Columbia Business School
Climate Knowledge Initiative

Powering Grids Deep Dive

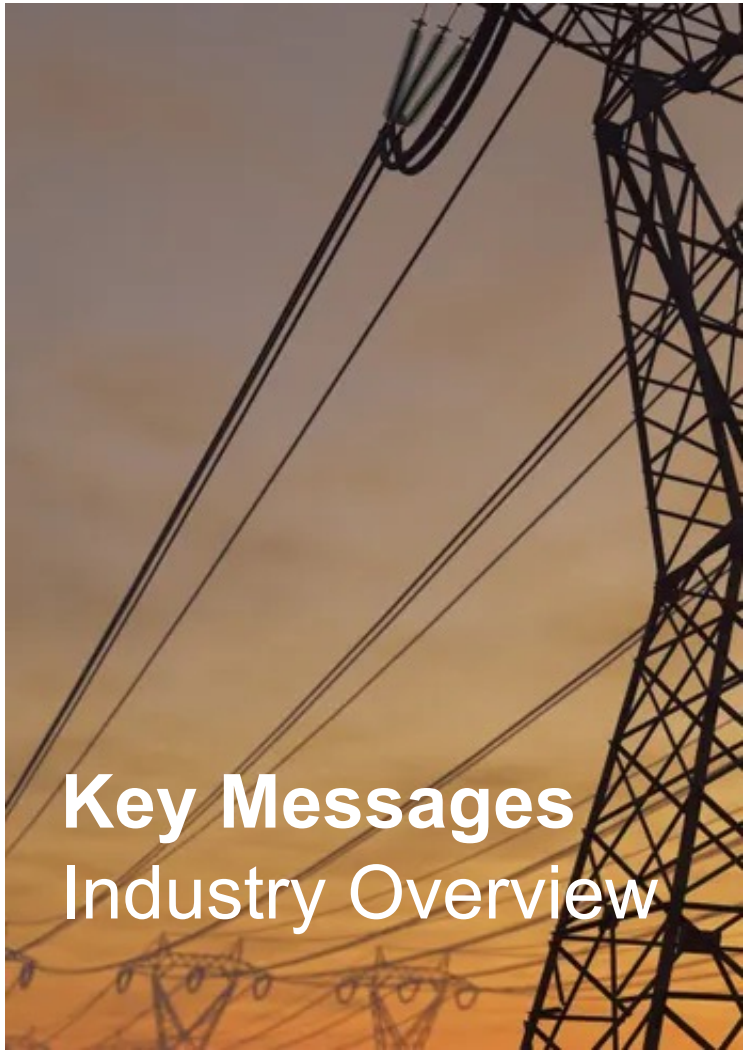
Gernot Wagner, Hasan Alawadhi, Sevgi Helin Tilkicioglu, Dominica Wambold, Ilayda Tezcan, Gunay Kiran, Stephanie Chen, Christy Wong, Ryon Roque, Vincent Sandow-Straesser, Isabel Hoyos, Ariela Farchi, and Pia Doris Morrow

Cite as: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative



Industry Overview



Four structural trends are driving the need to modernize and expand the grid

- **Rapid growth in electricity demand:** driven by AI and data centers and the electrification of transport and heating, demand is returning to growth in mature markets and could more than double globally by 2050.
- **Critical aging infrastructure:** over 70% of U.S. transmission assets and over 50% of U.S. distribution assets are more than 20 years old, necessitating urgent replacement
- **Structural shift in the energy system:** the grid is transitioning from centralized fossil fuel generation to a decentralized, multi directional network, as wind and solar rise from ≤20% of global generation in 2025 to ≥75% by 2050
- **Escalating climate and weather risk:** increased frequency and severity of extreme weather events require immediate, large scale grid hardening

Investment must scale sharply, and the cost of falling behind is already high

- Global grid investment is expected to exceed $500 billion in 2026, but needs to reach ~$600 billion a year by 2030 under Net Zero Emissions by 2050 scenario
- Grid related outages already cost the U.S. an estimated $54 billion a year, the highest among major economies

Coordination across a complex stakeholder map determines how fast upgrades get built

- Utilities, developers, regulators, and investors each hold a piece of the solution and must act in sync
- Priorities differ by region: the U.S. focuses on reliability and permitting, Europe on offshore integration, China on scale and curtailment

Interconnection and stronger institutions unlock savings that pay for the transition

- Europe's ENTSO-E lets countries trade power across borders, saving €8 to €23 billion a year between 2030 and 2050 while cutting curtailment
- Political and financial support can accelerate or stall progress; permitting and cost allocation rules need to keep pace with technology

Credit: Ilayda Tezcan, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

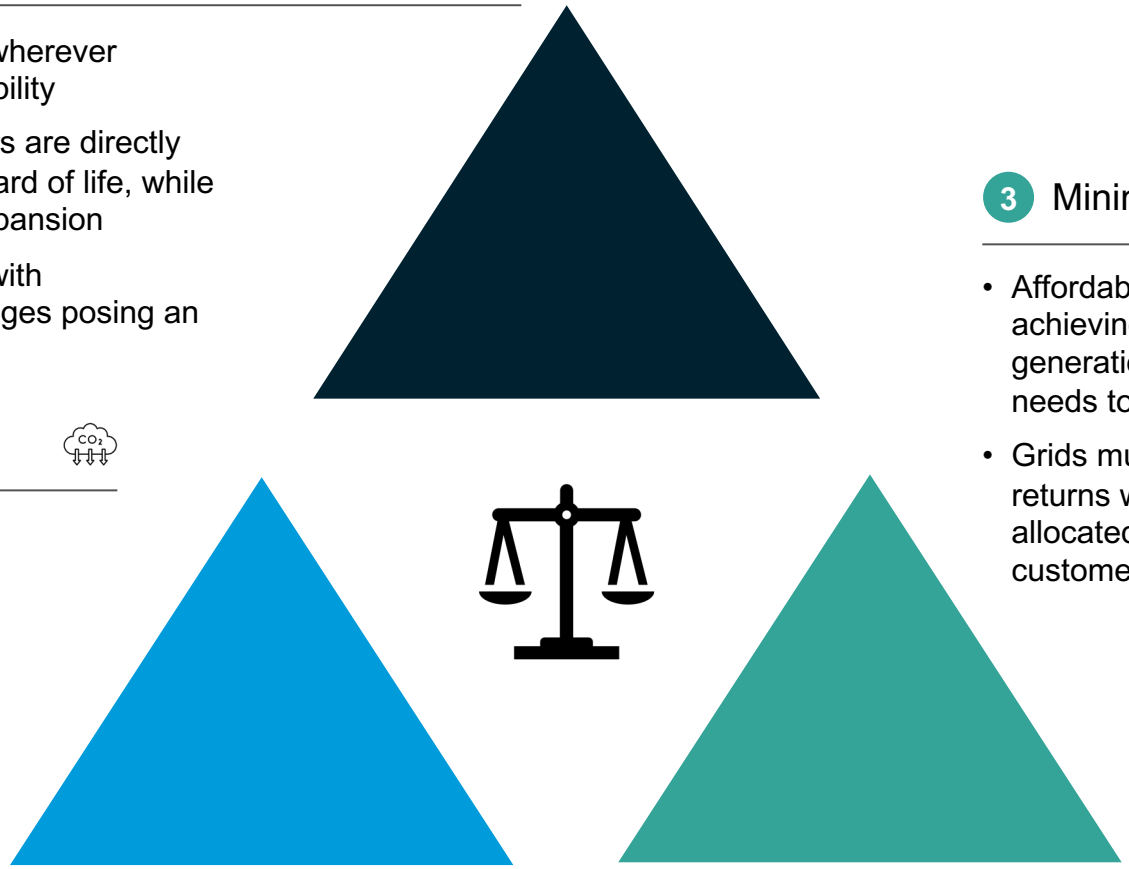
Modern energy grids are meant to provide power in a way that maximizes security while minimizing emissions and costs

1 Maximizing grid security

- Supply of energy must meet demand wherever required on the grid and maintain reliability
- Energy powers the economy; lost hours are directly related to lower productivity and standard of life, while constrained grids prevent industrial expansion
- Grids must be secure and sovereign, with cybersecurity and supply chain challenges posing an increasing threat to connected assets

2 Minimizing carbon emissions

- Intermittent and inverter-based technologies are being prioritized because they are the readiest source available and fastest to connect
- These technologies present unique challenges to the grid and its operations



3 Minimizing cost of power

- Affordable electricity is a human right, while achieving it and connecting any form of new generation requires expensive change that needs to be paid for somehow
- Grids must seek creative ways to achieve returns while ensuring that costs are fairly allocated and without raising backlash from customer costs

Credit: Hasan Alawadhi, Stephanie Chen, Sevgi Helin Tilkicioglu, Isabel Hoyos, Dominica Wambold, Ariela Farchi, Pia Doris Morrow, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

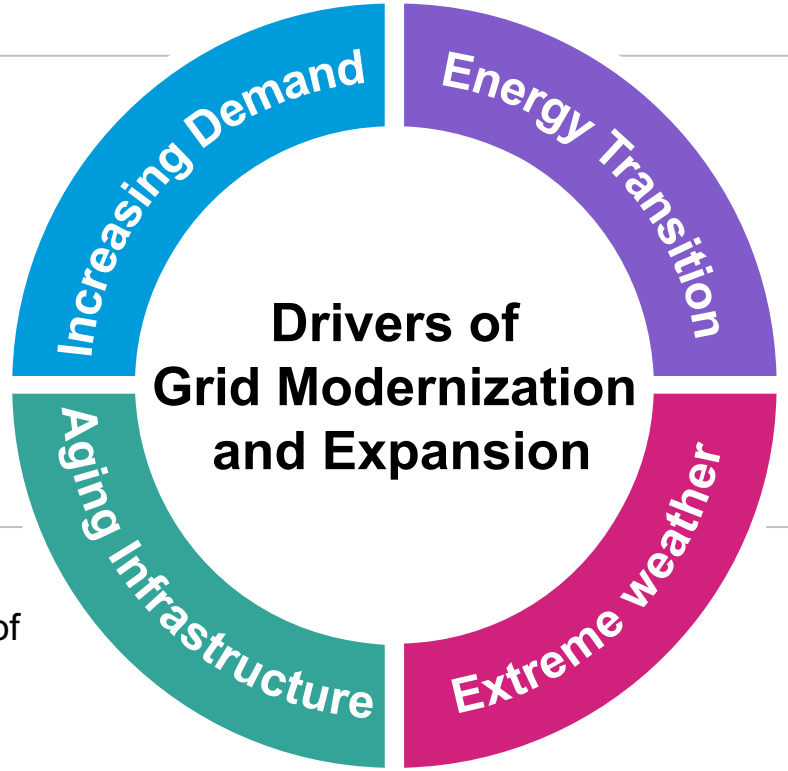
Global grids face the critical need to adapt due to demand growth, a changing energy landscape, aging assets and extreme weather

Rapid growth in electricity demand

- Driven by intensive load growth from AI/Data centers and the rapid electrification of transport and heating

Structural shift in the electricity system

- Transitioning from centralized fossil-fuel generation to a decentralized, multi-directional energy network with more distributed abundant energy resources



Critical aging infrastructure

- Over 40% of global grid assets (up to 70% in the U.S.) are reaching the end of their 50-year design life, necessitating urgent replacement

Escalating climate & weather events

- Increased frequency and severity of extreme weather events require immediate and large-scale grid hardening

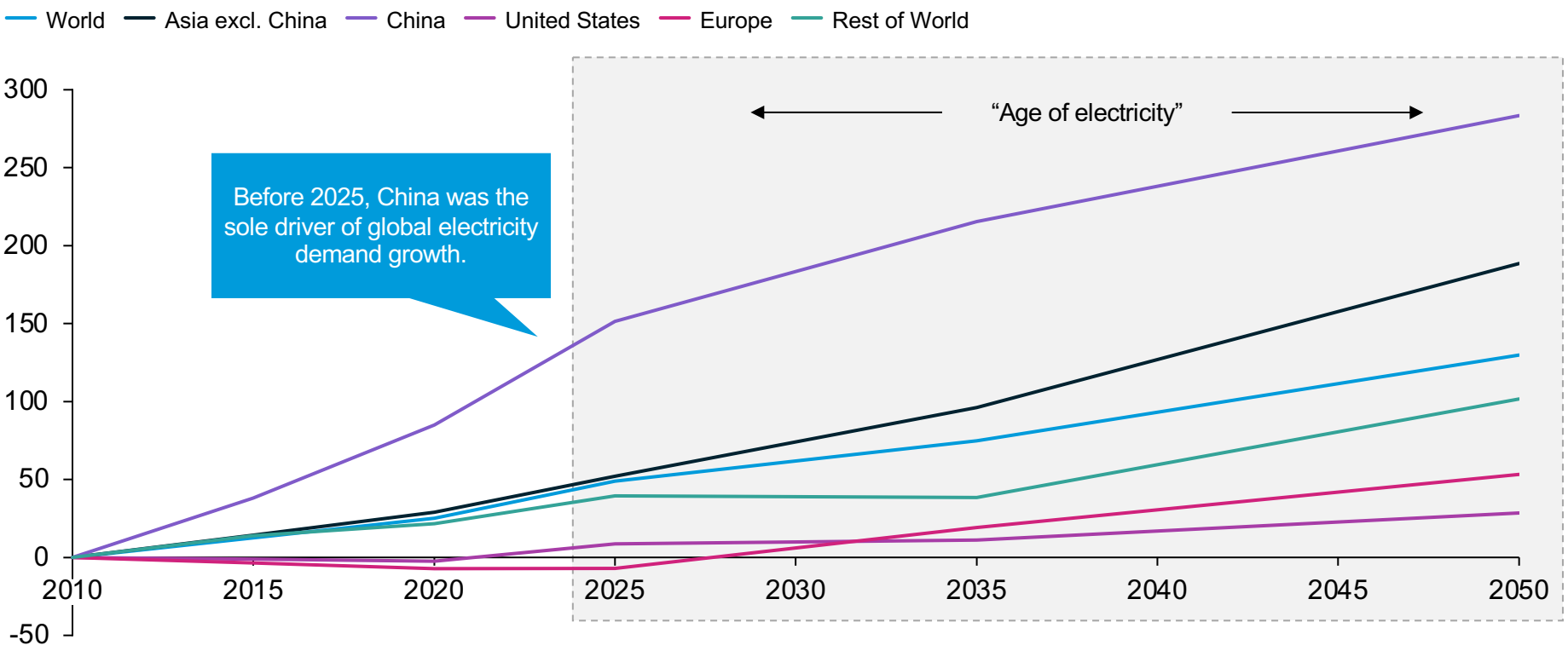
Sources: World Energy Investment (IEA, 2026); Global Landscape of Energy Transition Finance (IRENA, 2025).

Credit: Christy Wong, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Global electricity demand projected to accelerate across nearly all major regions, no longer solely led by China

Electrification, data centers, and other new loads are driving the "age of electricity," reversing decades of stagnant demand in mature markets

% Change in electricity final demand vs. 2010 baseline, 2010-2025 actuals, 2026-2050 forecasted[1]



Observations

- **China** has been the clear demand-growth outlier since 2010, with **electricity demand up ~150% by 2025** versus **~50% globally**
- **Sharp trajectory shift happens** in **mature markets: U.S. and European** demand was **broadly stagnant** through 2025 but **is projected to return to sustained growth**
- **Recent growth** from electrification, renewables, and data centers is a major **challenge for decades-old grid systems, requiring massive investment**
- **Other estimates** forecast electricity growth to exceed that of the IEA's Stated Policies Scenario, **more than doubling by 2050**

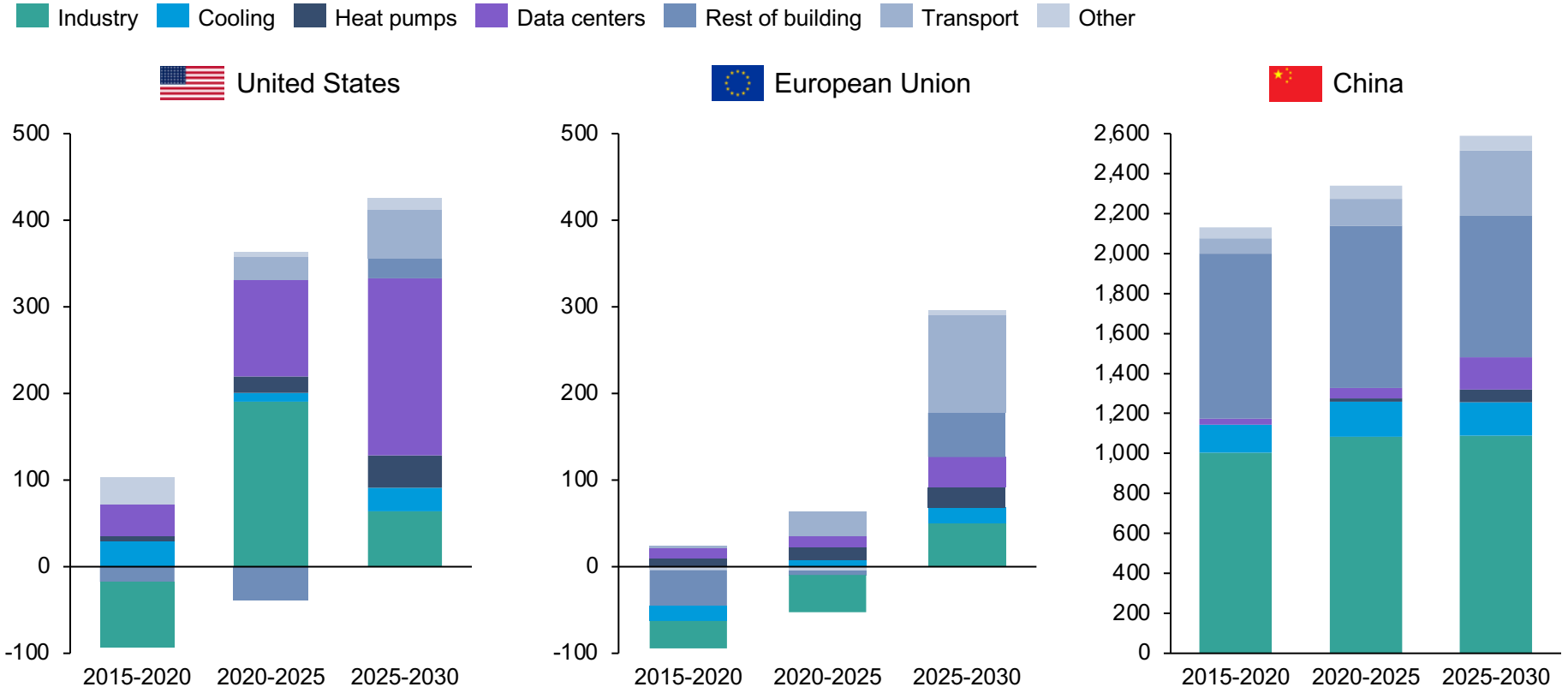
[1]2010-2025 data from Energy Institute 2026 Statistical Review of World Energy; 2026-2050 modeled based on IEA Stated Policies scenario, from IEA World Energy Outlook 2025
Sources: Statistical Review of World Energy (Energy Institute, 2026); World Energy Outlook 2025 (IEA, 2025); Electricity 2026 (IEA, 2026); New Energy Outlook (BNEF, 2026); Power generation from renewables set to jump 84% in next five years (BNEF, 2026).
Credit: Pia Doris Morrow, Ariela Farchi, Dominica Wambold, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Electrification and data centers are among primary drivers accelerating electricity demand across the US, EU, and China

By 2030, data centers projected to account for ~50% of U.S. demand growth, building and transport electrification lead in the EU, and industrial electrification in China

Electricity demand total growth by sector and end-use in the US, EU, and China, 2015-2030, TWh



Observations

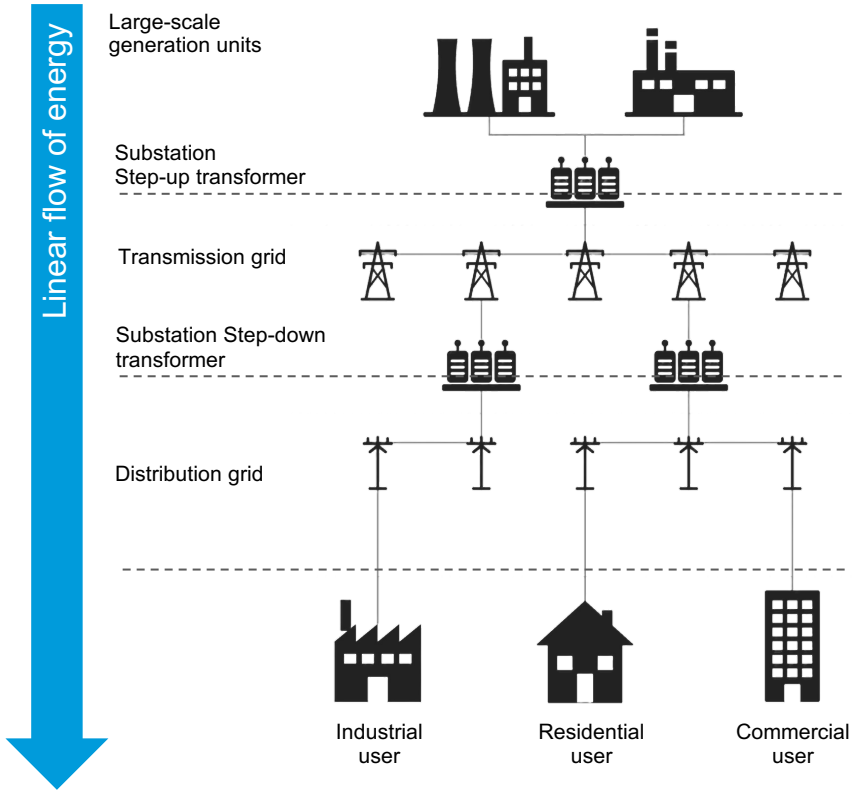
- **Building and transportation electrification, industry, and data centers** are leading to compounding electricity demand growth in the 2020s
- While **data center** electricity demand represents a small portion of all growth, its **average annual growth rate is expected to double again in the years ahead under base scenarios** and is the leading electricity demand growth driver in the U.S.
- Electricity demand characteristics from each of these drivers pose distinct challenges to grids; each **can drive significant increases in peak as well as average demand**, with different levels of predictability and control

Sources: Electricity 2026 (IEA, 2026); World Energy Investment 2026 (IEA, 2026).
Credit: Ilayda Tezcan, Dominica Wambold, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

The power grid is transforming from a one-way centralized system to a two-way distributed network

Traditional grids followed a one-way linear flow from generation to end use



Control
Centralized utility dispatch

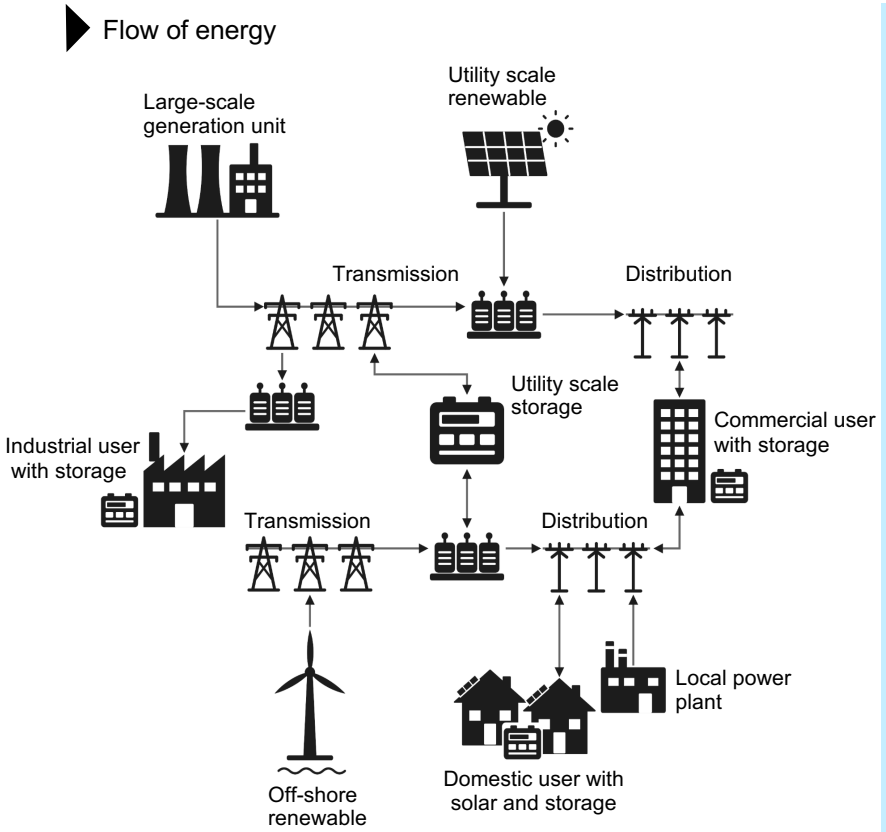
Resilience
Single point of failure, cascade risk

Scalability
Large capital-intensive T&D builds

Cost structure
High upfront infrastructure investment

Carbon profile
Fossil-fuel dominant at scale

Modern grids are increasingly networked due to distributed generation, which will reach 40% of global supply by 2040



Power flow
Multi-directional, prosumers[1] generate, consume & trade

Control
DERMS/ VPPs aggregate distributed resources

Resilience
Single point of failure, cascade risk

Scalability
Modular; incremental prosumer-driven

Cost structure
Lower marginal cost; prosumer & DER-financed

Carbon profile
High renewable (VRE) penetration enabled

[1]Producers/Consumers

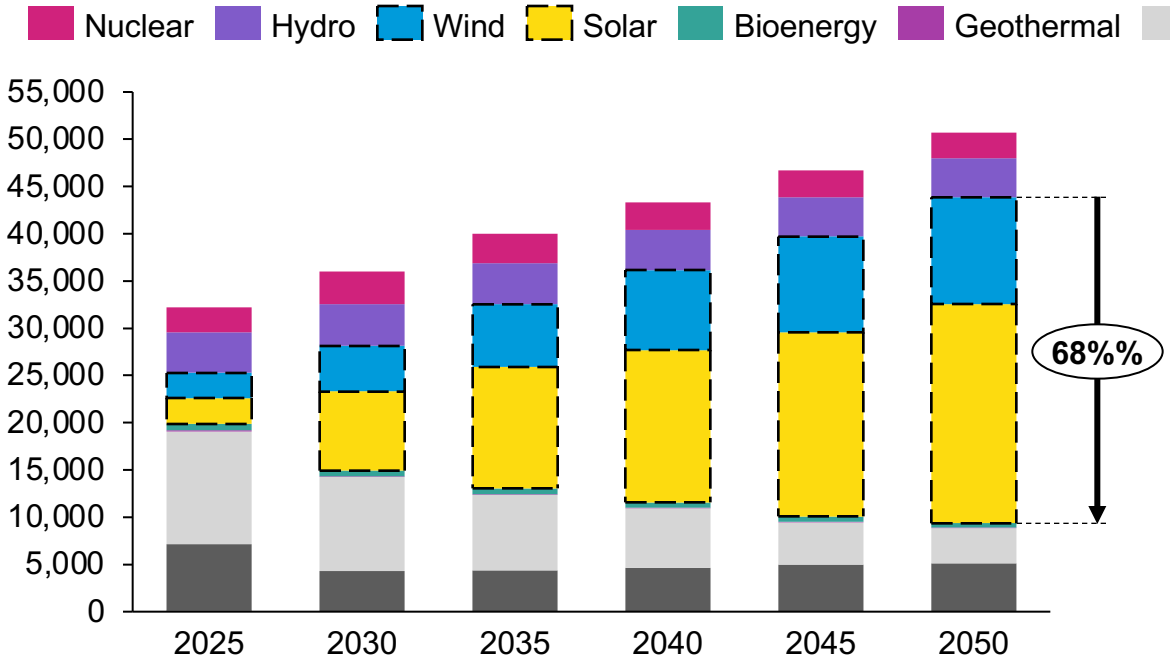
Sources: VPP Liftoff Report (DOE); Unlocking the potential of distributed energy resources (OECD, 2022); Integrating distributed energy resources in power distribution systems: A comprehensive review of impacts, challenges, and opportunities from a distribution system operator's perspective (Lee, 2026).

Credit: Christy Wong, Ariela Farchi, Brenda Rain, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Wind and solar are set to supply over 50% of global electricity by 2050, up from ~15% in 2025

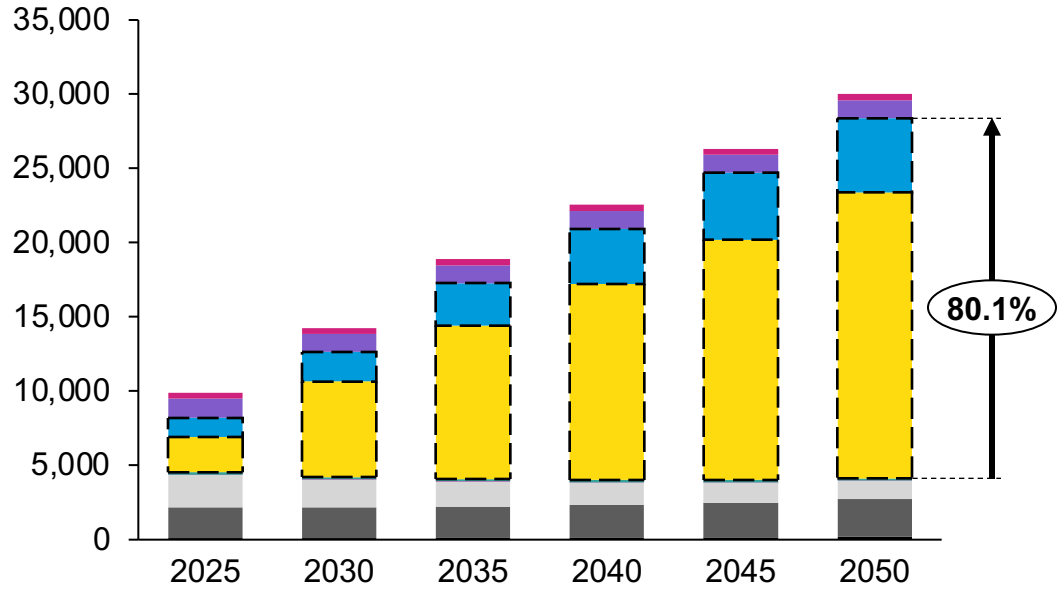
Clean energy sources approach ~80% of generation by 2050, led by wind and solar

World Electricity Generation by Source (TWh)[1]



Intermittent and inverter based clean-power is expected to be the dominant energy source of the future

World Installed Capacity by Source (GW_e)[1]



Observations

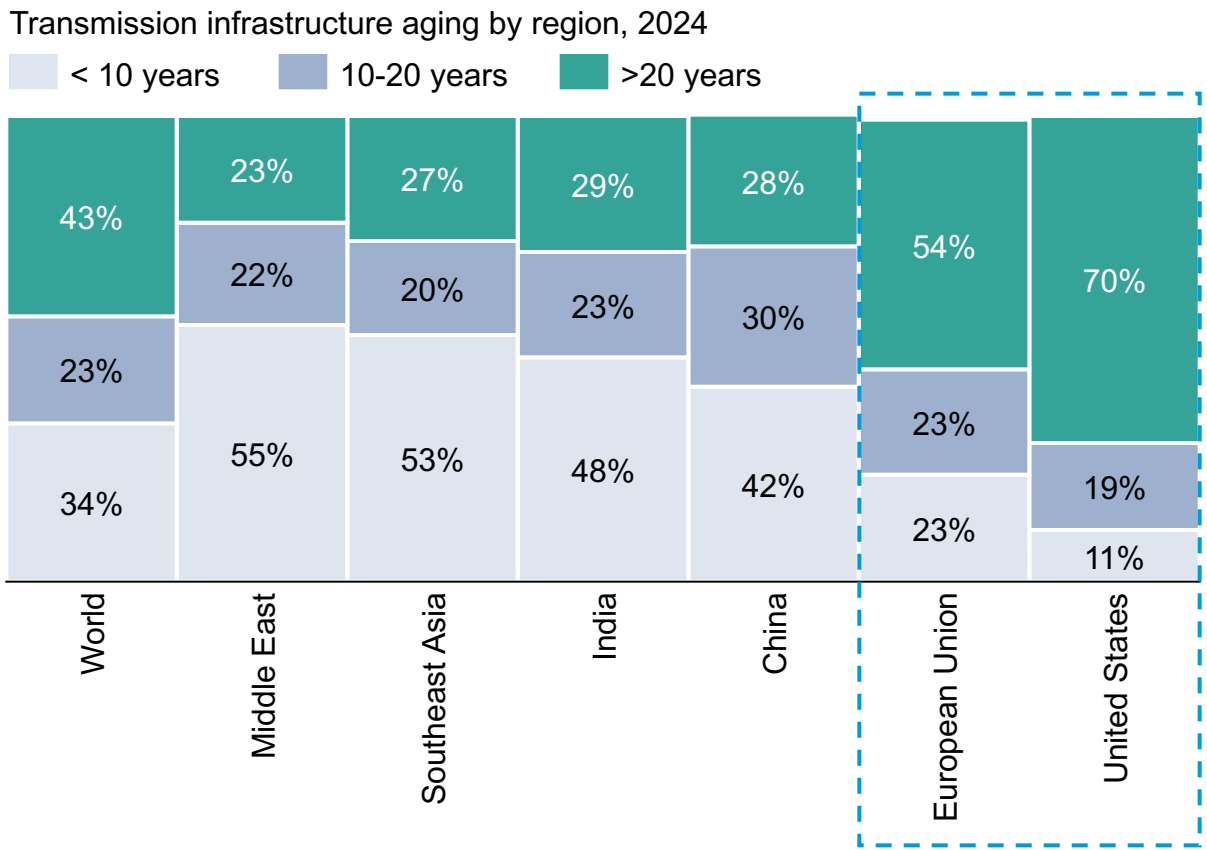
- Low-emissions electricity, including renewables and nuclear, rises from ~40% of generation in 2025 to ~80% by 2050
- Wind and solar drive most of the growth, increasing from ~16% to ~68% of generation and from ~37% to ~80% of installed capacity
- This shift increases reliance on variable, inverter-based resources, raising the need for grid flexibility, transmission expansion, storage, and system balancing

Sources: Working paper, Innovation uncertainty shapes divergent pathways toward decarbonization (Moers et al., 2026).
Credit: Ilayda Tezcan, Ariela Farchi, and and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

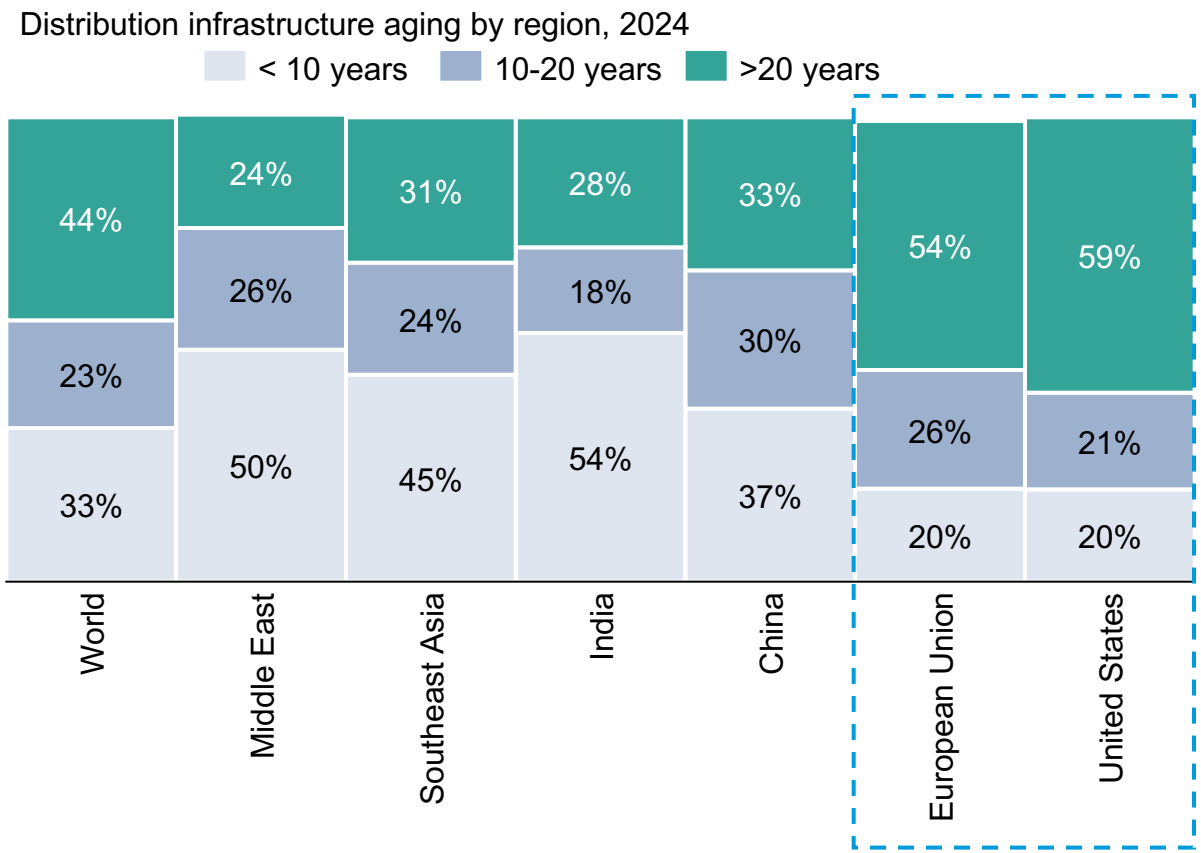
Columbia Business School
Climate Knowledge Initiative

Grid infrastructure is reaching or has passed its life expectancy in advanced economies, requiring urgent upgrades to be operational

+40% of global transmission infrastructure is over 20 years old; the U.S. accounts for the highest ratio, at 70%



EU and the U.S. lead in aging distribution: +50% are beyond useful life and need immediate modernization



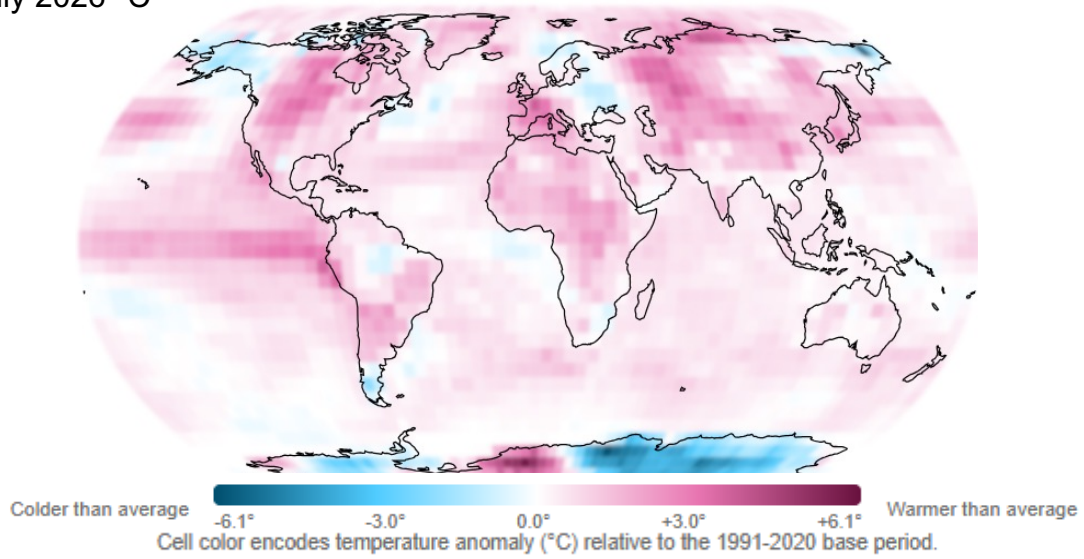
Sources: World Energy Outlook (IEA, 2025).
Credit: Christy Wong, Ariela Farchi, Brenda Rain, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Changing global temperatures and extreme weather events significantly disrupt grid operations

Temperatures are shifting from historical baselines, existing infrastructure isn't built to support this change

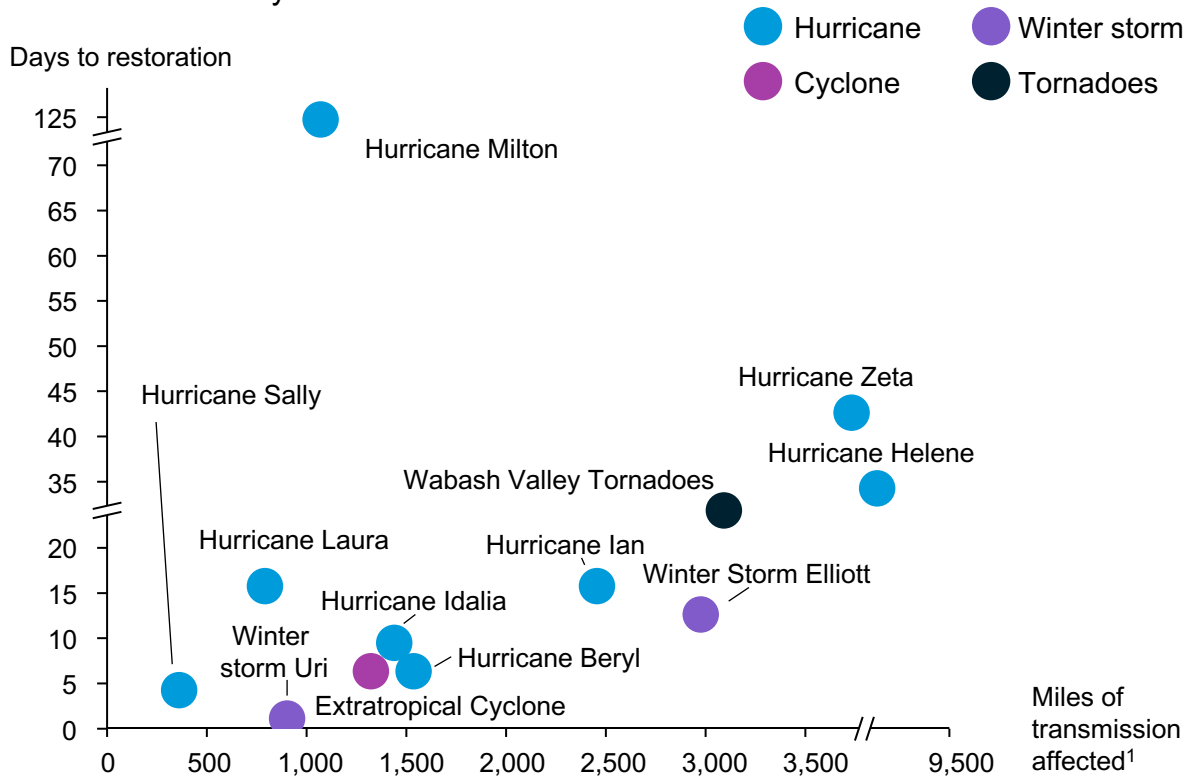
Gridded average temperature anomaly vs. 1991-2020 base period, July 2026 °C



- **Dual-Ended Grid Stress:** This rising thermal baseline creates compounding operational challenges, driving unprecedented electricity demand for cooling while simultaneously reducing the transmission capacity and efficiency of existing infrastructure
- Regions experiencing warmer than average temperatures, such as the **western EU, central Asia, and northern North America**, see significant infrastructure distress from increased energy demand

US Case Study: Extreme weather events directly damages critical grid infrastructure

Storm damage and recovery time on US transmission lines, miles affected x days to restoration



[1]Miles of transmission affected represents the approximate length of lines damaged, shut down, inspected, repaired, or otherwise impacted.

Sources: Temperature departure from global average (NCEI/NOAA, July 2026); A quieter hurricane season could still pummel US power grid (Claims Journal, 2026). Credit: Christy Wong Ka Ying, Brenda Rain, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Grids continue to face long-standing challenges globally, while capital flows, new technology, and policy provide opportunities

Grid reliability, interconnection queues, transmission congestion, grid infra deployment are key grid challenges…

Grid reliability & frequency instability
Retiring spinning generators, renewables entering the load, surging peak demand create reliability problems (outages due to NYC Heatwave 2026)

Interconnection queue backlogs
Cumulative active capacity in queues was 2.06 TWh at the end of 2025 in the US according to Lawrence Berkeley National Laboratory

Investment mismatch
Global increase in grid financing still lags behind power generation investments

Expansion permitting & cost allocation bottlenecks
Intra-state HVDC lines face regulatory hurdles and cost allocation challenges leading to long wait times (e.g. +10 years for Grain Belt Express approvals)

…yet increasing investor interest, demand-driven capital flows, and ready-to-deploy technologies provide a critical opportunity

Grid-scale battery storage, grid-forming inverters, demand flexibility

AI-automated queue planning software, changing infrastructure such as solid-state transformers, changing interconnection policy

Investment opportunities such as grid enhancing technologies, transmission build-out

Advanced reconductoring, composite wires, blended finance

Key takeaway

- As emerging trends compound long-standing bottlenecks with no easy-fix, solving this complex grid challenge requires a multi-pronged approach leveraging novel technologies, innovative capital structures, and modern regulatory frameworks.

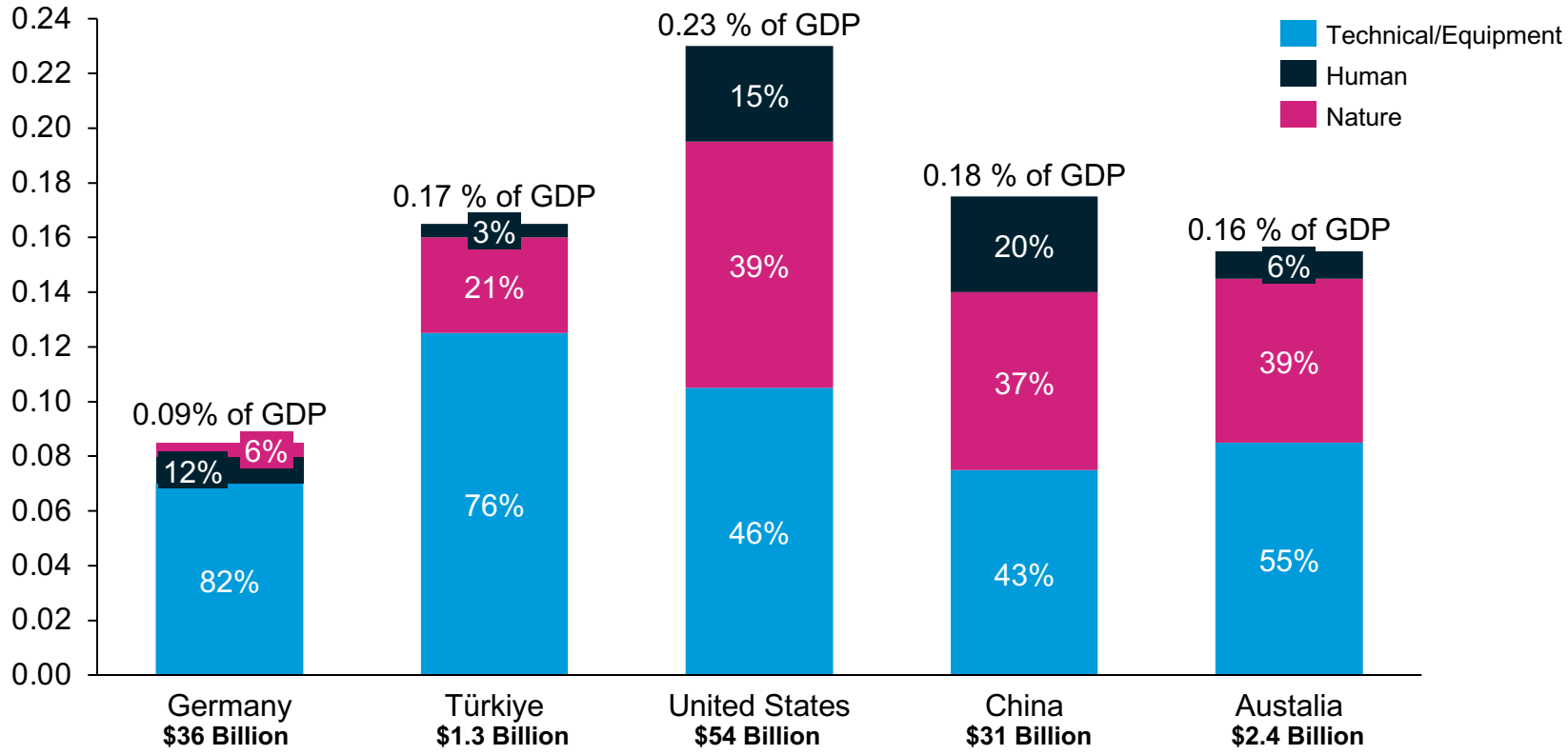
Source: Grain Belt Express, (Orennia, 2025); Empowering growth: The opportunity in Latin America's energy infrastructure (JP Morgan, 2025); US Interconnection Queues (LBNL, 2026), Intense heat knocks out power for thousands across New York City as resident search for relief (abc7, 2026)

Credit: Gunay Kiran, Ariela Farchi, Pia Doris Morrow, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Grid reliability failures impose large economic costs, with US showing the highest outage losses among selected markets

Equipment and technical failures represent ~50% of grid-related outage costs in the US, totaling ~$4.8B in 2021, a direct reflection of grid congestion

Estimated economic impact of grid-related outages by cause as a share of GDP in selected countries, 2021



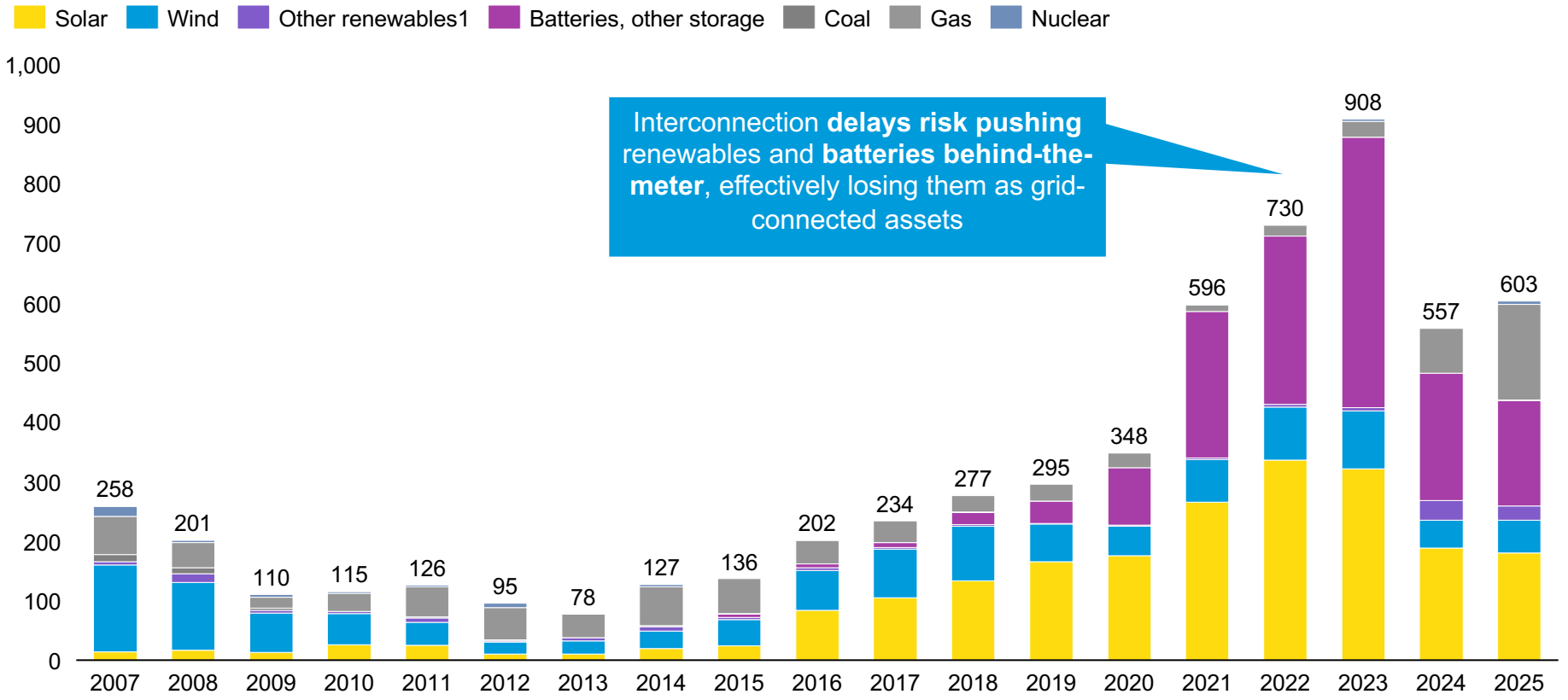
Observations

- Economic impact from grid-related outages has tripled in the United States and highest among the selected countries, estimated at **USD 54 billion annually**
- Outage-related losses in the U.S. account for roughly **0.23% of GDP**, exceeding China, Australia, Germany, and Türkiye
- Natural events and technical/equipment failures represent the largest contributors to outage costs across most markets
- Lengthy transmission development timelines, often exceeding a decade for major high-voltage projects, have constrained grid expansion and increased system congestion
- Outage losses impede economic and industrial development

Sources: Electricity Grids and Secure Energy Transitions (IEA, 2023).
Credit: Christy Wong, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Grid build out and interconnection delays are leading obstacles preventing existing capacity from coming online

Annual breakdown of US interconnection queues by energy source (GW)



Observations

- Connecting capacity to the grid is **a central obstacle globally, particularly in the US and EU:**
  - **Long feasibility studies** were designed **when only a few** new coal or gas plants **were connecting to grid**
  - **Grids at maximum capacity** force developers to **pay for new transmission lines** or **wait for expansion**
  - To reduce delays, FERC now requires **batch studies** and **adopts a 'first ready, first served' model**
- **Queue** volume **declined** in 2024 & 2025 due to withdrawals, not completions
  - 700GW+ in 2024 and 750GW in 2025 as first-ready, first-served cluster study models, capital requirements, and revenue **models reduced speculation**
  - **Declines** were concentrated in renewables and storage; **queues have since begun increasing again**

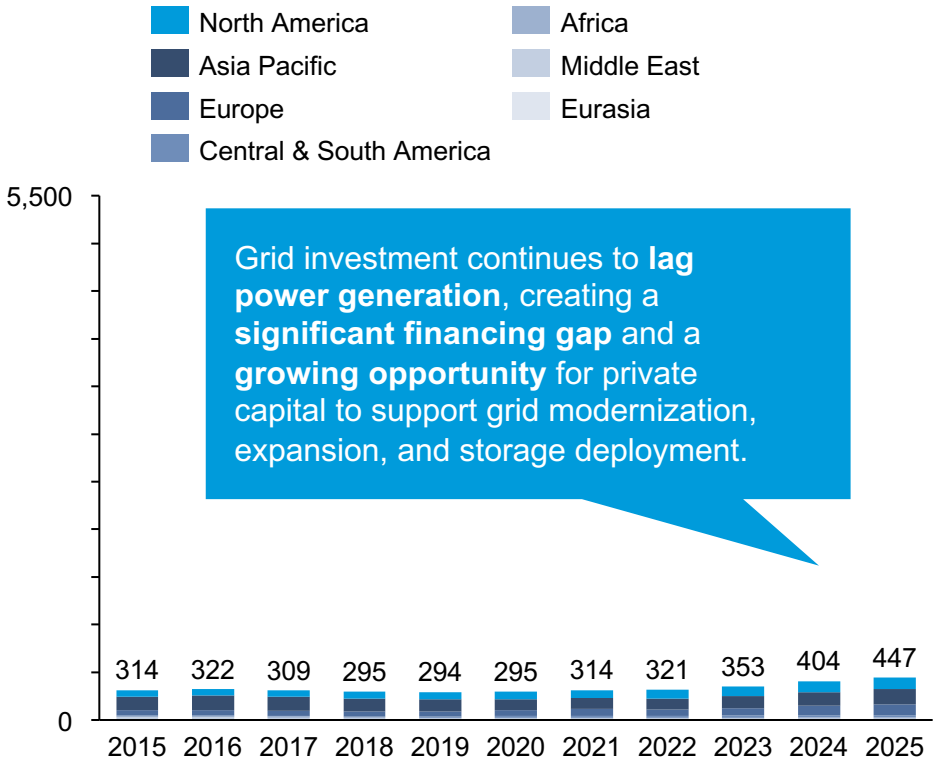
[1]Other renewables include geothermal; hydro; solar and wind; solar, wind, and battery; unknown and other.
Sources: Generation, Storage, and Hybrid Capacity in Interconnection Queues (Berkeley Lab, 2026); Generation, Storage, and Hybrid Capacity in Interconnection Queues (Berkeley Lab, 2025); FERC Transmission Reform (FERC, 2023); Tackling High Costs and Long Delays for Clean Energy Interconnection (US DOE, 2023); RES Policy Monitoring Database (Eclareon, 2025).
Credit: Leo Jin, Max de Boer, Lara Geiger, Marcelo Cibie, Heonjae Lee, Isabel Hoyos, Hyae Ryung Kim, Dominica Wambold, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

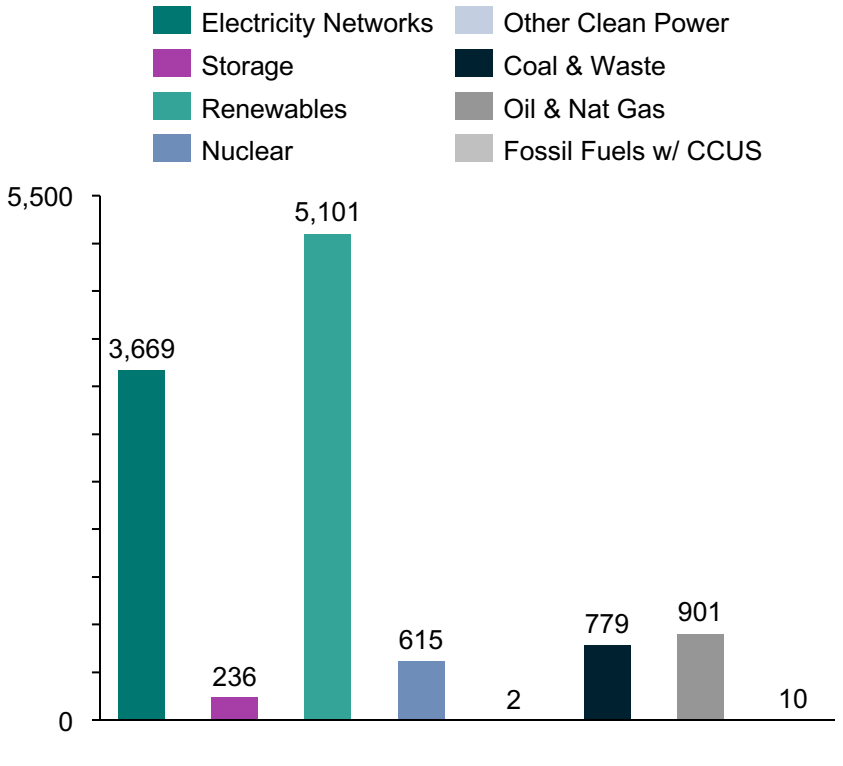
While financing flows into grids have been increasing globally, they still lag behind investments into power generation

Traditional grid investment flows have been growing globally, but further financing is required to match the investment into and expansion of power generation

Grids and utility scale storage investment by region, US$B, 2015-2025[1]



Cumulative power investments by source, $B, 2015-2025



Observations

- Grid financing has lagged behind load (demand) and generation investment growth
- Substantial **grid financing opportunities expand** beyond those tracked as 'Power' investments, including digital, end use, and generation associated investments
- Generation investment has been nearly double than grid investment for the last decade
- Grid-connected (front-of-meter) **storage is primed for sustained global investment**, tied closely to the deployment of variable renewables
- Investors can play a major role **in financing EMDE grids,** especially as international development financing dries up

[1]IEA WEI 2026 actuals for 2015-2025 and forecasted for 2026 by region for IEA's Power segment. [2.] IEA WEI generation investment by Source, 2015-2025.
Sources: World Energy Investment 2026 (IEA, 2026), World Energy Outlook 2025 (IEA, 2025), Batteries and Secure Energy Transitions (IEA, 2024)
Credit: Ariela Farchi, Dominica Wambold, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Permitting design is a trade-off between legitimacy and speed; coordinated planning with structured consent strikes best balance

	Ad hoc planning with full local veto	Coordinated planning with structured consent	Centralized planning with national overrides
Siting & Planning	• Local siting control • Case-by-case approvals • Reactive planning • No national override	• Regional/national corridor planning with structured consultation • Override as backstop.	• National planning, with eminent domain authority in infrastructure • Deemed strategic
Cost Allocation	• Generator pays for grid expansion • Costs flow via wholesale prices	• Regionalized cost sharing in future retail bills • Partial public funding possible	• National cost recovery through many means • Treated as strategic infrastructure
Efficiency & Queues	• Development done in solos with potential for bottlenecks and long queues/restudies	• Targeted transmission corridors • Potentially shorter queues and predictable timelines	• Infrastructure can precede generation • Maximizing deliverability
Congestion & Curtailment	• High grid congestion can lead to reactive upgrades	• Lower congestion as anticipatory build reduces curtailment	• Structurally the lowest congestion (if planned well)
Political Trade-Off	• High local legitimacy but with risk of delay	• Balanced legitimacy & speed	• High speed & certainty; risk of democratic pushback

Democratic yet slow — **Preferred policy pathway** — **Undemocratic yet efficient**

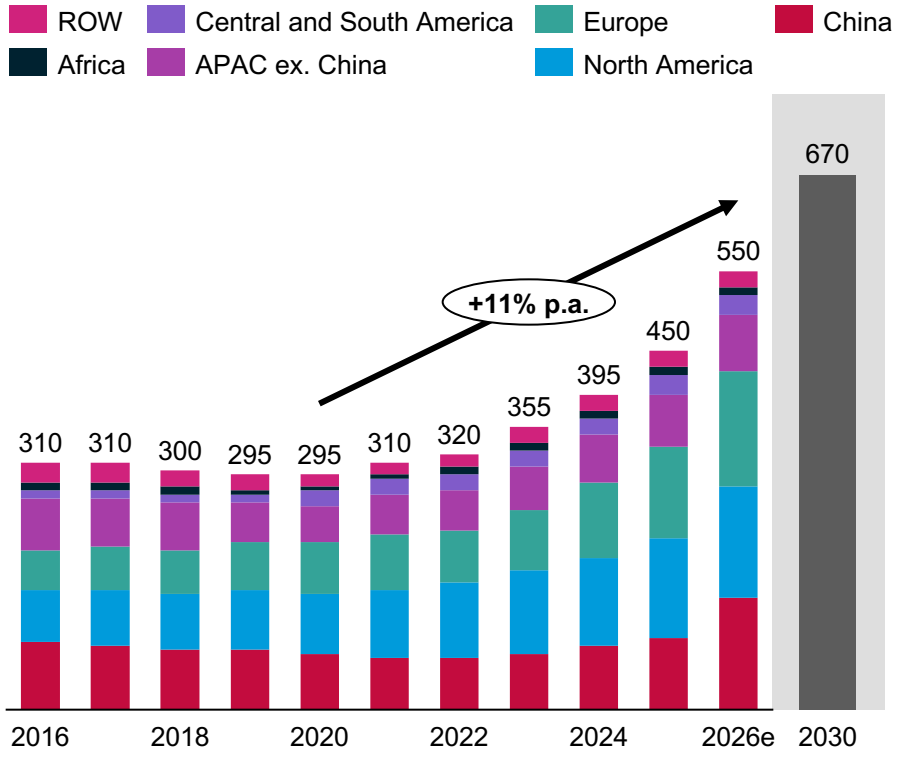
Sources: Transmission Interconnection Roadmap (DOE, 2025); Transmission planning and cost allocation (FERC, 2025); Customer-oriented approaches to generator interconnection (EBA, 2025).
Credit: Hasan Alawadhi, Stephanie Chen, Helin Tilkicioglu, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Global grid investment is expected to rise to +$500B in 2026 and increase through 2030, driven by infrastructure, materials, and labor

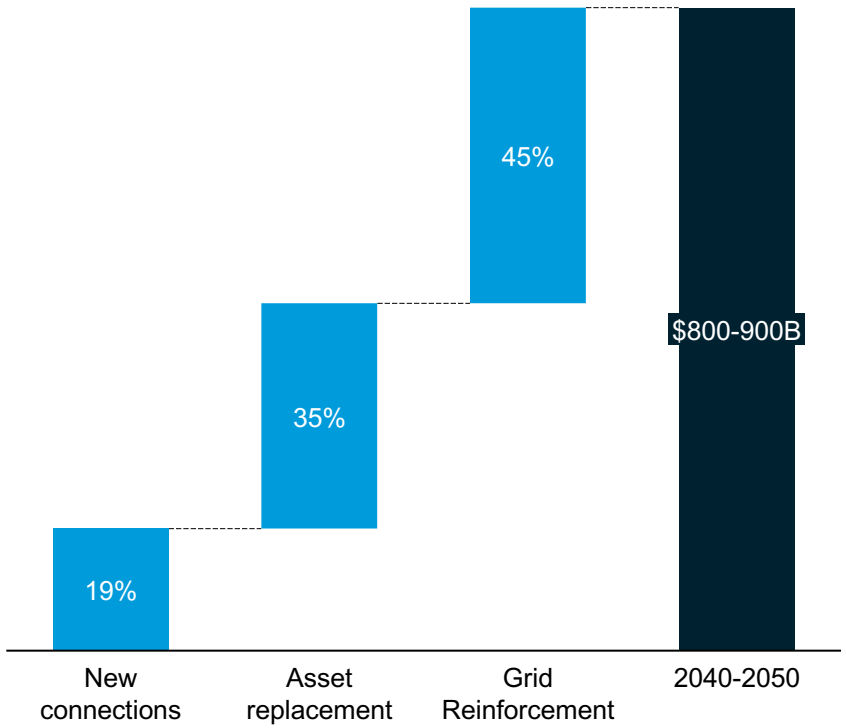
Investment grew ~85% over 5 years, targeted to reach $600B by 2030 in NZE[1]

Investment in power grid infrastructure, 2016-2026e USD Billions



2040-2050, 80% of investment needs to be used to modernize and 20% to expand

Breakdown of global annual investment required, 2040-2050



Observations

- Grid investment needs to be spread across **physical grid infrastructure**, and **grid enhancing technologies**
- Investing in **robust supply chains and a prepared work force,** alongside infrastructure and technology, will be critical to achieving global targets
  - Increasing costs of equipment divest grid investments away from potential new infrastructure
- **Venture capital investments** into grids has increased significantly in 10 years
  - Investment in grid **hardware** rose 4x from **~$200M in 2015 to ~$800M in 2025**
  - Investment into **optimization (reinforcements)** rose from **~$50M to ~$400M**
  - Largest rise was in VPPs and DERMS, from **~$50M to ~$650M**

[1]In line with Net Zero by 2050, as per IEA scenarios.

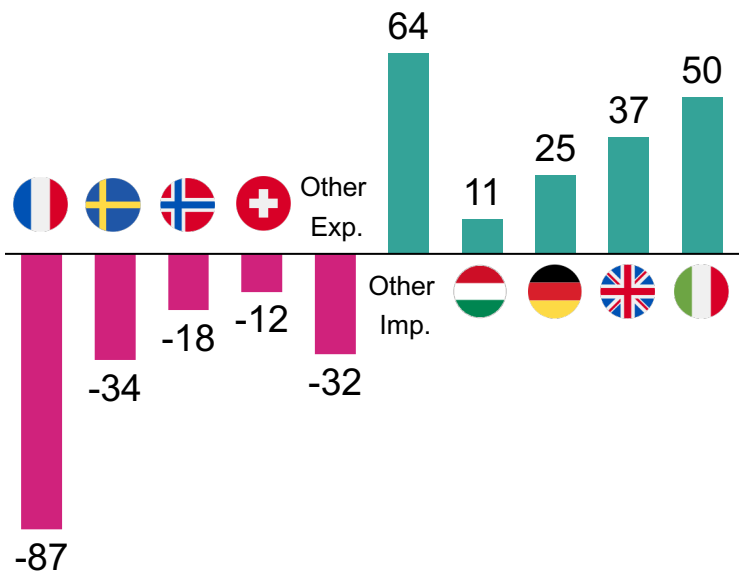
Sources: World energy investment (IEA, 2026); Global landscape of energy finance (IRENA, 2025); Building grids faster: the backbone of energy transmission (ETC, 2024)

Credit: Ariela Farchi, Brenda Rain, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Grid investments enable economic savings; cross-border trade can drive cost efficiency, renewables growth, and reduced curtailment

ENTSO-E members trading power through capital markets can realize savings of €1.5-1.8 per €1 invested

Net Exchange Volumes by member (2024, TWh)



Total Energy Exchange (2024): **480 TWh**

17% of total energy consumed in the EU

Further transmission and storage investments lead to savings

By 2030

Investing **5 Billion €/yr** → **8 Billion €/yr** cost reduction; **30 TWh/yr** avoided curtailment; **19 $MtCO_2e$/yr** avoided

By 2040

Investing **6 Billion €/yr** → **14 Billion €/yr** cost reduction; **343 TWh/yr** avoided curtailment; **27 Mton/yr** avoided CO_2

By 2050

Investing **13 Billion €/yr** → **23 Billion €/yr** cost reduction; **122 TWh/yr** avoided curtailment; **15 Mton/yr** avoided CO_2

Observations

- Through the ENTSO-E, **member states can exchange power** through efficient capital markets, **instead of relying on resources within their own borders**
- This leads to s**ome countries being net exporters** (France, Sweden, etc) or **net importers** (i.e. Italy, UK, etc.) depending on where power is more efficient to generate from
- ENTSO-E **expansion is essential** to the energy transition as it:
  - **Enables direct cost savings** through lower fuel costs, lower firming costs, lower compliance costs, avoided generation for security, price convergence
  - **Reduces RE curtailment requirements**, which also enables dispatch of cheaper power

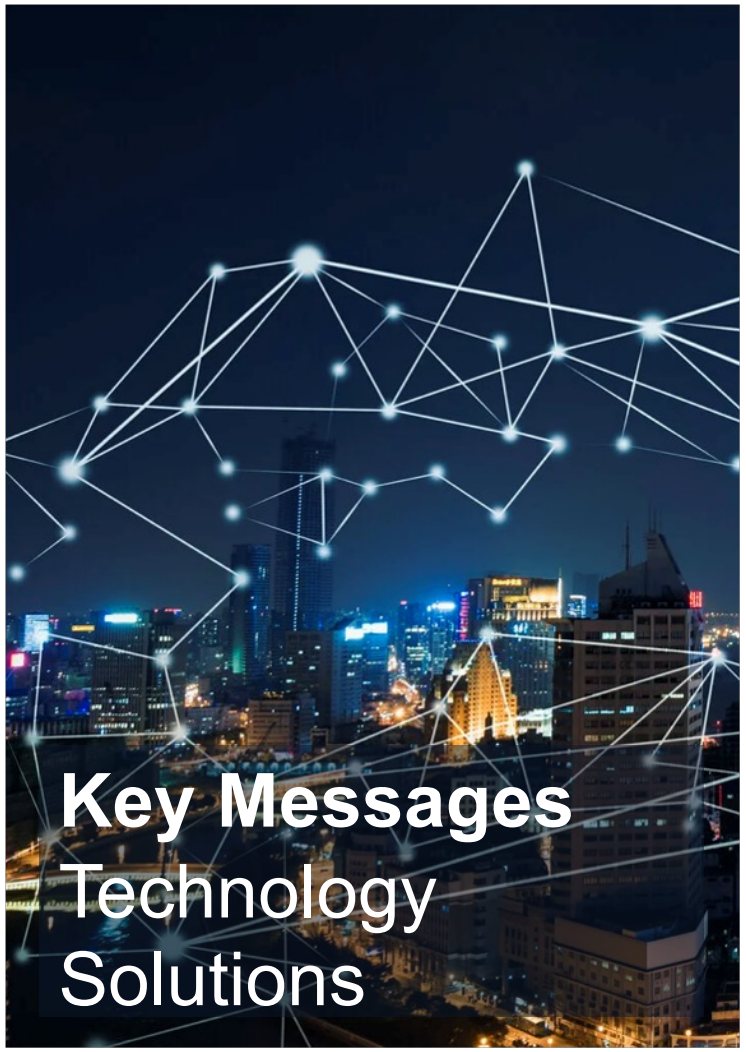
Sources: ENTSOE Factsheet (ENTSOE, 2025); ENTSOE TYNDP (ENTSOE, 2025).
Credit: Hasan Alawadhi, Stephanie Chen, Helin Tilkicioglu, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Columbia Business School
Climate Knowledge Initiative



Technology Solutions



Solutions fall into three pillars, each with a distinct speed to deploy and opportunity type

- **Expand:** new transmission and interconnection, 5-15+ years, $200B+ annually estimated 2030-2035
- **Modernize:** hardware upgrades to the grid including batteries, 1-4+ years, $200-400B/year estimated 2030-2035
- **Optimize:** digital optimization and demand mgmt., 1 to 2+ years, systems savings potential of $150B+ by 2035

Expanding grid is slowest lever, and permitting & cost allocation are binding constraints

- EMDEs need ~60M km of new lines, while +45M km of T&D lines must be replaced by 2050 globally
- **HVDC** moves large volumes of power over long distances with lower losses, and can connect distant generation to load centers, but its high converter station costs only pay off over long corridors
- China has built 45 ultra high voltage lines in about 15 years under central planning, while 36 U.S. HVDC projects, roughly 187 GW, remain stalled for lack of a cost allocation rule

Modernizing the grid draws significant capital flows, with battery applications expanding

- **Grid forming inverter** adoption must accelerate to keep grids stable as batteries and intermittent RE scale
- **Battery storage** is projected to draw $26B in U.S. spend in 2026 and over $100B globally, with a $330B U.S. long duration storage projection by 2050; decreasing costs are expanding the grid value of SATA and BESS
- **FACTS** can unlock capacity in months at a 30 to 1 benefit to cost ratio, AMI is a $22B+ market growing at over 12% a year, and digital twins can increase grid upgrade capital efficiency by 20-30%

Optimizing via digital and load orchestration tools delivers the most value per dollar spent

- **Load shifting** turns flexible household and business loads into grid assets and could save the U.S. power system over $15B a year by 2030; in **bidirectional charging**, **V2B** cuts building costs and provides backup, while **V2G** depends on market design
- **DERMS coordination** could grow U.S. VPP capacity to 80 to 160 GW by 2030, saving ~$10B a year, and cut projected transformer overloads from 81% to 28% by 2050
- **The global VPP** market is set to triple to $15B to $30B by the early 2030s, delivering peak capacity at 40% to 60% less cost than adding new gas peakers

Credit: Dominica Wambold, Ilayda Tezcan, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Optimizing, modernizing, and expanding will upgrade insufficient and aging infrastructure into a resilient, intelligent grid ecosystem

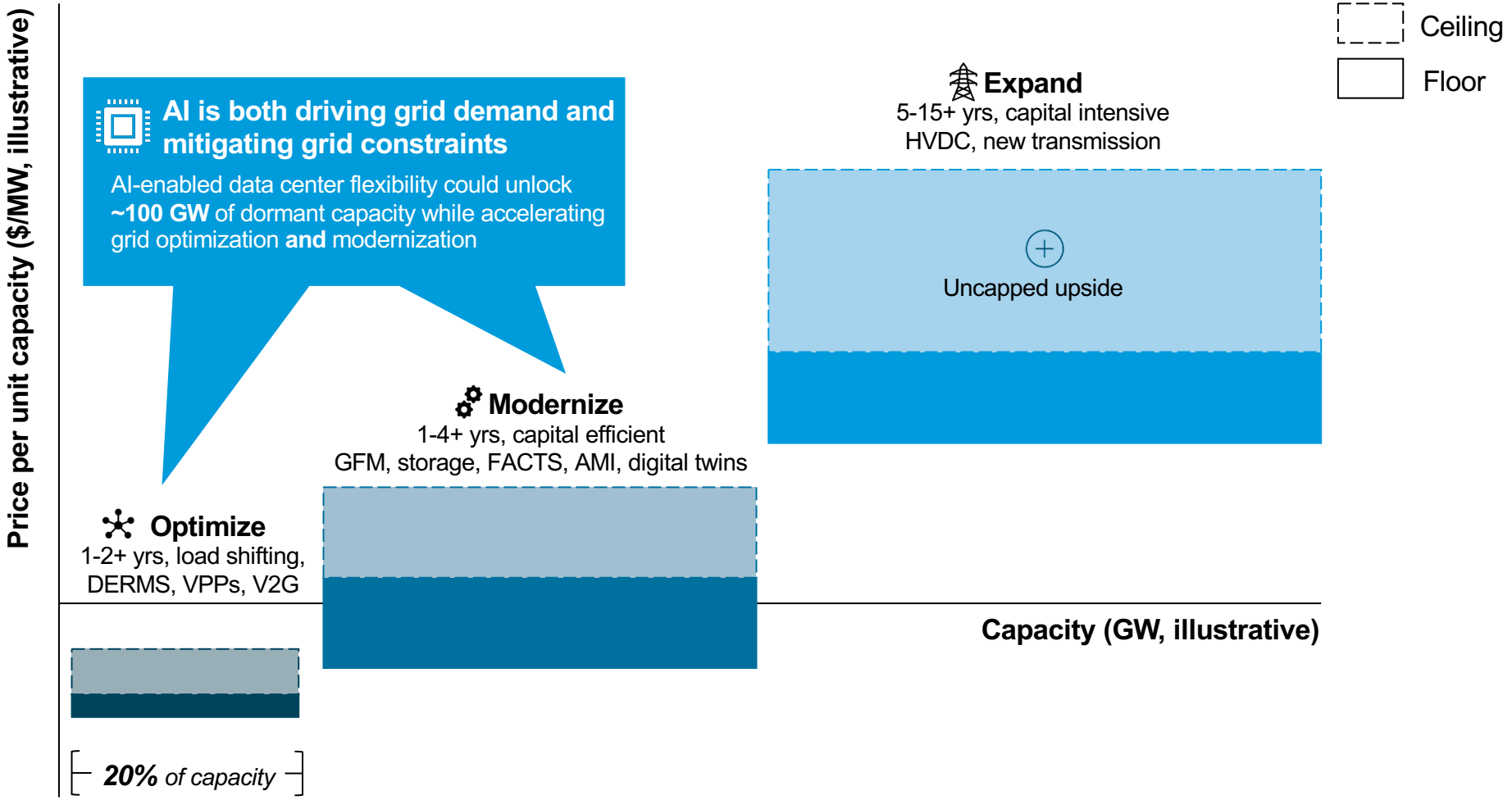
	Optimize grid assets	Modernize and harden the core	Expand grid networks
Definition	Maximize the value of the grid through digital intelligence and demand management	Upgrade and modernize the core with capital efficient physical and technical augmentation	Structurally extend the grid's network to integrate available and emerging generation
Physical and Capital Profile[1]	• Digital intelligence & demand-side solutions • Asset-light	• Hardware solutions at existing grid nodes • Capital efficient	• Net new and upgraded grid transmission • Capital intensive
Highlighted Solutions	• Load Shifting Technologies • Distributed Energy Resource Management Systems (DERMS) • Virtual Power Plants (VPPs) • Bi-directional charging	• Grid-Forming Inverters (GFM) • Grid-Scale Battery Storage • Flexible AC Transmission Systems (FACTS) • Advanced Metering Infrastructure (AMI) • Digital Twins	• New transmission and distribution • HVDC
Time to Deploy	• 1-2+ years	• 1-4+ years	• 5-15+ years
Investment Opportunity[2]	• Estimated $50-$150B+/yr from 2030-2035[1] • Systems savings potential of $150B+ by 2035	• Estimated $200B-$400B+/yr from 2030-2035	• Estimated $200B+/yr from 2030-2035
Key Policy Levers	• Performance based regulation reform • DER aggregation reform, NWA incentives	• Smart grid grants and incentive programs • Cap and floor and depreciation schemes	• Regional/interregional transmission planning • Permitting, siting, and queue reform

[1]The capital profile indicated is relative and intended to reflect the grid capital investment. [2]Investment opportunity is global and based on projected investments for highlighted solutions as defined in each solution area, supplemented by World Energy Investment 2025-2026 reports aligned to STEPS 2030 and BNEF NZE and ETS scenarios. Grid expansion is driven significantly by net-new wires (transmission & distribution); modernize & harden the core includes IEA's Power segment of battery storage; the optimize range includes grid orchestration software and a subset of end-use related charging infrastructure, with savings potential reflecting estimated grid value from demand flexibility. Sources: Building the future transmission grid (IEA, 2025); World Energy Investment (IEA, 2026); World Energy Investment (IEA, 2025); Electricity 2026 (IEA, 2026); Energy storage enters the 100 gigawatt era (BNEF, 2026); Electric Vehicle Outlook (BNEF, 2026); The Value of Demand Flexibility (IEA, 2025); Building grids faster (Energy Transitions Commission, 2024); Electricity Grids and Secure Electricity Transitions (IEA, 2023).

Credit: Dominica Wambold, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Optimizing existing assets unlocks the lowest-cost grid capacity, while expansion offers unlimited investment opportunity

Illustrative



Observations

- AI could turn turn **large loads into flexible grid assets,** unlocking existing capacity while catalyzing investment in grid optimization **and** modernization
  - **~100 GW of latent capacity:** Flexible data center demand could unlock substantial capacity from infrastructure that already exists
  - **Faster interconnection:** By reducing or shifting demand during constrained hours, large loads could connect without waiting for equivalent amounts of new grid build-out
  - **Investment catalyst:** Data center investment flows can help deploy grid optimization and modernization technologies, including for storage, DERMS, and grid-forming inverters
  - **Untapped capacity:** AI-enabled demand flexibility is estimated to be able to raise system efficiency up to 30% more broadly
- Globally, storage and flexibility offer a major potential source of bridge power to meet growing demand while deferring as much as **$1.8T in global grid investment through 2050**

Sources: Powering Intelligence (EPRI, 2026); The Value of Demand Flexibility (IEA, 2026); The Untapped Grid (Brattle, 2026); Rethinking Load Growth (Duke University, 2025); Unlocking Smart Grid Opportunities in Emerging Markets and Developing Economies (IEA, 2023). Credit: Pia Doris Morrow, Dominica Wambold, Ilayda Terzcan, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Scaling grid solutions requires overcoming distinct stakeholder bottlenecks across optimization, modernization, and expansion

Key bottlenecks range from market access in Optimize to utility incentives in Modernize and permitting and cost allocation in Expand

	Optimize grid assets Load shifting, DERMs, VPPs, V2G	Modernize and harden the core GFM, storage, FACTS, AMI, digital twins	Expand grid networks HVDC, new transmission
Regulators & policymakers[1]	Enable DER aggregation and compensation; load flexibility could deliver **>$15B** annual system savings	Set standards and create markets for reliability services; Ireland increased allowable non-synchronous penetration from **~50% to 75%**, targeting 95%	Resolve permitting and co-allocation to unlock **>100 GW** HVDC project pipeline
Utilities, planners & operators	Procure and orchestrate flexibility; **~200 GW** of cost-effective US load flexibility could reduce peak constraints	Deploy upgrades where they defer new build; FACTS can increase transmission capacity by **~30-50%**	Plan and operate new corridors capable of adding **multi-GW capacity per project**
Technology providers & developers	Scale orchestration platforms; coordinated DERs could form an **~80-160 GW VPP fleet**	Supply grid hard- and software; **>80%** of US storage capacity is front-of-meter	Develop HVDC systems offering **~30-50% lower losses** over long distances vs. comparable AC
Customers & beneficiaries	Monetize existing flexible assets; North America already has **between 30-60 GW of VPP capacity** on the grid	Participate through batteries, smart meters and flexible assets; AMI enables demand response and operational savings	Benefit from greater transfer capacity while ultimately funding regulated investment through tariffs
Investors & financiers	Fund asset-light platforms; coordinated DER/VPP deployment could generate **~$10B/year in grid savings**	Finance storage and regulated/ contracted grid assets across a rapidly scaling market	Provide long-duration infrastructure capital once permitting and cost allocation are resolved
→ **Critical stakeholder**	Utilities and market operators	Utilities and regulators	Regulators and planners
→ **Key bottleneck**	Market access & orchestration	Utility incentives & standards	Permitting, cost allocation & delivery capacity
Keys to unlock capacity	Make flexibility accessible, dispatchable & monetizable	Reward capacity unlocked, reliability delivered and costs avoided	Accelerate approvals and align who benefits with who pays

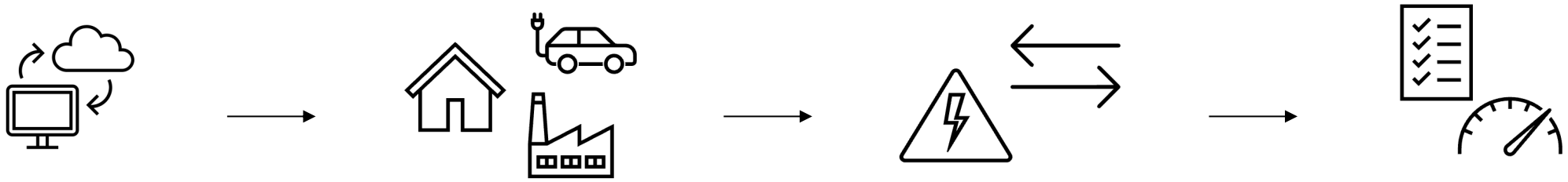
[1]Including permitting authorities.

Sources: VPP Liftoff Report (DOE); State Utility Incentives for Non-Wire Alternatives (Wharton,2020); Electricity Grids and Secure Energy Transitions (IEA, 2023). Credit: Pia Doris Morrow, Ariela Farchi, Dominica Wambold, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Observations

- Grid constraints are increasingly institutional, not technological:
  - **Optimizing** requires access to existing flexibility,
  - **Modernizing** requires mechanisms to monetize grid value,
  - **Expanding** requires agreement on approvals, cost allocation, and project delivery
- Barriers become more complex as solutions scale: Distributed-energy scaling is being held back by fragmented regulation and utility incentives, while transmission policy is explicitly focused on planning and cost allocation

Load Shifting Technologies move non-essential electricity use from high-demand periods to times when the grid is less stressed



1 **Device signaling** 2 **Flexible loads** 3 **Load shift** 4 **Compensation**

How does load shifting work?

1. Smart devices (data centers, thermostats, EV chargers, industrial controls) **receive signals from the utility** about when electricity is **cheap, expensive, or scarce**
2. When it is expensive, algorithms or customer-set preferences **determine which load can be delayed without affecting comfort or operations**
3. During high-demand periods, the device **reduces consumption** and during low-demand hours, it **increases consumption**.
4. Smart meters or built-in sensors **track the load shifts** so the system can fine-tune behavior, and the customer can benefit from **lower bills, incentives, or grid-support payments**

Why is it critical for the energy transition?

- Moves consumption away from peak hours, **reducing stress on lines, transformers, and generators**
- It helps **match demand to renewable production times**, rather than forcing renewables to follow a fixed demand profile
- By **shaving peaks and filling valleys**, load shifting **reduces the need for carbon-intensive peaker plants**
- Wider use of **smart thermostats, heat pumps, water heaters, industrial load control, and EV smart charging** linked to time-varying prices and automation

Advantages

- **Reduces peak load and grid stress**: Demand smoothing
- **Enhances renewable energy utilization**: Better alignment

Disadvantages

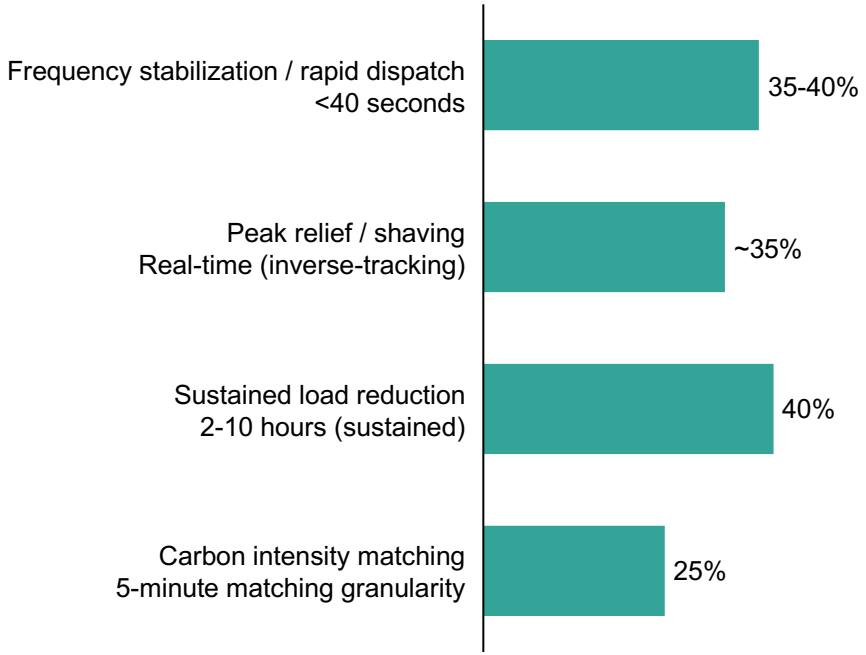
- **Customer behavior and participation**: Engagement needed
- **Communication reliability**: Stable signals
- **Limited visibility**: Data gaps without AMI or sensors

Source: Order No. 2222 Explainer: DERs in Electricity Markets (FERC, 2020); California's Biggest Battery Test Ever (PG&E, 2025); How Many Smart Meters Are Installed in the US? (EIA, 2023)
Credit: Sevgi Helin Tilkicioglu, Hasan Alawadhi, Pia Doris Morrow, Vincent Sandow-Straesser, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Load flexibility is a deployable solution that allows data centers to operate as grid-responsive assets

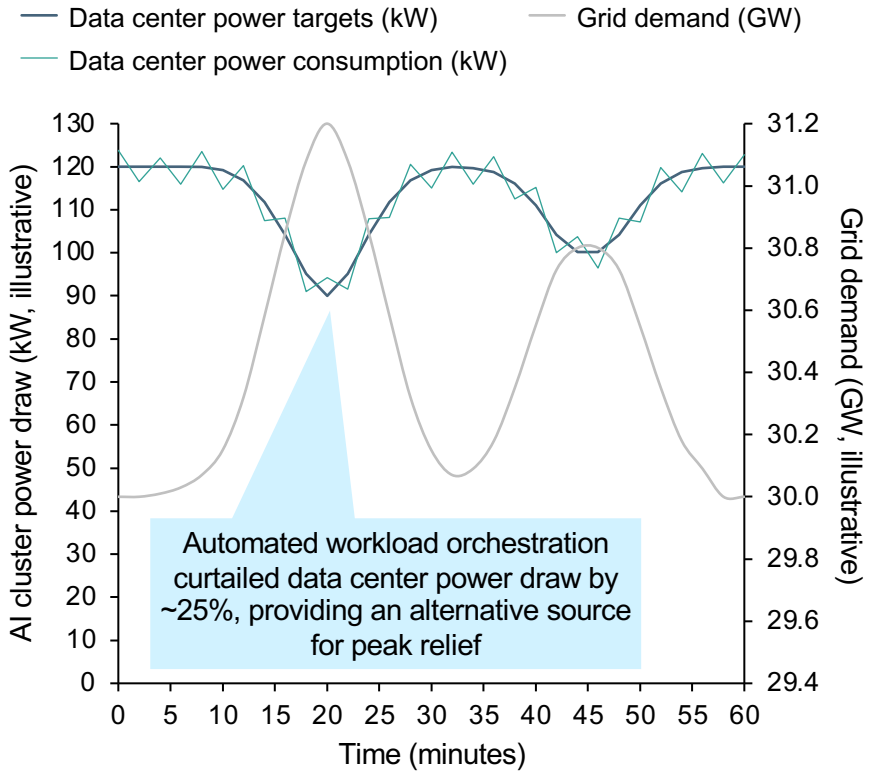
Emerald AI demonstrated data centers can shift up to 40% of non-critical load in <40 seconds

Flexible load capacity (load shedding potential) by grid service duration and response speed[1], % power drop



AI-automated demand response lowers data center consumption in response to peak demand

Demonstration of Peak Load relief (TV pickup effect example[2])



Observations

- Converting data centers from static to **flexible consumers improves speed-to-power and affordability** by making best use of existing infrastructure
- **Expedited access to constrained grids in exchange for flexibility guarantees** can effectively incentivize load-shifting adoption
- EPRI's DCFlex initiative and Mosaic framework provide **resources for utilities seeking to integrate data centers as flexible loads**
- **Emerald AI's workload orchestration solution has enabled operational-scale grid flexibility** in the U.K. and in several U.S. states
  - In a collaboration between Santa Clara, Emerald AI, and Silicon Valley Power, SVP is pioneering a program where **data centers that are willing to be flexible are more likely to be granted additional capacity**

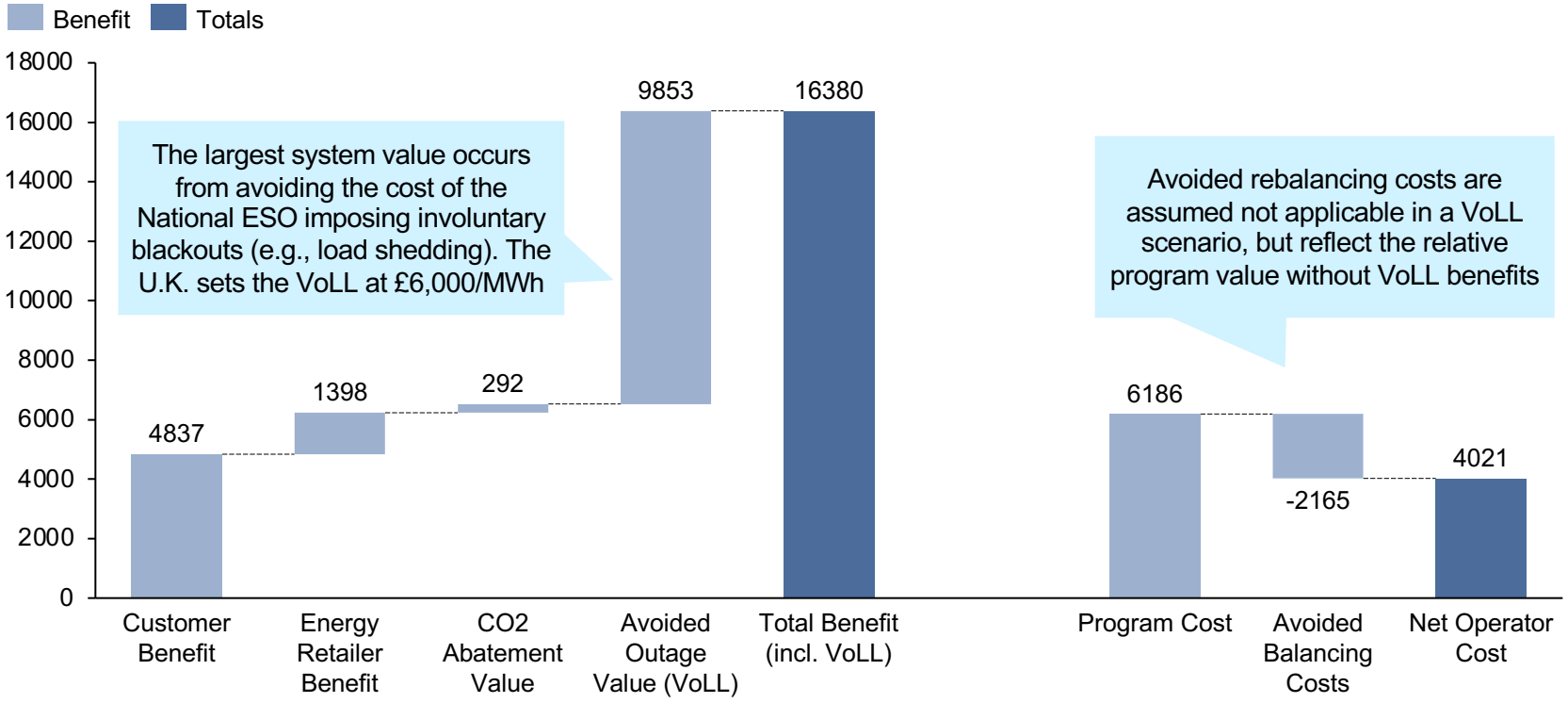
[1]Emerald AI, EPRI, National Grid, and Nebius 'AI Factory' modeling with automated clustered response to grid disturbances across multiple use cases and scenarios; [2] UK phenomenon – during football matches, use of domestic appliances, such as tea kettles, picks up significantly during half-time and at the end of the match, causing demand peaks. Sources: Power-Flexible AI Factories (Emerald AI, 2026); Flex Mosaic (EPRI, 2026); Global Effort to Prepare Future-Ready Grids (EPRI, 2025); AI data centers as grid-interactive assets (Nature Energy, 2025); Fast, Flexible Solutions for Data Centers (Rocky Mountain Institute, 2025); Blowing Off Steam (NVIDIA, 2026); AI drives demand, and will soon manage it (Silicon Valley Voice, 2026). Credit: Dominica Wambold, Ariela Farchi, Gunay Kiran, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

A U.K. program demonstrated system and customer benefits from demand response, particularly driven by blackout avoidance

Octopus Energy's Saving Sessions demand flexibility program provided customer benefits of ~ £5M, lifted energy retailer margins by ~£1M, and provided cost-effective insurance against blackout risk

Modeled system value (welfare analysis) of Octopus Energy's demand flexibility program (GBP '000, 2022-2023 pilot results)[1]



[1]Welfare analysis conducted by the Centre for Net Zero, evaluating the marginal value of public funds (MVPF) associated with Octopus Energy's version of the U.K.'s Demand Flexibility Service program; customer and energy retailer benefits are modeled as a split based on the paper methodology leading to an ~0.8% difference between the benefits derived and the program cost.

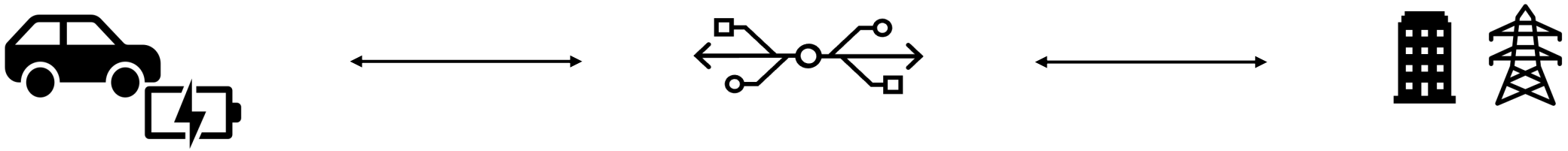
Sources: The Impact of Demand Response on Energy Consumption and Economic Welfare (Centre for Net Zero, 2024). A Demand-Side Alternative to Renewable Curtailment (National Bureau of Economic Research, 2026); Policy and regulation in virtual power plants development (Utilities Policy, 2026); VPP Liftoff Report (DOE).

Credit: Dominica Wambold, Pia Doris Morrow, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Observations

- **Demand side response**, enabled by technologies like VPPs and battery + renewables, **can increase investor returns and reduce system and customer costs** by providing an alternative to curtailment or generation overbuild
- **Avoiding costly Distribution upgrades** via demand response could help offset escalating costs
- VPPs could provide **peak capacity relief at up to 40-60% lower cost than new generation**, with deployment in as little as 6 months
- **Financing sources** for demand response and VPP implementation include policy-enabled ancillary service market revenues (enabled in the U.S. by FERC 2222), public subsidy (e.g., via U.S. DOE), and VC/Growth Equity

Bidirectional charging enables vehicle-to-building and vehicle-to-grid interactions, turning EVs into flexible energy storage



1 **Vehicle**

2 **Bidirectional charger**

3 **Buildings and energy grids**

How does Bidirectional Charging for grid systems work?

1. An EV first participates through **V1G**, where charging is intelligently timed or managed while electricity still flows one way from the grid to the vehicle
2. With a **bidirectional charger**, the EV can charge and discharge, enabling electricity stored in the car's battery to be used when needed
3. That stored electricity can be directed to budlings **(V2B)** or the grid **(V2G)** to reduce peak demand, support resilience, or optimize site electricity use
4. EVs are connect to the grid through a **bi-directional inverter** and **communication interface**, allowing an **aggregator or utility to coordinate discharge** across multiple vehicles simultaneously

   These aggregated EVs export to the grid and **respond to real-time utility or market signals**, such as frequency regulation or demand responses, to provide **system-wide flexibility and grid services**

Why is it critical for the energy transition?

- EV batteries represent a **rapidly growing flexible storage resource**
- Bidirectional charging can help **balance peaks, improve resilience, and support renewable integration**
- It allows parked vehicles to provide **value beyond transportation**
- It can **defer grid and building infrastructure upgrades** by using existing battery capacity

⊕ Advantages

- **Unlocks additional value from EV batteries** while vehicles are parked
- Can support **resilience, peak management, and renewable integration**
- **Creates value for EV owners** through lower bills/increased home resilience (V2B), or by generating revenue streams (V2G)

⊖ Disadvantages

- Requires **bidirectional-capable hardware, controls, and coordination**
- Depends on **standards, interconnection, and compensation mechanisms**
- Participation and value vary by **site readiness, driver behavior, and market design**

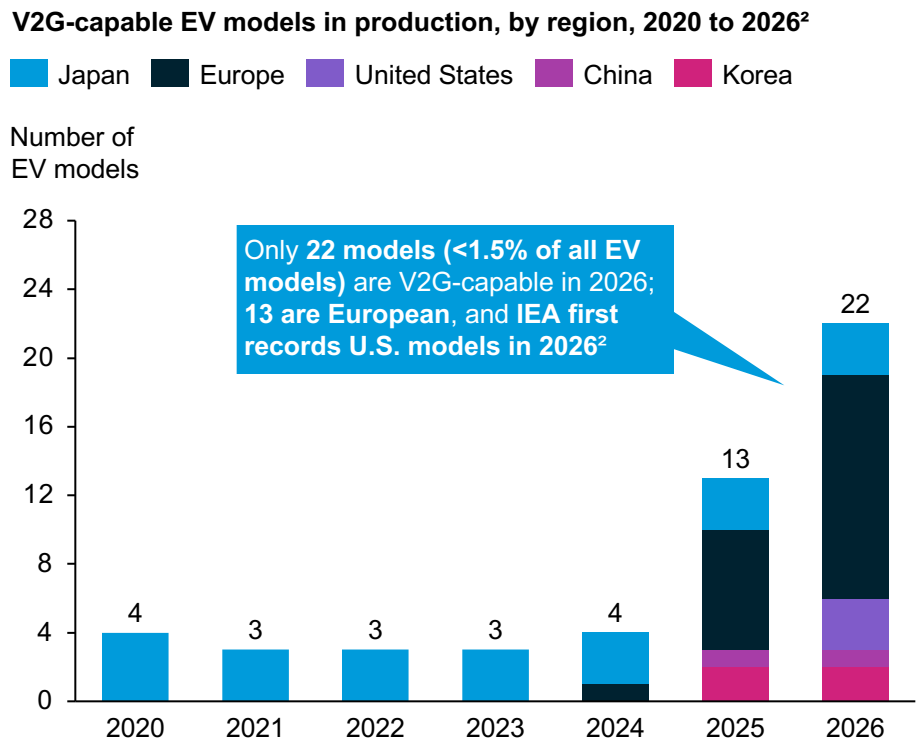
Source: Vehicle-to-Grid Integration Assessment Report, (US DOE, 2025); Global EV Outlook 2026, (IEA, 2026); EV Batteries Could Satisfy Short-Term Grid Storage Demand, (Nature, 2023)
Credit: Sevgi Helin Tilkicioglu, Hasan Alawadhi, Isabel Hoyos, Vincent Sandow-Straesser, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

V2B can cut building costs and provide backup; V2G can earn revenue but depends on approval and policy

V1G works today; V2B is emerging as backup power; V2G is limited to early offers and pilots

	V1G Smart charging	V2B / V2H Home or building	V2G Grid export
Power flow	One way; charging timed to match generation or ease congestion	Vehicle discharges to the home or building where it is parked	Vehicle exports power to the grid
Value captured	Lower charging cost and avoided peak load	Bill savings and backup power	Energy arbitrage, ancillary services and distribution-level services
Grid approval (typical U.S. practice)[3]	**No interconnection approval**; the system only charges	**Usually none if it discharges only in outages**, like a backup generator; **approval** if it discharges while grid-connected, like a stationary battery	**Interconnection approval**, as it discharges while the grid operates
Extra hardware	Smart charger or vehicle that adjusts charging on a signal; no bidirectional hardware	Bidirectional charger, **<$1.5k AC to $5k+ DC**; backup also needs a device that isolates the building from the grid	Bidirectional charger certified to local grid codes and able to communicate with the EV

Vehicle supply is the first constraint, as few EV models can send power back



Observations

- Smart charging (V1G) delivers **€19-42B a year in modeled European system savings**; V2G **adds up to €2.5B**[1]
- Bill savings do not equal grid relief; static time-of-use tariffs can lead many EVs to **charge or discharge at once**, worsening grid impacts
- **V2G offers** for private EV owners **only appeared in 2025** and V2G regulation **remains fragmented**
- In IEA's illustrative home case, ~$500 a year in benefit pays back a bidirectional charger in **~2 years (AC) to 10 years (DC)**
- Where no EV is parked on site, **a stationary battery competes with V2B**, as storage pack prices fell **45% to $70/kWh** in 2025

[1]The study also estimates €6.4B a year in V2G balancing-market revenue, a separate stream from system savings. V2H = vehicle-to-home, the residential form of V2B. [2] Counts read from the IEA chart; models included only if the manufacturer states the capability; 2026 as of IEA's April 2026 update. [3] Rules are set state by state and vary; e.g., California (Electric Rule 21) and PG&E follow this pattern.

Sources: Coordinated planning of European charging infrastructure and energy system for optimal V1G and V2G deployment (Nature Energy, 2026); Vehicle-to-grid technology (IEA, 2026); Global EV Outlook 2026 (IEA, 2026); Number of electric vehicle models in production with vehicle-to-grid charging capability, 2020-2026 (IEA, 2026); Vehicle-to-Everything (V2X) pilot programs (PG&E, 2026); Interconnection VGI Forum (CPUC, 2024); The X in V2X Matters (SEPA, 2023); New record lows for battery prices (BNEF, 2025).

Credit: Ilayda Tezcan, Pia Doris Morrow, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

U.S. pilots demonstrate bidirectional operation, but economics and deployment remain site-specific

PG&E's backup phases need no grid approval, while its grid-connected phases do; only Boulder reports realized bill savings

Five U.S. bidirectional charging cases, by type, scale and grid approval

	North Boulder Rec Center	PG&E Residential pilot	PG&E Commercial pilot	PG&E Microgrid pilot	Delmarva Power fleet pilot
Type	**V2B**	**V2H; V2G planned[1]**	**V2B and V2G**	**V2M (vehicle-to-microgrid)**	**V2G**
Location	Boulder, CO	Contra Costa and Yolo counties, CA	Oakland, CA	Humboldt County, CA	Newark, DE (PJM market)
Period	Dec 2020 to Nov 2021	As of Jun 2025	As of Jun 2025	As of Jun 2025	Final report, Mar 2026
Scale	1 city fleet Nissan LEAF on a two-way charger	3 customers	1 customer (Zum bus fleet), 74 chargers	3 airport staff customers, 4 chargers	4 Ford Mach-E fleet vehicles
Program scope	Cutting the building's demand charges	Home backup, then bill savings	Building backup, then bill savings and V2G	Community resiliency during outages	PJM frequency regulation on a recorded signal, and time-of-use arbitrage
Grid approval	Not stated in the report	**None for backup** (Phase I); **Rule 21 agreement** once grid-connected (Phase II)	**None for backup** (Phase I); **Rule 21 agreement** once grid-connected (Phase II)	**Rule 21 agreement** required for all participants	**Interconnection required**; simplified review only under 10 kW
Result	**$2,963.50** in demand charge savings[2]	Not yet reported[4]	Not yet reported[4]	Not yet reported[4]	**Modeled $1,102 to $3,359 a year** for a hypothetical 10 kW car[3]; PJM made no payment; no measurable battery degradation

[1]Automakers have not yet enabled V2G for vehicles in PG&E's residential pilot. [2] City-reported gross savings for one vehicle; installed cost and net return not disclosed. [3] Modeled from 2021 to 2025 average market prices; assumes vehicles are unavailable 40 hours a week; before aggregator fees, support and battery wear. [4] Status as of the CPUC summary of PG&E's V2X pilots, September 2025; Rule 21 is California's interconnection rule.

Sources: North Boulder Recreation Center Electric Vehicle Charging Station Pilot Annual Report (City of Boulder, 2022); PG&E Vehicle-to-Everything Pilots (CPUC, 2025); Evaluating the Capabilities and Value of V2G Grid Services in Fleet Operations (University of Delaware and Exelon, 2026).

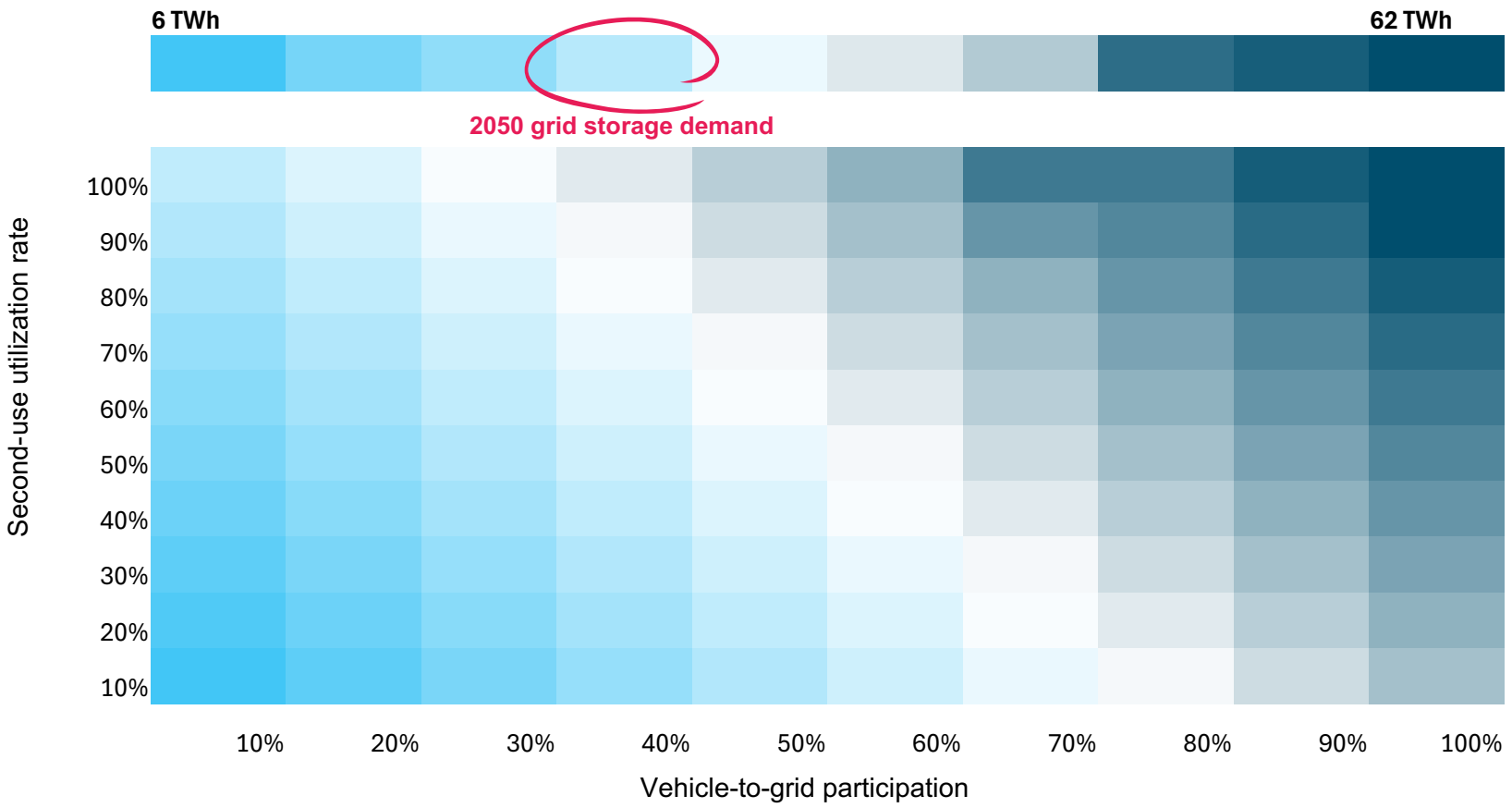
Credit: Ilayda Tezcan, Pia Doris Morrow, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Observations

- PG&E's pilot summary identifies **high bidirectional equipment costs, especially DC**, and **limited compatible EVs and chargers** as barriers
- OEM and charger-provider agreements took **longer than anticipated** in PG&E's pilots
- Delaware's fleet vehicles had to be **retrofitted with a bidirectional converter**
- Interconnection processes at most utilities were **designed for solar**, not yet adapted for batteries
- **Net metering is not yet required for V2G in most states**; without it, earlier Delaware-area calculations show regulation revenue can halve
- PG&E's microgrid pilot faced **control-system deployment issues and funding delays**

V2G could play a significant role in fulfilling grid storage demand, unlocking up to ~60 TWh in combination with second-use

Total actual available capacity under various conditions in STEP-NCX scenario in 2050



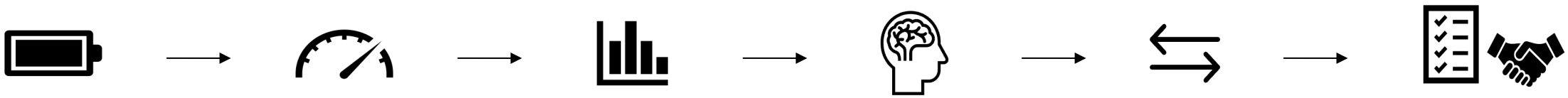
Observations

- Leveraging **V2G and re-use** are two **domestic sources for battery storage deployment**
- V2G participation in grids could play a role in providing the **real-world capacity for short-term grid storage**, with EV batteries together with second-use utilization rates reducing other battery and generation needs
- When both V2G participation rates and second-use rates are **at 50%,** the projected real-world capacity reaches **between 25 and 48 TWh by 2050** (STEP-NCX scenario)
- Meeting grid storage demands by 2050 (3.4 to 19.2 TWh) can be done with different combinations of V2G and second-use. **Without any second-use batteries** in stationary storage, grids would require V2G participation rates of an **achievable 12% to 43**%
- **Assuming half of second-use batteries** (retired EV batteries repurposed for stationary grid storage after falling below automotive performance thresholds) are used for grid storage, the required participation rate of **V2G drops to below 10%**

Source: Electric vehicle batteries alone could satisfy short-term grid storage demand by as early as 2030 (Nature, 2023).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, Dominica Wambold, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Distributed Energy Resource Management Systems orchestrate millions of small assets into a single, dispatchable grid resource



1. **Distributed energy resources**
2. **Metering & telemetry**
3. **Forecasting**
4. **Optimization**
5. **Dispatch & control**
6. **Verify & settle**

How does DERMS for grid systems work?

1. Distributed energy resources (DERs), e.g., **rooftop solar, batteries, EVs and thermostats**, are **connected and registered to the platform**
2. Each asset **continuously reports its output, state of charge and availability**
3. The platform **forecasts load, solar and wind output, prices and grid constraints**
4. It **optimizes a dispatch** that respects **grid limits and market signals**
5. Setpoints go back to the assets: **charge, discharge, curtail or shift load**
6. Delivered response is **verified and participants are paid**, then the loop repeats

Why is it critical for the energy transition?

- **Unlocks flexibility** hidden in millions of behind-the-meter assets, turning **passive load** into a **controllable, grid-supporting resource**
- Lets the distribution grid **absorb far more rooftop solar and EVs without costly wire upgrades**, by actively managing local flows
- By **aggregating DERs into virtual power plants**, it provides **capacity and ancillary services** otherwise met by fossil peakers
- Shifts the grid from centralized, supply-following dispatch to a **distributed, demand-flexible system**

Advantages

- **Defers grid capex**: Avoids new wires
- **Fast to deploy**: Software-led
- **Unlocks DER value**: Idle assets earn
- **Improves reliability**: Local flexibility
- **Integrates renewables**: Absorbs solar/wind swings

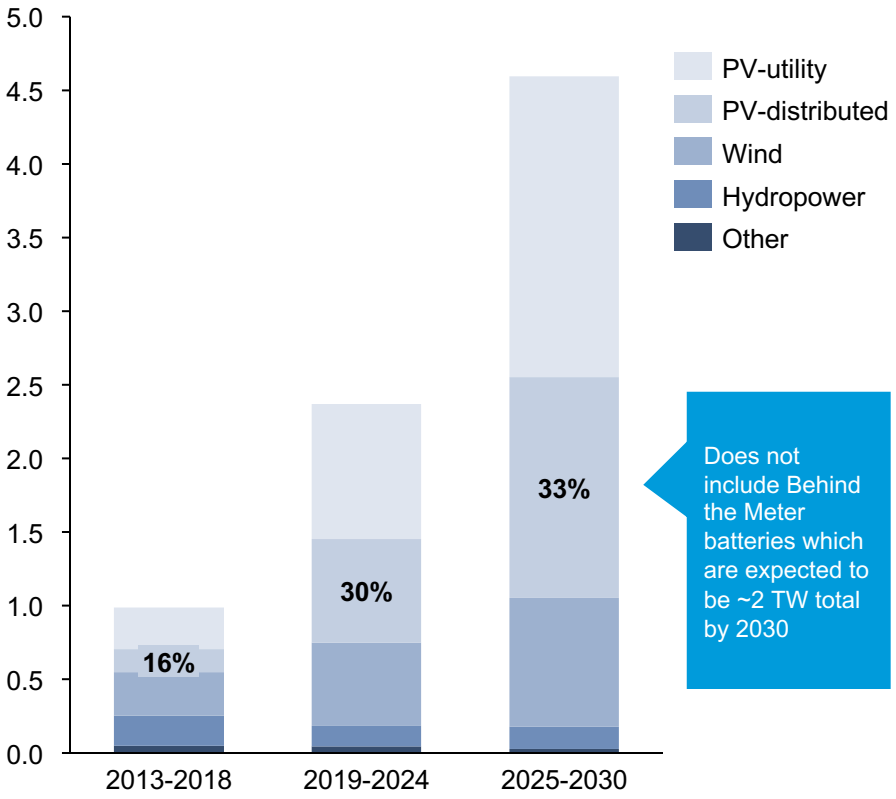
Disadvantages

- **Integration complexity**: Many vendors & systems
- **Needs enrollment & rules**: Opt-in, standards, FERC 2222
- **Cybersecurity**: Millions of endpoints to secure

Source: VPP Liftoff Report (DOE); Order No. 2222 Explainer: DERs in Electricity Markets (FERC, 2020); GridOS DERMS: Distributed Energy Resource Management System (GE Vernova, 2025).
Credit: Sevgi Helin Tilkicioglu, Hasan Alawadhi, Pia Doris Morrow, Vincent Sandow-Straesser, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

DERMS provide an increasingly distributed grid with improved visibility, dispatch efficiency, interoperability and market integration

Renewable power capacity growth by technology[1]
TW, 2013-2030



Visibility

Grid operators can see availability and charge level of resources behind the meter, enabling forecasts on generation

Dispatch and constraint management

Aggregates and dispatches DERs, optimizing peak shaving and economics while adhering to security constraints. Plus, settles C&I flexibility payments[1]

Interoperability and market integration

DERMS bridge the system gap integrating different DERs to the tech stack with dispatch optimization and wholesale / flexibility markets

Observations

- Without centralized coordination, **81% of US distribution transformers could be overloaded** by 2050, dropping to just **28% with DERMS-based coordination** and reducing peak load by 17%
- **DERMS unlocks DERs as dispatchable non-wires alternatives**, deferring costly infrastructure upgrades, tripling US VPP capacity to 80–160 GW by 2030 could save $10B annually in grid costs
- Enables **TSO-DSO coordination**, bridging two operators who historically lack real-time data exchange across the T/D interface

[1]DERMS are used to size metered loads of Commercial and Industrial (C&I) customers to figure out how much a C&I customer needs to be paid when their process load is curtailed and use the information credit the customer.

Sources: Renewable electricity capacity growth by technology segment (IEA, 2025); Coordinating distributed energy resources for reliability can significantly reduce future distribution grid upgrades and peak load (Navidi et al., Joule, 2023); VPP Liftoff Report (DOE); Use Cases and Digital Twins Solutions (ENTSO-E & DSO Entity, 2026); Batteries and Secure Energy Transitions (IEA, 2024).

Credit: Hasan Alawadhi, Isabel Hoyos, Dominica Wambold, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Flexibility markets, supported by DERMS, provide incentives for aggregated DERs and VPPs to respond to grid needs at scale

The EU and US have policies in place to encourage the participation of distributed resources in energy markets

U.S.

FERC 2222

- Allows DERs to participate in regional capacity, energy, and ancillary services markets
- A coordinatior aggregates DERs in order to meet size and performance requirements, and participate alongside traditional resources

EU

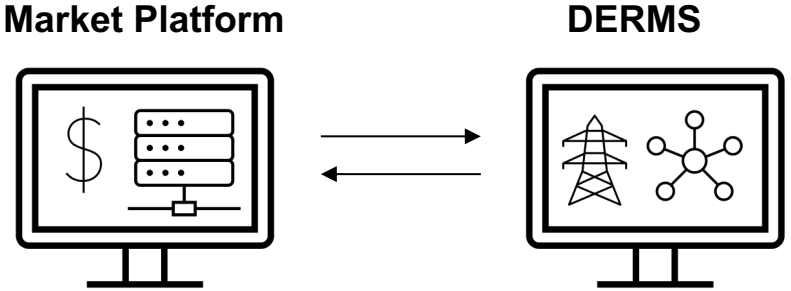
RED III

- Targets to increase renewable energy use across the EU
- Encourages engagement of DERs in electricity and flexibility markets through aggregators

EU Network Code-on-Demand Response

- Ensures that demand response resources can participate in wholesale electricity markets
- Standardise how demand response is measured
- Considers this key factor to energy security and the energy transition

GE's GridOS demonstrates how DERMS can collaborate with market platforms to improve flexibility operations



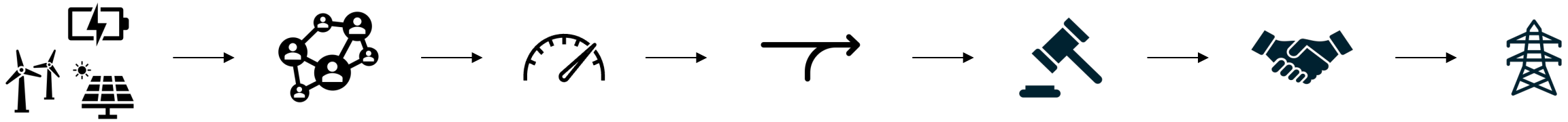
NODES piclo GE VERNOVA

	Market Platform	DERMS
Focus	• Marketplace operations • Commercial transactions	• Asset powerflow analysis • Grid physics
Who does it interact with?	• Portal for service providers to register DERs and submit bids	• Internal dashboard for grid or DER operators to manage flexibility
How does it facilitate flex markets?	• Clears bids based on economic criteria (best price)	• Screens bids against physical grid network models (capacity limits, voltage constraintsm etc)

Sources: GridOS DERMS and flexibility markets (GE Vernova, 2025); FERC order no. 2222: Fact sheet (FERC, 2020); Guidance on article 20a (EU, 2025); New code on demand response (EU ACER, 2025). Credit: Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Virtual power plants aggregate thousands of distributed assets into a single, dispatchable, market-facing power plant



How do VPPs work?

1. **Aggregate thousands of distributed energy resources (DERs)**, e.g., rooftop solar, home and commercial batteries, EVs and smart thermostats, into **one cloud-managed portfolio**
2. **Monitor every asset in real time** and **forecast generation, load and market prices**
3. **Optimize and dispatch** the resources. Software decides when each asset **charges, discharges or curtails** to meet grid and market needs
4. **Bid the combined capacity** into **wholesale energy, capacity and ancillary markets**, or into utility programs
5. **Deliver the committed service** and **share the revenue back with participating owners**

Why are they critical for the energy transition?

- Turn millions of DERs into **firm, dispatchable capacity**, with **no new power plant built**
- Deliver **peak capacity at roughly half the cost** of a new gas peaker or grid-scale battery, easing affordability
- Distributed batteries charging on midday solar and discharging at peak **absorb renewable variability and displace fossil peakers**
- Among the **fastest, cheapest ways to meet near-term load growth** (e.g., data centers and electrification) while transmission lags

Advantages

- **Fast & low-cost**: Deploys in months
- **Cheaper than peakers**: ~Half the cost
- **Pays participants**: Owners earn for it
- **Scales with DERs**: Solar, batteries, EVs
- **Boosts resilience**: Peaks & emergencies

Disadvantages

- **Market access**: Patchy rules, FERC 2222 to 2028
- **Interoperability**: Opt-in & multi-vendor control
- **Undervalued**: Operators cap & under-credit VPPs

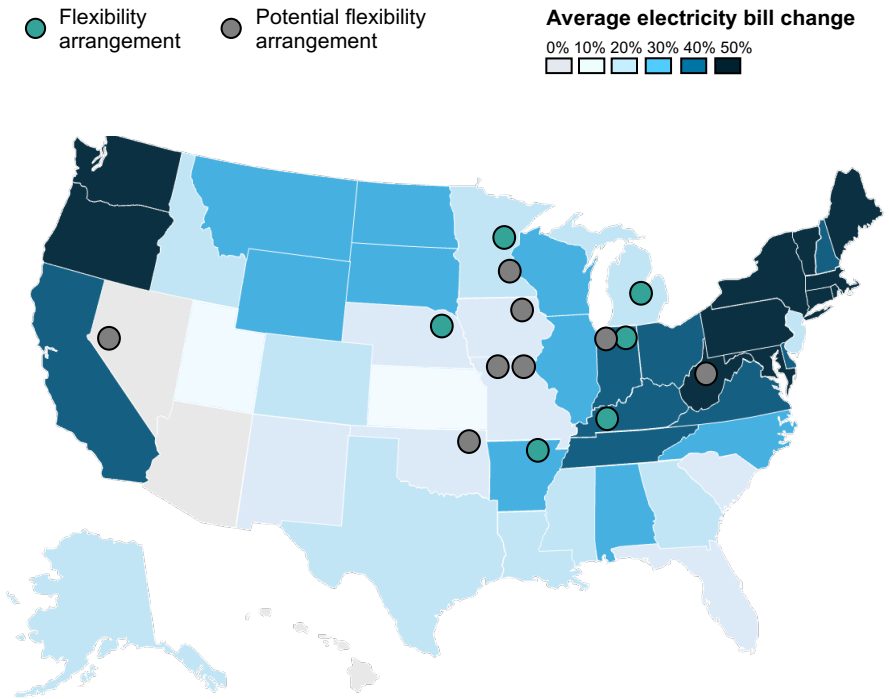
Source: Pathways to Commercial Liftoff: Virtual Power Plants (US DOE, 2025); 2025 North America VPP Market (Wood Mackenzie, 2025)
Credit: Vincent Sandow-Straesser, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

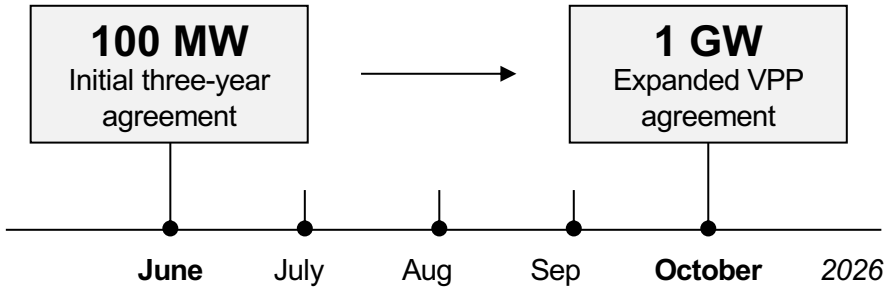
Google and Voltus expand their virtual power plant agreement tenfold to unlock 1 GW of flexible grid capacity

Demand flexibility agreements are expanding across U.S. data centers

Google locations with flexible data center agreements



Google and Voltus expand their PJM virtual power plant agreement to 1 GW



Deal Dynamics

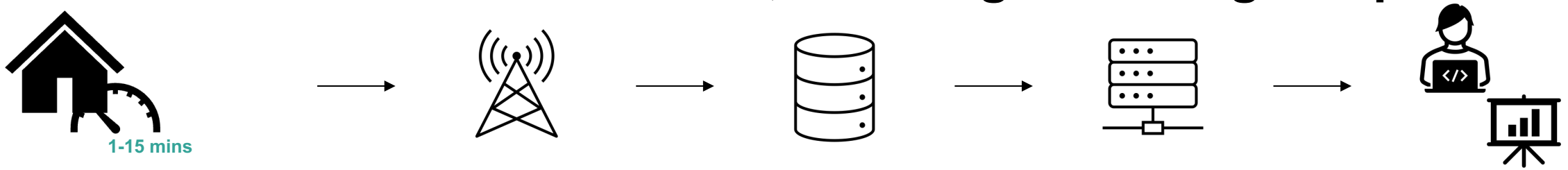
- Google funds a VPP operated by Voltus, aggregating **flexible resources from households and businesses across PJM**
- Voltus coordinates batteries, smart thermostats, and other flexible assets to **reduce electricity demand** during periods of grid stress
- The **original agreement** targeted up to **100 MW** of accredited distributed capacity annually over three years, with the same capacity re-enrolled or requalified each year
- The **October 2026 expansion** targets a **1 GW VPP**, scaling the BYOC model to help meet growing data center demand while compensating participating customers

Observations

- **VPPs offer a scalable, less infrastructure-intensive approach** to meeting growing electricity demand
- **Distributed flexibility** can deliver **benefits to households and businesses**
  - Participating customers receive **financial incentives** through bill savings and direct payments
  - Broader deployment of VPPs could **reduce the need for infrastructure** built primarily to meet peak demand
- **BYOC** demonstrates how **hyperscalers can finance additional grid capacity**
  - This presents a **capital-efficient solution** to improve grid utilization
  - Hyperscalers like Google bring in **critical financing**; data center investments can expedite the **flexibility technology learning curve**

Source: We are working with Voltus to build a 1 GW VPP (Google, 2026); Large Load Customer Projects and Tariffs (EEI, 2026); A new framework for DER value in the speed to power era (The Brattle Group, 2026); How we're making data centers more flexible to benefit power grids (Google, 2025); Google and Voltus to deliver grid capacity and local economic benefits through bring your own capacity agreement (Voltus, 2026); PJM Capacity Auction Procures 138,318 MW of Generation Resources as Work Continues To Address Growing Electricity Demand (PJM, 2026).
Credit: Ariela Farchi, Pia Doris Morrow, Dominica Wambold, Christy Wong, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Advanced Metering enables two-way digital communication between utilities and customers, enabling smarter grid operations



1. Smart meter
2. Communication tower
3. Utility software
4. Meter Data Management System (MDMS)
5. Utility

How does Advanced Metering Infrastructure (AMI) 2.0 work?

1. Each meter **communicates usage data between utilities and customers**, creating a **two-way digital link –** instead of a one-way, reading-only method
2. The utility's software receives the measurements, checks for errors, and organizes the data to **ensure accurate billing and reliable operational information**
3. The Meter Data Management System (MDMS) **stores** detailed consumption and generation data, applies validation rules, and **prepares the data** for billing, forecasting, outage detection, load analysis, and customer dashboards
4. The AMI **data** feeds many utility functions: **outage detection, demand response, dynamic pricing programs, remote connect/disconnect, and dashboards** that show customers their real-time electricity use

Why is it critical for the energy transition?

- Provides **near- real-time visibility of electricity use**
- Enables **dynamic tariffs, demand response, smart EV charging, and integration of rooftop solar and batteries** at scale
- Better data and price signals **help shift and reduce consumption**, lowering peak demand and **allowing more renewables to operate** without curtailment
- Smarter AMI 2.0 platforms **combine metering, grid monitoring, and customer apps** into one digital layer for the grid

Advantages

- **Better visibility:** Real-time data
- **Foundation for a smart grid:** Digital layer
- **Supports flexible demand:** Dynamic control
- **Faster outage detection:** Instant alerts
- **Multi-purpose**: Smart meters at customer premises, networks & MDM with utilities

Disadvantages

- **Upfront cost:** Major investment, utility-paid
- **Integration complexity:** System alignment
- **Customer acceptance:** Trust and adoption
- **Data utilization:** Despite high AMI adoption, deriving DER value of the analytics layer lags

Sources: Demand Response and Advanced Metering (FERC, 2025); Electricity Grids and Secruity Energy Transitions (IEA, 2024); What is advanced metering infrastructure (AMI) (IBM, 2026).
Credit: Sevgi Helin Tilkicioglu, Hasan Alawadhi, Isabel Hoyos, Dominica Wambold, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Closing the AMI implementation gap requires interoperability mandates, targeted grants, and demand response market pricing

Effective policy drives value capture, assisted by performance incentives and interoperability

Enabling Policies

System Design

- Set and govern time-of-use (TOU) rates, critical peak pricing, and real-time dynamic pricing to incentivize customer behavior
- Optimize pricing and measure impacts to ensure data translates into system savings

Regulation

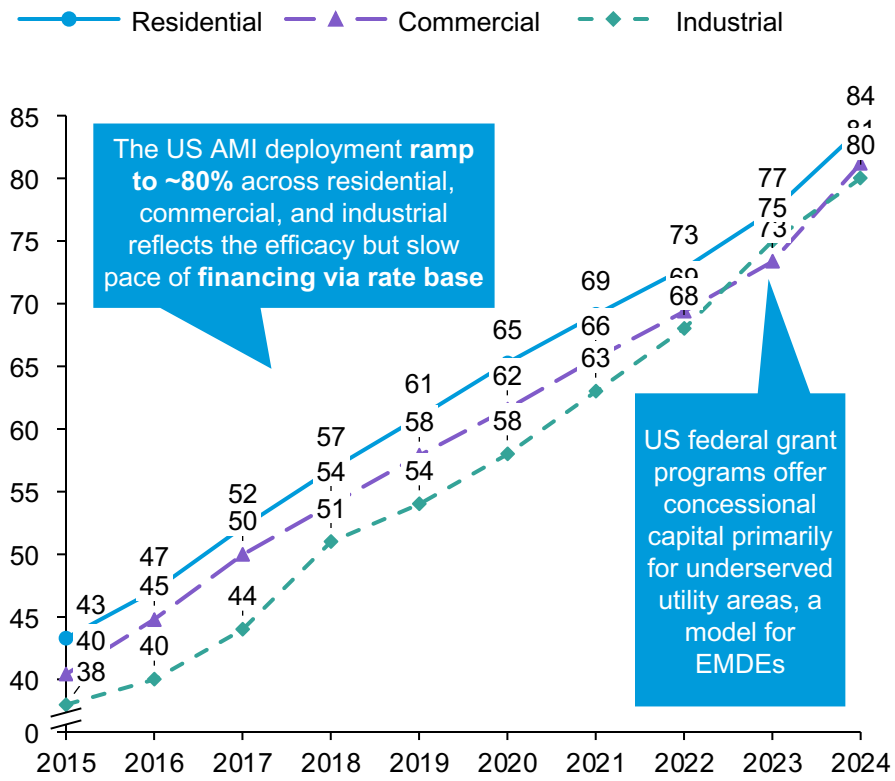
- Establish a national framework for AMI data sharing, interoperability, and cybersecurity
- Mandate functional interoperability, secure and non-discriminatory data governance, pay-for-performance, dynamic rating, and adoption

Public Finance

- Authorize concessional capital (incentives, grants, DFIs) to drive adoption, focusing on under-capitalized utility systems or regions
- Require default time-varying rates to access grants and other public revenue sources

AMI adoption is largely achieved via the rate base and grant funding

US AMI deployment percentage by application, 2015-2024



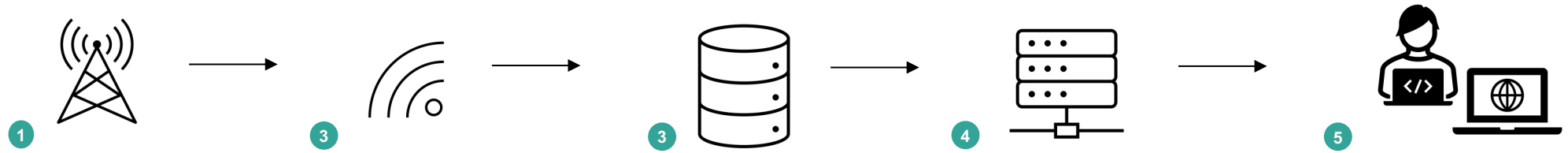
Observations

- The US pathway illustrates the 'slow and steady' route to AMI deployment in mature markets
  - Funded through the utility rate-base PUC process, with costs and system savings passed through via OpEx reductions
  - Evolution from AMI 1.0 to AMI 2.0 is in progress as meters age
- Concessional capital delivered via grants, development finance, and incentives can accelerate utility and customer adoption especially in undercapitalized areas
- Mandates may help drive high value data utilization and complete adoption throughout grid systems, maximizing the value of demand management programs
- AMI is a foundational technology for many demand response capabilities

Sources: Grid Resilience and Innovation Partnerships (U.S. DOE, 2026); Table 10.05. Advanced Metering Count by Technology Type (EIA, 2024); Advanced Grid Technologies (National Governors Association, 2025); Smart electricity meter market 2024: Global adoption landscape (IoT Analytics, 2024) .

Credit: Dominica Wambold, Sevgi Helin Tilkicioglu, Hasan Alawadhi, Pia Doris Morrow, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Digital Twins can create a real-time virtual model of grid assets and operations, providing a key tool for grid orchestration



How do Digital Twins for grid systems work?

1. Sensors collect **real-time field** data from grid equipment (e.g., voltage, current, temperature, faults, equipment condition)
2. SCADA / AMI systems **transmit and organize operational data** from control rooms and customer meters, giving **visibility into grid flows, outages, and demand patterns**
3. Asset-level data **adds the static physical context**: where equipment is located, what it is, how old it is, its capacity, condition, and maintenance history
4. System models **combine real-time electricity and asset data into a virtual grid model** that can simulate power flows, test scenarios, forecast risks, support planning and operations, and provide real-time monitoring & visualization

Why is it critical for the energy transition?

- Can **reduce costs** of and **accelerate and maximize the safe integration** of **renewable energy**
- Key enabler for integrating and **managing bi-directional resources and demand management**
- Scenario planning and advanced modeling capabilities **help planners and operators de-risk large system changes** required for the energy transition

Advantages

- **Asset value realization** – de-risks GETS
- **Utilization control** – system-wide visibility
- **Decision-making** – net-new simulation, scenario, and testing capabilities
- **Energy source integration** – facilitates generation, storage, DER, and EV sources

Disadvantages

- **Upfront cost** - major investment, utility-paid
- **Data quality and management** – quality and upkeep dependent
- **Complexity** – across assets and subsystems
- **Security** – cybersecurity and data security risk

Sources: Demand Response and Advanced Metering (FERC, 2025); Electricity Grids and Secruity Energy Transitions (IEA, 2024), What is advanced metering infrastructure (AMI) (IBM, 2026).
Credit: Helin Tilkicioglu, Hasan Alawadhi, Isabel Hoyos, Hyae Ryung Kim, Dominica Wambold, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Effective policy for digital twins targets system-level design to deliver savings and reliability as part of a smart grid strategy

Indian utilities enhanced grid operations by implementing substation digital twins

Percent savings per use case on each transformer

55%
Curtailment Cost Reduction

45%
Voltage Stability Cost Reduction

India: Digital Twins for enhanced distribution grid operation and management, implemented by Panitek Power under UNEP/IEA 3DEN Phase I, reduced utility technical and commercial losses

- Smart meters and sensors on 23 feeders across 4 substations enabled corrective action to improve asset utilization ($16K) and reduce energy losses ($36K/yr) per unit

Korea's state-run utility used digital twins in a smart grid to reduce its power costs[1]

Percent of annual electricity purchasing cost reduction

78%
Revenue Capture Savings

22%
Asset Utilization Savings

Korea: An AI-based power grid mgmt. system deployed by KEPCO enables safe integration of low-cost renewable sources and GETS through digital twin orchestration, increasing profitability

- Expected to reduce electricity procurement costs by $73.4M+ annually, improve efficiency and stability, and enable increased EV and renewables adoption

Regulators can unlock grid asset value with interoperable, secure digital twins

Near-term actions

- Define and mandate **interoperability standards** for grid digital twins to drive **system-wide optimization** and maintain a competitive vendor environment
- Establish **regulatory cost-recovery frameworks** to incentivize utility adoption (rate base inclusion)
- EMDE: Leverage IEA 3DEN to fund and scale pilots

Forward-looking opportunities

- As digital twins mature, **require their inclusion** and documentation with interconnection
- Establish and enforce **secure open-data exchange** governance models for orchestration technology
- **Prioritize data security**, interoperability, and public benefits for aspects supported by public finances

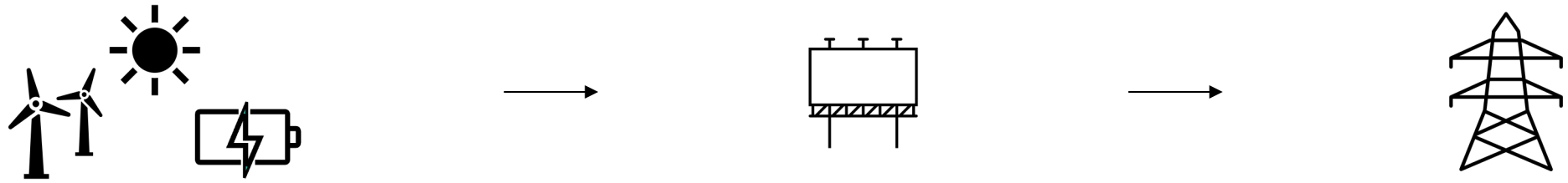
System-level benefits

- **5-10% estimated cost reduction** from Operations & Maintenance (O&M), in addition to outage reduction
- **20-30%** improved capital efficiency & operational performance of infrastructure upgrades with digital twins

Sources: 3DEN Phase I Case Studies (IEA, 2026); Digital Twins (McKinsey, 2025); Digital Twin in Energy & Power Market Size & Share (Global Market Insights, 2026); KEPCO deploys AI-powered grid system to cut annual power costs by $73 mil. (The Korea Times, 2026), Korea advances five strategies for Energy, AI shift.(DBR, 2026); Digital Twin Grid (WEF, 2026).

Credit: Dominica Wambold, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Grid-forming inverters paired with intermittent energy sources and battery enable the stability support critical for grid reliability



1. **Power generation & battery storage**
2. **Grid forming inverter (GFM)**
3. **Utility scale grid**

How do Grid-Forming Inverters (GFM) work?

1. GFMs **connect to inverter-based resources** (IBRs) like solar panels, wind systems, or batteries to **transform electricity from DC to AC** for grid integration in non-synchronous systems
2. GFMs adopted in place of Grid Following Inverters (GFLs) improve grid operations. While GFLs only match grid voltage and frequency, **GFMs enable active control of the AC output** through advanced power electronics
3. **GFMs enable grid stability** in by offsetting the loss of inertia from synchronous, turbine-based sources
   Advantages over GFLs:
   - A voltage source **independent of the grid**
   - **Frequency support** during a disturbance
   - **Monetizable** synthetic inertia
   - **Bi-directional** control
   - **Black start** capabilities

Why is it critical for the energy transition?

- **To integrate non-firm, synchronous power sources**, the grid needs an alternative source of stability
- Allow **high penetration of renewable**, non-synchronous energy sources in a grid
- Installing GFMs in place of GFLs as the default selection can **strengthen the overall grid**
- GFMs are required for renewable resources and batteries to be **compensated for inertia services**

Advantages

- Enables renewables and battery grid integration >60%
- Provides the hardware basis for **inertia services**
- Are **cost-competitive and** mature enough to deploy
- Procurable via **existing OEM supply chain**

Disadvantages

- **Incremental cost** (firmware, PCB, sensors, testing)
- **Integration resistance,** considered “emerging tech”
- **Without policy**, OEMs **lack demand signal** to ramp at scale and reduce premiums
- **Increased lead times** as supply chain is developed

Sources: Getting the Grid to Net-Zero (IEEE Spectrum, 2024); Introduction to Grid Forming Inverters (NREL, 2024); Optimization of power management in PV-based smart grids using grid-support and grid-forming inverters (PLoS, 2026).

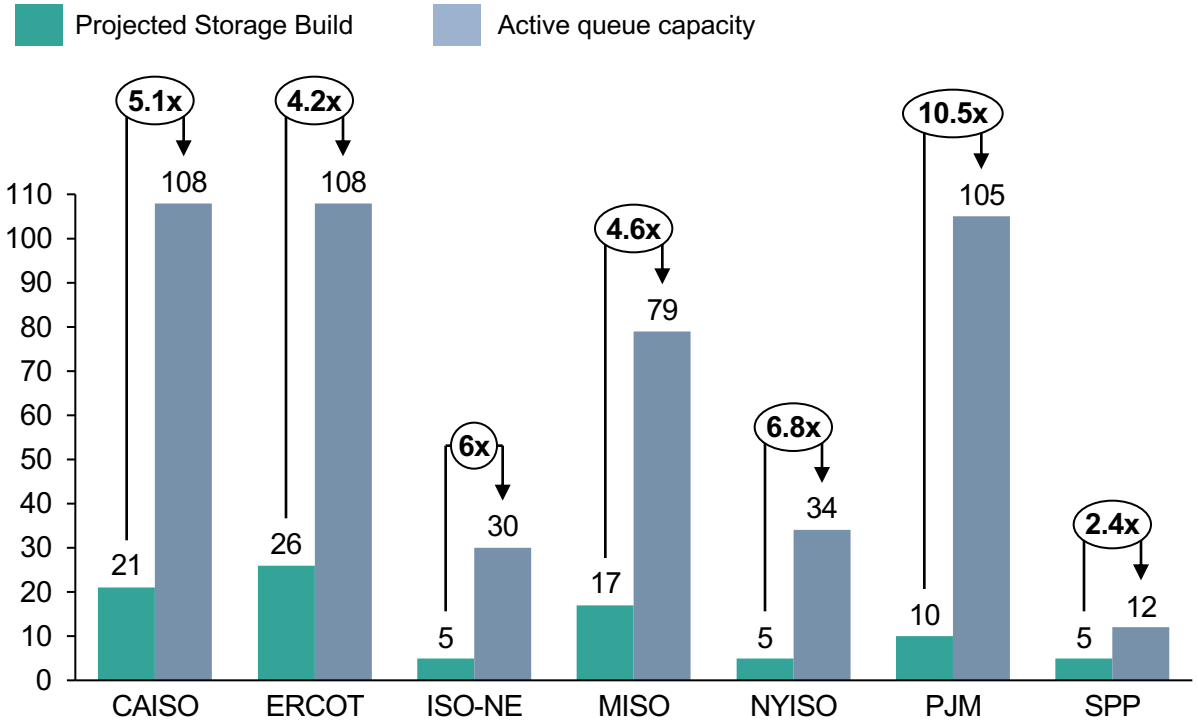
Credit: Dominica Wambold, Sevgi Helin Cikicioglu, Stephanie Chen, Pia Doris Morrow, and Gernot Wagner. Share with attribution: Wagner *et al.* “Powering Grids,” Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Mass adoption of grid-forming inverters is required to connect the pipeline of available energy resources to the grid

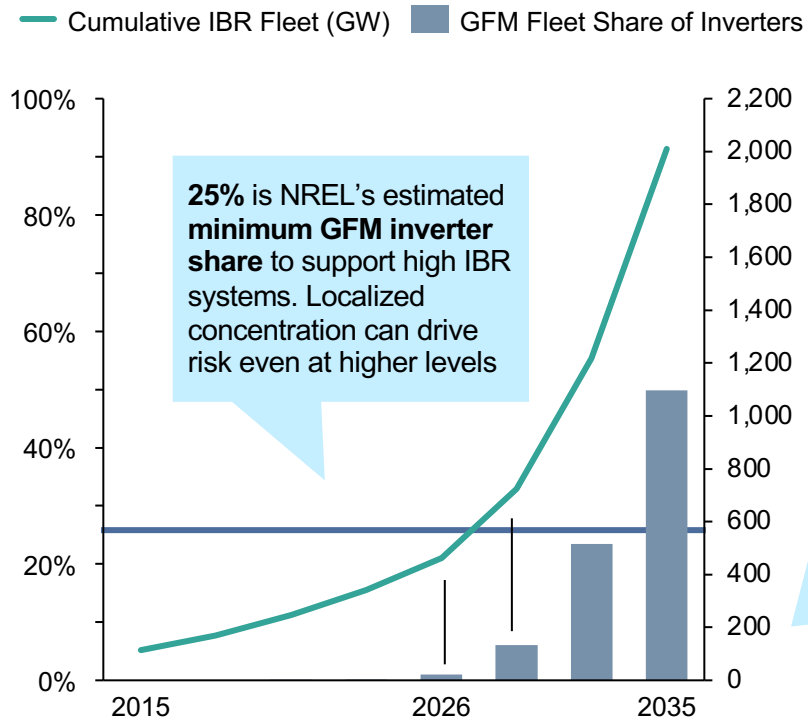
Requiring GFMs for energy storage in the active queue is critical to safely deploy this capacity into the grid

U.S. projected build through 2032 vs. active queue capacity, GW



Organic GFM deployment pathways do not meet NREL's safe minimum share of 25% for systems with 60%+ IBRs

U.S. IBR Capacity (GW) vs. GFM Inverter Share (%) Projections, 2015-2035



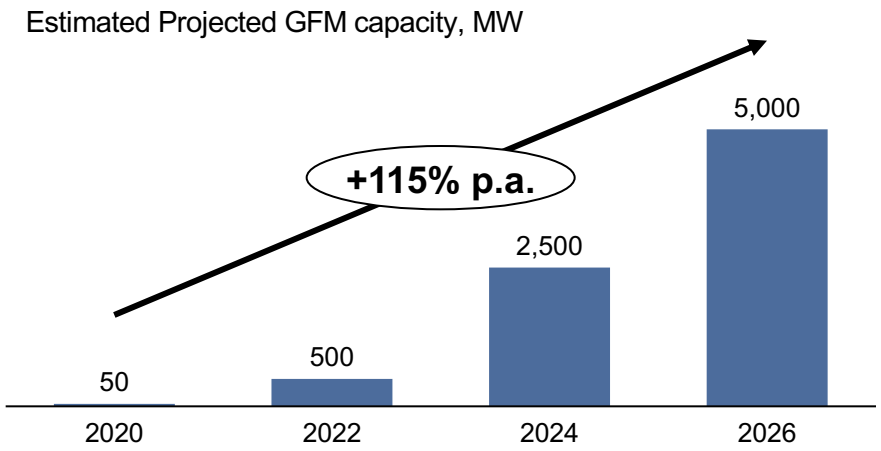
- Annual IBR capacity additions to the grid **exceed 90%** of all net-new grid energy resources
- Even anticipating NERC enforcement of reliability standards, current GFM adoption is **not sufficient** to ensure stability
- Nationwide, GFMs would remain **well below the 25% threshold** through 2033

The historic trajectory reflects true organic growth, with no regional or national mandates or enforced standards in place prior to 2026, while the projected trajectory anticipates an uplift from the 2026 ERCOT and 2027 Southwest Power Pool mandates for new inverter-based resources as well as the initiation of enforcement under FERC directives and NERC requirements for PRC-029-1 compliance. Projections proceeded 2026 U.S. supply chain restrictions on Chinese-made grid-firming inverters. Sources: US storage sector outlook (Wood MacKenzie, 2024); Queued Up (Lawrence Berkeley National Laboratory, 2026); Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035 (NREL, 2022); Electric Power Monthly Tables (U.S. EIA, 2026); FERC Order 901 Directives Mapping (NERC, 2026). Credit: Dominica Wambold, David Foye, Petr Jenicek, Birru Lucha, Hasan Alawadhi, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Policy is the most effective lever to enable GFM deployment, while market design and unified standards can unlock private financing

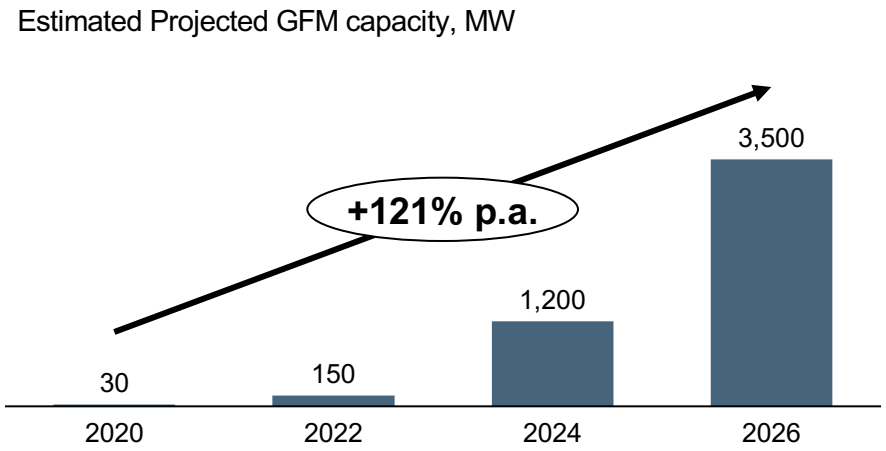
U.K.'s stability pathfinder program incentivized adoption through market creation and reform



Market Design & Unified Standards,
Subsidy-free policy lever

- Advance and adopt unified GFM standards
- Expand Ancillary Services market frameworks to include compensation for inertia and voltage support
  - Why: Enables debt financing without subsidy by providing predictable cashflows
  - Viability: Best addressed at national level, critical at the local level where instantaneous IBR generation can exceed 60%

Australia's system strength mandate focused on weak areas following a major blackout



Regulatory Mandate,
Interventionist option, where feasible

- Convert recommendations for GFMs to binding interconnection requirements for batteries and solar and wind generated electricity
- Adopt system-level integration requirements
  - Why: Sends demand signal to OEMs to scale, reduces cost
  - Viability: Likely only in high IBR penetration markets and best applied with burn-in time for supply chain readiness

Observations

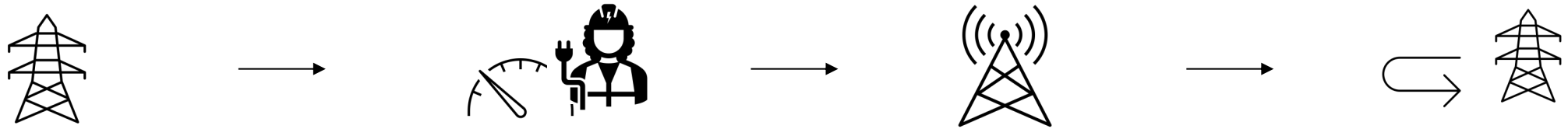
- Recommendations vary between system types, given the difference in generation ownership and general policy architectures and incentives
- In the U.S., ERCOT is leading out of necessity – NOGRR282 combined with a $1,500 incentive (implemented this year) are among measures intended to address the major risks that high battery and solar deployment have placed on the system
- In ISO/RTO areas, enforcement of FERC recommendations would help address the growing system risk, in line with Level 3 alert
- Globally, systems have tended to adopt GFM following a crisis, rather than proactively, incurring financial and reputational losses while setting back IBR adoption

Sources: White Paper (NERC, 2023); IEEE (2022); Stability Network Services (UK National Grid, 2026); Stability Pathfinder Phase 2 (National Grid, 2024), Sungrow (Energy Storage News, 2026), Grid-forming technology access standards technical requirement reviews (AEMO, 2025), Batteries continue to dominate NEM connections as pipeline grows (AEMO, 2026).

Credit: Dominica Wambold, Ariela Farchi Cohen, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Flexible AC transmission systems are critical, stabilizing power flow and voltage in real time for safe and reliable grid operations



1 **Transmission Line**

2 **FACTS systems**

3 **Controlling**

4 **Stabilizing Transmission**

How do FACTS for grid systems work?

1. When demand changes, **renewable output fluctuates**, or a line approaches its limit, causing **voltage drops, overload risk, or unstable power flow**
2. FACTS control systems **measure voltage, current, and phase angle,** and detect deviations from normal operating limits

   This helps controllers determine whether **power must be injected or absorbed, or redirected**
3. **High-speed electronic valves** switch on or off, changing electrical conditions on the line by **adjusting voltage support or line impedance**
4. The correction **prevents overloads, stabilizes voltage**, and allows **more power to flow safely** through the network

Why is it critical for the energy transition?

- **Allow operators to actively control power flow and voltage in real time**, allowing existing AC transmission lines to operate more effectively
- Provide fast, dynamic control that helps **integrate renewables without waiting for new transmission lines**
- Reduce the need for grid expansions by **increasing the usable capacity of existing infrastructure**
- Play a critical role in **congested corridors and renewable-heavy regions**

Advantages

- **Increases line capacity**: Better utilization
- **Reduces congestion**: Optimized flow
- **Avoids need for new lines**: Faster deployment

Disadvantages

- **High capital cost**: Device costs
- **Complex control systems**: Advanced software
- **Specialized maintenance**: Skilled workforce

Sources: How Advanced Transmission Technologies Can Revamp the US Power Grid (WRI, 2025); VPP Liftoff Report (DOE).

Credit: Sevgi Helin Tilkicioglu, Hasan Alawadhi, Pia Doris Morrow, Vincent Sandow-Straesser, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

FACTS devices reduce transmission bottlenecks and reliability risk by controlling power flow and voltage

VSC-based[1] | Thyristor-based[2]

Flexible AC Transmission Systems (FACTS)[3]

Category	System	Operational / investment value	Deployment maturity
Series Control line impedance or inject series voltage to manage line loading	**SSSC** – Static Synchronous Series Compensator **TCSC** – Thyristor-Controlled Series Capacitor **TSSC** – Thyristor-Switched Series Capacitor **TCSR** – Thyristor-Controlled Series Reactor	Helps operators relieve overloaded lines by shifting power flows across the network. Useful where congestion is recurring and new transmission is slow, expensive, or difficult to permit	
Shunt Inject or absorb reactive power to regulate local voltage	**STATCOM** – Static Synchronous Compensator **SVC** – Static VAR Compensator	Helps operators maintain voltage stability during heavy load, renewable output swings, or grid disturbances. Useful where voltage limits are blocking new load or renewable interconnection	
Combined series-shunt Coordinate series and shunt control to manage power flow and voltage	**UPFC** – Unified Power Flow Controller	Provides high-control capability on critical corridors by managing both line flow and voltage from one installation. Useful where a single constrained corridor has high reliability or congestion value	
Combined series-series Coordinate power flow across multiple transmission lines	**IPFC** – Interline Power Flow Controller	Helps operators balance loading across multiple transmission lines in the same corridor. Useful where one path overloads while nearby lines remain underused	

[1]Uses voltage-source converters. It is fast and flexible. [2]Prove technology, mainly used to control voltage (reactive power), less flexible. [3]Selected not exhaustive

Source: SVC PLUS (STATCOM) (Siemens Energy, 2025); Static Var Compensator (SVC) (Hitachi, 2025); Thyristor controlled series compensation (Hitachi, 2025); FACTS (ABB, 1999); Fixed series compensation (Hitachi, 2025); Unified power flow controller (Astrophysics Data System, 2001); Phase shifting transformer (PST) (Entsoe, 2025); Flexible AC Transmission System (EEP, 2015).

Credit: Sevgi Helin Tilkicioglu, Stephanie Chen, Hasan Alawadhi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Leveraging FACTS can lower capital and reinforcement costs by increasing capacity without building new lines

PG&E leverages reduced grid strain to support firm loads amid 1.4 GW of planned data center demand

San Jose, California, USA



Challenge

- Data centers are **projected** to add more more then **1.4GW of grid load**
- **No** near-term **plan for transmission expansion**
- **Maintain reliability** meeting NERC criteria

Solution

- **Redirect power flow** to underutilized lines and **increase available capacity**
  - Faster than reconductoring or energy storage

Outcomes

- Boosted **capacity** by **+100MW**
- Immediate **transfer relief**
- Created headroom for **510MW of firm load**
- **Solution is scalable** for future grid enhancements

National Grid unlocked significant transfer capacity to relieve bottlenecks and enable clean energy generation

England, United Kingdom



Challenge

- North-south boundary congestion **limited power flows** to **high-demand areas**
- An **evolving power flow network** is leading to inefficient use of infrastructure

Solution

- The Network Innovation Alliance (NIA) co-funded a project to:
  - **Ease network constraints**
  - **Boost clean power** flow into the grid
- Resolve key bottlenecks by **routing power to circuits where there is available capacity**
- Identify **best locations for GETs**

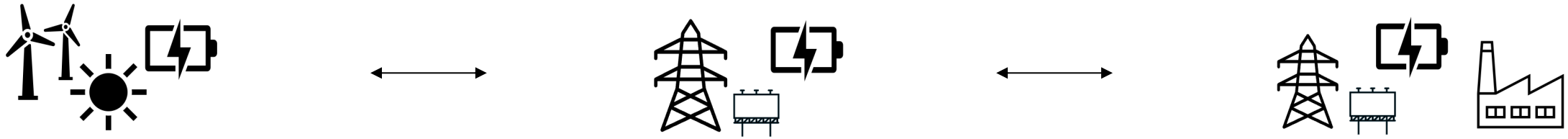
Outcomes

- **~$430M new infrastructure and constraint savings** over a 7-year period
- **~$445M consumer cost savings**
- **2GW** additional boundary capacity

Sources: PG&E San Jose project (Smart Wires); PG&E and Smart Wires enhance reliability (Smart Wires); National Grid to reduce grid bottlenecks (Smart Wires); NGET boundary project (Smart Wires).
Credit: Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Grid-scale batteries offer storage solutions for intermittency, transmission and distribution nodes, and reserve capacity



1. **Batteries + Intermittent Generation**
2. **Batteries + Transmission (SATA[1])**
3. **Batteries + Distribution**

How do grid-scale batteries work?

1. **At Generation** - co-located with intermittent generation charge during peak production and discharge during evening ramp, **reducing the need for curtailment** while **producing a more predictable grid energy source**
2. Storage as a Transmission Asset (**SATA**) - using **grid-scale storage at weak or congested nodes to reinforce and strengthen** the existing transmission network
3. **Nodal reinforcement at Distribution** - supports **localized grid resilience** and manages extreme load swings from clustered private assets or industrial manufacturing at the substation level **without overloading transformers**

Battery Energy Storage Systems (BESS) and Long-Duration Energy Storage (LDES) are **among the most scalable type of grid-scale storage.**

Why is it critical for the energy transition?

- Pairing battery with renewable sources **increases their ease of integration** and **value to grids and generators**
- Solar + storage is the **fastest energy technology to deploy**, enabling it to capture investment and meet rising electricity demand
- Increasingly attractive for **capacity and reserve functionality** as cost and ease of digital integration improve due to location **flexibility and fast-response capabilities**
- **LDES as an alternative** to new natural gas peaking capacity can **avoid stranded asset buildouts** with better scalability and flexibility

Advantages

- **Reduces curtailment:** Higher system value
- **Baseload matching:** Combined with VREs
- **Smoothing the curve:** Via energy shifting
- **Multi-purpose**: Offer peak shaving, load smoothing, and grid stability services (with GFMs)
- **Reduced CapEx:** With nodal reinforcement

Disadvantages

- **Revenue uncertainty:** Highly dependent on electricity market compensation mechanisms
- **Duration constraints:** For cost competitive technologies (though improving)
- **LDES cost profile:** Dependent on subsidy

[1]Storage as a transmission asset

Sources: How battery storage could unlock the grid and make power more affordable (World Economic Forum, 2026); Energy Storage Enters the 100 Gigawatt Era (BNEF, 2026), Why batteries are the electric grid's most powerful asset (SEIA, 2025), Grid Scale Storage (IEA, 2024).

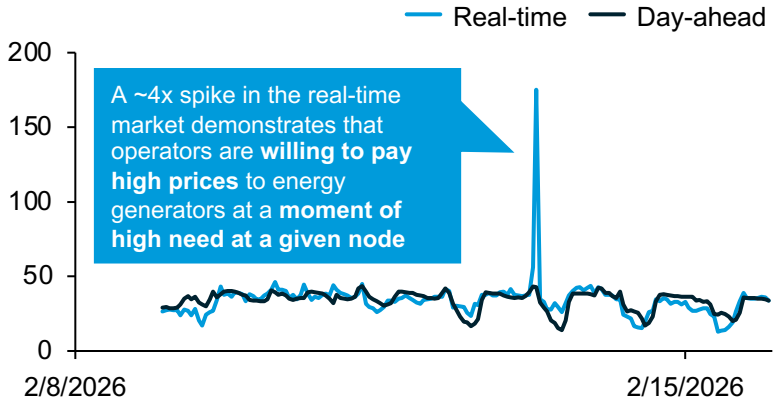
Credit: Dominica Wambold, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Locational Marginal Pricing (LMP) is a great efficiency mechanism and incentive for battery storage, as demonstrated by CAISO

LMPs are based on the need at a node, showing when/where demand is high

Hourly LMP at DLAP_PGAE node in CAISO, $/MWh, Feb 9 – Feb 16 2026

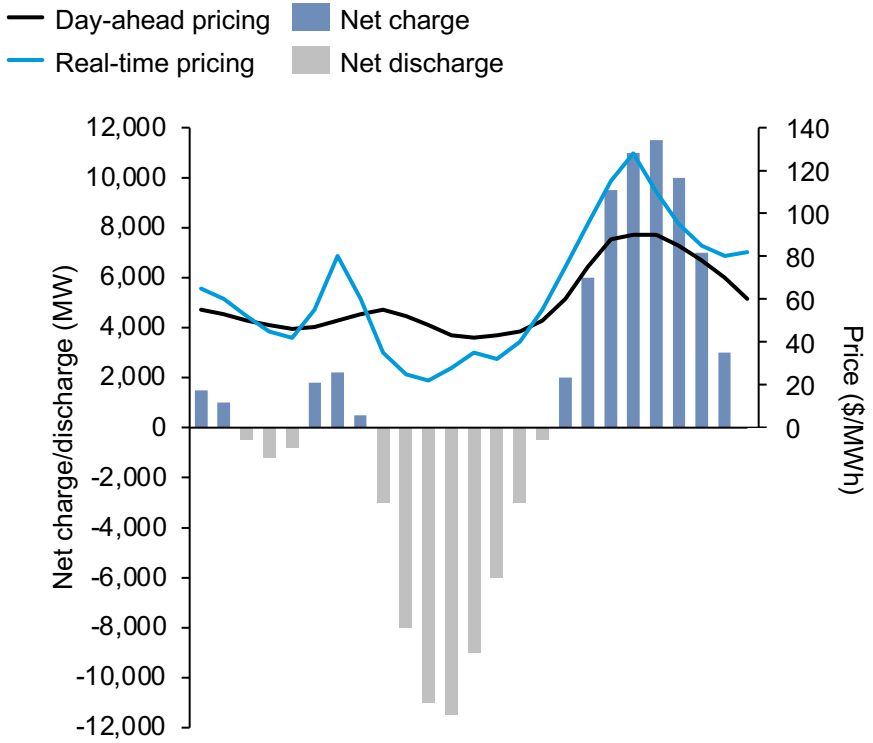


Clearing price at one location (node) is determined by:

- Cost of the next **marginal system-wide generation unit** at any given moment
- **Congestion relief** at a node i.e. if injecting power at one node relieves congestion, the price is higher
- **Transmission loss reduction** i.e. if injecting power at a node reduces overall loss, the price is higher

CAISO's LMP allows batteries to charge when prices are low (or negative) and discharge when prices are high, playing a key role in enabling profitable storage deployment

Net storage (MW) v. LMP in CAISO ($/MWh), Illustrative



LPM as a market enabler:

1. **Creates a business model for battery storage**
   - Volatility and negative prices during solar peaks make co-located batteries profitable through energy arbitrage
2. **Drives generators to internalize real system costs**
   - Congestion and loss costs are embedded in each node's price rather than socialized
3. **Prioritizes renewables and maximizes their returns**
   - Renewables are dispatched first because they have 0 marginal fuel costs
   - When fossils (high marginal fuel costs) set the clearing price, renewables earn the full price despite having no fuel costs
4. **Insufficient as a long-term investment signal**
   - LMPs trend toward zero, eroding the revenue that attracts clean investment
   - Sustained investment requires complementary policy tools: IRPs, PPAs, and capacity markets

Sources: Gridstatus.io, CAISO (Grid Status, 2026); 2023 Special Report on Battery Storage (CAISO, 2024); Locational Marginal Price (CAISO, 2010); How Congestion Impacts Locational Marginal Pricing (LMP) in CAISO (PCI, 2025); Wholesale Electricity Markets: Is it the LMP, or the LMP Alone? (UPenn, 2023).

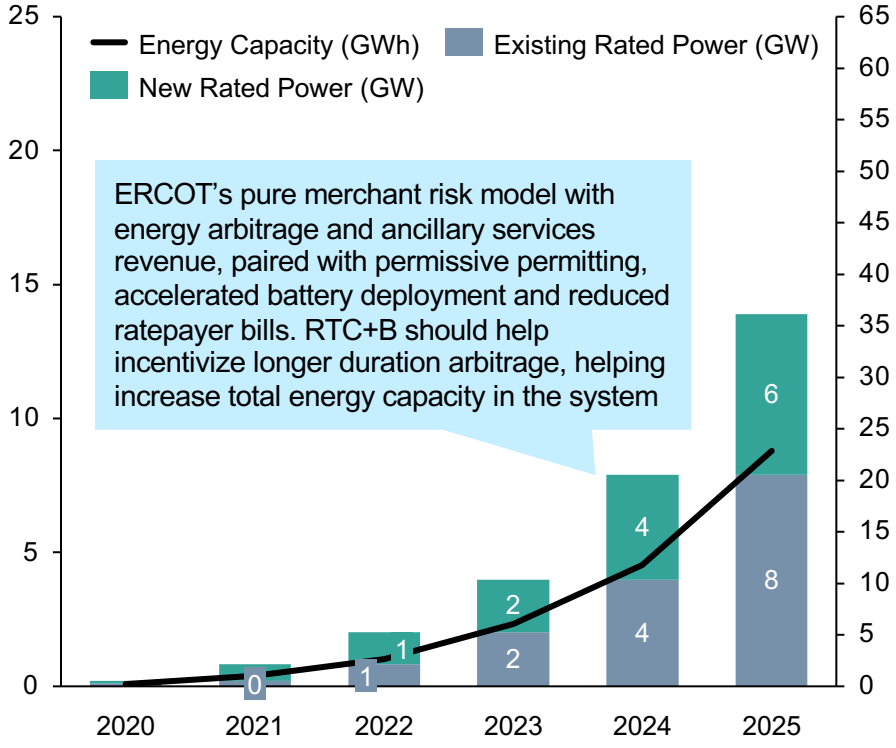
Credit: Hasan Alawadhi, Isabel Hoyos, Pia Doris Morrow, Ariela Farchi, Dominica Wambold, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

ERCOT and CAISO have driven highest U.S. battery deployment; CAISO's contracts helped achieve grid stability with renewables

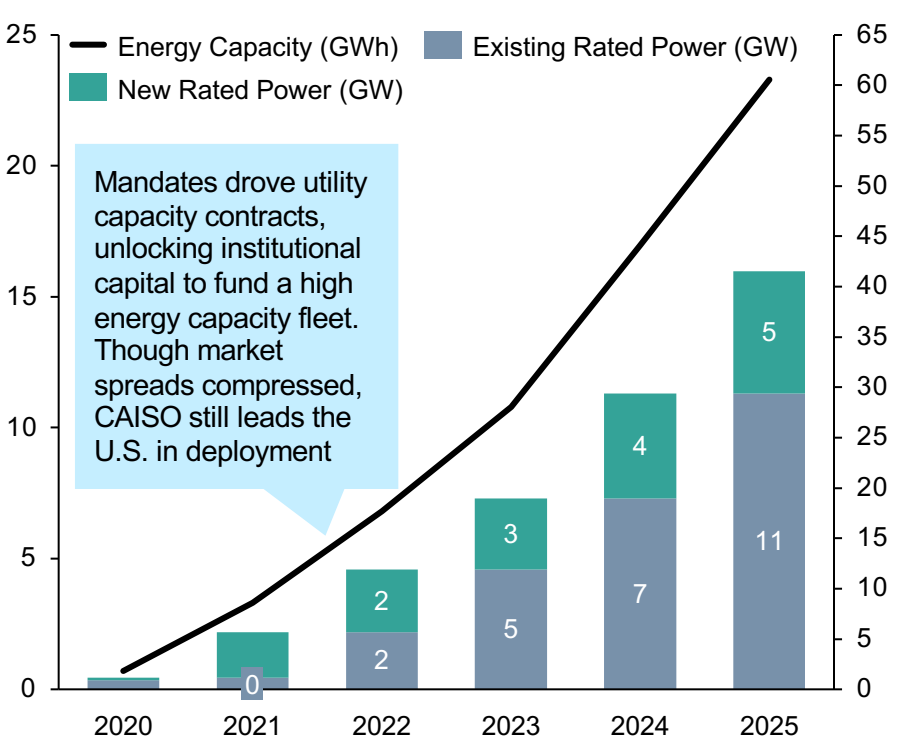
Private investment and arbitrage returns drove high battery deployment in ERCOT

ERCOT Battery Fleet, 2020-2026[1]



CAISO leads battery deployment, surpassing 15GW of rated power in 2025

CAISO Battery Fleet, 2020-2026[1]



Observations

- Battery deployment continues to accelerate as battery cell costs reduce and duration is extended
- The global battery storage market is **expected to exceed $100B in 2026,** led by grid-connected batteries (~80%)[2]
- Batteries can help balance the grid, complement renewables, and lower customer electricity costs
- Regulatory uncertainty, permitting, interconnection delays, and saturation are investor challenges
- Merchant project finance and ancillary markets are key financing mechanisms
- **Tolling** & **hybrid agreements** are emerging, and some developers are shifting towards behind-the-meter, contract-backed deals
- Contracts (capacity, resource adequacy) offer lower risk profiles

[1]Modo Energy reporting cross-referenced with CAISO and ERCOT data, respectively

Sources: ERCOT Annual Buildout Report (Modo Energy, 2026); CAISO battery fleet crosses 15 GW after record 4.7GW year (Modo Energy, 2026); Batteries have reshaped ERCOT's Ancillary Services Procurement (Waldoch, 2026); Understanding Battery Energy Storage Systems (Texas Solar + Storage Association, 2026); Battery storage is scaling up and taking on a larger system role (IEA, 2026); World Energy Investment (IEA, 2026); Special report on battery storage (CAISO, 2025), Gridstatus.io (Grid Status, 2026).

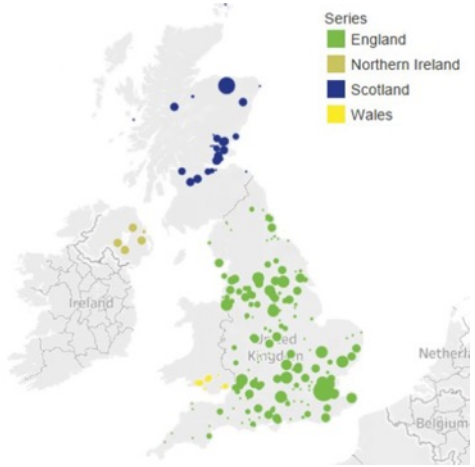
Credit: Dominica Wambold, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Capacity and flexibility market reform, long-term contracting, and R&D support are durable policy levers for grid-scale storage

UK's National Grid awarded GBP323M in 10-yr stability service contracts to BESS

U.K. 2026 battery footprint

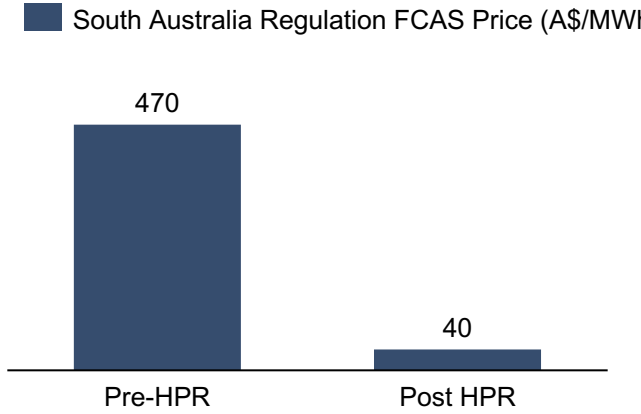


United Kingdom: National Grid ESO awarded GBP323M in 10-yr stability service contracts to utility-scale BESS projects, substituting BESS inertia & reactive power

- Demonstrated the effectiveness of using long-term contracted ancillary revenue to drive private sector BESS project financing; GBP14B target system savings

Australia demonstrated that battery + GFM + renewables reduces costs

Average high of South Australia FCAS regulation price 2016-2017 (pre-HPR) vs. 2018-2019, A$/MWh[1]



Australia: Hornsdale Power Reserve (Neoen/Tesla '17) demonstrated that renewables plus battery storage can substitute for grid-scale synchronous generation services (100MW/129MWh)

- Reduced South Australia's average Regulation FCAS price by ~90% vs. the pre-HRP baseline, bringing SA in line with other regions
- Demonstrated revenue and technical viability

Battery needs speed and standards to connect, and revenue certainty to finance

Near-term actions

- Establish, implement **guidance on battery reliability and standards**, incl. duration-based accreditation
- **Prioritize co-located** storage-plus-renewables **for interconnection requests** and construction starts
- **Expand SATA designation pathways** and capacity market eligibility for storage (e.g., FERC 841)

Forward-looking opportunities

- Establish **BESS/PPA tolling framework** with long-term contracts (aligned with lifecycles) to enable senior debt financing at lower cost of capital
- Reform ISO/RTO capacity markets to create a **storage-specific 'always available' capacity product** that compensates battery firm dispatch

System-level benefits

- **129% revenue growth** for BESS from **multi-stream stacking** vs. single revenue stream
- **<100ms** BESS **response time** v. 6+ seconds for peakers, improving grid flexibility

[1]Hornsdale was a primary catalyst in driving the Regulation FCAS prices down in SA but not all savings should be attributed to Hornsdale. 3rd party analysis by Aurecon (2022)

Sources: Grid Scale Storage (IEA, 2024); Interconnection Final Rule (FERC, 2024); Queued Up (Lawrence Berkeley National Laboratory, 2025); National Grid ESO, Stability Pathfinder Phase 2 (National Grid, 2024); Grid-scale battery energy storage systems (IEA, 2026); Stacking up the storage (Renewable UK, 2025); Hornsdale Power Reserve Expansion Project (ARENA, 2023).

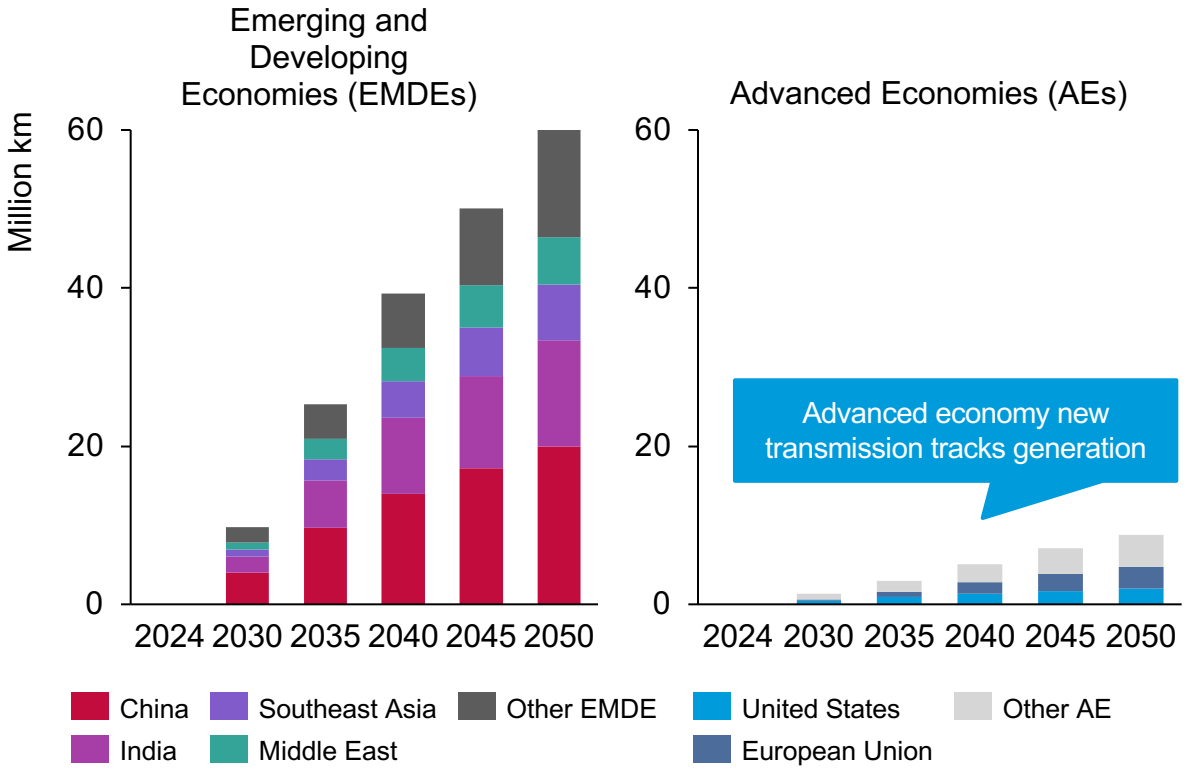
Credit: Dominica Wambold, Ariela Farchi and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Developing economies lead transmission expansion; replacement is a global need across both developing and advanced economies

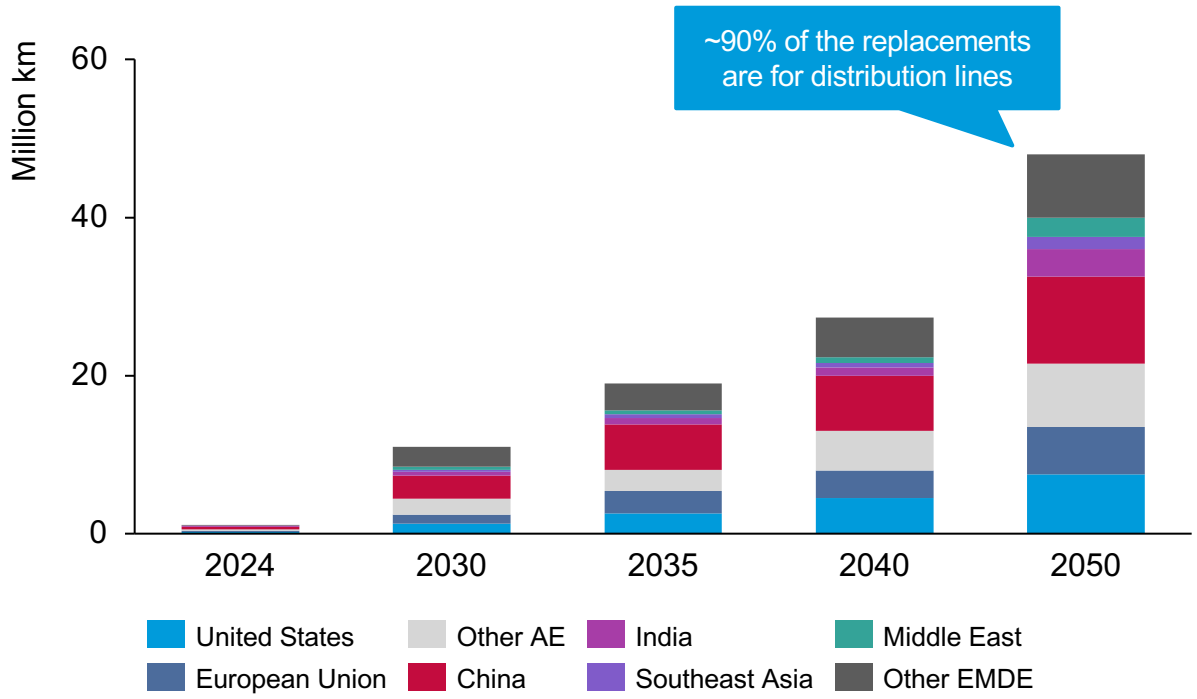
EMDEs[1] require ~60M km of new lines by 2050, driven by ~90% rising electricity demand and ~10% renewables

Expansion of grid lines by driver in selected region/country in the CPS[1], 2024-2050



Globally, 45M+ km of transmission and distribution lines must be replaced by 2050, led by the US and China

Grid line replacement by selected region/country and replacement share of grid additions in the CPS[1], 2024-2050

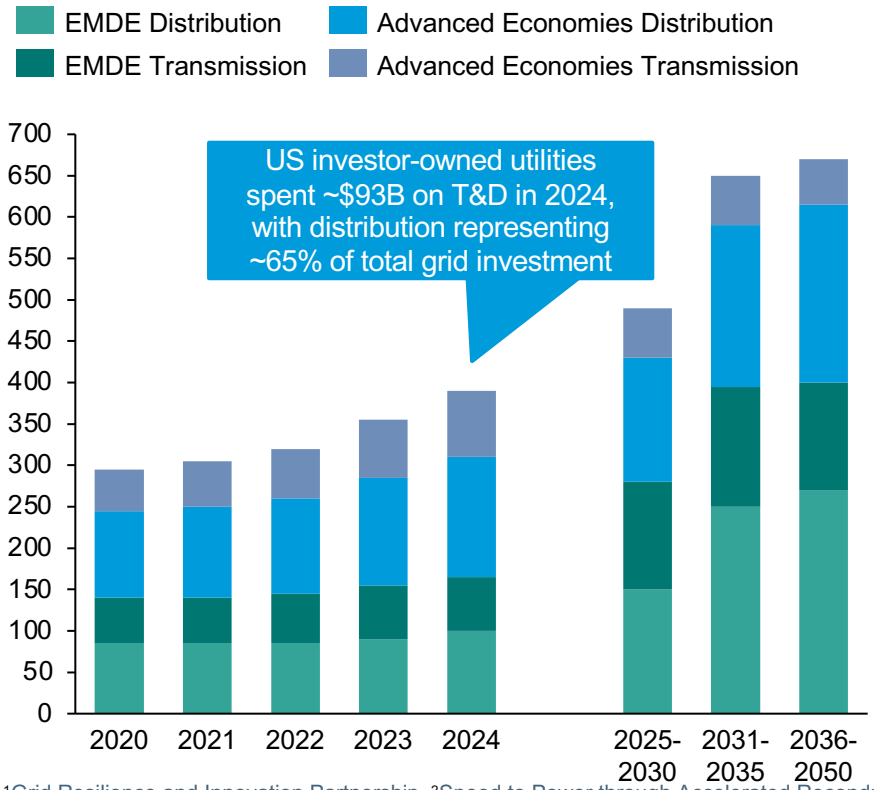


[1]Current Policies Scenario.
Sources: World Energy Outlook (IEA, 2025)
Credit: Ilayda Tezcan, Ariela Farchi and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Grid capex investment is accelerating globally and shifting toward EMDEs; in the US, infrastructure investment remains public-led

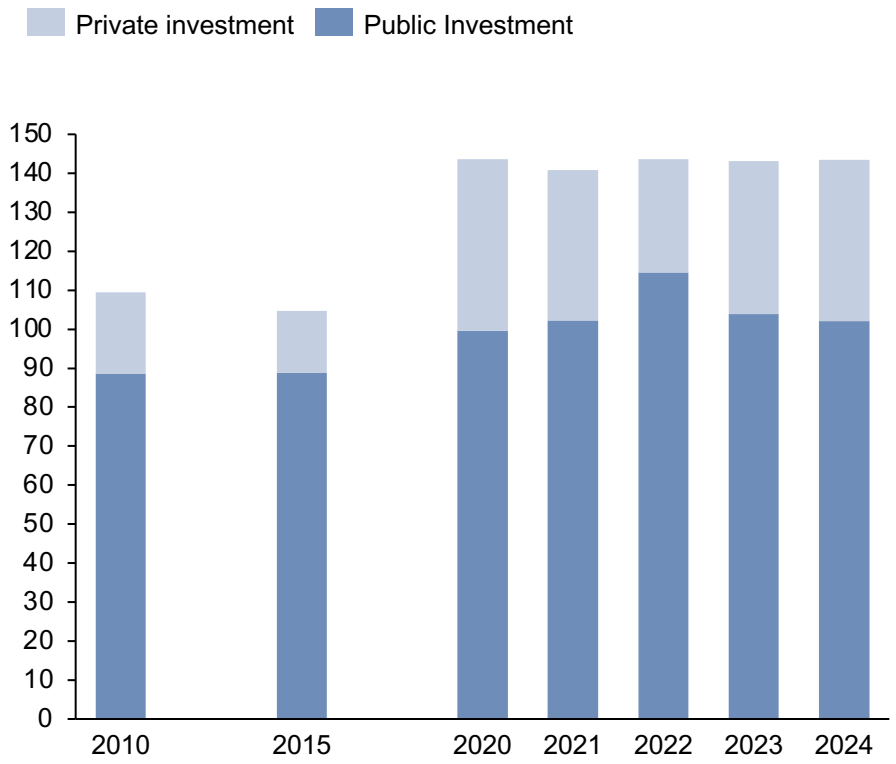
AEs drive grid investment today; EMDEs increase in volume and share by 2030s

Average annual grid investment by economic grouping in the CPS to 2035 (US$B, 2024, MER)



US power infra. investments are mostly public; private share increased since 2010

Private and public investments in US power infrastructure in US$B



Observations

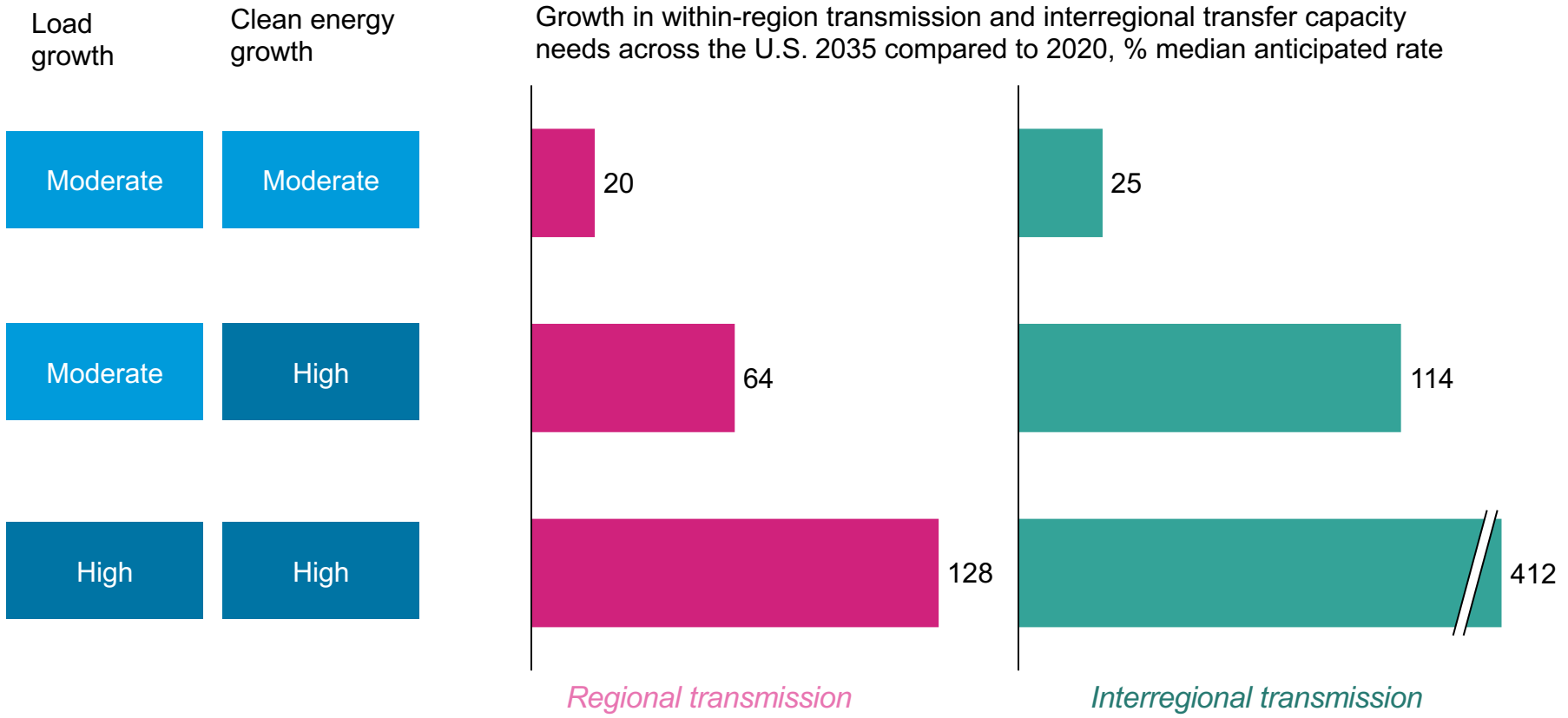
- Near-term grid investment is concentrated in **US, EU, and China**
- As grid investment shifts toward **EMDEs**, **financing becomes harder**:
  - Utilities often face limited tariff recovery
  - Higher cost of capital
  - Bankable regulation and stronger utility balance sheets become critical
- US private investment
  - Increased from **$17.6B to $37.6B** between the 2009-2016 and 2017-2024 periods, raising **private share from 17% to 24%**
- Federal support is targeted rather than fully sufficient:
  - GRIP[1] directs ~$10B for interconnection, modernization, resiliency
  - SPARK[2] adds ~$1.9B for reconductoring and advanced transmission technologies

[1]Grid Resilience and Innovation Partnership. [2]Speed to Power through Accelerated Reconductoring and other Key Advanced Transmission Technology Upgrades.
Sources: World Energy Investment (IEA, 2026), Industry Data (EEI, 2025), Funding the growth in the US power sector (Deloitte, 2025), Electricity Grids and Secure Energy Transitions (IEA, 2023).
Credit: Ilayda Tezcan, Ariela Farchi, Dominica Wambold, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Even under moderate load and clean electricity growth in the US, transmission investment is required, with capacity rising by 20-25%

Energy growth has a major impact on capacity needs across both regional and interregional transmission



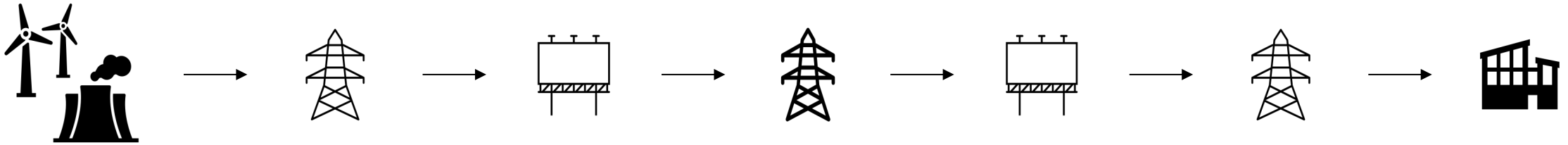
Observations

- **Both regional and interregional transmission capacity requirements increase** by 2035, even under moderate load and clean energy growth assumptions
- Interregional transfer capacity needs rise much faster than within-region transmission, highlighting **the increasing importance of moving power across regions rather than only strengthening local grids**
- Scenarios with **high clean energy growth show substantially higher** transmission needs
- As clean electricity growth is the main driver of capacity demand, **growth in nuclear and geothermal is critical**

Source: National Transmission Needs Study (US DOE, 2023).
Credit: Sevgi Helin Tilkicioglu, Ariela Farchi, Isabel Hoyos and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

High Voltage Direct Current enables multi-GW power transfer over thousands of kilometers efficiently



How do HVDC Transmission Lines work?

1. A converter station transforms AC into direct current (DC), which flows in one steady direction, **making long-distance transmission more efficient**
2. In HVDC lines the DC power moves through a line with **lower losses, better controllability, and greater efficiency** than an equivalent AC line
3. A second converter station changes the DC back into AC so it **can be used by the local grid**

Why they are critical for the energy transition?

- HVDC can move **large loads of power over long distances** with lower losses and precise control
- Makes it practical to **connect remote renewables** (offshore wind, desert solar, large hydro) **to distant demand centers**
- By reducing losses and unlocking large-scale renewables, HVDC **cuts the need for fossil generation and extra backup capacity**

Advantages

- **Efficient for long distance:** Lower losses
- **Ability to connect asynchronous** (different frequencies)[1] **systems:** Grid bridging
- **Suitability for underwater applications:** Subsea capable
- **Ability to handle longer periods of overload operations:** Stable transfer

Disadvantages

- **High upfront cost:** Major investment
- **Greater complexity in components:** Advanced equipment

[1]AC grids must stay synchronized with same frequency and timing. When two grids run at different frequencies (e.g., 50 vs 60 Hz) or aren't in sync, a direct AC connection would be unstable and HVDC interconnection via DC conversion would be needed

Source: Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation (EIA, 2018).

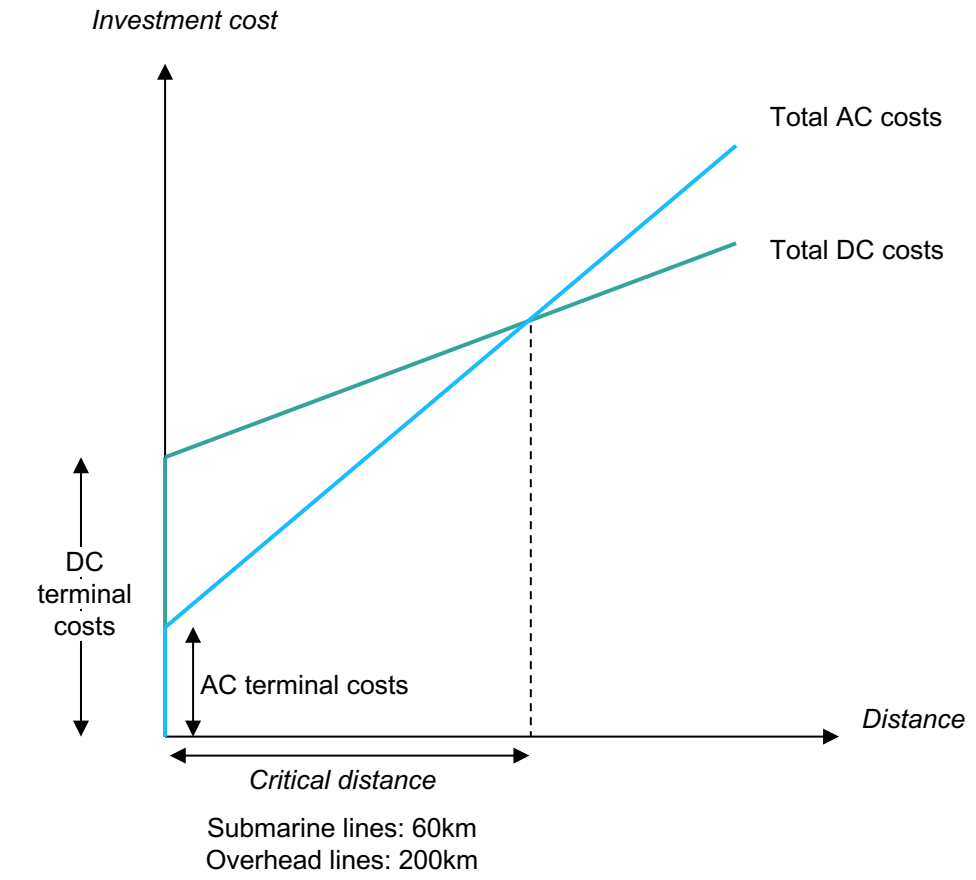
Credit: Sevgi Helin Tilkicioglu, Hasan Alawadhi, Pia Doris Morrow, Vincent Sandow-Straesser and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

HVDC benefits are realized with longer corridors, improving efficiency, lowering costs per delivered MWh

	HVAC (AC transmission)	HVDC (DC transmission)
How does it work?	• Electricity **changes direction** 50/60 times per second	• Electricity **flows one way** continuously going in one direction
How easy is it to connect to today's grid?	• **Very easy** - plugs in directly to existing AC • **Needs voltage control** and reactive support (FACTS tools) along the route	• **Needs converters** at each end, but then it can **connect** into asynchronous systems • Converters are expensive, but **HVDC lines** can be **simpler for long transfer**
How controllable is the power flow?	• **Less controllable**	• **Set and adjusted directly by the converters**
When does it make more sense?	• Usually best for **short to medium distances**	• Often best for **very long distances,** especially when moving bulk **power across regions**
What's the cost profile?	• **Lower upfront terminal cost**, but may **need more grid reinforcements**/reactive equipment as distance grows	• **High upfront cost at the ends** (converter stations) but **can be cheaper per delivered MWh** for long routes • Cost components (2017)**: 16% transmission line, 83% infrastructure, 1% services/other**

AC and DC lines cost comparison by distance



Source: Review, Special Report 60 years of HVDC (ABB, 2014); Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation (EIA, 2018).
Credit: Sevgi Helin Tilkicioglu, Hasan Alawadhi, Pia Doris Morrow, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Policy is critical for HVDC, with supportive environments enabling a low cost of capital and streamlined deployment across regions

U.S. Grain Belt plans halted by loan and permitting challenges

Description

A **542-mile (600 kV) HVDC line**, linking the **SPP, MISO, and AECI** grid regions to wind generation in Missouri

Cost

- **Phase 1 total cost ~$4.4B**.
- **Conditional DOE loan guarantee of up to $4.9B** to anchor private financing (Nov. 2024)
- **$1.7B in construction contracts** (May 2025)

Political involvement

- **DOE terminated the $4.9B loan guarantee** (July 2025)
  - Citing a speculative revenue model and non-binding utility contracts
  - Construction delayed
  - now seeking fully private financing to proceed

China's record-setting HVDC line transmits mostly coal power

Description

The Changji-Guquan (Zhundong-Wannan) UHVDC line **transmits coal, wind, and solar power 3,324 km.** At 12 GW capacity, it is **the world's highest-voltage, longest-distance HVDC line**

Cost

Total investment **~$7.2B (50B yuan)**
State-funded under NDRC approval

Political involvement

Commissioned in 2018; in 2024 transmitted **~55% coal-fired** electricity, **despite renewable energy mandate**

- **Provincial governments** at both sending and receiving ends **insist on guaranteed coal** operating hours as a financial condition, crowding out renewables

Australia's link, with joint local gov. ownership, promotes renewables

Description

Marinus Link in Australia is a **750 MW HVDC 345 km undersea and underground** interconnector, enabling **bi-directional flows of** Tasmania's **hydro/wind** and mainland **solar**

Cost

- Stage 1: **~$5B AUD** (2026-2030)
- Stage 2: **subject to future funding**
- **CEFC committed $3.8B in concessional finance** (Sep 2025) under the Rewiring the Nation program

Political involvement

- Joint government ownership: Commonwealth (49%), Victoria (33.3%), Tasmania (17.7%)

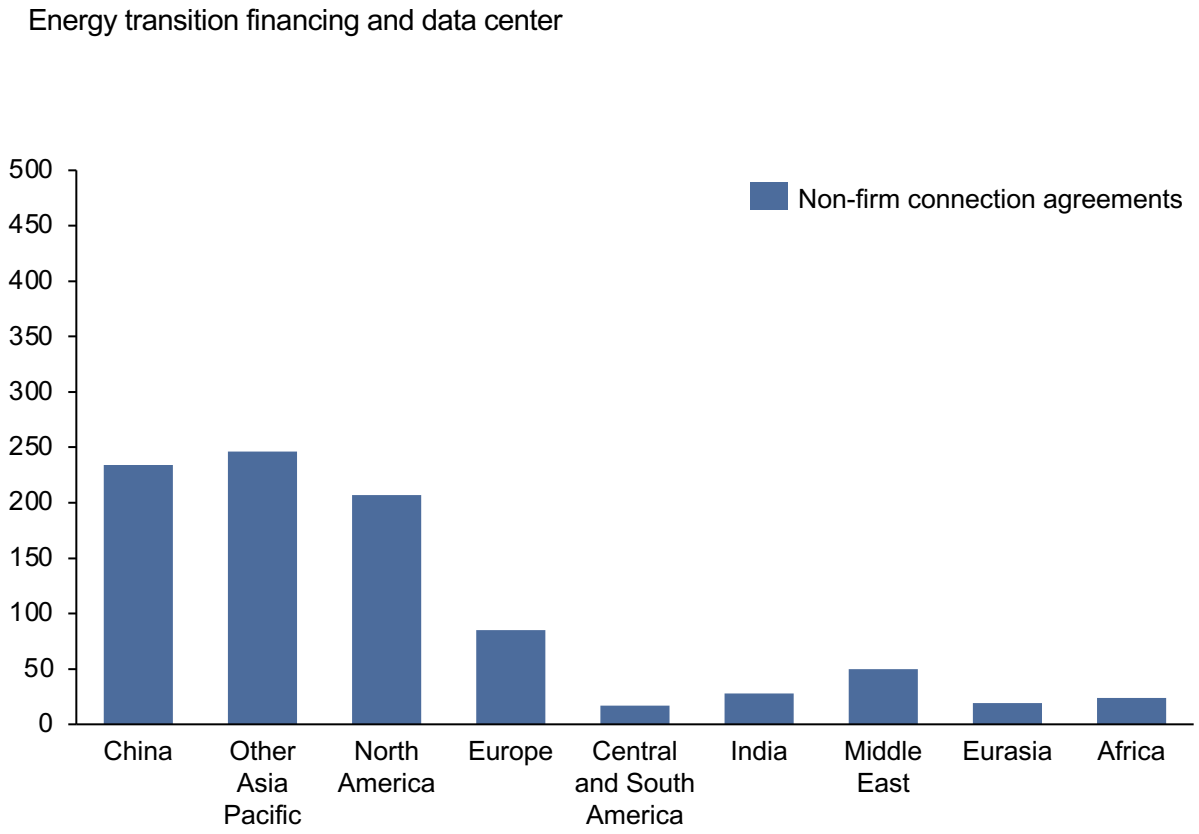
Sources: State high court rejects challenge to wind generated transmission (Capitol News, 2026); Department of Energy Terminates Taxpayer-Funded Financial Assistance for Grain Belt Express); DOE cancels $4.9B conditional loan for Grain Belt Express (Utility Dive, 2025); Grain Belt Express is the Latest FAST-41 Covered Project (Permitting dashboard, 2024); Changji-Guquan UHVDC five-year commissioning (China Daily, 2024); Trends and Contradictions in China's Renewable Energy Policy (CGEP, 2025); China struggles to capitalize on record renewables build-out (Japan Times, 2025); Done right, China's UHV grid can help phase out coal (Dialogue Earth, 2026); CEFC to invest in visionary Marinus link project (CEFC, 2025).

Credit: Christy Wong, Ariela Farchi, Dominica Wambold, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

The ~$7T of projected data center capital flows by 2030 can be instrumental in developing and deploying grid technologies

Data center capital flows reached ~$500B in 2025



Data center investments into key grid technologies can accelerate grid deployment and renewable integration

Optimize

- AI data center workload management and flexibility present new models for large load flexibility and demand response optimization
- Optimized technologies provide a key opportunity for joint financing arrangements, bridging Corporate and traditional VC, PE, and utilities
- Google and Voltus demonstrate successful BYOC commitments to enable customer Virtual Power Plant integration

Modernize

- Major utility investment priorities to upgrade existing grid infrastructure represent cost-effective opportunities for data center integration
- Data center investments can accelerate deployment of grid-scale battery and power electronics,(e.g., grid-forming inverters and FACTS)
- Achieving system-wide orchestration through advanced metering infrastructure ‘2.0’ and implementation of digital twin solutions advances both grid modernization and the feasibility of grid-connected data centers

Expand

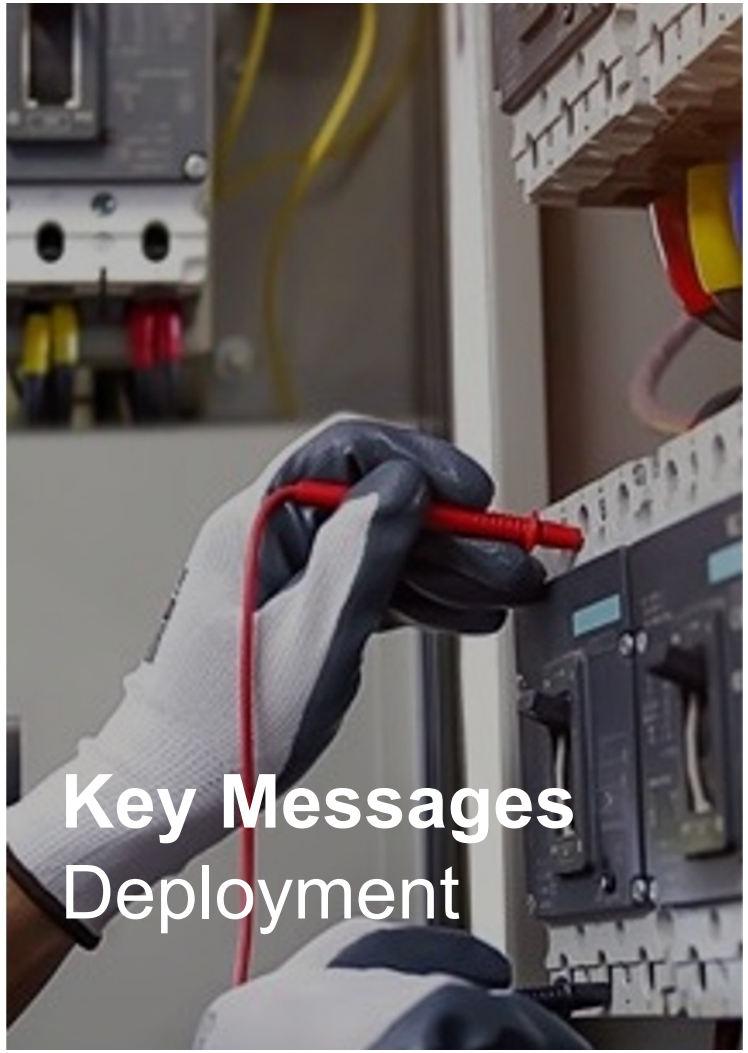
- The urgency of data center power demand and value derived from grid connectivity creates a strong incentive to integrate available IVR supply
- Hyperscaler risk capital provides a critical alternative to federal subsidy for the development and integration of clean firm power sources
- Case studies in Australia, the U.K., and the U.S. demonstrate successful collaboration models for data centers and grid expansion

Sources: 2026 Energy Investment Trends (BNEF, 2026); The $7 trillion data center build-out: how industrials can capture their share (McKinsey and Co, 2026).
Credit: Dominica Wambold, and Gernot Wagner. Share with attribution: Wagner *et al.* “Powering Grids,” Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative



Deployment



Optimizing existing infrastructure can unlock grid capacity faster than building new assets

- Demand flexibility and grid-enhancing technologies can **increase available capacity** while **reducing** the need for **costly, time-intensive infrastructure expansion**
- **Voltus and Google** target **100 MW** of flexibility annually over three years, while **PG&E** unlocked ~**100 MW approx. seven years faster** than a new transmission line

Regulatory frameworks must reward efficient use of existing grid assets

- **Avoided-cost assessments**, **performance-based incentives**, and **recognition of non-wires alternatives** can encourage faster, more cost-effective deployment
- **National Grid** deployed **SmartValve technology** across three substations and five circuits, unlocking ~**1.5 GW** of transmission capacity under the UK's **RIIO regulatory framework**

Electricity markets need to compensate flexibility and grid-stability services

- **Payments** for demand response, frequency regulation, reserves, and other ancillary services can **support reliability and higher renewable penetration**
- **EirGrid's DS3 program** supported an increase in allowable system non-synchronous penetration **from 50% in 2014 to 75% in 2024.**

Large-scale grid expansion depends on coordinated planning and streamlined permitting

- Aligning transmission development with generation locations, demand centers, and approval processes is essential to delivering infrastructure at scale
- **TenneT's ~700 km North-South transmission corridor** illustrates the **scale of infrastructure** required to connect renewable generation with demand centers

Bankable revenue models and access to long-term capital are critical deployment enablers

- Long-term contracts, diversified financing structures, and clear cost-recovery mechanisms can mobilize investment in capital-intensive grid projects
- **CHPE** secured **$6B financing package**, including $**5.2B in debt and $800M in equity**, supported by a **25-year NYSERDA contract**

Credit: Pia Doris Morrow, Gunay Kiran, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Global grid deployment demonstrate how capacity can be unlocked, modernized, and expanded across different time horizons

Time horizon	Case study	Capacity impact	Timing / status	Technology	Deployment enabler	Lessons learned
Short-term *Optimize & unleash capacity*	**Voltus – Google** *PJM, U.S.*	1 GW VPP capacity committed — Planned / Committed	Expansion announced in October 2026	VPP and distributed demand flexibility	Bring-your-own-capacity agreement	Unlock & scale capacity without new wires
Mid-term *Modernize tech, policy & market*	**PG&E** *California, U.S.*	+100 MW — Operational	Operational 2025; ~7 years ahead of new-line alternative	FACTS / SmartValve	CAISO avoided-cost evaluation; FERC framework	Retrofit faster than new transmission
	National Grid *UK*	~1.5 GW — Operational	Deployed	FACTS / SmartValve	Ofgem RIIO incentives	Rewarding efficiency can scale grid upgrades
	EirGrid DS3 *Ireland*	Higher allowable nonsynchronous generation for grid stability — Operational	2014-2024: Phased market modernization	Ancilary services / grid stability	New market products and comparison	Markets must reward system services
Long-term *Expand generation & transmission*	**TenneT** *Germany*	~700 km North-South transmission — Under construction	Long-term build-out; investment horizons 2030/2035	Underground transmission and offshore HVDC, financing of €117B planned through 2035	Permitting reform and large-scale capital	Planning, approvals and finance must align
	CHPE *Quebec – NYC*	1,250 MW — Under construction	Long-lead HVDC project	Buried HVDC with $6B financing package	Long-term contracted revenues and project finance	Revenue certainty enables major infrastructure

Disclaimer: The following examples are selected case study examples and non-exhaustive. Grid transition priorities and deployment pathways vary by region; no one-size-fits-all approach applies. TenneT's €117B is a company-wide capital plan, not the cost of the individual North-South transmission corridor. Figures should not be compared as equivalent project costs.

Sources: Google and Voltus to Deliver Grid Capacity and Local Economic Benefits Through Bring Your Own Capacity Agreement (Voltus, 2026); PG&E and Smart Wires Enhance Grid Reliability, Capacity for Data Centers in San Jose (PG&E Corporation, May 2025); World's First Large-Scale Use of Power Flow Technology on Transmission Network Will Unlock 1.5 GW (National Grid, May 2021); DS3 Programme: Delivering a Secure, Sustainable Electricity System(EirGrid, n.d.); TenneT Investor Relations (TenneT, 2026); Champlain Hudson Power Express Announces Financial Close (Champlain Hudson Power Express, 2022).

Credit: Pia Doris Morrow, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

> Deep dives on the following pages

Columbia Business School
Climate Knowledge Initiative

Google and Voltus demonstrate how large customers can scale grid flexibility through distributed resources

Voltus – Google (PJM, U.S.)

Planned / Committed

Key facts

1 GW
Expanded VPP capacity commitment

10x
Expansion from initial 100 MW agreement

Oct 2026
Expansion announced

Problem	Rapid growth in data-center electricity demand creates **need for additional capacity** that can be delivered faster than conventional grid expansion
Stakeholders	**Google** to provide funding **Voltus** to recruit, coordinate, and compensate participating customers **PJM** to provide relevant capacity-market context
Technology	**VPP aggregating batteries**, **smart thermostats**, and **flexible residential** and **commercial loads**
Deployment enabler	**Bring-your-own-capacity agreement** creates commercial incentive to aggregate existing flexible resources
Deployment model	Google funds Voltus to aggregate distributed flexibility, **expanding the original 100 MW agreement to a 1 GW VPP** commitment in October 2026
Lesson learned	Large electricity customers can **help finance** dispatchable grid capacity **without waiting** for new transmission construction

Policy insights

Implemented policies and mechanisms

- **PJM capacity-market framework** and existing demand-response participation arrangements
- **FERC Order 2222** establishes framework for aggregated DER participation in wholesale markets

Evolving policy opportunities

- Continued implementation of **DER aggregation rules**, clearer participation requirements and evolving **large-load/ bring-your-own-capacity arrangements**

Sources: Voltus and Google to Deliver Grid Capacity and Local Economic Benefits Through Bring Your Own Capacity Agreement (Voltus, 2026); Voltus Launches "Bring Your Own Capacity" Product to Support Data Center Growth and Grid Resiliency (Voltus, 2025).

Credit: Pia Doris Morrow, Gunay Kiran, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

PG&E showcases how grid-enhancing technologies can unlock capacity years ahead of new transmission

PG&E (California, U.S.)

Operational

Key facts

+100 MW
Capacity unlocked

Up to 34%
reduction in thermal overloads

~7 years
Earlier than new-line alternative

Problem	Transmission constraints in the San Jose area **limit the grid's ability to accommodate increasing electricity demand**
Technology	Smart Wires **SmartValve**, a flexible AC transmission system (FACTS) that controls power flows on existing infrastructure
Deployment model	SmartValve installation at Los Esteros provides approx. **100 MW of additional capacity** and **reduces overloads by up to 34%**
Stakeholders	**PG&E** as utility/ deployer **Smart Wires** as technology provider **CAISO** as transmission planner **CPUC and FERC** as regulators
Deployment enabler	**CAISO's avoided-cost evaluation** creates a framework for comparing grid-enhancing technologies with conventional network upgrades
Lesson learned	**Existing** infrastructure should be **evaluated for cost-effective upgrades** before committing to slower, more capital-intensive expansion

Policy insights

Implemented policies and mechanisms

- **CAISO Transmission Planning Process** and **avoided-cost assessment**
- **FERC Order 881** on transmission line ratings
- **FERC Order 1920** on long-term transmission planning

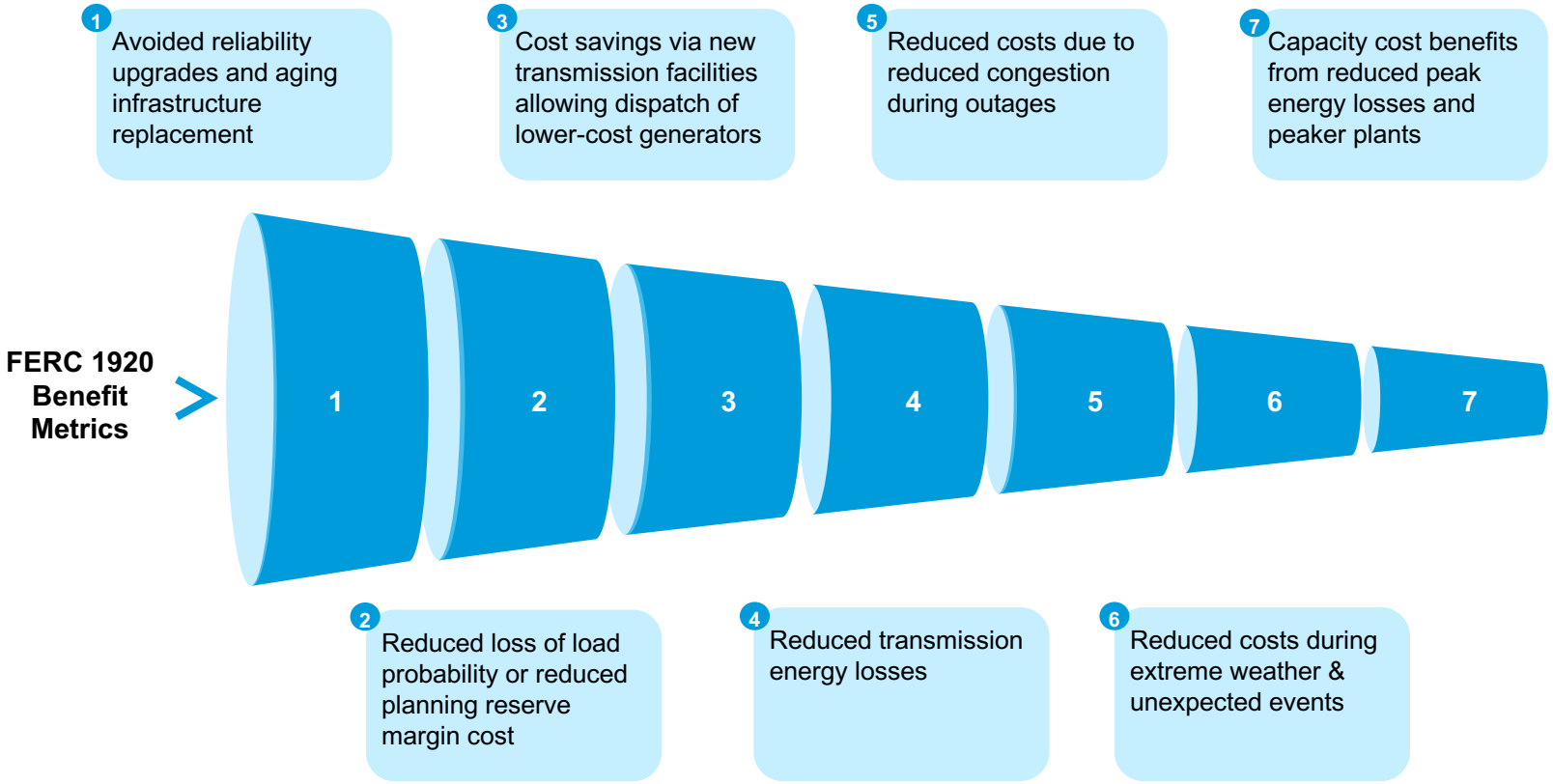
Evolving policy opportunities

- Stronger requirements to **evaluate grid-enhancing technologies** against new transmission and **improved cost-recovery incentives** for non-wires alternatives

Sources: PG&E and Smart Wires Enhance Grid Reliability, Capacity for Data Centers in San Jose (PG&E Corporation, 2025).
Credit: Pia Doris Morrow, Gunay Kiran, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

FERC Order 1920 improves grid reliability, lowers costs, and adapts the grid to changes in energy transition & climate via planning

Landmark rule issued, requires transmission providers to: plan for 20 yrs & update every 5 yrs, evaluate projects on 7 metrics, and be transparent on cost allocation…



…unlocking five key grid modernization and optimization outcomes

- Ensures **proactive & long-term regional transmission planning** over a 20 year horizon
- **Solves cost allocation bottleneck** by requiring regions to establish clear, upfront formulas to split costs based on who benefits from the seven metrics
- **Mandates consideration of Grid-Enhancing Technologies** (GETs) like dynamic line rating, incentivizing system optimization
- **Enhances transparency** in local transmission planning via stakeholder engagement before inputs are incorporated into regional planning
- **Addresses long-term transmission needs** by requiring the assessment of “right-sized replacements” for aging facilities
- **Encourages interregional transmission** lines

Sources: Explainer on the Transmission Planning and Cost Allocation Final Rule (FERC, 2025).
Credit: Gunay Kiran, Ariela Farchi Cohen, Pia Doris Morrow, Gernot Wagner. Share with attribution: Wagner *et al.* “Powering Grids,” Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Performance-based regulation can incentivize transmission capacity upgrades as shown by National Grid

National Grid (UK)

Operational

Key facts

~1.5 GW
Capacity unlocked

3
Substations

5
Circuits

Problem	**Uneven transmission** loading **limits the transfer** of electricity across existing network circuits
Technology	**SmartValve modular power-flow control devices** that redirect electricity across the network to relieve constrained circuits
Deployment model	**Large-scale installation** across **three substations** and **five circuits**, unlocking **approx. 1.5 GW**
Stakeholders	**National Grid Electricity Transmission**, **Smart Wires**, **Ofgem**, and the **electricity system operator** responsible for network option appraisal
Deployment enabler	**Ofgem's RIIO framework** and **Network Options Assessment** support consideration of efficient alternatives to conventional reinforcement
Lesson learned	**Utilities** are **more likely** to deploy capacity-enhancing technologies when **regulatory incentives reward efficiency** and **whole-system value**

Policy insights

Implemented policies and mechanisms

- **Ofgem's RIIO price-control framework, Totex Incentive Mechanism, Network Innovation Allowance,** and **Network Options Assessment**

Evolving policy opportunities

- **Further refinement** of **performance-based incentives** and **cost-sharing arrangements** that reward avoided network expenditure

Sources: World's First Large-Scale Use of Power Flow Technology on Transmission Network Will Unlock 1.5 GW of Electricity Capacity (National Grid, 2021).
Credit: Pia Doris Morrow, Gunay Kiran, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

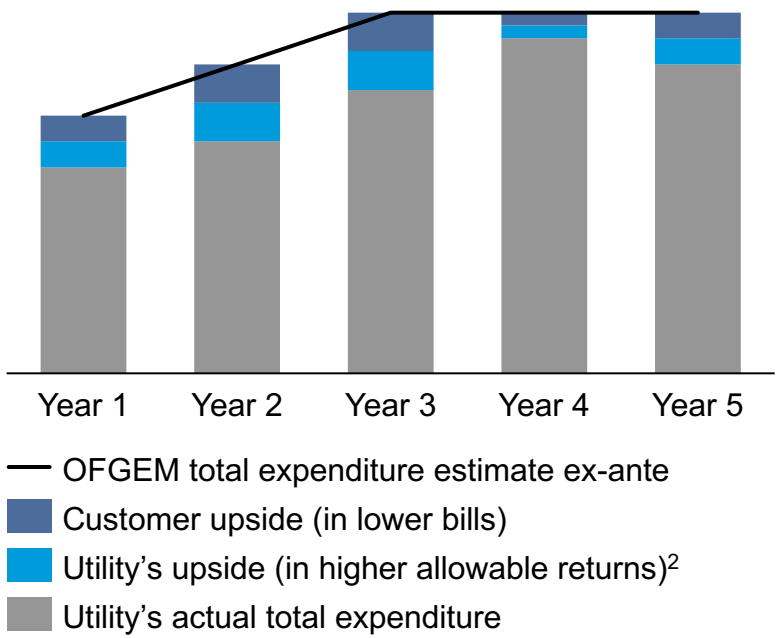
Regulation should incentivize and set standards for non-wire alternatives (NWA), energy efficiency & grid forming inverters (GFM)

Cost-of-Service Regulation for NWAs & GFMs saved billions in UK

	UK's RIIO-1[1] ofgem
Case study	• Ofgem (the UK's energy regulator), transitioned to **RIIO-1** (*Revenue = Incentives + Innovation + Outputs*), which allows utilities to recover TotEx savings • This framework rewards network companies for improving reliability, implementing innovative technologies, and finding cost effective non-wire alternatives (NWAs) • Took over from a traditional cost-of-service regulation, which incentivizes utilities to build heavy infrastructure to generate returns
Results	• Network operators recovered **£96 Billion** between 2010-2018 • This yielded a **38% net savings on UK consumer energy bills** compared to what customers would have paid with the traditional infrastructure expansion[2]

Utilities can bank a portion of savings from an estimate

Illustration of upside for utility under RIIO-2



Key regulatory changes needed for grid transition & set up for RIIO-2

1. Incentives **boosting non-wire alternatives** to investment i.e. RIIO, New York's Reforming Energy Vision (REV) or Demand Management Incentive Scheme (DMIS) of Australia, etc.
2. Regulations incentivizing **energy efficiency**
3. Mandating or incentivizing modern grid-balancing hardware, specifically naming **Grid Forming Inverters (GFM)**

RIIO-2

- **RIIO-ED2 operates on a 5-year vs. 8-year period** to reduce the risk of estimate divergence
- **More conservative allowances** and estimation mechanisms were set to better align capital returns and outputs, **requiring innovation for upside**
- There are now **explicit incentives for demand flexibility**

Key technologies utilized

- GFM (Grid Forming Inverters)
- NWAs relying on DERMS, VPPs and load shifting

[1] RIIO: Revenue = Incentives + Innovations + Output which is a performance-based regulatory framework for electricity and gas networks in Great Britain [2.] OFGEM adds a capitalization ratio multiplier to total expenditure or upside, meaning that a share of the total expenditure or upside in one year is added to the RAB and is recovered over a period, while the other share is recovered in that same year. [3.] Residential bills calculated assuming £1k energy bill of 28 million houses.

Source: Open letter on the RIIO-2 framework (OFGEM, 2017), OFGEM (2024), PICLO (2023).

Credit: Hasan Alawadhi, Pia Doris Morrow, Isabel Hoyos, Gunay Kiran, Dominica Wambold, Ariela Farchi Cohen, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

Permitting reform can accelerate grid interconnection by prioritizing project readiness and reducing queue bottlenecks

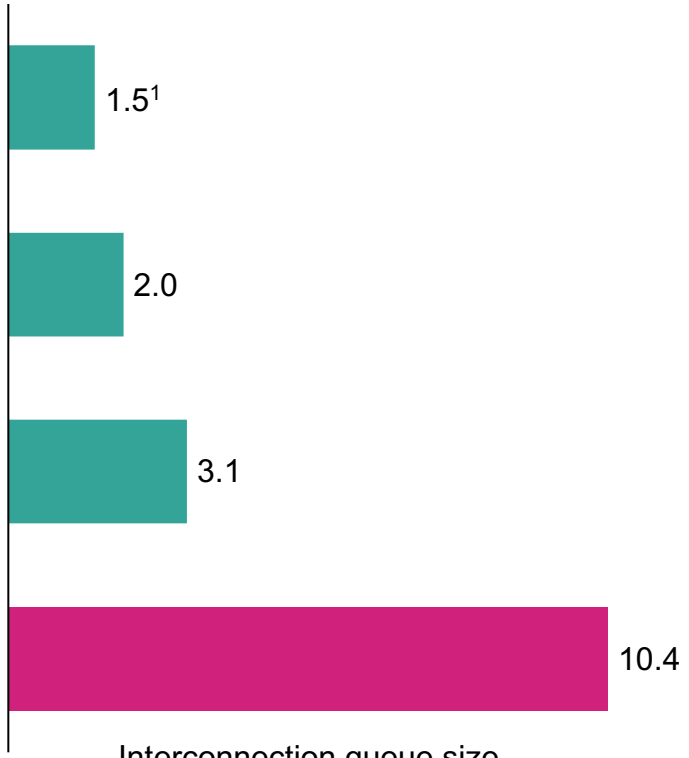
Stricter requirements, “connect & manage,” and “first ready, first served” systems have proved to reduce interconnection queues

entsoe
- Aggressive structural gating, predefined zoning & stricter upfront grid-readiness (removing first-come, first-served approach) limit developers from casually entering the queue

ercot
- **Connect & Manage approach**
- Dynamically manages grid bottlenecks in real-time by curtailment or market redispatch

California ISO
- Requires intensive studies
- **First ready, first served** system, prioritizing projects aligned with state-level plans

nationalgrid
- Strict First-Come, First-Served approach
- **Unviable projects** that applied years **ago blocked ready & funded projects**



Policy shift toward a hybrid “First Ready and Needed, First Served” approach

Observations

- **Interconnection speed is critical** to getting the required generation on the grid as soon as possible
- **ERCOT has faster interconnection** due to its “connect and manage” approach
- **CAISO needs ‘Resource Adequacy’ studies** making interconnection slower
- **FERC** mandated a transition from "first-come, first-served" to a **"first-ready, first-served”** approach, while **ENTSO-E and Natonal Grid** are also making similar changes

1. Interconnection queue size assumed here only includes renewables, so actual ratio will be higher

Sources: Energy Markets & Policy (2025); ERCOT (2025); CAISO (2025), ENTSOE Map (2025); ENTSOE (2025); Beyond (2025); GTLAW (2025); DUKES (2025).

Credit: Gunay Kiran, Hasan Alawadhi, Stephanie Chen, Helin Tilkicioglu, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* “Powering Grids,” Columbia Business School Climate Knowledge Initiative (29 October 2026).

Ancillary-service markets enable greater renewable integration as demonstrated by Ireland's DS3 program

EirGrid DS3 (Ireland)

Operational

Key facts

50%
Initial SNSP limit
2014

65%
Intermediate milestone
2018

75%
SNSP capability
2024

Problem	Higher shares of inverter-based renewable generation **require new ways to maintain frequency, voltage and system stability**
Stakeholders	**EirGrid** and **system-service providers**, including generation, storage, and other eligible flexibility resources
Technology	**Fast frequency response, reserve, reactive power, and other grid-stability capabilities**, supported by batteries, inverters, and control systems
Deployment enabler	Explicit ancillary-services products **create revenue for capabilities needed** to operate a more renewable electricity system
Deployment model	Secure Sustainable Electricity System (DS3) program develops and compensates services needed for a **high-renewables power system**
Lesson learned	Energy-only compensation is **insufficient where reliability depends on fast response, reserve, and voltage-support services**

Policy insights

Implemented policies and mechanisms

- **DS3 System Services arrangements** and **market compensation** for ancillary services such as fast frequency response, reserves and reactive power

Evolving policy opportunities

- Expanded participation for **DER aggregators** and **evolving technical standards,** and **compensation for grid-forming capabilities**

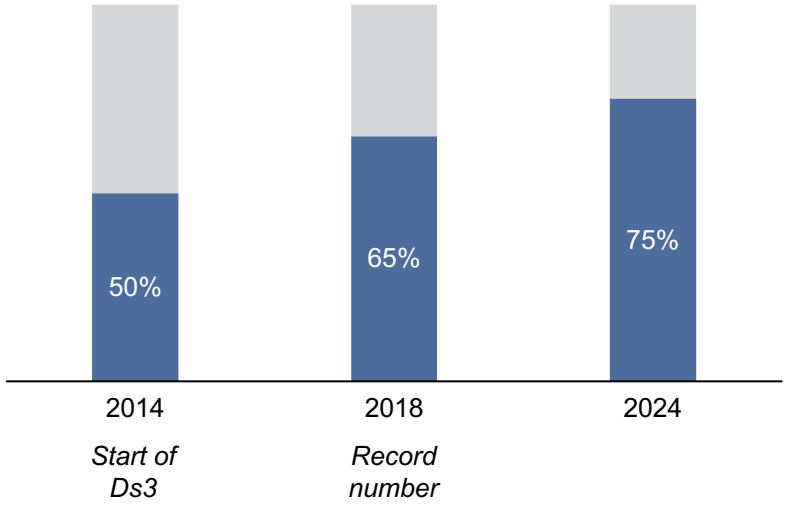
Sources: DS3 Programme – Delivering a Secure Sustainable Electricity System (EirGrid, n.d.); DS3 – Delivering a Secure, Sustainable Electricity System (EirGrid, 2015).
Credit: Pia Doris Morrow, Gunay Kiran, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Reformed capital recovery and allocation markets promote broad participation and deployment of distributed resources

Incentivizing ancillary services and facilitating DER integration are the backbone of a grid with high renewable penetration

	Ireland EIR Grid
Overview	• With EirGrid and SONI's DS3 program, Ireland managed a high penetration of non-synchronous renewable energy on its grid • To maintain stability, the power market evolved from compensation on energy output to rewarding performance and grid-stabilizing capabilities (ancillary services, e.g. reactive power, fast frequency response)
Success levers	• 12 distinct system service products to monetize vital grid capabilities (e.g., reactive power, ramping products, etc.) • Established market rules allowing DERs • Leveraged key modern grid technologies
Results	• **Increased Renewable Limits (SNSP)** • 2014 (Start of DS3): 50% • 2018 (Record milestone): 65% • 2024 (2024 capability): 75%

Ireland's SNSP[1] limits due to ancillary service market



Key technologies utilized

- Grid-forming inverters
- DERMS
- VPPs
- Grid-scale batteries

Observations

- **Assets should be rewarded for ancillary services** to the grid, not just the Megawatts, this includes reactive power, which will be a required asset in inverter-based generation future
- Ireland's DS3 program provides a successful example of a market-based framework, with **12 service products to compensate providers for supporting grid stability**
- Additionally, a **market for DERs to aggregate and sell directly to the grid** is needed as a way of improving economics

1. System Non-synchronous Production: Maximum percentage of non-synchronous inverter-based renewables provision in each hour
Sources: Ds3 System Services Protocol (2024); EirGrid (2025)

Credit: Gunay Kiran, Hasan Alawadhi, Stephanie Chen, Helin Tilkicioglu, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

TenneT illustrates how coordinated transmission planning and diversified financing connect generation surpluses to demand

TenneT (Germany)

Under construction

Key facts

~700 km
North-South transmission corridor

€67B
Company investment plan through 2030

€117B
Company investment plan through 2035

Problem
Northern Germany has renewable generation **surpluses** while the **South** faces a **supply deficit**

Stakeholders
TenneT, German authorities, financial institutions, and public/ private capital providers

Technology
Long-distance underground transmission, **HVDC** connections and **offshore grid** infrastructure

Deployment enabler
Coordinated transmission planning, German **permitting** legislations, and **diversified long-term financing**

Deployment model
Approx. **700 km of North-South transmission**, alongside **offshore connection projects** including LanWin1, LanWin2, LanWin5, and BalWin4

Lesson learned
Transmission expansion requires **alignment between generation geography**, **permitting**, **investment plans** and **access** to capital

Policy insights

Implemented policies and mechanisms

- **Germany's Federal Requirements Plan Act (BBPIG), Energy Industry Act (EnWG)** and **2022 Easter Package Provisions** prioritizing energy infrastructure

Evolving policy opportunities

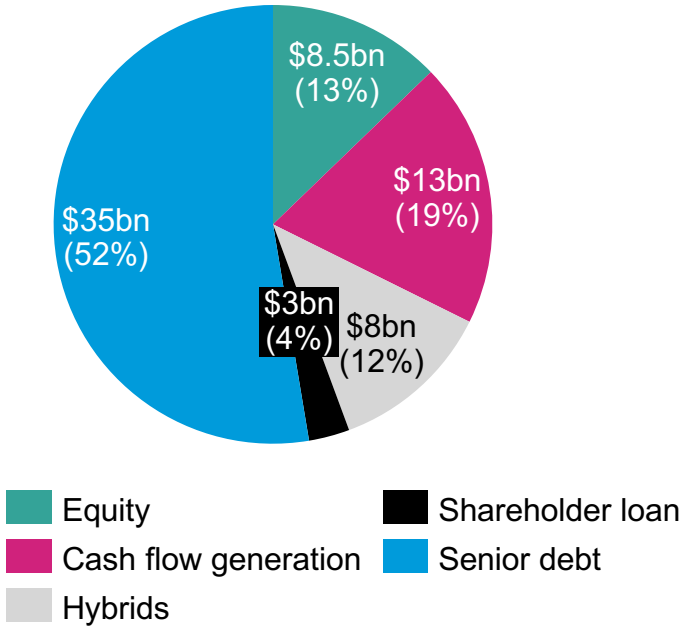
- **Continued permitting simplification**, **coordinated offshore/ onshore planning** and **financing arrangements** for major transmission investment

Sources: TenneT Investor Relations (TenneT, 2026).
Credit: Pia Doris Morrow, Gunay Kiran, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Large transmission projects like TenneT leverage innovative financing methods while maintaining traditional debt-to-equity ratios

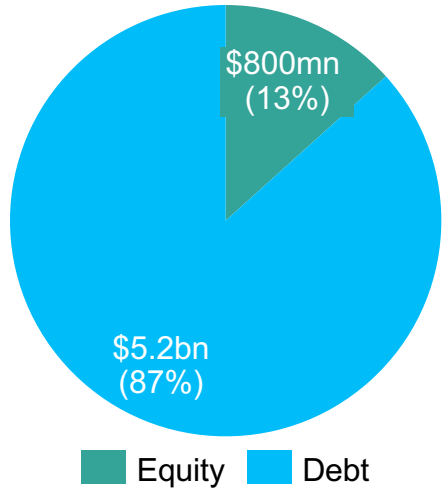
TenneT combined sovereign equity co-investors, green bonds & subordinated hybrid debt for this project

- The capital plan involves **€67 billion** in investments through 2030 and **€117 billion** through 2035
- Used HoldCo/OpCo Hybrid Capital Structure, allowing borrowing while protecting credit ratings
- Specifically structured to issue debt under the official European Green Bond Standard Regulation; a €3.5 billion European Green Bond was issued as senior unsecured debt
- A unique pre-committed €11.8 bn (surpassing planned €8.5 bn) equity cushion which combined a government development bank (**KfW**) with giant international private institutional pension and sovereign wealth funds (**APG**, **NBIM**, **GIC)**



Long-term power delivery agreements provide CHPE with revenue certainty needed to secure bank debt

- CHPE was designed by TDI and sponsored by Blackstone
- It is fully private and financed through a private investment package of $6 billion
- $800 million sponsor equity
- Non-recourse debt package raised from a large syndicate of commercial banks led by **Société Générale** supported by a group of coordinating lead arrangers: **MUFG, Mizuho, CIBC**
- $5.2 billion project-level debt
- Long-term NYSERDA Tier 4 REC contract (25 years) provides cash flow visibility needed to back $5.2B in debt



Key financing methods utilized
- Subordinated hybrid capital, European Green Bonds, long-term power delivery agreements, blended capital

Sources: Project documents provided by TenneT, CHPE (2026), Fitch Ratings (2026), Kirkland (2022), Blackstone (2022), CHPE News (2022), CHPE Legal (2022)
Credit: Gunay Kiran, Ariela Farchi Cohen, Pia Doris Morrow, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

The Champlain Hudson Power Express (CHPE) demonstrates how contracted revenues can finance major cross-border transmission



CHPE (Quebec – NYC)

Under construction

Key facts

1,250 MW
Transmission capacity

339 miles
Buried HVDC corridor

$6B
Project financing package

Problem	New York City needs **additional access to low-carbon electricity supply**, while major transmission construction faces permitting and financing challenges
Technology	**339-mile buried HVDC transmission link** connecting Quebec hydropower with New York City, including conversion to AC at the receiving end
Deployment model	**Privately sponsored, project-financed transmission** development
Stakeholders	**Hydro-Québec, Transmission Developers Inc., NYSERDA, Blackstone, commercial bank syndicate**, and **regulators** and **permitting** authorities
Deployment enabler	**Long-term NYSERDA Tier 4 renewable energy credit contract**, lender participation, buried routing, and trenchless construction techniques
Lesson learned	**Predictable contracted revenue** can attract **large-scale private debt and equity** to transmission projects

Policy insights

Implemented policies and mechanisms

- **New York's Tier 4 renewable energy credit procurement framework,** implemented through **NYSERA's** long-term contract
- Project permitting and approvals

Evolving policy opportunities

- Broader use of **long-term clean-energy procurement**, **transmission contracting** and **permitting approaches** for future cross-border projects

Sources: Champlain Hudson Power Express Announces Financial Close (Champlain Hudson Power Express, 2022); Tier 4 Program: Solicitation, Contract Awards and Program History (NYSERDA, n.d.); Kirkland Counsels Blackstone Portfolio Company, CHPE, on Financing of 339-Mile Clean Power Transmission Line from Québec to NYC (Kirkland & Ellis, 2022).

Credit: Pia Doris Morrow, Gunay Kiran, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Investors have a major opportunity to participate in funding the future of the U.S. grid; approaches vary primarily by system type

	Vertically Integrated	Restructured (ISO/RTO)	ERCOT
Geographic alignment	South, Northwest, Intermountain West	PJM, MISO, CAISO, ISO-NE, NYISO, SPP	Texas ('energy-only' market)
Planning mechanisms	• Integrated Resource Plans (IRPs) • Utility RFPs	• Regional transmission plans • FERC-1920 and cost allocation tariffs	• ERCOT-specific planning (e.g., CREZ) • Market price signals
Primary funding vehicles	Utility debt and equity (public markets) incl. for Non-Wire Alternatives (NWAs) and GETs	Utility debt and equity, merchant project finance, NWA contracts	Utility debt and equity, merchant project finance, wholesale market revenue
ROI mechanisms	• State policy • Regulated rate base inclusion	• Regional cost allocation • Aggregated DER markets	• Texas PUC Transmission Cost of Service • Merchant (market) driven (energy and ancillary revenue)
Key oversight bodies	• Public Utility Commissions (PUCs) • FERC (inter-state)	• ISOs/RTOs and FERC • State Public Utility Commissions	• Public Utility Commission of Texas • FERC (reliability-only)
	NERC**:** Authority for reliability standards; relevant with demand (load) increases to unlock investor opportunities including inter-system coordination, technologies benefitting from national standards, and where federal support can be tapped (e.g., ITCs, GRIP)		

Emerging financing models expand access from private capital to grid-connected assets

- **VPPAs**: Hedge revenue risk, enable PF
- **CTTs:** Absorb first-of-a-kind risk
- **BYOC**: 3rd party customer-sited capacity
- **Build-Transfer**: Offset cost & timeline risk
- **PBR & ADER**: Incentivize asset efficiency
- **Asset-backed securitization**: Grid & off-grid

Sources: World Energy Investment (IEA, 2026); GETS (Bipartisan Policy Institute, 2026); Energy Transition Investment Trends (BNEF, 2026); Grid resilience (J.P. Morgan, 2026); Queued Up (LBNL, 2026); Large Loads Letter (U.S. DOE, 2025); VPP Liftoff Report (DOE); Policy recommendations to unlock the value of LDES (C2ES, 2024).

Credit: Dominica Wambold, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

U.S. grid expansion is a coordination challenge across rules, capital, assets and siting

	Roles & Responsibilities	Planning & Need	Financing & Cost Allocation	Interconnection application	Siting& Permitting	Procurement & Construction
				Delay hotspot stages		
FERC	**Federal rule setter:** Sets interstate transmission, wholesale market, interconnection, cost-allocation rules	●	●	●		
DOE / GDO / national labs	**Federal deployment enabler:** Identifies national infrastructure needs, funds and de-risks projects, and informs planning	●	●		●	
NERC + Regional Entities	**Reliability authority:** Sets enforceable reliability, planning, operations and cybersecurity standards	●				
RTOs, ISOs, ERCOT	**Regional planners / operators:** Operate grid and markets, manage congestion & coordinate regional interconnection	●	●	●		
State PUCs / PSCs,	**State regulatory gatekeepers:** Approve utility investment, rates, cost recovery and siting where applicable	●	●	●	●	
State Energy Offices	**State policy coordinators:** Align with state energy policy, resilience & energy targets and federal funding opportunities	●				
Transmission owners, IOUs, public power, co-ops	**Asset owners / builders:** Build, own, maintain and modernize transmission and distribution assets	●	●	●	●	●
Federal land agencies, state/ local gov., Tribal gov.	**Permitting and public acceptance actors:** Determine whether projects can be sited, permitted & built on acceptable timelines				●	●
Generators, DCs, industrials	**Interconnection customers / demand drivers:** Create generation and load needs, submit interconnection requests	●	●	●		●
OEMs / EPCs / workforce / investors	**Delivery and capital ecosystem:** Provide equipment, EPC services, qualified labor, grid technologies and capital		●			●
				>4 yr median IR-to-COD[1]	**~4 yr federal permitting**	**>2.5 yr[2] equipment lead times + constrained EPC capacity**

Build & Deploy | Finance | Regulate | Demand

● Primary Decision Gate ● Secondary Influence

[1]Interconnection Request to Commercial Operation Date. [2] Q2 2025 at ~2.5 years (128 weeks) for power transformers and ~2.8 years (144 weeks) for Generator Step-Up (GSUs).

Sources: FERC Orders 1920 and 2023; CITAP (DOE, 2024); Long-Term Reliability Assessment (NERC 2024); 2025 Edition Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2024 (Berkeley Lab, 2025); Wood Mackenzie Q2 2025 Survey Results.

Credit: Ilayda Tezcan, Ariela Farchi, Pia Doris Morrow, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (29 October 2026).

Columbia Business School
Climate Knowledge Initiative

CKI Grids Team

Fellows



Hasan Alawadhi
MBA, Columbia Business School
Climate Knowledge Initiative Fellow



Dominica Wambold
MBA, Columbia Business School
Climate Knowledge Initiative Fellow



Gunay Kiran
MS in Sustainability Management
Climate Knowledge Initiative Fellow



Christy Wong
MPA, Columbia SIPA
Climate Knowledge Initiative Fellow



Vincent Sandow-Straesser
MS in Climate Finance
Climate Knowledge Initiative Fellow



Sevgi Helin Tilkicioglu
MBA, Columbia Business School
Climate Knowledge Initiative Fellow



Ilayda Tezcan
MBA, Columbia Business School
Climate Knowledge Initiative Fellow



Stephanie Chen
MBA, Columbia Business School
Climate Knowledge Initiative Fellow



Ryon Roque
BS in Civil Engineering
Climate Knowledge Initiative Fellow

CKI Team Staff, Faculty, and Alumna

Staff



Ariela Farchi Behar
MS in Sustainability Management
Staff Associate
af3487@columbia.edu



Pia Doris Morrow
MS in Sustainability Management
Staff Associate
pm3346@columbia.edu



Selen Bilgin Olmez
MS in Sustainability Management
Staff Associate
sb5151@columbia.edu

Faculty



Gernot Wagner
Senior Lecturer, Columbia Business School
Faculty Director, Climate Knowledge Initiative
gwagner@columbia.edu

Alumna



Isabel Hoyos
MS in Sustainability Management
Former Senior Staff Associate