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# How Investors Can Turn the Great Grid Upgrade into the Next Multi-Decade Investment Opportunity

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## Introduction

As outlined in **Part 1 of this paper**, grid operators in Europe and North America and their regulators are having to grapple with several mutually reinforcing and converging challenges such as ageing infrastructure, accelerating demand growth, and the need to integrate a burgeoning fleet of decentralised, intermittent renewable energy sources.

Against this backdrop, grid operators are increasingly turning to a set of technologies that promise faster, more capital-efficient relief. Rather than replacing existing infrastructure wholesale, these solutions focus on:

- Providing greater flexibility to smooth volatility,
- Extracting more value from existing assets to defer expensive replacement programmes,
- Ensuring a more decentralised system remains stable, and
- Improving operators' real-time visibility and control of system behaviour.

In Part 2, we explore what can be thought of as a 'New Energy Toolkit' for the modern grid.

We organise the following discussion around four core capabilities that operators of modern, digitised grids need to bolster: flexibility, capacity, stability, and visibility. The table in Figure 1 below maps the structural challenges outlined in Part 1 directly to these capabilities. What will become clear through Part 2 is that while there is no silver bullet technology that could resolve all the challenges simultaneously, taken together, these tools offer grid operators pragmatic pathways to increase effective capacity, enhance resilience, and maintain system stability in an operating environment that is becoming more complex, more volatile, and less forgiving of failure.

**FIGURE 1**

**Mapping Problems Discussed in Part 1 to Capabilities Discussed in Part 2**

| PART 1 PROBLEM | WHAT THE PROBLEM MEANS FOR THE GRID | PART 2 CAPABILITY |
|---|---|---|
| Ageing infrastructure & long replacement cycles | ▪ Critical assets are operating beyond design life<br>▪ Asset replacement programmes are protracted and expensive | ▪ Capacity (unlocking latent capacity from existing asset) |
| Extreme weather & climate-driven shocks | ▪ Weather events amplify asset stress, cause outages, and accelerate deterioration<br>▪ Resilience requirements exceed original grid design standards | ▪ Stability (under stress)<br>▪ Visibility (early detection of issues before they cascade) |
| Rising electricity demand | ▪ Unprecedented load growth intensifies congestion and pushes peak demand sharply upward | ▪ Capacity<br>▪ Flexibility (to reduce peak stress) |
| Proliferation of inverter-based renewables | ▪ Low physical inertia reduces system operating buffers<br>▪ Curtailment and stability constraints delay interconnections<br>▪ Bidirectional flows challenge legacy planning and distribution systems | ▪ Stability (frequency modulation and voltage control in low inertia contexts)<br>▪ Visibility<br>▪ Flexibility |
| Low real-time situational awareness | ▪ Unnecessarily wide margins of safety given limited real-time knowledge of asset stress, power flows, or emerging faults | ▪ Visibility |

## 1. Flexibility

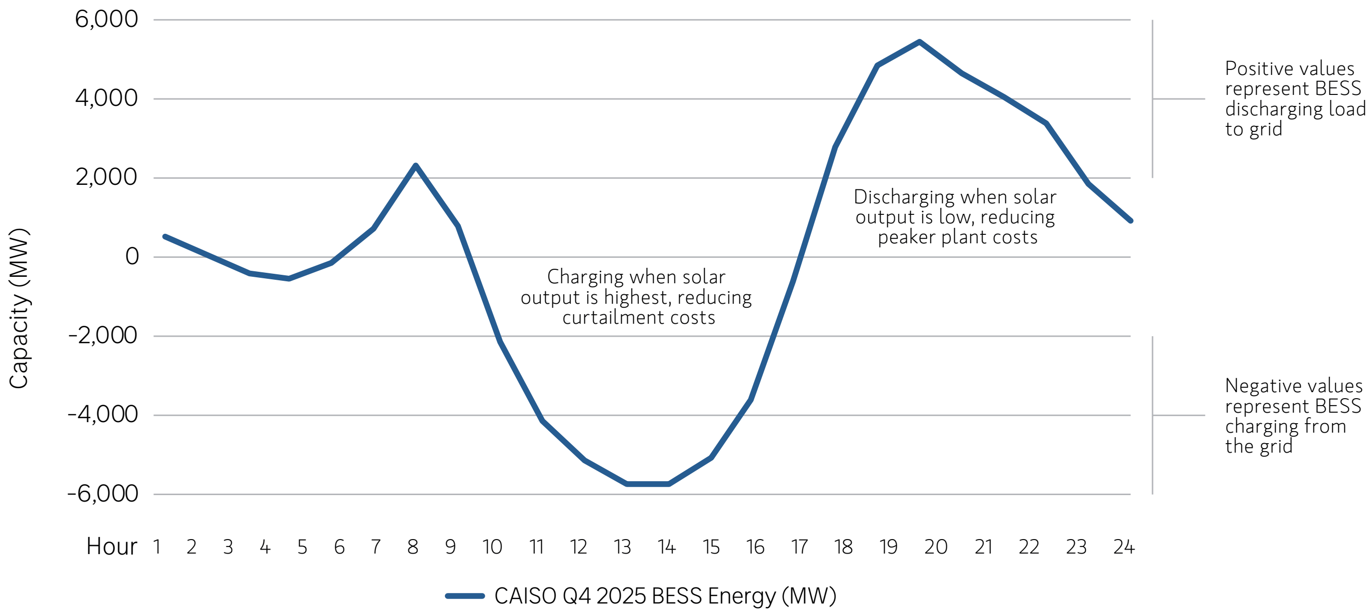
As discussed in Part 1 of this paper, both electricity supply and demand are becoming more variable as renewable energy sources become an ever-larger part of the generation mix, while electrification and new large loads are reshaping load profiles. In the context of these secular trends, flexibility as a tool that can smooth this volatility is fast emerging as a form of 'effective capacity'.

Grid-connected flexibility assets allow operators to absorb excess generation when it is abundant and inject power when and where it is scarce, smoothing short-term imbalances while keeping frequency, voltage, and congestion within tolerances. In practice, this flexibility increasingly comes from a combination of grid-scale Battery Energy Storage Systems (BESS) and aggregated behind-the-meter resources.

Indeed, grid-scale BESS are fast becoming the pre-eminent grid flexibility assets – in the US, BESS capacity grew 1016% 2020-2024 to reach 27 GW[1] , while in Europe some 17 GW of BESS capacity had been installed by year-end 2025.[2] California's grid operator (CAISO) treats batteries as a core balancing tool: in 2024 BESS provided 84% of the grid's regulation up and regulation down requirements, charging during periods of solar surplus and discharging into the evening net peak (cf. Figure 2).[3]

**FIGURE 2**

**CAISO Q4 2025 Average Hourly BESS Energy Schedule (MW)[4]**




[1] S&P Capital IQ via Rabobank, Battery energy storage systems: the foundations of a resilient energy future in the US, 18-Mar-2025.

[2] Aurora Energy Research, Battery Market Attractiveness Report 2025, Feb-2026.

[3] California Independent System Operator (CAISO), 2024 Special Report on Battery Storage, 29-May-2025.

[4] CAISO, Daily Energy Storage Report (Q4 2025).

Flexibility from BESS translates into economic value for grid operators and (ultimately) ratepayers through reducing curtailment costs (absorbing excess power in times of high renewables generation) and back-up generation costs (discharging load back to the grid in times of low renewables generation). Given these operational and economic advantages offered by grid-scale BESS, regulators and policymakers are thus encouraging operators to integrate more assets faster. In turn, this has led to the emergence of software – and services-oriented businesses that promise to better site, install, connect and operate grid-scale BESS assets (cf. Figure 3).

**FIGURE 3**

**Software That Accelerates BESS Deployment**

| CATEGORY | EXAMPLE SOFTWARE | WHAT IT DOES | WHY IT MATTERS |
|---|---|---|---|
| **Site Selection** | Planning software with software with hosting-capacity analytics | ■ Pre-screens candidate sites against real grid constraints<br>■ Dynamically calculates headroom so BESS developers can focus on sites optimal for the system | ■ Improves the quality of developers' BESS proposals<br>■ Allows operators to signal to developers exactly how much BESS capacity is needed and where<br>■ Reduces late-stage surprises (e.g. delays) for developers |
| **Interconnection** | Cluster-study orchestration platforms | ■ Digitise workflows to run cluster studies<br>■ Dynamically triage connection requests | ■ Enables shift to first ready, first served approach to queues<br>■ Improves queue hygiene by quickly identifying and removing speculative proposals |
| **Orchestration** | Market-dispatch & fleet optimisation software | ■ Co optimises BESS across energy and ancillary services using multi interval forecasting and constraints | ■ Orchestrates BESS charge/discharge cycles to deliver capacity when the system most needs it |
| **Flexibility Services** | Balancing-platform integration tools | ■ Integrates asset telemetry and bids with TSO balancing platforms so storage can earn for fast frequency services and restoration | ■ Ensures BESS owners are fairly and transparently compensated for system benefits |
| **Operations** | Lifecycle & reliability analytics tools | ■ Convert raw BMS/EMS data into reliability KPIs<br>■ Detect issues early and effect preventive maintenance | ■ Enables policy design and reform using real-world data to benchmark performance |

While grid-scale BESS is not a panacea for adding longer-term flexibility to the grid,[5] connecting more BESS assets can provide near-term relief as an alternative to adding expensive gas peaker capacity.[6] But for grid-scale BESS to provide short-term flexibility to the grid, it needs to get connected in time. Inefficiencies in managing interconnection queues as well as a burgeoning number of more speculative interconnection requests have meant that, in the US, some 890 GW of storage capacity was waiting to connect to the grid by year-end 2025 vs an installed capacity of 27 GW, with average wait times reaching 4 years.[7]

In response, several grid operators have reformed interconnection processes, adopting clustered studies, milestone enforcement and 'first-ready, first served' rules to improve queue hygiene and throughput.[8] In parallel, developers are employing AI-enabled network-simulation software at the planning stage to concentrate their capital on only those BESS projects that have the most viable prospect of securing connection. However, despite these and other concerted efforts reform queue management, connection queues are nevertheless expected to remain long for the foreseeable future.

[5] Thunder Said Energy (TSE), Dunkelflaute: how big do the batteries need to be?, 24-Jul-2025.

[6] Utility Dive, The physics of reliability: Why gas peakers alone can't save the modern grid, 3-Mar-2026.

[7] DOE Lawrence Berkely National Lab (LBNL), Queued up: Characteristics of Power Plants Seeking Transmission Interconnection, Dec-2025.

[8] Boston Consulting Group (BCG), Mind the Queue: Connection Reform for the Electricity Grid, Sep-2025.

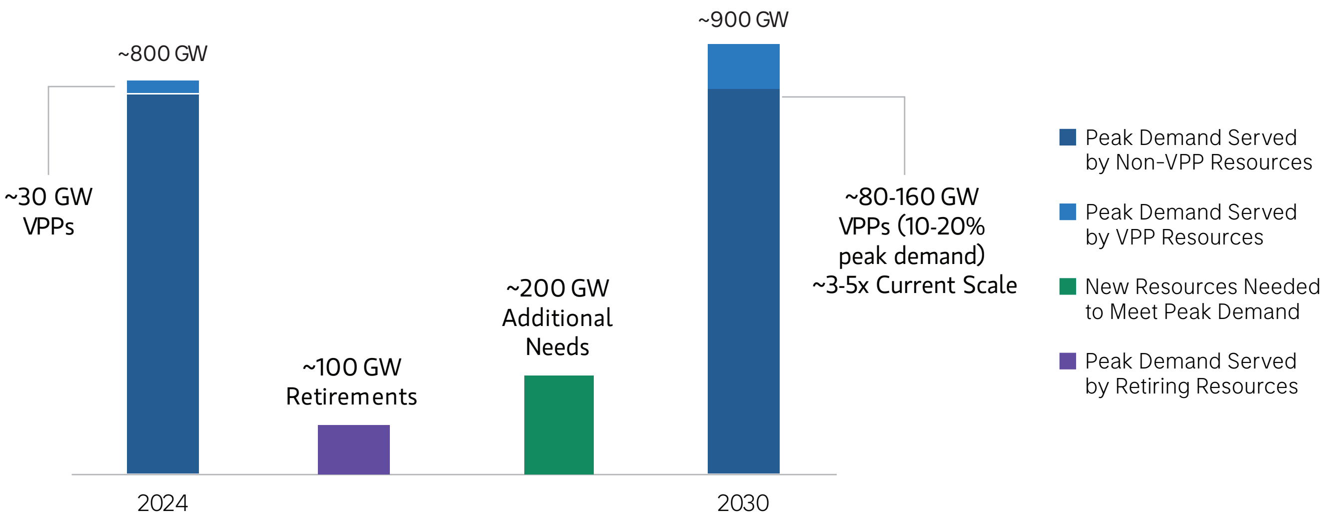
As such, policymakers are increasingly focused on flexibility that can be mobilised without having to wait for new assets to be connected. Treating distributed assets and controllable loads as a virtual fleet, which can be aggregated and dispatched like a power plant, allows operators to synthetically create flexible capacity equivalent to new BESS but available much faster.

In the US, some 30 GW of capacity (mainly residential batteries) is participating in such load-shifting programmes – often referred to as "Virtual Power Plants" (VPP) programmes – and this is expected to rise to 80-160 GW by 2030 (cf. Figure 4 below).

Rocky Mountain Institute indicates that there are some 500 VPP projects operating across the US, helping to add flexibility to grids in various ways.[9] In Vermont, Green Mountain Power directly controls enrolled residential batteries, while in Texas, ERCOT's Aggregate Distributed Energy Resource (ADER) pilot compensates battery-owners who volunteer their assets as dispatchable supply side resources to support the grid during supply shortfalls.[10,11] ERCOT expects the ADER programme to eventually provide multiple gigawatts of flexible supply when rolled out more comprehensively, demonstrating how operators can cost-effectively add meaningful 'effective capacity' that would otherwise cost billions of dollars.

**FIGURE 4**

**Department of Energy Projections for VPP Requirements**




As residential VPP programmes hold such significant potential, operators are beginning to explore whether instead of aggregating many small devices, they could extract flexibility from a smaller number of larger loads. In California, for instance, the Demand Side Grid Support Program launched in 2022 extrapolates lessons learned from residential VPP programmes to non-residential loads, providing compensation for voluntary consumption reduction, emergency power injection and other grid flexibility services.[12]

Some operators have gone even further, asking new large loads to demonstrate flexibility when submitting their interconnection requests. As explored in Part 1, the backlog of these requests has grown significantly as operators are concerned about strained network capacity and reduced system stability if they were to approve these requests.

[9] Brehm K. and Tobin M., Virtual Power Plant Flipbook, Rocky Mountain Institute/VP3, 2024.

[10] Green Mountain Power, GMP's Pioneering Network of Powerwall Batteries Delivers First-in-New-England Benefit for Customers & Grid, Cutting Carbon and Costs, 13-May-2021.

[11] Public Utility Commission of Texas (PUCT), 'Virtual Power Plants' to Provide Power to ERCOT Grid for the First Time, 23-Aug-2023.

[12] California Energy Commission, Demand Side Grid Support (DSGS) Program Guidelines Fifth Edition, Feb-2026.

The very public impacts from recent load loss events have amplified these concerns.[13,14,15] However, flexible operations can help address such caution around capacity and stability.

To compress time-to-power, data centre developers and tenants alike are demonstrating that their demands on the grid can, in fact, be flexible. For example, Google is implementing demand response based compute shifting across its data centre fleet, dynamically shifting non urgent tasks (e.g. video processing) across both time and space in response to real time grid conditions.[16] Subsequent demonstrations have extended this capability to machine learning workloads, with Google reporting successful demand response interventions during three grid stress events in collaboration with Omaha Public Power District, and confirming new agreements with utilities Indiana Michigan Power and the Tennessee Valley Authority to formalise such flexibility as an operational grid resource.[17]

With data centres already accounting for 33-42% of local electricity consumption in major European hubs, multiple European regulators and operators are now explicitly incorporating demand side flexibility from data centres into their planning frameworks.[18] The Centre on Regulation in Europe (CERRE) highlights multiple European cases in which data centres could provide grid support services, ranging from load shifting to injecting or absorbing power through battery-powered on-site back-up power systems. It is estimated that some 50-60 GW of demand side flexibility could be thus unlocked across the EU by 2035.[19]

Flexibility reduces peak pressure, dampens volatility, and buys time. But it cannot, on its own, overcome the physical limits of already-saturated transmission corridors. This is precisely why modern grid strategy increasingly pairs flexibility with a parallel suite of technologies and operational measures that extract additional usable transfer capability from existing lines. As the next section shows, these capacity tools are an essential complement to flexibility tools that together enable operators to maintain reliability today while buying time to build the networks required for tomorrow.

## 2. Capacity

Expanding the capacity of the grid via conventional multi-year capital expenditure programmes remains essential, but long permitting timelines and supply chain constraints mean this is not a solution to near-term grid congestion. Operators are thus increasingly focused on extracting more from assets already in the ground. This 'latent capacity' can be unlocked physically, operationally and algorithmically using grid-enhancing technologies already available today.

Innovations in materials science can help unlock additional load capacity on existing transmission lines without having to rebuild the entire system. Large-scale reconductoring with advanced composite-core conductors is an established way for utilities to increase line capacity and operating lifetimes with limited incremental permitting or infrastructure requirements.[20] More than 90,000 miles of advanced conductors have been deployed globally. And, by some estimates, reconductoring could deliver almost 90% of the additional transmission capacity needed by 2035 in a much more cost- and time-efficient manner than building new transmission lines.[21] In the US, American Electric Power increased the capacity of two 120-mile 345kV circuits by ~95% using composite core conductors, completing the project in under two years.[22] Reconductoring projects in the Netherlands and Belgium have delivered 50-110% increases in capacity using high-temperature low-sag and composite-core conductors.

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[13] North American Electric Reliability Corporation (NERC), Incident Review: Considering Simultaneous Voltage-Sensitive Load Reductions, 8-Jan-2025.

[14] NERC presentation to Federal Electricity Reliability Council (FERC), NERC Activities and Plans to Address Reliability Impacts from Large Load Integration, 17-Apr-2025.

[15] NERC, Large Loads Action Plan.

[16] Google, Supporting power grids with demand response at Google data centers, 4-Oct-2023.

[17] Google, How we're making data centers more flexible to benefit power grids, 4-Aug-2025.

[18] Ember Energy, Grids for data centres: ambitious grid planning can win Europe's AI race, 19-Jun-2025.

[19] Centre on Regulation in Europe (CERRE), From Gridlock to Grid Asset: Data Centres for Digital Sovereignty, Energy Resilience, and Competitiveness, 30-Sep-2025.

[20] Chojkiewicz, E. et al., Accelerating transmission capacity expansion by using advanced conductors in existing right-of-way, Proc. Natl. Acad. Sci. U.S.A. 121 (40) e2411207121, 2024.

[21] Chojkiewicz, E. et al., Advanced Conductors Can Accelerate the Rapid Transmission Expansion Required for a Clean Grid, 2024.

[22] DOE, Advanced Conductor Scan Report, Aug-2024.

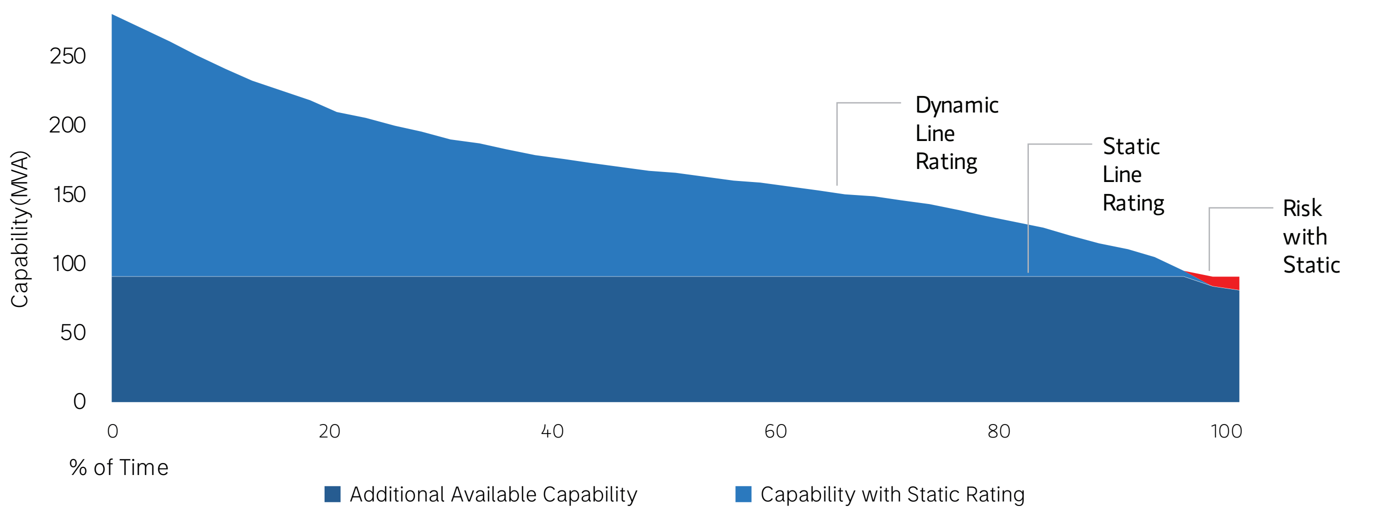
As such, the Dutch and Belgian TSOs recently announced plans to reconductor most of their high-voltage lines by 2035 rather than adding new lines.[23,24] In the UK, meanwhile, National Grid has incorporated reconductoring as a central pillar of its plan to deliver major capacity increases while avoiding billions in constraint costs.[25]

While reconductoring physically increases the amount of current a line can carry, many grid constraints arise not from hardware limits but from conservative operational assumptions. Leveraging hardware and software solutions to challenge and overcome these assumptions represents a second, complementary opportunity to unlock capacity without touching the steel. As power lines transmit more electricity, they heat up and drop closer to the ground ('sag'), materially increasing operational risk and safety concerns. On cold, windy days, more power can be transmitted because the ambient conditions help to cool the line, reducing sag and, therefore, operational risk. Typically, operators determine the capacity of a line using static line ratings based on long-term averages and historical meteorological data, factoring in a large safety margin to compensate for day-to-day volatility in weather.

A suite of technologies has emerged in recent years that promise to unlock additional line capacity by dynamically tailoring line ratings to real-time weather data and short-term, higher-precision forecasts (cf. Figure 5). Dynamic Line Ratings (DLR) have been found to help unlock additional capacity in almost 90% of operating hours.[26] Moreover, DLR systems can be deployed rapidly – often in under three months – at less than 5% of the cost of reconductoring or new line construction. Reporting on DLR sensor deployments across its high voltage system, Dutch TSO TenneT states that weather-conditioned operation can provide up to 30% extra transmission capacity, while, in New York, National Grid has demonstrated that dynamic ratings could unlock ~190 MW of additional capacity, avoiding ~350 MW of wind curtailment and 1.1 million tons of $CO_2$e emissions annually.[27,28]

**FIGURE 5**

**Illustrative Comparison of DLR vs Static Line Ratings[29]**




[23] Elia Group, Federal Development Plan 2024 – 2034.

[24] Chojkiewicz, E. et al., Accelerating transmission capacity expansion by using advanced conductors in existing right-of-way, Proc. Natl. Acad. Sci. U.S.A. 121 (40) e2411207121, 2024.

[25] National Grid Electricity Transmission, RIIO-T3 Business Plan, Dec-2024.

[26] Uski-Joutsenvuo, S. and Pasonen, R., Maximising Power Line Transmission Capability by Employing Dynamic Line Ratings -Technical Survey and Applicability in Finland, Feb-2013.

[27] LineVision Inc, National Grid Enables Wind and Solar with Dynamic Line Ratings, 2023.

[28] Tennet, Intelligent use of wind and cooling creates more transmission capacity, 4-Jul-2024.

[29] Cardenas J., Dominguez S. and Kommu R., Experiences in dynamic line rating (DLR) using a wireless line monitoring system (ILMS), Mar-2020.

However, unlocking additional headroom on lines only creates value if power flows can be actively diverted to make use of it. Advanced Power Flow Controllers (APFC) – often described as modern, distributed Flexible AC Transmission Systems (FACTS) devices – act like valves, redirecting electricity away from overloaded lines onto underutilised corridors.[30] In the UK, National Grid has deployed dozens of APFC devices, unlocking some 1.5 GW of capacity and deferring some £400m of conventional upgrades to reinforce the network.[31,32] In New York State, a single APFC installation estimated to be $8-10m cheaper than conventional upgrades unlocked ~185 MW of additional transfer capacity.[33]

Software-driven topology optimisation extends this approach by identifying switching actions that reconfigure the network in real-time or under contingency conditions. As a commercially mature, asset-light solution that dynamically optimises power flows through existing power lines via automated circuit breaker adjustments, topology optimisation software promises to deliver meaningful congestion cost savings for network operators.[34] At Alliant Energy in Iowa, automated line reconfiguration using topology optimisation software reduced congestion costs by nearly 50% over two years, with analysis suggesting even greater savings (up to 80%) could have been achieved.[35]

Crucially, DOE analysis demonstrates that these tools compound rather than merely add to one another: studies show that combining DLR with power-flow control can materially reduce renewable curtailment costs by 23-43% and deliver substantial cost savings to operators.[36] Furthermore, National Grid's capital expenditure plan for its UK transmission network explicitly cites how the deployment of power flow control devices and DLR will unlock additional capacity from existing assets, ultimately helping to avoid an estimated £12 billion of system constraint costs.[37]

Taken together, grid-enhancing technologies demonstrate that significant latent capacity already exists within today's networks. Combining physical upgrades, sensor-driven operational intelligence, and advanced control software, operators can unlock latent capacity quickly and cost-effectively. Yet higher utilisation of network infrastructure increases the importance of maintaining system stability, particularly in grids with a proliferation of inverter-based resources.

## 3. Stability

Grid operators must ensure that the frequency of the grid remains within narrow error bars to prevent cascading failures and damage to critical equipment on both the supply side (e.g. power plants) and the demand side (e.g. substations and even household appliances). Sudden swings in frequency and voltage (e.g. a power plant unexpectedly going offline or the 2,800 MW demand spike in the UK during the penalty shoot-out in the 1990 England vs Germany World Cup semi-final) can lead to a cascade of failures, potentially resulting in blackouts if the system cannot respond to the swings in time.[38,39]

For much of their history, grids have benefited from the margin of safety provided by the inertia created as conventional power plants produce electricity with synchronous generators. These large spinning machines produce Alternating Current (AC) electricity at a particular frequency and voltage. The kinetic energy in their spinning rotors provides inertia, a buffer against frequency and

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[30] Electric Power Research Institute (EPRI), Advanced Power Flow Controllers Technical Brief, 19-Jun-2024.

[31] National Grid, World's first large-scale use of power flow technology on transmission network will unlock 1.5GW of electricity capacity, 10-May-2021.

[32] Smart Wires, National Grid: Northern England projects, 2-Apr-2024.

[33] Smart Wires, Smart Wires collaborates with Central Hudson Gas & Electric to provide 185 MW extra capacity for renewable energy in New York, 18-Sep-2024.

[34] Ruiz P. et al., Transmission Topology Optimization Case Studies in SPP and ERCOT, 24-Jun-2020.

[35] Ruiz P. and Myhre M., Congestion Mitigation with Transmission Reconfigurations, Organization of MISO States Market and Transmission Work Groups meeting, 11-Mar-2024, slides 10 and 17.

[36] DOE, Grid-Enhancing Technologies: A Case Study on Ratepayer Impact, Apr-2022.

[37] National Grid, RIIO-T3 Business Plan published: framework to deliver most significant step forward in the UK's transmission network for a generation, 18-Dec-2024.

[38] NERC, Incident Review: Considering Simultaneous Voltage-Sensitive Load Reductions, 8-Jan-2025.

[39] National Grid Electricity System Operator, National Grid ESO expects 900MW electricity demand spike during ENG-GER match, 29-Jun-2021.

voltage swings, as a byproduct. As a result, grids are designed and operated in such a way that even if the largest generation source goes offline, the other generation sources connected to the grid can pick up the slack and ensure the grid frequency never drops below a particular point.

Most inverter-coupled renewables, however, do not provide inertia in the same way to the grid.[40] And as renewables constitute a growing share of the generation mix, grid operators must therefore find alternative ways of providing inertia to keep the grid stable.

One option is to add physical inertia using synchronous condensers, which mimic the synchronous generators of conventional power plants but are installed solely to provide inertia and reactive power/voltage support to the grid. These can be built from scratch (e.g. the Rothienorman project in Northeast Scotland) or by repurposing the induction generators of mothballed power plants (e.g. FirstEnergy's project at the Eastlake Power Plant near Cleveland, Ohio).[41,42]

Inverters create yet further complications for grid operators. Inverters convert the Direct Current (DC) produced by renewable energy sources to grid-compatible Alternating Current (AC); however, the waveform of this AC output is shaped by software that synchronises the output with voltage and frequency signals the inverter can 'see' on the grid. As the number of inverter-based resources (i.e. renewables) outnumbers conventional synchronised generators, so does the likelihood that echo and amplify noise and distortions from the desired smooth AC signal.[43]

This fragility matters operationally: in weak-grid or fault conditions, such grid-following devices are programmed to automatically disconnect rather than support the system. As such, some grid operators have delayed or constrained new renewable interconnections on stability grounds.

'Grid-forming' inverters, however, are emerging as a key solution for grids with a high number of inverter-based power sources. Rather than merely following an existing waveform, they use software controls to establish and hold voltage and frequency over short timescales (e.g. a few milliseconds), allowing inverter-based assets to behave more like stabilising resources. Crucially, the software can vary the output waveform over a slightly longer timescale to better synchronise with other grid-connected generation sources.[44] Such inverters have already been integrated into some grid-scale batteries, and recently helped stabilise the grid in Scotland when a large wood-burning generator shut down without warning.[45]

Islanded grids with high renewables penetration also demonstrate how grid-forming inverters can deliver system stability benefits. The Hawaiian island of Kauai has deployed multiple large (i.e., 10MW+) grid-forming inverters, which have meaningfully enhanced grid stability.[46] The stability benefits provided by these grid-forming inverters have allowed renewables to provide some 45% of the annual load (and ~90% at peak times).[47] Cheaper than synchronous condensers, the stability services provided by the power electronics in grid-forming inverters are fast emerging as an indispensable stability solution indispensable stability solutions. Indeed, grid operators are increasingly operating with the principle that maintaining system stability depends on ensuring that new capacity actively supports the system to which it connects.

The experience on Kauai also underscored that stabilising a modern, inverter rich grid is ultimately a data problem as much as a hardware problem. The National Laboratory of the Rockies's analysis showed that only once accurate operational data operational data had revealed which

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40 For the sake of completeness, it is important to note that renewables can provide some small amounts of inertia via voltage droop or frequency support via power electronics.

41 Quinbrook Infrastructure Partners, Quinbrook's first synchronous condenser in Scotland now built and operating, 8-Jan-2025.

42 Fairley, P., Zombie Coal Plants Reanimated to Stabilize the Grid, Institute of Electrical and Electronics Engineers (IEEE) Spectrum, 24-Jul-2015.

43 Thunder Said Energy, Grid-Forming Inverters: islands in the sun?, 12-Dec-2024.

44 IEEE Spectrum, Grid-forming Inverters will Take Us to 100% Renewable Energy, 13-Apr-2024.

45 Fairley, P., Grid-Scale Batteries in Scotland Stabilize Power, IEEE Spectrum, 4-Aug-2025.

46 National Laboratory of the Rockies, With Inverters, an Island Adapts to Changing Physics of the Power Grids, 8-Jan-2026.

47 Thunder Said Energy, Grid-Forming Inverters: islands in the sun?, 12-Dec-2024.

specific generators were driving frequency oscillations could operators target the right interventions at the right time. In other words, advanced stability tools – from synchronous condensers to grid forming inverters – deliver their full value only when they operate within a system that can see itself with sufficiently high resolution.[48]

Taken together, these insights reinforce a central theme of this whitepaper: hardware alone cannot deliver a more stable, higher utilisation system unless operators have the visibility to coordinate it safely. Section 4 therefore turns to the capability that makes deeper electrification, tighter operating margins, and higher renewable penetration manageable in practice – visibility, the informational layer that allows all other tools in the New Energy Toolkit to function as an integrated whole.

## 4. Visibility

As asset utilisation rises and inverter-based resources proliferate, operators need real time situational awareness and control systems that can coordinate and orchestrate bidirectional flows of electricity and the increasingly heterogeneous operations of thousands of digitised assets. To the extent that the modern grid is "basically a bunch of synchronized computers," data, software and analytics are as critical as poles and wires if operators are to be able to run their systems ever-closer to their physical limits without compromising reliability, stability and affordability.[49]

High quality data is the substrate on which all downstream visibility, forecasting, and operational decision tools depend. At the transmission level, for instance, Phasor Measurement Units (PMUs), deployed to form wide-area monitoring networks, represent a step-change in visibility. These devices stream high-frequency synchrophasor data, enabling operators to detect oscillations, validate models post-event, and monitor inertia and system strength in real-time.

In Texas, ERCOT has recently expanded its PMU network to more than 270 devices, linking its PMU network from dozens to more than 270 devices, linking the data to applications including oscillation detection and real-time inertia monitoring.[50] In the UK, National Grid ESO uses PMU data to monitor system inertia against critical thresholds, while ISO New England deploys PMU-based tools to detect the low-frequency oscillations that are often leading indicators of imminent cascading outages.[51,52] The formalisation of PMU-based monitoring by NERC's Synchronized Measurement Working Group shows how high-fidelity telemetry data is now embedded within the core reliability fabric of modern power systems.[53]

The greater visibility provided by such tools does not deliver reliability on its own – value is realised when visibility is coupled to automated control. The concept of a 'self-healing' grid pairs enhanced visibility with automated responses to compress fault location and restoration intervals from minutes to seconds, materially reducing the number of customers affected by faults. In essence, a self-healing grid behaves like an immune system detecting emerging problems, predicting potential failures, and initiating corrective responses to minimise impact.[54]

Real world deployments underscore the impact of self healing grids at scale. Duke Energy Florida's self-healing network covers ~82% of its customers, and helped avoid millions of outage hours during the particularly severe 2024 hurricane season.[55] Similarly, in the UK, SSEN's Automated Power Restoration System, rolled out in 2022, is designed to automatically 'self restore' supply in under three minutes following contingency events.[56] At a more granular level, Fault Location, Isolation and Service Restoration (FLISR) systems represent a commercially mature subset of these capabilities. By integrating relays, sensors, and SCADA-connected switches, FLISR enables automated fault detection and network reconfiguration without dispatching field crews.

[48] National Laboratory of the Rockies, With Inverters, an Island Adapts to Changing Physics of the Power Grids, 8-Jan-2026.

[49] Quote from Any Hoke, Principal Engineer at National Laboratory of the Rockies from: National Laboratory of the Rockies, With Inverters, an Island Adapts to Changing Physics of the Power Grids, 8-Jan-2026.

[50] Electricity Reliability Council of Texas (ERCOT), Updates and Future Plans for PMU and WAMS, Oct-2024.

[51] National Grid ESO, System Inertia Monitoring – NASPI Webinar, Jun-2021.

[52] Independent System Operator – New England (ISO-NE), Oscillation Source Location and Mitigation Measures in Daily Operations, 2018.

[53] NERC, Synchronized Measurement Working Group.

[54] National Energy Technology Laboratory (NETL), Research on the Characteristics of a Smart Grid by the NETL Modern Grid Strategy Team, 2008.

[55] Duke Energy, Climate Resilience and Adaptation Study, Dec-2024.

[56] Scottish & Southern Electricity Networks (SSEN), SSEN marks milestone in 'self-restoring' electricity supply system, 22-Nov-2022.

The National Electrical Manufacturers Association reports that integrated FLISR deployments reduce restoration times from tens of minutes or hours to seconds, ultimately improving network resilience during system stress.[57]

Beyond system-level automated responses to network faults, resilience increasingly depends on the ability to rigorously monitor the conditions of grid assets and intervene with repairs before failures occur. In such a way, operators are shifting from periodic, calendar-based maintenance regimes to data-driven, conditions-based asset management.

Transformers are a case in point. Online dissolved gas analysis (DGA) sensors on transformers enable continuous detection of fault conditions that would otherwise be invisible between periodic tests. EPRI's case studies of multiple utilities show that real-time case studies show that real-time DGA monitoring can detect fault progression earlier and with greater accuracy than traditional laboratory sampling.[58]

Hydro Québec has extended this by integrating DGA, moisture, on-load tap changer (OLTC), and bushing data with standard substation SCADA systems, enabling automated, trend-based alerts and maintenance triggers. The International Council on Large Electric Systems (CIGRE) now recommends this sort of integrated approach to asset monitoring in its technical literature – a clear case of how high-resolution data on individual assets can contribute to system-wide resilience when paired with automated controls and software solutions.[59]

A similar dynamic applies to vegetation management. Because vegetation is cited as the cause of ~20% of outage incidents across the US, the DOE explicitly encourages utilities to adopt proactive, analytics-driven vegetation management strategies as one of the most cost-effective resilience investments.[60] In Minnesota, Lake Region Electric Cooperative reduced vegetation management costs by 80% and tree-related outages by 30% after deploying a software solution to model corridor risk.[61] In the UK, UKPN's 'Project Satelline' demonstrated that using satellite data processed by AI-enabled software reduced data processing times from ~6 months to ~2 weeks while achieving 98% radial clearance accuracy.[62]

Across both examples, a common pattern emerges: high-frequency, high-fidelity data collection provides operators with greater visibility into the networks they are responsible for. And, when this greater visibility is ingested And, when this data is ingested by advanced software, operating costs can be combined with, advanced software, operating costs can be lowered without compromising reliability outcomes.

As these data streams mature, value is increasingly realised by software that can clean and combine them into a system-level, unified platform that combines visibility, analytics and control. Software solutions that help operators consolidate, interpret and ultimately act on the heterogeneous data streams they receive from grid assets (as shown in Figure 6) can deliver meaningful efficiencies. Network-level digital twins – high-fidelity replicas of grid assets and network states – are a case in point. By enabling operators to simulate outages, switching actions, congestion events, and extreme-weather scenarios, digital twin models help identify structural bottlenecks and reliability risks ex ante.[63] A meta analysis of 122 studies finds reductions in system downtime of 15-45% and operating cost savings of up to 30% from the deployment of digital twins.[64] National Grid's Triton digital twin consolidates thousands of datasets and reports a ~70% reduction in analysis time to reach network planning decisions.[65]

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**FIGURE 6**

## Data Streams That Feed into Network Models

| DATA STREAM | DESCRIPTION | PRIMARY USE CASES[66] |
|---|---|---|
| **SCADA Telemetry** | Real-time voltages, currents, breaker status | Real-time monitoring, contingency analysis, control actions |
| **PMUs** | High-speed phasor data | Dynamic stability monitoring, oscillation detection, inertia estimation |
| **EMS / Market Data** | Dispatch schedules, bids, LMPs | Congestion management, dispatch |
| **Weather Data** | Temperature, wind, irradiation, icing forecasts | DLR, renewable output forecasting, outage risk estimation |
| **Asset Condition Data** | Transformer oil, breaker health, thermal scans | Predictive maintenance, O&M planning |
| **Renewable & DER Telemetry** | Renewables output, DER status | Balancing, congestion forecasting, voltage control |
| **Load Forecast** | Supply and demand forecasts | Unit commitment, capacity planning, reserve scheduling |
| **Geospatial & Vegetation Data** | Satellite/LiDAR corridor risk | Vegetation management, wildfire risk mitigation |
| **Cybersecurity Data** | OT network traffic, intrusion alerts | Protect EMS/SCADA, anomaly detection |
| **Regulatory & Market Feeds** | Tariffs, interconnection queues | Capital planning decisions |

For distribution networks, Advanced Distribution Management Systems (ADMS) are a foundational tool for many of the 'smart' capabilities discussed above. ADMS platforms integrate SCADA, outage management, distribution automation and control applications into a unified environment. In turn, this enables automation applications (e.g. FLISR and other advanced network-planning and -management tools.[67,68] PG&E has positioned ADMS as the core of its grid modernisation strategy, replacing fragmented legacy systems with a single, integrated platform.[69] ADMS is very much a commercially mature solution, with a significant majority of US utilities either deploying or operating this software at scale today.[70,71]

ADMS platforms are increasingly complemented by Distributed Energy Resource Management Systems (DERMS), which enable the connection and orchestration of large numbers of decentralised assets. PG&E, for instance, has integrated DERMS with its ADMS to manage bidirectional flows of information and electricity at a scale that already includes >700,000 behind-the-meter PV systems, allowing it to implement its industry-leading VPP programmes, which require the sophisticated coordination of thousands of individual assets simultaneously.[72] The value proposition of DERMS integrated with ADMS is straightforward: once operators have a coherent, data-rich model of the distribution network, automation and optimisation applications can translate this heightened awareness into quantifiable benefits.[73] Deployed together, ADMS and DERMS serve as complementary foundational layers of an operating system for modern grids and ultimately allow grid operators to deploy the various constituents of the New Energy Toolkit.[74]

[66] Table compiled using information from the following: NERC (North American Electric Reliability Corporation): Real-Time Monitoring and Control Guideline, (Nov-2017), IEEE Power & Energy Society: Power System Dynamic Performance Monitoring Using PMUs, FERC Order 881: Managing Transmission Line Ratings, CIGRÉ Technical Brochures: Dynamic Line Rating and Grid Enhancing Technologies, EPRI Reports: Vegetation Management and Geospatial Analytics for Utilities and NIST Cybersecurity Framework for ICS.

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[68] NREL, Utility and Grid Operator Resources for Future Power Systems Webinar Series - Advance Distribution Management System, 5-Jun-2025.

[69] California Public Utilities Commission (CPUC), California's Grid Modernization Report to the Governor and Legislature, Dec-2025, p.15.

[70] Krishnan & Associates, Empowering the Grid: Unveiling the Potential of DERMS in Modern Utilities. Prepared for Oracle Energy & Water, 2024.

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[72] Pacific Gas & Electric (PG&E), Grid Modernization Progress Report Apr 2024, CPUC filing. https://gridworks.org/wp-content/uploads/2024/04/PGE-Grid-Modernization-Report_April-2024.pdf.

[73] National Renewable Electricity Laboratory (NREL), Utility and Grid Operator Resources for Future Power Systems Webinar Series-Advance Distribution Management System, 5-Jun-2025.

[74] UK Power Networks, PEA and Project Registration Document, 2019.

Indeed, visibility is the connective tissue that allows flexibility, capacity, and stability solutions to operate as a coherent system rather than as isolated interventions. As grids become more distributed, faster moving, and more tightly constrained, the limiting factor is no longer access to data but the ability to integrate, interpret, and operationalise it in real-time. High-fidelity sensing, shared network models, and automated control platforms transform theoretical headroom into deployable capability, allowing operators to run closer to physical limits without compromising reliability. Yet visibility, like every other element of the New Energy Toolkit, compounds value only when deployed in concert with complementary tools.

This brings the central argument of Part 2 into focus: the decisive challenge facing grid operators, regulators, and investors is not the invention of new technologies, but the disciplined integration of some of the commercially mature tools discussed above into coherent, system level operating models that compound value across the network. In essence, the opportunity lies in scaling, financing and integrating proven solutions.

## Conclusion

The discussion above leads to a simple conclusion: the grid's most pressing challenges – volatile demand, constrained transmission capacity, declining inertia, and rising operational complexity – will not be adequately addressed through isolated interventions or a 'silver bullet' technology, but through the coordinated deployment of a toolkit of solutions available today. Flexibility assets increase effective capacity only when transmission headroom can be dynamically unlocked; capacity enhancing tools realise their potential only when operators have the visibility to deploy them dynamically; and stability solutions depend on high fidelity data and control architectures that allow the system to run closer to physical limits without compromising reliability.

Figure 7 expands Figure 1 by mapping the technologies discussed above in Part 2 to the problems discussed in Part 1.

**FIGURE 7**

**Mapping Part 2 Solutions to Part 1 Problems**

| PART 1 PROBLEM | NEW ENERGY TOOLKIT SOLUTIONS (PART 2) |
|---|---|
| **Ageing infrastructure & long replacement cycles** | ▪ **Reconductoring / advanced conductors:** increase thermal capacity within existing corridors<br>▪ **Dynamic Line Ratings (DLR):** unlock capacity using real-time conditions<br>▪ **APFC & topology optimisation:** redirect flows and relieve congestion |
| **Extreme weather & climate-driven shocks** | ▪ **Self-healing / FLISR:** automated fault isolation and restoration<br>▪ **PMUs / WAMS:** early detection of instability<br>▪ **Synchronous condensers & grid-forming inverters:** maintain inertia and voltage support<br>▪ **Digital twins:** simulate shocks and identify weak points |
| **Rising demand (electrification, reshoring, data centres)** | ▪ **Grid-scale BESS:** fast-response flexibility and peak shaving<br>▪ **VPPs & demand-side flexibility:** dispatchable distributed capacity<br>▪ **Hosting capacity analytics / interconnection tools:** accelerate viable connections<br>▪ **DLR / APFC / topology optimisation:** create headroom for new loads |
| **Growth of inverter-based resources (renewables)** | ▪ **Grid-forming inverters:** synthetic inertia and stabilisation<br>▪ **Synchronous condensers:** inertia and system strength<br>▪ **Forecasting + visibility tools:** reduce curtailment and improve dispatch |
| **Distributed energy resources** | ▪ **ADMS & DERMS:** integrated control of distributed assets<br>▪ **BESS / DER orchestration software:** optimise fleet behaviour<br>▪ **High-fidelity telemetry:** improve modelling and dispatch accuracy |
| **Limited situational awareness** | ▪ **PMUs / high-speed telemetry:** real-time system monitoring<br>▪ **Asset monitoring (e.g. DGA):** early fault detection<br>▪ **Vegetation analytics (satellite + AI):** reduce outage risk<br>▪ **Digital twins:** integrated system-level insight |

The analytical message is therefore straightforward: the technologies required to address today's constraints already exist and are commercially mature, but their impact depends on disciplined integration rather than incremental, siloed adoption. A grid built around this principle shifts from managing scarcity to dynamically orchestrating a complex ensemble of physical assets, high-fidelity data and intelligent software within a coherent operational fabric. When deployed together, the tools discussed above compound in value, translating latent headroom into real, dispatchable capability and enabling operators to defer capital expenditure, reduce curtailment, and strengthen resilience in a more electrified, inverter rich system.

Yet technological maturity alone is insufficient to drive system-wide adoption. The decisive barrier is institutional: regulatory frameworks, procurement models, cost recovery rules, and investment incentives still reflect a world in which grid value was measured primarily through physical expansion rather than through utilisation, efficiency, and resilience. The next phase of the Great Grid Upgrade therefore hinges not on inventing new technologies but on aligning governance, incentives, and capital flows with the integrated operating model outlined above.

Part 3 takes up this challenge directly. It examines how regulatory reform, market design, and capital allocation must evolve to unlock the full value of the New Energy Toolkit, and how policy and investment structures can accelerate its deployment at system scale. For investors, the opportunity is not simply funding more grid infrastructure, but to back the software, services and enabling hardware that allow existing and future infrastructure to be used more intelligently.

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