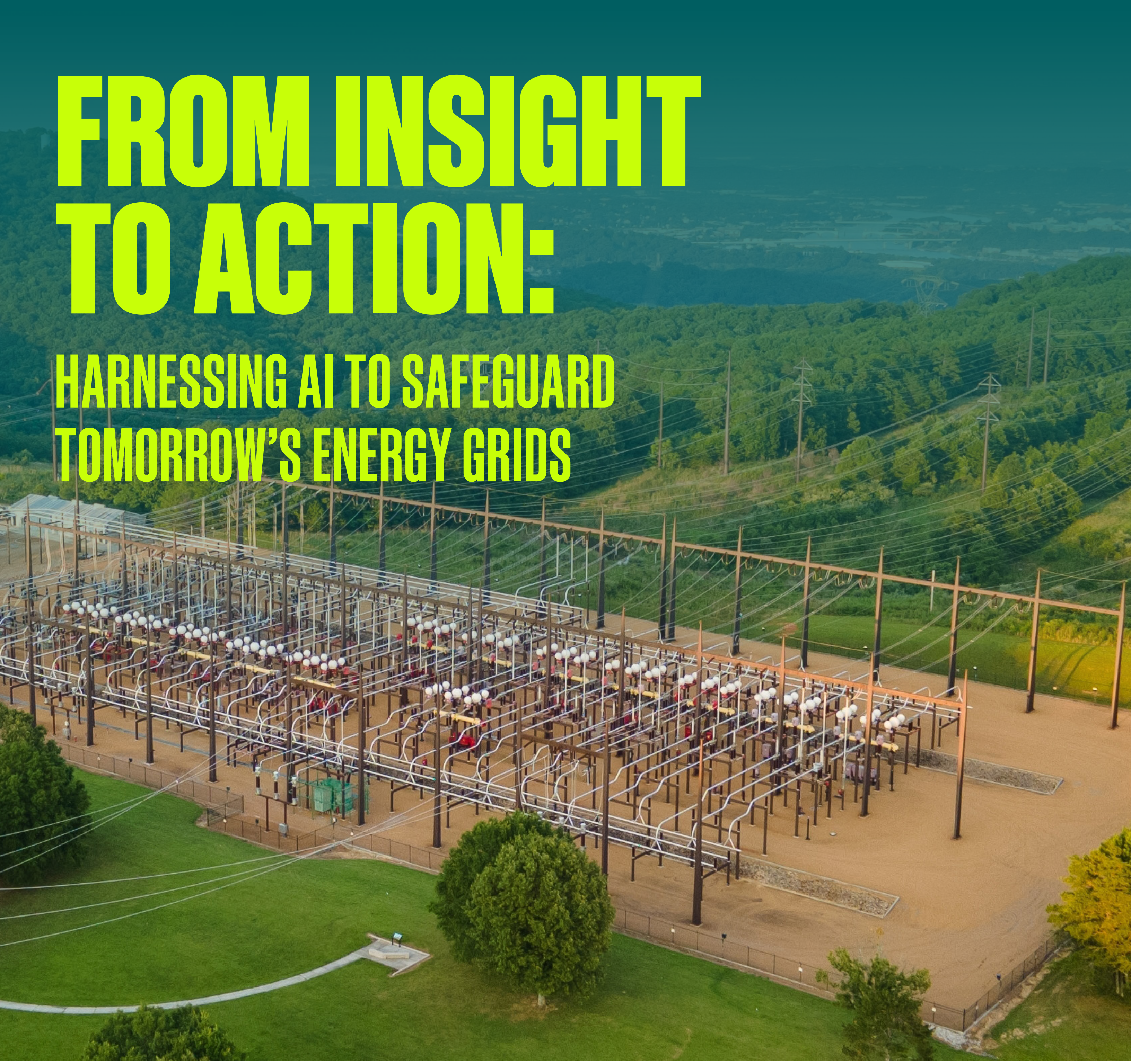
FROM INSIGHT TO ACTION:

HARNESSING AI TO SAFEGUARD TOMORROW'S ENERGY GRIDS



GE VERNOVA

Harnessing AI to Safeguard Tomorrow's Energy Grids

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ABSTRACT

The $195 billion Texas blackout in 2021 is an example of what happens when an already stressed grid is pushed beyond its limits by external forces, specifically extreme weather. If organizations fail to address the escalating grid challenges of a rapidly transforming grid, the results can be disastrous. This white paper examines virtualization technologies that enable proactive resilience and dynamic grid management. Utilities must integrate diverse data sources, leverage digital twins, and adopt software-defined automation for both current and future grid expansions. These strategies shift operations from reactive recovery to predictive protection, avoiding disastrous consequences before they happen, helping to reduce outages, improve reliability, and cut costs.

Through real-world case studies, the paper offers insights into implementation strategies, addresses challenges such as cybersecurity and legacy system integration, and explores future trends in agentic AI and spatial computing. Ultimately, these insights empower engineers, operators, policymakers, executives, and other stakeholders to develop scalable, resilient grids for a sustainable energy future.

INTRODUCTION

The white paper *AI at the Helm: Redefining The Future of the Grid* explores artificial intelligence (AI) and all its varied fields (e.g., machine learning, natural language processing, computer vision, deep learning with neural networks) as the critical arsenal for enhancing stability, efficiency, and allowing seamless integration of renewable energy in an increasingly complex grid landscape shaped by surging demand, supply variability, extreme weather, distributed energy resources and other external forces.

This paper proposes a comprehensive approach: software-defined systems that simulate and enhance grid operations in real-time. This reduces reliance on physical infrastructure and the need for reactive manual recovery. It also highlights proactive strategies that help utilities anticipate disruptions and enhance their resilience against extreme weather, fluctuating renewable energy sources, and cyber threats.

The urgency is clear. Between 2015 and 2020, the United States experienced 426 major blackouts, with peaks during summer and fall (e.g., 60 events in August).[1, 2] Both the frequency and severity of these outages have increased after 2017, with outages lasting longer than a day and increasing by 20% annually since 2019.[3, 4] In 2023, the state of Texas accounted for 13% of all U.S. outages.[5, 6] By 2024, the weather alone was responsible for 14 major transmission events.[7, 8]

These challenges, driven by higher demand resulting from the electrification of the transportation sector, the reshoring of manufacturing, and the rapid expansion of new data centers, reflect 21st century global pressures. They include delays in replacing long-lead transformers (averaging 80 to 210 weeks, according to the May 2025 NERC 2025 Summer Reliability Assessment), and other critical equipment, grid instability from frequency fluctuations and generation losses, and cybersecurity threats such as ransomware attacks, data spoofing, and model poisoning that can degrade operations or, even worse, altogether disable energy infrastructure.

The evidence underscores an urgent shift: utilities must move from reactive recovery to predictive protection. The remainder of this paper presents actionable insights through real-world case studies, empowering engineers, operators, policymakers, and executives to address the challenges of grid modernization. Practical examples, such as mitigating the impacts of extreme weather and integrating diverse energy sources, provide a roadmap for AI-driven virtualization to enhance grid resilience.

1: https://urbanclimate.gatech.edu/current-projects/blackout-tracker/

2: https://paylesspower.com/blog/blackout-tracker/

3: https://stories.tamu.edu/news/2025/08/14/texas-am-researchers-map-americas-power-outage-hot-spots-using-ai/

4: https://www.newsweek.com/map-us-counties-blackout-electricity-power-outage-vulnerability-2113927

5: https://paylesspower.com/blog/top-states-at-risk-for-power-outages/

6: https://www.houstonchronicle.com/business/energy/article/texas-leads-nation-power-outages-18887152.php

7: https://www.climatecentral.org/climate-matters/weather-related-power-outages-rising

8: https://www.ncei.noaa.gov/access/billions/events.pdf

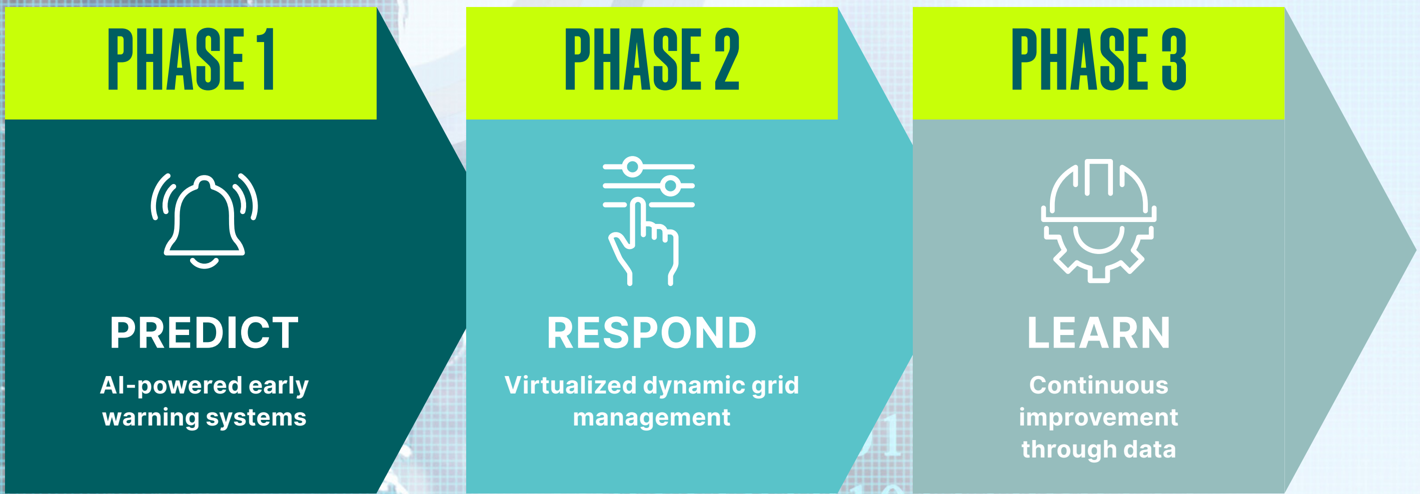

Figure 1. The Grid Resilience Journey.

AI-DRIVEN VIRTUALIZATION FOR GRID RESILIENCE

To champion this transition, we propose a “Resilience Journey” framework—Predict, Respond, Learn—that transforms grid operations **(Figure 1)**. AI forecasts failures, such as transformer trips, by analyzing weather, sensor, and historical operational data, offering asset-specific, early warnings to prevent outages. Virtualization enables rapid recovery by reducing response times from minutes or hours to mere seconds through software-defined automation. Continuous data analytics refine strategies, boosting flexibility through virtual testing and optimization, helping utilities proactively address the integration of renewables, aging infrastructure, and extreme weather events. The true power of AI lies in its ability to provide a holistic view by fusing diverse data sources and types.

PREDICT

Phase 1: Predictive Early Warning Systems

AI shifts the focus from passive reaction to proactive foresight with grid management. This stage utilizes the five AI system requirements (Distilling Raw Data, Nowcasting, Predicting, Optimizing, and Autonomous Control) explored in *AI at the Helm: Redefining the Future of the Grid* to create predictive early warning systems. AI-powered data fusion combines environmental data, current grid conditions, and other data sources (e.g., weather forecasts, sensor data from transformers and substations, and historical records) to anticipate failures and line congestion. Integrating electrical currents, thermal imaging, chemical gas analysis, and mechanical vibrations from IoT sensors allows for the delivery of prescriptive alerts, such as reducing load on transformers to avert failures days in advance.

Examples include combining real-time phasor measurement units (PMUs) with environmental data, such as meteorological models and grid conditions, to detect transformer anomalies and prevent outages by identifying potential plant trips days in advance. Utilities have the potential to forecast equipment stress resulting from extreme weather or congestion caused by renewable energy generation, thereby reducing outages and improving grid stability. Any predictive solution must incorporate these features into software-defined automation, supporting virtualization strategies that simulate scenarios and avoid costly physical upgrades while ensuring resilience.

AI-driven predictive decision-making analyzes vast quantities of data to forecast changing demand and expected equipment wear based on those conditions. For example, AI-driven applications can deliver a significant improvement in predicting asset failures and improve fault detection using synchrophasors. Large language models analyze synchrophasor data streams to detect faults, processing terabytes of grid-wide inputs to prevent congestion in renewable-heavy networks proactively.

RESPOND

Phase 2: Dynamic Response and Virtualization

Extreme weather, variable renewable energy sources, and cyber threats require utilities to evolve from a reactive to a proactive response. AI-powered virtualization facilitates this transformation.

In Phase 2, software-defined networking (SDN) and virtualized Intelligent Electronic Devices (IEDs) enable utilities to simulate their infrastructure and reroute power in real-time. This ensures uninterrupted service during unexpected drops in renewable energy or demand spikes. Virtualized systems integrate real-time analytics from IoT sensors and edge computing. They respond immediately to localized disruptions.

Integration with SCADA and EMS systems improves resilience and safeguards against vulnerabilities, such as generation loss that can cause the grid to collapse within seconds due to frequency fluctuations.

Finally, digital substation solutions will utilize SDN and network function virtualization (NFV) to develop flexible, virtualized networks that respond in real time to grid conditions, ensuring reliable communication across distributed resources without hardware overhauls.

LEARN

Phase 3: Continuous Learning and Improvement

Improved adaptability through iterative learning from IoT sensor data and historical trends is another essential tool for improving grid resilience. Advanced data analytics enable predictive decision-making by identifying equipment failures or demand surges in advance, which allows data centers, for example, to meet their 99.995% uptime requirement while also decreasing their reliance on physical upgrades.

The Grid Resilience Journey produces actionable strategies that harness AI and virtualization to deliver measurable business impact by reducing recovery times while maintaining grid stability. Furthermore, utilities can achieve significant cost savings by lowering annual outage costs, while also enhancing customer satisfaction through demonstrable improvements in service reliability ratings. Reliability improvements are reflected in stronger System Average Interruption Duration Index (SAIDI) scores, indicating fewer and shorter interruptions. Operational efficiency is enhanced through lower emergency response costs and faster recovery times. Together, these benefits create a future-ready grid that is not only more resilient to extreme weather, renewable variability, and cyber threats but also more sustainable and economically efficient **(Figure 2)**.

COST SAVINGS

Reduction in annual outage costs

CUSTOMER SATISFACTION

% increase in satisfaction ratings

RELIABILITY IMPROVEMENT

% improvement in SAIDI scores

OPERATIONAL EFFICIENCY

% reduction in emergency response costs

Figure 2. The business impact of actionable strategies that improve grid resilience.

CASE STUDIES

These below illustrate the urgency and opportunities of AI-driven resilience:

TEXAS BLACKOUT (2021)

The 2021 Texas blackout, caused by a severe winter storm, highlights the urgent need for AI-driven resilience in grid management, aligning with this white paper's themes of the need for grid stability and sustainability. On February 15, 2021, a significant failure in the ERCOT grid left approximately 4.5 million homes without power, resulting in 246 deaths and causing $195 billion in damages, which nearly led to the system's total collapse. The event highlights the vulnerability of aging infrastructure. It demonstrates how AI-driven virtualization could have mitigated the catastrophe by simulating grid responses, preventing cascading failures, enhancing reliability, and facilitating the integration of renewable energy through balanced variable loads.

HEATHROW AIRPORT/NATIONAL GRID (2025)

The March 21, 2025, power outage at Heathrow Airport, triggered by a preventable fire at the North Hyde Substation, exposed critical vulnerabilities in the UK's aging electricity infrastructure. A catastrophic failure in a transformer bushing—caused by moisture ingress in insulation that National Grid had identified as a risk in 2018 but failed to adequately address—led to the loss of all three on-site transformers, resulting in a complete blackout. This incident disrupted over 1,350 flights, stranded nearly 300,000 passengers, and affected 67,000 homes and businesses, resulting in economic losses of millions.

In response, National Grid's comprehensive grid upgrade initiatives—collectively known as the Great Grid Upgrade—directly target these deficiencies to prevent similar disruptions, particularly for high-demand critical infrastructure like Heathrow. Spanning 2025 to 2031, these efforts involve an unprecedented investment of up to £35 billion in transmission enhancements, including a baseline allocation exceeding £11 billion for maintaining and modernizing existing networks. AI tools enable predictive maintenance by leveraging machine learning and digital twin analytics to detect early signs of equipment degradation—such as moisture ingress in transformers—and allow for preemptive interventions that avert failures, like the North Hyde Substation incident.

IBERIAN BLACKOUT (2025)

The blackout event in April 2025 in Spain and Portugal shows how AI can improve grid stability. At 11:20 AM, PMUs detected frequency fluctuations, causing a 15 GW generation loss within five seconds and an interconnection loss with France, according to Red Eléctrica de España. AI-based applications can monitor phasor measurement units (PMUs) in real-time, forecasting frequency fluctuations and effective inertia levels using renewables data and weather inputs, enabling proactive load balancing to avert the rapid 15 GW generation loss observed in the 2025 Iberian blackout. Near real-time adjustments could have helped prevent this by quickly balancing loads and predicting frequency changes using real-time weather and demand data.

COLONIAL PIPELINE CYBERATTACK (2021)

The Colonial Pipeline ransomware cyberattack in May 2021 highlights the importance of strong cybersecurity for a resilient grid infrastructure. The compromise of a legacy virtual private network (VPN) account lacking multi-factor authentication allowed the DarkSide ransomware group to gain initial access to the company's IT network and deploy malware that encrypted critical systems, halting pipeline operations. This vulnerability stemmed from a leaked password on the dark web, enabling unauthorized entry despite the operational technology (OT) network remaining secure. The company enacted the shutdown of the 5,500-mile pipeline—disrupting nearly half of the East Coast's fuel supply for eight days— as a precautionary measure in response to the ransomware cyberattack. An AI-powered anomaly detection system and secure protocols could have identified the intrusion instantly, mitigating risks in virtualized systems. A zero-trust cybersecurity framework will enhance grid reliability and sustainability by protecting against continually evolving cyber threats.

TRANSELEC, CHILE (2023)

Transelec's success in Chile underscores the role of AI in enhancing grid performance, aligning with the themes of sustainability and efficiency presented in this paper. As Chile's top transmission service operator, Transelec utilized AI-driven network modeling to oversee its 11,000 km system, reducing outage times by 25% through predictive maintenance, as detailed in *Transelec's 2023 sustainability report*. AI-enabled asset management lowered failure risks by as much as 50% and significantly reduced outage durations through predictive analytics and IT integration. A modern set of AI based solutions should be able to simulate grid scenarios and incorporate renewables, tackling fluctuating demand and aging infrastructure.

IMPLEMENTATION STRATEGIES AND CHALLENGES

Strategies for addressing the growing energy demand must be modernized **(Figure 3)**. Industry solutions should also enhance device lifecycle management for virtualized intelligent electronic devices by automating updates and configurations to connect legacy systems with modern edge analytics, all while ensuring zero downtime for critical loads.

- Legacy system integration complexity and costs
- Real-time performance of virtualized systems
- Cybersecurity concerns with increased connectivity
- Staff training and cultural change management
- Initial capital investment requirements
- Regulatory compliance and approval process

Figure 3. Reality Check on Implementation.

Furthermore, advanced remote management tools must be adopted to centralize device oversight, enabling over-the-air updates, access to historical performance trends, and long-term maintenance support—extending up to a decade—for critical assets. This approach bridges gaps in legacy systems while ensuring zero downtime in high-demand environments such as data centers.

Utilities should implement these solutions through a carefully phased rollout, beginning with an assessment of vulnerabilities aligned with modernization goals, such as stabilizing infrastructure in the face of rising annual demand. A pilot phase can then test performance in controlled segments, followed by a network-wide expansion using modular designs and open standards, such as IEC 61850, for seamless SCADA/EMS compatibility. Open protocols should also be adopted to ensure future integration with DERMS/EMS platforms.

Key challenges, such as legacy mapping and real-time performance, are addressed through hybrid architectures and edge computing, which enable low-latency analytics. Increased cybersecurity risks associated with expanded connectivity are mitigated by advanced cyber threat detection tools that meet regulatory standards. Workforce readiness is enhanced through intuitive user interfaces and structured change management programs, while regulatory compliance and capital justification require strategic planning to secure incentives for digital upgrades.

Most utilities emphasize gradual progress and collaboration, supported by an actionable 1–18-month project roadmap **(Figure 4)**: Months 1-3 assess the current state and identify vulnerabilities; Months 4-6 implement pilots; Months 7-12 prioritize initiatives and engage stakeholders (utilities, regulators, vendors); and Months 13-18 achieve full deployment with continuous AI-driven optimization. A "Start small, Think big, Move fast" mindset fosters innovation, reduces risks, and ensures reliable energy delivery amid increasing loads from intermittent renewables and energy-hungry data centers.

Figure 4. Roadmap to Resilience

STEP 1 **ASSESSMENT (1-2 MONTHS)**
Current state analysis, vulnerability identification, stakeholder alignment

STEP 2 **PILOT PROJECT (3-8 MONTHS)**
Small scale implementation, proof of concept, early wins demonstration

STEP 3 **SCALED DEPLOYMENT (9-18 MONTHS)**
Phased rollout, staff training, full integration with existing systems

FUTURE IMPLICATIONS

As the grid evolves to meet rising demands and integrates new technologies, utilities must continuously monitor emerging trends, explore expansion opportunities, and adopt a proactive mindset.

EMERGING TECHNOLOGY TRENDS

AI advancements are set to revolutionize grid operations. Agentic AI enables autonomous systems to predict and prevent disruptions independently.

Spatial computing provides immersive visualizations for complex grid scenarios, such as simulating data center integrations that require 99.995% uptime and multiple redundant assets.

Further advancements, such as the integration of infrared thermography within asset performance systems, will enable the integration of thermal, chemical, and electrical properties for accurate fault prediction in high-load environments. These capabilities will help utilities manage steadily rising electricity demand.

In addition, cutting-edge visual intelligence platforms will utilize AI to create interactive grid maps and anomaly visualizations, empowering operators to simulate and respond to scenarios—ranging from data center load changes to severe weather —within immersive environments.

SCALING AND INTEGRATION OPPORTUNITIES

Solutions must scale to city-wide networks by incorporating AI-enabled controls for decentralized management. This includes advanced energy storage and vehicle-to-grid systems to balance loads from intermittent renewable energy sources. Policy incentives for digital upgrades will accelerate adoption, ensuring resilient grids in high-demand scenarios, such as the Iberian Peninsula crisis, where faults can be detected in microseconds with next-generation digital systems.

ADOPTION MINDSET

Utilities should embrace the mantra “Start small. Think big. Move fast.” Initial pilots can validate AI features in targeted areas, such as those with a high concentration of renewable energy sources, like microgrids. These pilots can then be expanded to network-wide implementations, applying lessons learned from past events such as the 2021 Texas blackout. Moving with urgency enables utilities to enhance performance, foster innovation, mitigate risks, and accelerate grid modernization to meet the growing demands for both reliability and efficiency.

CONCLUSION

The future of grid modernization depends on resilience built through prediction rather than reaction. AI driven solutions enable utilities to anticipate failures and disruptions with predictive early warning systems, shifting from passive responses to proactive planning. Virtualization empowers rapid responses to crises, accelerating recovery from extreme weather events or cyber threats through software-defined automation.

Moreover, AI strengthens the grid with every incident, learning continuously from data fusion, historical trends, and real-world events. The result is a more resilient grid with refined energy flows, capable of responding quickly and effectively to unexpected challenges.

Learn More

Discover the steps you can take to safeguard energy grids by visiting **GE Vernova Grid Solutions** or by **contacting our experts for further insights.**

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