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Energy Resilience Assessment Against the Backdrop of Global Energy Supply Shocks: Theoretical Framework, Key Indicators, and International Experiences

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Abstract. Against the backdrop of global energy supply being frequently impacted by geopolitical conflicts, extreme climate events, and structural contradictions in energy transition, energy resilience has emerged as a core issue in global governance and energy research. The paper systematically reviews the theoretical evolution trajectory and integrated framework of energy resilience, explores its assessment methods and key indicators, and summarizes the differentiated paths in international practices. The conclusions are drawn as follows: First, energy resilience is not a single static attribute, but a dynamic complex system that requires the intertwining of technology, society, and policies. Second, the diversification of international energy resilience paths primarily stems from the "adaptive choices" made by countries at different stages of development and with varying economic and technical backgrounds. Developed countries rely on the dual drive of "technology + capital" to build energy resilience, while developing countries focus on low-cost and targeted breakthroughs in energy resilience paths. Moreover, the effectiveness of energy resilience does not lie in whether the model is "advanced or not", but in whether it forms a dynamic adaptation with the country's actual conditions and risk characteristics.

Keywords: Energy resilience, geopolitical conflicts, energy transition.

1. Introduction

In recent years, the global energy system has been experiencing unprecedented shocks: the restructuring of global energy trade triggered by geopolitical conflicts (for instance, the Russia-Ukraine conflict has led to the restructuring of energy trade flows and heightened the risk of industrial chain disruptions), the paralysis of infrastructure caused by extreme climate events, and the structural contradictions in the connection between traditional and new energy systems amid energy transition. These factors have jointly pushed "energy resilience" to the core issue in global governance and energy research [1]. Energy systems are no longer merely static carriers pursuing efficiency and cost; rather, they are complex carriers that need to maintain core functions, recover quickly, and adapt dynamically in constantly changing environments.

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Starting with Holing, who laid the foundation for the theory of ecological resilience, he proposed that the essence of system resilience is "the ability to maintain core functions after being disturbed" rather than pursuing static stability [2]. Later, Panteli et al. introduced the concept of resilience into power systems, expanded the traditional "resilience triangle model" and put forward the "resilience trapezoid model" [3]. Based on the traditional resilience triangle, this model, for the first time, divided the entire process of energy systems responding to extreme events into three main stages: the disturbance progress, the post-disturbance degraded state, and the restorative state. The theoretical connotation of energy resilience has extended from a single "risk resistance capacity" to a multi-dimensional concept encompassing system structure, operational mechanisms, and social responses. However, existing studies still have limitations: first, most existing theoretical frameworks focus on specific fields such as electricity or oil, lacking integration of the coupling relationships among multi-energy systems; second, evaluation indicators usually emphasize the technical level (e.g., the recovery time of power systems after emergencies), with insufficient quantification of social equity (such as the Gini coefficient of global energy distribution); third, there exist differentiated resilience development paths between developed and developing countries.

Against this backdrop, this paper analyzes energy resilience amid global energy supply shocks from three dimensions: integrating the interdisciplinary perspectives of ecological resilience, complex system theory, and energy science; elaborating on the methods and key indicators for energy resilience assessment; and comparing energy resilience practices across different countries.

2. Theoretical evolution and integration framework of energy resilience

2.1. Theoretical origin tracing

As an emerging and increasingly critical research field, energy resilience does not have its theoretical roots in traditional engineering or energy economics, but rather in the ecological science of the 1970s. In his seminal 1973 paper "Resilience and Stability of Ecological Systems",Canadian ecologist C.S. Holling first systematically defined "ecological resilience" [2]. He defined ecological resilience as: the enduring capacity of a system to maintain its original functions, structure, identity, and feedback mechanisms after absorbing disturbances, undergoing reorganization, and experiencing changes. The core breakthrough of this definition lies in the shift from the previous focus on the "constancy" of system states to emphasizing the "persistence" of the system amid dynamic changes.

2.2. Expansion in the energy field

The transfer of ecological resilience theory to energy systems is not a simple conceptual transplantation, but an in-depth reconstruction that integrates the technical characteristics and operational laws of energy systems. From the late 20th century to the early 21st century, as extreme weather events increasingly impacted power systems, scholars began to introduce "resilience" from the ecological field into energy research. However, its early applications were mostly limited to static descriptions of "anti-interference capability" and failed to capture the dynamic response characteristics of energy systems.

Panteli et al. proposed the "Resilience Trapezoid", which marked a pivotal breakthrough in the theory of energy resilience [3]. Building upon the traditional "resilience triangle" (which only focuses on the post-disaster recovery stage), this model, for the first time, divided the entire process of energy systems responding to extreme events into three core stages: the disturbance progress, the

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post-disturbance degraded state, and the restorative state. It systematically depicts the dynamic trajectory from the occurrence of a shock to full recovery. Consistent with the essence of ecological resilience, which emphasizes "maintaining core functions", the core innovation of this model lies in realizing a two-dimensional assessment of energy systems—encompassing both "functional continuity" and "physical integrity"—by distinguishing between "operational resilience" and "infrastructure resilience".

Operational resilience focuses on maintaining system functions, with "load guarantee rate" and "power generation capacity availability rate" as core indicators to measure the continuity of power supply to critical loads (such as hospitals and transportation hubs) during extreme events. For instance, in the case of a hurricane impact, even if some transmission lines are damaged, the ability to ensure power supply to critical loads through strategies like load transfer and dispatch of distributed power sources reflects high operational resilience.

Infrastructure resilience, by contrast, concerns the damage resistance of physical assets. It uses indicators such as "transmission line availability rate" and "substation integrity rate" to reflect the physical integrity of hardware like towers and cables amid disasters.

2.3. Multidisciplinary integrated perspective

The complexity and dynamics of energy systems mean that their resilience assessment cannot be confined to a single disciplinary perspective. With the diversification of extreme event types (such as geopolitical conflicts, climate disasters, and technical failures) and energy transition (e.g., the increasing proportion of renewable energy), the interdisciplinary integration of ecology, engineering, social sciences, complex systems theory, and other disciplines has gradually formed a more three-dimensional and integrated framework for energy resilience. This framework not only inherits the core understanding of "resilience" from various disciplines but also fills the blind spots of single perspectives through cross-disciplinary dialogue, providing a systematic tool for analyzing the behavior of energy systems under multiple shocks.

Holling's theory of ecological resilience laid the foundation for multidisciplinary integration. Its core proposition—"a system's ability to maintain core functions after disturbances"—has, when extended to energy systems, developed profound mutual influence with complex systems theory. Complex systems theory emphasizes the multi-level interactivity of energy systems: from micro-level distributed energy units (e.g., residential photovoltaics) to meso-level regional microgrids, and further to macro-level transnational transmission networks. Each level is intercoupled through material flows (e.g., fuels), information flows (e.g., dispatching instructions), and capital flows (e.g., electricity pricing mechanisms), forming a network structure where "a single move affects the whole system" [4]. Such coupling relationships mean that a single disturbance can spread to the entire system through cascading effects. For example, a hurricane causing transmission line outages in a certain region (a micro-level disturbance) may trigger a sudden surge in load in adjacent regions, which in turn activates protective devices and leads to power outages on a larger scale (meso-level spread), ultimately impacting national electricity market prices (macro-level impact).

3. Methods and key indicators for energy resilience assessment

Energy resilience assessment aims to quantify the ability of energy systems to maintain core functions, recover quickly, and adapt dynamically in the face of various disturbances. The construction of its methods and evaluation indicator systems is key to understanding and enhancing energy resilience. In complex energy systems, a single indicator or method cannot fully assess

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resilience characteristics; instead, it is usually necessary to comprehensively consider the multi-dimensional attributes and dynamic evolution of the system.

3.1. Arup group limited energy resilience framework

The ARUP Energy Resilience Framework provides a comprehensive and systematic perspective for assessing the resilience of energy systems. Composed of three core dimensions and supported by 11 specific objectives, the framework conducts an in-depth analysis of the resilience status of energy systems from such aspects as leadership and strategy, economy and society, infrastructure and ecosystems [5].

The Leadership and Strategy dimension encompasses Strategic Vision, Integrated Governance, and Effective Regulation. A clear strategic vision demands long-term planning for the future development trends of the energy sector, while fully accounting for the direction and progress of the energy transition. Integrated governance underscores inter-departmental and cross-sectoral collaboration. Governments, scholars, non-governmental organizations, and enterprises, among others, need to strengthen close cooperation. For instance, when formulating a regional energy planning scheme, it is essential to coordinate and comprehensively consider multiple dimensions like energy supply, land use, and environmental protection. Effective regulation balances the “energy trilemma” of energy security, sustainability, and affordability via clear mandates and ensures well-defined and robust implementation mechanisms, such as the access mechanisms for the energy industry.

The Economic and Social Value dimension encompasses objectives such as Empowered and Engaged Consumers, Sustainable Financial Systems, Whole-System Thinking, and Effective Disaster Response and Recovery. Consumer participation is crucial: through energy education and incentive mechanisms, consumers are encouraged to actively engage in responses—for instance, voluntarily reducing electricity usage during peak hours can effectively ease the pressure on energy supply. Sustainable financial systems provide funding support for energy resilience projects, such as green bonds financing renewable energy initiatives. Whole-System Thinking requires viewing the energy system as interconnected with other infrastructure systems like transportation and communications, considering their synergies and potential risk transmission, for example, the impact of the widespread adoption of electric vehicles on the power system. Effective disaster response and recovery mechanisms ensure that the energy system can recover quickly after a disaster, minimizing losses, such as establishing emergency energy reserves and relevant emergency repair teams.

The dimension of physical infrastructure and its ecosystem focuses on objectives such as the resilience of infrastructure, ecosystem integration, technological innovation and adaptability, and resource management and sustainability. The resilience of infrastructure is reflected in the ability of energy facilities to withstand shocks like natural disasters and technical failures, such as reinforcing transmission lines to resist damage from natural disasters; ecosystem integration emphasizes the harmonious coexistence between the energy system and natural ecosystems, for example, focusing on protecting the surrounding ecological environment during energy development; technological innovation and adaptability require relevant departments to continuously introduce new technologies to enhance the flexibility and response speed of the energy system, such as using smart grid technology to achieve precise and efficient power dispatching; and resource management and sustainability focus on the rational development and efficient utilization of energy resources to ensure the long-term stability of energy supply, such as optimizing the ratio between fossil energy extraction and renewable energy production.

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3.2. Geopolitical risk index

Geopolitical risk refers to the international political risks triggered by changes in the original geopolitical interest structure of a region, which result from activities such as development, shaping, competition, or control carried out by state and non-state actors in specific overseas geographical spaces. Its formation mechanism mainly includes strategic rivalry between major powers, the contest between maritime and land powers, games triggered by geographically sensitive regions, and competition in the field of geo-economics [6]. Against the backdrop of complex international politics, geopolitical risks have led to fluctuations in international crude oil prices, exerting destructive impacts on global economic growth, energy security, and more [7].

The Geopolitical Risk Index (GPRI) is a core indicator that quantifies the degree to which energy systems are disturbed by geopolitical factors. It reflects the level of geopolitical risks and aims to capture the potential impacts of shocks and pressures in the geopolitical sphere (such as threats of war, terrorist attacks, nuclear crises, etc.) on socio-economic systems [8]. With the transnational expansion of energy supply chains (e.g., Europe's dependence on Russian natural gas, the global impact of oil exports from the Middle East), the impact of non-traditional risks such as geopolitical conflicts, sanctions policies, and resource competition on energy supply has become increasingly prominent. Traditional technology-oriented resilience assessments struggle to cover such systemic risks, making the Geopolitical Risk Index a key tool to fill this gap.

4. International practices and differences in energy resilience building

In the process of responding to supply shocks, the global energy system has developed diversified paths for resilience building. Developed countries, relying on technological advantages and capital accumulation, focus on systematic institutional design and the application of cutting-edge technologies. Whereas developing countries, constrained by resource limitations, mostly tackle resilience bottlenecks through adaptive innovations. The practices of both sides not only show complementarity but also expose the structural contradictions in global energy governance.

4.1. Developed countries or regions—dual-driven by technology and capital

The energy resilience building of developed countries centers on "proactive defense + dynamic adaptation" and is policy-driven. By integrating technological innovation and capital investment, they have constructed a multi-dimensional resilience system. In responding to energy crises and climate governance, the EU actively promotes energy transition and proactively addresses the potential negative impacts of energy crises [9]. Japan, on the other hand, adapts to local conditions and takes the initiative to establish a distributed energy network layout to enhance energy resilience, thereby reducing losses caused by natural disasters. Both the EU and Japan are distinctly representative in terms of energy resilience building.

4.2. EU: energy autonomy and diversified transition proceeding in parallel

Against the backdrop of the chaos in the global energy market triggered by the Russia-Ukraine conflict and the threat to its economic security arising from the EU's reliance on energy imports from Russia, first, accelerate the substitution of renewable energy and strengthen infrastructure for wind power and solar energy; second, establish a new energy platform adopting the "joint procurement mechanism" model, aiming to import natural gas from sources such as the United States, Egypt, and West Africa to ensure the diversification of energy supply options; third, increase

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additional investment by 210 billion euros to speed up the establishment of a pan-European integrated energy market, with a focus on areas such as improvements in industrial cleanliness and power grid transformation, in a bid to accelerate the clean energy transition of all member states. In summary, the plan aims to break free from dependence on Russian energy by 2032 and achieve carbon neutrality by 2050 through diversifying energy sources, promoting energy conservation, and accelerating the development of renewable energy [10].

4.3. Japan: integration of distributed energy networks and disaster response

After the Fukushima nuclear accident, the vulnerability of Japan's centralized energy was exposed. In 2014, hydrogen energy was first positioned as a "core secondary energy". In 2017, Japan issued the National Hydrogen Strategy, taking hydrogen and ammonia energy technologies as a breakthrough point to achieve carbon neutrality goals and ensure energy security [11]. At the same time, Japan has promoted the "local energy autonomy" strategy, building distributed networks centered on hydrogen energy in regions such as Miyagi Prefecture. Community-level hydrogen energy storage systems can maintain power supply for critical loads during typhoons.

4.4. Developing countries or regions: adaptive innovation under resource constraints

Developing countries, constrained by conditions such as funding shortages and backward technology, see their energy and electricity resilience building exhibit the characteristic of being "problem-oriented"—that is, they focus on addressing potential risks through low-cost innovations and localized solutions. For example, Malaysia, as a low-lying island country, is vulnerable to natural disasters caused by rising sea levels. To reduce the risk of energy supply chain disruptions in the face of natural disasters, Malaysia has promoted solar and wind power projects. The construction of these energy projects ensures a stable power supply during natural disasters [12].

5. Conclusion

Energy resilience is not a static attribute of a single dimension, but a complex system where technological systems, social responses, and policy mechanisms are intertwined and dynamically evolving. Its core characteristics are reflected in the guarantee of functional continuity at the technological level, collaboration among multiple subjects at the social level, and systematic governance design at the policy level. These three aspects complement each other, jointly supporting the energy system to maintain its core functions and evolve dynamically in response to shocks.

The diversification and differences in international energy resilience paths essentially stem from the "adaptive choices" of countries at different development stages and with distinct economic and technological backgrounds. Developed countries rely on the "technology + capital" dual-driven model to pursue forward-looking resilience development paths. In contrast, constrained by various factors, developing countries focus their adaptive innovations on low-cost and targeted breakthroughs. Although the two follow different paths, they jointly reveal a core law: the effectiveness of energy resilience does not lie in whether a model is "advanced" or not, but in whether it forms dynamic adaptation with a country's actual conditions and risk characteristics. This differentiation also provides insights for global energy governance: the international community needs to abandon "one-size-fits-all standards" and help developing countries enhance their resilience based on localized innovation through technology transfer, financial support, and experience sharing, ultimately building a more equitable and collaborative global energy resilience network.

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References

[1] China National Petroleum Corporation Economic and Technical Research Institute (2022) Global Energy Security Report (2022). Year of Crisis under Geopolitical Change. 2, 40-46.
[2] Holling, C.S. (1973) Resilience and Stability of Ecological Systems. Annual Review of Ecology and Systematics, 4, 1-23.
[3] Panteli, M., Mancarella, P., Trakas, D.N., Kyriakides, E. and Hatziargyriou, N.D. (2017) Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems. IEEE Transactions on Power Systems, 32, 4752-4763.
[4] Jesse, B.-J., Kramer, G.J. and Koning, V. (2024) Characterization of Necessary Elements for a Definition of Resilience for the Energy System. Energy, Sustainability and Society, 14, 46.
[5] ARUP (2023) Future-proofing Energy Systems: The Energy Resilience Framework. International Outlook. 6, 41-46.
[6] Zhang, X.T. and Xu, Z.H. (2020) Geopolitical Risks and Responses of Major Overseas Projects under the "Belt and Road Initiative" — Conceptual and Theoretical Construction. International Outlook, 12, 80-96.
[7] Li, Z., Shi, Q. and Bu, L. (2021) Are Geopolitical Risks Influencing Factors of International Crude Oil Price Fluctuations?: An Analysis Based on the GARCH-MIDAS Model. World Economy Studies, 11, 18-32.
[8] Caldara, D. and Iacoviello, M. (2022) Measuring Geopolitical Risk. American Economic Review, 112, 1194-1225.
[9] Pan, J.H., Dong, X.C., Cui, H.J., Ding, C. and Yan, B. (2023) The European Energy Crisis and Its Impact Analysis. International Economic Review, 1, 9-37.
[10] Chen, X., Li, X. and He, M. (2022) EU's Active Transition to Renewable Energy. Ecological Economy, 38, 2-4.
[11] Ministry of Economy, Trade and Industry, Japan (2023) Basic Hydrogen Strategy. Council for Renewable Energy and Hydrogen-related Ministers Report, 3, 2-4.
[12] FluxFair (2023) Harnessing Renewable Potential: Building Disaster Resilience in Developing Economies, 38, 21-24.