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CONCEPTUAL PRINCIPLES FOR RESILIENT DEVELOPMENT OF ENERGY INFRASTRUCTURE

1. State of the Energy Sector and Contemporary Challenges

The war has significantly impacted the functioning of the Ukrainian energy sector. Due to their economic, humanitarian, and geopolitical significance, energy infrastructure facilities are frequent targets of Russian aggression. Despite this, the Ukrainian power system has demonstrated remarkable resilience, and energy professionals have shown exceptional skill in maintaining the sector's stability even during wartime. As of July 2022, the «Energy Security» working group's materials for the Ukraine Recovery Plan noted that approximately 4 % of generating capacity was destroyed in combat, with another 35 % located in occupied territories. Notably, the largest nuclear power plant in Europe (Zaporizhzhia) operates within the Ukrainian power system but remains under constant pressure from Russian occupiers. The plant's production capacity is 6000 MW, which accounts for 43 % of the total capacity of all Ukrainian nuclear power stations.

Since October 2022, extensive attacks on energy infrastructure have posed new challenges not only for the stable operation of Ukraine's energy sector but also for the European energy system ENTSO-E, which Ukraine joined on March 16, 2022. Against this backdrop, research on enhancing and ensuring the resilience of Ukraine's energy sector is critically important. Moreover, the relevance of research in this field is underscored by a clear trend in the increase of relevant scientific publications worldwide (from ten publications in the Scopus database in 2013 to over one hundred in 2023). Therefore, the conceptual principles of economic, ecological, and technological functioning and development of energy facilities must consider and rely on the concept of resilience.

The timeliness and prospective nature of research in this area are also evidenced by the fact that the introduction and a specific section (Strengthening Cybersecurity and Resilience in the Energy System) of the EU action plan for digitalizing the energy system (Communication from The Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of the Regions, Strasbourg, 18.10.2022) are linked specifically to enhancing energy resilience.

Although there is currently no universally accepted definition of «resilience» in scientific publications and normative documents worldwide, one of the most comprehensive definitions can be considered as proposed based on publication [1]: resilience of a particular system is its ability to counter hybrid threats, absorb disruptions, reorganize, maintain essentially the same functions and feedback over time, and continue to evolve along a certain trajectory. This ability arises from the nature, diversity, redundancy, and interaction among components involved in creating various functions. Resilience is a system attribute and applies to various subsystems.

The practical significance and importance of this direction are further emphasized by the fact that ensuring the resilience of Ukraine's electrical power as a component of the country's national stability is among the main strategic tasks, as noted in the national report «National Resilience of Ukraine: Strategy for Responding to Challenges and Preempting Hybrid Threats» [2].

2. General Concept of Resilience

«Resilience» is a term that has become the subject of active discussion and is used in various contexts, sometimes being misinterpreted. This ambiguity can lead to poor outcomes and distort the fundamental concept underlying the management of diverse complex systems such as ecosystems, businesses, societies, rivers, cities, communities, and energy sectors.

In general terms, resilience is defined as the ability of a system to withstand impacts and maintain its functionality at a roughly equivalent level. It is measured by the extent to which a system can experience significant changes without crossing a critical threshold and shifting into a state from which it would need to recover. Based on the analysis of publications, particularly drawing on research [3], let us consider the general concept of resilience.

The concept of resilience comprises two important aspects: firstly, the system should be able to recognize and avoid (or, if necessary, adapt to) critical points or barriers; secondly, it should have the ability to avoid crossing unknown and unexpected barriers by exploring the attributes of the system that provide its overall resilience.

It is important to note that resilience is not always a desirable quality. For example, dictatorial regimes, degraded landscapes, and pathological states of individuals can be highly resilient. However, the main challenge lies in knowing how to reduce resilience in such cases [3].

The most common misinterpretation of resilience is perceiving it as «recovery». In reality, resilience involves the ability to adapt and change, reorganize while maintaining functionality. It's about changing to remain stable. A resilient system responds to disturbances by altering the interaction of its components and how it functions. It remains a learning system that adapts from its mistakes to better handle similar challenges in the future. It does not return to its previous state. Resilient systems are learning and evolving systems.

Moreover, it is important to distinguish resilience from reliability. Reliability typically indicates the ability of a system to withstand impacts while remaining unchanged, sometimes referred to as «technical robustness». This significantly differs from the idea of resilience, which involves change and adaptation in response to impacts. However, variations in interpretations exist where these two concepts are distinguished. But in environments of decision-makers who are not researchers, there is a tendency to perceive resilience as «hardening», as the ability to remain unchanged and robust against changes and stress. Overall, this can lead to a deterioration in resilience.

Equally important is the necessity to create resilience not only to specific threats but generally to all aspects of a system in the face of any disturbances. Excessive resilience in one aspect can lead to a loss of resilience in another. For instance, attempts to increase a forest's resilience to fires through extensive use of controlled burning can decrease the resilience of small animal species during droughts. Forests with high spatial diversity, featuring various stages of post-fire recovery, are generally more resilient to diverse disturbances than forests focused solely on creating fire resistance. Let us consider more aspects that contribute to overall resilience, and below are some of the key attributes that often remain unnoticed or misunderstood [3]:

1. Diversity of Responses: The first attribute on the resilience list is recognizing the importance of diverse methods to achieve the same result, considering different possibilities for responding to various types of disturbances. For example, in some ecosystems, plants, particularly legumes, have the ability to remove nitrogen from the air, which is crucial for the health and productivity of the entire ecosystem. In a resilient ecosystem, this function can be performed by various plant species, each capable of responding differently to external influences such as drought, frost, fire, disease, etc. Regardless of changes in the

environment, a resilient ecosystem can continue to fix nitrogen. However, in modern society, the management of corporations, public sector agencies, and various complex structures often dominates the paradigm of «efficiency» and «minimizing the unnecessary», which can lead to a lack of response diversity. At the same time, investments in maintaining response diversity, which is important for supporting resilience, are undervalued or not properly considered.

2. Impact of Disturbances: An ecosystem always protected from fire gradually loses its ability to withstand fire, although some species may need fire for seed sowing. Where fires are a natural part of the environment, it is necessary to periodically allow fire to maintain resilience. However, it is important to know the limits that cannot be crossed; too intense or insufficiently intense fire can cause serious damage and lead to the loss of other species. A comparison can be made that children who are forbidden to play in the dirt may grow up with a weakened immune system and develop allergies later in life. Attempts to completely prevent one type of disturbance for the sake of safety can worsen resilience. To ensure resilience to various types of disturbances, access to a full spectrum of ecological (natural and social) conditions is necessary. This can be compared to a probing process in which it is necessary to avoid crossing the boundary of stresses and disturbances.

3. Modularity: This is the ability of a system to be neither too strongly nor too weakly connected. Too strongly connected systems are vulnerable to the rapid spread of diseases (such as the coronavirus), cascading failures (for example, the global financial crisis), improper task performance, bad ideas, etc. On the other hand, insufficiently connected systems may be inadequately efficient in management, learning, and responding to crises and other challenges. The correct modularity of a system depends on the specific context and requires a careful balance between the level of connections and separateness. This balance requires constant monitoring and adjustment, as changes in one aspect can affect others.

4. Speed of Response to Shocks and Changes in the System: The ability to quickly respond to unexpected events and changes in the system is crucial for resilience. Having too many stages in the reporting and approval procedure can significantly slow down the response to events. The widespread tendency to add more checks and approval processes to ensure safety and legal compliance can reduce resilience and lead to bureaucracy. Therefore, it is important to ensure the efficiency of regulated processes and simplify the response to crises.

5. Capacity for Transformation When Necessary: Sometimes it is necessary to make fundamental changes to the system if it is threatened

by catastrophic change or due to changes in the environment. Resilience includes understanding when transformation is inevitable and the ability to rethink the system or its components in such a way that the new system provides what is most valued and necessary. Transformation may require changes in goals and approaches and may occur under changed environmental conditions. It is important to recognize the need for such a capacity for transformation to maintain the resilience of the system. The resilience of systems is a critical aspect of ensuring their stability and ability to withstand various challenges and disturbances. Resilience and transformation are not opposites; they can be complementary. Maintaining resilience at one level may require transformative changes at other levels.

6. Thinking, Planning, and Managing at Various Levels: One of the most common reasons for undesirable outcomes in planning and management is focusing only on the level of the perceived problem. A resilient complex system cannot be understood or managed at a single level. All complex systems operate at multiple levels, and the interaction between levels is critical for resilience. In some cases, cross-level effects reduce resilience at the focus level, in others, they enhance it.

7. Leadership, Not Management: The future environment and future states of all complex systems are inherently uncertain. Attempts to design and manage them towards some desired state are doomed to fail. Resilience involves maintaining capabilities, learning how to manage the system within a set of «good» states, and avoiding transition to «bad» states. This involves learning where not to go, rather than ideally managing where to go.

In the context of resilience, it is important to consider various attributes and aspects that contribute to a system's ability to survive and function in conditions of uncertainty and change.

First, it is important to consider the diversity of responses, which means recognizing the importance of different methods of achieving the same result, considering different types of disturbances. A resilient system must be able to respond to various external influences, such as drought, frost, fire, diseases, etc. A lack of response diversity can lead to a loss of system resilience.

Second, systems should be modular, i.e., capable of being neither too strongly nor too weakly connected. Too strong connectivity can make the system vulnerable to the rapid spread of failures, while insufficient connectivity can impair its management and coordination.

Third, the speed of response to shocks and changes in the system is important for resilience. Systems should be able to quickly adapt to unexpected events and changes in conditions.

Fourth, the ability to transform the system when necessary is also important for resilience. Sometimes fundamental changes need to be made to the system to ensure its ability to adapt to new conditions and challenges.

In addition, systems must be capable of thinking, planning, and managing at various scales, as all complex systems operate at multiple scales, and the interaction between them is crucial for stability. Managing and learning how to manage the system within a set of «good» states is an important aspect of resilience, as well as avoiding the transition to «bad» states.

It should also be noted that attempts to protect the system by maintaining it in a constant state can impair its resilience. It is important to consider the impact of the full spectrum of changes and take into account all resilience attributes for proper assessment and support of system stability.

3. Resilience of Systems

The guidance framework for resilience includes risk analysis as a central component. Risk analysis depends on characterizing threats, vulnerabilities, and the consequences of adverse events to determine the expected loss of critical functionality. The definition of resilience by the U.S. National Academy of Sciences incorporates risk within a broader context of a system's ability to plan, recover, and adapt to adverse events over time. Within the system's functionality profile, risk is interpreted as a general reduction in critical functionality, and system resilience is associated with the slope of the absorption curve and the shape of the recovery curve—indicating the temporal effect of the adverse event on the system. The dashed line indicates that highly resilient systems may adapt in such a way that the system's functionality may improve relative to its initial performance, thereby enhancing the system's resilience to future adverse events. A roadmap for enhancing the resilience of any complex system should include the following [4]:

– Specific methods for defining and measuring resilience;

– New modeling and simulation techniques for highly complex systems;

– Development of resilience engineering;

– Approaches to stakeholder engagement.

Necessary strategies for engaging with policy receivers to support the transition to resilience management through legislative, regulatory, and other means are essential.

The U.S. National Academy of Sciences defines resilience as «the ability to prepare and plan for, absorb, recover from, and successfully adapt to adverse events». Conceptually, risk analysis quantitatively assesses the probability that a system will reach the lowest point of its critical functionality profile. Risk management helps the system prepare and plan for adverse events, while resilience management goes further by integrating the system's temporal potential to absorb and recover from adverse events, and then adapt (Fig. 1).

Figure 1. Illustration of System Resilience

Source:[4]

Resilience is not a substitute for fundamental system design or risk management. Instead, resilience is a complementary attribute that utilizes strategies of adaptation and mitigation to enhance traditional risk management. Strategies for enhancing resilience can take the form of flexible response, decentralized decision-making, modularity, redundancy, ensuring component interaction independence, or a combination of adaptive strategies to minimize functionality loss and enhance the steepness of the recovery curve (Fig. 2).

The magnitude of the initial disturbance reflects the overall risk to the system, while the shape of the recovery curve is controlled by the system's resilience. The area under the curve is an indicator of the system's overall functionality. Systems facing high risks and high resilience perform better than those facing similar risks but with low resilience. Systems with low risk but also low resilience may perform as well as systems with high risk and high resilience.

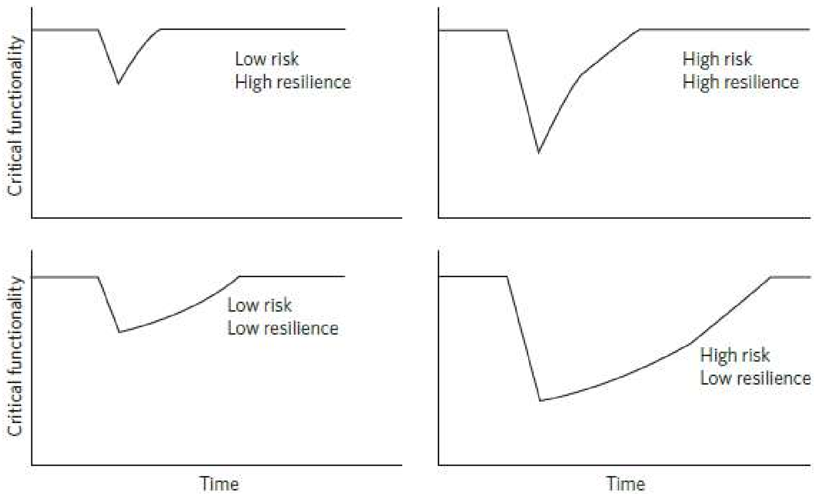

Figure 2. Schematic Representation of Changes in Critical Functionality Over Time Demonstrates the Interaction of Risk and Resilience in System Performance During an Adverse Event

Source: [4]

4. Taxonomy for Energy Resilience

Overall, a review of the literature allows for the determination of a suitable taxonomy for energy resilience. The most useful classification can be obtained by considering key terms extracted and derived through textual analysis [5, 6]:

1. Resilience in Systems: Utilizing flexibility and adaptability to adverse impacts [7, 8].

2. Approaches to Energy Resilience that emphasize and explore the concept of assessment and metrics. Assessment is fundamental for ensuring appropriate resilience measures [9]. These measures should be aimed at improving economic performance and environmental sustainability.

3. Approaches to Energy Resilience that emphasize the concept of security and analyze potential sources of risk management [10,11]. The diversity of energy supply sources and sustainable resources is a fundamental issue in this context [12].

4. Urban or Regional Approaches to Energy Resilience – where resilience is emphasized and based on the spatial level [13].

5. Community-based Approach to Energy Resilience, focused on specific and active support of local communities [14]. The community approach to energy resilience aims to balance social values and environmental impact.

6. Policy-based Approach to Energy Resilience, involving national-level interventions [15].

7. Sectoral Approaches to Energy Resilience (biofuels, bioenergy, etc. [16]).

5. Indicators of Energy Resilience

Based on a review of the literature, 20 key indicators have been identified that can be used to assess the resilience of the power sector:

1. Reliability of Energy Supply: Frequency and duration of energy supply interruptions.

2. Diversification of Energy Sources: Variety and distribution of energy sources.

3. Energy Reserve Capacity: Level of strategic energy reserves.

4. Flexibility of the Energy System: The ability of the system to adapt to changes in consumption (demand) and generation (supply).

5. Recovery Efficiency: Speed of the energy system's recovery after disruptions.

6. Renewability of Energy: Percentage of renewable sources in the overall energy balance.

7. Energy Independence: Degree of dependence on imported energy sources.

8. Financial Stability of the Energy Sector: Ability of the sector to withstand financial fluctuations.

9. Level of Technological Advancement: Use of advanced technologies in the energy sector.

10. Cybersecurity: Protection of energy infrastructure from cyberattacks.

11. Environmental Sustainability: Impact of energy activities on the environment.

12. Market Integration: Ability to operate effectively under market conditions.

13. Social Support: Level of public support for energy policy.

14. Institutional Stability: Stability and efficiency of energy legislation and policy.

15. Climate Change Resilience: Ability of the system to adapt to the effects of climate change.

16. Energy Accessibility for the Population: Level of accessibility and price dynamics of energy for consumers.

17. Infrastructure Reliability: Condition and efficiency of energy infrastructure.

18. Innovativeness: Level of implementation of new technologies and innovative solutions.

19. International Cooperation: Collaboration in the international energy sector.

20. Regulatory Adaptiveness: Ability of legislation to quickly adapt to changes in the sector.

6. Components of Resilience

The resilience of the power sector is defined by several key components that allow the system to withstand, adapt to, and recover from various types of disruptions or challenges (Fig. 3). Analysis of contemporary scientific approaches has identified the following main components of power sector resilience:

1. Modularity: The system's structure is divided into independent modules that can function separately. This allows for isolating issues and preventing their spread throughout the system.

2. Flexibility: The system's ability to quickly adapt to changes in energy demand and supply, as well as new operating conditions.

3. Reliability: The system's stability during designed and emergency conditions, capable of preventing or minimizing supply interruptions.

4. Recoverability: The system's ability to quickly recover from interruptions and damages.

5. Diversification of Energy Sources: Utilizing a variety of energy sources (renewable, fossil, nuclear) to reduce dependence on any single type of resource.

6. Cybersecurity: Protection of systems from cyberattacks and other forms of cyber threats.

7. Infrastructure Robustness: The physical robustness of the energy infrastructure, capable of withstanding natural disasters and other physical challenges.

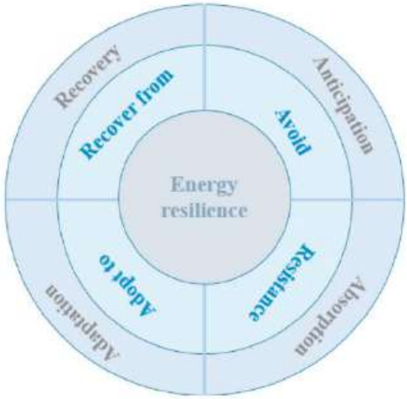

Figure 3. Main Components of Energy System Resilience

Source:[1]

8. Environmental Sustainability: Minimizing negative environmental impacts, ensuring sustainable resource use.

9. Innovativeness: Implementation of new technologies and solutions to enhance the efficiency and resilience of the system.

10. Regulatory Support: Presence of legislative and regulatory frameworks that facilitate the development and support of resilience.

11. Social Responsibility: Considering the needs and interests of local communities and consumers.

12. International Cooperation: Collaboration with other countries and international organizations for knowledge and resource exchange.

13. Risk Management: Identification, analysis, and management of potential risks to the system.

14. Integration of Renewable Sources: Incorporation of renewable energy sources, such as solar and wind, to provide additional resilience.

15. Organizational Structure: Effective management, organizational structures, and procedures that facilitate response to challenges and ensure resilience.

7. Assessing the Resilience of Power Systems

Authors [17] have proposed a framework of approaches for measuring resilience (Fig. 4), divided into two main categories: «Metric-Based» (individual metrics, indices, dashboard analytics, and decision analytics) and «Model-Based» (processes, statistical/Bayesian, networks, game-theoretic approaches, and simulations/agent-based). Each subcategory pertains to different methods of analysis and tools that can be used to assess the system's resilience.

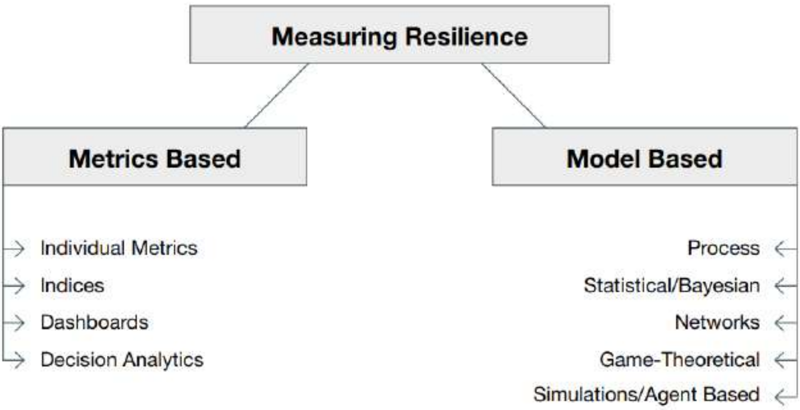

Figure 4. Metric and Model Approaches
to Resilience Assessment

Source:[17]

The graph (Fig. 5) depicts two trajectories of system value over time: one with resilience (green line) and another without resilience (red line). The stages of system development are marked as «Diagnosis and Conceptualization», «Design and Implementation», and «Operation and Maintenance». The green line illustrates an increase in value over time due to resilience, whereas the red line shows lesser value growth and a potential collapse of the system. The difference between the two curves illustrates the «value of resilience».

Table 1 presents a set of characteristics and factors affecting the resilience of energy systems, including references to sources that have explored them. Robustness and speed are considered in the context of infrastructure systems and were discussed in [18]. Adaptiveness, anticipation of unexpected events, response, and recovery in supply chains were explored in [19]. Planning/preparation, recovery, absorption, and adaptation regarding energy systems are discussed in [20].

Article [21] proposes a multi-criteria decision-making (MCDA) approach to assess the resilience of electricity supply, considering the interaction of criteria. The study evaluated 35 European countries using 17 interrelated assessment criteria through two complementary MCDA methods. Choquet integrals were used as importance measures to adequately account for interactions among criteria.

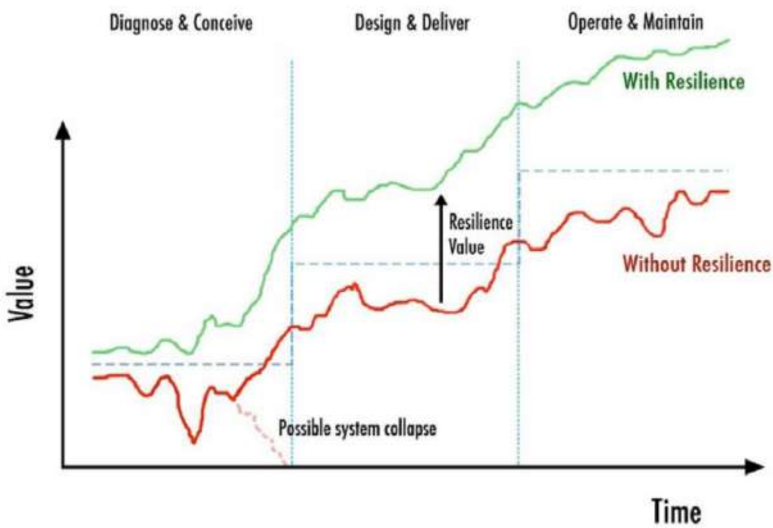

Figure 5. Illustrative Example of Value Generation under the Impact of Shocks and Stressors

Source: [17]

A detailed analysis of indicators and models for assessing the resilience of power systems is presented in [1]. Specifically, the Resilience Indicator (RC) as a measure for calculating system resilience. They divided the cost of resilience into two categories: costs associated with reduced system performance (SI), and costs associated with recovery measures (TRE). Thus, the cost of resilience is calculated as a function of System Impact Cost (SIC), Market Recovery Cost (MREC), Transport Recovery Cost (TREC), and Target Market Value of Production (TMV):

$$RC = \frac{SIC + MREC + TREC}{TMV}$$

Table 1

SET OF CHARACTERISTICS AND FACTORS OF ENERGY SYSTEM RESILIENCE

Characteristics and Factors	Considered Systems	Source
Robustness, Speed	Infrastructure Systems	McDaniels et al. (2008) [18]
Adaptiveness, Anticipation of Unexpected Events, Response, Recovery, System Control	Supply Chains	Ponomarov and Holcomb (2009) [19]
Anticipation of Unexpected Events, Adaptive Response, System Control, Robustness	Supply Chains	Ponis and Koronis (2012) [22]
Planning/Preparation, Recovery, Absorption, Adaptation	Energy Systems	Roege et al. (2014) [20]
Resilience, Recoverability	Supply Chains	Melnyk et al. (2014) [23]
Robustness, Speed	Engineering Systems	Zobel and Khansa (2014) [24]
Durability	Engineering Systems	Woods (2015) [25]
Preparation, Recovery, Mitigation, Response	Energy Systems	Philieps et al. (2016) [26]
Anticipation of Unexpected Events, Resilience, Recoverability, Flexibility, Redundancy	Supply Chains	Kamalahmadi and Melatparast (2016) [5]
Diversity	Energy Systems	Sato et al. (2017) [21]
Resource Efficiency, Durability	Energy Systems	Schlor et al. (2018) [27]
Absorption, Recovery	Solar Energy Installations	Wang et al. (2019) [28]
Preparedness, Recovery Capability, Adaptive Capacity	Microgrid Systems	Akhtar et al. (2019) [29]
Adaptive Capacity	Microgrid Systems	Ajaz (2019) [30]

Source: [1]

Conclusions

1. Definition of Resilience: Resilience is defined as the ability to prepare and plan for, absorb, recover from, and successfully adapt to adverse events.

2. Contextual Importance of Resilience: In the context of resilience, it is crucial to consider various attributes and aspects that contribute to a system's ability to survive and function under uncertainty and change. Firstly, the diversity of responses, which highlights the importance of different methods to achieve the same result while considering various types of disturbances. Secondly, systems must be modular, meaning they should not be too tightly or too loosely interconnected. Thirdly, the speed of response to shocks and changes within the system is critical for resilience. Systems must be able to quickly adapt to unexpected events and changes in conditions. Fourthly, the capacity for system transformation when necessary is also crucial for resilience. Sometimes, fundamental changes are needed within the system to ensure it can adapt to new conditions and challenges.

3. Key Indicators for Assessing Power System Resilience: Based on the literature review, 20 primary indicators have been identified for assessing the resilience of power systems. These include the reliability of energy supply; diversification of energy sources; energy reserve capacity; flexibility of the energy system; efficiency of recovery; renewability of energy; energy independence; financial stability of the energy sector; level of technological advancement; cybersecurity; environmental sustainability; market integration; social support; institutional stability; resilience to climate changes; energy accessibility for the population; infrastructure reliability; innovativeness; international cooperation; and regulatory adaptiveness.

4. Methods of Resilience Assessment: Assessment methods can be divided into two main categories: «Metric-Based» (individual metrics, indices, dashboard analytics, and decision analytics) and «Model-Based» (processes, statistical/Bayesian, networks, game-theoretic approaches, and simulations/agent-based).

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