World Energy Markets Outlook

Turn disruption into action

28th Edition

Capgemini

Welcome to the 28th edition of the World Energy Markets Outlook



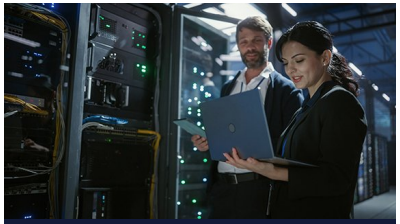
01 Global Outlook



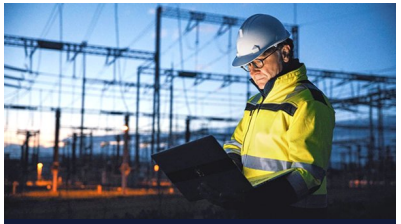
02 Digital Sovereignty



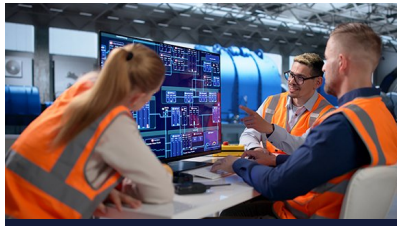
03 Capital Projects



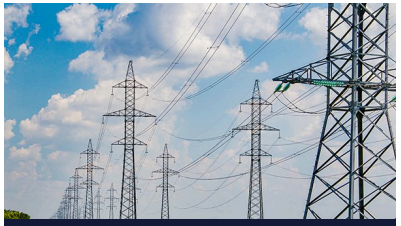
04 Data Centers



05 Grid Modernization



06 Grid Congestion



07 Grid Balancing



08 Flex Markets



09 Climate Change Adaptation



10 Battery Energy Storage System



11 Nuclear Renaissance



12 Oil & Gas

01

GLOBAL OUTLOOK

From shock to strategy:

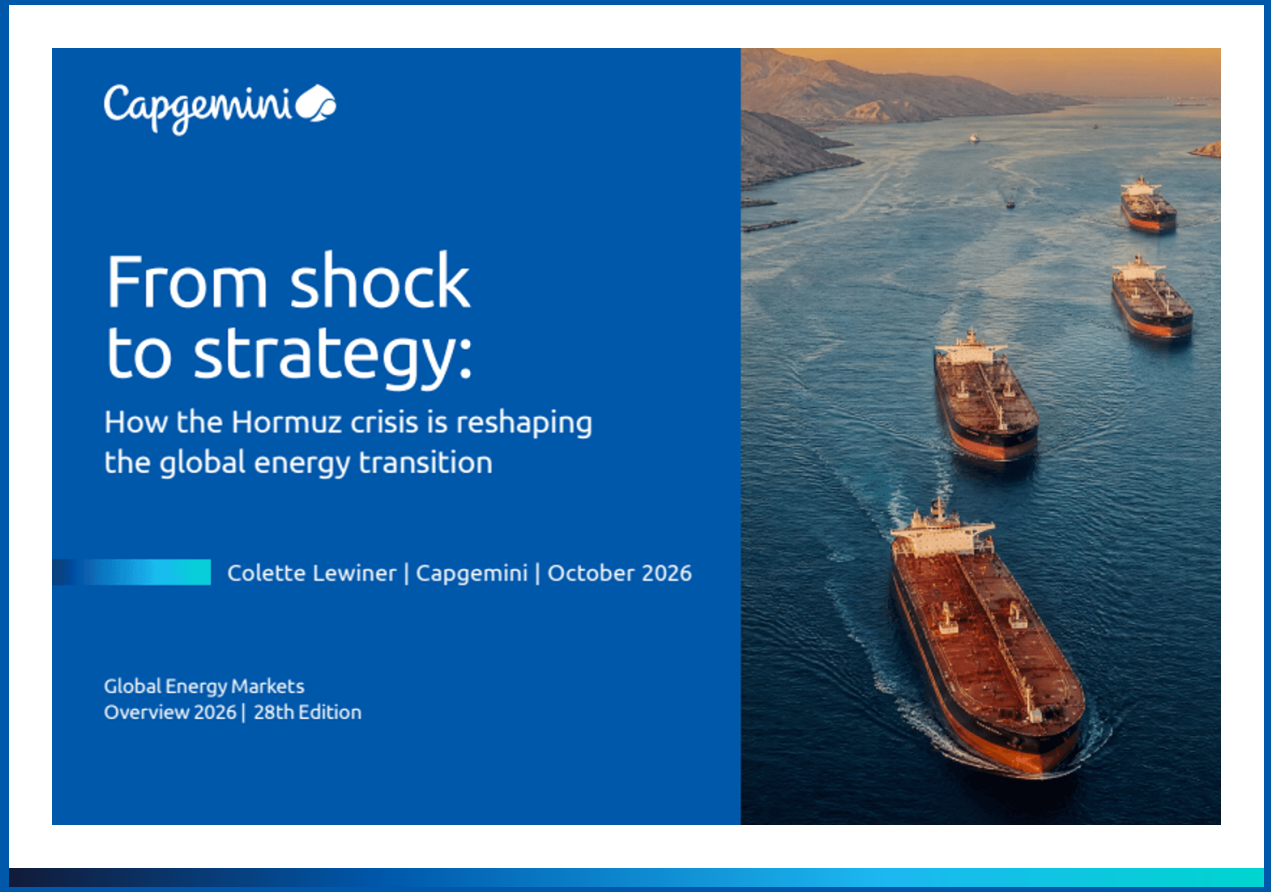
How the Hormuz crisis is reshaping the global energy transition.



From shock to strategy:

How the Hormuz crisis is reshaping the global energy transition.

Click on the PDF to download and read the full report.



02

DIGITAL SOVEREIGNTY

Energy: the forgotten pillar of digital sovereignty



DIGITAL SOVEREIGNTY

Energy: the forgotten pillar of digital sovereignty

Cloud made infrastructure invisible. AI is making energy visible again.

For more than a decade, cloud computing made infrastructure invisible, consumed on demand and abstracted away from the physical world of power stations, substations and cooling systems. Artificial intelligence is reversing that abstraction. As models grow and inference scales, the physical foundations of digital infrastructure, and above all the energy that sustains them, are becoming visible again.

This matters because digital sovereignty has moved from policy ambition to executive imperative. It is now a board-level concern, driven by geopolitical fragmentation, tightening regulation, concentrated cloud markets and deepening AI dependency. Capgemini Research Institute research finds that digital sovereignty is a top board priority for 44% of organizations, yet most still frame it narrowly around cloud, data, legal jurisdiction and cybersecurity.

That framing is incomplete. Sovereignty is not a cloud question; it is a full-stack business resilience question spanning cloud, data, AI, energy, hardware, software, cybersecurity and connectivity. As AI drives unprecedented demand for compute, and compute depends on assured, scalable power, energy is emerging as the ultimate constraint, and therefore a foundational element of sovereignty itself. Tellingly, energy is the least considered sovereignty dimension, cited by just 35% of organizations.

This article argues that without resilient, predictable access to energy, digital sovereignty cannot be achieved. Sovereignty is not isolation or self-sufficiency; it is the capacity to maintain control and continuity while managing dependencies deliberately. Energy belongs at the center of that calculation, for every AI-intensive organization, not only for the Energy and utilities sector.



Capgemini Research Institute research finds that digital sovereignty is a top board priority for 44% of organizations.



1. The surge of digital sovereignty

Digital sovereignty has entered the mainstream as a strategic business priority. A globalized, highly connected economy has created a network of dependence in which the failure, or restriction, of a single technology provider can trigger cascading disruption. More than 90% of organizations report that most of their digital products, services, infrastructure and intellectual property are imported.

Several forces are converging. Geopolitical fragmentation and extraterritorial legislation have made jurisdictional exposure a default assumption. Regulation is intensifying, from NIS2 and DORA to the AI Act and the European Union's Tech Sovereignty Package. Cloud markets remain highly concentrated, AI is deepening dependence on a small number of platforms, and supply chains for critical components are exposed to shock.

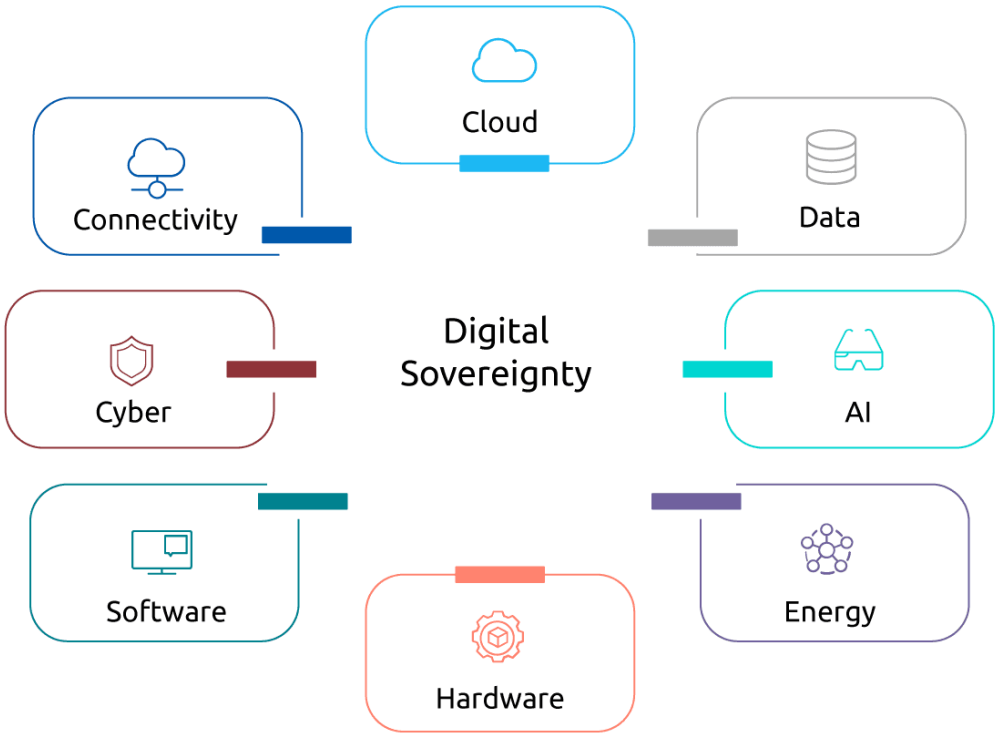
The result is sustained board-level attention, with sovereignty now sitting alongside ESG, cyber and geopolitical risk on the board agenda. Crucially, most executives view it not as ideology but as risk management: the central question is how to strengthen sovereignty without sacrificing competitiveness.

2. Sovereignty beyond cloud

Sovereignty conversations that begin with cloud too often end there. Yet a credible posture spans eight interdependent dimensions: cloud provides controllable and portable infrastructure; data requires governed storage, processing and movement; AI depends on models, platforms, compute and oversight; energy powers the digital estate; hardware provides its physical foundation; software enables its functionality; cybersecurity protects it; and connectivity links it across fixed, mobile, private, cross-border and satellite networks. Each can be examined determining who can access assets, who runs them, whether the stack is portable and reversible, and which jurisdictions hold sway.

These dimensions are not independent workstreams. A resilient cloud architecture can still fail if the semiconductor supply chain is compromised; a sovereign data strategy can be undermined by a non-sovereign connectivity layer; and any digital estate can be halted by loss of power. Sovereignty is therefore a full-stack business resilience question, not a procurement decision about where data sits.

Figure 1: Dimensions of the tech stack included in Capgemini's definition of digital sovereignty



3. The rise of compute sovereignty

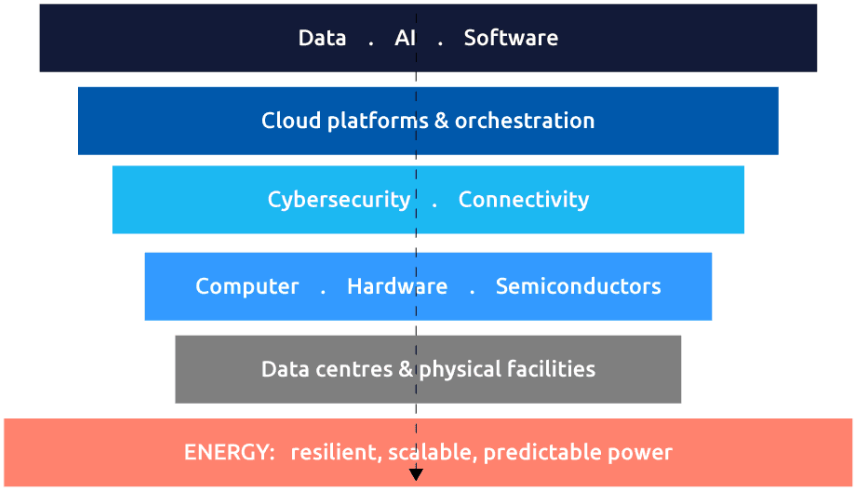
Data sovereignty, cloud sovereignty and AI sovereignty each matter. But as AI reshapes the technology landscape, they increasingly converge on a single, unifying concern: compute sovereignty, the assured ability to access, control and sustain the processing capacity on which digital value depends.

Compute is where the eight dimensions meet. It rests on semiconductors and specialized hardware, on the data centers that house them, on the networks that connect them, on the cloud platforms that orchestrate them, and on the energy that powers and cools them. A weakness in any one layer becomes a weakness in an organization's ability to train models, run inference and operate critical services.

Compute is becoming a strategic input to competitiveness, not a commodity bought on demand. When it is constrained, whether by supply allocation, regulation or power availability, AI ambitions, product roadmaps and national competitiveness are constrained with it. Framing sovereignty around compute forces leaders to look past the application layer to the physical foundations beneath it.

Figure 2: The Full Sovereignty Technology Stack

Each layer rests on the one beneath; energy is the base



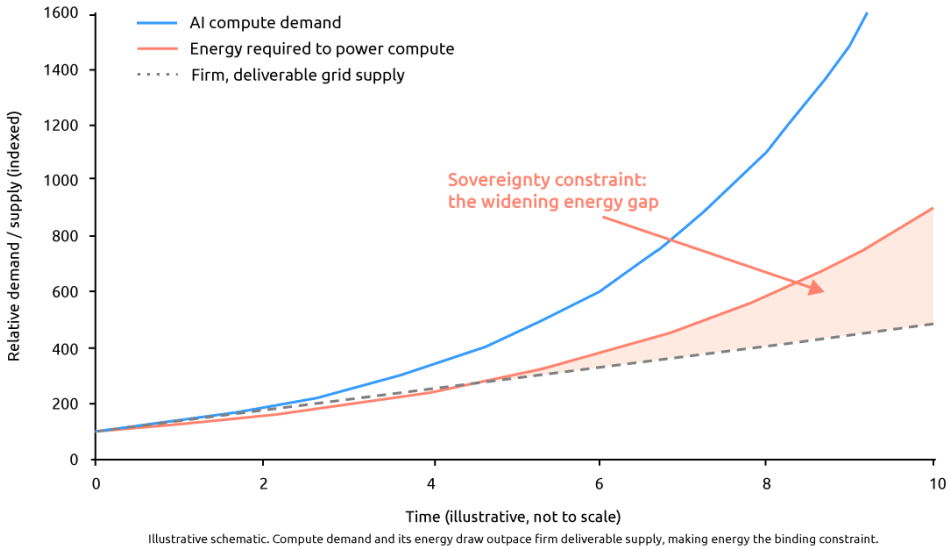
Without assured energy, the layers above cannot be sustained

4. Energy as the forgotten pillar of digital sovereignty

Of those foundations, energy is the most consequential and the least examined. AI workloads are driving unprecedented demand for power, turning data-center energy consumption from a sustainability footnote into a strategic infrastructure question. Access to firm, scalable and predictable power is fast becoming a primary determinant of where data centers are built, which cloud regions are viable, and where AI capacity can be located at all.

Supply cannot be assumed. The energy transition is adding large volumes of variable renewable generation, challenging grid operators to maintain balance and stability. Grid congestion can delay or cap new connections; contracted capacity does not guarantee real-time delivery when the network is constrained. Energy availability is therefore not a binary condition but a dynamic, price- and time-dependent constraint: a real-time optimization problem met through local generation, storage, demand flexibility and diversified supply rather than a single grid connection.

Figure 3: Energy vs Compute Demand



Illustrative schematic. Compute demand and its energy draw outpace firm deliverable supply, making energy the binding constraint.

The energy and utilities sector illustrates the point. Grid operators already balance decentralized solar, wind and hydro against rising, concentrated demand from electric vehicles, electrified industry and AI data centers. The convergence of IT and operational technology in smart grids and industrial controls creates both new capability and new exposure, and the most sensitive assets, nuclear generation among them, justify air-gapped separation. Some hyperscalers are now contracting nuclear capacity, including small modular reactors, to secure long-term supply, though these remain largely at pilot and licensing stages rather than ready at scale.

The strategic implication reaches well beyond that sector. For any AI-intensive organization, energy is now a first-order input to digital strategy, not a downstream operational consequence. This is why energy is the foundational pillar: without assured, resilient access to power, the other dimensions of sovereignty cannot be sustained. It is also why energy's status as the least considered dimension is a strategic blind spot rather than a minor omission.



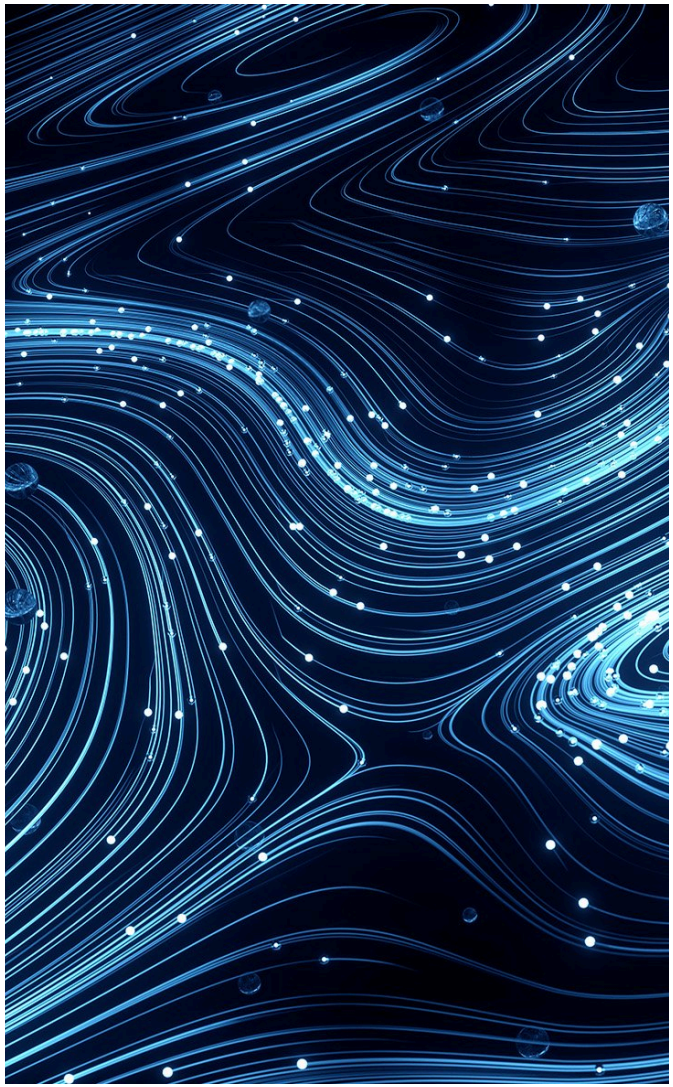
5. The sovereignty measures continuum

Because sovereignty is a spectrum of controls rather than a flag to be planted, organizations can position themselves along a continuum of progressively stronger measures. These range from legal frameworks and contractual protections, through cloud and data-center break-glass arrangements, international cooperation and Minimum Viable Organization planning, to mission-critical segregation, public-cloud sovereignty controls, multi-cloud strategies and “develop-low, deploy-high” models. They extend further to private cloud, sovereign cloud, portability and reversibility measures, air-gapped environments and, at the far end, mobile or self-contained data center concepts.

No point on this continuum is universally correct. The right posture is risk-based and workload-specific: a customer collaboration platform and a national control system sit in very different places, and over-classification is as costly as under-classification. This is the essence of managed interdependence: not eliminating dependencies, but choosing them deliberately, building controlled reversibility, and retaining the ability to adapt as conditions shift.

6. How organizations should begin their sovereignty journey

A practical starting point does not require a grand program. Leaders can begin by elevating sovereignty to a genuine board-level discussion with a defined risk appetite. From there: identify the critical business capabilities that must keep running under stress; assess the digital and energy dependencies beneath them; define an acceptable level of risk exposure; prioritize resilience investments accordingly; build sovereignty into operating models rather than one-off compliance; and foster innovation through managed interdependence, using diversified, sovereignty-aware options as a source of resilience and negotiating strength.



Conclusion

Cloud made infrastructure invisible. AI is making energy visible again. As AI-driven economies emerge, the ability to secure resilient, scalable and predictable power is becoming a prerequisite for digital independence. Digital sovereignty is not merely about controlling cloud, data or AI; it is about sustaining the compute, and therefore the energy, on which all of them depend.



Energy sovereignty is becoming foundational to digital sovereignty, and organizations that recognize this early will be better positioned to execute their strategies when others cannot.

Authors



Rene Kerkmeester
Global Vice President, Integrated Power Lead, Capgemini



Geert-Willem Haasjes
Vice President & Technology Evangelist, Capgemini



Rob Kernehan
Vice President & Technology Evangelist, Capgemini

03

CAPITAL PROJECTS

Construction: the critical path towards capital efficiency



CAPITAL PROJECTS

Construction: the critical path towards capital efficiency

How the industry must reinvent itself to deliver the infrastructure the world needs

In the most recent World Energy Investment report, IEA projected global energy spending to reach $3.4 trillion in 2026, a 5% increase over the previous year.[1] Analysis also showed high investment in clean energy, with two dollars flowing to renewables, nuclear, grids, storage, low-emissions fuels, efficiency and electrification for every one dollar invested in oil, natural gas and coal.[2]

But investment alone will not deliver the energy transition.

$3T
Expected global energy investment in 2026 (IEA)

5%
YOY increase between 2025-2026 (IEA)



[1] https://www.iea.org/reports/world-energy-investment-2025

[2] https://www.iea.org/reports/world-energy-investment-2025

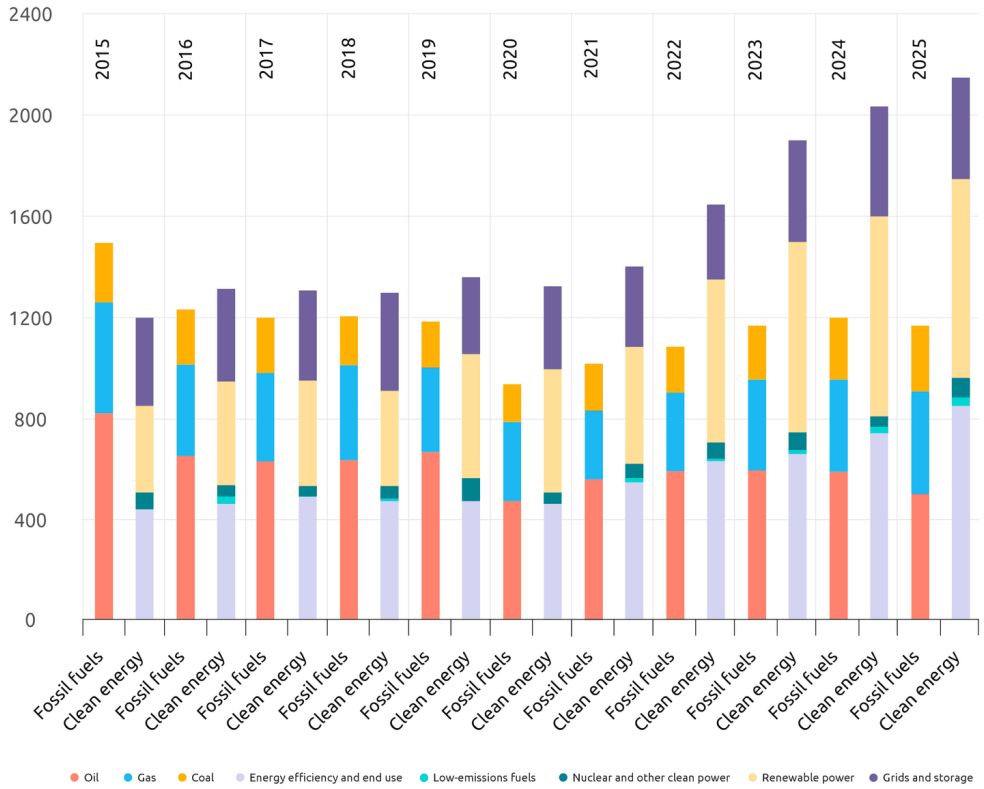
As demand surges and spending accelerates, the energy industry's greatest challenge has shifted from funding infrastructure to building it. Grid connections, transmission upgrades, interconnectors, and other critical assets must all be delivered at a speed and scale that the current construction delivery model cannot support.

As a result, construction has become one of the defining constraints of the global energy transition. Overcoming it requires a fundamental reinvention of how infrastructure is designed, engineered and delivered.

Here we explore how the construction industry must evolve toward a fundamentally different model—one that is outcome-led, alliance-based, digitally integrated, and focused on delivering value across the entire asset lifecycle—and why doing so will not only support the energy transition, but also help fulfill the sector's own growth ambitions and meet capital efficiency expectations.

Figure 1: IEA: Global investment in clean energy and fossil fuels, 2015-2025

IEA (2025), Global investment in clean energy and fossil fuels, 2015-2025, IEA, Paris3



[3] https://www.iea.org/data-and-statistics/charts/global-investment-in-clean-energy-and-fossil-fuels-2015-2025

Figure 2: IEA: Clean energy investments by region, 2025[4]

China	$627 billion
European Union	$386 billion
United States	$400 billion
Other emerging markets and developing economies	$300 billion
Other advanced economies	$175 billion
Japan and Korea	$103 billion
India	$100 billion

What needs to change in construction. (And why the answer isn't just AI.)

Despite unprecedented demand for new energy infrastructure, construction productivity has increased by just 0.4% annually over the past two decades, compared with around 3% in manufacturing and 2% across the broader economy.[5]

However, in recent years, momentum is beginning to build. In 2024, more than 64% of construction firms were using or piloting AI to improve efficiency and reduce costs.[6]

While this growing adoption is encouraging, technology alone, especially when deployed as point solutions, won't solve the industry's overarching productivity challenge. Instead, construction organizations need to rethink how they operate, how people and partners work together, and the foundations that support them. Here we offer five interconnected changes that can help the construction industry scale delivery and support the energy transition.

[4] https://www.iea.org/reports/world-energy-investment-2025/executive-summary

[5] https://www.vsimple.com/blog/mckinsey-study-shows-the-construction-industry-is-in-a-productivity-rut

[6] https://www.startus-insights.com/innovators-guide/construction-industry-trends/

Change 1: The operating model

Construction organizations have traditionally been designed to manage individual projects, with governance, decision-making and resources optimized for project delivery rather than portfolio-wide outcomes. However, that model was never intended to support the unprecedented scale of investment now flowing into the industry, particularly across energy infrastructure.

Rather than managing individual contracts in isolation, construction organizations must become outcome-led, aligning owners, engineers and contractors around shared objectives and value creation across the asset lifecycle. To do that, the delivery model itself also needs to evolve.

Today's models remain largely engineering-centric, with responsibility for digital innovation often absorbed into traditional roles.

Instead, digital transformation integrators should have an explicit place alongside engineering and delivery partners, bringing dedicated AI, data and digital expertise into the project from the outset.

The role of these digital transformation integrators is not simply to implement technology, but to continuously challenge and evolve how projects are designed, delivered and operated. This ensures reinvention and innovation have clear ownership rather than relying on engineering teams to drive that agenda alongside their core responsibilities.

This new operating model creates the conditions for delivering more projects, more efficiently and with greater certainty. But achieving those outcomes also requires changing how the work itself gets done.

Updating the operating model: Key actions

- √ Embed desired outcomes from the earliest stages of planning.
- √ Align commercial incentives around long-term asset performance rather than individual project milestones.
- √ Make decisions based on total cost of ownership rather than the cost of delivery alone.
- √ Establish the digital integrator as an explicit role in the delivery model, bringing the dedicated AI, data and digital capabilities needed to challenge traditional engineering-centric approaches and transform project and asset performance.

Change 2: Ways of working

An outcome-led operating model calls for new ways of working. As AI capabilities mature, the opportunity is no longer simply to automate existing processes, but to redesign them around people and AI agents working together from the outset.

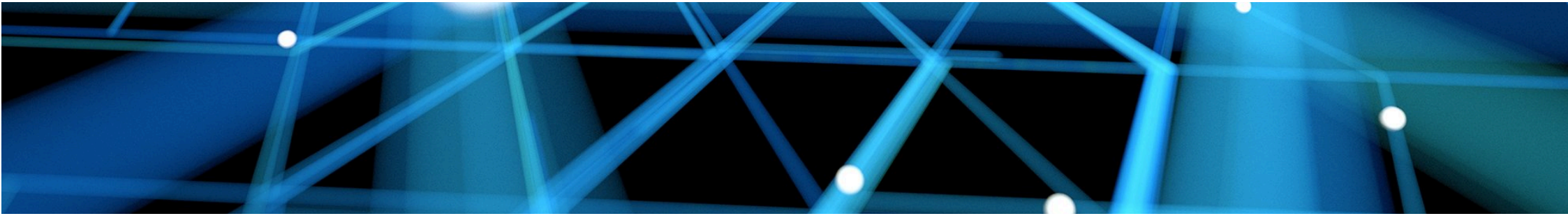
Core tasks within design development, engineering reviews, cost estimation, procurement planning and commissioning can all be reimagined around collaborative human-AI workflows that improve quality, reduce rework and accelerate delivery.

For example, AI can continuously review evolving designs for constructability, cost, schedule and compliance, providing engineers with immediate feedback rather than waiting for formal review gates. This allows teams to identify issues earlier, make decisions faster and reduce the costly rework that often occurs later in construction.

But greater AI autonomy also requires a fundamental shift in governance. Policies, controls and oversight need to be embedded into these new ways of working so that organizations can define what agents can do, where human intervention is required and how risk is managed. An agentic control plane is needed to provide that governance layer, allowing organizations to increase autonomy while maintaining appropriate control and accountability.

Human-AI workforce: Key actions

- √ Redesign processes around human-AI collaboration rather than automating existing workflows.
- √ Shift decision-making earlier in the project lifecycle to reduce downstream rework and risk.
- √ Evolve governance for an agentic environment, using an agentic control plane to embed the policies, controls and oversight that govern how AI agents operate as autonomy increases.



Change 3: Workforce capabilities

Redesigning how work gets done also means rethinking the skills and expertise needed to deliver it. Existing workforce shortages, now compounded by surging demand for data center development, make it increasingly important to amplify the expertise of engineers, estimators, quantity surveyors and project managers.

This is where AI can play a useful role. For example, intelligent tools can review thousands of pages of engineering documentation, compare design revisions or generate quantity take-offs in minutes rather than days. Engineers remain responsible for validating decisions, but AI frees them to focus more of their time on solving complex technical problems.

AI can also help organizations capture and transfer specialist knowledge across projects and sectors. For example, proven use cases developed in oil and gas can inform the delivery of data centers and other energy infrastructure, helping construction teams apply established engineering and project delivery practices in their industry.

Realizing this opportunity requires new competencies. Engineers, project managers and commercial professionals will increasingly need to understand not only how to use AI tools, but how to work alongside them—deciding when to rely on AI, when to challenge its recommendations and how to adapt their day-to-day work to focus on higher-value tasks.

Building workforce capabilities: Key actions

- √ Invest in AI literacy across engineering, commercial and project delivery teams.
- √ Redesign roles so people focus on high-value tasks.
- √ Capture and transfer specialist knowledge from related industries using AI, helping teams apply proven expertise to infrastructure challenges.
- √ Embed human oversight into AI-enabled workflows to ensure engineering quality, safety and accountability.



Change 4: Partnership ecosystem

Even the most capable workforce cannot deliver complex infrastructure programs in isolation. Most major projects rely on complex networks of owners, designers, contractors, suppliers and technology partners. Yet many still operate through fragmented contracts, disconnected systems and sequential handoffs that limit visibility, slow decision-making and create unnecessary rework.

Delivering construction programs at scale, including the energy transition, requires a more connected partner ecosystem. Rather than optimizing individual organizations, successful projects will increasingly optimize outcomes across the entire value chain. That means sharing information earlier, collaborating continuously and working from common digital platforms that give every participant access to the same trusted data and project insights.

The industry is already beginning to move in this direction. Early Contractor Involvement (ECI) is becoming increasingly common, bringing contractors into projects sooner so constructability, cost and delivery risks can be addressed before designs are finalized. At the same time, Modern Methods of Construction (MMC) and standardized product platforms—such as the UK's TIP 2030 Product Platform Rulebook—are encouraging repeatable designs, industrialized delivery and greater collaboration across the supply chain. The rapid growth of offsite construction also reflects this broader shift toward more integrated ways of delivering infrastructure.

AI has the potential to accelerate these models further by connecting people, data and decisions across organizational boundaries. Rather than simply improving how individual organizations perform, it enables the entire delivery ecosystem to operate as a more coordinated, intelligent network.

Driving collaboration: Key actions

- √ Shift to an alliance-based model that brings owners, designers, contractors and technology partners together earlier.
- √ Replace fragmented handoffs with shared digital environments that provide every partner with access to trusted information.
- √ Align commercial incentives around program outcomes rather than individual contractual performance.
- √ Standardize delivery through MMC, reusable product platforms, and industrialized approaches that improve quality, repeatability, and speed.

Change 5: The technology foundation

Connecting people, workflows and partners requires a technology foundation designed around how infrastructure will be delivered and operated, not simply the systems used to manage individual projects today. Yet many construction organizations still rely on fragmented legacy systems built to manage documents, transactions and project activities in isolation.

Cloud adoption is helping modernize the industry's technology estate, with 60% of construction firms expected to adopt cloud-based construction management systems in 2025.[7] But modernization needs to go further. Organizations must reduce technical debt and evolve existing systems to support AI, while also building the new enterprise technology stack required for an agentic future—one capable of supporting AI agents, greater autonomy and new forms of human-AI collaboration.

That shift also requires organizations to rethink how work gets done and the technology that supports it. Core enterprise processes designed around traditional roles and workflows cannot simply have AI layered on top. They will need to be reinvented around a hybrid human-AI workforce, with interoperable platforms and a unified digital backbone connecting engineering, commercial and operational data across the asset lifecycle.

The technology foundation should therefore be defined with the future operating model in mind, beginning as early as the final investment decision (FID). By working backward from how an asset will ultimately be delivered, operated and maintained, organizations can determine the data, systems, agentic capabilities and interoperability requirements needed across design, construction, commissioning and operations—and build toward that future rather than trying to connect everything after delivery.

Modernizing the tech foundation: Key actions

- √ Define the future operating model at FID and work backward to establish the data and technology foundations required across the asset lifecycle.
- √ Modernize the existing technology stack to reduce technical debt and create an AI-ready foundation that can support new capabilities as they emerge.
- √ Reinvent core enterprise processes for a hybrid human-AI workforce, rather than layering AI onto processes designed around traditional ways of working.

[7] https://scoop.market.us/construction-software-statistics/

Where AI changes the game

If organizational transformation creates the conditions for change, AI becomes the engine that accelerates it. Its greatest value comes when it is embedded across the entire capital delivery lifecycle rather than deployed as isolated point solutions. Here we explore high-value use cases across the construction lifecycle.

Plan: The biggest gains come before construction starts

AI can assess site suitability, identify environmental and regulatory risks, detect design clashes and support greater standardization. But the bigger opportunity is to improve the decisions made before construction begins. By connecting data, decisions and workflows, AI-powered feedback loops can help teams anticipate emerging risks, model forward-looking scenarios and rapidly evaluate trade-offs across cost, schedule, safety and performance. With appropriate risk controls and human oversight, teams can understand the implications of different choices earlier and act with greater speed and confidence, avoiding unnecessary pauses and costly decisions that become difficult to reverse once construction begins.

The potential impact of this shift is significant. Our analysis reveals that AI-enabled approaches can reduce engineering, design and delivery effort by 30–50% and help infrastructure programs move 20–30% faster. However, the value isn't simply fewer hours or lower costs. By accelerating design and decision-making, organizations can free up scarce engineering capacity, keep projects moving and address risks while there is still time to act—allowing gains made during planning to carry through construction and commissioning.

Build: Enable safer, more efficient delivery

During construction, AI provides real-time visibility into progress, quality, materials and emerging risks while improving reporting and decision-making. It also enhances site safety through predictive analytics and computer vision, with some applications reducing safety incidents by 36%.[8]

Operate: Designing for tomorrow

As control rooms and operational environments become increasingly autonomous, today's infrastructure must be built with tomorrow's operations in mind. Digitally connected, AI-ready assets will be better positioned to support more intelligent, efficient and sustainable operations throughout their lifecycle.

Maintain: From reactive to predictive

AI transforms asset maintenance by analyzing real-time sensor data to detect anomalies, predict equipment failures and recommend timely interventions. This shift from reactive to proactive maintenance improves safety, reliability and cost efficiency, reducing equipment downtime by up to 50%.[9]

[8] https://www.sitesafetyai.com/blog/construction-safety-statistics-2023

[9] https://artesis.com/10-proven-machine-maintenance-strategies-that-cut-downtime-in-2026/#key-benefits-for-reducing-downtime

Capital project excellence in Offshore Wind

Capgemini has published a new research report, “Capital Project Excellence in Offshore Wind,” examining why projects continue to face cost overruns, delays, and margin pressure despite advances in turbine technology and installation methods. Based on a survey of 150 senior offshore wind professionals across Europe, the report finds that only 13% of respondents rate recent projects as performing well on cost, while 92% have observed cascading rework caused by late design freeze.

More importantly the study reveals the industry’s biggest capability gap: 57% of executives say decision speed and quality will be critical to future success, yet only 17% believe their organization performs well today. It explains how integrated digital and AI-enabled project controls can help close this 40-points gap by providing earlier risk detection, faster impact assessment, and decision-ready options across planning, costs, risk, contracts and interfaces.

Download full report



Seizing the opportunity ahead

For decades, the construction industry has trailed other sectors in adopting advanced technology. While that has contributed to today's delivery challenge, it also presents a unique opportunity. Rather than following the same incremental modernization journey as other sectors, construction has the chance to leapfrog it, embracing AI-native ways of working while continuing its broader digital transformation.

Getting there will require more than applying AI to traditional ways of working. Construction's engineering-led delivery models have evolved largely through incremental innovation, but the shift to an AI-enabled industry demands a more fundamental transformation. Digital capabilities need to become integral to how projects are structured and delivered, alongside engineering expertise, with new operating models, technology foundations and ways of working designed around what AI now makes possible.

For organizations willing to rethink how they operate, the rewards extend well beyond productivity. AI-enabled delivery models can shorten project timelines, reduce costs, improve margins and increase delivery capacity at a time when demand for energy infrastructure has never been greater. As project owners increasingly seek partners that can deliver faster, more efficiently and with greater certainty, the ability to combine AI with new operating models, technology platforms and ways of working will become a defining source of competitive advantage.

Authors



Paul Haggerty
Vice President, UK Market Head of Energy Transition & Utilities, Capgemini



Claire Gauthier
Executive Vice President, Global Lead of Energy & Utilities, Capgemini

04

DATA CENTERS

How AI can help orchestrate the energy system it needs



DATA CENTERS

How AI can help orchestrate the energy system it needs

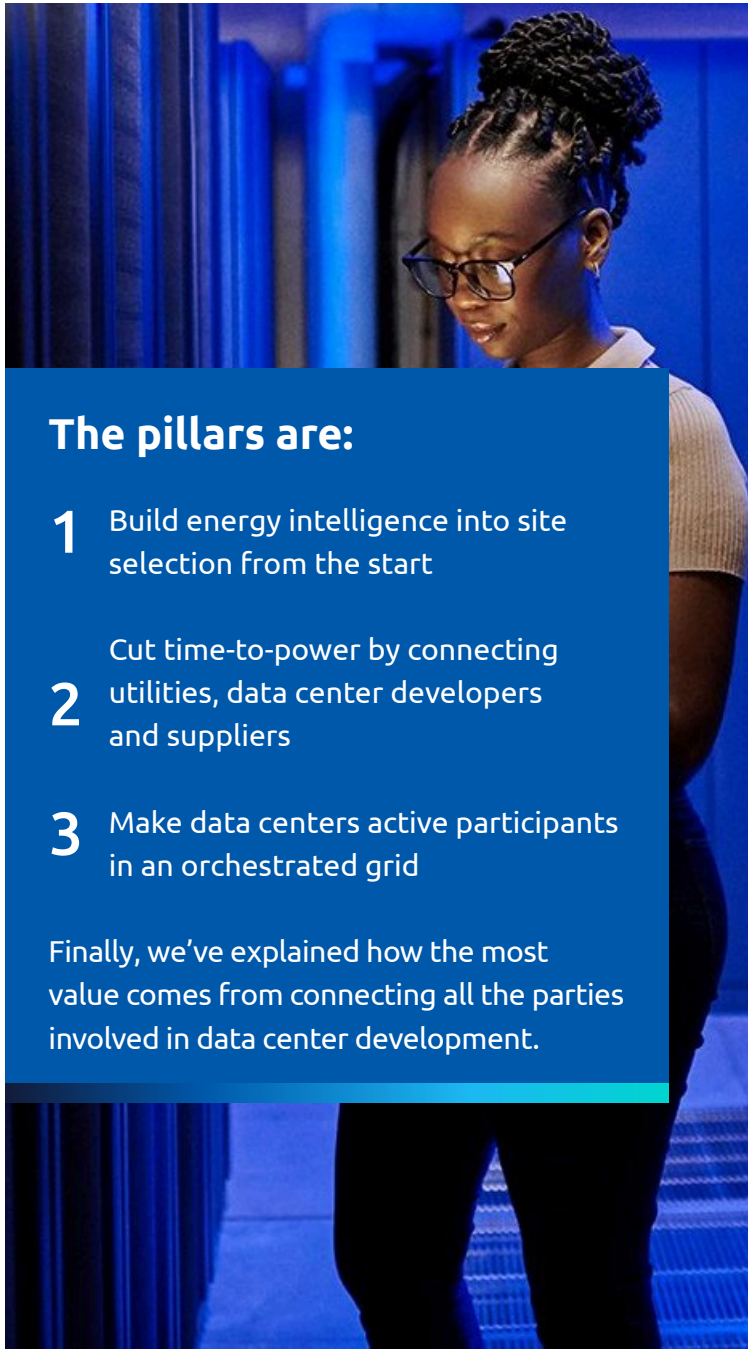
AI is the defining technology of our age. Yet the more we use it to work and live, the more data centers we need to meet the demand – and the bigger the strain on the energy system.

The International Energy Agency (IEA) expects data center electricity consumption to almost double from around 485 TWh in 2025 to around 950 TWh by 2030.[1] That's slightly more than the total electricity consumption of Japan today. New research from the Capgemini Research Institute[2] (CRI) predicts that the proportion of demand stemming from AI training and inferencing will rise from 25% to 60% in the next three to five years. The same research finds that 77% of electricity executives believe data-center demand will grow faster than supply, with 68% anticipating shortages as a result.

Data center developers have similar concerns. In several key US markets, developers expect to have access to power up to two years sooner than utilities can deliver it. And in the European Union, wait times for securing a grid connection already range from two to ten years.[3]

But while AI drives increasing amounts of the demand for data center power, it can also play a key role in meeting it. Electricity executives recognize this potential: the CRI research finds that six out of 10 anticipate AI will unlock significant efficiency and operational gains.[4]

In this article, we've shown how AI technologies can transform activities across three pillars – focusing on the benefits for utilities and data center developers.



The pillars are:

1. Build energy intelligence into site selection from the start
2. Cut time-to-power by connecting utilities, data center developers and suppliers
3. Make data centers active participants in an orchestrated grid

Finally, we've explained how the most value comes from connecting all the parties involved in data center development.

[1] https://iea.blob.core.windows.net/assets/3179f7f8-01f6-4dd6-bffa-c9f7b73f1dc9/KeyQuestionsonEnergyandAI.pdf

1. Build energy intelligence into site selection from the start

Data centers aren't new players in the energy system. But the growing use of AI means the loads they create are larger, more time-sensitive and clustered, with many connecting to the grid at once.

Demand is also hard to predict: 67% of electricity executives in the CRI research[5] refer to "phantom" data-center load requests, where around one in five (19%) never materialize. And 77% foresee issues predicting future demand accurately – reinforcing the need for a system that can flex to cope with unpredictability.

Uncertainty of a different kind also plagues data center developers. A site that ticks the right land and tax boxes may not be viable because the grid lacks the necessary capacity. The connection timelines may also be too slow, or the local generation mix too carbon intensive.

The grid isn't the only constraint. Growing community concerns about water use, electricity bills and climate risk are putting pressure on politicians in several US states. New York recently became the first state to pause permitting for new hyperscale data center development[6] so it can create new regulation. Developers must now build these risks into their assessments before selecting sites.

AI can transform how both parties approach planning. For utilities, it can combine and analyze data on factors like grid constraints, energy prices and the wider power market. Its insights can help them predict demand from a data center cluster, and plan the new infrastructure or capacity needed to meet it – rather than responding to each new connection request. Digital twins can then test the available options, from grid upgrades to new renewables. They can also model different scenarios to test the impact of various plans within a long project lifecycle.

For data center developers, an AI model can help speed up the processes involved in selecting a site, like assessing power and water availability, permitting complexity, and proximity to generation. And by flagging risks manual analysis might discover later or miss, it can help developers filter out unviable sites, sooner.

Example: In the US state of Oregon, home to several large data center clusters, an AI platform has freed up 80MW of unused grid capacity for Portland General Electric.[7] The utility will route the capacity to meet data center demand.

[2] https://www.capgemini.com/insights/research-library/data-centers-and-electricity-demand utm_source=linkedIn_ol&utm_medium=social&utm_content=eneryutilities_advocacy_image_CRIreport_none&utm_campaign=energyutilities_data_centres

2. Cut time-to-power by connecting utilities, data center developers and suppliers

It's not enough to secure the power for a new data center. For developers to deliver it on time, the physical infrastructure – substations, transmission upgrades, transformers and more – must also be in place.

The potential bottlenecks for utilities are substations and upgrades; for data centers, it's cooling systems and, of course, the supply of graphics processing units (GPUs). Meanwhile, transformers, switchgear, permitting, and commissioning can hold up projects on both sides. And as several run on the same critical path as the data center itself, delays can mean missing a go-live date.

AI can help turn time-to-power into a strategic advantage for data center developers. It can help to validate early designs, spotting issues like missing specifications and compliance gaps. Digital twins can then help test designs and plans for sequencing construction and commissioning before work starts. For utilities, it can help speed up permitting and regulatory filing for grid upgrades.

Both parties can benefit from AI project controls to help them predict and spot when schedules slip or costs overrun. Having a clearer view of long-lead orders can also help them avoid shortages of key equipment like transformers, switchgear, and cooling systems.

But the biggest benefit may come from coordination. Having a shared view of the project means that all the main players have the full picture – reducing risk and keeping delivery on track.

Example: The Chain Reaction platform[8] brings together energy producers, power distributors, data center developers and contractors to speed up the development of AI infrastructure in the US. Pulling together data from these parties provides a clear, joined-up view across projects – surfacing issues before they happen and speeding up delivery.

[3] https://www.iea.org/commentaries/overcoming-energy-constraints-is-key-to-delivering-on-europe-s-data-centre-goals

[4] https://www.capgemini.com/insights/research-library/data-centers-and-electricity-demand?utm_source=linkedIn_ol&utm_medium=social&utm_content=eneryutilities_advocacy_image_CRIreport_none&utm_campaign=energyutilities_data_centres

[5] https://www.capgemini.com/insights/research-library/data-centers-and-electricity-demand?utm_source=linkedIn_ol&utm_medium=social&utm_content=eneryutilities_advocacy_image_CRIreport_none&utm_campaign=energyutilities_data_centres

3. Make data centers active participants in an orchestrated grid

Once built and connected, data centers make heavy demands on an already congested grid. In Europe, for example, demand from data centers is projected to hit 168 TWh by 2030, up from 96 TWh in 2024.[9] But its grids weren't built to absorb this kind of load – increasing the risk of an unreliable supply.

AI technologies such as Emerald AI can help by improving how utilities forecast loads and predict congestion and outages. They can also make data centers more efficient by optimizing cooling systems, power storage, server use and which flexible workloads happen, when and where.

At a portfolio level, this allows data centers to move qualifying workloads to regions with lower congestion, prices, or emissions, while using batteries to reduce peak demand. But the real shift comes when data centers work within the energy system – flexing how much power they take from the grid and when, rather than passively consuming it.

Change is already underway. Nearly three in ten[10] data center operators say they deploy on-site power solutions and 39% plan to add them within the next one to two years. Once these assets are in place, utilities can integrate data centers into their DERMS and ADMS platforms, virtual power plants and grid-edge intelligence. This then allows utilities to see the data center's flexible assets and call upon them when needed. And by responding automatically to signals from the grid, data centers can take part in demand response programs.

This more collaborative way of working will help balance supply and demand by helping utilities to orchestrate the power system.

Example: In a UK demonstration project,[11] an AI orchestration platform responded to over 200 real-time grid events by managing the power consumption of a cluster of data center GPUs. Over the five-day demo, power demand was cut by up to 40% without disrupting critical workloads.

[6] https://www.governor.ny.gov/news/first-statewide-moratorium-new-hyperscale-data-centers-launched-governor-kathy-hochul

[7] https://www.cleanthesky.com/innovation/power-acceleration-platform

[8] https://www.hpcwire.com/off-the-wire/palantir-launches-chain-reaction-to-build-american-ai-infrastructure/#:~:text=entirely%20different%20scale.-,Chain%20Reaction%20is%20designed%20to%20address%20this%20directly%20by%20accelerating,of%20meeting%20AI's%20massive%20demand

[9] https://www.capgemini.com/insights/research-library/data-centers-and-electricity-demand?utm_source=linkedIn_ol&utm_medium=social&utm_content=eneryutilities_advocacy_image_CRIreport_none&utm_campaign=energyutilities_data_centres

Powered by connection

While we've presented our recommendations across three pillars, none is independent of the others – and improvements in one area ripple across the chain.

When energy is built into planning, developers rule out unviable sites, and utilities have early warning of future large loads. This means they can invest proactively, which in turn makes more sites viable in the next round of site selection.

When project execution improves, the utility can rely on the demand forecast and commit to upgrades early. As a result, the data center's project timelines become more predictable. And when data centers can flex their demand, utilities can manage peaks without building new infrastructure, while data centers can turn flexibility into a commercial benefit.

That's why the biggest benefit comes from connecting all three pillars in a single energy operating model.

In this model, utilities, developers, regulators, investors, and policymakers share data on a single platform. This allows for an integrated approach to energy and site planning, along with a real-time view of the project – schedule, costs, risk and bottlenecks.

It enables AI to plan and model different scenarios across demand, supply, flexibility and investments. It gives utilities visibility of data center demand at a cluster level, which allows them to provide a more reliable service across the whole portfolio. And crucially, it allows data centers and grid systems to coordinate their operations in real time. So delays show up as soon as they happen, not months down the line.



[10] https://www.capgemini.com/insights/research-library/data-centers-and-electricity-demand?utm_source=linkedIn_ol&utm_medium=social&utm_content=eneryutilities_advocacy_image_CRIreport_non

[11] https://www.datacenterdynamics.com/en/news/emerald-ai-releases-results-of-uk-demonstration-project-in-partnership-with-national-grid/

Conclusion: No AI without energy collaboration

AI can help utilities and data center developers plan power earlier, build energy infrastructure faster and run data centers as flexible participants in an orchestrated grid. But this potential is too often locked away in silos that rarely speak the same language or work from the same data. The real value emerges when these layers are connected end-to-end – enabling organizations to collaborate with each other and with other players in an AI operating model.

These models can be complex to deliver and require specialists who understand and can deliver across the whole value chain. If you can secure the right partners, you can turn what has historically been a set of unrelated activities into a self-reinforcing cycle that benefits everyone.



Authors



Edouard Le Bonté
Director, Sustainability Development Lead, Energy & Utilities, Capgemini



Hubert Clement
Vice President Energy & Utilities, Battery Sector Lead, Capgemini



Claire Gauthier
Executive Vice President, Global Lead of Energy & Utilities, Capgemini



Rayan Cherif
Strategy & Transformation Managing Consultant, Capgemini

05

GRID MODERNIZATION

The grid investment gap

Why utilities must modernize fast



GRID MODERNIZATION

The grid investment gap: why utilities must modernize fast

Grid modernization is now a system-wide imperative

The electric grid modernization global perspective

This article examines the solutions available to meet fast-growing electric demand in a new T&D paradigm.

The electric grid congestion imperative

With renewable and electricity demand growth, multiple network congestions are happening or will happen. What is the grid congestion situation, and what solutions can be leveraged to secure the supply at fair costs?

Grid balancing: algorithmic warfare on the grid

Challenges, market chaos, suitable market design, the flexibility arsenal and perspective.

Flexibility in power markets

A global view on need and readiness organized around six key dimensions.

Climate change adaptation for T&D operators

Climate change leads to more frequent and more intense weather events. Discover how utilities can make their networks more resilient and respond faster and more efficiently to the disasters. Adapt or pay.



Electricity flows will more than double by 2050, intensifying grid challenges worldwide

Electrification is at a new tipping point. Electricity demand is expected to more than double by 2050. Meeting it will require around 80 million kilometers of new or upgraded power lines by 2040, almost doubling today's global network.

- Continuous economic growth is increasing overall energy demand by around 2% each year.
- As fossil fuels are replaced by low-carbon electricity, electricity demand is growing faster, at around 3% to 4% per year.
- Investment in low-carbon energy is now roughly twice the investment in fossil fuels.
- The main demand drivers are: transport electrification; booming data center demand; reindustrialization and industrial decarbonization; heat pumps and low-carbon hydrogen; the next phase of electrification in developing countries; and expanding wind and solar connections, which is, by far, the largest area of energy investment.

The network model has fundamentally changed

Historical paradigm	New paradigm
Centralized and dispatchable generation	Distributed and variable generation
Passive demand	Flexible and controllable demand
Post-event correction	Imbalance prevention
Hardware-centric operations	Software- and data-centric orchestration, AI
Thermal and hydro reserves	Storage, demand response, interconnections
Centralized and sequential operations	Local and multi-horizon operations
Historical paradigm	New paradigm

The climate change adaptation challenge

Storms, heatwaves, droughts, wildfires, heavy rain, floods, cold snaps and wet snow are affecting networks more frequently and severely. The impact reaches every voltage level, across both underground and overhead lines.

Grid operators must reduce these risks, make networks more resilient and respond faster when severe weather strikes. Climate adaptation is therefore a major trigger for grid transformation, not a separate infrastructure issue.

Various other challenges should be met

- Many aging grids must be replaced or modernized.
- Real-time balancing, flexibility management, outage management and climate response are making operations more complex.
- Operating models are being renewed and, in some areas, reinvented through digital technologies, data and AI.
- The smart grid model must extend intelligence, visibility and automation deeper into the network.



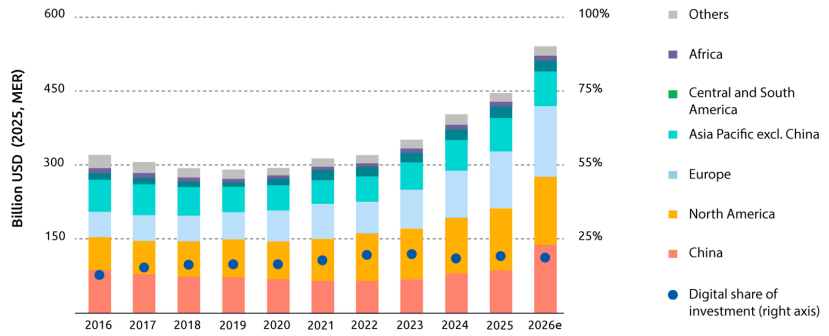
New lines are essential, but slow and capital-intensive. Operators must do more with existing grids

A landmark 2021 study by the International Energy Agency found that building new high-voltage transmission lines can take more than 10 years across the full lifecycle, from decision-making and planning to permitting, construction, and commissioning.

Grid investment is already growing by more than 10% a year, increasing the costs ultimately borne by consumers. Yet this is still not enough to keep pace with electricity demand. As IEA Executive Director Fatih Birol said, “Any dollar invested in renewables should trigger a dollar invested in grids.” The world remains far from that ratio.

The challenge is therefore twofold: expand and modernize the grid, while extracting more capacity, resilience and efficiency from existing assets. Building new infrastructure alone cannot deliver the required pace at an affordable cost.

Figure 1: Grid investment is rising, but the gap remains



IEA. CC BY 4.0

Power grid investments gained momentum in recent years after a period of stagnation relative to generation. Europe, the United States and China are leading the rebound, accounting for more than two-thirds of global investment growth from 2023 to 2025.

- Global grid investment is estimated at $541 billion in 2026, compared with $694 billion invested in renewables in 2025.
- Smart-grid investment represents approximately 15% of total transmission investment and 30% of total distribution investment.

Sources: IEA analysis based on financial statements of transmission and distribution companies; S&P (2026), Capital IQ data; and Global Transmission (2025) data.

Figure 2: Grid-enhancing technologies can unlock more from existing networks

Grid-enhancing technology solutions	Capacity increase	Cost	Implementation lead time
Dynamic Line Rating Temporarily increasing line capacity under specific technical conditions (sag control)	20-30%	$	1-2 years
Dynamic Transformer Rating Temporarily increasing transformer capacity under specific technical conditions	5-15%	$	1-2 years
Topology optimization Using software to optimize network configuration and relieve constraints	5-15%	$	1-2 years
Advanced power flow control Using flexible AC transmission systems to modify line reactance	10-20%	$	2-3 years
Storage as a Transmission Asset (SATA) Operating lines close to 100% of their thermal rating	30-40%	$	2-3 years
Reconductoring Retrofitting lines with higher-capacity conductors	50-100%	$$	3-4 years
Voltage uprating Increasing the voltage level (for example, from 10 kV to 20 kV)	100-200%	$$	4-7 years
New HV lines	10-20%	$$$	7+ years

Global grid investment is estimated at $541 billion in 2026, compared with $694 billion invested in renewables in 2025.

Smart-grid investment represents approximately 15% of total transmission investment and 30% of total distribution investment.

Sources: IEA analysis based on financial statements of transmission and distribution companies; S&P (2026), Capital IQ data; and Global Transmission (2025) data.

A capital-intensive transformation with a growing digital and AI dimension

Capital intensity and dimensions

Building or modernizing the electric networks requires significant investment with various characteristics:

- Projects range from around two years for low-voltage lines to more than 10 years for high-voltage lines in some geographies.
- Permitting can account for up to half of total project duration, depending on geography and local regulation, while larger assets often face strong local opposition.
- Underground lines are more resilient to climate-related events but can cost several times more than overhead lines.
- Grid assets typically remain in service for 40 to 50 years, making today's decisions long-term commitments.
- Asset investment planning tools improve project efficiency by supporting grid-enhancing technology choices, prioritizing critical lines, securing project lifecycles and managing assets from cradle to grave. Intelligent engineering platforms provide a complementary engineering backbone.
- Because public grids are regulated assets, transmission and distribution system operators must comply with local rules and secure regulatory approval for projects.
- Investment intensity and the efficiency of both investment and operations directly affect electricity costs. Affordability is therefore a critical success factor for the energy transition.



The digital and AI opportunity

Grid technologies are moving from hardware-centric to software- and data-centric operations. Digital, data and AI now account for around 20% of total grid investment, and that share is growing.

Alongside asset investment planning, five digital domains stand out. Each can improve asset management and operational efficiency, but each requires deliberate investment, operating model change and disciplined scaling.

- **Network instrumentation.** Equip critical lines and nodes first so that grids can generate reliable data, extend intelligence to the edge and support greater automation.
- **The control room of the future.** Rising operational complexity is increasing the need for integrated digital tools, better situational awareness and progressively higher levels of supervised automation.
- **Balancing and flexibility.** Use a broader portfolio of flexibility resources and market mechanisms, as explored in the companion WEMO articles on grid balancing and flexible markets.
- **AI industrialization.** Move beyond isolated pilots and quick wins where the use case is mature. Generative and agentic AI can support parts of the grid operations value chain, provided operating changes, governance, acceptance and human oversight are part of the design from the outset. The combination of the control room of the future and agentic AI has the potential to reshape grid operations over time.
- **Digital engineering.** Use digital and AI-enabled engineering tools to manage the portfolio of grid expansion and modernization projects more efficiently.



Conclusion

The modernization challenge cannot be solved by choosing between new infrastructure and smarter use of existing assets. Utilities need both. The leaders will be those that combine disciplined capital planning, grid-enhancing technologies, resilient engineering, digital operations and carefully industrialized AI to expand capacity at speed while protecting reliability and affordability.



Author



Philippe Vié
Senior Advisor, Energy and Utilities, Capgemini

06

GRID CONGESTION

The imperative to tackle grid congestion – how utilities can respond



GRID CONGESTION

The imperative to tackle grid congestion – how utilities can respond

The global energy transition is reshaping electricity systems faster than at any point in recent decades. In doing so, it's placing unprecedented pressure on power networks and making grid congestion one of the greatest barriers to economic growth, electrification, and decarbonization.

Electricity demand is expected to more than double by 2050 in many markets as electric vehicles, heat pumps, hydrogen production facilities, data centers, and industrial electrification significantly increase power consumption. At the same time, renewable generation is being deployed at record pace, often in locations far from demand centers. It's also increasingly connected at the distribution level rather than through traditional centralized generation models.

The result is a growing mismatch between where electricity is generated, where it's needed, and how much capacity is available to transport it. Networks originally designed for predictable, one-way power flows are now managing increasingly complex, bi-directional flows from distributed solar, wind, and storage resources. Large-scale data centers are adding further strain; although they accounted for around 1.5% of global electricity demand in 2024, their electricity consumption is expected to almost double by 2030. In some regions, connection requests already consume a significant share of available grid capacity.

These pressures are creating widespread congestion across transmission and distribution networks, delaying renewable energy connections, slowing industrial investments, increasing operating costs, and limiting the pace of electrification. What was once considered a localized operational issue has become a strategic challenge with far-reaching economic consequences, influencing infrastructure investment, affordability, reliability, and national competitiveness. As connection queues continue to grow and network capacity becomes increasingly constrained, addressing grid congestion has become a critical priority for utilities, regulators, and policymakers worldwide.

A global challenge with significant economic consequences

Grid congestion is becoming a systemic challenge across both mature and emerging electricity markets.

Rising congestion costs, longer connection queues, renewable curtailment and pressure on network infrastructure all point to the same conclusion: grids are struggling to keep pace with the energy transition.

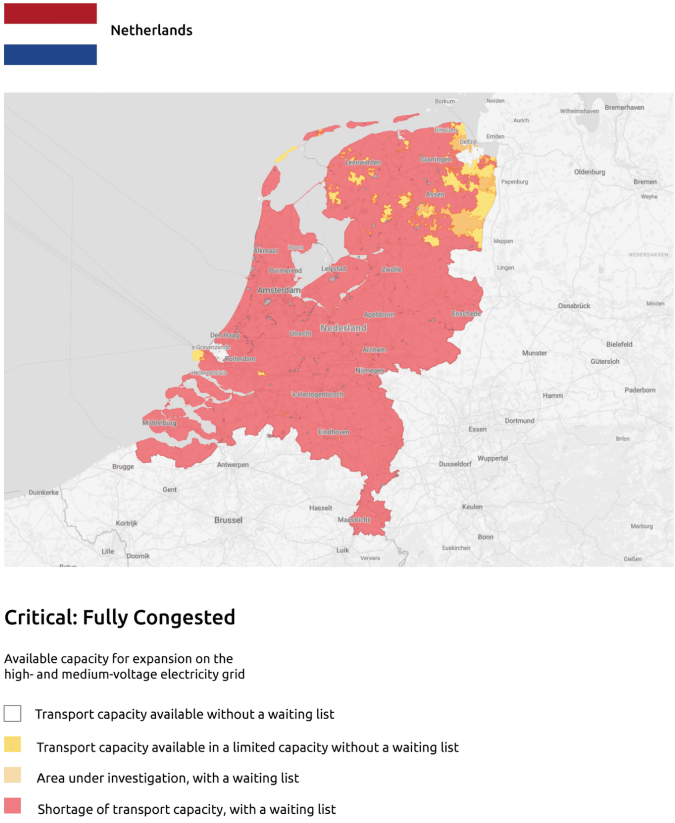
The Netherlands: congestion has become a constraint on economic growth

The Netherlands illustrates how grid congestion has evolved from a technical challenge into a strategic economic issue. In several regions, network capacity constraints have halted new customer connections, while congestion-management costs reached €278 million in 2023. That follows €340 million in 2021 and a peak of €388 million in 2022.

In 2025, TenneT reported that through innovative measures such as flexible connection contracts, it had unlocked access to up to 9.1 GW of off-grid capacity – equivalent to more than 40% of national peak demand. Yet the ongoing high annual costs of congestion highlight how grid constraints are increasingly shaping investment decisions, delaying electrification programs, and slowing the connection of new businesses and energy projects.

Figure 1: Netherlands congestion map and key congestion statistics

Map taken from the IEA

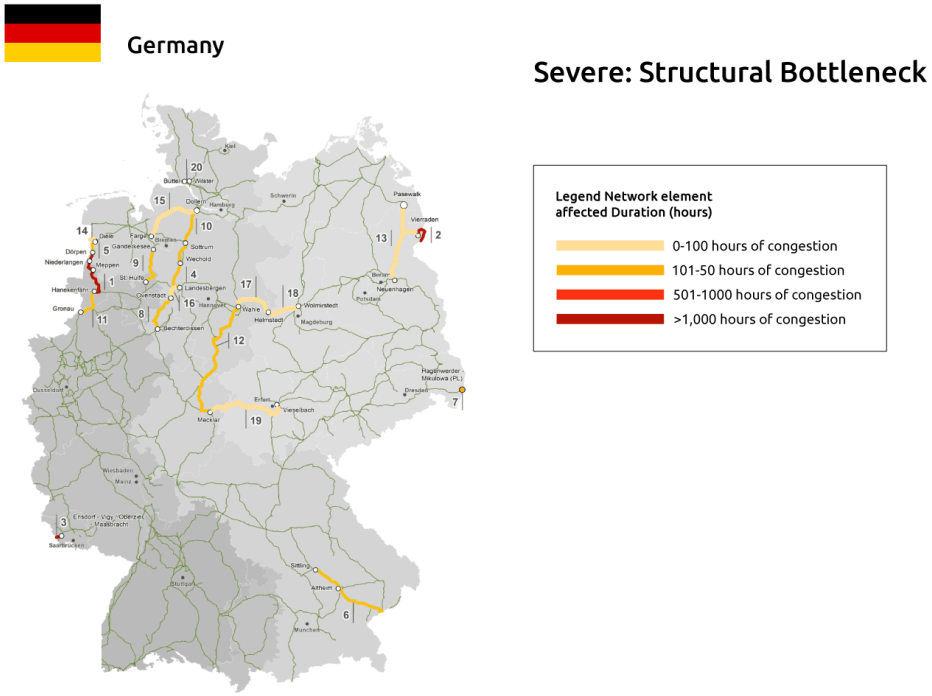


Germany: renewable growth is exposing structural transmission bottlenecks

Germany's congestion challenge stems from the mismatch between renewable generation in the north and major industrial demand in the south and west – making the north-south transmission corridor a critical bottleneck. As grid upgrades struggle to keep pace, solar curtailment nearly doubled in 2024, rising 97% to 1.41 TWh. Meanwhile, distribution network congestion increased to 26% of cases, up from 20% in 2023, indicating grid stress is shifting downstream. With annual congestion costs reaching approximately €2.6 billion in 2024, Germany demonstrates how network constraints can increase costs, curtail renewable generation, and slow the energy transition.

Figure 2: Germany congestion management and renewable curtailment impacts

Map taken from smard.de



United Kingdom: balancing costs continue to rise

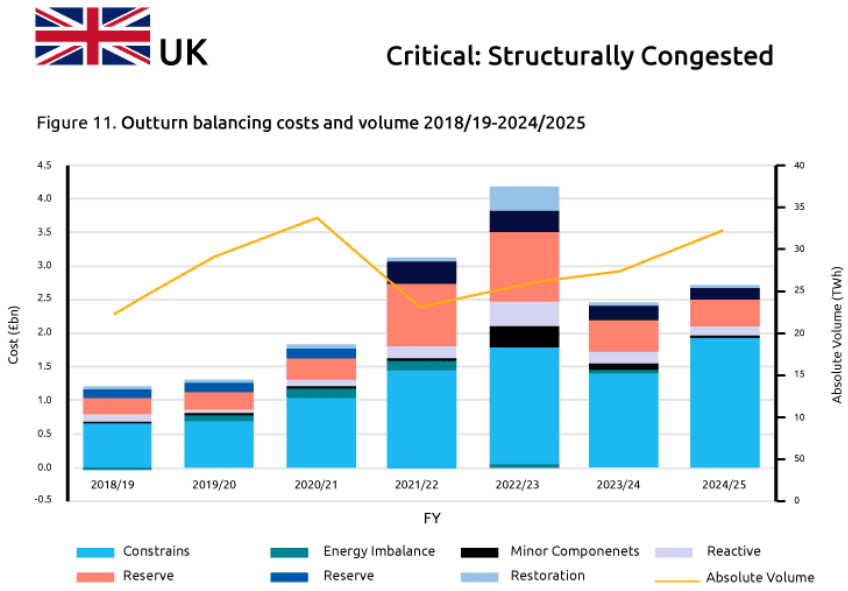
In Great Britain, grid congestion is increasingly reflected in rising system balancing costs as transmission constraints limit the efficient movement of renewable electricity across the network. Grid balancing costs have nearly tripled over the last six years, increasing from approximately £1 billion in 2018/19 to £2.7 billion in 2024/25. Congestion is now the primary driver and thermal constraints account for 63% of total costs.

Scotland remains one of the clearest examples of the challenge, with structural transmission constraints resulting in the curtailment of approximately 13% of available wind generation.

The UK's experience shows how network bottlenecks can increase system costs, constrain renewable integration, and widen the gap between grid capability and energy transition ambitions.

Figure 3: UK balancing costs and transmission bottlenecks

Map taken from NESO

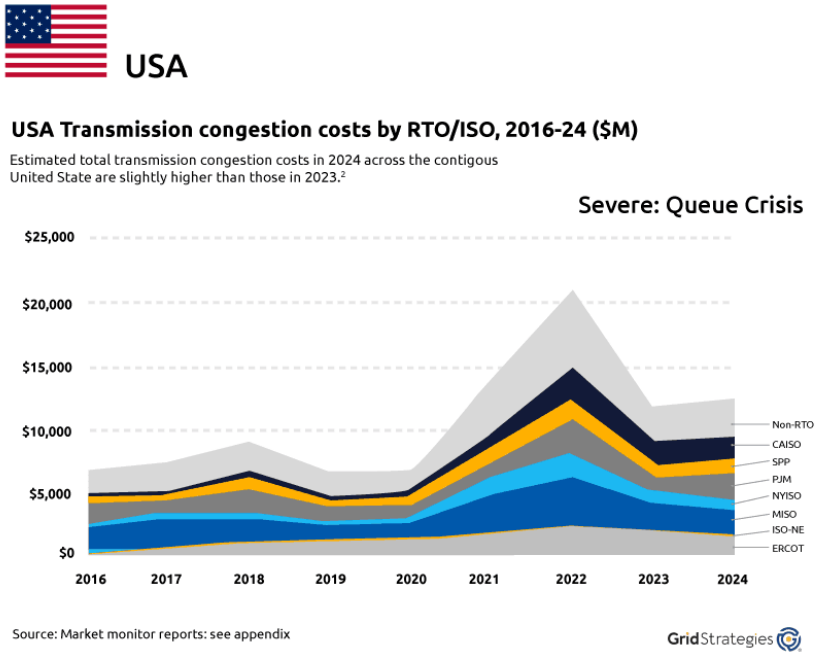


United States: connection queues have reached unprecedented levels

The US power grid is facing a severe connection queue crisis, driven by rapidly rising transmission congestion and limited grid capacity. By 2024, the connection queue had grown to 2,290 GW, far exceeding the 1,322 GW of installed generation capacity. Congestion costs had reached approximately $12.3 billion per year, with transmission bottlenecks continuing to worsen across regional grid operators. If all queued projects were connected, US generation capacity would nearly triple. This points to a significant mismatch between renewable energy development and the grid's ability to accommodate new generation without major infrastructure upgrades.

Figure 4: US transmission congestion costs and interconnection queue growth

Map taken from Grid Strategies



Belgium: congestion is increasingly moving downstream

Belgium is experiencing growing electricity grid congestion, particularly in Flanders and parts of central and southern Belgium. As of 2024, 16 of 235 transformer substations in Flanders were congested, with several overhead lines nearing saturation. Constraints are concentrated at the interface between Elia's 110 kV transmission network and Fluvius' distribution network, where bottlenecks can affect wider areas. To manage limited capacity, new connections above 1 MVA in congested zones are restricted to flexible access arrangements, highlighting the need for grid reinforcement and increased network flexibility.

Figure 5: Belgium congestion hotspots and transmission-distribution interface constraints

Map taken from Elia Group

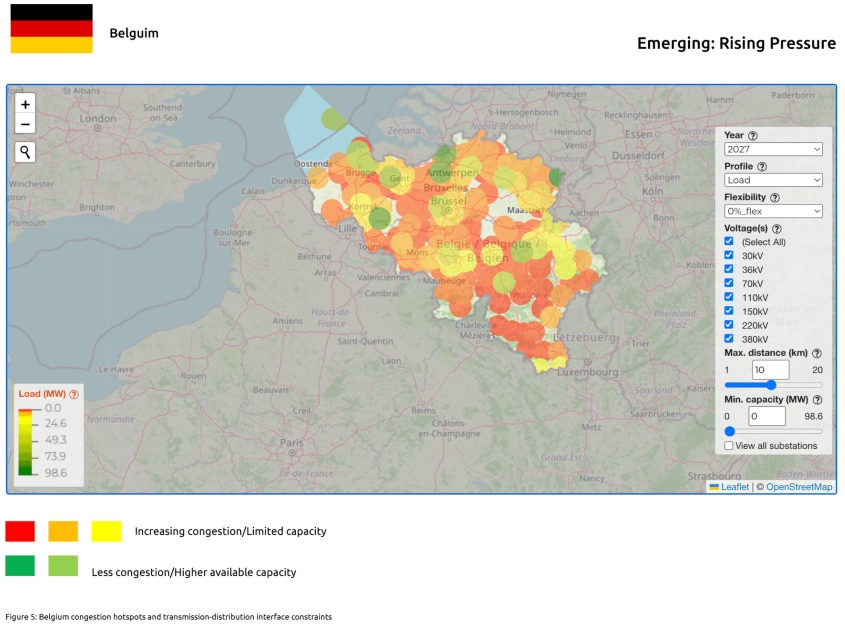


Figure 5: Belgium congestion hotspots and transmission-distribution interface constraints

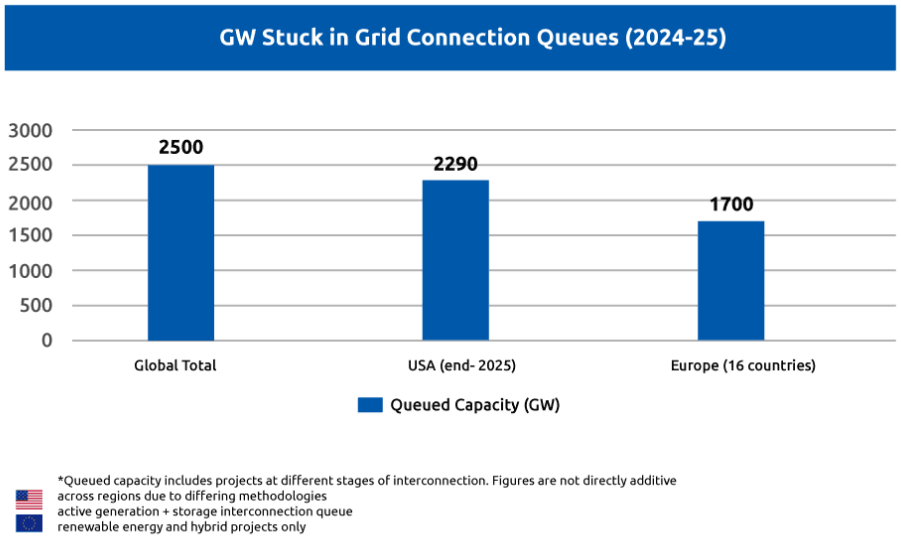
Connection queues are becoming the clearest symptom of grid stress

Across major power markets, renewable generation, storage, industrial projects and data centers are waiting years to connect to the grid because available capacity is increasingly constrained.

Active interconnection queues have reached approximately 2,500 GW globally (2024-2025). In the United States, projects awaiting connection represent almost twice the country's installed generation capacity, while European queues continue to grow as renewable deployment outpaces grid reinforcement.

These delays are increasing project costs, slowing investment decisions and postponing new clean energy capacity. As a result, connection queues are turning from an administrative bottleneck into a structural constraint on economic growth, electrification and decarbonization.

Figure 6: Global connection queues and scale comparison



*Queued capacity includes projects at different stages of interconnection. Figures are not directly additive across regions due to differing methodologies
active generation + storage interconnection queue
renewable energy and hybrid projects only

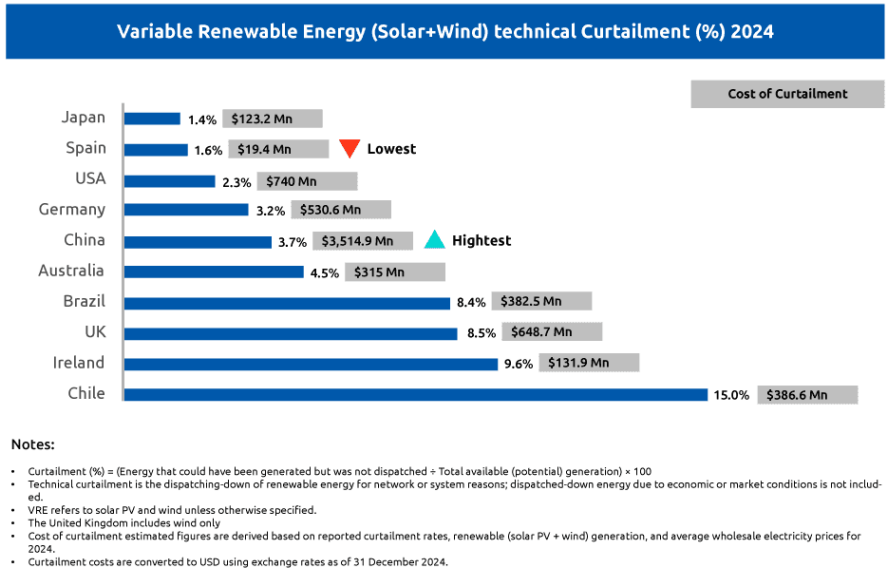
Curtailment is becoming the second congestion hurdle

Securing a grid connection is no longer enough. Even after projects connect, many grids cannot absorb all the renewable electricity generated, forcing operators to curtail output that could otherwise support decarbonization.

Curtailment is becoming another clear sign that network infrastructure isn't keeping pace with renewable deployment, creating economic losses for developers and reducing the efficiency of the energy transition.

Chile records some of the highest curtailment levels among major renewable markets, while Ireland, the United Kingdom and Brazil are also seeing elevated rates. Larger markets, such as the US, Germany and China, are absorbing substantial financial losses as increasing renewable output cannot reach consumers when and where it's needed.

Figure 7: Renewable energy curtailment rates and estimated economic impact



Notes:

- Curtailment (%) = (Energy that could have been generated but was not dispatched ÷ Total available (potential) generation) × 100
- Technical curtailment is the dispatching-down of renewable energy for network or system reasons; dispatched-down energy due to economic or market conditions is not included.
- VRE refers to solar PV and wind unless otherwise specified.
- The United Kingdom includes wind only
- Cost of curtailment estimated figures are derived based on reported curtailment rates, renewable (solar PV + wind) generation, and average wholesale electricity prices for 2024.
- Curtailment costs are converted to USD using exchange rates as of 31 December 2024.

Multiple forces are reshaping the grid

Grid congestion is being driven by several structural shifts happening at once across electricity systems.

Electrification is accelerating demand: 32.9 million new electric vehicles were added in 2025, with EV fleet electricity consumption reaching 250 TWh and expected to rise further by 2035.

Data centers are adding major pressure. They already represented about 1.5% of global electricity demand, or roughly 485 TWh, in 2025 – and their share is expected to double to around 3% by 2030.

Renewables, storage and microgrids are also changing power flows, replacing one-way centralized supply with more complex bi-directional flows that require tighter coordination across grid operators and market participants.



New lines cannot be the only solution to such wide-ranging challenges

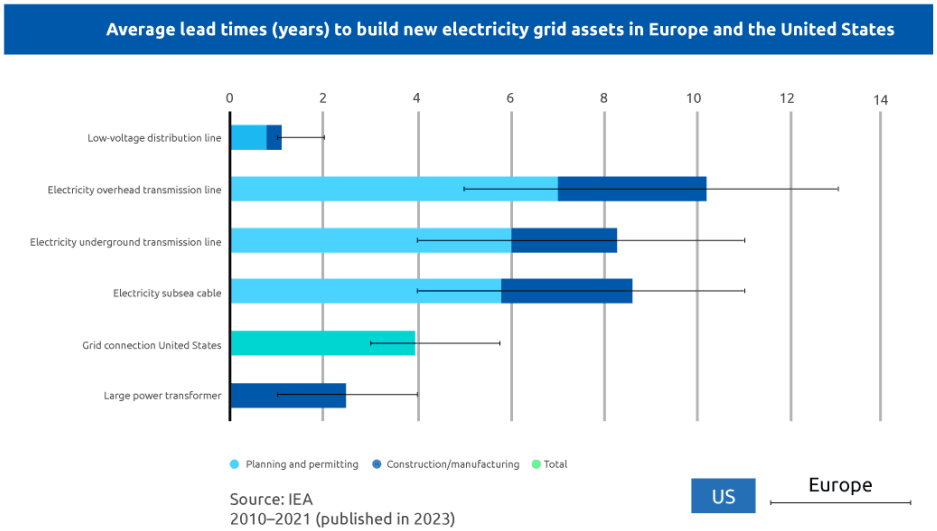
Grid reinforcement remains essential, but new transmission and distribution infrastructure alone cannot solve congestion fast enough.

Building new assets can take years of planning, permitting, land acquisition, construction and commissioning – in some markets, close to a decade. Yet congestion decisions often need to be made within months.

Utilities therefore need to maximize existing grid capacity while continuing long-term network expansion, combining infrastructure investment with operational efficiency rather than treating them as alternatives.

Figure 8: Average lead time for grid infrastructure development

Data relates to the period 2010 to 2021, published by the IEA in 2023.



Grid-enhancing technologies are becoming an essential part of the solution

Utilities no longer need to rely only on traditional infrastructure investment. Grid-enhancing technologies (GETs) can improve asset utilization, increase operational flexibility and unlock capacity faster.

Key options include dynamic line rating and dynamic transformer rating, topology optimization, advanced power flow control and storage as a transmission asset (SATA).

For persistent congestion, utilities may still need reconductoring, voltage uprating or new transmission infrastructure. The priority is selecting the right mix of solutions for each asset, region and congestion scenario.

Figure 9: Grid-enhancing technologies comparison matrix

EGT (Grid-Enhancing Technologies) solutions	Capacity increase	Cost	Implementation lead time
Dynamic line rating Increasing temporarily line capacity under technical conditions (sag control)	20–30%	$	1–2 years
Dynamic transformer rating Increasing temporarily transformer capacity under technical conditions	5–15%	$	1–2 years
Topology optimization Software optimal network configuration to relieve constraint	5–15%	$	1–2 years
Advanced power flow control Flexible AC transmission systems using the lines reactance	10–20%	$$	2–3 years
Storage as a transmission asset – SATA Operating lines close to 100% thermal rating	30–40%	$$	2–3 years
Reconductoring Retrofitting lines with higher-capacity conductors	50–100%	$$$	3–4 years
Voltage uprating Increase voltage level (ex. 10kV to 20kV)	100–200	$$$$	4–7 years
New HV lines	10–20%	$$$$$	7+ years

Source: IEA Electricity 2026

Addressing congestion with proven practices and tailored interventions

The reality is that congestion management is becoming increasingly portfolio driven.

Utilities must understand current and future congestion risks, identify emerging demand and generation hotspots, and continuously evaluate mitigation options.

Leading organizations are moving towards dynamic congestion management models that combine:

- Continuous congestion monitoring
- Future congestion forecasting
- Stakeholder engagement
- Asset investment planning
- Grid-enhancing technologies
- Storage deployment
- Demand and generation flexibility
- Targeted infrastructure expansion.

Rather than treating congestion as an operational issue alone, successful utilities are increasingly managing it as a strategic portfolio challenge.



Conclusion: congestion management will become a core utility capability

Grid congestion is becoming a defining challenge for modern electricity systems as electrification, distributed renewables, data center growth and changing consumption patterns outpace traditional grid expansion.

While new infrastructure remains critical, utilities can no longer rely on transmission and distribution expansion alone. Success will depend on combining investment with advanced monitoring, forecasting, flexibility, storage and grid-enhancing technologies.

Utilities that build these capabilities fastest will be better positioned to maintain reliability and affordability while enabling electrification, renewable integration and economic growth.



Authors



Philippe Vié
Senior Advisor, Energy and Utilities, Capgemini



Rene Kerkmeester
Global Vice President, Integrated Power, Capgemini

07

GRID BALANCING

The algorithmic grid

How flexibility tools and AI can help balance a stressed system



GRID BALANCING

The algorithmic grid: how flexibility tools and AI can help balance a stressed system

For more than a century, power systems have run on one unforgiving rule: at every moment, the amount of electricity being generated must match the amount being used.

Historically, large dispatchable power stations, centralized networks and control rooms centered on frequency and voltage stability kept that balance. The energy transition is changing all that. Electrification, variable renewables, distributed energy resources, new consumption patterns and volatile markets are creating a faster, more uncertain and fragmented system.

The IEA estimates that meeting climate targets will require adding or replacing about 80 million kilometers of electricity networks by 2040 – roughly the entire global grid today – while investment needs to rise sharply. But physical infrastructure alone cannot solve such a complex problem. That's why today's grid is no longer balanced only by steel and copper, but by algorithms, data and distributed flexibility.

Who operates the grid is changing too: transmission system operators (TSOs) and distribution system operators (DSOs) used to coordinate this between them. Now, grid system operators are emerging, who balance the whole distributed system in real time and coordinate markets.

This shift reflects a deeper change in what balancing requires. The central question has changed from "How do we react to imbalance?" to "How do we anticipate and prevent problems before they happen, at the lowest cost to the system?"

Across advanced markets, demand is already growing faster than grids can connect and respond. The future balancing challenge is therefore also a speed challenge: the grid must plan, connect and operate faster than demand is growing.

> "Today's grid is no longer balanced only by steel and copper, but by algorithms, data and distributed flexibility."

Navigating a complex system

The old model was straightforward: large, centralized and largely dispatchable power stations served predictable, stable demand. Reserve margins, hydro and thermal plants, interconnections and balancing mechanisms fixed any deviations. That model is being displaced by weather-dependent generation, two-way flows and consumers who also generate, store or shift energy.

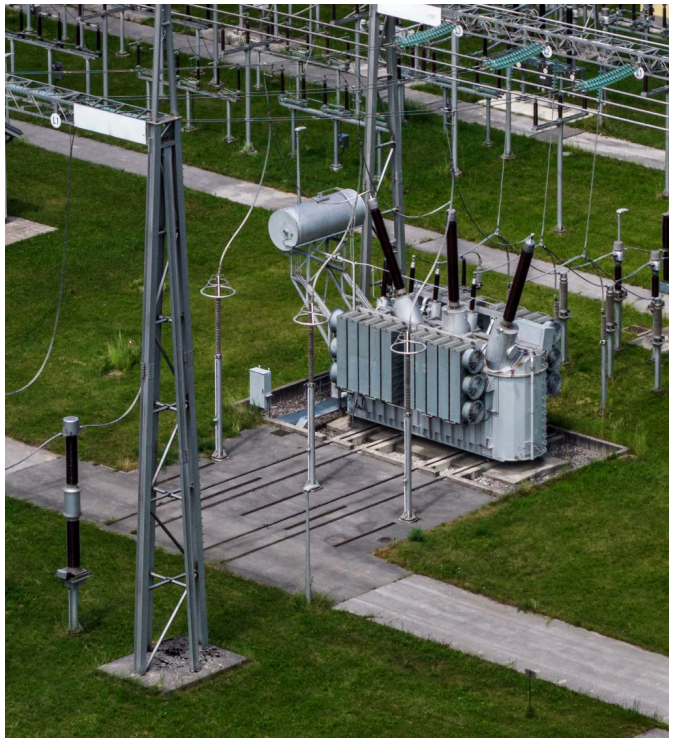
Three forces are reshaping what balance looks like – and requires – today:

1. Fragmented supply

Millions of solar installations, wind farms, batteries, energy communities and industrial assets are already generating power. The IEA expects this renewable capacity to grow by more than 5,500 GW between 2024 and 2030, with solar and wind representing about 95% of that growth. By 2030, four in 10 new solar additions could be distributed – moving part of the balancing problem on to networks designed for one-way delivery.

What's more, unlike synchronous machines in large power plants, electronics-based generation like solar and wind don't naturally resist sudden changes in frequency. So advanced hardware and software are increasingly important for keeping the grid stable.

These changes have reduced the amount of direct control that grid system operators have over the resources that could support balance. TSOs are running their assets closer to dynamic limits. DSOs need to get much better at seeing what's happening on their networks, as well as at forecasting, managing voltage and coordinating flexible assets. Meanwhile, decarbonization, permitting, economics, drought and climate variability are constraining traditional sources of flexibility – thermal and hydro energy. Curtailment, co-located storage, flexible networks and responsive demand must fill the gap. Put simply: as production becomes less dispatchable, demand must become more flexible.



> As production becomes less dispatchable, demand must become more flexible."

2. Dynamic demand

Demand is no longer a stable, predictable curve. Electric vehicles, heat pumps, data centers, electrolyzers, industrial electrification, cooling and smart buildings are creating large, localized and weather-sensitive loads. Data centers alone consumed around 485 TWh in 2025 and are expected to almost double their consumption to 950 TWh by 2030. The global EV fleet could reach 250 million vehicles by 2030, while the IEA's net-zero pathway depends on 600 million heat pumps being installed globally.

These flexible assets also represent a huge pool of potential flexibility. To unleash their value, they must be bundled together, signed up to contracts, accurately measured, predictable and controllable.

Achieving this requires interoperable platforms, market access, trusted baselines, attractive payment and consumer trust. But while advanced markets optimize flexibility, emerging markets are often still building the foundations on which flexibility will depend.

> "While advanced markets optimize flexibility, emerging markets are often still building the foundations on which flexibility will depend."

3. Market chaos

Negative electricity prices, grid congestion and rising emergency management costs aren't anomalies. They're signs that there isn't enough flexibility, storage or coordination in the system. When renewable output is high and demand can't absorb it, prices fall – sometimes to below zero. When output drops or demand spikes, prices rise.

In response to this volatility, European platforms such as PICASSO and TERRE are starting to pool balancing resources across borders. But progress is slow. In the meantime, a well-designed market does more than price electricity. It considers how quickly an asset can respond, where it's located and how reliably it can deliver.

Together, these three forces mean that keeping the grid balanced is no longer only the operator's job. It involves coordinating across the whole system.



> "Keeping the grid balanced is no longer only the operator's job. It requires coordination across the whole system."

The flexibility arsenal

There's no silver bullet for reaching this goal. Instead, the grid will need a portfolio of complementary approaches, chosen based on how fast they can respond, where they are and what the system needs at any given moment. Flexibility is becoming both a set of physical technologies and a set of financial instruments and market mechanisms, all working together.

The main approaches are:

- **Storage: the system shock absorber**
  Lithium-ion batteries can respond very quickly, absorb solar power, relieve local congestion, and charge and discharge in response to supply and demand. Pumped hydro provides large-scale storage daily or weekly, but it's limited by geography and long build times. Thermal storage shifts heating and cooling loads. Hydrogen and synthetic fuels could eventually cover prolonged or seasonal periods of low renewable output, though they're less efficient overall. Smart EV charging lets car batteries draw power at times that suit the grid, while vehicle-to-grid may eventually allow them to feed it back when it's needed (subject to business models, technical standards and customer acceptance).
- **Demand response: the least visible resource**
  Getting consumers to shift or reduce consumption when the grid needs it can reduce peaks, absorb surplus renewable power, avoid congestion and lower the amount of reserve needed. All without building new infrastructure. Industrial sites, buildings, EV fleets and homes can all participate, but industrializing this approach requires certification, aggregation, measurement, activation and settlement. Platforms like Equigy, Piclo and NODES show that standardized ways of procuring local flexibility have begun to emerge. Virtual power plants can also bundle large numbers of distributed assets into single, reliable market resources.
- **Enhanced grids: doing more with existing assets**
  Dynamic line rating adjusts how much power transmission lines carry based on real-time weather conditions. Phasor Measurement Units (PMUs) and high-frequency sensors give operators a clearer picture of stability across the network. Grid-forming converters help maintain stability as electronics-based generation grows. These technologies don't replace physical investment. They help prioritize it, defer it when flexibility is more efficient and get the most out of assets.

To sum up: storage absorbs volatility. AI anticipates it. Markets reveal its value.

> Storage absorbs volatility. AI anticipates it. Markets reveal its value."

From ‘forecast and react’ to ‘predict and prevent’: The role of AI and tech in grid balancing

The tools and approaches we’ve described provide the foundations of flexibility. But balancing the grid across distributed assets, markets and ever-changing conditions is already moving beyond human capability alone.

If, as ENTSO-E predicts, European flexibility needs double between 2025 and 2033, operators will need to forecast deviations, anticipate congestion, model load behavior and optimize assets across local and wholesale markets. AI will be essential, but it won’t replace operators or electrical engineers. It will expand what they can do by processing enormous volumes of data simultaneously: weather forecasts, market prices, asset conditions, customer behavior and physical network constraints.

Control rooms will become data-intensive environments, supported by probabilistic alerts – which predict the likelihood of congestion within a certain time span – automated recommendations and digital simulations. Supervised automation is a realistic goal: AI detects, predicts and recommends. Human operators validate, prioritize and intervene when conditions move outside normal parameters.

AI’s main uses include:

- forecasting renewable output and demand in the very short term
- optimizing assets across storage, demand response and interconnections
- detecting anomalies and predicting risks before they happen
- activating assets while being aware of constraints
- simulating extreme scenarios and stress-testing plans in real time through digital twins
- giving operators visibility and control over distributed assets through ADMS and DERMS platforms

The operating loop making this happen is easy to describe but hard to scale:

1. Sense what’s happening across the system and predict what’s coming
2. Optimize the use of flexible assets, within network constraints
3. Act automatically or semi-automatically under human supervision
4. Learn from the results and improve

As a result, the future grid won’t only be reinforced. It’ll be predicted, optimized and automated.

> “The future grid won’t only be reinforced. It’ll be predicted, optimized and automated."

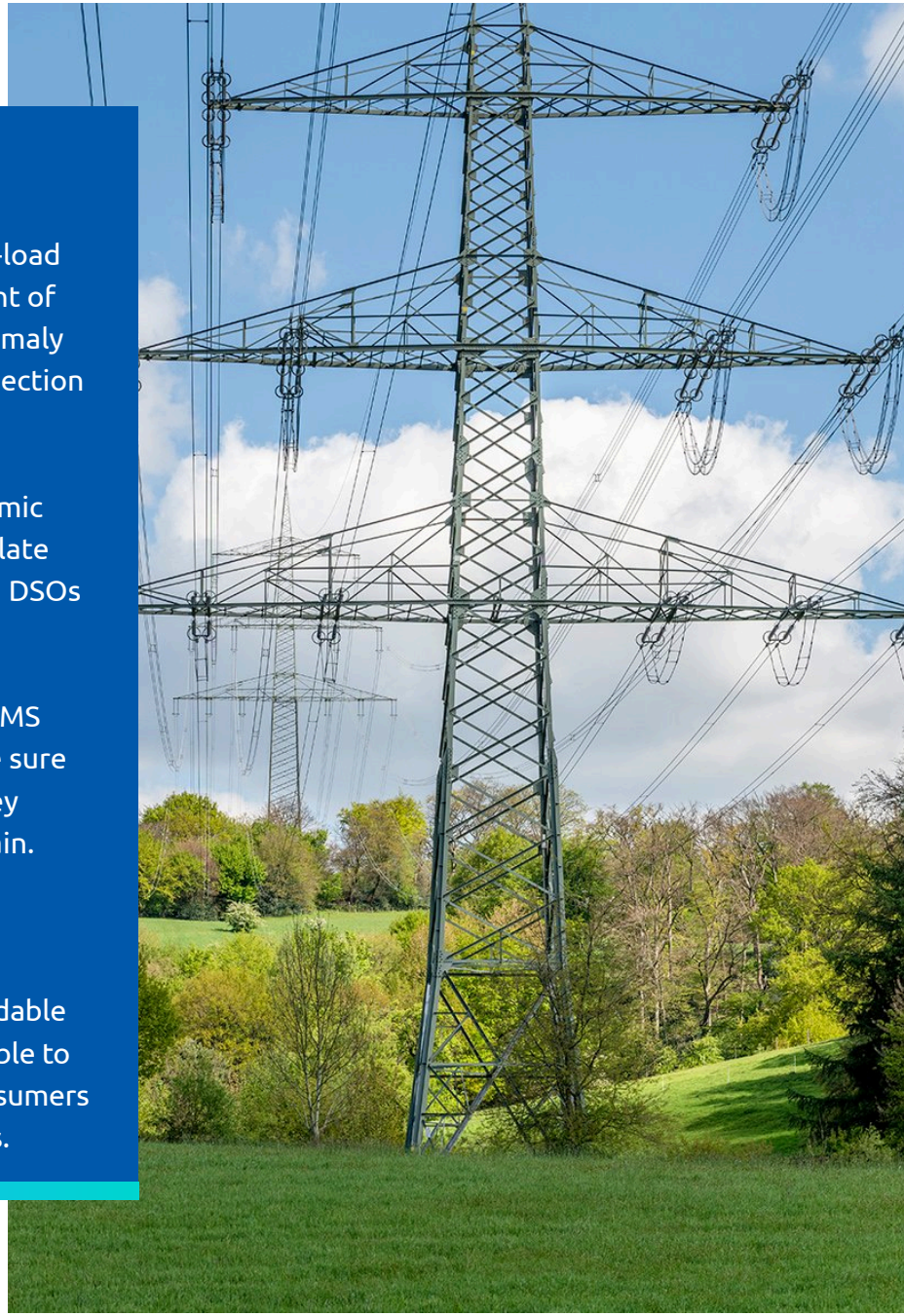
Modern grid balancing: who needs to do what?

Grid system operators (in the US, ISOs or RTOs): Align detailed load forecasting, large-load connections, capacity planning and real-time reliability tools. Accelerate the deployment of multi-duration storage. Deploy advanced forecasting, multi-asset optimization and anomaly detection and track the results in lower balancing costs, fewer outages and faster connection of new loads.

TSOs: Renew aging assets and build climate resilience into infrastructure. Deploy Dynamic Line Rating, digital twins and PMUs to get more out of existing infrastructure and simulate stress scenarios before they occur. Strengthen coordination with system operators and DSOs by sharing constraints and operational data across time horizons.

DSOs: Get a much clearer view of what's happening at a local level through ADMS, DERMS and low-voltage sensors. Open local flexibility markets, standardize products and make sure assets are fairly paid for how quickly they respond, where they are and how reliably they deliver. Ensure flexible connections and coordinate with the operators above in the chain. Local flexibility won't replace the need for network reinforcement, but it can target investment more precisely and make better use of what already exists.

Aggregators: Bundle thousands of small assets into tradeable portfolios that are dependable and measurable. Increasingly, value depends not just on owning an asset, but on being able to activate it at the right time, in the right place and in the right market. Producers and consumers can support this by combining generation, storage, demand response and smarter tariffs.



Flexibility is the new capacity

As the energy transition gathers pace, power system security will no longer depend only on how much generation capacity is installed, but on the ability to forecast, shift, store and orchestrate electricity across the system. Storage is the shock absorber. Demand is a resource. Digital platforms are the coordination layer. AI is the engine of anticipation.

This transformation means that operators are becoming conductors of a system that's more distributed and volatile, but potentially more intelligent. And while it's largely invisible to consumers, the shift will determine whether power systems can absorb electrification and renewable growth without compromising security of supply, competitiveness or stability.

Sources

IEA, Electricity Grids and Secure Energy Transitions, 2023: grid investment needs, 80 million km of networks by 2040 and the role of grids in the transition.

IEA, Renewables 2024: renewable capacity growth, more than 5,500 GW by 2030 and the dominant role of solar and wind.

ACER, 2024 Market Monitoring Report: negative prices, congestion, flexibility and balancing market integration.

ENTSO-E, Balancing Report 2024: European balancing platforms and TSO role.

ENTSO-E, System Flexibility Needs for the Energy Transition: increasing flexibility needs and prolonged renewable shortfall events.

European Commission, Electricity Market Design: storage, demand response and flexibility in market reform.

ENTSO-E / EU DSO Entity, Network Code on Demand Response: integration of demand-side flexibility, aggregation and storage.

MISO / OMS, 2025 Resource Adequacy Survey: load growth, data centers, seasonal reliability risks and capacity needs.

ERCOT, 2025 Long-Term Load Forecast Update: large-load forecasting and data-center-driven planning challenges.

NERC, 2025 State of Reliability: data centers, inverter-based resources, BESS reliability and operational modeling challenges.

IEA, Energy and AI: data center electricity demand growth and supply implications.

IEA, India cooling demand analysis: rising night-time electricity demand and cooling-driven peak implications

Authors



Nicolas Carayon
Vice President, Global EDF/Enedis/Rte Delivery Partner, Innovation Director, Capgemini



Mercy Paul
Director, Lead Energy & Utilities Industry Platform, Capgemini



Hariharan Krishnamurthy
Vice President, E&U Head of Industry ERD, Capgemini

08

FLEX MARKETS

Unlocking energy market flexibility with AI



MARKET FLEXIBILITY

Unlocking energy market flexibility with AI

Power markets globally are facing the same challenge: governments and energy companies are adding renewables faster than grids can absorb them.

The resulting stress is visible in prices, wasted energy and intervention costs in many energy markets. On May 1, 2026, German day-ahead prices hit the exchange floor of -€499.99/MWh. In 2025, Spain, the Netherlands and Sweden's SE2 zone recorded high levels of negative pricing, while billions of watts of wind and solar were wasted in Australia. In the same year, Germany spent €3.07 billion on managing grid congestion, and Spain spent between €3.3 and €3.8 billion.

For companies operating in these markets, this is a margin story more than an environmental one. Volatility on this scale destroys value for participants who can't respond and creates value for those who can. The same hour that wipes out revenue for a generator selling at market rates pays a battery operator to absorb energy. The gap between those two outcomes is widening every year, and it's decided by operational capability, not asset ownership.

Germany's power market is a case in point. It holds one of the largest flexibility fleets in the world, with roughly 16 GW of batteries, two million electric vehicles and two million heat pumps. Yet it still can't exploit this potential. The barrier isn't the hardware, but everything between it and the market: metering, market access and the ability to act on a price signal within fixed time slots.

Flexibility readiness depends on six dimensions

To better understand what's holding participants back, we assessed the flexibility readiness of 11 energy markets across six dimensions:

D1: How much stress the grid is under.

D2: Whether the market creates meaningful price signals.

D3: How extensively smart meters are used.

D4: How much flexible capacity exists.

D5: Whether assets are approved to take part in energy markets.

D6: Whether models exist for monetizing that participation.

We then divided these into three clusters:

1
Market design readiness:
grid and system stress (D1) and price signal formation (D2).

2
Technology readiness:
metering and data infrastructure (D3) and installed flexible capacity (D4).

3
Market participant readiness:
market access and prequalification (D5) and commercial models (D6).



The result: participants influence or control five of those dimensions

It's common for market participants to assume that readiness is a regulatory problem that only governments can fix. But our analysis finds that only one of the six dimensions is genuinely outside of their influence.

Figure 1: Where energy market participants can act on their own initiative

Degree of control of market participants	Dimensions	What this means in practice
Direct control	D4 Flexible capacity D5 Market access and prequalification D6 Commercial models	Investment, process and business-model decisions. No regulator has to move first.
Strong influence	D2 Price signals D3 Metering and data	Retailers decide whether price signals reach customers. Any asset owner can install its own sub-metering ahead of the national rollout.
Response only	D1 Grid and system stress	Set by network operators and regulation. Participants shape their exposure by choosing where they site their assets and how they bid when congestion strikes.

This finding matters because the three dimensions participants control directly are those where value can be created. In Germany, only 2.55 GW of a 16 GW battery fleet is prequalified for trade. And across Europe, under 20% of an estimated 100 GW of demand-side flexibility reaches the market.

Neither of these gaps require a regulator to close them. They require someone to do prequalification work, build the trading capability, and stand up the commercial model.

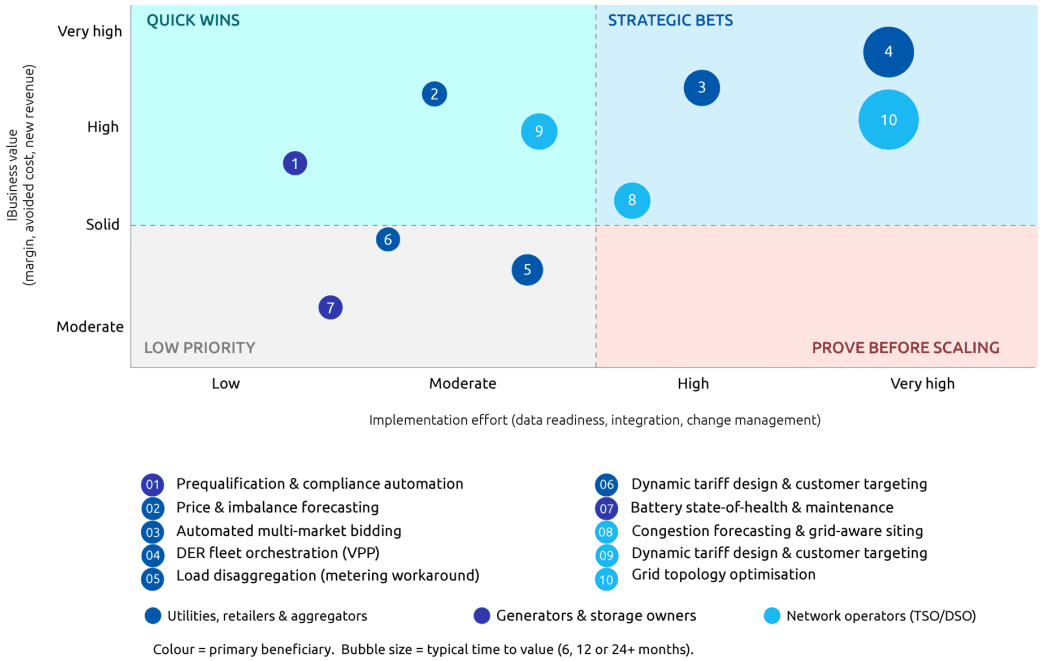
Where AI creates value

The main case for AI here is feasibility, not efficiency. A team of traders can dispatch a conventional portfolio of 10 thermal units. They can't dispatch 200,000 heat pumps, home batteries and vehicle chargers. Each asset has its own availability, state of charge, customer preferences and network constraints. And the best course of action changes every 15 minutes, across several markets at once.

Only AI can coordinate assets on that scale. That's why algorithms dispatch every large distributed portfolio in operation today – from Kraken's 2 GW residential fleet to Tesla's Autobidder across 33 sites.

But even for participants working with smaller portfolios, AI can create value across all five dimensions where they have influence or control. This chart maps practical use cases against the effort needed to implement them and the business value they create.

Figure 2: Where AI creates value for energy market participants – effort against benefit



Four ways to unlock that value

1. Go after the quick wins. Prequalification and compliance automation is the most underrated item on the chart. Automating this document- and process-heavy bottleneck would unlock otherwise inaccessible revenue, yet none of the markets we examined has done it.

Price and imbalance forecasting is the highest-value low-effort case. That's because better forecasts reduce the reserve a portfolio must hold and improve every subsequent bidding decision. Google DeepMind raised the value of a 700 MW wind fleet by around 20% by improving its day-ahead bids. And the UK's National Energy System Operator (NESO) reports a 33% more accurate solar forecast from satellite nowcasting. Both build on data companies already hold.

2. Commit to orchestration – it requires more effort but brings the biggest gains. Orchestrating a distributed fleet is one of the hardest activities in our assessment, requiring device connectivity, real-time data pipelines and a change in how the trading floor works. But it also separates the aggregators gaining market share from those losing it.

The same applies to automated bidding across multiple markets. Peer-reviewed work on intraday battery trading finds that optimizing continuously earns 58% more than optimizing hourly. Modo Energy has recorded individual batteries earning up to 70% more than the fleet average in a single month, in the same market. The difference is better optimizing software, not better hardware.

3. For network operators, the prize is avoiding capital expenditure. The UK's National Grid uses dynamic line rating across 275km of transmission lines; Terna in Italy uses it across roughly 20 connections. Both TSOs claim it allows existing lines to carry 40% more current and, in one case, avoided a €24 million line replacement.

Meanwhile, in France, RTE's "Learning to Run a Power Network" challenge showed that optimizing grid topology relieves congestion by reconfiguring the network, rather than paying generators to redispatch. With markets including Germany and Spain spending upwards of €3 billion on congestion management, even small percentage gains make a material difference.

4. Don't let poor metering stand in the way. AI acts on data, and data means meters – presenting a challenge for markets where coverage is low. Load disaggregation (estimating what individual devices consume based on readings from a single meter) can partially fill the data gap. That's why it appears on the chart, despite modest returns. But it's a workaround, not a substitute. In a market without widespread metering, the only way to build a successful business case for AI is to install sub-meters ahead of a national rollout.



Where you start depends on what you own

For utilities, retailers and aggregators: the first move is forecasting, because it improves every downstream decision and needs no new assets. The second is deciding whether to build a data & AI orchestration platform in-house or partner with a specialist.

For generators and storage owners: the fastest return is to automate prequalification and bidding across every product the asset is technically capable of serving.

For network operators: dynamic line rating and congestion forecasting release capacity from existing infrastructure years before new lines can be built. And both are defensible to a regulator on avoided-cost grounds.

Final word

Flexibility is the binding constraint on the energy transition, and market design is the global bottleneck. But waiting for market design to improve isn't a strategy. Participants can influence or control five of the six dimensions that determine flexibility readiness – and AI can help turn that readiness into commercial advantage.

The uncomfortable truth, though, is that it can't create readiness where it doesn't already exist. Applied to a portfolio that's metered, market-accessible and price-exposed, AI compounds returns. Applied to one that isn't, it produces impressive models and no margin. Companies that close the readiness gap first will find that the same volatility punishing their competitors becomes their most reliable source of value.



Sources:

Capgemini World Energy Markets Observatory flexibility readiness analysis across 11 markets, drawing on Bundesnetzagentur, EPEX SPOT, REE, RTE, TenneT, Nord Pool, NESO, AEMO, CAISO, FERC, regelleistung.net, IEA, Modo Energy and BCG Platinion.

Company-published figures from Octopus Energy, Tesla, National Grid, Terna and Google DeepMind. Company capacities and optimization uplift claims are self-reported.

Authors



Torben Schuster
Vice president, Head of Energy Transition and Utilities, Capgemini



Christian Bussar
Manager, Energy Transition and Utilities, Capgemini

09

CLIMATE CHANGE ADAPTATION

Adapting to a fast-changing climate

Why utilities must act now to manage the unpredictable



CLIMATE CHANGE ADAPTATION

Adapting to a fast-changing climate – why utilities must act now to manage the unpredictable

In January 2025, Storm Éowyn tore across the UK and Ireland as the region's most powerful windstorm in a decade. In a matter of hours, it cut power to more than a million homes, knocked out telecoms networks, and triggered knock-on disruption to transport and water services. It wasn't an isolated case and showed a real risk facing utilities everywhere: a single climate event cascading through an entire interconnected system in real time.

The impacts of climate change are putting power networks globally under huge stress. Heatwaves and prolonged droughts make generation less efficient, limit how much power transmission and distribution lines can carry and make equipment degrade faster. Wildfires pose direct threats to overhead lines, substations and network integrity.

Flooding, storms, extreme rainfall, and the soil erosion they bring, damage equipment and restrict access for maintenance and recovery operations, so outages last longer. And cold weather affects equipment performance, puts more mechanical stress on lines and drives sharp peaks in demand.

The effects of this exposure on customers and the bottom line are already substantial. In the US, JD Power found that 45% of utility customers experienced a power outage in the first half of 2025. Almost half (48%) of those outages were caused by extreme weather.

The picture looks to worsen globally over time. The Oak Ridge National Laboratory found that major outages cost $121 billion in 2024. Capgemini's "Climate adaptation: Harnessing tech-driven resilience to create sustainable value" report found that without action, a typical large listed utility could lose up to $4.6bn/year in the 2050s.

What's more, climate risk is now volatile, financially material, and something investors and regulators increasingly expect to see priced and managed. This means utilities must commit capital now against risks that don't behave in predictable ways. It's a substantial challenge, but the choice is clear: adapt now or pay later.

A single hazard can cause system-wide failures

The challenge for utilities isn't only that extreme weather events are becoming more frequent and intense. It's that those hazards are compounding and cascading across a single interconnected system.

The grid is increasingly being stressed by five overlapping hazard families: heatwaves and droughts, wildfires, storms and tropical cyclones, floods and heavy rainfall, and cold waves with wet snow. Two or more of these hazards often strike at one time, compounding the stress on the system. For example, heatwaves increase conductor sag, transformer stress, and cooling demand at the same time as drought creates combustible conditions and reduces field accessibility.

This means that what appear as separate risks on paper become a single compound event in practice: higher load, weaker assets, greater fire ignition risk, and slower restoration. As a result, utilities can no longer treat thermal risk and wildfire risk as separate workstreams.

One hazard can also affect multiple parts of the system, causing the disruption to cascade and potentially become a system-wide failure. Storm Éowyn was an example of this: a single storm brought down both power and telecoms, then rippled into transport and water services – underscoring the interdependence of modern infrastructure.

Larger network operators are generally furthest ahead on this journey, with the most mature ones treating resilience as a systematic, risk-based capability. They're also concentrating resources on the most critical infrastructure and partnering with specialists to get better at anticipating, absorbing and recovering from increasingly severe events.



This is why climate risk is now an uncertainty problem for utilities. The traditional single-hazard, static resilience planning models cannot capture these kinds of compound, cascading failures. Instead, utilities must move beyond hazard-specific mitigation towards integrated adaptation.

The cost of adaptation versus the cost of inaction

Climate adaptation has become a strategic priority across the sector, not only among those leading the field. But measures to improve resilience, such as asset hardening, automation, and network redesign, require substantial upfront investment. By contrast, the cost of failing to invest – outages, infrastructure damage, restoration costs, regulatory penalties, and wider societal disruption – is immediate and significant.

This asymmetry helps to explain why many utilities still don't consistently assess and prioritize large-scale resilience investments, even as the potential cost of not doing so rises. And unlike in other sectors, there's little opportunity to transfer climate-related infrastructure risk to insurers.

Which pot the money comes from can present another problem. Traditional regulatory models reward CapEx, where physical assets generate predictable, rate-based returns. Yet many of the most effective solutions, such as predictive analytics, real-time monitoring and real-time optimization, are OpEx-driven and harder to justify. This can create an investment bias towards capital-intensive options over more flexible, lower-cost alternatives.

The fundamental challenge is that resilience has moved far beyond a network-design problem.

> Today, utilities must decide how much capital to commit now, to guard against risks that don't behave predictably.



Assessing climate risk: a prerequisite to effective resilience planning

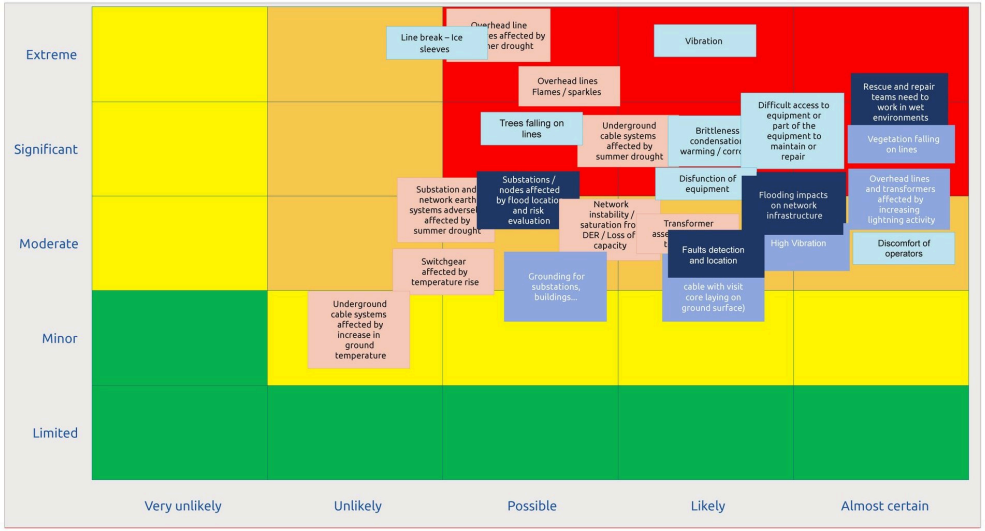
Before utilities can decide where to invest, which assets to strengthen, or how to prepare for extreme events, they first need a clear view of their vulnerabilities and priorities.

A structured climate risk assessment provides that view by identifying potential threats and organizing them by priority. High-priority risks are both highly likely to happen and to have potentially severe effects on operations or customers. Medium-priority risks may need targeted mitigation or monitoring, while lower-priority risks may be managed through existing controls.

Identifying where to intervene most urgently is only the first step. The challenge is turning those findings into practical adaptation and resilience measures that strengthen the network before, during and after extreme events.

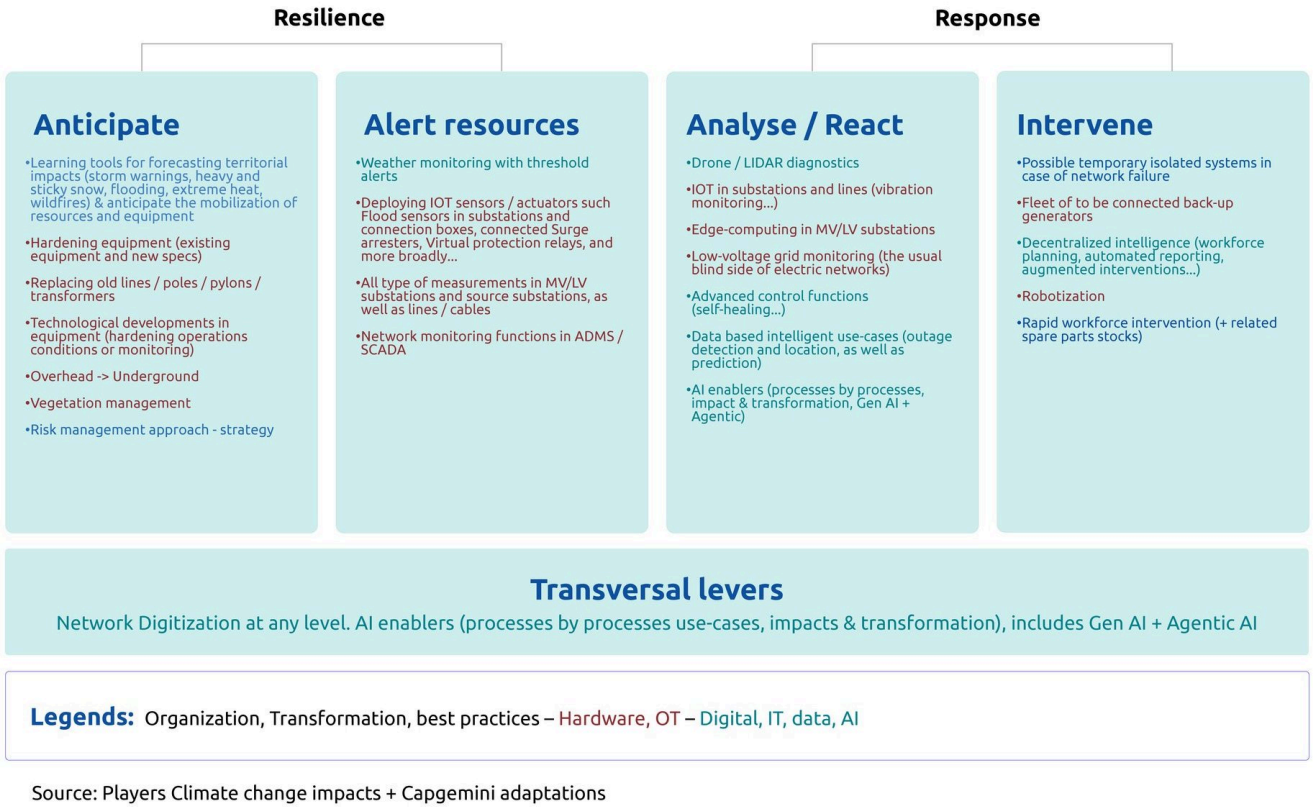
Leading utilities are increasingly adopting resilience frameworks that combine infrastructure hardening, operational preparedness, real-time monitoring, and rapid-response capabilities within a single integrated architecture.

Figure 1: A sample climate risk assessment, with risks organized by severity and likelihood



As Figure 2 shows, in these frameworks, resilience can be broken into four interconnected stages: anticipate, alert and monitor, analyze and respond, and intervene and recover.

Figure 2: The four stages of resilience



Source: Players Climate change impacts + Capgemini adaptations

Anticipate

The priority is anticipating future risks and reducing exposure before events occur. This includes using climate projections, hazard forecasting, network modeling, and asset vulnerability assessments to understand future operating conditions. It also encompasses long-term adaptation actions such as strengthening existing infrastructure, replacing old cables, undergrounding selected assets, improving vegetation management practices, and embedding climate risk considerations into asset investment strategies.

Alert and monitor

Resilience increasingly depends on situational awareness. Utilities are expanding the use of sensors, weather-monitoring systems, connected devices, and network monitoring platforms to warn them about abnormal operating conditions early. By connecting advanced SCADA, ADMS, and outage management systems to intelligent sensors and actuators at the edge, operators can also detect developing risks, monitor asset conditions in real time, and mobilize resources before failures happen.

Analyze and respond

Once an event has begun, utilities need to rapidly assess impacts and make informed operational decisions. Technologies such as drones, LiDAR, edge computing, intelligent substations, and AI-enabled analytics can give them a clearer view across the network and help them identify faults faster. Advanced network control capabilities, predictive analytics, and self-healing functions allow operators to shorten outages and speed up repairs in increasingly complex operating environments.

Intervene and recover

The final stage focuses on maintaining a continuous service and recovering faster. This includes using temporary generation, reconfiguring network assets, mobilizing an emergency workforce, managing spare parts, and coordinating with telecommunications, water, transport, and emergency services. The goal isn't simply to restore power quickly, but to minimize the wider societal impacts that can emerge when critical infrastructure systems fail simultaneously.

Underlying all four stages is a set of capabilities that increasingly determine resilience. Network digitization, advanced data platforms, AI-enabled decision support, integrated operational technology (OT) and information technology (IT) systems, and workforce transformation all provide the foundation for more adaptive and responsive networks.

Importantly, resilience doesn't come from any single technology or intervention. Each utility will need to define an adaptation pathway that reflects its specific geography, climate exposures, asset base, regulatory environment, and investment priorities. What matters is having a structured framework that links climate risk assessment directly to resilience action.

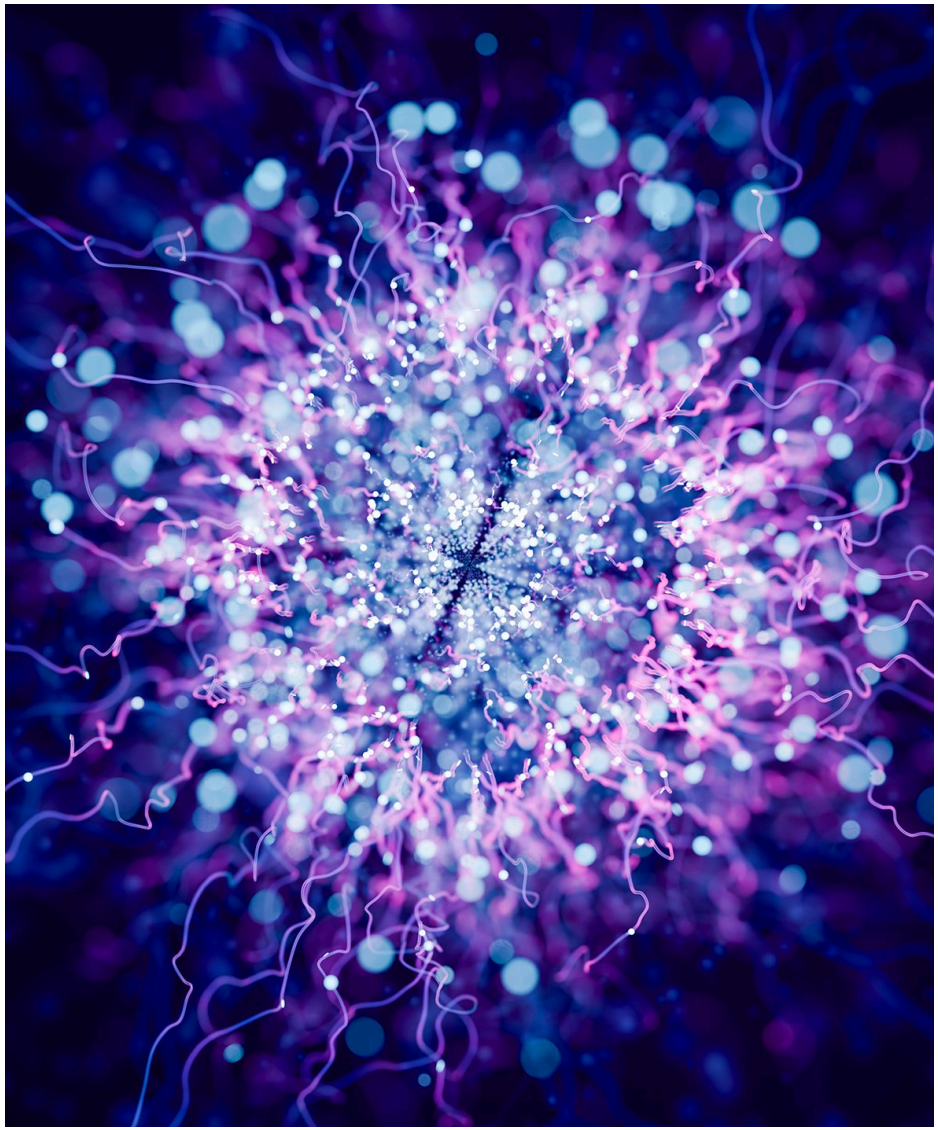
Looking ahead: how AI could turn a periodic sequence into a continuous, connected loop

As we've shown, technology underpins each of these stages. But as climate risks become more complex and less predictable, the volume of data these technologies generate is outpacing what operators can process manually. Ultimately, this will drive utilities to adopt AI-enabled, model-driven operations, in which the four separate steps act as a continuous, connected loop.

In practice, that means combining OT, IT, weather intelligence, and asset data into one live view of the network's exposure to climate risks. This means operators can monitor conditions and respond to emerging risks in real time, rather than analyzing each system separately after an event.

It also means giving intelligence more room to act: supporting, and in some cases carrying out, interventions within clear governance and safety boundaries, instead of only informing a human's decision. Once intelligence can act, resilience will evolve from a series of discrete projects into a continuously adaptive capability embedded throughout operations. A loop of monitoring, identifying risks, modeling scenarios, responding, prioritizing resources, and learning – rather than fixed planning and investment cycles.

It may be a way off yet, but this AI-enabled approach will help to close the gap between the unpredictable nature of climate risk and how utilities have traditionally managed it.



Final word

The message for utilities is clear: understanding climate risks isn't enough. As those risks become more systemic and interconnected, resilience must be managed as a continuous cycle of assessment, prioritization, preparation, response, and recovery – not a series of one-off investments.

The utilities that connect climate scenarios, risk intelligence, operational readiness, and investment planning will be best placed to protect their networks, their customers, and their capital in an increasingly volatile climate. Whether the next event is another Storm Éowyn or something we haven't seen yet, these utilities will do more than just keep the lights on.



Authors



Thomas Hernandez
Executive Vice President, Global Head of Energy & Utilities, Capgemini



Mercy Paul
Director, Lead Energy & Utilities Industry Platform, Capgemini



Philippe Vié
Senior Advisor, Energy and Utilities, Capgemini



Manuel Castro
Vice President, Energy & Utilities Lead, Capgemini

10

BATTERY ENERGY STORAGE SYSTEM

Beyond the battery: making BESS returns last



BATTERY ENERGY STORAGE SYSTEM

Beyond the battery: making BESS returns last

How asset owners can protect profitability through revenue optimization, digitalization, and AI

In 2025, the world added 108 GW of battery storage, a 40% increase from the previous year, bringing global installed capacity to 11 times its 2021 level.[1]

The system needs these batteries as wind and solar continue to grow, electricity demand rises, driven in particular by electrification and surging data center consumption, and grids become increasingly congested.

But growing demand for battery storage does not guarantee strong returns for every project. The first utility-scale batteries entered markets with limited competition and strong demand for fast-response services, creating attractive opportunities through ancillary-service revenues. That period is ending. System operators buy only the reserve capacity they need, and as battery capacity exceeds that demand, prices fall toward cost.

Texas shows how quickly these economics can change. Enverus estimates that average battery revenues in ERCOT fell from $149/kW in 2023 to a projected $17/kW in 2025, while the share coming from ancillary services dropped from 84% to 48%.[2] A mild summer contributed to the decline in 2025, but the underlying competitive pressure remains: the battery fleet will continue to grow even as weather-driven demand fluctuates.[3]

Europe is seeing a similar shift. In the U.K., ancillary services accounted for 87% of battery revenues between 2020 and 2022, but now make up roughly one-third.[4] Further, as the market became more saturated, Dynamic Containment Low prices fell 86% in just nine months after June 2022. Now competition is set to intensify: more than 90 GW of battery capacity holds queue positions in Great Britain, compared with a 2035 target of 29 GW[6], prompting the government to identify storage oversupply as an emerging risk.[7]

This underscores the financial risk of BESS. The asset can perform as intended and serve the grid, yet still fail to deliver the expected returns.

108 GW
global battery capacity additions 2025

63 GW
new battery capacity China 2025

19 GW
new battery capacity U.S. 2025

Where the money goes next

Revenue is shifting toward wholesale trading, capacity mechanisms, congestion management, and contracted grid support.

Wholesale trading offers a larger revenue opportunity, but capturing it is more complex. Returns depend on price spreads shaped by weather, renewable output, and network conditions, and a disproportionate share can come from just a handful of days.

For example, S&P Global found that two-hour batteries in ERCOT and Australia earned nearly half their annual revenue during the top 10% of days.[5] If a battery is unavailable, lacks sufficient charge or is poorly positioned on those critical days, a significant share of its annual revenue can be lost.

Lower hardware costs have helped offset some of the pressure on returns. S&P estimates that BESS capital expenditures fell by around 30% between 2022 and 2024, with payback periods for systems of up to four hours often remaining below ten years.[6] But lower CapEx cannot fully compensate for a poorly located asset, an unfavorable contract or ineffective dispatch.

Two similar batteries in the same market can now generate vastly different returns. In ERCOT in January 2026, the top quartile of optimizers captured at least 76% of the available spread, compared with just 27% for the bottom quartile.[7] While these batteries operated on the same grid, in the same month, during the same weather, their return differed based on how effectively the opportunity was captured.

This evolution is changing what it takes for operators to succeed. The physical asset still defines the opportunity, but how it is operated increasingly determines its earning potential. That puts the digital and operational layer at the center of the next phase of BESS economics.

[1] https://www.iea.org/reports/global-energy-review-2026/technology-battery-storage

[2] https://www.enverus.com/newsroom/ercot-battery-profits-drop-as-market-saturation-reshapes-texas-storage/

[3] https://modoenergy.com/research/why-were-ercot-battery-revenues-so-low-in-2025-weather-energy-arbitrage-builodout

[4] https://modoenergy.com/research/en/how-does-battery-energy-storage-make-money

[5] https://www.spglobal.com/energy/en/news-research/blog/energy-transition/110625-declining-costs-shifting-revenues-evolving-business-case-for-battery-storage

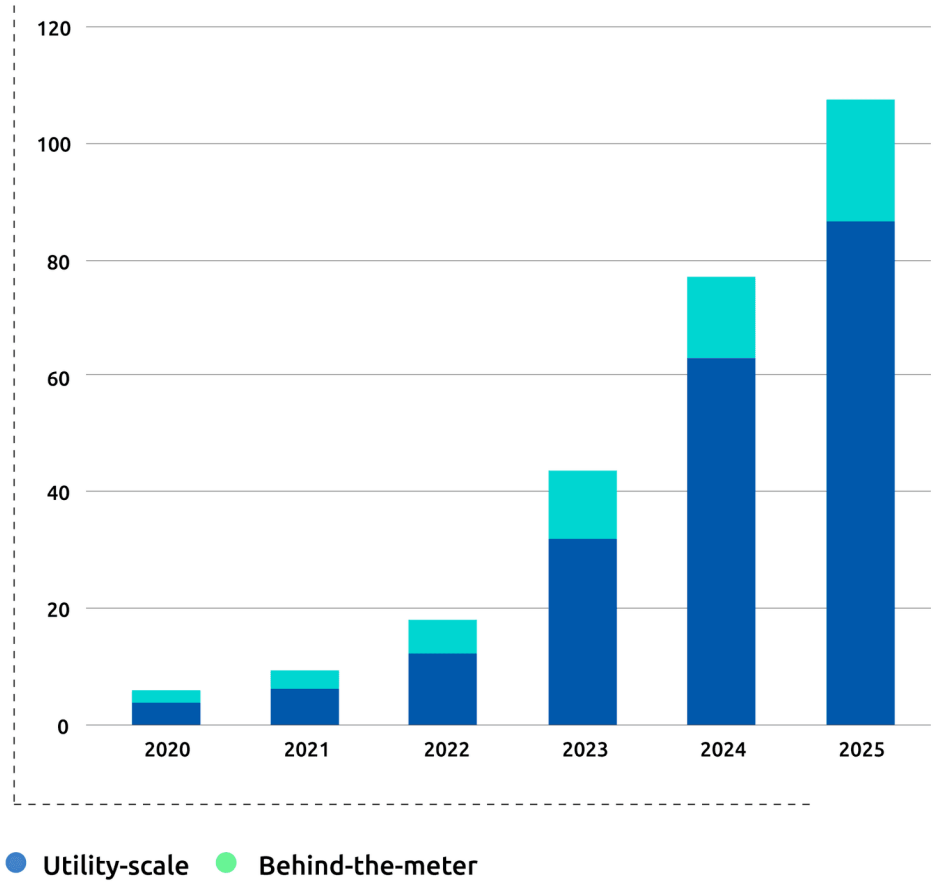
[6] https://www.spglobal.com/energy/en/news-research/blog/energy-transition/110625-declining-costs-shifting-revenues-evolving-business-case-for-battery-storage

[7] https://modoenergy.com/research/en/ercot-march-2026-bess-benchmark-batteries-fern-revenues

BESS returns begin with capital-project fundamentals. But as markets become more competitive, how effectively the asset operates increasingly determines what it can earn.

Battery specifications: What a battery can do	Battery operations: What a battery can earn
• Power • Duration • Efficiency • Degradation constraints	When the battery charges/ discharges What markets it participates in How revenues are stacked How reliably capacity is available How commercial opportunities are balanced against battery health

Figure 1: IEA: Global battery storage additions: 2021-2025



Source: IEA[8]

[8] IEA (2026), Global battery storage capacity additions, 2020-2025, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-battery-storage-capacity-additions-2020-2025, License: CC BY 4.0

Five questions to ask before every BESS investment decision

Our analysis reveals a five-point stress test every project should pass, backed by real numbers.

1. If ancillary revenue falls by half, does the project still work?
2. If the optimizer runs 10–15% below the top quartile, what happens to equity returns?
3. If the asset misses the ten best revenue days of the year, what is left?
4. If cycling doubles, who pays for the degradation?
5. If the asset must refinance in a weaker merchant market, will lenders still lend?

A project that fails this test may still add useful capacity to the grid, but it will not pay its investors.

Capgemini's BESS economic model runs three futures, all defined by real market conditions and asset operations: two to four hours of duration, one to two cycles a day, and falling CapEx.

Favorable case	Base case	Stressed case
Renewables keep spreads wide and demand for ancillary services holds, so a merchant stack works	Spreads and ancillary prices both compress and merchant revenue alone becomes marginal	Batteries far outnumber reserve requirements, spreads narrow and undifferentiated merchant operators lose money



The race for returns is heating up for BESS operators

For BESS operators, the race for megawatts is still on, but there is a new dimension: the need for returns. The same battery can be sold three ways:

1. A fully merchant asset keeps all the upside and downside. Cash flows swing and debt is hard to raise. This suits owners with strong balance sheets and a portfolio that can absorb a bad year.
2. A full toll hands dispatch and market risk to an offtaker for a fixed payment. The owner gets bankable income and gives up the upside. The cycling limits and availability terms must fit the battery's warranty and physics. If they do not, the toll turns into a stream of penalties.
3. A hybrid model contracts part of the capacity, often 40–50%, and trades the rest. The contracted share sets a floor and the merchant share keeps some upside. In our scenarios this is the only structure that stays viable in all three futures, as long as it is run with discipline.

The market is moving this way. Modo Energy tracked 82 BESS financing deals in Europe in 2025, up from 25 the year before. Disclosed debt rose from €1.4 billion to €6.1 billion, while standalone tolls went from three to 15.[9] Lenders are adapting with mini-perm loans, cash sweeps and broader warranty packages. Owners should expect to negotiate these as standard terms.

One important difference between battery storage and renewables remains. With solar, for example, lenders finance a relatively predictable generation profile. With batteries, they are increasingly financing a trading strategy, with revenues that depend on market conditions and operating decisions. That makes BESS inherently harder to finance.



[9] https://modoenergy.com/research/en/march-2026-europe-battery-financing-deal-report-2025

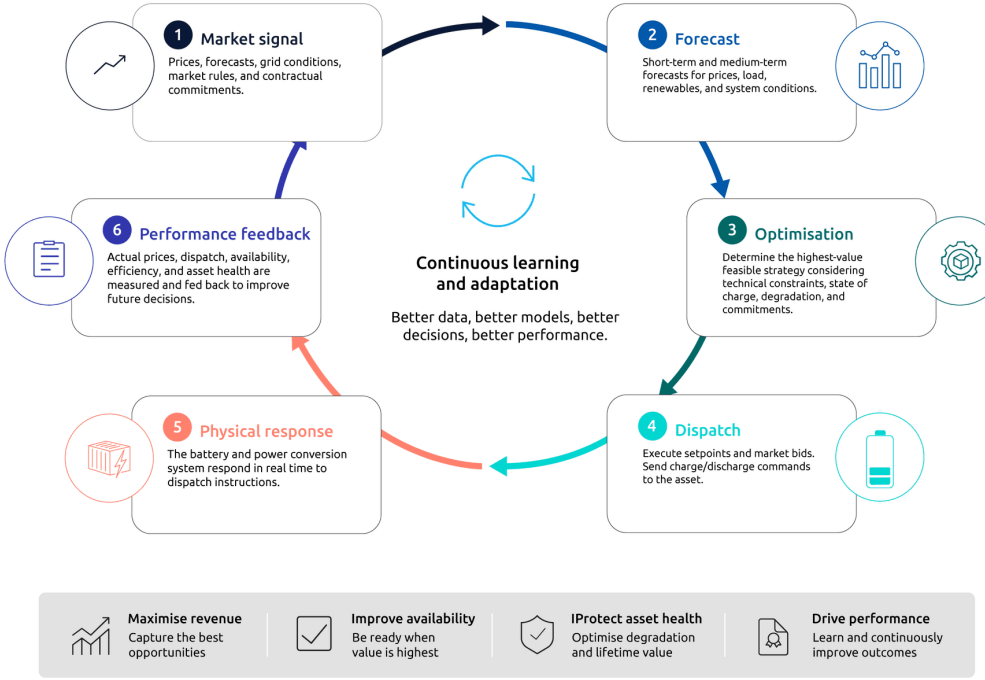
Operations now sits in the revenue model

A contract only protects the revenue that the battery actually earns. A wind farm converts the wind it gets. However, a battery must decide, thousands of times a year, when to charge, when to discharge, which market to bid and how much capacity to hold back. Each decision must respect state of charge, grid limits, temperature, degradation, and warranty.

The advantage lies in how precisely each understands what the asset can do, and how effectively that intelligence translates into commercial decisions through functions like energy management system (EMS) optimization, asset intelligence, and AI-enabled trading platforms. Actual results flow back into forecasts and asset models. When the optimizer assumes a state of charge the battery does not have, the bid fails and the imbalance bill arrives.

Figure 2: Closed-loop optimization across markets and assets

From market signal to performance feedback



Knowing the asset pays.

Operations and maintenance (O&M) has become a revenue function. A battery can report high annual availability and still be down on the three days that make its year. Poor thermal management speeds degradation. Maintenance planned without a view of the market can take the asset out during a price spike. Under a toll or a floor, shortfalls trigger penalties. Every maintenance window, augmentation plan, and extra cycle should be priced against the revenue it puts at risk.

Based on our experience working with BESS operators, that deeper understanding can enable operators to safely access 1–5% more capacity from the same physical system. Across a large fleet, that is capacity without CapEx.

Recent research using real-world data from a large-scale BESS reinforces the value of that precision. In the study, data-driven component modeling reduced unfulfilled energy delivery by 78.2% and balancing-energy costs caused by deviations by 71.7%. Together, this limited balancing-energy costs to just 1.8% of trading revenue.[10]

But knowing how much capacity is available is only the first step. Owners also need to determine where and when that capacity can create the greatest value. Greater visibility into battery condition can inform how an asset should be deployed while balancing immediate revenue against degradation, availability, and asset life. An asset suited to frequent ancillary-service dispatch, for example, may warrant a different strategy from one better positioned for energy arbitrage or longer-duration dispatch.

That flexibility will become increasingly important because there is no single successor to ancillary services. Future BESS returns are likely to come from a shifting mix of energy arbitrage, capacity markets, renewable firming, grid services and behind-the-meter applications. New opportunities are emerging as well. Data centers, for example, represent a growing market as operators seek to supplement constrained grid connections, integrate on-site generation, and manage rapidly increasing power requirements.

Owners therefore need assets and digital architectures capable of following value as it moves. Open, scalable EMS platforms that can connect to new markets, services and technologies can preserve that optionality, whereas a closed model ties the asset to the markets of the year it was commissioned.

[10] https://www.sciencedirect.com/science/article/pii/S0306261925020707?utm_source=chatgpt.com

Digitalization and AI as the new source of competitive advantage

Behind every AI model is data. And for BESS operators, this can be a challenge as data is often spread across original equipment manufacturer (OEM), battery management system (BMS), supervisory control and data acquisition (SCADA), EMS and trading systems, with inconsistent timestamps, definitions and formats. That fragmentation makes it difficult to pinpoint why an asset underperforms, whether the issue lies with the battery, market conditions or the optimizer.

Asset owners should therefore establish clear data rights before signing contracts with OEMs and optimizers. They can outsource O&M or trading to specialists, but should retain control of the asset data model that underpins performance and optimization.

Once the data holds, the next step is moving from prediction to continuous optimization. An AI layer integrated with the EMS can interpret changing market conditions, from intraday price movements to emerging grid events, and adjust dispatch decisions as actual conditions diverge from forecasts. Rather than relying on operators to identify every change and determine the appropriate response, AI can help determine when to charge, discharge or preserve capacity within predefined operational and commercial constraints.

For example, Finnish investment manager Exilion had been operating a 6 MW / 6.6 MWh BESS for five years when, in 2023, it introduced an automated multi-market optimization tool. After this deployment, the asset subsequently generated €40,700/MW/month, a 132% revenue increase compared with its previous trading strategy; the solution also helped reduce the cycle count of their battery by 63%.[11]

Importantly, intelligence generated through these solutions hold value long after a dispatch decision is made. As owners accumulate operating data across different suppliers, chemistries, configurations, and conditions, AI can identify patterns in reliability, degradation, and performance. Those insights can feed back into maintenance strategies, procurement and even the design of future assets. This creates a learning loop where operating an asset generates intelligence that can improve both current performance and future investment decisions.

[11] https://capaloai.com/case-studies/exilion/?utm_source=chatgpt.com

From individual asset to portfolio economics

At portfolio scale, the challenge becomes more complex: which battery should pursue which opportunity, and when?

Answering that question requires a common data model across OEMs, consistent performance metrics and an operating model that connects commercial and asset decisions. Traders need visibility into available capacity and the degradation cost of using it, while asset managers need to understand what that capacity is worth in the market. Without that shared view, each team optimizes for its own objectives at the expense of overall margin. Clear decision rights are equally important: who sets commercial priorities, who adjusts dispatch limits and when operators can override the EMS.

Cybersecurity belongs in the same plan. A BESS links substations, operational technology, cloud analytics, market platforms, and third parties. Securing those connections protects revenue as well as the grid itself.

Finally, operating data should also shape procurement. Reliability and degradation patterns across suppliers and chemistries are evidence for the next purchase. European industrial policy may change which BESS and BMS suppliers qualify for support, and owners who buy for the whole portfolio will adjust faster.

Six disciplines for durable returns in BESS

1. **Design for optionality.** Site, duration, connection rights, controls and market qualification should open several revenue paths over 10 to 15 years.
2. **Structure for resilience.** Test merchant, hybrid and toll structures against the downside scenario, financing needs and the value of the flexibility being transferred.
3. **Manage availability and degradation as financial variables.** The value of uptime depends on when the asset is available. The value of dispatch depends on the revenue it captures relative to the degradation and opportunity cost it creates.
4. **Build the data and operating model before commissioning.** Data rights, integration, EMS choice and decision rights belong in the investment case.
5. **Optimize the portfolio, not just the asset.** The objective should be to optimize economics across the portfolio, beyond individual sites, balancing immediate revenue with availability, degradation and lifetime asset value.
6. **Bring asset management and trading closer together.** For BESS, physical performance and commercial opportunity are inseparable. Connecting these functions allows owners to optimize for margin rather than managing technical and commercial performance separately.

Conclusion

Battery storage will keep growing. Returns will not necessarily follow the same trajectory.

These disciplines depend on one another. A strong optimizer cannot overcome a weak grid connection, and a bankable toll cannot compensate for terms the battery cannot meet. As BESS markets mature, durable returns will depend on getting the whole investment case right: asset design, commercial structure and operations working together from the start.



Authors



Florent Andrillon
Executive Vice President, Energy Transition & Sustainable growth advisor & Global Head of Climate Tech, Capgemini



Remi Dachicourt
Director, Renewables & Decarbonized Power Generation, Capgemini



Shashi Kant Singh
Senior Manager- Renewables, BESS & Hydrogen, Capgemini



Patrick Neary
Manager, Energy & Utilities, Capgemini

11

NUCLEAR RENAISSANCE

Tripling nuclear capacity by 2050

Why AI will play an essential role in the next nuclear renaissance



NUCLEAR RENAISSANCE

Tripling nuclear capacity by 2050

Why AI will play an essential role in the next nuclear renaissance

The most recent *World Nuclear Outlook Report* projects that global nuclear capacity will reach 1,428 GWe by 2050—a figure 228 GWe higher than the target set out in the *Declaration to Triple Nuclear Energy.*[1] With the industry's ambition for new nuclear made clear, the challenge now is making it deliverable at scale.

Standing in the way are two closely connected challenges: the industry's need for financing models capable of mobilizing capital over long project lifecycles and the ability to give investors confidence that projects can be executed predictably and repeatably.

The upshot is that progress on one tends to reinforce the other. With greater certainty around costs and timelines, organizations can strengthen the investment case; meanwhile, access to capital enables the industry to build the supply chains, workforce, and digital capabilities required to deliver at scale.

While the nuclear renaissance is a global mission, the path to realizing it will vary by region. In this article, we explore how that journey is taking shape across markets, where AI can help accelerate progress, and where organizations should start.



[1] https://world-nuclear.org/news-and-media/press-statements/tripling-global-nuclear-energy-by-2050-within-reach-if-governments-act-now

Different markets, different paths to investment

Across regions, different models are emerging to finance the next wave of nuclear development.

For example, in the U.S., the current administration recently signed an $80 billion agreement with Westinghouse Electric Company to support a new fleet of AP1000 reactors[2] and also invested $2.7 billion to strengthen domestic uranium enrichment.[3] Private capital is also flowing. U.S. nuclear startups have attracted significant investment[4], while major energy consumers including Amazon, Dow, Google and Meta have pledged support for increasing nuclear capacity as they seek reliable, carbon-free power, driven by AI use and data centers.[5]

Europe, however, presents a different financing picture. Political support for nuclear is growing, but converting that support into final investment decisions requires complex financing structures and sustained government involvement.

In France, for example, EDF's €72.8 billion program to build six EPR2 reactors[6] illustrates the scale of political commitment to new nuclear, but also the complexity of establishing financing mechanisms that align with both national ambitions and the European regulatory framework. Similarly, in the U.K., Sizewell C demonstrates both the depth of public commitment while highlighting the challenges that come along with assembling a financing structure capable of reaching a final investment decision.[7] Sweden, meanwhile, has accelerated its nuclear policy and introduced dedicated state support mechanisms to help unlock investment and reduce financing risks for future projects.[8]

[2] https://www.klgates.com/thought-leadership/US-Government-Announces-Historic-80-Billion-Nuclear-Partn ership-with-Westinghouse-Electric-Company-Cameco-Corporation-and-Brookfield-Asset-Management-to-Construct-AP1000-Reactor-Fleet-10-30-2025

[3] https://www.energy.gov/articles/fact-sheet-golden-era-american-nuclear-energy-has-arrived

[4] https://www.nei.org/news/taking-the-investment-pulse-q4-2025

[5] https://world-nuclear.org/news-and-media/press-statements/tripling-global-nuclear-energy-by-2050-within-reach-if-governments-act-now

[6] https://www.world-nuclear-news.org/articles/ec-launches-investigation-into-french-nuclear-funding-plans

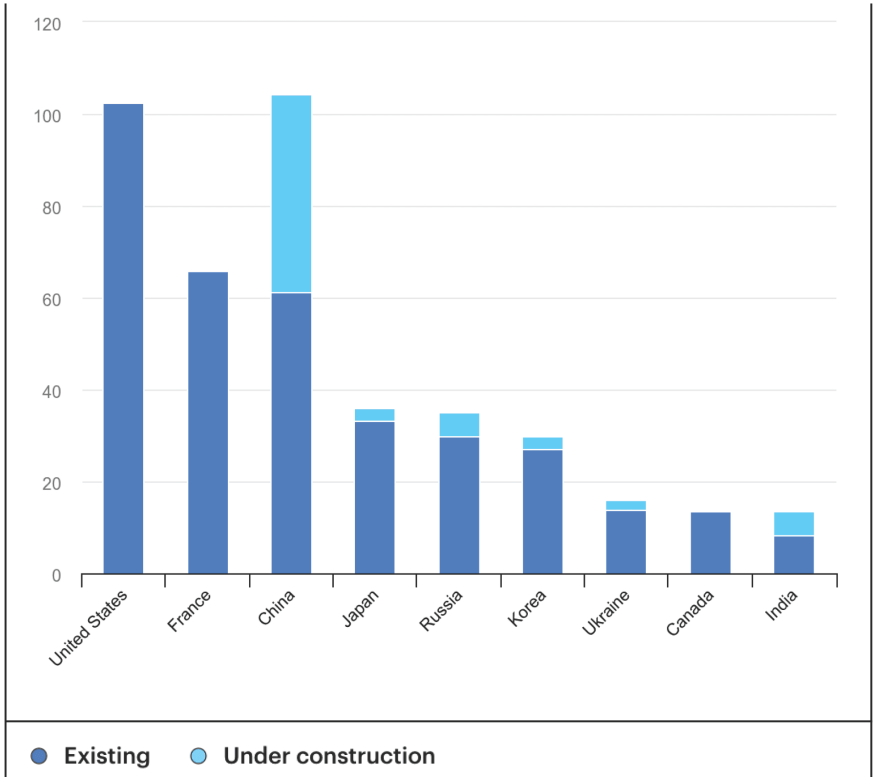
[7] https://www.nao.org.uk/press-releases/government-adopts-novel-finance-structure-for-sizewell-c-and-will-need-to-monitor-risks-closely/

[8] https://www.government.se/government-policy/nuclear-financing/

Small modular reactors (SMRs) provide another lens into how nuclear investment is evolving. Across Europe, countries including the U.K., Sweden and Poland are advancing initiatives, but many remain at an early stage where public funding is supporting development and demonstration rather than large-scale commercial deployment. In the U.S., federal support is increasingly focused on moving SMRs closer to deployment, including $800 million awarded to TVA and Holtec for initial advanced light-water SMR projects.[9]

In short, there is no single financing model for the next generation of nuclear. In all cases, however, the objective is the same: improve delivery predictability to strengthen investor confidence and unlock the capital needed to scale.

Figure 1: IEA: Nuclear capacity in operation and under construction in selected regions, 2025



https://www.iea.org/data-and-statistics/charts/nuclear-capacity-in-operation-and-under-construction-in-selected-regions-2025

[9] https://www.energy.gov/articles/fact-sheet-golden-era-american-nuclear-energy-has-arrived?utm_source= chatgpt.com

Investment beyond the reactor

Financing is only one part of the challenge when it comes to scaling new nuclear. The industry also needs to demonstrate that it can put that capital to work effectively. Projects including Olkiluoto 3 in Finland, Flamanville 3 in France and Hinkley Point C in the U.K., as well as the Westinghouse AP1000 units at Vogtle in the U.S. and APR1400 projects in South Korea have demonstrated how first-of-a-kind designs, fragmented supply chains, workforce constraints and engineering complexity can translate into significant cost and schedule pressures.

This underscores why the next wave of investment must focus on more than reactor technology. Scaling nuclear requires parallel investment in the ecosystem needed to deliver it including expanding supply chain and manufacturing capacity, developing and transferring critical workforce skills, strengthening digital engineering, configuration and information management, and deploying AI-enabled engineering and project-delivery capabilities. Together, these investments establish an industrial base capable of moving from one-off projects toward more repeatable delivery.

AI has a specific role to play in that equation. While intelligent technology will not eliminate the inherent complexity of nuclear construction, it can help make it more manageable. Applied with consistency across the lifecycle, AI can improve engineering productivity, capture and reuse institutional knowledge, accelerate design reviews, strengthen configuration control and make large volumes of documentation easier to manage. These capabilities can help identify issues earlier, reduce rework and create greater consistency.

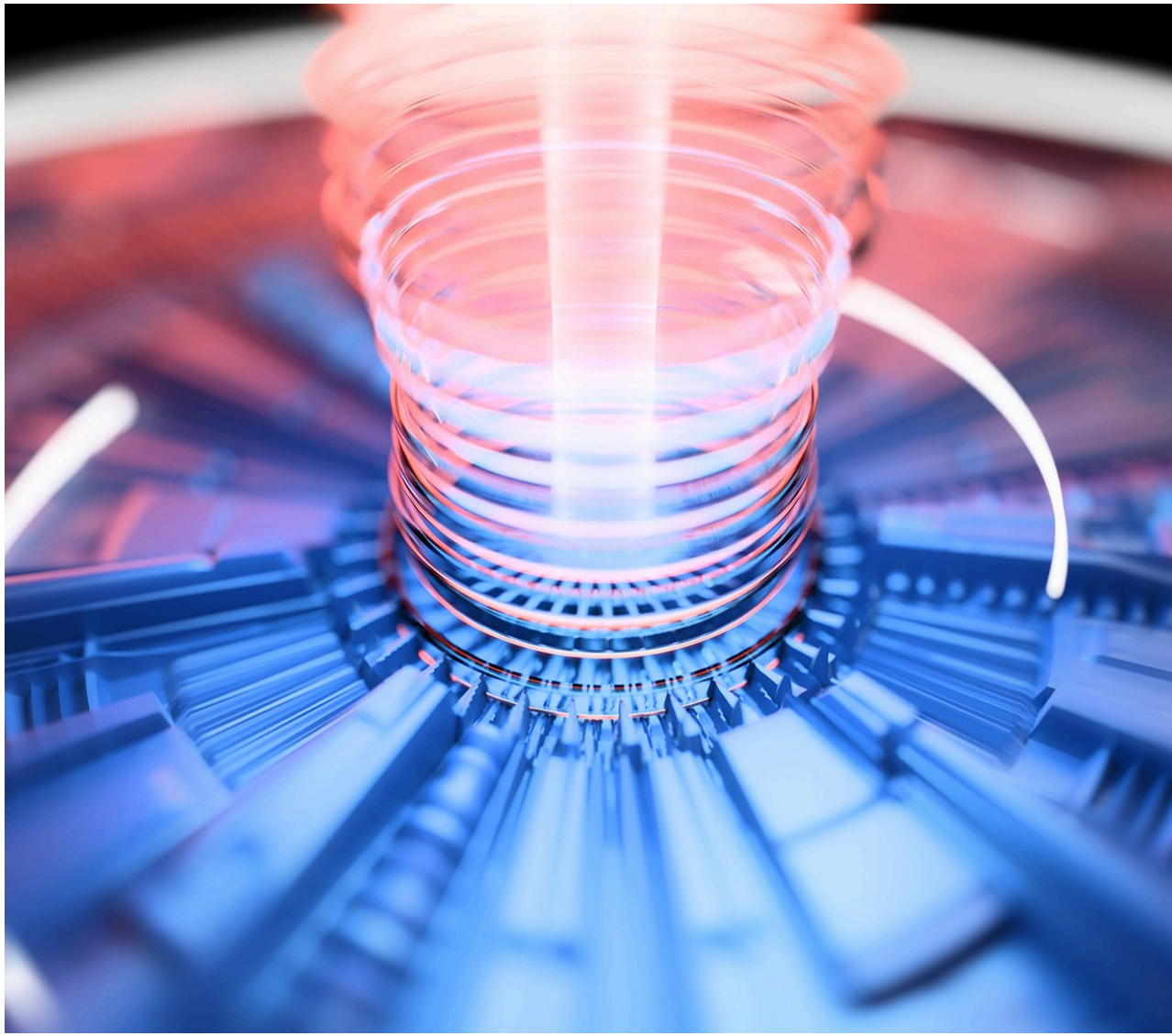
The real—and realistic—opportunity across all AI application areas is greater predictability. Over time, it can strengthen confidence in cost and schedule performance and, in turn, the investment case for new nuclear.



Embracing AI as part of the solution

The nuclear industry has historically taken a measured approach to innovation, with the adoption of new technologies proceeding cautiously even before the digital era. Today, that long-standing approach is being tested by the accelerating pace of technological change, as every new technology and evolution of it must still meet the industry's stringent safety, security and regulatory standards. Concerns around digital sovereignty further raise the bar, with organizations needing to protect sensitive engineering data, operational procedures and proprietary reactor knowledge.

At the same time, nuclear organizations must face the new reality: tripling global capacity using today's engineering practices is simply not achievable. To meet growth targets, the industry must begin treating AI not as an optional innovation, but as an essential part of the solution. Next we outline a practical path forward for how the nuclear industry can embrace AI safely and effectively.



1. Reuse proven AI patterns from adjacent industries.

Nuclear does not need to invent an entirely new AI playbook. In fact, many of the challenges it needs to solve are familiar to other highly regulated, engineering-intensive industries. The opportunity is to learn from those approaches and apply AI where it can accelerate and enhance them.

For example, when it comes to engineering knowledge management, aerospace engineers must navigate enormous volumes of technical documentation, design specifications and maintenance records. Nuclear organizations face a comparable challenge across engineering drawings, design-basis documents, licensing submissions, operating procedures and decades of configuration-controlled records. As in aerospace, AI can help engineers at nuclear organizations find and connect relevant information faster, surface relationships between documents and changes, and make institutional knowledge easier to access and reuse.

Additional application areas with strong applicability to the nuclear industry are outlined below.

Proven AI approaches can provide a useful starting point, but they must be adapted to nuclear's requirements for safety, explainability, traceability and oversight. In short: borrow the pattern, but engineer it for nuclear.

> "As in aerospace, AI can help engineers at nuclear organizations find and connect relevant information faster, surface relationships between documents and changes, and make institutional knowledge easier to access and reuse."

Aerospace	Engineering knowledge and configuration management, design-change impact analysis and navigating vast volumes of technical documentation
Automotive	Design reuse, engineering productivity and standardization across programs and sites
Defense	Relevant models for secure and sovereign AI environments, controlled access to sensitive information and rigorous traceability
Oil & gas	Digital technologies for asset management, maintenance optimization, digital twins and complex capital-project delivery

2. Start with application areas where risk is lowest.

Adapting proven approaches does not mean applying AI everywhere at once. For nuclear, the logical starting point is outside safety-critical systems with relatively low-risk applications. This allows organizations to tap into valuable speed and productivity improvements while building the governance and operational experience needed to expand AI into more complex applications.

Engineering knowledge management, intelligent document search, design-review support, configuration management and regulatory and licensing documentation can all help engineers work more efficiently by making information easier to find, connect, and use. At the same time, using AI in this way keeps qualified experts firmly in the decision-making loop. In the table below we provide a list of relatively low-risk AI applications and their associated delivery value in nuclear.

Application area	AI task	Delivery value
Engineering knowledge management	Capture and organize engineering knowledge, surface relevant lessons learned, recommend similar designs, answer technical queries.	Reduces time spent searching for information, improves design consistency and prevents repeating mistakes.
Intelligent document search	Search and retrieve information across drawings, specifications, procedures and technical reports using natural language.	Accelerates engineering decisions and minimizes project delays.
Design review support	Compare design revisions, identify inconsistencies, flag missing requirements, summarize changes and highlight issues for review.	Speeds design reviews, reduces rework and helps teams focus on higher-value technical decisions.
Configuration management	Detect inconsistencies between engineering documents; identify change impacts; validate document completeness.	Improves configuration control, reduces errors and supports smoother project execution.
Regulatory documentation	Draft regulatory submissions, summarize technical evidence, cross-reference requirements, identify missing information and maintain traceability between design and regulations.	Reduces documentation effort, shortens regulatory preparation cycles and improves the quality and consistency of submissions while maintaining human oversight.



Once organizations have established confidence through lower-risk applications, they can begin applying AI to more complex engineering and operational challenges.

For example, for engineering teams, a single design modification can affect hundreds of drawings, specifications, procurement documents and licensing records. AI can help identify downstream impacts, surface affected documentation, and support engineers in assessing changes more quickly and consistently. This can help reduce rework and shorten engineering cycles while ensuring every recommendation remains subject to human review and approval.

From there, organizations can expand into more advanced applications, including outage planning, predictive maintenance, operational support, and licensing and safety analysis through intelligent document generation and end-to-end traceability.

Embedding AI in this way across the nuclear lifecycle is crucial for meeting the industry's long-term capacity ambitions by enabling projects to be delivered more predictably, repeatably and at scale.

Building trust to deliver the nuclear renaissance

As organizations move toward more advanced application areas, the question becomes not simply where AI can add value, but whether engineers and operators are prepared to rely on it and regulators are willing to accept it. Explainable models, qualified data, robust cybersecurity, traceable outputs and clear governance become enablers, rather than constraints, when built in from the start.

Thankfully, the industry has a strong foundation to build on. Nuclear has spent decades establishing a culture in which safety, traceability and accountability are non-negotiable. AI needs to operate within—and ultimately reinforce—those same principles. That means ensuring people understand how outputs are generated and which information they are based on, maintaining appropriate human oversight, and establishing clear accountability for how AI-informed decisions are made.

Importantly, trust in AI does not come from assuming its outputs are always correct. AI systems are inherently probabilistic and should not operate in isolation in nuclear environments. Instead, organizations will increasingly rely on hybrid approaches that combine AI with deterministic engineering tools, physics-based models and human oversight. Together, these controls help ensure that AI-generated insights remain explainable, verifiable, and appropriate for nuclear applications.

When engineers, operators and regulators trust how AI is governed and used, organizations can apply it more broadly. In turn, those gains can translate into greater predictability in cost, schedule and delivery—strengthening the investment case for the projects that follow. Building trust in AI can therefore do more than accelerate adoption; it can help give investors greater confidence in the industry's ability to turn today's nuclear ambition into predictable, repeatable deployment at scale.

Authors



Sven Sers
Global Lead for Nuclear, Capgemini



Denis Bourguignon
Director, Capgemini

12

OIL & GAS

Turning volatility into advantage:

How AI can build resilience and create value across the oil, gas and LNG value chains



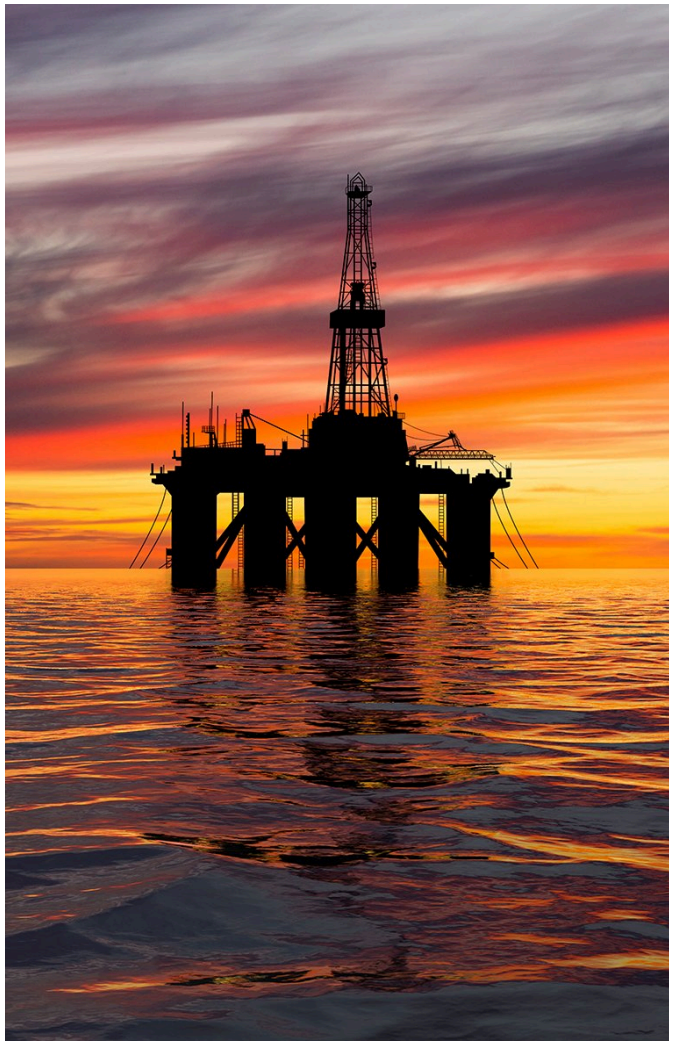
OIL & GAS

Turning volatility into advantage: How AI can build resilience and create value across the oil, gas and LNG value chains

On Monday, your trading desk is staring at widening regional spreads and a sudden repricing of flexible freight contracts. On Wednesday, an unplanned outage cascades through your midstream network, forcing you to rethink your nominations. And on Friday, you realize the downstream plan you made two weeks ago is already out of date. Feedstock prices have moved, product demand has shifted, and your maintenance window has tightened.

This isn't a product of a bad decision. It's the "new normal" for the global oil, gas and LNG industry. Economic and geopolitical uncertainty are driving fuel price volatility and making forecasting harder. Logistical chokepoints – from canals to conflict zones – can also extend routes, raise costs, and disrupt energy supply chains.

In this environment, where it's impossible to predict the next move or shock, companies must get much faster at spotting and responding to signals. The only way to achieve this step change in decision-making – and become an adaptive enterprise – is through AI.



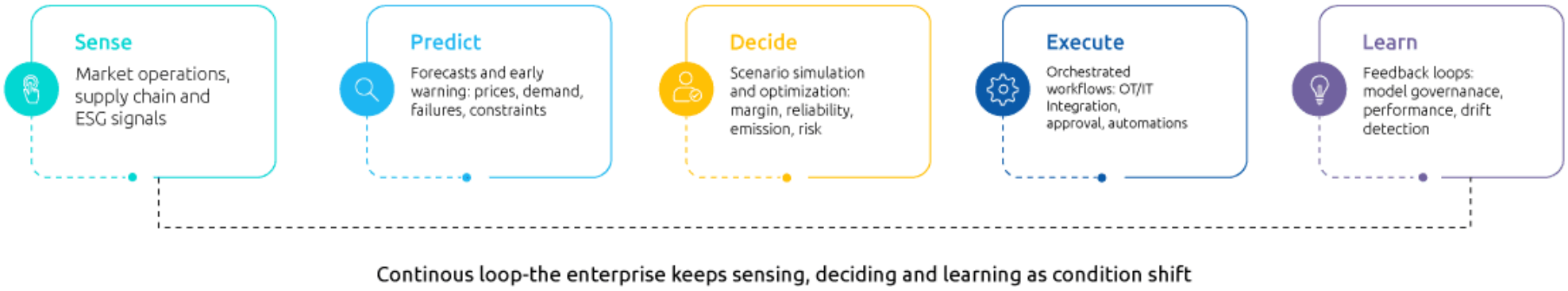
From optimizing regularly to adapting continually

Traditionally, organizations assumed that optimizing would mostly go to plan. But today's value chain is more like a live system: interdependent, constraint-driven, and sensitive to changes and shocks.

That's particularly true of LNG, where every part of the chain is tightly connected – from upstream supply and liquefaction reliability to shipping constraints and regas demand. Add to this the ripple effect of global benchmark prices, and the importance of flexible cargoes, and a small disruption in one part of the chain can have a big knock-on effect on the business.

The answer isn't a sharper forecast – it's a better way to decide when the forecast is uncertain and identify trade-offs to mitigate risks or seize immediate market opportunities. No model will reliably call the next shock, so the edge comes from how fast you turn signals into sound decisions – through an AI-enabled system that continuously senses change, tests scenarios, and recommends actions, with forecasts feeding in as one input. This creates an "adaptive enterprise loop" (see Figure 1), in which you optimize continuously and resilience moves from a slogan to an embedded capability.

Figure 1: The adaptive enterprise loop, enabled by AI
AI senses change, tests scenarios and recommends action-continuously



Where AI can add value

AI brings the most value at points where slightly better decisions bring big results. It detects signals humans might miss, calculates trade-offs, and recommends actions – all while respecting your constraints and appetite for risk.

These points exist along the chain:

Upstream: protecting production and costs

In uncertainty, upstream resilience often means preventing avoidable downtime and optimizing production. AI helps by spotting potential failures earlier, scheduling maintenance for optimal times, and continually fine-tuning production so you get the most output for the lowest cost.

Midstream: keeping a continuous flow

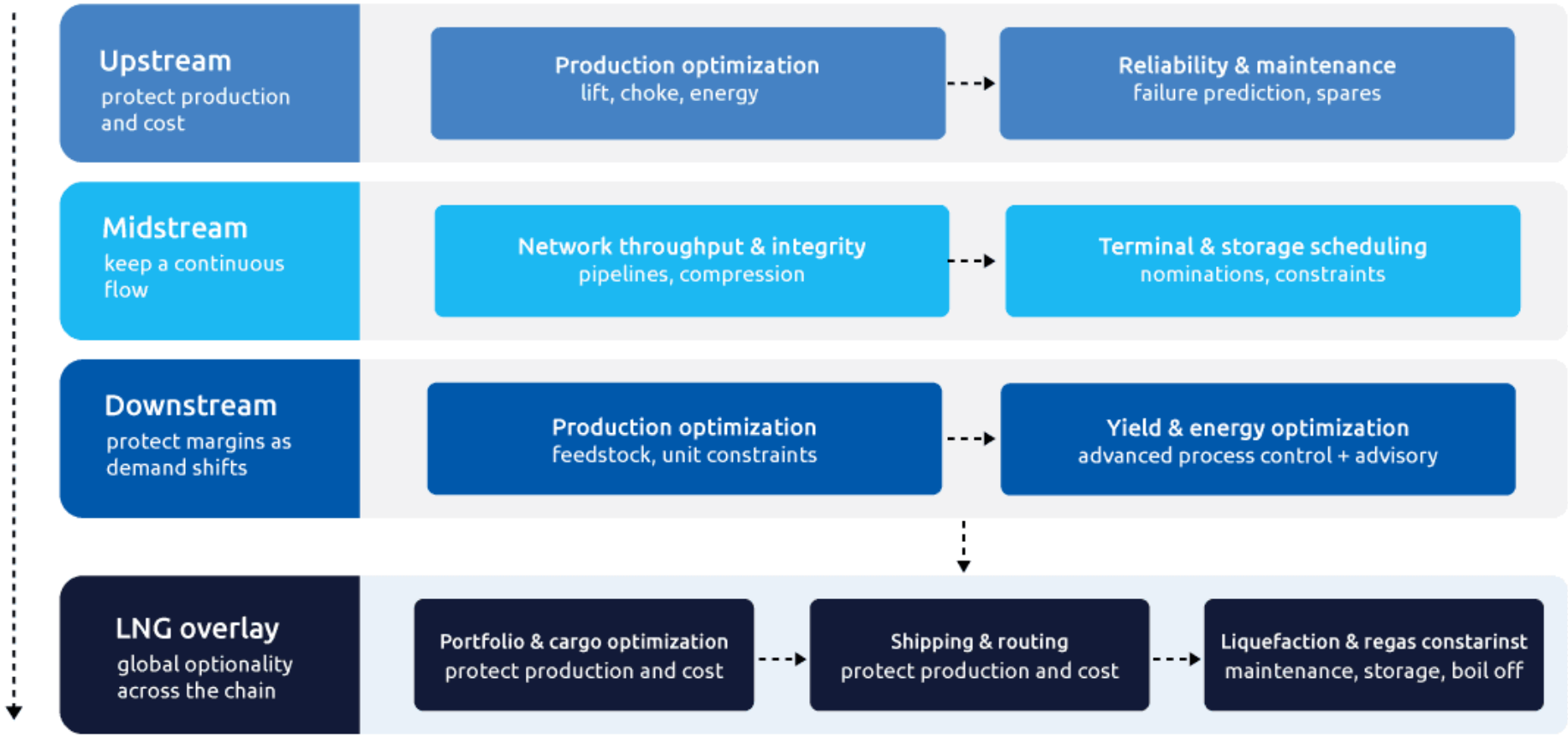
Bottlenecks, storage constraints, and issues with asset integrity can eat away at midstream value. Compression schedules and the availability of terminals to receive or dispatch product are also factors. AI can help by detecting anomalies, predicting and managing disruption, optimizing shipping costs, and factoring all that into scheduling to keep the network moving.

Downstream: protecting margins when demand is shifting

Refineries and chemical plants win when they continually adapt to changing conditions. That means keeping must-run operations going and responding to feedstock economics, while updating product slates and maintenance windows. AI-supported scheduling can help cut the time needed to adjust your operating plan from days to hours.

Figure 2: Optimizing operations end-to-end with AI

Better decisions at every link in the value chain with an LNG overlay tying them together



LNG: the ultimate test of adaptive optimization

The LNG market is growing steadily, but a sudden shock – like a war breaking out – can drive up demand beyond what the existing infrastructure can meet.

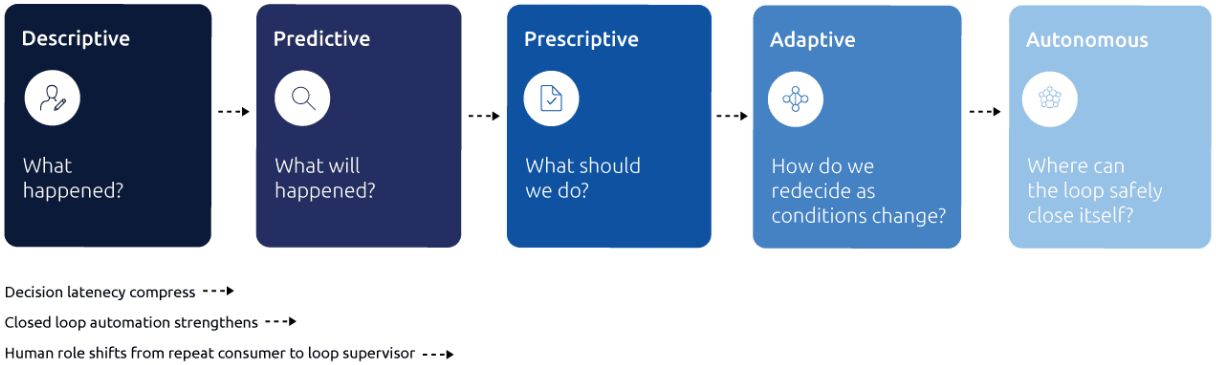
This forces companies to make complex logistical decisions, fast, to avoid overwhelming their facilities. AI can help them make the best use of what's available by allocating cargoes continuously based on netbacks, constraints, and risk appetite. It can look at congestion, weather risk, and contractual windows to pick the best shipping routes and schedules. It can also use early market signals to anticipate shifts in demand and price. And it can provide a clear view of your total risk exposure – from physical positions to commercial contracts.

How mature is your AI decision-making?

Most companies already use analytics to make decisions in individual functions. But to optimize your operations and gain a competitive edge, you need to do it holistically. That means building an operating model where AI improves, speeds up, and governs the decisions that matter most across your enterprise.

As a first step, you need to assess where your organization is on the maturity ladder (Figure 3).

Figure 3: The maturity ladder: from reporting to closed loop adaptation



In our experience, most organizations describe themselves as adaptive when they're in fact prescriptive. That means they use predictive models to feed human-authored playbooks, with people still bridging the gap.

These models answer the question: "What's the best action to take, given today's limitations?"

Meanwhile, adaptive models recognize that the constraints themselves are moving. So, they adjust their recommendations continuously, closing the loop with controlled automation.

There are five things which distinguish adaptive organizations in your industry. Here is an example of each:

1. **A unified data foundation with clear ownership and quality management.** Most LNG operators have data on cargo nominations, AIS vessel telemetry, weather and route risk, JKM-TTF-HH spreads, and terminal slot availability. An adaptive operator pulls it all together so traders can query the data in real time.
2. **An AI model that recommends, not just reports.** A refinery replaces its weekly LP with an AI scheduler that assesses margins, hydrogen levels, and tank capacity every four hours. It articulates trade-offs and generates insights. The scheduler then recommends crude slate and unit runs to improve the bottom line.
3. **Scenario simulations and digital twins that test options before committing.** Should a general manager stick to current maintenance schedules for the liquefaction train and potentially miss cargo commitments? Or delay maintenance by 10 days and take the reliability risk? A digital twin quantifies the trade-off.
4. **Clarity around which decisions AI makes, who governs the exceptions and how humans stay in the loop.** In a daily 30-minute huddle, attendees from commercial, operations and shipping review AI scenarios – deciding on cargo diversions under a set cost threshold and escalating any above it.
5. **Integrated decision-making across the value chain.** A Category-3 storm forces a precautionary shut-in of 400 kbpd offshore and three days of midstream pipeline outages – cutting feedstock to refineries and feed gas to an LNG export terminal. Rather than each desk reacting alone, an AI decision layer models the whole position together: it sequences the shut-in and restart for fastest recovery, reroutes flows through alternate pipelines and storage, flags which refineries can bridge on stored crude, and prices the choices for the cargoes it can no longer fill – defer, draw inventory, or swap with a partner. It hands the team a coordinated, costed plan in hours, rather than the days a manual cross-functional scramble would take.

> "In our experience, most organizations describe themselves as adaptive when they're in fact prescriptive."

Struggling to secure investment? Focus on measurable business value

To get C-suite buy-in and funding at scale, you need to show that investing in AI will make your organization outperform its competitors – not only mitigate risk.

Tracking the right metrics will be key. Margins should increase from improved netbacks, reduced give-away, and better slate decisions. Reliability and throughput should also increase because you have fewer unplanned disruptions – and recover from them faster.

The same goes for working capital (because less is caught up in inventory) and decision speed, thanks to faster planning cycles and fewer manual overrides. Your risk should be less concentrated, too, with clear triggers for when to hedge. And because AI finds the cleanest route to production, your emissions intensity improves.

Help your organization take a leap of faith

To really move the needle on the metrics that matter, you'll need a strong, well-managed data foundation that spans the whole chain – including third-party data such as weather forecasts and vessel positions. But don't treat it as a prerequisite to finish before AI can pay off; that's how proofs of concept stall, waiting for a perfect platform that never arrives. Build the foundation use case by use case, letting it widen with each deployment.

Our message is: don’t be the place where proofs of concept come to die. Instead, start small – where uncertainty is hurting your business most and AI offers the greatest gains. That could be in routing LNG cargo and avoiding demurrage, optimizing short-interval scheduling in refineries, maintaining midstream flow during disruption or maintaining critical equipment. Then repeat the same pattern: establish a baseline, run a pilot, embed the solution in your workflow and expand it across assets and the enterprise.



Conclusion

Volatility is the new normal – and, when handled well, the new advantage. The edge won't come from a better forecast but from better decisions when the forecast breaks. Build the AI-powered adaptive loop that senses, tests and acts, and you stop bracing for the next shock and start trading on it – capturing spreads and protecting margins while rivals are still rebuilding last week's plan by hand. That's what turning volatility into advantage looks like.



Authors



Chad Klekar
Vice President, Global O&G Operational Efficiency Lead, Capgemini



Claire Gauthier
Executive Vice President, Global Lead of Energy & Utilities, Capgemini

Contributors list

Contributors list



Wilson Mackenzie
Senior Manager, Capgemini



Sachin S
Senior Manager, Energy and Utilities Industry Platform, Capgemini



Dinesh Sathianathan
Vice President, UK Head of Nuclear & Capital Delivery, Capgemini



Adrian Caswell
Director, Energy & Utilities, Capgemini



Karen Haggerty
Executive Vice President, Chief Sales Officer & Head of ET&U, Capgemini



Amit Gupta
Program Manager, Energy & Utilities Industry Platform, Capgemini



Franz Adler
Director Energy & Utilities, Head of Data & AI, Capgemini



Salih Salman
Manager Data & AI Strategy, Digital & Business Transformation, Energy Transition & Utilities, Capgemini



Andy Vickers
Vice President, Engineering & AI, Capgemini

Thank you for reading

World Energy Markets Outlook

Insights and recommendations for a more sovereign, resilient, reliable, and affordable energy future.

Follow us on LinkedIn for more information



Cookies [1] [2] Terms [1] [2] Privacy [1] [2]

POWERED BY TURTL