

STRATEGIC ASSET MANAGEMENT | ENERGY | UTILITIES | INFRASTRUCTURE

# Utilities and Infrastructure at Crossroads

## Becoming truly resilient or failing?

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*Resilience in global utilities and critical infrastructure. Navigating a crossroads of geopolitical disruption, energy transition, digitalization, and asset deterioration.*

**Ennio H.A.R. Neumann Senese**

Group CEO, OHROS Consulting Group

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## EXECUTIVE SUMMARY

# Utilities and Infrastructure at a Crossroads

The global utilities and critical infrastructure sector stand at the most consequential crossroads in its post-war history. Power grids, water networks, gas transmission systems, district heating, telecommunications backbone, and transport infrastructure simultaneously face geopolitical aggression, accelerating physical asset deterioration, the deep structural demands of the energy transition, and an exponentially expanding cybersecurity threat surface. The convergence of these forces in 2026 has created the most demanding operating environment the sector has ever encountered.



The choice before every utility executive, infrastructure board, and national regulator is binary and immediate: invest now in the five dimensions of genuine resilience; geopolitical positioning, supply chain and asset architecture, asset intelligence, energy transition integration, and cybersecurity, or accept that failure, and not resilience, becomes the default destination.

The data demands attention. The IEA's World Energy Investment Report 2025 identifies a \$4.8 trillion annual energy investment requirement under its Net Zero Emissions by 2050 Scenario, against current global spending of \$3.3 trillion, a gap that closing demands nearly a tripling of clean energy funding by 2030. The World Economic Forum places the cumulative consequence of inaction at a \$15 trillion global infrastructure investment shortfall by 2040, capital that governments alone cannot mobilise, making private sector engagement not optional but structural.

ENTSO-E's European Resource Adequacy Assessment 2025 confirms that several EU member states face tightening adequacy margins by 2028, with 6 to 8 GW of capacity at risk of decommissioning in the short-to-mid term and no significant new investment yet visible in

that window. And Gartner's global survey of over 4,200 business and technology leaders, published in late 2024, finds that fewer than half of all digital initiatives meet their intended outcomes — a result that carries existential weight for asset-intensive utilities managing infrastructure with average ages exceeding 40 years.

As Dr. Kate Doubleday of the Rocky Mountain Institute observed at the Global Clean Energy Action Forum 2025: critical infrastructure resilience is no longer an engineering problem, it is a governance, investment, and strategic intelligence problem. The utilities and infrastructure operators that build resilience deliberately, with disciplined investment across all five dimensions, will define essential services for the next generation. Those that do not will deliver the blackouts, water failures, and supply disruptions that define the next decade of public consequence.

## CHAPTER 1

# A Sector Under Siege: The State of Utilities and Infrastructure in 2026

## 1.1 The Perfect Storm Arrives

At the World Utilities Congress 2025 in Abu Dhabi, senior executives delivered a warning that proved immediately prescient: the sector was approaching a ‘stress convergence’, the simultaneous arrival of multiple structural disruptions that individually would be manageable but together would test the integrity of infrastructure systems not designed for compound shock.

That convergence materialized in full by early 2026. The Strait of Hormuz crisis of February 2026, triggered by joint U.S.-Israeli air strikes on Iran, drove gas prices to levels not seen since the 2022 European energy crisis, immediately straining gas-fired power generation economics across Europe and Asia. Gulf LNG exports, critical to European gas supply security, were disrupted for six weeks. Grid operators across the continent activated emergency demand reduction protocols. Several EU member states invoked energy emergency legislation for the first time since the 1970s.

But geopolitical shock only amplified pre-existing structural fragilities. European electricity grids carry average transformer ages of 42 years, against a design life of 30-40 years. Water treatment infrastructure in the UK, France, and Germany averages 47 years of age. Gas transmission networks in Southern and Eastern Europe were built predominantly in the 1970s and 1980s, with inspection and replacement cycles now running a decade behind schedule. The storm did not create the vulnerability, it revealed decades of deferred investment decisions.

**Table 1 — Utilities and Infrastructure: Key Stress Indicators, 2025–2026**

Indicator	Verified Data & Source
<b>Annual clean energy investment required to reach net zero by early 2030s</b>	<b>~\$4.8 trillion/yr</b> <i>IEA World Energy Outlook 2025 (NZE Scenario)</i>
<b>Current global clean energy investment (2025)</b>	<b>\$2.2 trillion/yr — gap vs net-zero target remains substantial</b> <i>IEA World Energy Investment Report 2025</i>
<b>Global infrastructure investment shortfall by 2040</b>	<b>\$15 trillion cumulative investment gap (not lost productivity)</b> <i>WEF / Global Infrastructure Hub</i>

Indicator	Verified Data & Source
<b>EU grid adequacy risks by 2028</b>	<b>Several EU member states face tight adequacy margins; 6–8 GW at decommissioning risk</b> <i>ENTSO-E ERAA 2025</i>
<b>Average age of European electricity grid assets</b>	<b>~40 years (many distribution grids will exceed 40 years by 2030)</b> <i>Eurelectric / EIB 2025; Breakthrough Energy</i>
<b>UK / France / Germany water infrastructure average age</b>	<b>UK water pipes partly Victorian-era; EU pipe leakage rates indicate widespread aging</b> <i>EEA / AMCS 2024</i>
<b>Global cybercrime cost (2025 estimate)</b>	<b>~\$10.5 trillion annually (projected)</b> <i>Cybersecurity Ventures 2020 forecast</i>
<b>OT/ICS ransomware incidents against industrial organisations, 2024</b>	<b>Up 87% year-on-year</b> <i>Dragos OT/ICS Cybersecurity Report 2025 (8th Annual Year in Review)</i>
<b>Digital initiatives meeting targeted business outcomes</b>	<b>Only 48% of digital initiatives met or exceeded targets</b> <i>Gartner global survey of 4,200+ leaders (late 2024), cited in MIT Sloan Management Review</i>
<b>EU annual green investment gap to meet 2030 climate targets</b>	<b>€477 billion/yr additional investment required</b> <i>European Commission, 2023/2024</i>

Sources: IEA World Energy Outlook 2025 & World Energy Investment 2025 | ENTSO-E ERAA 2025 | WEF / Global Infrastructure Hub | Dragos OT/ICS Cybersecurity Report 2025 | European Commission 2023/2024 | Gartner 2024 / MIT Sloan Management Review | EIB 2025 | Cybersecurity Ventures

## 1.2 The Hormuz Transmission: How an Oil Shock Becomes a Grid Crisis

The Strait of Hormuz crisis exposed a structural interconnection that utility operators had systematically underweighted in risk models: the transmission channel from oil and gas supply disruption to electricity grid stability is faster, more direct, and more severe than most scenario planning assumed.

Gulf LNG exports — representing approximately 20% of European LNG import capacity — were disrupted for six weeks. Gas storage draw-down rates in Germany, France, Italy, and the Netherlands accelerated to levels not seen since February 2022. Gas-fired capacity — which provided 22% of EU electricity generation in 2025 — faced immediate fuel cost spikes of 40–60%, forcing grid operators to activate expensive peaking capacity and demand reduction simultaneously. Wholesale electricity prices in Germany and France briefly touched €280/MWh, triggering industrial demand curtailment across energy-intensive manufacturing.

The cascade extended beyond electricity. District heating networks dependent on gas — serving approximately 60 million Europeans — faced immediate supply pressure. Desalination

plants in Gulf states, providing drinking water to millions, faced dual pressure from the geopolitical disruption and the fuel cost shock. Water utilities in arid climates discovered that energy security and water security are not separate resilience challenges — they are one integrated system.

*“In energy systems, it is often the loss of certainty, more than an actual shortage, that drives the cascade. Utilities that had not stress-tested their gas dependency discovered this in real time.”*

**Ennio R. Neumann Senese, CEO, OHROS Consulting Group (Amstelveen, March 2026)**

## 1.3 The Ukraine Conflict: Direct Infrastructure Attack as the New Normal

The deliberate, systematic targeting of Ukrainian power grid infrastructure since 2022 has provided the sector with the most comprehensive real-world stress test of utility resilience in the modern era. Over 60% of Ukraine’s electricity generation capacity was damaged or destroyed at peak impact. Transformer supply chains globally were strained as emergency replacement demand collided with manufacturing lead times of 12-18 months for large power transformers.

The lessons transferred immediately and directly to utility risk planning across Europe and beyond. ENTSO-E’s 2025 adequacy report explicitly incorporated ‘conflict-adjacent infrastructure attack’ as a scenario category for the first time. NATO’s Critical Infrastructure Protection framework was updated to designate electricity, gas, water, and digital communications as Tier 1 national security assets.

The Dragos ICS/OT Security Report 2025 documents a 47% year-on-year increase in cyber incidents targeting utility operational technology, a trajectory that makes infrastructure cybersecurity not a future concern but a present operating reality.

### External Research: The Infrastructure Stress Environment

- **IEA World Energy Investment (2025):** Annual clean energy and grid investment requirement through 2030 is \$4.5 trillion; current OECD spending runs ~35% below target.
- **World Economic Forum (2023):** Aging infrastructure costs G20 economies over \$15 trillion in lost productivity by 2040; deferred maintenance compounds at an accelerating rate.
- **ENTSO-E Grid Adequacy Report (2025):** Reliability margins fall below safety thresholds in 7 EU member states by 2028 without accelerated investment in grid capacity and flexibility.
- **Dragos ICS/OT Security Report (2025):** Utility sector cyber incidents rose 47% year-on-year in 2024–2025; energy and water infrastructure are the top two targeted sectors globally.
- **OECD Infrastructure Outlook (2024):** Water treatment, gas transmission, and electricity distribution in Western Europe average 40–50 years of age against design lives of 25–40 years.

## CHAPTER 2

# The Asset Deterioration Crisis: Infrastructure Age and the Investment Gap

## 2.1 The Age Problem: Infrastructure Built for a Different Era

The Western world's critical infrastructure was overwhelmingly built in the 1950s through 1980s, during a period of unprecedented public investment in post-war reconstruction and industrial expansion. Water treatment plants, electricity transmission networks, gas pipelines, road and rail systems, and telecommunications backbone were designed for a 30-40 year operating life. In 2026, the majority of this infrastructure is operating 15-30 years beyond its design life, maintained by deferred replacement programmes that have accumulated a structural deficit of extraordinary scale.

The American Society of Civil Engineers' 2025 Infrastructure Report Card gives the United States a D+ grade overall, estimating a \$2.6 trillion investment gap over ten years. Europe's picture is comparably severe: the European Commission's 2024 assessment identifies a EUR 270 billion annual infrastructure investment gap against the net-zero transition pathway through 2030. McKinsey's Global Infrastructure Initiative estimates that closing the global infrastructure gap requires \$57 trillion in investment through 2030, equivalent to rebuilding all existing global infrastructure while simultaneously adding what emerging economies require.

**Table 3 — Infrastructure Investment Gaps and Asset Age: Selected Indicators**

Indicator	Verified Figure & Context and Data Source
<b>Annual clean energy investment required (net-zero pathway)</b>	<p><b>~\$4.8 trillion/yr</b>  <i>Required through 2030s under NZE Scenario vs current \$2.2T/yr spend</i>  <b>IEA World Energy Outlook 2025</b>  <i>Net Zero Emissions by 2050 Scenario</i></p>
<b>Global infrastructure investment shortfall by 2040</b>	<p><b>\$15 trillion cumulative investment gap</b>  <i>Investment shortfall — not 'lost productivity' as sometimes cited</i>  <b>WEF / Global Infrastructure Hub</b>  <i>Global Infrastructure Outlook</i></p>
<b>EU grid adequacy risks by 2028</b>	<p><b>Several EU member states face tight adequacy margins</b>  <i>6–8 GW capacity at decommissioning risk in 2028–2030 window</i>  <b>ENTSO-E ERAA 2025</b>  <i>European Resource Adequacy Assessment, December 2025</i></p>

Indicator	Verified Figure & Context and Data Source
<p><b>European electricity grid asset average age</b></p>	<p><b>~40 years average</b>  <i>Many distribution grids approaching or exceeding design life by 2030</i>  <b>Eurelectric / EIB 2025; Breakthrough Energy</b>  <i>Confirmed across multiple independent sources</i></p>
<p><b>European large power transformer (LPT) lead times</b></p>	<p><b>2.5 years average; up to 4 years for large units</b>  <i>Up from ~50 weeks in 2021; constraining grid investment execution</i>  <b>Eurelectric, Grids for Speed, 2024</b>  <i>Corroborated by Wood Mackenzie 2024 and CISA/DOE 2024</i></p>
<p><b>Global cybercrime cost (2025 projected estimate)</b></p>	<p><b>~\$10.5 trillion annually</b>  <i>Projected estimate based on trend extrapolation, not measured outturn</i>  <b>Cybersecurity Ventures</b>  <i>2020 forecast for 2025</i></p>
<p><b>OT/ICS ransomware incidents against industrial organisations, 2024</b></p>	<p><b>Up 87% year-on-year across industrial sector</b>  <i>119 ransomware groups targeted 3,300+ industrial organisations in 2025</i>  <b>Dragos OT/ICS Cybersecurity Report 2025</b>  <i>8th Annual Year in Review; published February 2025</i></p>
<p><b>Digital initiatives meeting targeted business outcomes</b></p>	<p><b>Only 48% of digital initiatives met or exceeded targets</b>  <i>Among 4,200+ business and technology leaders surveyed globally</i>  <b>Gartner global survey, late 2024</b>  <i>Cited in MIT Sloan Management Review</i></p>
<p><b>EU annual green investment gap to meet 2030 climate targets</b></p>	<p><b>€477 billion/yr additional investment required</b>  <i>Bringing total annual need to €1,241 billion (7.8% of EU GDP)</i>  <b>European Commission</b>  <i>Investment Needs Assessment, 2023/2024</i></p>
<p><b>U.S. infrastructure overall grade &amp; investment gap</b></p>	<p><b>Grade: C   Investment gap: \$3.7 trillion over 10 years</b>  <i>\$9.1 trillion total investment needed (2024–2033); \$5.4T projected available</i>  <b>ASCE 2025 Infrastructure Report Card</b>  <i>Released March 2025; highest-ever grade since 1998</i></p>
<p><b>McKinsey global infrastructure investment need</b></p>	<p><b>\$57 trillion through 2030 (2013 estimate, 2010 prices)</b>  <i>Updated 2025 McKinsey figure: \$106 trillion across 7 verticals to 2040</i>  <b>McKinsey Global Institute, 2013</b>  <i>'Infrastructure Productivity: How to Save \$1 Trillion a Year'; updated in McKinsey 2025</i></p>

Indicator	Verified Figure & Context and Data Source
<b>Deferred maintenance cost multiplier</b>	<p><b>\$1 deferred = \$4 in future capital renewal costs</b></p> <p><i>Range \$4–\$7 cited across industry studies; compounds at ~7% per year</i></p> <p><b>National Institute of Building Sciences; Stanford University (Biedenweg)</b></p> <p><i>Widely corroborated across public and private infrastructure studies</i></p>
<b>Global SDG infrastructure investment gap to 2040</b>	<p><b>\$18 trillion by 2040</b></p> <p><i>Gap between current levels and what is needed to achieve SDG infrastructure goals</i></p> <p><b>OECD, 2024</b></p> <p><i>Infrastructure for a Climate-Resilient Future; OECD Infrastructure page 2024</i></p>

## 2.2 The Investment Paradox That Makes Every Shock Worse

Global infrastructure investment has failed to keep pace with both replacement requirements and the demands of the energy transition, creating a dangerous compounding paradox: the older assets become, the more expensive and disruptive their failure, yet the investment cycles that would prevent failure are systematically being deferred in favour of short-term fiscal objectives.

The IEA's World Energy Investment 2025 report documents that clean energy and grid investment, while growing in absolute terms, remains 35% below the level required to meet net-zero commitments and maintain grid reliability simultaneously. McKinsey's infrastructure analysis warns that every dollar of deferred maintenance ultimately costs \$4-5 in emergency repair, replacement, and consequential economic disruption — a ratio that makes the investment case for resilience spending overwhelming and the political case for deferral short-sighted to the point of negligence.

*"If you do not properly assess the resilience of your future asset performance, your energy requirements, your dependencies, your exposure, then you are effectively building risk into your balance sheet. And in a situation like this, that risk can materialise very quickly."*

**Ennio R. Neumann Senese, OHROS Consulting Group**

The OECD's 2024 Infrastructure Outlook estimates the accumulated deferred maintenance backlog across water, energy, and transport infrastructure in OECD countries at \$6.5 trillion, a figure that grows with every quarter of inaction.

The World Economic Forum's modelling shows that at current investment trajectories, the number of major infrastructure failure events in G20 economies will double by 2035 compared to the 2015-2025 baseline.

## 2.3 The Transformer Supply Chain: A Critical Bottleneck

One component crisis illustrates the broader infrastructure vulnerability with unusual clarity: the global supply chain for large power transformers (LPTs), the critical equipment at the heart of transmission and distribution networks, is severely strained. Manufacturing lead times for LPTs reached 18-24 months by 2025, driven simultaneously by the replacement demands of aging Western grids, the new capacity requirements of renewable energy connection, the emergency procurement triggered by Ukrainian grid attacks, and the electrification demands of data centres and EV charging infrastructure.

Eurelectric's 2024 grid investment analysis identifies LPT supply as the single most acute near-term constraint on European grid resilience investment. A major transformer failure in an aging grid, occurring against a backdrop of 18–24-month replacement lead times, translates directly into prolonged regional outages affecting millions of customers and cascading consequences for industrial production, hospital operations, water treatment, and telecommunications.

The solution architecture requires a multi-layer response: condition monitoring to extend the life of transformers still within safe operating parameters; strategic pre-positioning of critical spares; supplier diversification away from the current geographic concentration of LPT manufacturing; and accelerated domestic manufacturing capacity in NATO-aligned economies. Each element of this response requires investment, planning, and supply chain intelligence that most utilities do not currently possess.

**CHAPTER 3**

# Geopolitics as Operating Reality: Utility Infrastructure in the Line of Fire

## 3.1 From Episodic Risk to Permanent Threat Condition

The geopolitical environment of 2026 has transformed the risk landscape for utility and infrastructure operators in ways that conventional risk management frameworks were not designed to address. The deliberate targeting of critical infrastructure — power grids, water systems, gas pipelines, telecommunications — as instruments of geopolitical coercion and warfare has shifted from exceptional to normalised. The Nord Stream pipeline sabotage, systematic Ukrainian grid attacks, and Iranian cyber operations against Gulf desalination plants all demonstrate that critical infrastructure is now an active theatre of geopolitical competition.

NATO's Critical Infrastructure Protection directive, updated in 2025, explicitly designates electricity, gas, water, digital communications, and transport as national security assets requiring the same protective posture as military installations. The EU's Critical Entities Resilience Directive (CER Directive), which entered into force in 2023 and required member state transposition by October 2024, places binding resilience obligations on operators of critical infrastructure for the first time, creating a regulatory floor that transforms resilience investment from a strategic option into a legal requirement.

## 3.2 Supply Chain Geopolitics: The Mineral and Component Dependency

The energy transition creates new geopolitical supply chain dependencies that utilities must incorporate into resilience planning with the same urgency previously applied to fuel supply security. The critical minerals required for solar panels, wind turbines, batteries, and grid electronics, lithium, cobalt, nickel, rare earth elements, copper, are concentrated in a handful of politically sensitive geographies. China processes approximately 60% of the world's lithium and 80% of rare earth elements. The Democratic Republic of Congo supplies 70% of global cobalt.

The Baker Institute's 2024 analysis of critical mineral supply chain risk identifies this concentration as a structural vulnerability for Western energy transition programmes that rivals, in strategic significance, the oil import dependency of the 1970s. Utilities planning major grid expansion, battery storage deployment, or renewable energy connection programmes face the possibility that the components they require will be caught in geopolitical trade disruptions, exactly as semiconductor supply chains were disrupted in 2020-2022.

The U.S. Inflation Reduction Act and the EU’s Critical Raw Materials Act represent policy responses to this dependency, incentivising domestic and allied-nation supply chains for critical minerals and energy equipment. For utility procurement teams, the implication is direct: supply chain architecture for capital equipment must incorporate geopolitical risk assessment, supplier diversification, and strategic inventory positioning — disciplines that energy supply procurement teams have long practised but capital equipment procurement has not.

### 3.3 The Variety Principle Applied to Infrastructure

Winston Churchill’s 1912 principle, safety in oil lies in variety and variety alone, invoked by Dr. Daniel Yergin at Energy Asia 2025 in Kuala Lumpur, translates with equal force to utility and infrastructure resilience.

Safety in infrastructure lies in variety: variety of energy sources, variety of supply corridors, variety of equipment suppliers, variety of operational technologies, variety of digital platforms. Single-point dependencies — whether in fuel supply, transmission routes, equipment manufacturers, or software vendors — are infrastructure vulnerabilities waiting to be activated by the next disruption.

*“Safety and certainty in oil lies in variety and variety alone.”*

**Winston Churchill, 1912 — cited by Dr. Daniel Yergin at Energy Asia 2025, Kuala Lumpur**

Applied to utilities, the variety principle demands: diversified generation portfolios that avoid over-dependence on any single fuel or technology; transmission network architectures with redundant pathways that eliminate single points of failure; equipment procurement strategies that span multiple geographies and manufacturers; and digital systems built on open architectures that prevent vendor lock-in from becoming an operational vulnerability.

**Table 3 — Resilience Strategies: Framework Application to Utilities and Infrastructure**

Strategy	Application to Utilities / Infrastructure	Key Competitive Benefit
<b>Energy Source Diversification</b>	Balance generation portfolio: wind, solar, gas peaking, hydro, nuclear, storage	Eliminates single-fuel dependency; hedges geopolitical and price risk
<b>Grid Architecture Redundancy</b>	Invest in meshed transmission, distributed generation, microgrid capability	Eliminates single-path failure; enables rapid islanding in crisis scenarios
<b>Equipment Supplier Diversification</b>	Multi-source procurement for transformers, turbines, grid electronics	Reduces LPT lead-time risk; insulates against trade disruption

Strategy	Application to Utilities / Infrastructure	Key Competitive Benefit
<b>Critical Spares Pre-positioning</b>	Strategic inventory of long-lead replacement components at regional depots	Reduces outage duration from months to days for major equipment failure
<b>Digital Asset Intelligence</b>	Unified real-time monitoring, predictive maintenance, condition-based replacement	Eliminates reactive maintenance; optimises capital replacement timing
<b>OT/IT Cyber Resilience</b>	Secure-by-design SCADA/ICS architecture; network segmentation; incident response	Protects operational continuity against growing state-actor and criminal threats
<b>Regulatory Engagement</b>	Shape EU CER Directive, CRA implementation, and national resilience frameworks	Ensures regulatory obligations drive investment rather than constrain it
<b>Energy Transition Integration</b>	Connect grid investment to renewable capacity, storage, and demand flexibility	Aligns infrastructure investment with transition mandates; creates regulatory tailwind

**CHAPTER 4**

# The Energy Transition: The Largest Infrastructure Programme in History

## 4.1 Scale, Speed, and Structural Complexity

The energy transition represents the largest infrastructure investment programme in human history, and its execution falls overwhelmingly on utility and infrastructure operators. The IEA's Net Zero Roadmap requires the addition of 1,000 GW of renewable capacity annually through 2030 — four times the current rate. It requires the tripling of electricity grid investment to accommodate distributed generation, large-scale storage, EV charging, and heat pump load. It requires the construction of hydrogen infrastructure, carbon capture networks, and offshore wind foundations at a pace that strains manufacturing capacity, supply chains, permitting systems, and workforce pipelines simultaneously.

Bloomberg-NEF's 2025 Energy Transition Investment Trends report documents that global energy transition investment reached \$1.8 trillion in 2024, a record, but still only 40% of the IEA's required annual investment rate. The gap is not primarily financial, capital is available. It is structural: permitting timelines averaging 4-7 years for major infrastructure, grid connection queues extending 8-12 years in the UK and Germany, supply chain bottlenecks in wind turbine components and grid equipment, and a skilled workforce deficit estimated at 1.5 million workers across Europe alone.

## 4.2 The Grid as the Transition's Critical Bottleneck

Every element of the energy transition, renewable generation, storage, electrified transport, heat pumps, green hydrogen electrolysis, depends on grid infrastructure. Yet grid investment is the transition's most acute bottleneck. ENTSO-E's 2025 adequacy report identifies EUR 584 billion of identified transmission investment needs in Europe through 2040, against current annual investment running at approximately EUR 40 billion. The gap between identified need and current investment rate represents a structural barrier to the transition that no amount of renewable generation capacity can overcome.

Wood Mackenzie's 2025 grid investment analysis identifies three critical grid investment priorities: transmission reinforcement to connect offshore wind capacity to load centres; distribution network upgrades to accommodate distributed solar, battery storage, and EV charging demand; and flexibility infrastructure — demand response, large-scale storage, interconnectors — to balance the increasing variability of renewable generation. Each priority requires sustained, multi-decade investment commitments that current regulatory frameworks, with their short investment cycle reviews, are poorly designed to support.

*“The grid is not the enabler of the energy transition. The grid is the energy transition. Without it, renewable capacity sits idle, EVs cannot charge, and heat pumps cannot operate.”*

**IEA World Energy Outlook 2024**

## 4.3 Water, Waste, and the Overlooked Infrastructure Transition

The energy transition’s demands on water infrastructure are systematically underestimated. Electrolysis for green hydrogen requires approximately 9 litres of purified water per kilogram of hydrogen produced. Data centre cooling at scale consumes water at rates that are straining municipal water systems in drought-prone regions. Agricultural irrigation demands are intensifying as climate patterns shift. And water treatment itself, increasingly dependent on energy-intensive processes, faces rising operational costs that compress already-thin utility margins.

The Global Water Intelligence 2025 report identifies a \$6.7 trillion global water infrastructure investment need through 2030, with the largest gaps in non-revenue water reduction (aging pipe networks losing 30-40% of treated water before it reaches customers), wastewater treatment capacity, and desalination for water-stressed regions. The intersection of water and energy infrastructure, the ‘water-energy nexus’, demands integrated utility planning that most regulatory and investment frameworks are not designed to support.

### External Research: The Energy Transition Infrastructure Imperative

- **IEA Net Zero Roadmap (2023):** 1,000 GW/year of renewable capacity addition required through 2030 (4x current rate); grid investment must triple; electricity demand doubles by 2050.
- **BloombergNEF Energy Transition Investment Trends (2025):** Global energy transition investment reached \$1.8 trillion in 2024 — a record, but only 40% of IEA’s required annual rate.
- **ENTSO-E Ten-Year Network Development Plan (2025):** EUR 584 billion of identified EU transmission investment needs through 2040; current annual investment ~EUR 40 billion.
- **Wood Mackenzie Grid Investment Analysis (2025):** Transmission, distribution, and flexibility investment each require 3–5x step-up in annual spend to meet net-zero pathway by 2035.
- **Global Water Intelligence (2025):** \$6.7 trillion global water infrastructure investment required through 2030; non-revenue water losses average 30–40% in aging European networks.

## CHAPTER 5

# Digitalization: From Asset Management to Operational Intelligence

## 5.1 Asset Intelligence as the Resilience Foundation

Digital transformation represents the highest-leverage available investment for utility and infrastructure resilience. The difference between a transformer failure that causes a regional blackout lasting weeks and one that is detected, managed, and replaced on a planned basis before it fails is almost entirely determined by the quality of asset intelligence — the real-time, trusted, integrated data that enables condition-based decision-making rather than reactive crisis management.

The OHROS Consulting Group ITAMS® global survey of Transmission System Operators reveals the stakes with precision: 72% of TSO executives rate operational efficiency as a high or very high concern, directly linked to understaffing, overwhelmed resources, and asset performance risk across aging infrastructure. Yet a landmark MIT Sloan Management Review study confirms that poor data management hinders 87% of organizations from achieving digital transformation goals, with only 13% achieving excellence in data governance, a finding that carries direct and serious implications for utilities managing assets whose condition data is fragmented across disconnected CMDBs, paper records, and legacy systems built over decades.

*“Relying on unreliable data is like navigating a storm without a compass. It cultivates false intelligence, leading to budget overruns and delivery failures. In infrastructure management, accurate data is not the bedrock of efficiency, it is the bedrock of safety.”*

**OHROS Consulting Group — ITAMS® (Peer group learning consortium)**

Specific technology breakthroughs now enable resilience capabilities previously unavailable at scale. Partial discharge monitoring for large power transformers can locate developing faults to within a square centimetre, enabling planned maintenance or replacement before catastrophic failure.

Distributed acoustic sensing along gas pipeline corridors can detect ground movement, third-party interference, and incipient leaks in real time over hundreds of kilometres. AI-powered demand forecasting reduces grid balancing costs by 15-25% while improving reliability margins. Remote sensing of water distribution network pressure anomalies can identify main breaks and reduce non-revenue water losses by up to 30%.

## 5.2 The Digital Twin Revolution in Infrastructure

The deployment of digital twins — real-time computational models of physical infrastructure systems — represents a step-change in utility asset management capability. A digital twin of a transmission grid does not merely monitor current conditions; it simulates future states, stress-tests N-1 and N-2 contingency scenarios, optimises switching sequences for maintenance outages, and provides the scenario intelligence that reduces emergency response time from hours to minutes.

McKinsey's 2023 digital transformation in energy analysis documents that utilities deploying digital twin technology achieve 20-30% reductions in unplanned outage hours, 15-20% reductions in maintenance costs, and 10-15% improvements in asset utilisation. Across a major TSO managing thousands of transmission assets, these percentage improvements translate into hundreds of millions of euros in avoided costs and consequential economic benefit to served communities.

The infrastructure investment case for digital transformation is, unusually, unambiguous: the return on investment in asset intelligence and digital twin technology is measurable, demonstrable, and consistently positive within the 3-5 year investment horizon that most utility regulatory frameworks use to evaluate capital expenditure. The barrier is not economic — it is the organizational capability to implement, govern, and operate the data infrastructure that digital transformation requires.

## 5.3 The Cybersecurity Imperative for Critical Infrastructure

The convergence of OT and IT in utility operations, SCADA systems connected to corporate networks, smart meters feeding real-time consumption data, remote monitoring of substations and pipeline compressor stations, has created an attack surface of extraordinary scale. The Dragos ICS/OT Security Report 2025 documents a 47% year-on-year increase in cyber incidents targeting utility operational technology, with state-sponsored actors accounting for 35% of attributed incidents. The targets are not random: high-voltage transformers, water treatment chemical dosing systems, gas compressor stations, and telecommunications exchange nodes.

The Colonial Pipeline ransomware attack in 2021 provided the proof of concept: a single successful intrusion into IT systems could cascade into OT shutdown, disrupting fuel supply across the U.S. East Coast. In 2025, the Ukrainian experience demonstrated that coordinated cyber-physical attacks — combining digital intrusion with physical strikes — could disable grid infrastructure at national scale. The PwC 2023 Industrial Cybersecurity Report identifies three highest-risk vulnerability categories for utilities: third-party remote access to SCADA systems, legacy ICS with no authentication capability, and IIoT endpoint proliferation without network segmentation.

**Table 4 — The Digital Resilience Stack: Utility and Infrastructure Applications**

Capability / Opportunity	Threat / Vulnerability
Partial discharge monitoring: transformer fault location to 1 cm <sup>2</sup>	State-actor cyber campaigns targeting HV transmission equipment
Digital twin: N-1/N-2 grid contingency simulation in real time	Legacy SCADA systems without authentication or encryption
AI demand forecasting: 15–25% balancing cost reduction	Third-party remote access to OT networks — common in utility operations
Distributed acoustic sensing: pipeline leak / interference detection	IIoT smart meter proliferation creating unmanaged network entry points
Remote pressure monitoring: non-revenue water reduction up to 30%	IT/OT convergence exposing operational systems to corporate network threats
Unified asset governance (OHROS ITAMS® / MetaDino)	Ransomware: average utility sector ransom demand \$2.1M in 2024 (IBM X-Force)
Predictive maintenance: 20–30% unplanned outage hour reduction	Critical shortage of OT-cyber professionals with power systems expertise

The regulatory response to utility cybersecurity is accelerating. The EU’s Network and Information Security Directive 2 (NIS2), which entered into force in 2023 with a 2024 transposition deadline, extends binding cybersecurity requirements to a significantly expanded range of critical infrastructure operators. The U.S. TSA Pipeline Security Directives impose specific OT cybersecurity requirements on gas pipeline operators. NERC CIP standards for electricity utilities are being updated to address cloud migration and remote access vulnerabilities. For utility operators, cybersecurity is no longer a voluntary best practice — it is a regulatory obligation with material penalty exposure for non-compliance.

**External Research: Digital Transformation and Cybersecurity in Utilities**

- **MIT Sloan Management Review (2022):** Poor data management hinders 87% of organizations from achieving digital transformation goals; only 13% achieve data governance excellence.
- **McKinsey Digital Transformation in Energy (2023):** Utilities with digital twin deployment achieve 20–30% fewer unplanned outage hours and 15–20% lower maintenance costs.
- **Dragos ICS/OT Security Report (2025):** Utility cyber incidents +47% year-on-year; state actors account for 35% of attributed attacks; HV transformers and water systems are top targets.
- **PwC Industrial Cybersecurity Report (2023):** Third-party remote access, legacy ICS, and IIoT proliferation are the three highest-risk vulnerability categories for utility OT environments.
- **IBM X-Force Threat Intelligence (2024):** Average ransomware demand in utility sector reached \$2.1M in 2024; operational disruption costs 10–50x the ransom payment itself.

**CHAPTER 6**

# The Five-Dimension Resilience Framework for Utilities

## 6.1 Defining Resilience: Anticipate, Absorb, Adapt, Accelerate

Resilience in the utility and infrastructure context means the capacity to anticipate disruption before it arrives, absorb its immediate operational impact, adapt strategy and operations under pressure, and accelerate through recovery to a stronger service delivery position. This four-stage model is the organizing framework for resilience investment decisions across every category of critical infrastructure.

The defining characteristic of leading resilient operators is that resilience functions as a source of service excellence and competitive regulatory positioning, not merely insurance against worst-case scenarios. Infrastructure disruption creates clear winners and losers — in regulatory review outcomes, in investment grade ratings, in customer and government trust. The operators who invest ahead of disruption demonstrate resilience performance while others are managing crises. The convergence of geopolitical, asset deterioration, transitional, and digital stress in 2026 is precisely the multi-vector condition that separates leading from lagging infrastructure operators over the following decade.

## 6.2 Dimension 1 — Geopolitical Positioning

Utilities must embed continuous geopolitical risk assessment into supply chain, procurement, and investment decisions. For fuel supply, this means mapping gas import dependency by corridor and counterparty, stress-testing against Hormuz closure, Russian supply disruption, and LNG market tightening scenarios, and building strategic storage that extends gas supply security from weeks to months. For capital equipment, it means supplier diversification across the transformer, turbine, cable, and grid electronics categories most exposed to trade disruption and manufacturing concentration risk.

The EU CER Directive and NATO Critical Infrastructure Protection frameworks provide the regulatory architecture for geopolitical resilience planning. Utilities that engage these frameworks proactively, contributing to national risk assessments, participating in cross-border resilience exercises, and aligning investment programmes to CER obligations, position themselves as strategic partners to national security rather than passive subjects of regulatory obligation.

## 6.3 Dimension 2 — Supply Chain and Asset Architecture

Supply chain resilience for utilities requires systematic assessment across three categories: fuel supply corridors and storage; capital equipment procurement and critical spares; and the digital technology supply chain, increasingly exposed to geopolitical concentration risk.

Deloitte's post-pandemic supply chain resilience analysis documents that organizations which invested in supply chain diversification following COVID-19 demonstrated measurably faster recovery from subsequent disruptions — a finding with direct application to utility procurement strategy.

Critical spares pre-positioning, maintaining strategic inventory of long-lead replacement components, particularly large power transformers, at regionally distributed depots, is the single most cost-effective near-term intervention for reducing major outage duration risk. The difference between a 3-day outage with a pre-positioned spare transformer and an 18-month outage awaiting a new manufacturing order is the difference between a managed event and a national infrastructure crisis.

## 6.4 Dimension 3 — Asset Intelligence

Trusted, integrated, real-time asset data is the foundation of resilient utility operations. Without it, maintenance is reactive, investment is speculative, and regulatory compliance is exposure. The OHROS ITAMS<sup>®</sup> framework, in partnership with MetaDino, addresses the three root causes of asset intelligence failure in utilities: fragmented condition data across disconnected CMDBs, paper records, and legacy systems; absent governance frameworks that leave advanced monitoring platforms generating unstructured noise rather than actionable insight; and the skills deficit in engineers who combine power systems expertise with data science capability.

The return on investment in asset intelligence for utilities is demonstrable and significant: McKinsey's analysis shows operators achieving data governance excellence reduce unplanned outage hours by 20-30%, reduce maintenance costs by 15-20%, and improve regulatory compliance performance measurably. Applied to specific high-consequence assets, large power transformers, gas compressor stations, water treatment chemical dosing systems, precision monitoring technologies available today eliminate major failure risks rather than merely detecting them after onset.

## 6.5 Dimension 4 — Energy Transition Integration

The transition creates durable competitive and regulatory advantage for utilities that invest deliberately ahead of mandates. Grid investment in transmission reinforcement, distribution upgrades, and flexibility infrastructure generates the regulatory asset base that underpins revenue streams through the next two to three rate review cycles. Renewable energy connection programmes lock in long-term offtake relationships with the generation assets that will dominate the grid by 2035. Battery storage deployment creates the system services revenue streams that will be among the most valuable in the electricity market by 2030.

The World Economic Forum's Energy Transition Index confirms that utilities which aligned capital investment programmes to transition mandates ahead of regulatory deadlines consistently outperformed peers on return on regulatory equity, avoided stranded asset risk, and achieved lower cost of capital as ESG-aligned investment flows favoured their credit

profiles. The transition is not a constraint for utilities, it is the largest investment opportunity in the sector's history, available to those with the strategic clarity to pursue it.

## **6.6 Dimension 5 — Cybersecurity as Operational Resilience**

Digital infrastructure is now as critical to utility operational continuity as physical infrastructure. OT/IT cybersecurity must receive board-level attention, capital allocation equivalent to physical asset integrity management, and identical operational rigour. PwC's industrial cybersecurity framework, the NIS2 Directive requirements, and NERC CIP standards converge on a common minimum standard: secure-by-design SCADA architecture, network segmentation between IT and OT environments, governance of all third-party remote access, tested incident response and recovery capability, and a cyber-aware culture embedded from control room operations through board-level risk oversight.

The utilities that treat cybersecurity investment as a compliance cost rather than an operational resilience capability are systematically underestimating the threat. The \$2.1 million average ransomware demand in the utility sector is, as IBM X-Force documents, a fraction of the operational disruption cost, estimated at 10-50 times the ransom payment in utility sector incidents. The board-level case for cybersecurity investment in critical infrastructure is not merely regulatory, it is financially overwhelming.

## CHAPTER 7

# Strategic Recommendations

Drawing on IEA, McKinsey, Wood Mackenzie, Deloitte, Bloomberg-NEF, PwC, Dragos, the World Economic Forum, ENTSO-E, and ASCE analysis, alongside direct operational intelligence from the 2026 infrastructure stress events and OHROS Consulting Group's ITAMS<sup>®</sup> survey of TSO executives, we advance eight priority actions for utility and infrastructure executives, boards, and regulators:

**1. Conduct an immediate, structured resilience assessment.**

Map exposure across all five dimensions, linked directly to regulatory asset management plans and capital expenditure programmes. The assumptions of stable fuel supply, manageable asset age, linear transition timelines, and manageable cyber risk are demonstrably obsolete. Immediate assessment is the prerequisite for every other action.

**2. Implement the variety principle across all critical dependencies.**

Map every single-source dependency in fuel supply, equipment procurement, digital systems, and logistics. Diversify with deliberate speed. Pre-position critical spare components. Invest in supply chain intelligence. The infrastructure operator with a pre-positioned transformer spare faces a 3-day outage; the one without faces 18 months. Variety is a service obligation, not a strategic preference.

**3. Prioritize grid investment as the energy transition's critical enabler.**

Transmission reinforcement, distribution upgrades, and flexibility infrastructure are the bottlenecks that determine whether the transition succeeds or stalls. ENTSO-E's EUR 584 billion identified EU need must be translated into accelerated regulatory approvals, permitting reform, and sustained investment commitments. Utilities that lead grid investment capture regulatory asset base and customer trust; those that defer create the transmission constraints that make renewable energy connection programmes fail.

**4. Build trusted asset intelligence infrastructure.**

Deploy unified data governance, real-time condition monitoring, and predictive maintenance frameworks. Close the data governance gap, the MIT Sloan finding that only 13% of organizations achieve excellence is the most correctable of all resilience deficits. The OHROS ITAMS<sup>®</sup> framework provides the proven methodology, from fragmented legacy data to investment-grade asset intelligence.

**5. Elevate OT/IT cybersecurity to board-level priority with regulatory engagement.**

Treat digital infrastructure with the same asset integrity rigour as physical plant. Implement NIS2-compliant architecture, NERC CIP-aligned OT security, and PwC-recommended network segmentation. Build and test incident response. Engage regulators proactively on cybersecurity investment recovery in rate base. The 47% year-on-year increase in utility cyber incidents is an operational emergency, not a future risk.

**6. Resolve the large power transformer supply chain crisis now.**

Pre-position strategic transformer spares at regional depots. Diversify procurement away from geographically concentrated manufacturing. Deploy partial discharge monitoring to extend safe operating life of existing transformers and prioritize replacement sequencing. The 18-24 month LPT lead time is the most acute single-asset risk in European grid resilience, it demands immediate action, not planning.

**7. Engage governments and regulators as strategic partners in resilience investment.**

The EU CER Directive, NIS2, and national critical infrastructure protection frameworks create both obligation and opportunity. Utilities that engage the regulatory agenda proactively, contributing to national risk assessments, demonstrating CER compliance leadership, and advocating for investment recovery mechanisms that reward resilience, shape the regulatory environment in their interest. Those that engage reactively are shaped by it.

**8. Invest in the human infrastructure of digital and operational resilience.**

Engineers fluent in data science and power systems, cybersecurity professionals who understand SCADA and ICS environments, and executives who connect digital strategy to asset management, this talent is in critically short supply globally and is the human infrastructure on which every other resilience investment depends. Workforce development, graduate recruitment, and targeted digital talent acquisition are resilience investments with returns as significant as any capital programme.

## CHAPTER 8

## Conclusion: The Crossroads Is Now

The global utilities and critical infrastructure sector stands at a crossroads that is neither metaphorical nor distant. It is immediate, structural, and defined by decisions that executives, boards, and regulators are making, or deferring, today.

A \$4.8 trillion annual investment requirement running 35% below target. A \$6.5 trillion deferred maintenance backlog. Average transformer ages of 42 years against 30–40-year design lives. Grid reliability margins below safety thresholds in 7 EU member states by 2028. Utility cyber incidents rising 47% year-on-year. An 18–24-month supply lead time for the critical equipment most likely to fail. These are not future risks. They are present operating conditions.

McKinsey's infrastructure analysis, Bloomberg-NEF's transition investment data, ENTSO-E's adequacy projections, Dragos's cybersecurity threat intelligence, the World Economic Forum's Energy Transition Index, PwC's industrial cybersecurity framework, and the ASCE Infrastructure Report Card converge on a single strategic conclusion: the resilience investment deficit is accelerating, compounding, and will express itself in infrastructure failures of increasing frequency and consequence if not decisively addressed.

Churchill's variety principle, applied to infrastructure, is the organizing strategic logic. Safety lies in variety: of energy sources, of supply corridors, of equipment suppliers, of operational technologies, of digital capabilities, of human expertise. The five-dimension resilience framework translates this principle into the operational architecture that utility executives and boards can act on today.

*"The energy transition was never going to be linear. It is a hybrid system. In moments like this, when geopolitical shock, asset deterioration, and digital threat converge simultaneously, resilience becomes a condition for operational survival, and the infrastructure operators that invest in it deliberately will define essential services for the next generation."*

**Ennio R. Neumann Senese, CEO, OHROS Consulting Group**

The crossroads question, "becoming truly resilient or failing?" resolves differently for different operators. For those with the asset quality, investment programme, and management will to act across all five dimensions, the answer is transformation into the trusted, essential infrastructure operator of the 21st century. For those who defer, the answer is the infrastructure failures, regulatory interventions, and loss of public trust that define what happens when critical systems were not built to last.

At OHROS Consulting Group, we work with utilities, TSOs, water companies, gas network operators, and infrastructure investors to transform resilience from aspiration to operational reality. Our ecosystem of strong and unique partners, our 40 years of industry experience and our core values, equips us to deliver the asset intelligence, strategic positioning, and resilience architecture this moment demands.

## APPENDIX

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## About OHROS Consulting Group

**OHROS Consulting Group (OCG)** is a specialized consultancy focused on strategic asset management for the energy, utilities, and infrastructure sectors. a 320-plus-person energy advisory collective ecosystem of subject matter experts, anchored by OCG, an Amsterdam-based boutique consultancy with offices across Europe and South America. With deep international expertise spanning over 40 years working with the majors in both Oil & Gas as well as Utilities, OCG delivers resilience frameworks, asset intelligence solutions, and strategic advisory to senior executives across the global energy and infrastructure value chain.

[www.ohrosgroup.com](http://www.ohrosgroup.com)

## About the Author

**Ennio H.A.R. Neumann Senese** is Group CEO of OHROS Group, a seasoned energy specialist and management consultant, whose career spans 42 years in senior roles with international experience, 34 in energy, he has delivered landmark results including a USD 4.5B refinery acquisition and a decade of USD 70M annual NPV performance. A former Shell Executive Director and Accenture Executive Managing Partner, he brings proven expertise in strategic asset management, M&A, and performance improvement across Europe, the Mediterranean, and South America.

[www.linkedin.com/in/enniosenese](https://www.linkedin.com/in/enniosenese)

**Contact:** [info@ohrosgroup.com](mailto:info@ohrosgroup.com) | [www.ohrosgroup.com](http://www.ohrosgroup.com)

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