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Powering Grids Executive Summary

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 (28 September 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; they are the readiest source available and fastest to connect
- These 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

Sources: CKI Analysis (2026).

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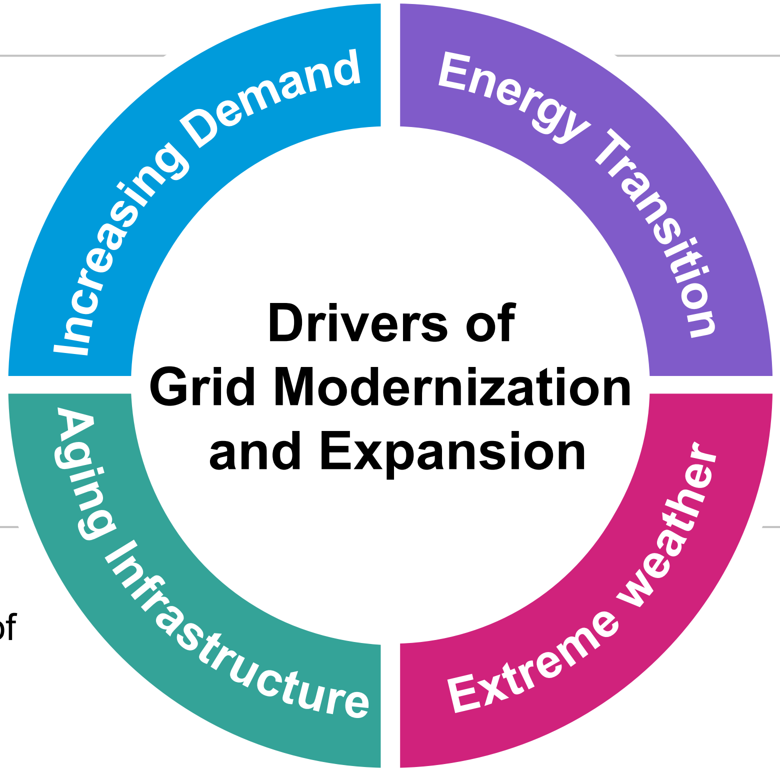
Global grids face the critical need to adapt due to demand growth, a changing energy landscape, aging assets and extreme weather

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

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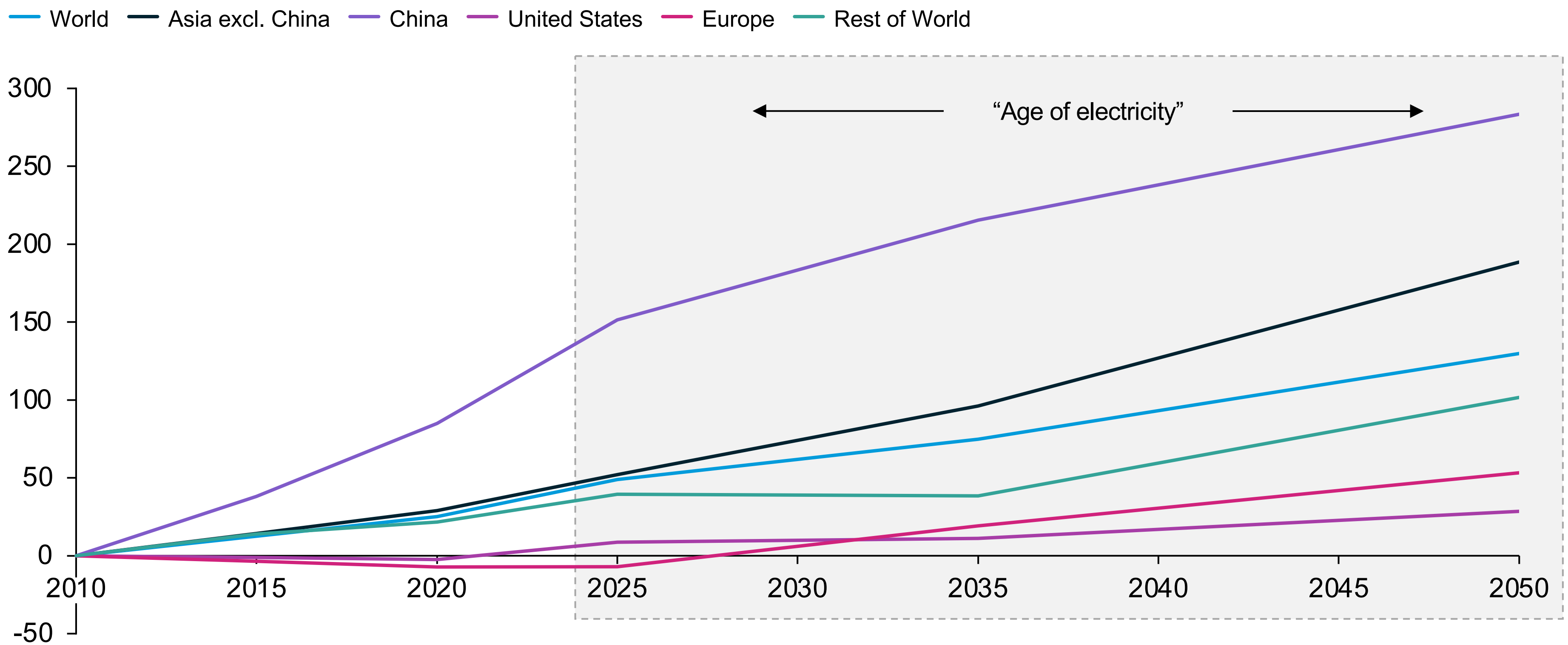
Global electricity demand growth has been led by China, but is projected to accelerate across nearly all major regions

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).

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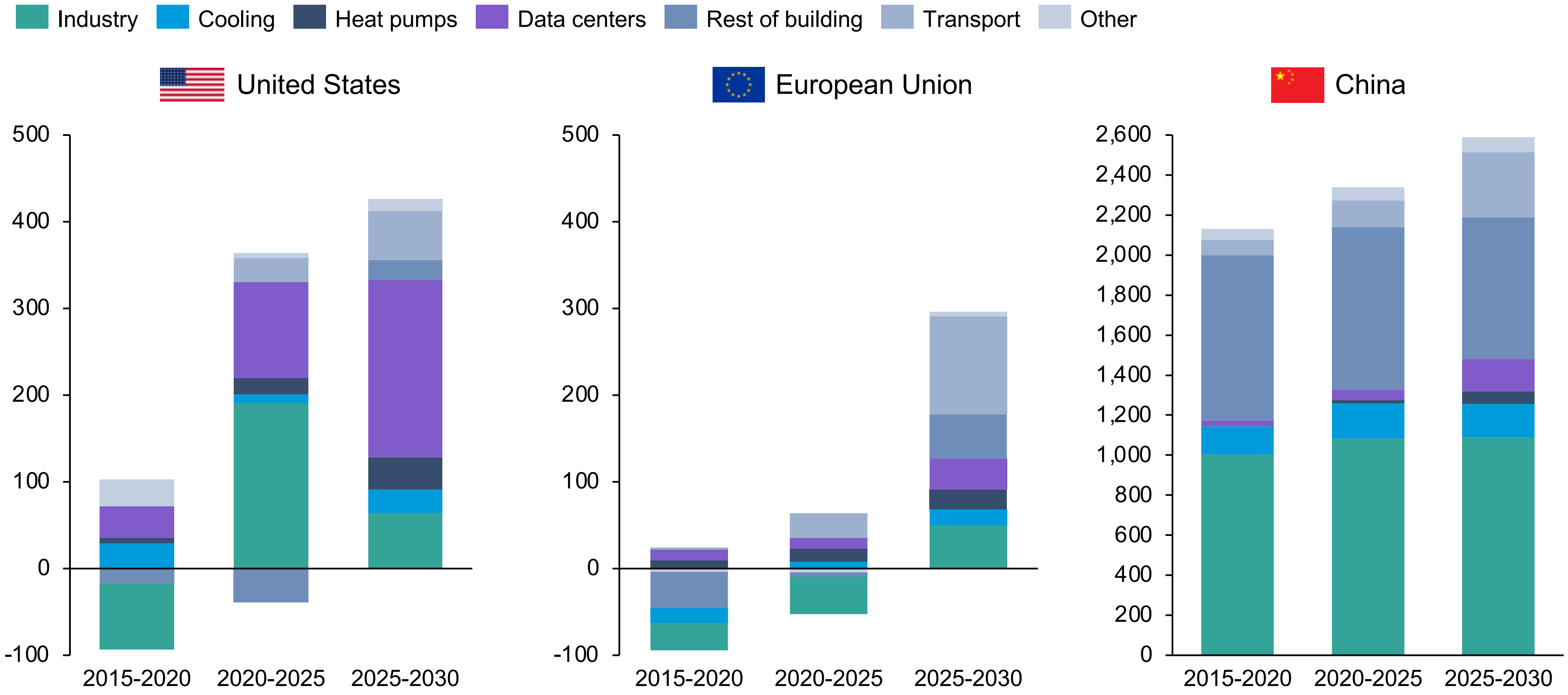
Electrification and data centers are among primary drivers accelerating electricity demand across the US, EU, and China

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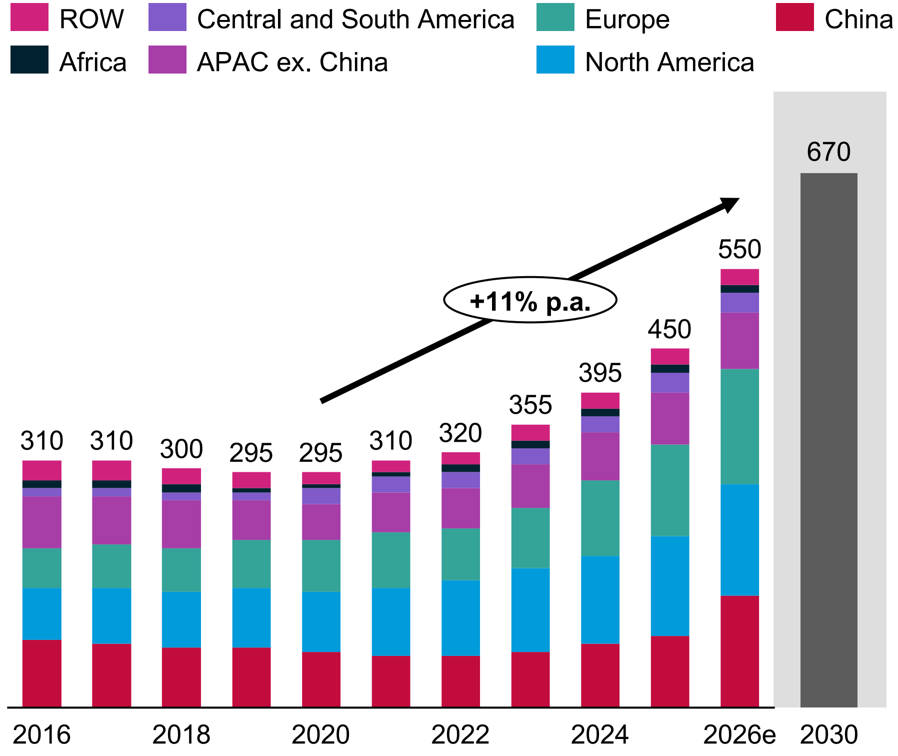
Global grid investment is expected to rise to +$500B in 2026 and increase through 2030, driven by infrastructure, materials, and labor

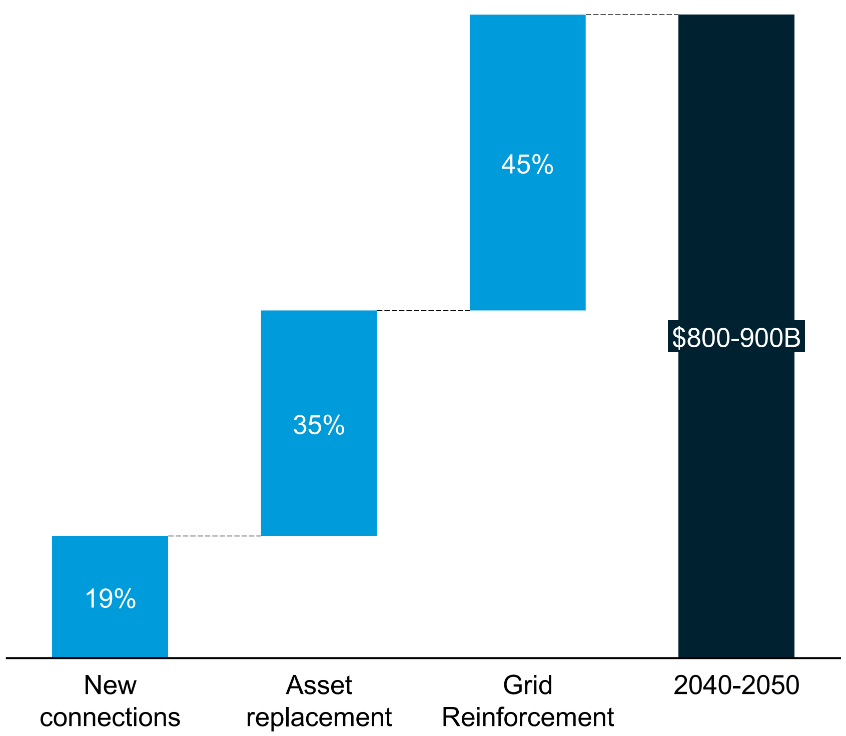
Investment grew ~85% over 5 years, targeted to reach $600B by 2030 in NZE[1]

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 **optimisation (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 (28 September 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 (e.g., battery system capital efficiency vs. new transmission) and intended to reflect the grid capital investment (e.g., excludes consumer EV batteries).
[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).

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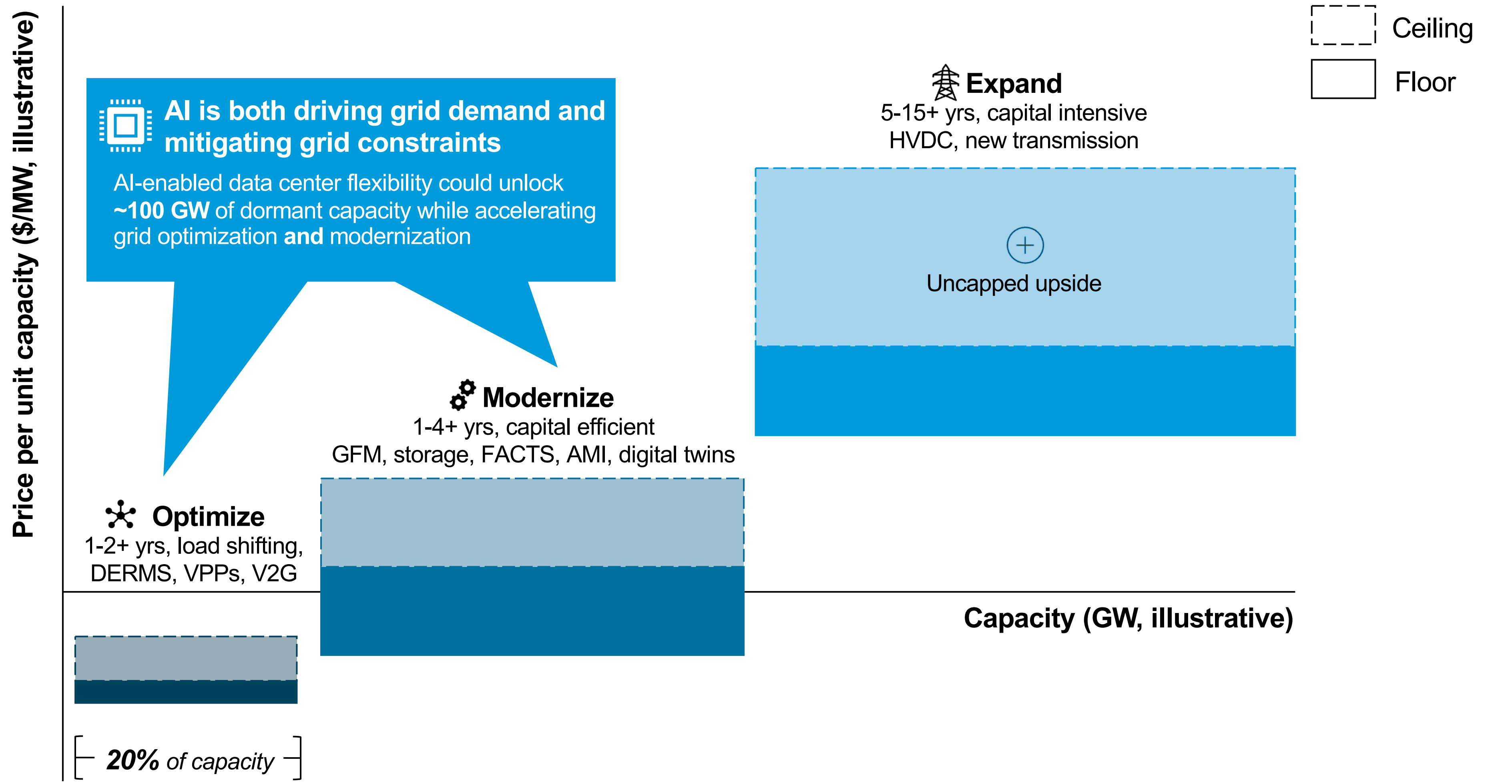
Optimizing existing assets unlocks the lowest-cost grid capacity, while expansion offers unlimited investment opportunity

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 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).

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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

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

[1]Including permitting authorities.

Sources: Virtual Power Plants Projects (U.S. Department of Energy, 2026); Pathways to Commercial Liftoff: Virtual Power Plants (U.S. Department of Energy, 2025); Operating Procedure for Calculation of NWA Financial Incentives (NY Dept of Public, 2020-2022); Electricity Grids and Secure Energy Transitions (IEA, 2023).

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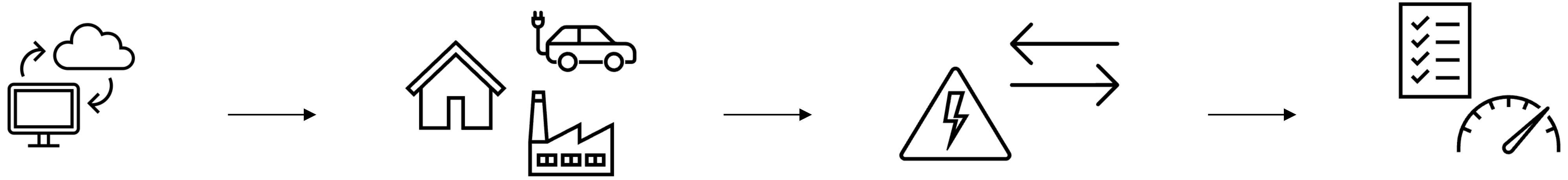
Load Shifting Technologies move non-essential electricity use from high-demand periods to times when the grid is less stressed



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

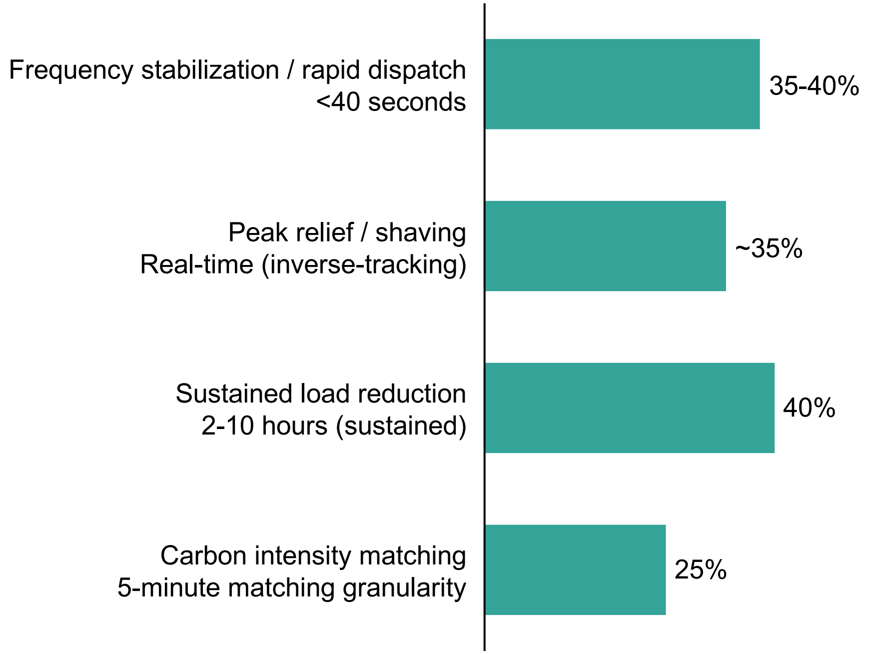
Source: Order No. 2222 Explainer: DERs in Electricity Markets (FERC, 2020); California's Biggest Battery Test Ever (PG&E, 2025); How Many Smart Meters Are Installed in the US? (EIA, 2023)

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 (28 September 2026).

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

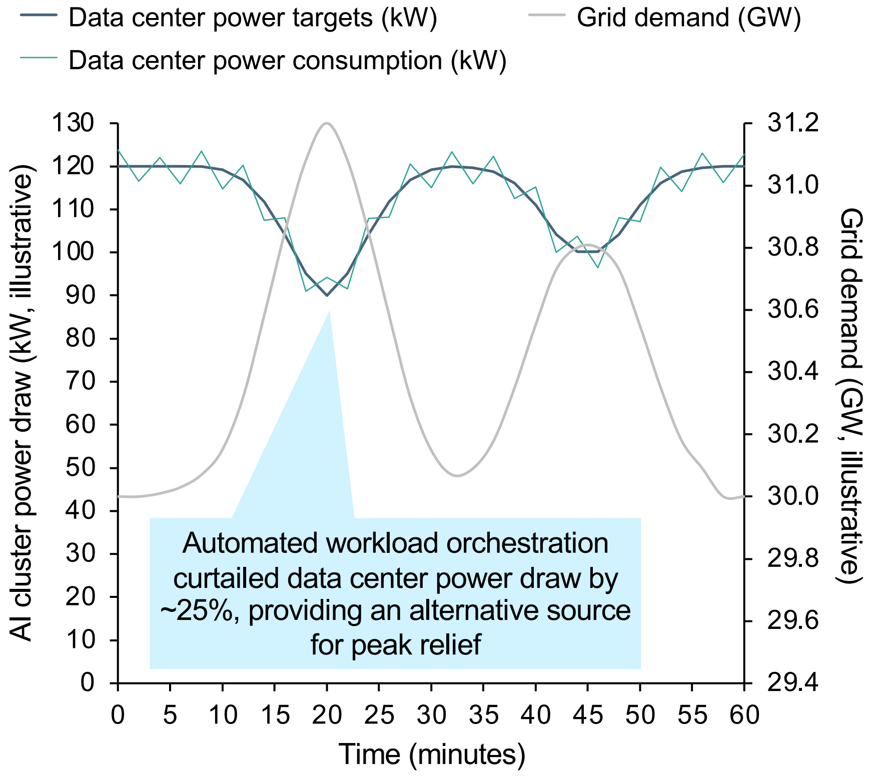
Emerald AI demonstrated data centers can shift up to 40% of non-critical load in <40 seconds

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).

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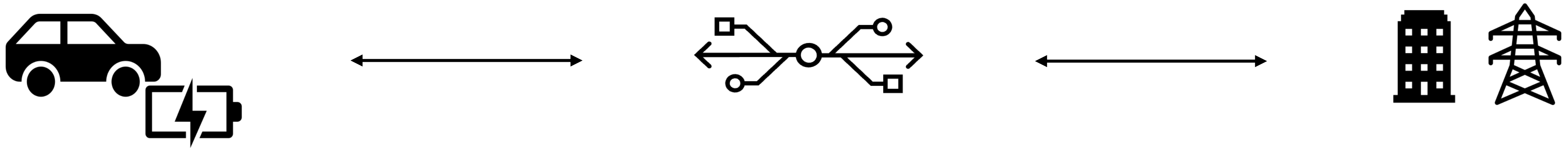
Bidirectional charging enables vehicle-to-building and vehicle-to-grid interactions, turning EVs into flexible energy storage



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)

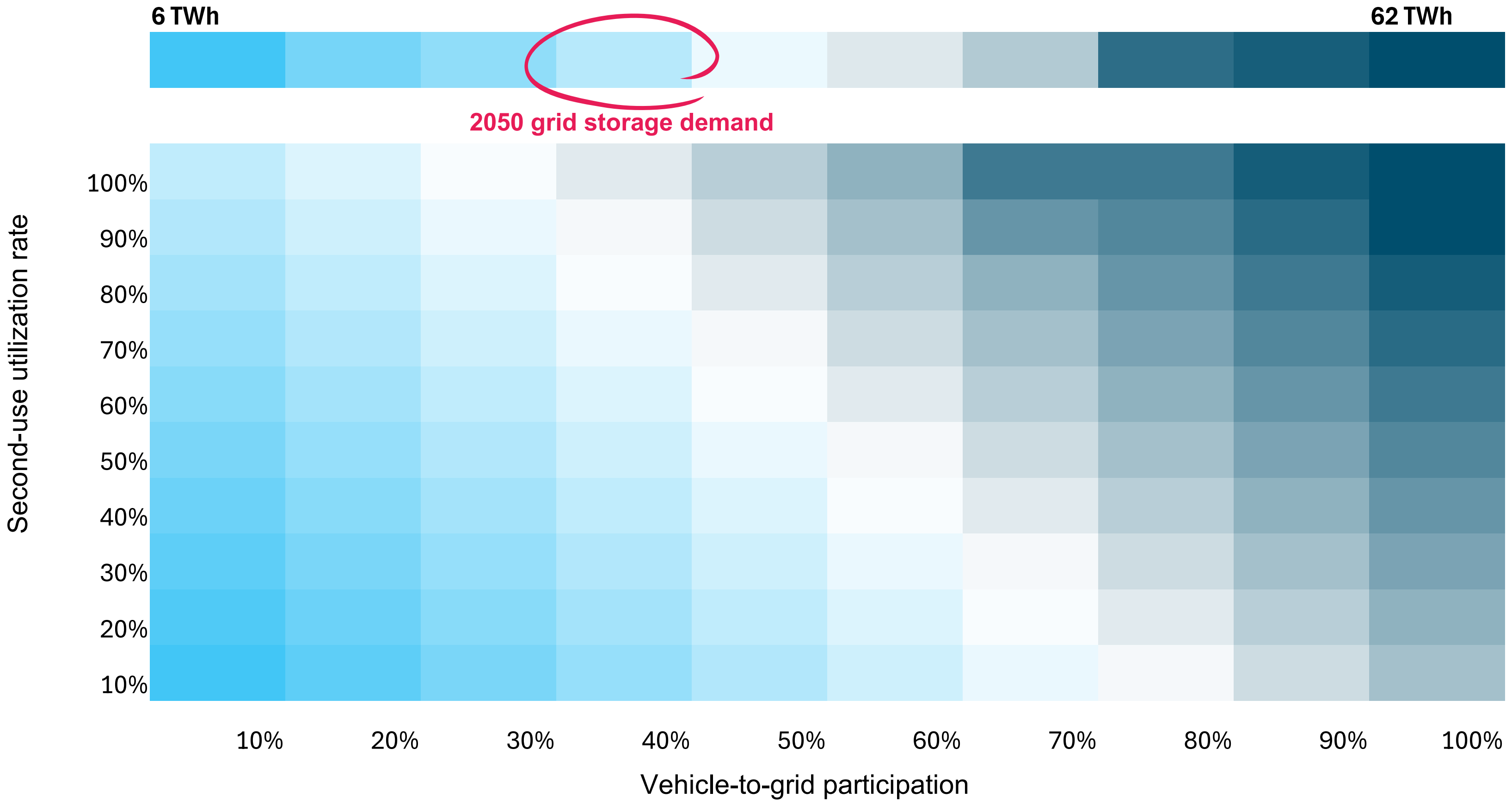
− Disadvantages

- 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)

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

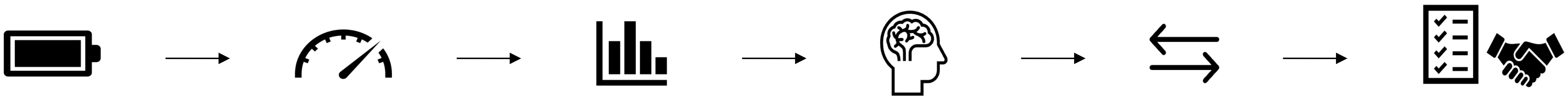


Observations

- 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 (28 September 2026).

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: Pathways to Commercial Liftoff: Virtual Power Plants (US DOE, 2025); Order No. 2222 Explainer: DERs in Electricity Markets (FERC, 2020); GridOS DERMS: Distributed Energy Resource Management System (GE Vernova, 2025).

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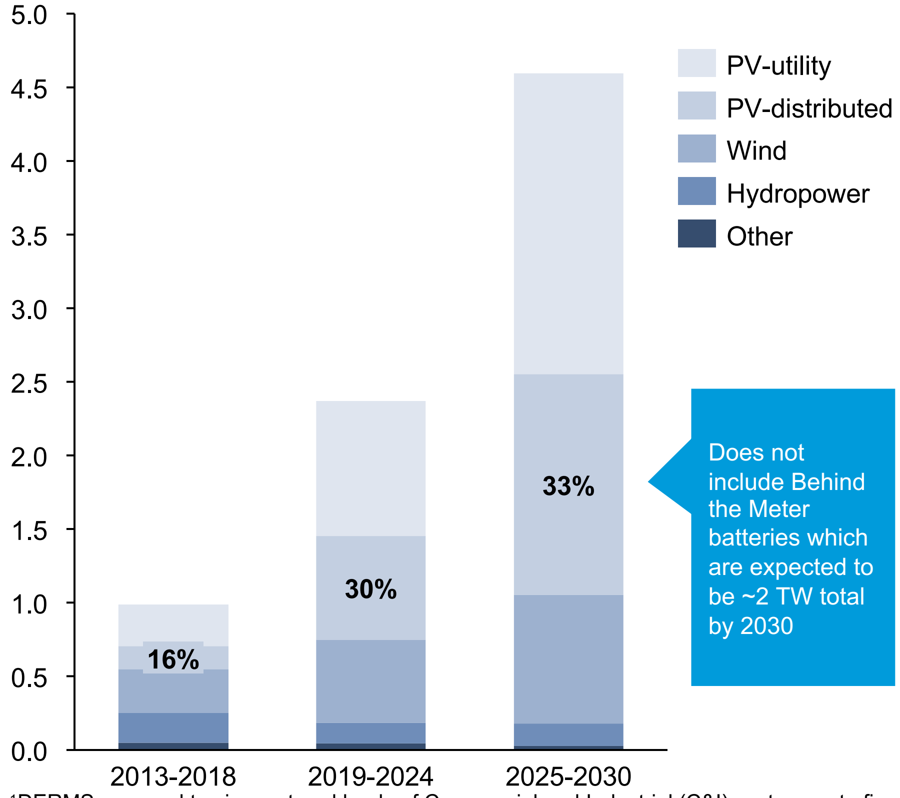
DERMS provide an increasingly distributed grid with improved visibility, dispatch efficiency, interoperability and market integration

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, settle 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); US DOE VPP Liftoff (U.S. DOE, 2025); Use Cases and Digital Twins Solutions (ENTSO-E & DSO Entity, 2026); Batteries and Secure Energy Transitions (IEA, 2024).

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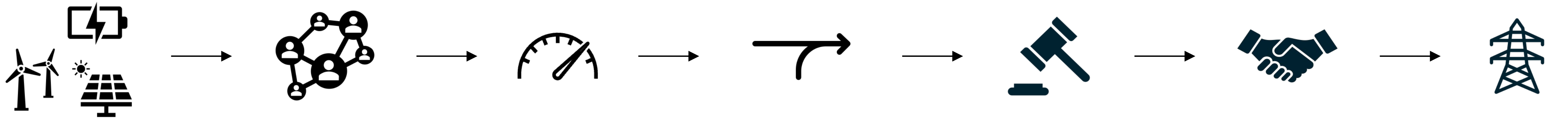
Virtual power plants aggregate thousands of distributed assets into a single, dispatchable, market-facing power plant



Distributed energy resources → 1 Aggregate → 2 Monitor & forecast → 3 Optimize & dispatch → 4 Bid into markets → 5 Deliver & settle → Grid & wholesale markets

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 (28 September 2026).

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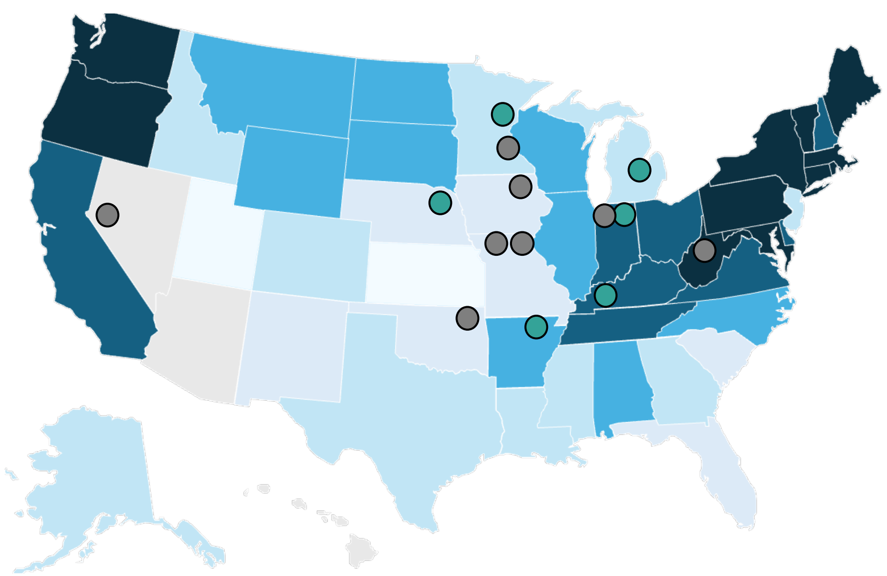
Google and Voltus collaborate on building a virtual power plant to unlock flexible capacity for datacenters

Demand flexibility agreements are in place for data centers across the U.S.

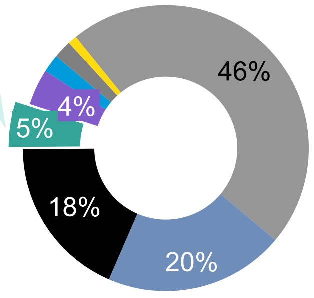
Google locations with flexible data center agreements



The Voltus-Google BYOC deal unlocks 100MW of accredited capacity in PJM

Supply mix cleared in PJM '28-'29 auction, MW

Voltus will aggregate up to 100 MW of DERs each year (batteries, smart thermostats, and other flexible assets) from local businesses and homes into a Google-funded VPP



Deal Dynamics

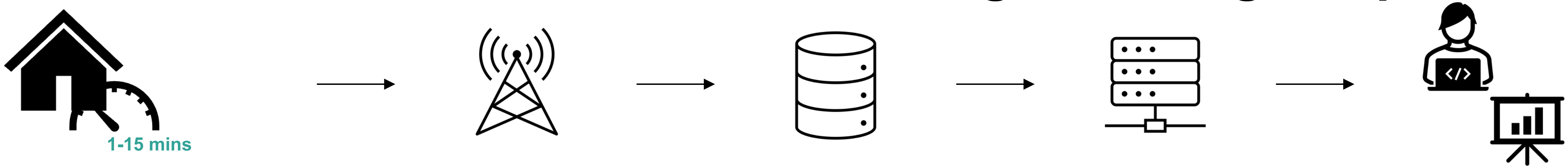
- Google compensates Voltus to aggregate 100MW annually of customer flexibility over 3 years in a PPA-like structure
- Voltus centralizes and compensates customers who participate in the VPP to respond to demand signals via an automated system
- The agreement contributes to aggregating capacity to meet increased demand from data centers and bridge PJM's shortfall, increasing grid resilience

Observations

- A **Virtual Power Plant (VPP) eases the need for asset-heavy solutions** to meet increasing demand
- **Engaging distributed resources through demand flexibility** can deliver significant energy benefits to households, commercial, and industrial consumers
  - Estimates in the U.S. project up to **$110- $170 B in savings** over the next decade
  - This presents a **capital-efficient solution to improve grid utilization**
- BYOC is an example of how **big tech can participate in grid investments;** hyperscalers like Google bring in critical financing
  - Data center investments can expedite the flexibility technology learning curve

Source: 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, Dominica Wambold, Christy Wong, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (28 September 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

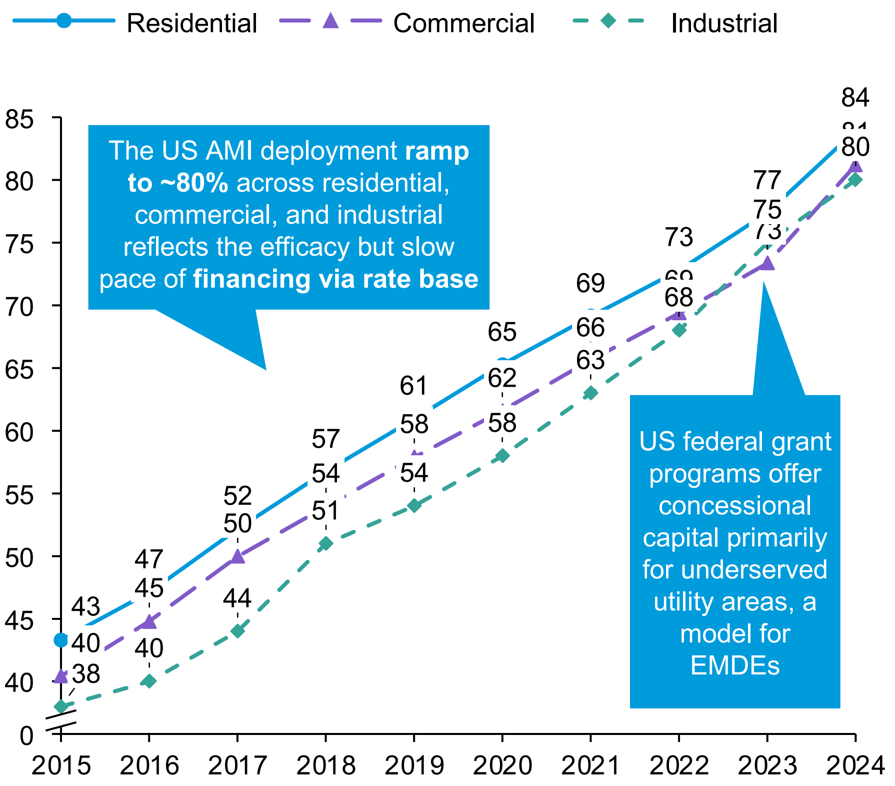
Closing the AMI implementation gap requires interoperability mandates, targeted grants, and demand response market pricing

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



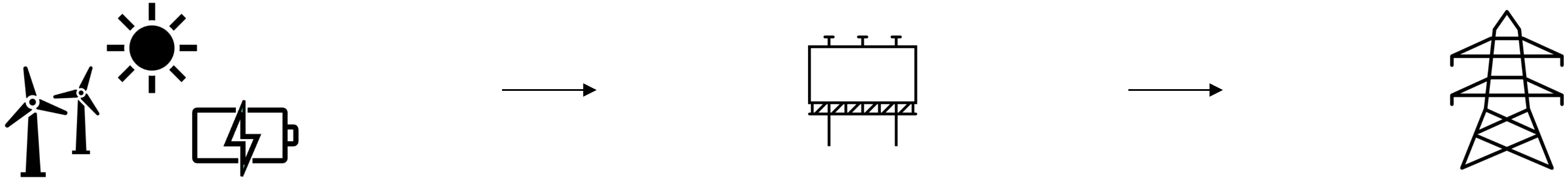
Observations

- 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 (28 September 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**
- 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

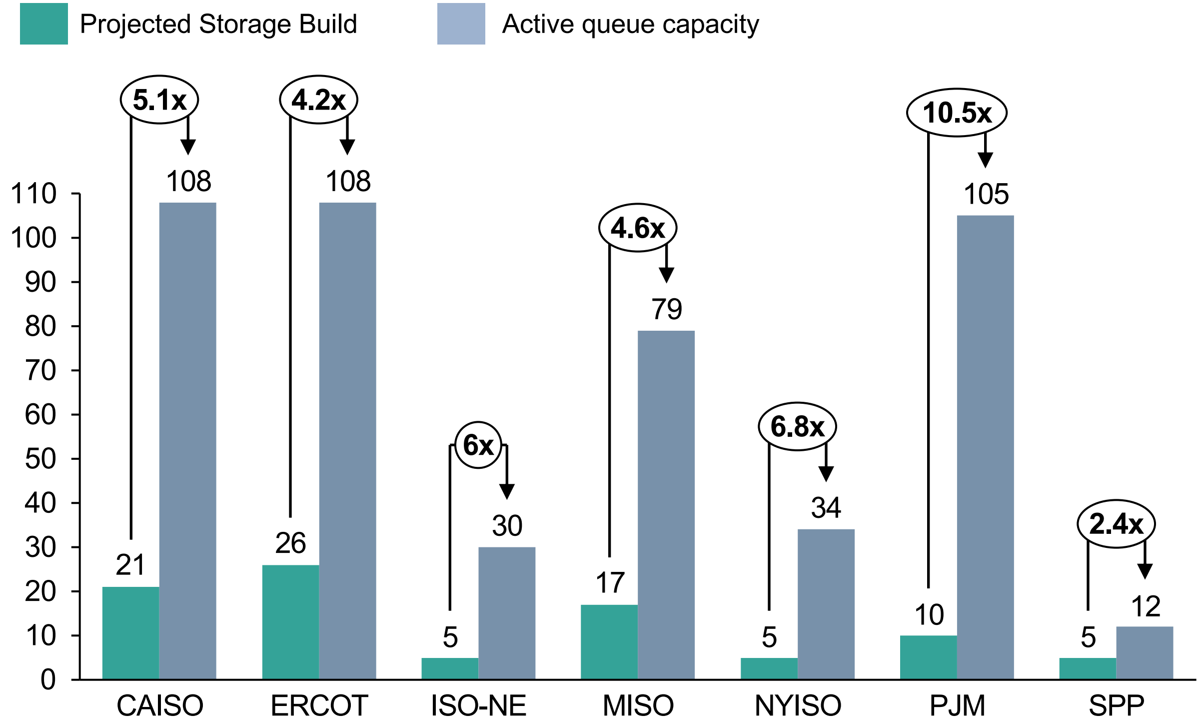
- **Incremental cost** (firmware, PCB, sensors, testing)
- **Integration resistance,** considered "emerging tech"
- **Without policy**, OEMs **lack demand signal** to ramp at scale and reduce premiums
- **Increased lead times** as supply chain is developed

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).

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

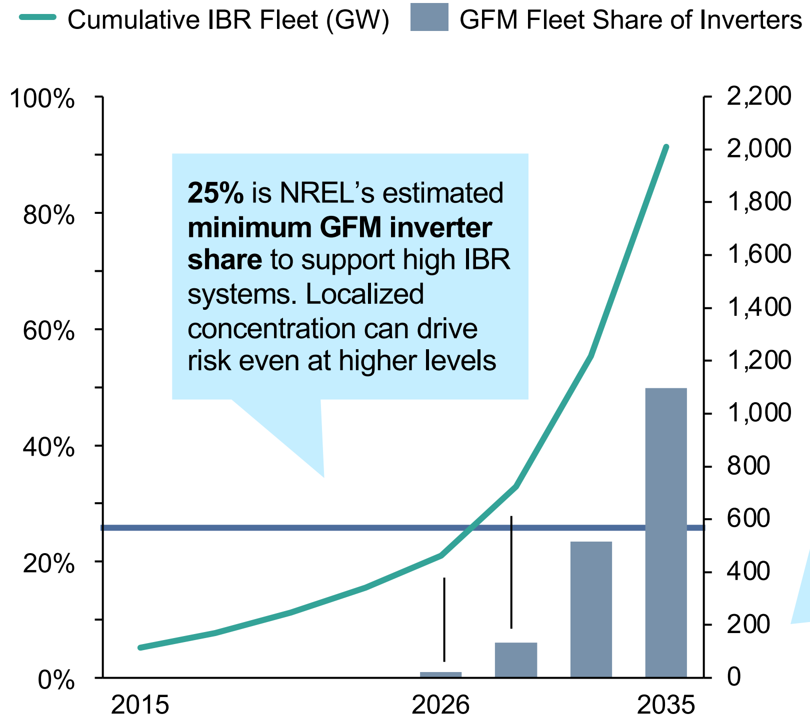
Requiring GFMs for energy storage in the active queue is critical to safely deploy this capacity into the grid

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



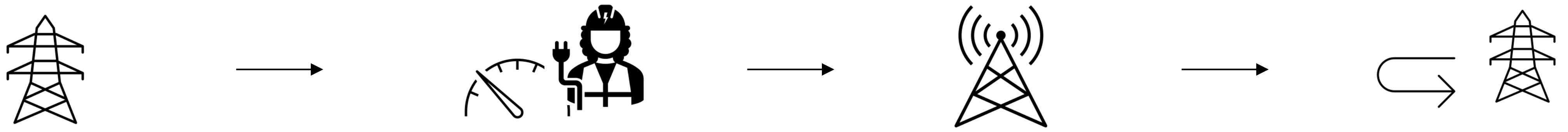
- Annual IBR capacity additions to the grid **exceed 90%** of all net-new grid energy resources
- Even anticipating NERC enforcement of reliability standards, current GFM adoption is **not sufficient** to ensure stability
- Nationwide, GFMs would remain **well below the 25% threshold** through 2033

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 (28 September 2026).

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
- **Enables to avoid 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); Pathways to Commercial Liftoff: Innovative Grid Deployment (US DOE, 2024).

Credit: Sevgi Helin Tilkicioglu, Hasan Alawadhi, Pia Doris Morrow, Vincent Sandow-Straesser, Ariela Farchi, and Gernot Wagner.

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]

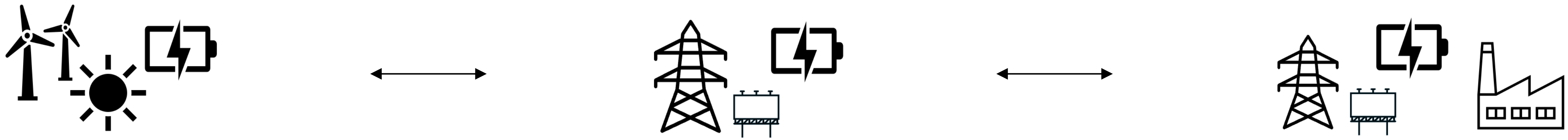
Category	System	Operational / investment value	Deployment maturity
Series Control line impedance or inject series voltage to manage line loading	**SSSC** – Static Synchronous Series Compensator **TCSC** – Thyristor-Controlled Series Capacitor **TSSC** – Thyristor-Switched Series Capacitor **TCSR** – 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	

Deployment maturity: Low – High

[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).

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

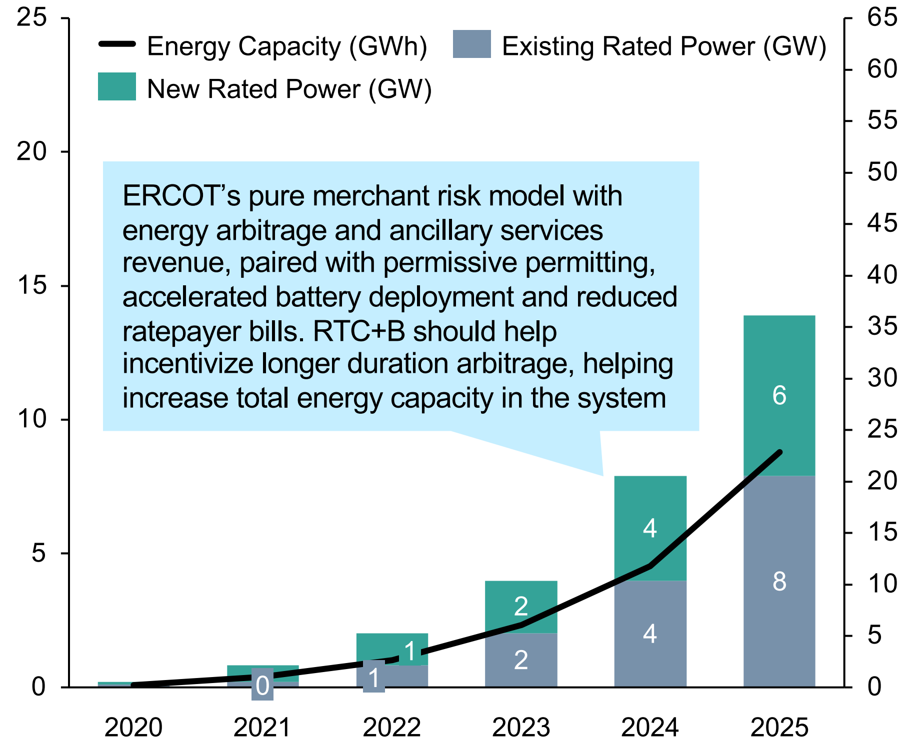
Sources: How battery storage could unlock the grid and make power more affordable (World Economic Forum, 2026); Energy Storage Enters the 100 Gigawatt Era (BNEF, 2026), Why batteries are the electric grid's most powerful asset (SEIA, 2025), Grid Scale Storage (IEA, 2024).

Credit: Dominica Wambold, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (28 September 2026).

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

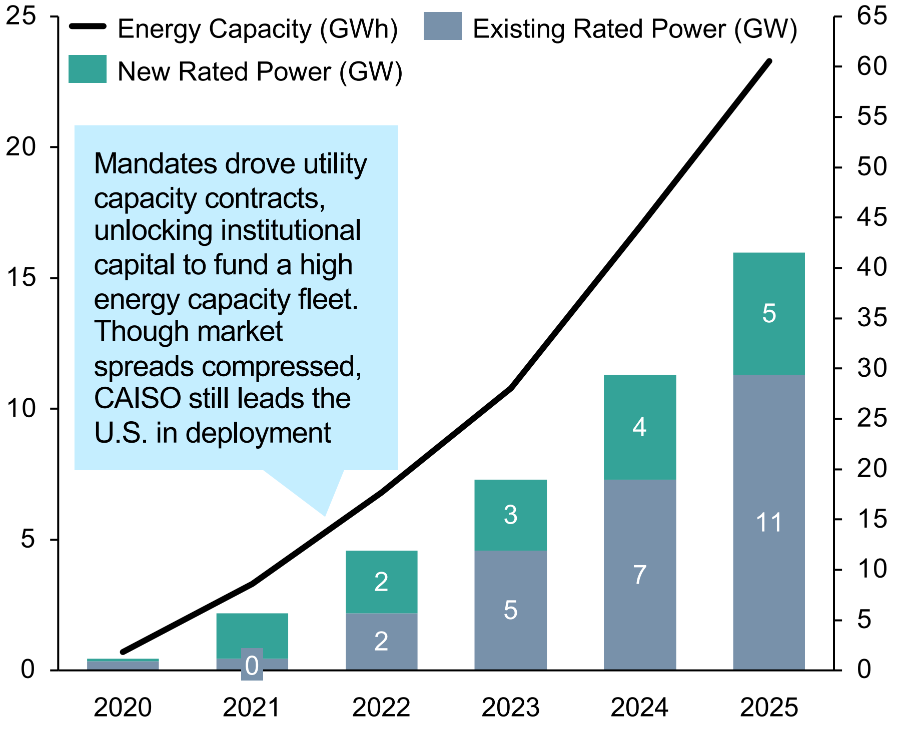
Private investment and arbitrage returns drove high battery deployment in ERCOT

ERCOT Battery Fleet, 2020-2026[1]



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

CAISO Battery Fleet, 2020-2026[1]



Observations

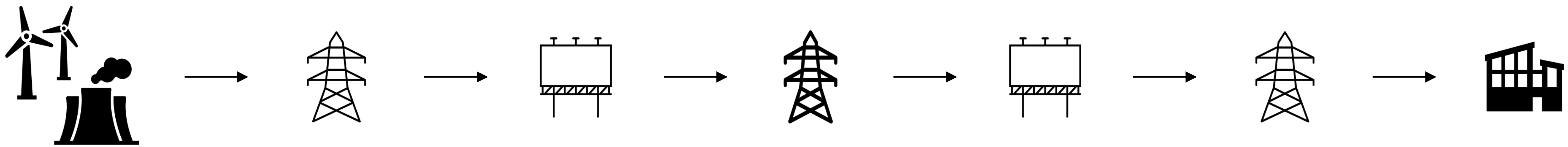
- Battery deployment continues to accelerate as battery cell costs reduce and duration is extended
- The global battery storage market is **expected to exceed $100B in 2026,** led by grid-connected batteries (~80%)[2]
- Batteries can help balance the grid, complement renewables, and lower customer electricity 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 (28 September 2026).

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



Power generation → **AC Transmission Line** → (1) **AC to DC converter** → (2) **HVDC Transmission Line** → (3) **DC to AC converter** → **AC Transmission Line** → **Distribution and end use**

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 (28 September 2026).

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

Delay hotspot stages (Interconnection application; Siting & Permitting; Procurement & Construction)

	Roles & Responsibilities	Planning & Need	Financing & Cost Allocation	Interconnection application	Siting& Permitting	Procurement & Construction
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 (28 September 2026).

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