically guarantee an increase in crisis resilience. Their effectiveness depends on the extent to which they are integrated with crisis-management plans, emergency procedures, business continuity strategies, critical infrastructure protection systems, and mechanisms of inter-institutional coordination. Microgrids, energy storage systems, and local generation sources can support energy security only when they are embedded in coherent legal, organisational, operational, and communication frameworks.

An important conclusion is that energy resilience should not be reduced to technical reliability or grid stability. From the perspective of crisis management, resilience also includes the ability to anticipate threats, absorb disruptions, maintain critical functions, adapt to changing conditions, reconfigure resources, coordinate actors, communicate effectively, and recover after a crisis. This means that the resilience of distributed energy systems has a multidimensional character, combining technological, organisational, institutional, informational, and social elements.

The analysis also highlights the importance of the local and regional levels. Distributed energy systems may serve as local crisis resources capable of maintaining power supply to critical facilities such as hospitals, water treatment plants, crisis-management centres, emergency services, communication systems, and temporary shelters. However, the use of this potential requires prior identification of resources, clear allocation of responsibility, development of emergency procedures, integration with local crisis-management plans, and regular testing through exercises and simulations.

Future empirical work should also maintain a rolling literature update, especially for rapidly developing 2023–2025 themes such as resilient DER management systems, grid-forming microgrids, islanding detection, cyber-resilient DER control, resilience valuation

and climate-proof distribution planning. Including these streams will prevent the model from being anchored primarily in 2010–2020 literature and will make subsequent validation more consistent with the current research frontier.

The findings further indicate the need to recognise prosumers, energy communities, energy clusters, local governments, and local enterprises as active participants in the energy security system. In distributed energy models, end users are no longer only passive consumers but may become actors of local resilience through energy generation, storage, demand reduction, and participation in local balancing mechanisms. This creates new opportunities for strengthening crisis preparedness but also requires legal, organisational, educational, and communication mechanisms that clearly define roles and responsibilities.

The proposed model may have practical application in assessing the preparedness of local governments, distribution system operators, public administration bodies, and other stakeholders responsible for energy security. It can be used to identify gaps in emergency procedures, assess the integration of distributed energy resources with crisis plans, evaluate the protection of vulnerable consumers, and design crisis exercise scenarios. In this sense, the model provides a basis for moving from general declarations of energy resilience towards more operational criteria for its assessment and measurement.

At the same time, the study has several limitations. The analysis is conceptual and is based primarily on a scoping review of scientific literature and exploratory text analysis. Although this approach made it possible to identify the main research streams and gaps, it does not allow for direct empirical verification of the effectiveness of specific crisis-management mechanisms. In addition, the use of literature indexed mainly in the Web of Science Core Collection limits the scope of the analysis, as practical documents, operator reports, crisis-management plans, technical standards, and administrative studies may contain relevant knowledge that is not fully represented in academic publications.

Future research should therefore focus on the empirical validation and operationalisation of the proposed model. Particularly important directions include case studies of local and regional energy systems, analysis of crisis-management plans and strategic documents, expert interviews, surveys among stakeholders, and simulations of disruption scenarios. Further studies should also develop measurable indicators of crisis resilience, including islanding capability, duration of maintaining critical functions, response time, recovery time, effectiveness of crisis communication, availability of reserve resources, protection of vulnerable consumers, and the level of inter-institutional coordination.

Further research may also benefit from the use of agent-based modelling, system dynamics, network analysis, and scenario simulations. These methods would make it possible to examine how distributed energy systems behave under conditions of cascading failures, cyberattacks, extreme weather events, infrastructure overloads, communication disruptions, or the simultaneous occurrence of several threats. Such analyses could help determine under which conditions energy decentralisation strengthens systemic resilience and under which conditions it may generate new vulnerabilities.

In conclusion, distributed energy systems should be treated as a strategic instrument for strengthening energy security, protecting critical infrastructure, and ensuring the continuity of essential public services under crisis conditions. Their role goes beyond technological modernisation and climate policy, extending into the domains of public safety, civil protection, local resilience, and crisis management. The development of distributed energy systems may therefore become one of the key elements of modern crisis management, provided that it is integrated with coherent legal regulations, strategic planning, institutional coordination, operational procedures, crisis communication, and social participation.

Author Contributions: Conceptualization, M.R., T.N., A.G. and K.W.; methodology, M.R. and T.N.; formal analysis, A.G. and K.W.; investigation, M.R. and K.W.; data curation, M.R. and A.G.; writing—original draft preparation, T.N.; writing—review and editing, M.R., A.G., M.J., B.K. and A.S.; visualisation, K.W.; project administration, T.N. and A.G.; funding acquisition, A.G. and T.N.; resources, M.R., T.N., M.J., B.K. and A.S.; software, M.R. and K.W. All authors have read and agreed to the published version of the manuscript.

Funding: The research leading to these results has received funding from the project titled “Cluster for innovative energy” in the frame of the programme “HORIZON-MSCA-2022-SE-01” under the grant agreement number 101129820. The study was co-financed by the Minister of Science under the “Regional Excellence Initiative”.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Rinaldi, S.M.; Peerenboom, J.P.; Kelly, T.K. Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies. *IEEE Control Syst. Mag.* **2001**, *21*, 11–25. [\[CrossRef\]](#)
2. Panteli, M.; Mancarella, P. The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience. *IEEE Power Energy Mag.* **2015**, *13*, 58–66. [\[CrossRef\]](#)
3. Bhusal, N.; Abdelmalak, M.; Kamruzzaman, M.; Benidris, M. Power System Resilience: Current Practices, Challenges, and Future Directions. *IEEE Access* **2020**, *8*, 18064–18086. [\[CrossRef\]](#)
4. Guo, H.; Zheng, C.; Iu, H.H.-C.; Fernando, T. A Critical Review of Cascading Failure Analysis and Modeling of Power System. *Renew. Sustain. Energy Rev.* **2017**, *80*, 9–22. [\[CrossRef\]](#)
5. Holling, C.S. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23. [\[CrossRef\]](#)
6. Bie, Z.; Lin, Y.; Li, G.; Li, F. Battling the Extreme: A Study on the Power System Resilience. *Proc. IEEE* **2017**, *105*, 1253–1266. [\[CrossRef\]](#)
7. Lopes, J.A.P.; Moreira, C.L.; Madureira, A.G. Defining Control Strategies for MicroGrids Islanded Operation. *IEEE Trans. Power Syst.* **2006**, *21*, 916–924. [\[CrossRef\]](#)
8. Gilani, M.A.; Kazemi, A.; Ghasemi, M. Distribution System Resilience Enhancement by Microgrid Formation Considering Distributed Energy Resources. *Energy* **2020**, *191*, 116442. [\[CrossRef\]](#)
9. Hirsch, A.; Parag, Y.; Guerrero, J. Microgrids: A Review of Technologies, Key Drivers, and Outstanding Issues. *Renew. Sustain. Energy Rev.* **2018**, *90*, 402–411. [\[CrossRef\]](#)
10. Ines, C.; Guilherme, P.L.; Marin-Gonzalez, E.; Gahrs, S.; Hall, S.; Holstenkamp, L. Regulatory Challenges and Opportunities for Collective Renewable Energy Prosumers in the EU. *Energy Policy* **2020**, *138*, 111212. [\[CrossRef\]](#)
11. Arksey, H.; O'Malley, L. Scoping studies: Towards a methodological framework. *Int. J. Soc. Res. Methodol.* **2005**, *8*, 19–32. [\[CrossRef\]](#)
12. Levac, D.; Colquhoun, H.; O'Brien, K.K. Scoping studies: Advancing the methodology. *Implement. Sci.* **2010**, *5*, 69. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Agama, E.J.; Zubairu, U.M. Sustainability Reporting: A Systematic Review. *Econ. Manag. Sustain.* **2022**, *7*, 32–46. [\[CrossRef\]](#)
14. Wojciechowski, W.; Niewiadomski, A.; Bilan, Y. Ecological and Secure Electricity Microgrids—Monitoring and Forecasting Challenges. *Hum. Technol.* **2025**, *21*, 469–473. [\[CrossRef\]](#)
15. Ouyang, M. Review on modeling and simulation of interdependent critical infrastructure systems. *Reliab. Eng. Syst. Saf.* **2014**, *121*, 43–60. [\[CrossRef\]](#)
16. Billanes, J.D.; Jørgensen, B.N.; Ma, Z. A framework for resilient community microgrids: Review of operational strategies and performance metrics. *Energies* **2025**, *18*, 405. [\[CrossRef\]](#)
17. Heidari-Akhijahani, A.; Butler-Purphy, K.L. A review on black-start service restoration of active distribution systems and microgrids. *Energies* **2024**, *17*, 100. [\[CrossRef\]](#)
18. Cheng, Q.; Zhang, Z.; Wang, Y.; Zhang, L. A review of distributed energy systems: Technologies, classification, and applications. *Sustainability* **2025**, *17*, 1346. [\[CrossRef\]](#)
19. Naseri, N.; Aboudrar, I.; El Hani, S.; Ait-Ahmed, N.; Motahhir, S.; Machmoum, M. Energy transition and resilient control for enhancing power availability in microgrids based on North African countries: A review. *Appl. Sci.* **2024**, *14*, 6121. [\[CrossRef\]](#)
20. Rickerson, W.; Gillis, J.; Bulkeley, M. *The Value of Resilience for Distributed Energy Resources*; National Renewable Energy Laboratory/NARUC: Golden, CO, USA, 2024.

21. Mohanty, A.; Ramasamy, A.K.; Verayiah, R.; Bastia, S.; Dash, S.S.; Cuce, E.; Khan, T.M.Y.; Soudagar, M.E.M. Power system resilience and strategies for a sustainable infrastructure: A review. *Alex. Eng. J.* **2024**, *105*, 261–279. [\[CrossRef\]](#)
22. Zidane, T.E.K.; Muis, Z.A.; Ho, W.S.; Zahraoui, Y.; Aziz, A.S.; Su, C.-L.; Mekhilef, S.; Campana, P.E. Power systems and microgrids resilience enhancement strategies: A review. *Renew. Sustain. Energy Rev.* **2025**, *207*, 114953. [\[CrossRef\]](#)
23. Kulkarni, M.S.; Mishra, S.; Sudabattula, S.K.; Sharma, N.K.; Basha, D.B.; Bajaj, M.; Tuka, M.B. Enhancing grid resiliency in distributed energy systems through a comprehensive review and comparative analysis of islanding detection methods. *Sci. Rep.* **2024**, *14*, 12124. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Adham, M.; Keene, S.; Bass, R.B. Distributed Energy Resources: A Systematic Literature Review. *Energy Rep.* **2025**, *13*, 1980–1999. [\[CrossRef\]](#)
25. Zitelman, K.; Barnes, J.; Converge Strategies LLC; National Renewable Energy Laboratory. *Advancing Electric System Resilience with Distributed Energy Resources: A Review of State Policies*; NREL/NARUC: Washington, DC, USA, 2024.
26. Aslam, M.U.; Miah, M.S.; Amin, B.M.R.; Shah, R.; Amjady, N. Application of Energy Storage Systems to Enhance Power System Resilience: A Review. *Energies* **2025**, *18*, 3883. [\[CrossRef\]](#)
27. Koirala, B.P.; Koliou, E.; Friege, J.; Hakvoort, R.A.; Herder, P.M. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. *Renew. Sustain. Energy Rev.* **2016**, *56*, 722–744. [\[CrossRef\]](#)
28. Barabino, E.; Fioriti, D.; Guerrazzi, E.; Mariuzzo, I.; Poli, D. Energy Communities: A review on trends, energy system modelling, business models, and optimisation objectives. *Sustain. Energy Grids Netw.* **2023**, *36*, 101187. [\[CrossRef\]](#)
29. Akinyele, D.; Belikov, J.; Levron, Y. Battery storage technologies for electrical applications: Impact in stand-alone photovoltaic systems. *Energies* **2017**, *10*, 1760. [\[CrossRef\]](#)
30. Mishra, S.; Anderson, K.; Miller, B.; Boyer, K.; Warren, A. Microgrid resilience: A holistic approach for assessing threats, identifying vulnerabilities, and designing corresponding mitigation strategies. *Appl. Energy* **2020**, *264*, 114726. [\[CrossRef\]](#)
31. Wang, Y.; Rousis, A.O.; Strbac, G. On microgrids and resilience: A comprehensive review on modeling and operational strategies. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110313. [\[CrossRef\]](#)
32. Wang, Y.; Chen, C.; Wang, J.; Baldick, R. Research on resilience of power systems under natural disasters—A review. *IEEE Trans. Power Syst.* **2016**, *31*, 1604–1613. [\[CrossRef\]](#)
33. Jasiūnas, J.; Lund, P.D.; Mikkola, J. Energy system resilience—A review. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111476. [\[CrossRef\]](#)
34. Siano, P. Demand Response and Smart Grids—A Survey. *Renew. Sustain. Energy Rev.* **2014**, *30*, 461–478. [\[CrossRef\]](#)
35. O’Connell, N.; Pinson, P.; Madsen, H.; O’Malley, M. Benefits and Challenges of Electrical Demand Response: A Critical Review. *Renew. Sustain. Energy Rev.* **2014**, *39*, 686–699. [\[CrossRef\]](#)
36. Ackermann, T.; Andersson, G.; Söder, L. Distributed generation: A definition. *Electr. Power Syst. Res.* **2001**, *57*, 195–204. [\[CrossRef\]](#)
37. Lund, H.; Østergaard, P.A.; Connolly, D.; Mathiesen, B.V. Smart energy and smart energy systems. *Energy* **2017**, *137*, 556–565. [\[CrossRef\]](#)
38. Cherp, A.; Vinichenko, V.; Jewell, J.; Brutschin, E.; Sovacool, B. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Res. Soc. Sci.* **2018**, *37*, 175–190. [\[CrossRef\]](#)
39. Markolf, S.A.; Chester, M.V.; Eisenberg, D.A.; Iwaniec, D.M.; Davidson, C.I.; Zimmerman, R.; Miller, T.R.; Ruddell, B.L.; Chang, H. Interdependent infrastructure as linked social, ecological, and technological systems (SETs) to address lock-in and enhance resilience. *Earth’s Future* **2018**, *6*, 1638–1659. [\[CrossRef\]](#)
40. Martišauskas, L.; Augutis, J.; Krikštolaitis, R.; Urbonas, R.; Šarūnienė, I.; Kopustinskas, V. A Framework to Assess the Resilience of Energy Systems Based on Quantitative Indicators. *Energies* **2022**, *15*, 4040. [\[CrossRef\]](#)
41. Wang, J.J.; Jing, Y.Y.; Zhang, C.F.; Zhao, J.H. Review on Multi-Criteria Decision Analysis Aid in Sustainable Energy Decision-Making. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2263–2278. [\[CrossRef\]](#)
42. Gungor, V.C.; Sahin, D.; Kocak, T.; Ergut, S.; Buccella, C.; Cecati, C.; Hancke, G.P. Smart Grid Technologies: Communication Technologies and Standards. *IEEE Trans. Ind. Inform.* **2011**, *7*, 529–539. [\[CrossRef\]](#)
43. Šreimikienė, D. Ranking of Baltic States on Progress Towards the Main Energy Security Goals of European Energy Union Strategy. *J. Int. Stud.* **2020**, *13*, 24–37. [\[CrossRef\]](#)
44. Pescaroli, G.; Alexander, D. Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. *Nat. Hazards* **2016**, *82*, 175–192. [\[CrossRef\]](#)
45. Uslar, M.; Specht, M.; Dänekas, C.; Trefke, J.; Rohjans, S.; González, J.M.; Rosinger, C.; Bleiker, R. *Standardization in Smart Grids: Introduction to IT-Related Methodologies, Architectures and Standards*; SpringerBriefs in Energy; Springer: Berlin/Heidelberg, Germany, 2013. [\[CrossRef\]](#)
46. Morkūnas, M.; Volkov, A.; Pazienza, P. How Resistant Is the Agricultural Sector? Economic Resilience Exploited. *Econ. Sociol.* **2018**, *11*, 321–332. [\[CrossRef\]](#)
47. Bruneau, M.; Chang, S.E.; Eguchi, R.T.; Lee, G.C.; O’Rourke, T.D.; Reinhorn, A.M.; Shinozuka, M.; Tierney, K.; Wallace, W.A.; von Winterfeldt, D. A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthq. Spectra* **2003**, *19*, 733–752. [\[CrossRef\]](#)

48. Johnson, R.B.; Onwuegbuzie, A.J.; Turner, L.A. Toward a Definition of Mixed Methods Research. *J. Mix. Methods Res.* **2007**, *1*, 112–133. [\[CrossRef\]](#)
49. Henry, D.; Ramirez-Marquez, J.E. Generic metrics and quantitative approaches for system resilience as a function of time. *Reliab. Eng. Syst. Saf.* **2012**, *99*, 114–122. [\[CrossRef\]](#)
50. Madni, A.M.; Jackson, S. Towards a conceptual framework for resilience engineering. *IEEE Syst. J.* **2009**, *3*, 181–191. [\[CrossRef\]](#)
51. Sterman, J.D. Learning from evidence in a complex world. *Am. J. Public Health* **2006**, *96*, 505–514. [\[CrossRef\]](#) [\[PubMed\]](#)
52. Sargent, R.G. Verification and validation of simulation models. *J. Simul.* **2013**, *7*, 12–24. [\[CrossRef\]](#)
53. Eisenhardt, K.M. Building theories from case study research. *Acad. Manag. Rev.* **1989**, *14*, 532–550. [\[CrossRef\]](#)
54. Epstein, J.M. Why Model? *J. Artif. Soc. Soc. Simul.* **2008**, *11*, 12.
55. Amer, M.; Daim, T.U.; Jetter, A. A review of scenario planning. *Futures* **2013**, *46*, 23–40. [\[CrossRef\]](#)
56. Hanna, R.; Gross, R.; Speirs, J.; Heptonstall, P.; Gambhir, A. How do energy systems model and scenario studies explicitly represent socio-economic, political and technological disruption and discontinuity? Implications for policy and practitioners. *Energy Policy* **2021**, *149*, 111984. [\[CrossRef\]](#)
57. Hinkin, T.R. A Brief Tutorial on the Development of Measures for Use in Survey Questionnaires. *Organ. Res. Methods* **1998**, *1*, 104–121. [\[CrossRef\]](#)
58. Churchill, G.A., Jr. A Paradigm for Developing Better Measures of Marketing Constructs. *J. Mark. Res.* **1979**, *16*, 64–73. [\[CrossRef\]](#)
59. Cronbach, L.J. Coefficient Alpha and the Internal Structure of Tests. *Psychometrika* **1951**, *16*, 297–334. [\[CrossRef\]](#)
60. Fornell, C.; Larcker, D.F. Evaluating Structural Equation Models with Unobservable Variables and Measurement Error. *J. Mark. Res.* **1981**, *18*, 39–50. [\[CrossRef\]](#)
61. Podsakoff, P.M.; MacKenzie, S.B.; Lee, J.Y.; Podsakoff, N.P. Common Method Biases in Behavioral Research: A Critical Review of the Literature and Recommended Remedies. *J. Appl. Psychol.* **2003**, *88*, 879–903. [\[CrossRef\]](#) [\[PubMed\]](#)
62. Boin, A.; 't Hart, P.; Stern, E.; Sundelius, B. *The Politics of Crisis Management: Public Leadership Under Pressure*; Cambridge University Press: Cambridge, UK, 2009. [\[CrossRef\]](#)
63. Cutter, S.L.; Barnes, L.; Berry, M.; Burton, C.; Evans, E.; Tate, E.; Webb, J. A Place-Based Model for Understanding Community Resilience to Natural Disasters. *Glob. Environ. Change* **2008**, *18*, 598–606. [\[CrossRef\]](#)
64. Francis, R.; Bekera, B. A Metric and Frameworks for Resilience Analysis of Engineered and Infrastructure Systems. *Reliab. Eng. Syst. Saf.* **2014**, *121*, 90–103. [\[CrossRef\]](#)
65. Ayyub, B.M. Systems Resilience for Multihazard Environments: Definition, Metrics, and Valuation for Decision Making. *Risk Anal.* **2014**, *34*, 340–355. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Boin, A.; McConnell, A. Preparing for Critical Infrastructure Breakdowns: The Limits of Crisis Management and the Need for Resilience. *J. Contingencies Crisis Manag.* **2007**, *15*, 50–59. [\[CrossRef\]](#)
67. Ansell, C.; Boin, A.; Keller, A. Managing Transboundary Crises: Identifying the Building Blocks of an Effective Response System. *J. Contingencies Crisis Manag.* **2010**, *18*, 195–207. [\[CrossRef\]](#)
68. Zio, E. Challenges in the Vulnerability and Risk Analysis of Critical Infrastructures. *Reliab. Eng. Syst. Saf.* **2016**, *152*, 137–150. [\[CrossRef\]](#)
69. Ten, C.W.; Manimaran, G.; Liu, C.C. Cybersecurity for Critical Infrastructures: Attack and Defense Modeling. *IEEE Trans. Syst. Man. Cybern. A Syst. Hum.* **2010**, *40*, 853–865. [\[CrossRef\]](#)
70. Cinelli, M.; Coles, S.R.; Kirwan, K. Analysis of the Potentials of Multi Criteria Decision Analysis Methods to Conduct Sustainability Assessment. *Ecol. Econ.* **2014**, *46*, 138–148. [\[CrossRef\]](#)
71. Mitchell, R.K.; Agle, B.R.; Wood, D.J. Toward a Theory of Stakeholder Identification and Salience: Defining the Principle of Who and What Really Counts. *Acad. Manag. Rev.* **1997**, *22*, 853–886. [\[CrossRef\]](#)
72. Reed, M.S.; Graves, A.; Dandy, N.; Posthumus, H.; Hubacek, K.; Morris, J.; Prell, C.; Quinn, C.H.; Stringer, L.C. Who's in and Why? A Typology of Stakeholder Analysis Methods for Natural Resource Management. *J. Environ. Manag.* **2009**, *90*, 1933–1949. [\[CrossRef\]](#) [\[PubMed\]](#)
73. Bauwens, T. Explaining the Diversity of Motivations behind Community Renewable Energy. *Energy Policy* **2016**, *93*, 278–290. [\[CrossRef\]](#)
74. Walker, G.; Devine-Wright, P. Community Renewable Energy: What Should It Mean? *Energy Policy* **2008**, *36*, 497–500. [\[CrossRef\]](#)
75. Walker, G.; Devine-Wright, P.; Hunter, S.; High, H.; Evans, B. Trust and Community: Exploring the Meanings, Contexts and Dynamics of Community Renewable Energy. *Energy Policy* **2010**, *38*, 2655–2663. [\[CrossRef\]](#)
76. Herbane, B. Rethinking organizational resilience and strategic renewal in SMEs. *Entrep. Reg. Dev.* **2019**, *31*, 476–495. [\[CrossRef\]](#)
77. Palensky, P.; Dietrich, D. Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads. *IEEE Trans. Ind. Inform.* **2011**, *7*, 381–388. [\[CrossRef\]](#)
78. Dunn, B.; Kamath, H.; Tarascon, J.M. Electrical Energy Storage for the Grid: A Battery of Choices. *Science* **2011**, *334*, 928–935. [\[CrossRef\]](#) [\[PubMed\]](#)
79. Vovk, Y.; Aulin, V.; Vovk, I.; Romaniuk, S.; Syhlovyyi, M.; Vovk, O.; Palianytsia, V.; Zabytivskyi, V. Electric Vehicle Charging Infrastructure Optimization on International Transport Corridors: Economic Analysis and EU Regulatory Alignment in Ukraine. *J. Sustain. Dev. Transp. Logist.* **2025**, *10*, 6–28. [\[CrossRef\]](#)

80. Kharlamova, G.; Chernyak, O.; Nate, S. Renewable Energy and Security for Ukraine: Challenge or Smart Way? *J. Int. Stud.* **2016**, *9*, 88–115. [\[CrossRef\]](#)
81. Lasseter, R.H. MicroGrids. In Proceedings of the IEEE Power Engineering Society Winter Meeting, New York, NY, USA, 27–31 January 2002; pp. 305–308. [\[CrossRef\]](#)
82. Ton, D.T.; Smith, M.A. The U.S. Department of Energy’s Microgrid Initiative. *Electr. J.* **2012**, *25*, 84–94. [\[CrossRef\]](#)
83. Geels, F.W. Technological Transitions as Evolutionary Reconfiguration Processes: A Multi-Level Perspective and a Case-Study. *Res. Policy* **2002**, *31*, 1257–1274. [\[CrossRef\]](#)
84. Farhangi, H. The Path of the Smart Grid. *IEEE Power Energy Mag.* **2010**, *8*, 18–28. [\[CrossRef\]](#)
85. Gigauri, I.; Bogacz-Wojtanowska, E. Effects of the Pandemic Crisis on Social Enterprise: A Case Study from Georgia. *Econ. Sociol.* **2022**, *15*, 312–334. [\[CrossRef\]](#)
86. Simionescu, M. The Circular Economy and Sustainable Development in the European Union’s New Member States. *Econ. Manag. Sustain.* **2023**, *8*, 6–15. [\[CrossRef\]](#)
87. Guerrero, J.M.; Vasquez, J.C.; Matas, J.; de Vicuna, L.G.; Castilla, M. Hierarchical Control of Droop-Controlled AC and DC Microgrids-A General Approach Toward Standardization. *IEEE Trans. Ind. Electron.* **2011**, *58*, 158–172. [\[CrossRef\]](#)
88. Nosar, A. Resilient Warehouse Supply Chains in Post-Conflict Economies: Evidence on Prepositioning, Multi-Echelon Inventory, and Lateral Transshipment. *J. Sustain. Dev. Transp. Logist.* **2025**, *10*, 98–106. [\[CrossRef\]](#)
89. Łazaroiu, G.; Szpilko, D.; Gedeon, T.; Halicka, K.; Rzepka, A. Digital Technologies Supporting Predictive Healthcare: Review of Research Trends. *Hum. Technol.* **2025**, *21*, 694–730. [\[CrossRef\]](#)
90. Walker, B.; Holling, C.S.; Carpenter, S.R.; Kinzig, A. Resilience, Adaptability and Transformability in Social-Ecological Systems. *Ecol. Soc.* **2004**, *9*, 5. [\[CrossRef\]](#)
91. Tricco, A.C.; Lillie, E.; Zarin, W.; O’Brien, K.K.; Colquhoun, H.; Levac, D.; Moher, D.; Peters, M.D.J.; Horsley, T.; Weeks, L.; et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and explanation. *Ann. Intern. Med.* **2018**, *169*, 467–473. [\[CrossRef\]](#) [\[PubMed\]](#)
92. Peters, M.D.J.; Godfrey, C.M.; Khalil, H.; McInerney, P.; Parker, D.; Soares, C.B. Guidance for conducting systematic scoping reviews. *Int. J. Evid.-Based Healthc.* **2015**, *13*, 141–146. [\[CrossRef\]](#) [\[PubMed\]](#)
93. Cobo, M.J.; López-Herrera, A.G.; Herrera-Viedma, E.; Herrera, F. Science mapping software tools: Review, analysis, and cooperative study among tools. *J. Am. Soc. Inf. Sci. Technol.* **2011**, *62*, 1382–1402. [\[CrossRef\]](#)
94. Rizzoli, V.; da Silveira, A.; De Falco, M.; Sarrica, M. Two Sides of the Same Coin: How to Integrate Social Network Analysis and Topic Detection to Investigate Shared Contents and Communicative Interactions in Social Representations. *Int. Rev. Social. Psychol.* **2024**, *37*, 21. [\[CrossRef\]](#) [\[PubMed\]](#)
95. Bolton, R.; Foxon, T.J. Infrastructure transformation as a socio-technical process—Implications for the governance of energy distribution networks in the UK. *Technol. Forecast. Social. Change* **2015**, *90*, 538–550. [\[CrossRef\]](#)
96. Gao, J.; Buldyrev, S.V.; Stanley, H.E.; Havlin, S. Networks formed from interdependent networks. *Nat. Phys.* **2012**, *8*, 40–48. [\[CrossRef\]](#)
97. Buldyrev, S.V.; Parshani, R.; Paul, G.; Stanley, H.E.; Havlin, S. Catastrophic cascade of failures in interdependent networks. *Nature* **2010**, *464*, 1025–1028. [\[CrossRef\]](#) [\[PubMed\]](#)
98. Macal, C.M.; North, M.J. Tutorial on agent-based modelling and simulation. *J. Simul.* **2010**, *4*, 151–162. [\[CrossRef\]](#)
99. Bonabeau, E. Agent-based modeling: Methods and techniques for simulating human systems. *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 7280–7287. [\[CrossRef\]](#) [\[PubMed\]](#)
100. Kusz, B.; Kusz, D.; Jurgilewicz, O.; Jurgilewicz, M.; Kozicki, B.; Topolewski, S. The technical efficiency of Polish energy sector companies of different sizes. *Energies* **2025**, *18*, 2534. [\[CrossRef\]](#)
101. Reuters. Polish power system is safe despite flooding, grid operator says. *Reuters*, 18 September 2024.
102. Euronews. Several thousands in Poland’s south cut off from electricity after severe storms. *Euronews*, 7 June 2025.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.