Analysing the meaning of energy resilience

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Abstract

This report examines the meaning of energy resilience and the ways it is conceptualised across the energy-systems literature. Energy resilience is broadly defined as the capacity of an energy system to maintain acceptable service despite natural, technical, economic, or social disruptions. Drawing on multiple frameworks, the report highlights four core resilience characteristics, anticipation, absorption, adaptation, and recovery, and explains how they shape system behaviour before, during, and after disruptive events. The analysis reviews key perspectives on resilience, its evolution, and its relationship to vulnerability, energy security, and sustainability. It also synthesizes findings from bibliometric studies that reveal fragmented definitions and diverse research directions. Together, these insights provide a structured foundation for understanding energy resilience in increasingly complex and integrated energy systems.

Keywords

Energy resilience, energy reliability, energy robustness, energy flexibility, energy vulnerability

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1. Introduction

Resilience is the ability to endure and recover from natural or human-made disruptions. Energy resilience is the capacity of an energy system to keep delivering acceptable service despite climatic, economic, technological, or social shocks. When resilience declines, vital energy services may be lost, and the system can shift into unstable or fundamentally different configurations (Afgan, 2010). Resilience comes from adaptive monitoring, not more rules. A resilient system stays in control by understanding past, present, and future conditions and by responding with adequate resources. Without foresight, systems become reactive, lose time, and fall behind events. Resilience depends on dynamic knowledge, the ability to anticipate the unexpected, and sufficient competence and resources. Continuous learning strengthens these capacities. Collapse occurs when systems fail to anticipate, notice, or act on problems; resilient systems do the opposite. Resilience engineering therefore focuses on building the ability to anticipate, perceive, and respond, using adaptive approaches rather than static or oversimplified models.

2. Energy Resilience

2.1 Defining Energy Resilience (Ahmadi et al., 2021 and Schmitz et al., 2025)

Ahmadi et al. (2021) emphasize that damage to energy systems from natural or human-made disruptions, along with their links to socio-economic systems, makes understanding energy system resilience essential. Energy systems span both supply and demand and operate across multiple levels, including resources (such as oil, gas, coal, nuclear, solar, wind, biomass, and hydro), conversion processes, transportation, storage, distribution, and end-use consumption.

Schmitz et al. (2025) argue that despite its widespread use, resilience has no single universal definition, as its meaning varies across disciplines and contexts. It is widely viewed as a multidimensional concept, spanning areas such as energy imports, supply chains, energy communities, and critical infrastructures. Broadly, resilience can be understood as the ability of a system to remain viable by reducing vulnerability and increasing adaptive capacity before, during, or after disruptive events.

Energy system resilience is similarly defined as the system’s ability to withstand and recover from shocks across technical, economic, social, environmental, and institutional dimensions.

2.2.1 Evolution of the term Resilience (Monie et al., 2025)

Figure *1* shows how the term resilience has developed in time.

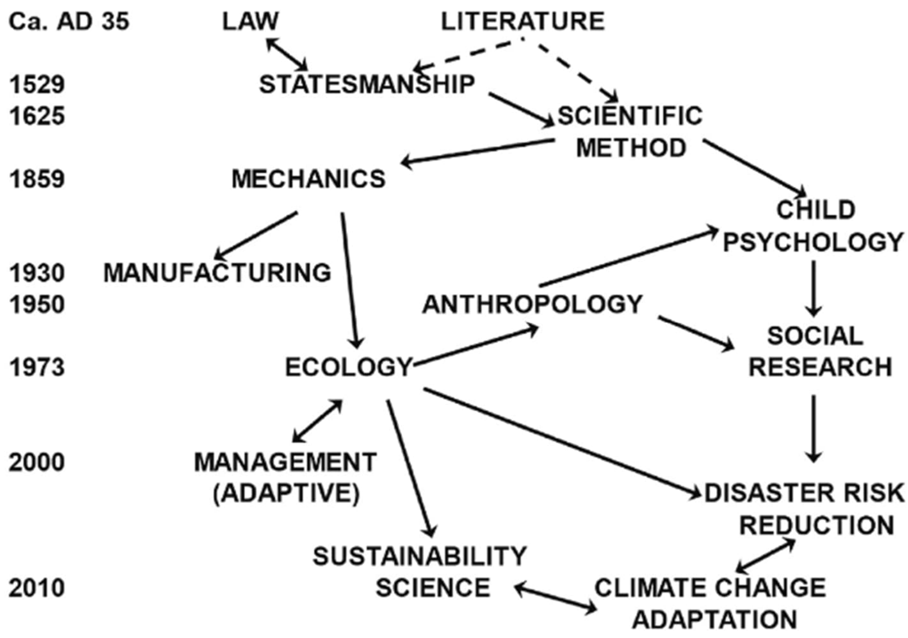

Figure 1. Evolution of the term resilience (Monie et al., 2025)

Monie et al. (2025) assert that energy system resilience today is examined through the lens of specific threat types, such as extreme weather, technical failures, cyberattacks, or geopolitical disruptions, or within the boundaries of a particular energy sector, including electricity, oil, or gas. As a result, resilience remains a highly context-dependent concept, which limits the extent to which it can be generalized.

2.2.2 Bibliometric analysis of energy resilience (Janta et al., 2025)

Janta et al. (2025) carried out a bibliometric analysis of energy resilience. They used bibliometric analysis of Scopus data (search: *energy OR power W/2 resilien***) to map the energy-resilience research landscape. Using Word Growth, Trend Topics, Co-occurrence, and Co-citation tools, they identified key themes, including power grids, climate- and disaster-related resilience, reliability, and energy efficiency. Trending topics included microgrids, power-system resilience, renewables, and critical infrastructure. Four topic clusters emerged, overarching themes, disruption-related resilience, normal-operation resilience, and enabling technologies, each informing a corresponding definition of energy resilience. Global frameworks like the Paris

Agreement[1], COP26[2], and the Sendai Framework[3] emphasize strengthening resilience across communities, infrastructure, and public health. Energy systems are increasingly vulnerable to climate-driven disruptions, as seen in major blackout events, and even renewable integration can heighten risks. Although energy resilience is widely discussed, its definitions vary, making research directions unclear. In the power sector, it can refer to reliable microgrids, emergency performance, or links to energy efficiency. Without a shared understanding, efforts to improve energy resilience risk becoming fragmented rather than aligned with policy goals. Several studies have tried to define energy resilience, linking it to abilities, such as planning, absorbing, recovering, and adapting, and to dimensions like awareness, availability, affordability, and acceptability. Other work connects resilience to diversity, redundancy, efficiency, or system states before and after disruption. Despite overlaps, definitions still differ, leading to inconsistent research directions.

2.2.3 Viewpoints regarding energy resilience

Dabbous et al. (2025) highlight that energy resilience is increasingly important for global development and aligns with the United Nation (UN) sustainable development goals (SDGs). They assert that diverse studies propose various ways to measure it, but economic and social dimensions remain underexplored. Existing research offers different indicators and models, from household-level solar solutions to national and multi-regional assessments, often focusing on renewable energy, access, and efficiency. However, the concepts of resilience, vulnerability, and sustainability are still not clearly distinguished. Following recent work, the study of Dabbous et al. (2025) treats energy resilience as a multidimensional index built on three pillars: renewable energy, energy access, and energy efficiency.

Dong et al. (2021) emphasise that research on energy resilience has expanded rapidly, but measuring it effectively remains a challenge. Existing studies propose frameworks, indicators, and models, that usually focus on energy access, renewables, and efficiency. These are varying from urban-scale assessments to micro-level and multi-regional analyses. However, most work overlooks comprehensive economic evaluation and the broader socioeconomic impacts of energy resilience, leaving these areas underexplored.

Gatto and Drago (2020) assert that resilience began as a system's ability to "bounce back," but modern thinking sees it as "bouncing forward" meaning improving through learning and adaptation. Today it's viewed as the capacity to enhance performance amid continuous, sustainable change across social, economic, and ecological systems, aligning well with modern energy policy. Resilience is broad and policy-dependent. It appears across many SDGs, from social and climate resilience to resilient infrastructure, cities, and ecosystems.

[1] https://unfccc.int/process-and-meetings/the-paris-agreement C
[2] https://www.un.org/en/climatechange/cop26
[3] https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

Jasiūnas et al. (2021) highlight that resilience is the ability of energy systems to withstand and quickly recover from major disruptions. Their review outlines key resilience terminology and maps a wide range of threats. Energy system resilience and energy security clearly overlap, but the boundary between them is blurry. Related concepts include reliability, robustness, risk, stability, vulnerability, flexibility, agility, survivability, and fault tolerance. Erker et al. (2017) highlight that despite extensive research, resilience still lacks a unified definition. Originating from fields like ecology, physics, and psychology, the concept now spans environmental, social, and economic systems. According to them, energy resilience is the ability to withstand energy disruptions while maintaining affordable energy services. A resilient system can quickly recover and adapt after a crisis. Resilience appears in three forms:

1. ***Resistance:*** absorbing disturbances while protecting key functions.
2. ***Recovery:*** restoring stability after a main disruption without major structural change.
3. ***Adaptation or transformation***: learning from crises and reorganizing systems, from small adjustments to full structural shifts.

2.2.4 Resilience and vulnerability (Erker et al., 2017)

Erker et al. (2017) address key questions about which functions are most vulnerable, what should be protected, and how to evaluate resilience. They identify types of energy crises, essential resources, and framework conditions, and introduce a new method for assessing community-level resilience during fossil-fuel crises they call the Regional Energy Resilience Assessment (RERA).

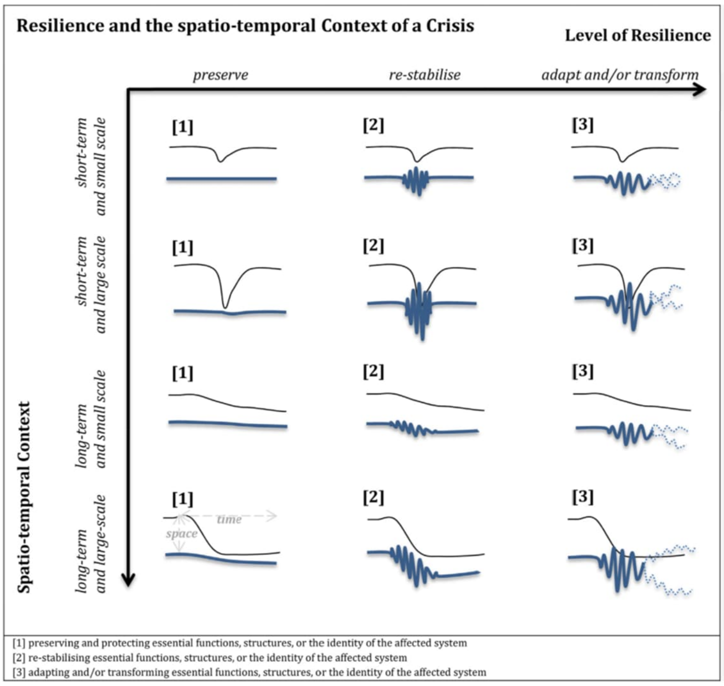

Figure 2 . Conceptualized resilience levels in the spatio-temporal context of a crisis (Erker et al., 2017)

Resilience depends on the timing and scale of a crisis as shown in Figure 2. Long-lasting disruptions allow deeper system changes, while short shocks limit how much a system can adapt. Small-scale events affect only parts of the system, whereas large-scale disruptions, like nuclear accidents or grid failures, can reshape entire energy networks. How a system responds depends on prior decisions and the willingness to change.

Resilience is closely linked to vulnerability (susceptibility before a shock) and adaptive capacity (ability to adjust during or after a shock) as shown in Figure 3. Highly resilient systems are those that are less vulnerable and more adaptive, though improving one part of a system can unintentionally increase risks elsewhere. Because of these trade-offs, the appropriate resilience strategy must be chosen case by case.

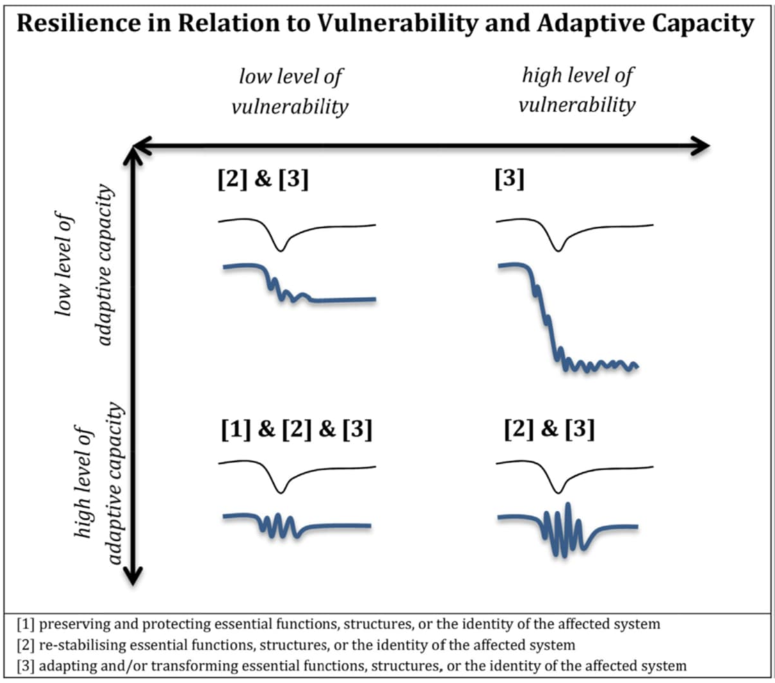

Figure 3. Resilience in relation to vulnerability and adaptive capacity (Erker et al., 2017).

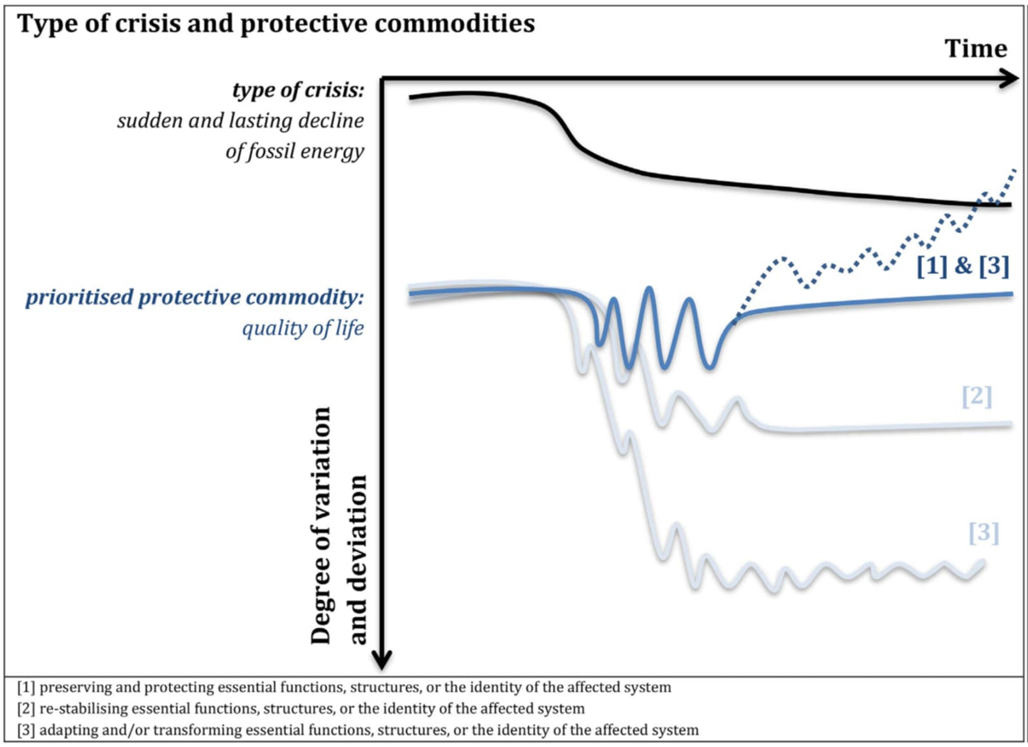

Figure 4. Type of energy crisis in relation to the protective commodities (Erker et al., 2017).

Schmitz et al. (2025) consider that it is useful to distinguish between shock events and slow-burn processes (SBPs) when assessing threats to energy security and resilience. Table 1 shows an overview of different classification criteria of shock and SBPs.

Table 1. Overview of different classification criteria of chock events and SBPs (Schmitz et al., 2025)

Criterion	Shock events	Slow burn processes (SBPs)
Temporal dynamic	Sudden onset, may have short- or long-term effects	Gradual onset, unfolding over extended periods
Probability of occurrence	Varies depending on the event and context	Varies depending on the process and context
Impact profile	Typically abrupt with immediate effects, can have lasting consequences	Progressive in nature, may escalate if unaddressed
Predictability / Early warning	Often difficult to anticipate, limited early warning	Generally observable, early indicators may appear
Implications for energy security	Requires rapid adaptation of infrastructure, supply chains, and governance systems	Requires continuous adaptation of infrastructure, supply chains, and governance systems
Requirements for resilience strategies	Needs absorptive, adaptive, and potentially transformative capacities (depending on magnitude and context)	Needs absorptive, adaptive, and potentially transformative capacities (depending on magnitude and context)

According to Schmitz et al. (2025), Figure 5 shows the interrelations between definitions for terms relevant to energy security and resilience in energy systems and their transformation.

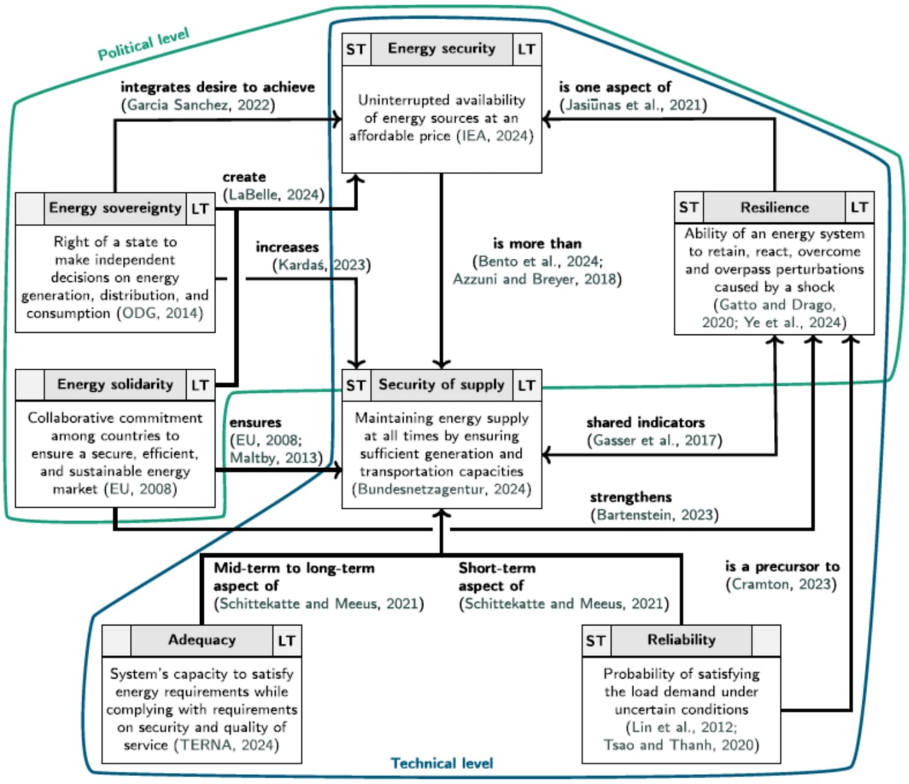

Figure 5. Interrelations between definitions for terms relevant to energy security and resilience in energy systems and their transformation (Schmitz et al., 2025)

In Figure 5 the white text boxes show definitions found in literature. The labels "ST" means short-term and "LT" long-term context. The interrelations between terms are shown by arrows. Strengthening energy system resilience naturally supports both energy security and security of supply.

2.5 Key resilience characteristics

Resilience traits differ across studies, and no single quantitative model or agreed-upon metrics exist (Ahmadi et al., 2021). Prior work highlights four core characteristics, namely anticipation, absorption, adaptation, and recovery and form the basis for defining quantitative resilience indicators.

For energy systems, these translate into:

- ***Anticipation***: means learning, adapting, taking preventive action, resisting impacts, and supporting recovery. Anticipation is a key aspect of energy system resilience. Unanticipated or emerging system behaviours can trigger cascading failures, so predicting and preparing for disruptions strengthens robustness and adaptability.

- ***Absorption:*** is a key resilience trait. It reflects an energy system's ability to withstand disruptive events, limit their impact, and keep critical functions operating. A system with strong absorptive capacity can endure disturbances, isolate their effects, and minimize consequences with minimal effort.
- ***Adaptation:*** adapting when conditions change. Adaptive capacity is the system's ability to reorganize during a disruption, adjust to new conditions, and restore performance without full recovery actions. It involves learning from the event, updating procedures, reconfiguring the system, and training personnel. Strong adaptive capacity allows the energy system to quickly adjust its structure and operations to changing demands.
- ***Recovery:*** restoring function afterward. Recovery is the system's ability to restore damaged functions after a disruption. It involves repairing components, returning performance to normal levels, and re-establishing services in a timely way to limit losses and prevent further problems. A resilient energy system can return to a stable operating state once a disruption has occurred.

Figure 6 depicts the main characteristics of energy resilience.

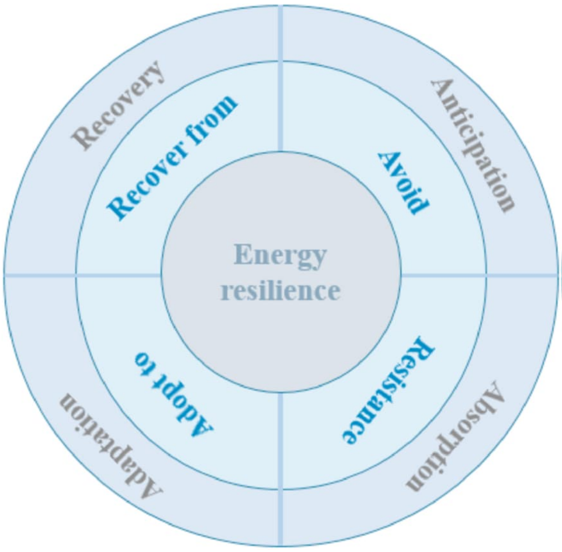

Figure 6. Main characteristics of energy resilience (Ahmadi et al., 2021).

2.6 Relationship between characters and states of energy system resilience

Figure 7 shows how an energy system's performance changes over time when a disruption occurs. Under normal conditions, performance rises as demand grows. When a disruptive event hits, performance drops, then gradually recovers as functions are restored and the system returns to its pre-event level.

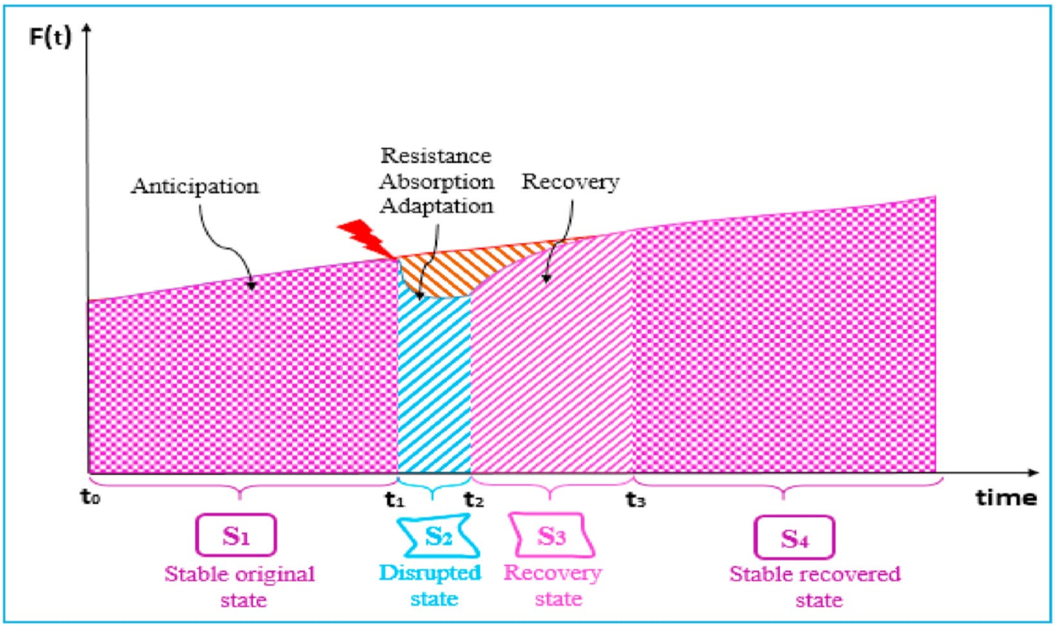

Figure 7. The relationship between the characters of energy system resilience and the states of energy system resilience (Ahmadi et al., 2021).

State 1 is the system's normal, stable operating condition. In this phase, anticipating potential disruptions allows preventive actions, such as adding backup units, designing alternatives, and monitoring system status. Using historical data and information and communication technologies (ICTs) also helps predict damage and strengthen resilience before a disruption occurs.

State 2. The disrupted state begins when a disruptive event reduces system performance. In this phase, resilience depends on how well the system resists and absorbs the impact, how much damage spreads through critical components, and how effectively it can adapt to slow further degradation. Identifying vulnerable components and deploying adaptive technologies on both the supply and demand sides are key actions for stabilizing the system quickly.

State 3. The recovery state is the period when the system moves from damage back to stability. In this phase, the system repairs components, restores performance, and returns services to normal. Recovery depends on how much performance was lost and how long it takes to regain equilibrium, which in turn relies on available restoration resources. Actions such as re-energizing lines, repairing equipment, restarting units, and restoring load occur here.

State 4. The recovered state begins once restoration is complete. If the system was performing well before the disruption, it returns to that level; if not, its recovered performance may differ. This phase serves as a long-term prevention stage, where the disruption is analysed and weaknesses identified to improve resilience for future events.

Conclusion

Energy resilience is a multifaceted concept shaped by system structure, threat types, and evolving social and environmental conditions. The literature shows that resilience cannot be captured by a single definition; instead, it reflects a system's ability to anticipate, absorb, adapt, and recover from disruptions. Integrated energy systems, climate-driven hazards, and growing cyber risks increase the need for flexible, cross-sector approaches. Although existing frameworks and models offer valuable insights, they remain fragmented and highlight the need for clearer distinctions between resilience, vulnerability, and energy security. Strengthening energy resilience will require continuous learning, adaptable governance, and analytical tools capable of capturing dynamic interactions across modern energy systems.

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