

# THE RESILIENT POWER GRID

A ROADMAP TO ANTICIPATING AND  
ADDRESSING THREATS



GE VERNOVA



# EXECUTIVE SUMMARY

Extreme weather events, cybersecurity threats, rapid electricity demand growth, aging infrastructure, and rising inverter-based renewables penetration create unprecedented stress on global power systems. Power grid resilience has become a key challenge of the 21st century. It is critical for energy security, economic competitiveness, and a successful energy transition.

These pressures are no longer isolated risks; they are systemic and increasingly interconnected. Climate shocks are intensifying in frequency and severity. Cyber threats now intersect directly with national security. Renewables integration and Electrification are accelerating supply and demand volatility and operational complexity. Together, these forces are reshaping how resilience must be understood and delivered.

Resilience transcends metrics such as redundancy, availability, stability, and reliability, encompassing a system's ability to withstand shocks and recover quickly across time, geography, and interdependent systems. This requires context-specific strategies and innovative technologies that anticipate, adapt, and respond dynamically.

This whitepaper highlights six resilience action measures: anticipate, prepare, absorb, sustain, recover, and adapt. It draws lessons from Ukraine's cyber-attacks, Mexico's recovery from hurricane Otis, Vietnam's demand surge, and Saudi Arabia's renewables integration.

A roadmap for action is provided. It includes six strategic pillars for resilient power grid design comprised of: 1) integrated system planning,

2) strategic sourcing and supply chain resiliency, 3) interconnection development and enhancement, 4) digital intelligence and automation, 5) hybrid solution optimization, and 6) human-system interaction, along with a phased implementation framework.

GE Vernova has more than 125 years of experience integrating hardware, digital platforms, and system planning, helping grid operators and system planners to identify and dissect issues, and address them. But technology alone is not enough—resilience must be investable, supported by market design and policies that value inertia, frequency response, and voltage support in addition to historical metrics. A holistic approach is crucial to ensure that resilience investments are both immediate and sustainable, bridging technical innovation, regulatory frameworks, and capital allocation.

The takeaway is clear: failure to innovate, plan, and invest today may result in higher future costs for grid operators, and ultimately for consumers. Resilience is not just a goal, it is a system-wide, cross-disciplinary imperative. It requires both immediate action and long-term structural transformation. When strategy, technology, policy, and financing converge, we don't just protect power systems, we make them smarter, safer, and truly future-ready.



**Grid resilience is non-negotiable. You can't run a 21st-century economy on 20th-century infrastructure."**

**- Scott Strazik**  
Chief Executive Officer  
and President, GE Vernova



# 1. GRID RESILIENCE AS A STRATEGIC PRIORITY

Global power systems are facing unprecedented challenges. These include extreme weather events and cybersecurity threats to soaring electricity demand and renewable energy prominence. Metrics such as redundancy, stability, availability, and reliability are no longer sufficient on their own to guarantee a continuous supply of electricity to end users. Power grids have become much more complex, and interdependent at the same time as they have aged. The way power grids are contemplated, planned, prioritized, and invested in must change. Power grid resilience has emerged as the overarching concept uniting these elements into a critical global priority.

Simply put, grid resilience has been described as a power system's ability to "bounce back" from disruptions, but it entails much more than a simple response to an event. Modern power systems are complex "systems of systems" that span fuel supply, generation, transmission and distribution networks, and end users across multiple owners and jurisdictions. Their growing interdependence means that localized disruptions can rapidly propagate across regions and sectors. Building resilience therefore requires robust technical solutions underpinned with supportive economic and regulatory frameworks. Without it, disruptions can cascade into blackouts, safety risks, and economic losses, threatening energy and national security. This makes a holistic approach to grid resilience urgent.

The energy transition is reshaping global energy systems like never before as we enter the era of electrification. Electricity demand is set to rise 86% by 2050 compared to

2024 according to the International Energy Agency's Stated Policies scenario. This tremendous growth is expected to occur while rapid renewables deployment, digitalization, and grid interconnections including at the generation, transmission, distribution, and demand levels, transform operations. As electrification accelerates and inverter-based resources expand, resilient grid infrastructure becomes not optional, but foundational to maintaining system stability and economic competitiveness. These power system shifts coincide with rising cyber and physical threats, supply chain challenges, as well as increasing political and economic volatility. Resilient grid infrastructure is increasingly recognized for its strategic value in national and regional security contexts, complementing its operational and economic importance.

Operating conditions are evolving rapidly due to technological change, new load profiles, policy shifts, and environmental factors. As a result, grid operators face increasingly complex challenges that are difficult to predict using historical assumptions. Continuous innovation, including advanced monitoring, edge computing, and distributed controls, is essential to anticipate and respond effectively, supporting resilience across transmission and distribution networks. These capabilities are no longer enhancements; they are core requirements for operating increasingly dynamic and decentralized systems.



In addition to these challenges, supply chain strengthening is critical to improving resilience. This calls for the development of long-term strategic partnerships, similar to those used in the defense sector, that extend beyond equipment and technology supply to include joint innovation, governance frameworks, and sustainable financing mechanisms. By elevating supply chains from transactional procurement functions to strategic enablers of grid security and long-term system reliability, these partnerships help build robust, resilient ecosystems capable of withstanding disruptions while supporting the evolving needs of modern power systems.

It is important to recognize that a one-size-fits-all approach is not appropriate for future grid development. The optimal type of electricity system is likely to depend on factors such as the condition of existing infrastructure, projected demand growth, and government priorities regarding generation technologies. Considering the current geopolitical landscape, maintaining flexibility and exploring multiple approaches could help ensure solutions are relevant across regions. Flexibility and the exploration of multiple pathways are therefore strategic necessities in an increasingly uncertain geopolitical and economic environment. This nuanced perspective supports the design of tailored strategies that address local challenges and opportunities, contributing to more resilient and sustainable power systems worldwide.

Meeting this challenge requires ecosystem-wide innovation. Centralized, predictable grids must evolve into intelligent, adaptive networks integrating distributed resources while incorporating new large-scale loads including data centers and AI facilities, operating autonomously, and responding in real-time to emerging threats.

**Power grid resilience is no longer limited to recovery after an event. Resilience now requires the ability to anticipate, prepare, absorb, sustain, recover, and adapt, so that critical systems operate under all conditions. This demands stronger interconnections, more integrated systems, robust protection, pre-deployment of critical equipment, hardening of systems and equipment, and effective safeguards. As the world becomes less resilient, grids must become more resilient.**

As resilience becomes a defining requirement of modern power systems, GE Vernova seeks to move it beyond ambition and into implementation. Resilience must run through the very core of electrical power systems, shaping planning, design, operations, and investment to deliver reliable, affordable, and sustainable electricity. In an era defined by electrification, digitalization, and geopolitical uncertainty, resilient grids are not only operational assets: they are strategic national infrastructure.

## 2. WHAT RESILIENCE REALLY MEANS FOR POWER SYSTEMS

In today's electrical power systems, resilience has emerged as a defining system attribute, not just a technical add-on. It encompasses and transcends concepts such as redundancy, stability, availability, and reliability by focusing on power system behaviors under stress and recovery over time. Understanding resilience means reframing traditional concepts within a system-wide perspective.

### 2.1 Redundancy

Redundancy is the deliberate inclusion of backup elements in a power system to maintain functionality and protect the system when primary components fail. This may involve additional generators, parallel transmission and distribution lines, or duplicate control systems, all designed to take over seamlessly and prevent service interruptions.

Redundant systems provide essential protection by offering alternative pathways for electricity delivery and operation, enhancing reliability, stability, and availability. Redundant generation is particularly crucial for critical infrastructure such as hospitals, data centers, and communication networks, ensuring continuity of service even under adverse conditions or during maintenance.

However, modern power systems are increasingly exposed to correlated and cascading events that exceed the protection offered by traditional reliability standards designed for single-component failures. Addressing these risks requires deploying AI, digital tools, and advanced grid technologies, including Flexible AC Transmission Systems

(FACTS) and Grid Enhancement Technologies (GETs), to enhance system visibility, anticipation, and response capabilities and strengthen overall resilience and stability.

### 2.2 Stability

Stability refers to a power system's ability, for a given initial operating condition, to maintain or quickly regain operating equilibrium after a disturbance. This includes keeping frequency, the heartbeat of the grid, voltage, and power flows within safe limits, as even small deviations can ripple into widespread instability. Inertia, traditionally provided by spinning turbines and generators that can operate regardless of the weather, acts as the first responder, resisting sudden shifts in frequency and giving control systems time to act. Voltage support ensures safe operation of sensitive equipment.

Historically, large synchronous generators, i.e., gas, coal, hydro, or nuclear, have underpinned stability, providing inertia, voltage, and frequency control. As grids integrate more inverter-based resources that can be weather dependent, such as wind turbines, solar panels, and battery storage, stability mechanisms may be reduced or altered. Achieving a more resilient grid will likely require scaling the use of grid-forming inverters for these resources, enabling them to actively support frequency, voltage, and overall network stability. New strategies are therefore needed to keep the system stable under increasingly dynamic and complex conditions.



## 2.3 Availability

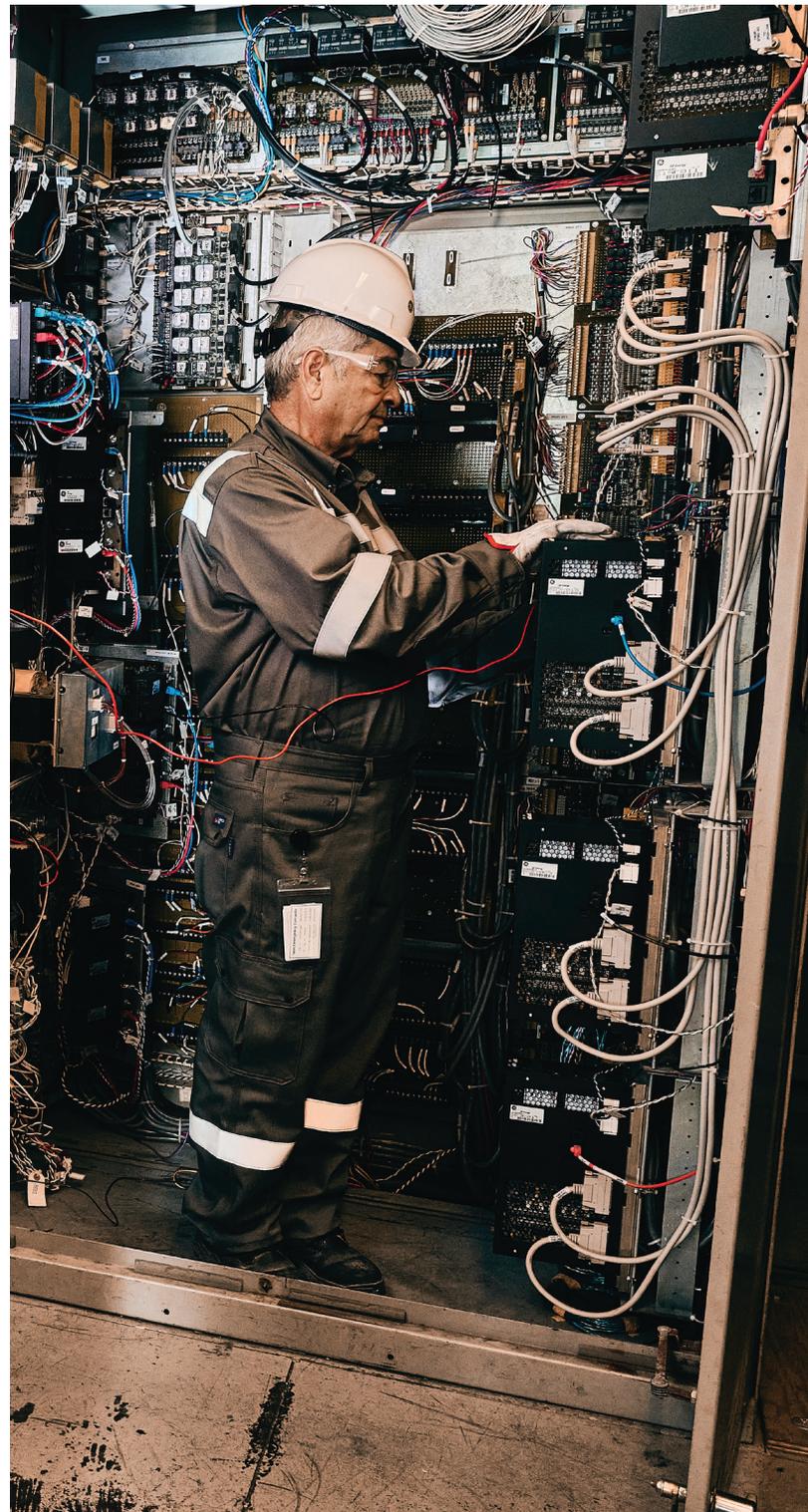
Availability refers to the proportion of time a power generation system asset or component is ready to perform its function. It accounts for planned maintenance, unplanned outages, and repair times. Even perfectly functioning assets only contribute to readiness if Transmission System Operators (TSOs) and Distribution System Operators (DSOs) can dispatch and integrate them efficiently, ensuring seamless supply across all levels. Beyond individual asset performance, higher availability also supports system-wide resource adequacy by increasing the effective supply capacity available to meet demand.

Achieving high availability requires robust equipment, proactive maintenance, spare parts management, and rapid restoration. Unlike reliability, which measures service delivery, availability focuses on the operational readiness of assets themselves. High availability is critical for essential services, ensuring generation, transmission, and distribution systems can meet demand whenever required.

## 2.4 Reliability

Reliability refers to a power system's ability to deliver an adequate, secure, and stable flow of electricity whenever consumers need it. Simply put, when a user flips the light switch, the power is there. It encompasses elements of stability, redundancy, and availability, but also means that the system remains functional during unanticipated, but common, disturbances, such as the loss of a generation unit or the failure of a network component. When disruptions occur, the grid must be able to isolate the problem and maintain service. Other systemic factors, such as grid congestion, transmission constraints, or operational bottlenecks, can also impact reliability and must be managed to ensure continuous service.

Reliability is measured through indicators like outage frequency, duration, and severity. Protection schemes, backup generation, and operational procedures all help maintain continuous service. Reliable power is essential not just for daily life but also for critical infrastructure such as hospitals, transport networks, and communications, where interruptions can have serious societal and economic impacts. As a cornerstone of the energy trilemma, alongside affordability and sustainability, reliability is fundamental to building resilient energy systems.

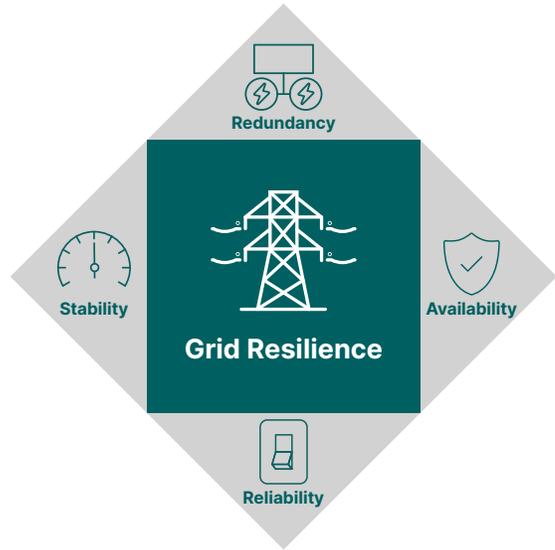


## 2.5 Resilience

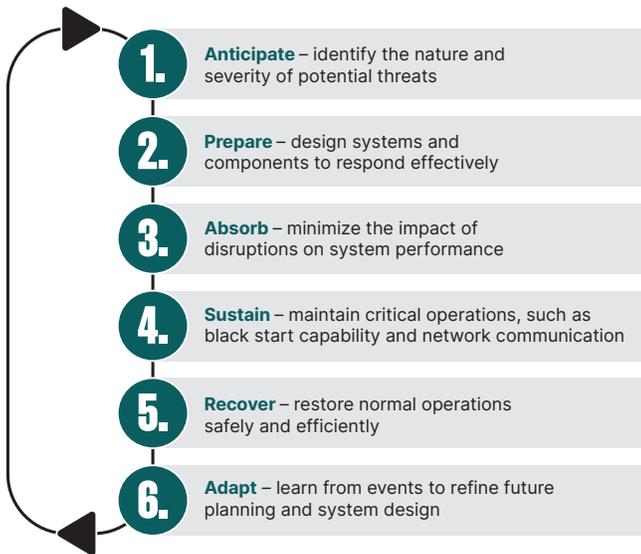
The Pacific Northwest National Laboratory defines power grid resilience as the ability of the electricity system to prepare for and adapt to changing conditions, and to withstand and recover rapidly from disruptions.

Resilience has both temporal and spatial dimensions, covering system performance before, during, and after disruptive events, and across widely distributed infrastructure that may span multiple jurisdictions. It is inherently threat-driven, as vulnerabilities vary with geographic location, system design, and the criticality of demand, from hospitals and data centers to telecommunications networks.

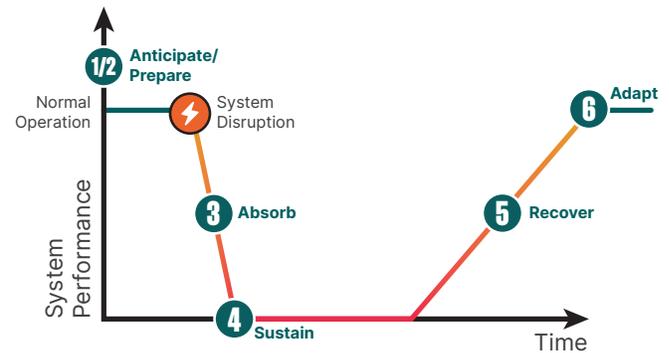
For this paper, we will consider power grid resilience design to consist of a set of actionable measures that, if successfully addressed, will improve system resilience. These are often illustrated using a “Resilience Trapezoid”, which shows how system performance evolves during disruptions:



**Figure 1:** Taken together, redundancy, stability, availability, and reliability form the technical foundation of power systems, but resilience goes further. It emerges from how these attributes interact under stress, across time, and at system scale.



These six steps form a continuous, iterative cycle where lessons feed back into the anticipate and prepare steps, informing design and investment decisions. This enables systems to evolve, adapt to threats, and become progressively more resilient.



**Figure 2:** The Resilience Trapezoid Showing Total System Failure

**Grid resilience assessment is not a one-time task but an ongoing process that must adapt to evolving threats and technological advancements.**

# 3. GLOBAL PRESSURES, LOCAL STRESS: WHAT'S THREATENING OUR GRIDS?

Power grids worldwide face growing pressures from extreme weather, cybersecurity threats, rising electricity demand, and the rapid expansion of inverter-based renewable energy, with aging infrastructure that often exceeds its original design life. With society and industry increasingly reliant on electricity, resilience is no longer optional. It is central to national energy security and is often considered a country's second line of defense. Resilience ultimately depends on how specific grid assets perform under stress. In practice, grid failures are often triggered by the loss of critical components, such as large power transformers, substations, feeders, interconnectors, or control rooms, whose failure can cascade across wide areas and create disproportionate impacts. Across regions, power transformers repeatedly emerge as a critical vulnerability, given their long lead times, limited manufacturing capacity, and lack of readily available spares.

At the same time, resilience challenges are increasingly emerging at the distribution level. Many disruptions now originate in low- and medium-voltage (LV and MV) networks, where electric vehicles (EVs), heat pumps, rooftop PV, batteries, and data centers connect, often with limited real-time visibility. Enhancing observability through smart meters, sensors, and digital twins allows operators to monitor conditions, predict failures, and test resilience strategies. Automation, including automated switches and fault isolation devices, can shorten response times and mitigate cascading impacts. Integrating these technologies ensures the distribution grid can accommodate growing numbers of Distributed Energy Resources (DERs) and large, unpredictable loads while maintaining reliability. Meeting these emerging demands will require targeted technology deployment and investment, which may also influence overall system costs. The examples that follow show how grids can be strengthened against these threats.



## 3.1 Extreme Weather Events: Hurricane Otis, Mexico (October 2023)

In October 2023, Hurricane Otis devastated the Mexican State of Guerrero, specifically the city of Acapulco on Mexico's west coast. In less than 12 hours, it intensified from Category 1 to Category 5, with winds exceeding 270 km/h, becoming the strongest hurricane on record for this part of Mexico. The storm caused 52 fatalities, 32 missing people, and extensive infrastructure damage: more than 270,000 homes, 600 hotels and condominiums, and 120 hospitals and clinics were affected.

The electricity network suffered severe losses, including damage to 39 high-voltage transmission lines, 155 medium-voltage circuits, 1,195 transformers, 13,525 transmission poles, and 7,007 medium- and low-voltage spans. More than half a million people in the Acapulco area were left without power. Total damages were valued in the \$12–16 billion range, making it one of Mexico's costliest disasters. This extensive damage illustrates how the failure of critical components can significantly slow restoration and amplify socio-economic impacts following extreme weather events.

The national utility, Comisión Federal de Electricidad (CFE), implemented rapid provisional repairs to restore essential services within 10 days, completing full reconstruction in under five months. Following this crisis, the Mexican government announced an \$8.2 billion investment plan to modernize and expand the national transmission grid, emphasizing the need for infrastructure capable of withstanding extreme weather events. This case underscores how climate-induced disasters can expose grid vulnerabilities and drive long-term resilience investments.



### 3.2 Cybersecurity and Physical Threats in Conflict Zones: Ukraine (ongoing)

On February 24, 2022, Russian troops invaded Ukraine. Historically tied to Russia, Ukraine's power grid quickly faced attacks on generation and transmission assets, particularly ahead of the 2022/2023 winter, when heating outages threatened civilians. Beginning as early as 2015, Russian Intelligence (GRU) had conducted cyberattacks targeting grid assets and disrupting regional power distribution. Although approximately 225,000 people were impacted, the outages were relatively brief and lasted only a few hours. By 2022, Russian cyberattacks were quickly neutralized due to Ukrainian preparedness and their approach of "vigilant cyber hygiene", i.e., maintaining and sanitizing internal cyber networks.

The conflict demonstrated that cyber risk is only one dimension of power system security, as physical attacks on visible and accessible grid assets produced far more severe and lasting impacts. Before the war, Ukraine relied on large, centralized stations with about 37 GW of available capacity. By mid-2024, nearly all thermal plants and most hydroelectric capacity had been damaged. Between March and July 2024, 9.2 GW, almost half of the remaining available capacity, was lost, causing widespread rolling blackouts. This concentration of capacity in a limited number of assets created critical choke points, whose destruction had disproportionate system-wide consequences.

The country continues to face challenges to its power sector. The winter of 2025/26 is one of the coldest on record, and Russian drone and missile attacks continue, with hundreds of thousands of Ukrainian people left without heat or light. As the country rebuilds, DERs, including small gas turbines, reciprocating engines, solar photovoltaic (PV), and battery storage, have become critical. Their speed, modularity, and scalability make them well suited to rapidly

changing conditions. The IEA's 2024 study of Ukraine's power system highlights that decentralization, including interconnections to neighboring countries, is essential for resilience, addressing immediate winter deficits while laying the groundwork for a modern, adaptable grid. In any case, Ukraine's experience demonstrates that grid resilience is inseparable from national security: power infrastructure itself became a target of war, showing how energy security now directly intersects with defense, and why risk-based protection of critical assets must complement cyber resilience efforts.

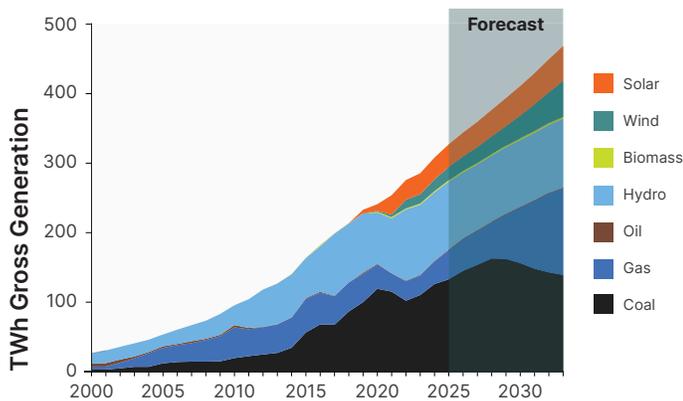


### 3.3 Rising Electricity Demand Growth: Vietnam's Energy Transition

Since the year 2000, Vietnam's electricity demand increased tenfold, with coal power now providing nearly 40% of generation, supplanting hydropower to keep pace with rapidly rising demand.

Vietnam's Power Development Plan VIII (PDP8), adopted in May 2023 and revised in April 2025, projects 10–12% annual electricity demand growth through 2030. The updated plan sharply raises renewable targets, primarily focusing on onshore and near-shore wind, expands battery storage goals, and reintroduces 4–6 GW of nuclear capacity by 2035. It also sets tighter greenhouse gas emissions targets aligned with a net-zero vision by 2050, reinforcing the country's commitment to sustainable growth and energy security given that 45% of their energy is imported.

To enhance grid resilience, Vietnam plans high-voltage transmission lines and substation upgrades (500 kV and 220 kV), mandatory battery storage for centralized solar, smart grid technologies such as high-voltage direct current (HVDC) transmission lines, Static VAR Compensators (SVC), Static VAR Generators (SVG), FACTS, promotion

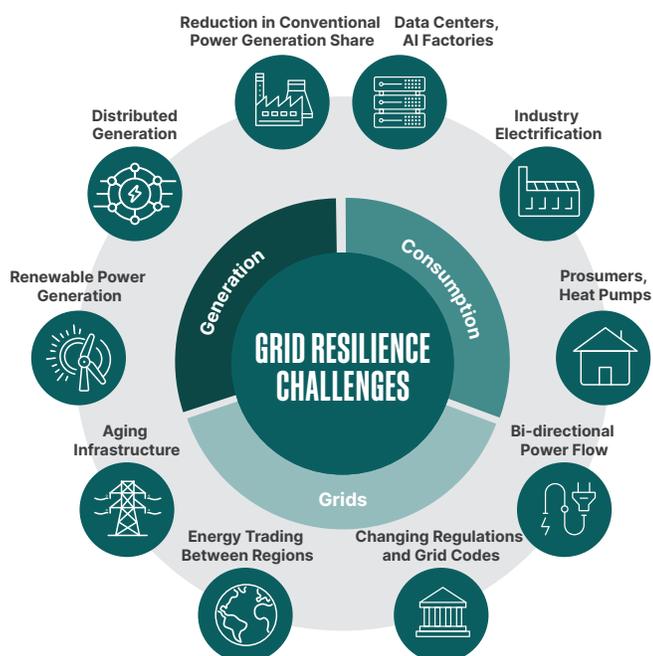


**Figure 3: Vietnam Electricity Generation**  
**Source:** GE Vernova 2025 Global Power Outlook

of distributed generation, and regional interconnections as part of ASEAN integration. Yet, financing remains a major challenge, with \$135 billion needed by 2030 and up to \$523 billion by 2050, requiring stable PPAs, protection against Vietnamese currency (VND) volatility, and cost-reflective transmission tariffs to attract private investment.

Beyond infrastructure, the revised PDP8 emphasizes a sustainable, diversified, and market-oriented power sector, setting tighter environmental targets while de-risking the investment environment. Successful implementation will strengthen energy security, enhance resilience, and support continued growth and prosperity.

## A new paradigm for Future Grids



## 3.4 Unprecedented, Rapid Renewables Growth: Saudi Arabia's 2030 Ambition

Under its Vision 2030 program, the Kingdom of Saudi Arabia (KSA) aims to source 50% of its electricity demand from renewables and 50% from natural gas by 2030, replacing the ~50% historically generated from oil. To reach this goal, KSA launched the National Renewable Energy Program (NREP) in 2017, subsequently raising targets from 58 GW to 100–130 GW of solar and wind capacity by 2030. Since the commissioning of the 300 MW Sakaka PV project in 2019 (KSA's first large-scale grid-connected utility solar plant), more than 12 GW of renewable capacity has come online, with over 30 GW currently in the pipeline.

Recognizing the resilience challenges posed by this rapid shift to inverter-based resources, KSA has implemented targeted measures to ensure a safe, stable, and flexible power system.

- **Grid interconnections:** A ±500 kV HVDC link with Egypt, valued at \$1.8 billion and spanning 1,350 km, is under construction and expected to be operational by 2026. Using three converter stations to bridge Egypt's 50 Hz grid and KSA's 60 Hz system, it will enable up to 3 GW of power transfer, supporting inter-regional stability and peak load demand.
- **Battery storage:** More than 12 GW / 48 GWh of storage is expected by 2030, including a 12.5 GWh project, the world's largest. Batteries will act as a real-time buffer between variable renewables and the oil and gas generation fleet, stabilizing the grid, managing peaks, providing fast frequency response, and enabling black-start capability.

- **Synchronous condensers:** As oil- and gas-fired generation is progressively displaced, synchronous condensers provide critical inertia, voltage regulation, and reactive power, strengthening system stability and fault ride-through on the grid under high inverter-based renewables penetration. Recently, the Saudi Electric Company made the decision to stabilize electricity coming from multiple renewables sites across the country with synchronous condensers.
- **Advanced grid software:** KSA is deploying Artificial Intelligence/Machine Learning (AI/ML) analytics, Supervisory Control and Data Acquisition (SCADA) automation, smart metering, protection management, and storage integration to manage demand growth and large-scale renewables. These tools enable anticipatory operation, rapid disturbance isolation, and flexible control for critical loads such as Neom, KSA’s flagship smart city, and emerging AI data centers.

These measures reflect KSA’s recognition that reaching 50% renewables by 2030, and ultimately 100% by 2050, requires parallel transformation of grid architecture, operations, and control. Saudi Arabia’s approach shows that large-scale renewables deployment must be matched by ambitious grid investments and regional cooperation to maintain long-term resilience and energy security.



## Grid Resilience Under Pressure: Strategic Implications from Global Case Studies

Case Study	Primary Pressure	Impact on the Grid	Strategic Response/ Implication	Key Lesson for Grid Leaders
<b>Hurricane Otis – Mexico</b>	Extreme weather events	Severe infrastructure damage, exposing vulnerabilities in transmission networks	Rapid provisional repairs and a \$8.2B grid modernization plan, highlighting the need for climate-resilient infrastructure	Plan proactively for climate extremes; invest in resilient infrastructure before crises occur
<b>Conflict-Related Threats – Ukraine</b>	Cybersecurity and physical attacks	Targeted cyber and physical attacks on grid assets, highlighting the link between resilience and national security	Deployment of DERs and strengthened interconnections to enhance redundancy and flexibility	Treat cyber and physical resilience as integral to national security; diversify resources and interconnections
<b>Energy Transition – Vietnam</b>	Rapid electricity demand growth	Tenfold increase in demand, requiring high-voltage expansion and battery storage integration	Revised PDP VIII with tighter emissions targets and market-oriented reforms	Anticipate demand surges; align planning with both modernization and decarbonization goals
<b>2030 Renewable Ambition – Saudi Arabia</b>	Accelerated renewables deployment	Rapid transformation from large-scale renewables, creating stability and flexibility challenges	Advanced grid software, battery storage, and interconnections to maintain stability	Integrate renewables with planning, technology, and flexibility measures to maintain operational stability

# 4. FROM POLICY INTENT TO POWER GRID RESILIENCE: ALIGNING TECHNOLOGY, POLICY, AND FINANCING

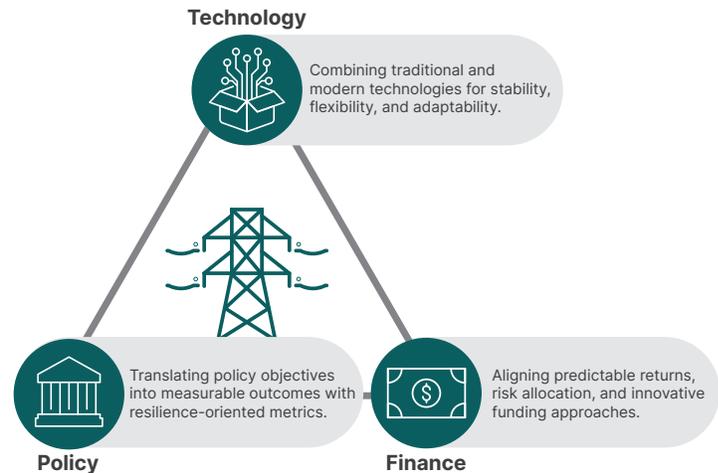
Over the past decade, power grid resilience has evolved from primarily a technical issue to a major policy and financial challenge. For networks characterized by long asset lifetimes, high upfront costs, and low-risk regulated returns, resilience outcomes depend not only on technology deployment but also on how policy makers set priorities and incentives, and how these are perceived by investors and lenders. Ensuring that grids can withstand disturbances, adapt to evolving conditions, and maintain reliable service now requires alignment across three pillars: technology, policy, and financing.

## 4.1 Technology Readiness: Putting the Pieces Together

Technology advances focused on power grid resilience now provide the tools needed as electricity systems decarbonize, electrification grows, and societies increasingly rely on uninterrupted power. Key capabilities are needed to absorb shocks, respond flexibly, and evolve for the future.

- **Stability** remains foundational to resilience, and modern power systems must maintain inertia, voltage, and frequency under both normal and stressed conditions. A portfolio approach can help absorb disturbances without triggering widespread outages. It combines traditional large synchronous generation, synchronous condensers, Static Synchronous Compensators (STATCOMs), HVDC transmission lines, and grid-forming BESS. It also includes next-generation power flow control technologies such as Static Synchronous Series Compensators (SSSC) and Unified Power Flow Controllers (UPFC), which integrate the benefits of Fixed Series Capacitors (FSC) and STATCOMs. Together, these technologies support both grid stability and flexibility.
- **Flexibility** complements stability equipment by enabling rapid response to variability, uncertainty, and dynamic loads, such as through demand response programs. Demand response should be recognized as a critical resilience tool, supported by automation that reacts to real-time price signals and incentives such as rebates or lower electricity rates. AI-enabled systems, large loads, DERs, and grid-forming BESS add another layer of flexibility. Electro-intensive applications such as data centers, steel and metals mills, or oil and gas plants can also contribute, provided they operate under mini-grids

## Strategic Implications and Key Actions



or microgrids. Advanced orchestration and supportive regulations ensure these resources act in concert. The convergence of AI, real-time markets, and demand response further enhances resilience, with AI predicting potential disruptions and triggering actions autonomously. Cases such as Ukraine’s deployment of DERs and Vietnam’s planned battery storage illustrate how flexibility mitigates local and systemic risks. Recognizing demand response and smart loads as resilience mechanisms is key to maintaining grid stability under stress.

- **Grid Enhancement Technologies (GETs)** complement demand response by providing immediate, tangible benefits for grid resilience. They enhance system stability, optimize power flows, and reduce reliance on peaking plants. While GETs improve efficiency and operations, they do not fully resolve high electricity costs. Considering total system costs, including CAPEX, OPEX, and long-term financial impacts, is essential to balance resilience with affordability.
- **Adaptability** enables the grid to learn, adjust, and respond. Coordinating across assets and operations, digital twins, planning platforms, wide-area monitoring, and orchestration tools help operators anticipate risks, optimize investments, and adjust operations. In Ukraine, Vietnam, or Saudi Arabia, these capabilities support rapid responses to shocks and high renewables penetration.

GE Vernova technology such as Grid Automation solutions, GridOS, PlanOS, and GridBeats provide system-level visibility and coordination, allowing networks to adapt while maintaining reliable service.

- **Full network visibility and control are essential to deploy**

**AI and other resilience tools.** This is especially critical at the distribution level, where DERs, electric vehicles, and new large loads are increasingly connected, but it also applies to transmission operations. Close coordination between TSOs and DSOs ensures planning and real-time operations are aligned and resilience measures are applied consistently. Advanced monitoring, digital twins, and integrated control systems give operators situational awareness, enabling faster responses, proactive risk management, and optimized system performance under stress. Next generation technologies (SSSC and UPFC), which combine the control benefits of STATCOM with power flow flexibility, further enhance operator oversight, supporting both grid stability and flexibility across transmission and distribution networks.

- **AI** and the increasing electricity demands from data centers is challenging grid resilience at the same time that it is redefining grid resilience possibilities, offering revolutionary tools to manage increasingly complex electricity systems. ML forecasts renewables output, natural language processing analyzes operational and regulatory data, computer vision monitors infrastructure, and deep learning optimizes operations in real time. By processing vast and diverse datasets, AI enables operators to better anticipate disturbances, adapt dynamically, and integrate high shares of renewables without compromising reliability. This capability has already been demonstrated in Saudi Arabia's deployment of advanced grid software. Beyond efficiency gains, AI represents a paradigm shift, providing a powerful tool for operators to plan, visualize, control, and safeguard the modern power system.

Together, these capabilities show that achieving resilient, decarbonized, and affordable grids is not only about deploying technologies. It also requires orchestrating them as an integrated system, informed by real-world experience and supported by advanced tools and appropriate market structures.

## 4.2 Regulatory Frameworks: Translating Policy Objectives into Outcomes

Regulatory design determines whether resilience ambitions are realized on the ground. Traditional metrics such as SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index)

assess system-level reliability under normal operating conditions by measuring outage duration and frequency. By contrast, resilience-oriented metrics that capture climate exposure, asset criticality, and recovery time should guide investment decisions. While traditional metrics capture overall system reliability, they provide limited insight into how quickly power is restored following outages. Metrics such as CAIDI (Customer Average Interruption Duration Index) complement SAIDI and SAIFI by including average restoration time per event, offering a more customer-focused perspective on resilience. Examples of regulatory measures can be found around the globe:

- **Anticipatory investment remuneration:** frameworks approve upfront funding for transmission and distribution upgrades, linking cost recovery to future resilience performance. For example, the UK RIIO framework allows TSOs and utilities to invest ahead of congestion or failure, with £28 billion (\$38 billion) approved for 2026–2031, and National Grid's RIIO-T3 plan proposing up to £35 billion (\$47 billion) for transmission, ensuring these investments are bankable.
- **Streamlined permitting and cost allocation:** regulations simplify cross-border infrastructure investment while safeguarding returns, facilitating early-stage resilience projects. The EU TEN-E Regulation (2022) and Action Plan for Grids (2023) streamline permitting, allocate costs for Projects of Common Interest, and help secure stable returns, supporting early deployment of strategic interconnections.
- **Shared reserves and operational coordination:** inter-operator standards and agreements enable resource pooling and power rerouting during extreme events, boosting system-wide resilience. Examples include the North American Electric Reliability Corporation (NERC) Reliability Standards and coordination across US grid operators, and in Central America SIEPAC facilitates mutual aid, shared reserves, and faster restoration after extreme weather events or other disruptions.
- **Regulatory sandboxes:** controlled environments allow piloting of innovative solutions while mitigating risk. For example, Singapore's Energy Market Authority (EMA) tests Virtual Power Plants (VPPs) aggregating DERs to provide ancillary services, allowing authorities to assess resilience performance, inform permanent regulation, and reduce financial and operational uncertainty.

### 4.3 Financing Resilience: Bankability and Risk Allocation

Financing resilient electricity grids requires aligning predictable returns, risk allocation, and innovative funding approaches. Key measures include:

- Bankable remuneration frameworks:** Clear rules for cost recovery, such as allowed returns on equity (ROE) or weighted average cost of capital (WACC), are essential to attract investors and lenders. Large infrastructure projects are typically funded with equity from investors and debt from lenders, who are well aligned on the required bankability framework, though it remains important to differentiate the two sources of capital. For example, regulated returns on Spanish electricity grid investments are currently approximately 6.6 %, though ~7.5 % is argued by industry experts to be needed to support modernization projects.
- Incentives for reliability and coordination:** Regulatory mechanisms encourage investments that enhance power grid resilience. In the United States, the Federal Energy Regulatory Commission (FERC) Final Rule in Order No. 679 (2006), implemented in Section 219 of the Federal Power Act, established ROE adders to compensate utilities for the risks and challenges of a transmission project, for forming a transmission-only company (transco), or for companies joining an RTO/ISO. Order No. 679 requires that companies requesting an incentive for a transmission project show the project either lowers the cost of delivered power by reducing congestion or ensures reliability. In Australia, ex-ante revenue allowances give utilities predictable returns for long-lived transmission investments while encouraging efficiency.
- Public Private Partnerships (PPPs):** Public concessional capital is used to de-risk grid investments, providing a signal to the market which can attract private

financing and lower the cost of capital. In Turkey (2025), the World Bank provided approximately \$748 million in concessional loans and grants (including International Bank for Reconstruction and Development, and Clean Technology Fund financing) to modernize and expand the national transmission network, facilitating large-scale renewable integration.

- Guarantees and risk-sharing instruments:** Credit and political risk guarantees improve the bankability of long-term network assets, particularly in emerging markets. In Latin America (2024), the European Investment Bank and BNP Paribas implemented a funded risk-sharing facility of up to \$160 million, enabling at least \$320 million of lending for renewable energy and electricity transmission projects, demonstrating how guarantees can mobilize private capital while reducing investment risks.
- Modernization of funding allocation and outcome based regulations:** Regulatory frameworks are evolving to treat operational and capital expenditures on equal footing through TOTEX approaches and output based incentives. In Europe, regulators including the Council of European Energy Regulators (CEER ) are exploring mechanisms such as TOTEX benchmarking and neutrality to reduce CAPEX bias and encourage cost effective investment in flexibility and digital solutions.

**By combining these measures, resilience investments become tangible and scalable. Technological innovation provides the necessary hardware and software solutions, regulatory clarity defines what counts as resilient, remuneration frameworks together with public and political commitment ensure bankability, and hybrid financing enables long-term deployment of high-value grid infrastructure. Together, these elements enable grids to respond effectively to climate stress, electrification, and increasing interdependence while attracting capital for secure, reliable, and resilient electricity systems.**

### Interconnected Enablers of Power System Resilience

Power System Attribute	Technology Enablers	Policy & Regulatory Enablers	Financing & Economic Enablers
 <b>Redundancy</b>	Distributed energy resources (DERs), network meshing, modular generation, multi-path transmission architectures	Security-of-supply standards, planning criteria, approval of anticipatory investments	Cost recovery for redundant assets, regulated remuneration
 <b>Stability</b>	Synchronous generation, synchronous condensers, STATCOMs, grid-forming inverters, grid-forming BESS	Grid codes, stability requirements, system service obligations	Remuneration of inertia, voltage, and frequency services
 <b>Availability</b>	Asset monitoring systems, predictive maintenance, digital asset management, spare-parts optimization	Dispatch rules, maintenance coordination, performance-based regulation	Predictable revenues, incentives linked to asset availability
 <b>Reliability</b>	Protection schemes, automation, self-healing networks, fast fault detection and isolation	Reliability metrics (SAIDI/SAIFI), outage management requirements	Financial incentives tied to reliability performance
 <b>Resilience</b> (system level outcome)	Flexibility (demand response, storage), adaptability (HVDC interconnectors, digital twins), and AI-enabled orchestration (forecasting, optimization, autonomous control)	Resilience-oriented metrics, emergency coordination frameworks, regulatory sandboxes	Risk-sharing mechanisms, long-term bankability, blended and concessional finance



## 5. ROADMAP FOR ACTION: DESIGNING THE FUTURE-PROOF GRID

The need to move from resilience ambition to operational reality is clear: existing power grids cannot withstand the accelerating pace of severe weather events, cyber threats, electrification, and renewables deployment without systematic transformation. True resilience arises from coordinated planning, operations, and adaptation rather than isolated technologies. Strategic implementation is therefore essential. This requires aligning stakeholders, integrating stress-tested systems, and enabling networks to evolve as threats intensify.

Innovation drives this transformation. Future-ready grids demand breakthrough solutions: advanced materials for extreme weather, quantum-enabled cybersecurity, autonomous restoration, and hybrid technologies unimaginable a decade ago. The stakes are high, and delayed action risks cascading failures and setbacks to the energy transition. Lessons from Mexico to Saudi Arabia show that resilience succeeds through strategic coordination, not ad-hoc responses.

### 5.1 Six Strategic Pillars for Resilient Power Grid Design

Transforming power grid resilience from concept to reality requires coordinated action across six interconnected elements, each addressing critical vulnerabilities while creating synergies that amplify overall system capabilities:

- **Integrated System Planning:** Begin with a comprehensive approach that considers the entire system: generation, demand, transmission and distribution grids, flexibility, markets, and supply chains. This framework evaluates multidimensional threats and constraints across the entire energy system.
- **Strategic Sourcing and Supply Chain Resilience:** Study the most vulnerable and longest lead-time components (e.g., transformers), ensuring emergency stocks are strategically positioned for rapid deployment. Consider

incentivizing local production of key components. This mitigates risks from supply disruptions, geopolitical uncertainties, and critical material shortages.

- **Interconnection Development and Enhancement:** Enable neighboring grids to serve as stabilizing forces and backup power sources during local disruptions. This requires interjurisdictional cooperation and market frameworks that facilitate inter-regional and cross-border electricity trade and mutual support.
- **Digital Intelligence and Automation:** Deploy AI, smart grids, and Internet of Things (IoT) devices to unlock efficiency gains, reduce transmission costs, and create anticipatory grid management capabilities that prevent disruptions before they occur.
- **Hybrid Solution Optimization:** Combine the best attributes of hardware and software solutions to amplify performance, enhance grid stability, and enable flexibility. STATCOMs paired with synchronous condensers expand voltage control capabilities. FACTS equipment, including advanced power flow control technologies such as SSSC and UPFC, further improves performance and grid stability. These technologies combine the advantages of FSC and STATCOM. When integrated with digital platforms, they enable proactive rather than reactive grid management and enhance system flexibility.
- **Human-System Interaction:** Modern power systems are too complex to operate manually, and resilience increasingly depends on operators' visibility, decision support, and speed of response. Training, simulation exercises, and advanced decision support systems enhance decision-making under stress. Collaborative frameworks and coordination mechanisms ensure effective responses during disruptions, reflecting real-world experiences such as Ukraine's grid operations under conflict.

GE Vernova has the expertise and resources to support stakeholders as they work to design their resilient power grids, and the hardware and software solutions to successfully implement the design.

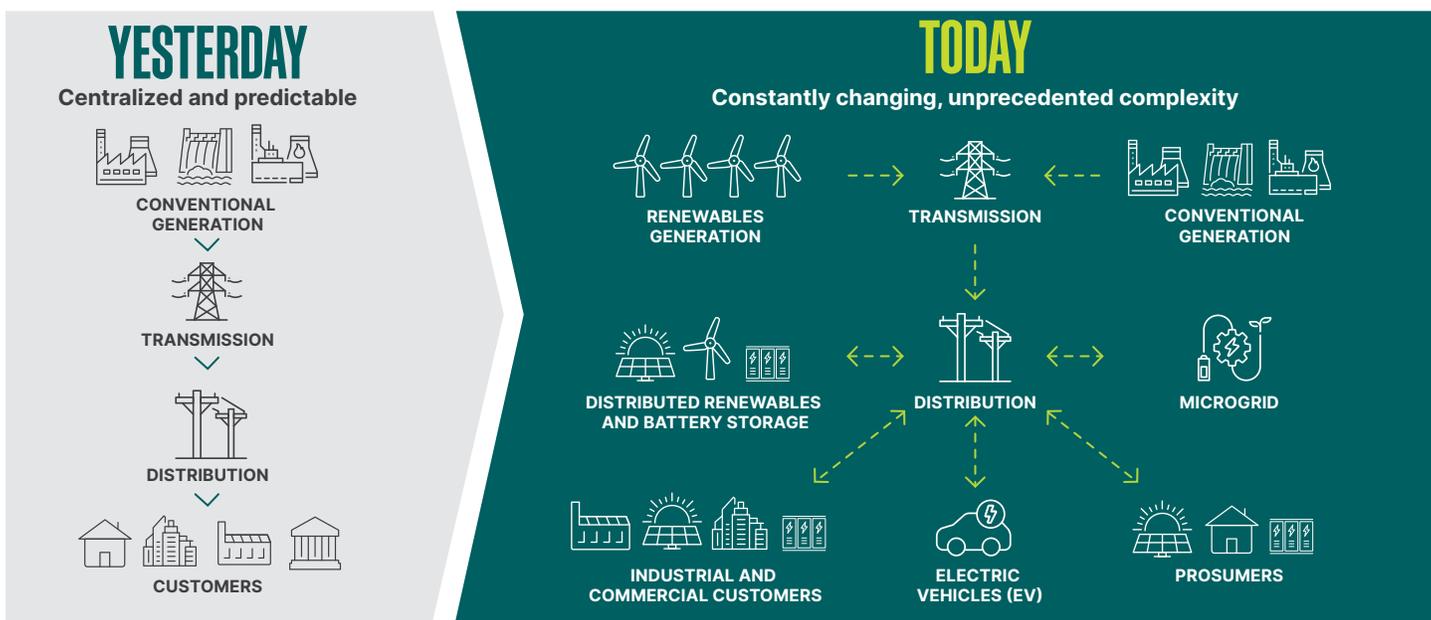
## 5.2 Phased Implementation Framework

Successful resilience deployment requires careful sequencing that builds capabilities progressively while delivering immediate value. This phased approach balances urgent needs with long-term transformation goals:

- **Short-term:** Deploy proven technologies where operational benefits are clear. Examples include grid-forming storage, microgrids for critical facilities, and enhanced monitoring systems.
- **Medium-term:** Scale integrated solutions and regional coordination through hybrid deployments, advanced controls, and cross-border and inter-regional resilience agreements.
- **Long-term:** Transform system architecture around distributed resilience principles through fundamental market design, regulatory, and operational changes that make resilience a core system attribute.



## Energy Transition Increases Grid Complexity



# 6. CONCLUSION: RESILIENCE AS AN ENGINE FOR GROWTH AND TRUST

Power grids worldwide are at an inflection point. The convergence of severe weather events, cyber threats, rapid electrification, and renewables deployment is creating stress conditions far beyond what existing infrastructure was designed to handle. Power grid resilience has evolved from an engineering consideration to a strategic imperative that determines whether the energy transition succeeds or fails.

The economic implications of grid resilience extend far beyond electricity systems themselves. Power outages cost the U.S. economy about \$150 billion annually, a figure that continues to grow as digital dependence intensifies. Resilient grids don't just prevent blackouts; they support national security and enable economic competitiveness by providing the stable platform necessary for advanced manufacturing, digital services, and energy-intensive technologies driving future growth.

Achieving resilient, decarbonized grids requires fundamental innovation across multiple domains: advanced materials, predictive algorithms, novel market mechanisms, and hybrid technologies. Future grids must be designed for continuous adaptation. They must be able to integrate new technologies seamlessly, respond dynamically to evolving threats, and learn from each disruption.

Evidence from Mexico's rapid recovery from Hurricane Otis, Ukraine's distributed resource deployment, Vietnam's power system expansion, and Saudi Arabia's grid modernization, demonstrates that resilient grids are achievable when three conditions align: integrated system planning, innovative technologies providing multiple value streams, and investment frameworks that make resilience financially attractive. Countries that invest proactively in grid resilience will attract energy-intensive industries, support faster economic growth, and accelerate their energy transition. Conversely, regions that delay face mounting risks: more frequent disruptions, reduced competitiveness, and potentially catastrophic system failures.



**In a new energy world, where electrical power is reaching a major role, energy security now depends on power grid resiliency. GE Vernova is committed to providing the most innovative systems, equipment, and software to meet this renewed imperative for the world."**

**- Philippe Piron**  
Chief Executive Officer of  
GE Vernova's Electrification Segment

Power grid resilience is no longer optional. It has become a cornerstone of 21st-century energy security and national strategic autonomy. The necessary tools already exist: technology, financing, and regulation. What remains is bold strategic vision and coordinated action to deploy them at scale. GE Vernova, with its suite of hardware, software, consulting, and financing solutions, is uniquely positioned to help grid operators and system planners navigate this new paradigm.

## CALL TO ACTION: A Paradigm Shift for Grid Resilience

A resilient grid will not emerge from incremental upgrades: it requires a leadership reset. Grid infrastructure can no longer be treated as a cost center to be optimized. It must be managed as a strategic asset underpinning economic stability, national security, and the energy transition.

To build a grid that can withstand volatility, electrify demand, and decarbonize at speed, stakeholders and decision makers must act decisively in four areas:

- 1. Make Total Observability Non-Negotiable:** Resilience begins with visibility across the entire power system, from generation to transmission and distribution. Scale digital intelligence, advanced sensing, and real-time analytics to eliminate blind spots and enable predictive response. You cannot stabilize what you cannot see.
- 2. Secure Strategic Supply Chains:** Move beyond lowest-bid procurement toward long-term partnerships that safeguard critical, long-lead components such as power transformers. Resilience depends on supply certainty and forward planning.
- 3. Redesign Markets to Value Stability:** Advocate for market mechanisms that reward essential system services, not just energy volume. These include inertia, frequency response, and voltage support. Reliability must be explicitly valued, not treated as an externality.
- 4. Align Policy and Financing with Resilience Goals:** Work with policymakers and financial institutions to unlock regulatory clarity, targeted incentives, and blended financing structures that de-risk grid investment. Capital must flow toward long-term system strength rather than short-term cost minimization.

The transition to a resilient grid is not only technical. It is also strategic, regulatory, and financial, and it requires coordinated action across technology, markets, and policy. Leaders who recognize grid infrastructure as a strategic platform, rather than simply hardware, will shape the next era of grid resilience and ultimately the success of the energy transition.

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## Glossary

AI	Artificial Intelligence
ASEAN	Association of Southeast Asian Nations
BESS	Battery Energy Storage System
CAIDI	Customer Average Interruption Duration Index
DER	Distributed Energy Resource
DSO	Distribution System Operator
FACTS	Flexible AC Transmission System
FSC	Fixed Series Capacitors
HVDC	High-Voltage Direct-Current
IoT	Internet of Things
ML	Machine learning
PPA	Power Purchase Agreement
ROE	Return on Equity
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensators
SVC	Static VAR Compensator
SVG	Static VAR Generator
TSO	Transmission System Operator
UPFC	Unified Power Flow Controller
VND	Vietnamese Dong
VPP	Virtual Power Plant
WACC	Weighted Average Cost of Capital

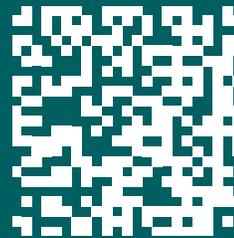
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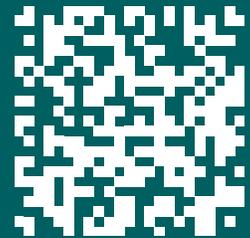
## Additional GE Vernova grid resilience resources are available:



Grid Solutions Library



Electrification Software Resources



Consulting Services Resources



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