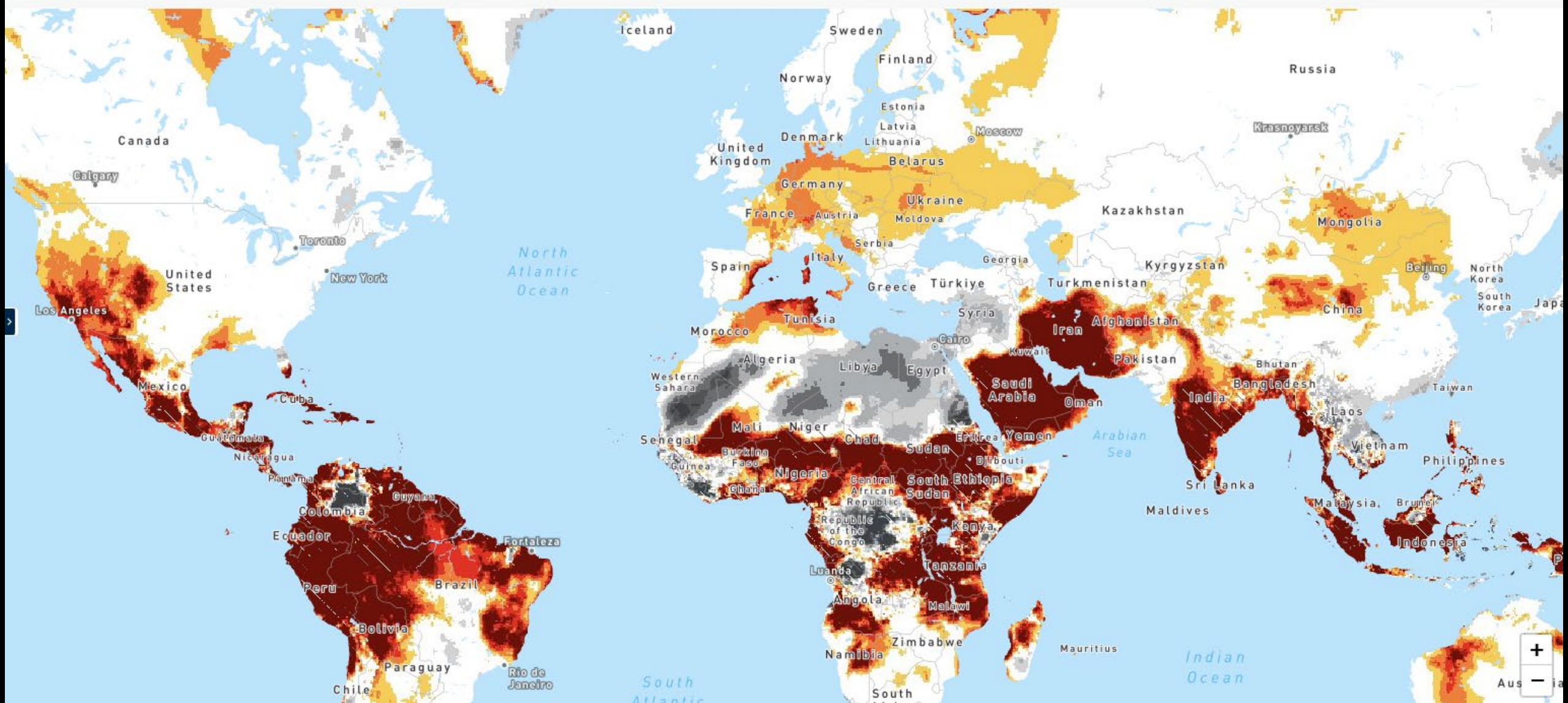


Climate Shift Index [Learn more...](#)

for average temperatures, Oct 7, 2026

Change in likelihood due to climate change



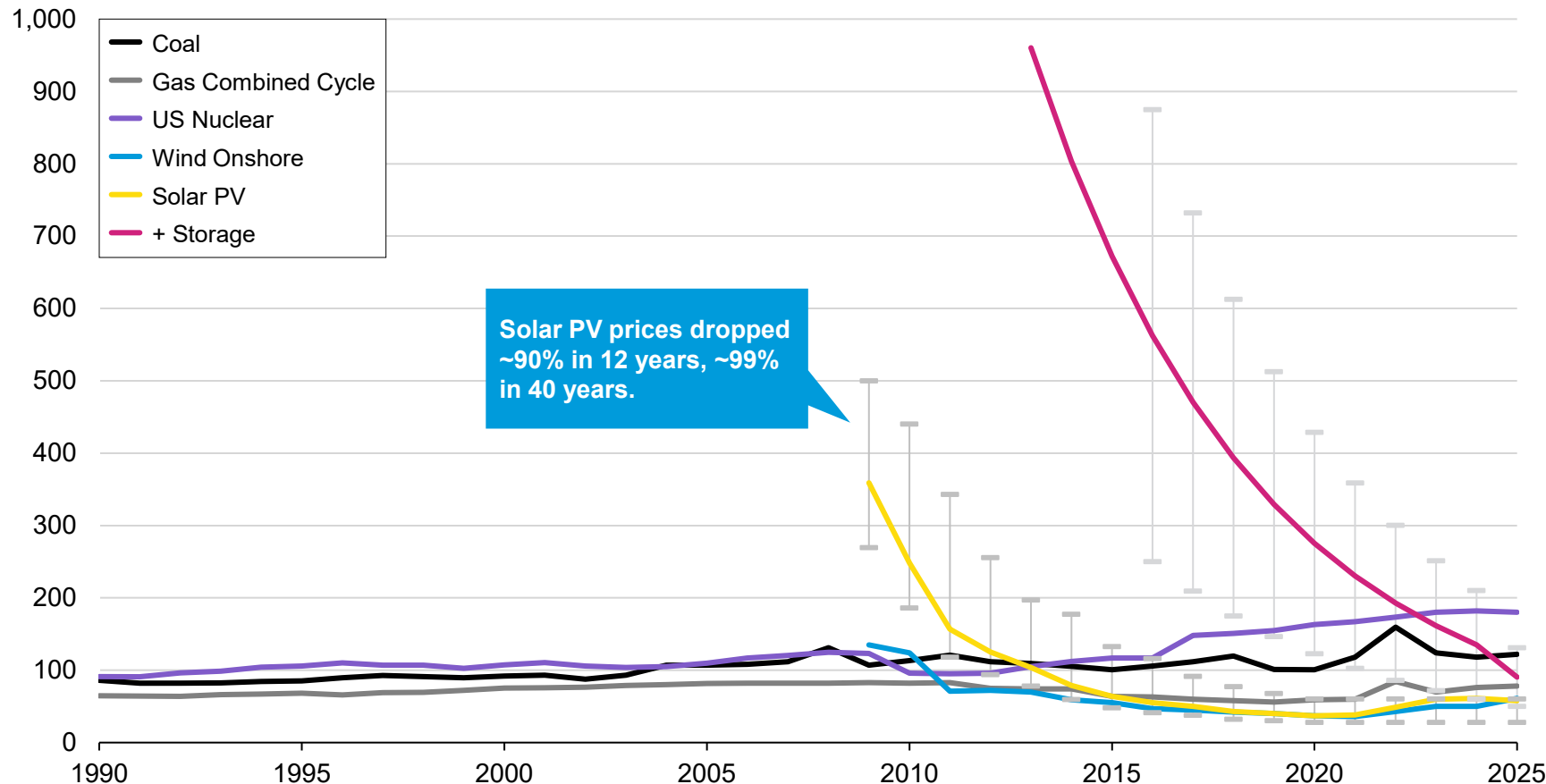
Source: climatecentral.org/climate-shift-index

Not *if*, *when*



Utility-scale solar and wind now cheaper than fossil fuels, battery storage costs not far behind and falling fast

Levelized cost of electricity (LCOE) & storage (LCOS) (\$USD/MWh)



Observations

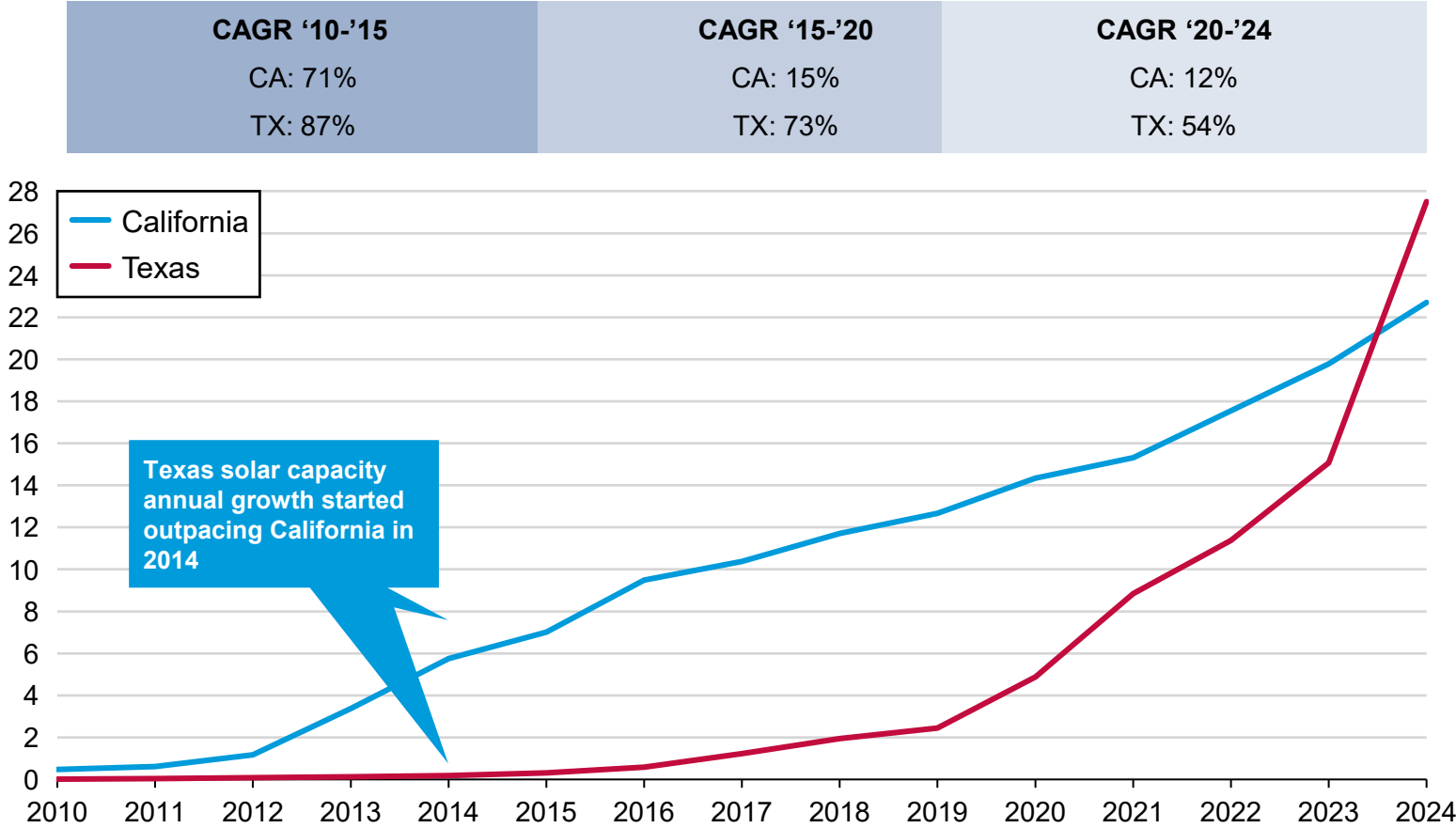
- **Solar photovoltaic (PV) prices dropped by ~80% in the past decade**, wind by ~70%, and lithium-ion battery costs by ~90%.
 - PV price drop primarily driven by **improvements in module efficiency** and **economies of scale**.
 - **Onshore wind** remained the cheapest for the longest, **now beaten by PV**.
 - Lithium-ion **battery costs fell 20% in 2023 alone**.
- **Gas combined cycle power plants cheaper than coal**, more expensive than both solar and wind.
 - Rapid scale-up of utility-scale batteries “killer app” to replace gas on grid.
 - **Battery prices expected to continue falling** due to cell manufacturing overcapacity, economies of scale, and switch to lower-cost lithium-iron-phosphate (LFP) batteries.

Sources: Lazard, [LCOE+](#) (2025); Our World in Data, [Our World in Data](#) (2024); Energy Institute, [Statistical Review of World Energy](#) (2024); BNEF, [Battery Price Survey](#) (2024); Kavlak *et al.*, [Evaluating the Causes of Cost Reduction in Photovoltaic Modules](#) (2018).

Credit: Hyae Ryung Kim, Xiaodan Zhu, and Gernot Wagner. [Share with attribution](#): Kim *et al.*, “[Scaling Solar](#)” (14 August 2025).

Deregulated Texas energy market boon for solar, surpassing California in 2024

Total installed utility-scale solar capacity in Texas and California (GW)



Observations

- **Texas surpassed California** as leading solar PV state after adding 1.6 GW in Q2 of 2024 (ACP).
- Texas installed nearly **9 GW of new solar by the end of 2024** – over one-fourth of the U.S. 2024 additions – for a **total capacity of 27.5 GW** (ACP).
- Texas is **expected to install 11.6 GW** new utility-scale solar in 2025 (EIA).
- **Texas’ advantage:**
 - ⊕ Deregulated, electricity-only energy market
 - ⊕ Streamlined approval process
 - ⊕ Abundant land
 - ⊖ Minimal state-incentives
- **California’s challenge:**
 - ⊕ Strong state incentives
 - ⊖ Strict regulations
 - ⊖ Interconnection delays

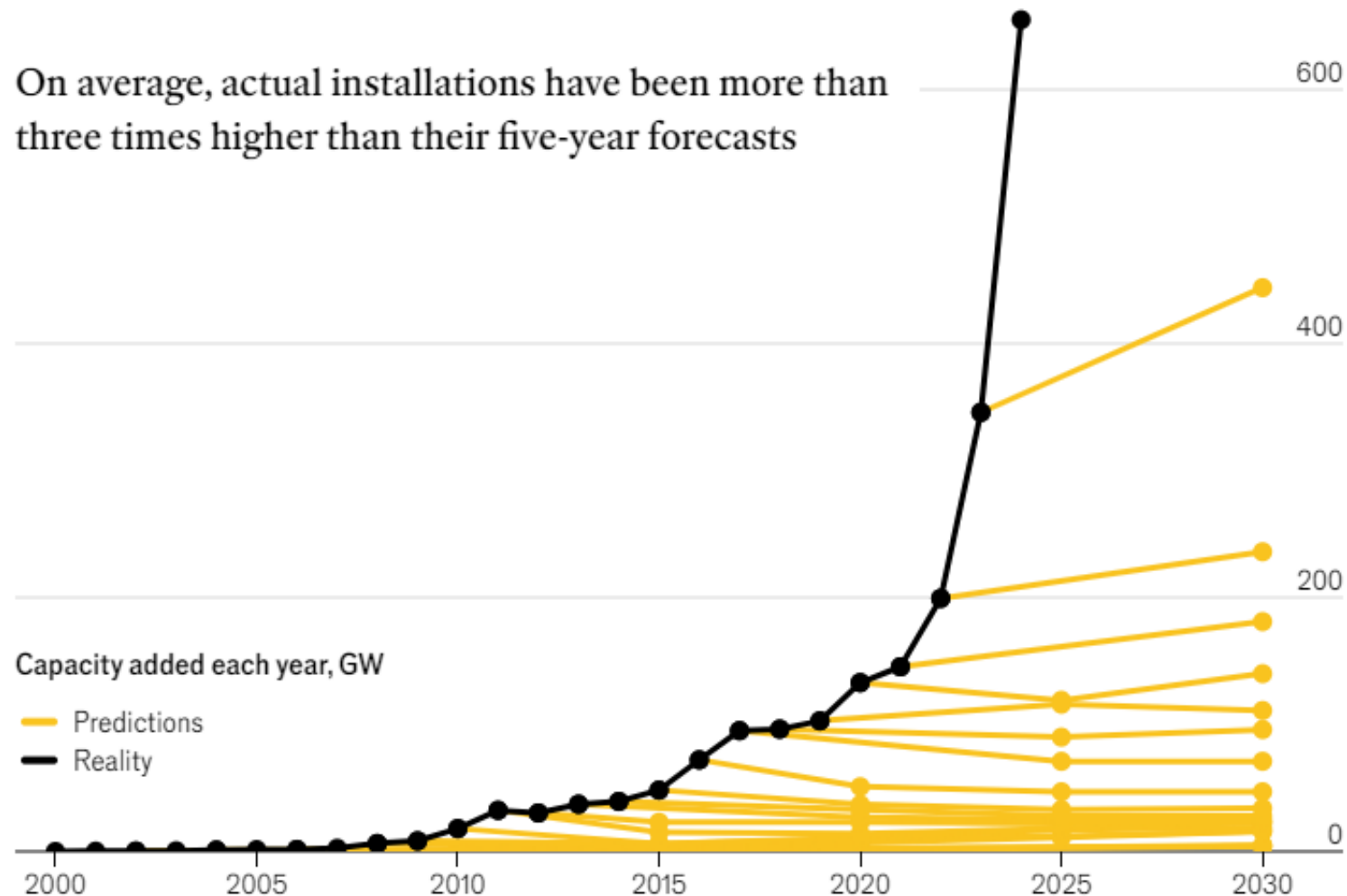
Source: ACP, [Clean Power in 2024](#) (2025); EIA, [Solar, Battery Storage to Lead New U.S. Generating Capacity Additions in 2025](#) (2025).
Credit: Hyae Ryung Kim, Taicheng Jin, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Kim *et al.*, “Scaling Solar” (14 August 2025).

DAWN OF THE SOLAR AGE

A SPECIAL ISSUE

↓ **EASY PV** *how solar outgrew expectations*

On average, actual installations have been more than three times higher than their five-year forecasts

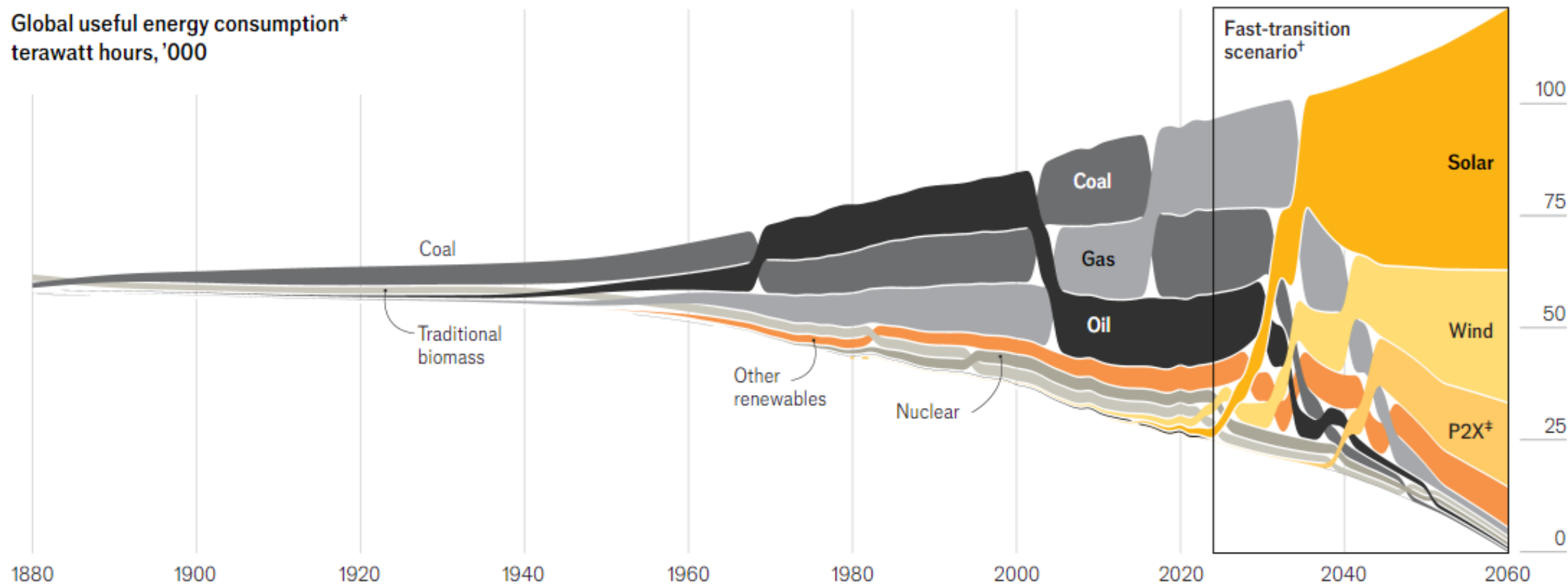


Installations for 2024 are an estimate from BloombergNEF for direct current solar capacity

Sources: IEA; Energy Institute; BloombergNEF

↓ **HERE COMES THE SUN** *the past and a possible future*

Global useful energy consumption*
terawatt hours, '000

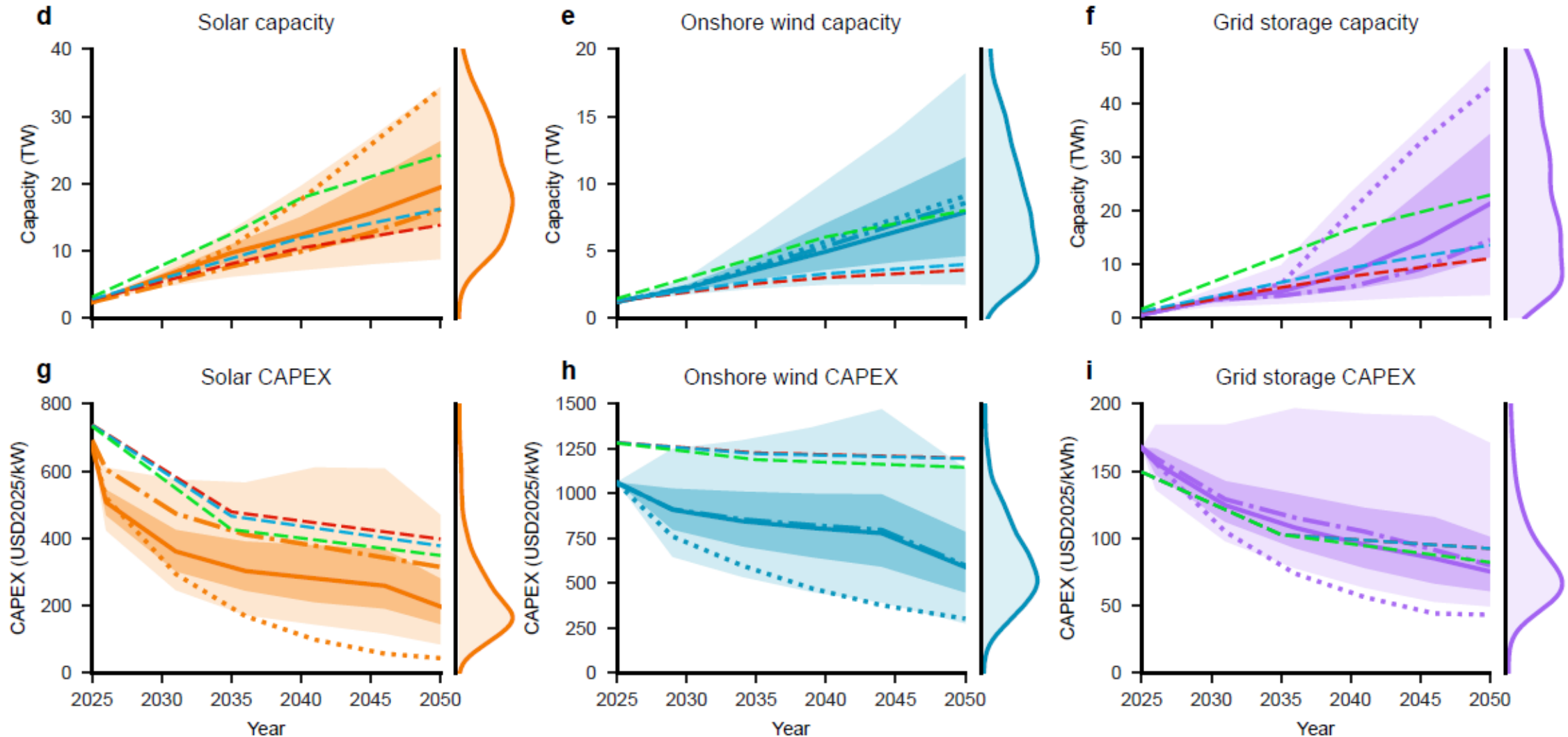


Sources: Rupert Way; Our World in Data

*Primary energy adjusted for waste-heat losses [†]From Way et al. (2022) [‡]Electricity-conversion technologies (eg green hydrogen)

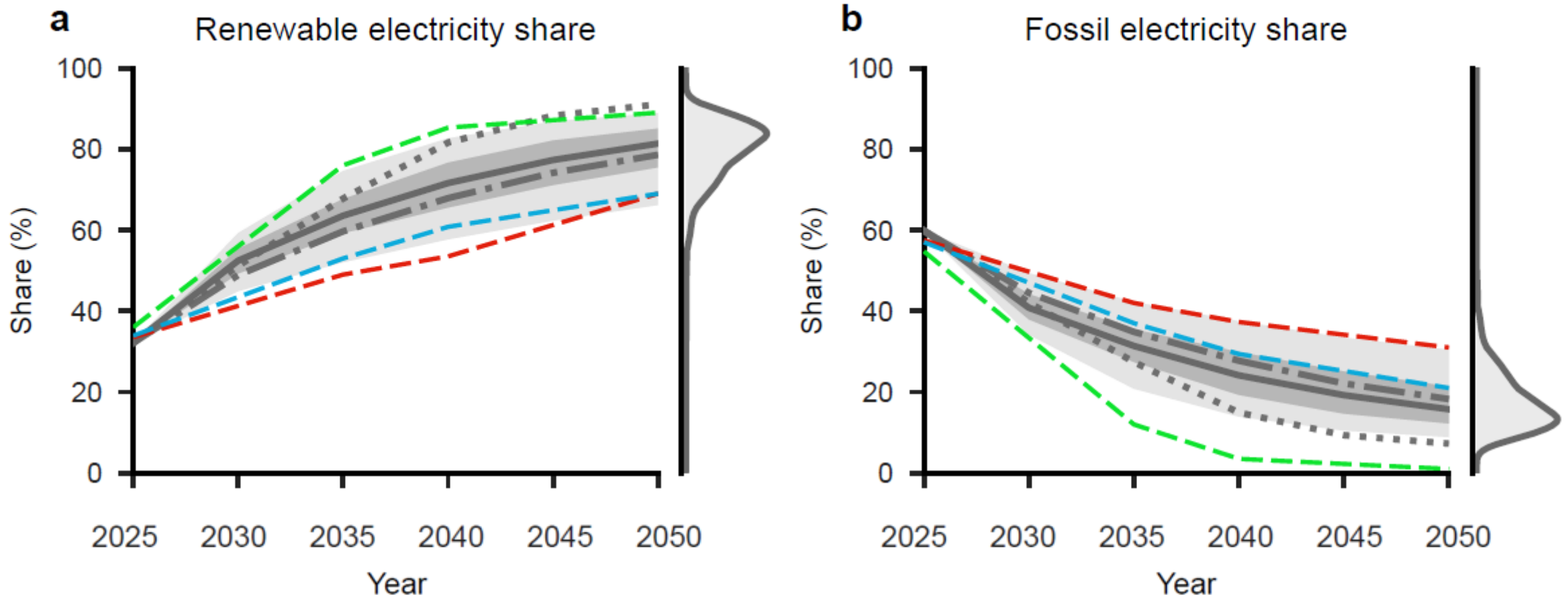
Source: *Economist* "[Sun Machines](#)" (20 June 2024)

Large spread of solar, wind, and grid storage pathways...



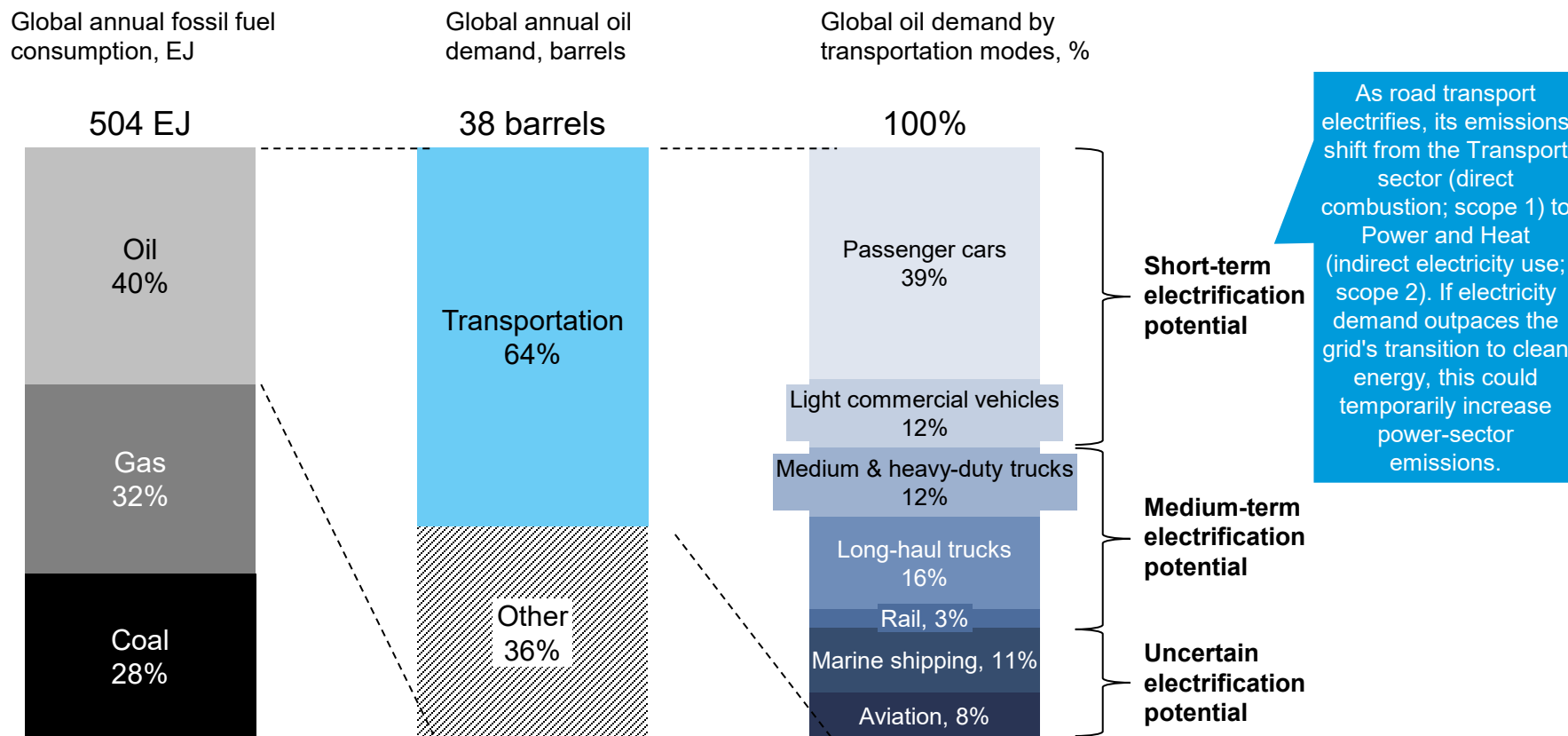
Consistently high (>75%) renewables share by 2050

Correspondingly low fossil electricity share (<20%)



Combustion engines account for >60% global oil consumption, with ~50% of those vehicles electrifiable in the short term

Oil is the largest fossil fuel due to transportation, where only passenger vehicles (~50% demand) have a clear electrification path; shipping and aviation lack ready alternatives

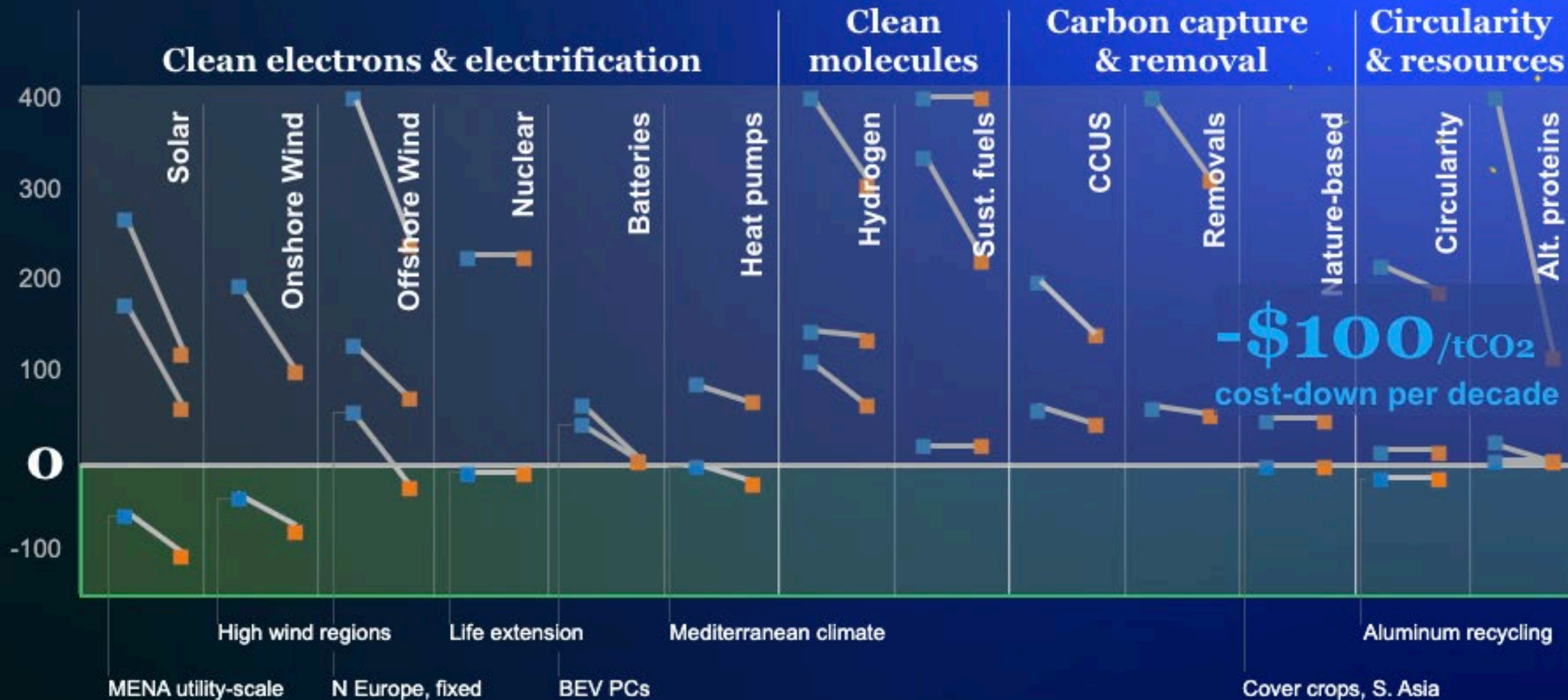


Observations

- Transportation is still the major off-taker of current oil production – with over 64% of around 38 billion barrels of oil being consumed
- Smaller engines, making up around 60% of the transportation sector and used in passenger and light commercial vehicles, are easier to electrify
- Direct electrification faces structural constraints in high energy-density applications, as used in shipping, trucking and aviation. Decarbonization pathways likely rely on synthetic fuels, biofuels, hydrogen derivatives, and efficiency improvements rather than direct electrification

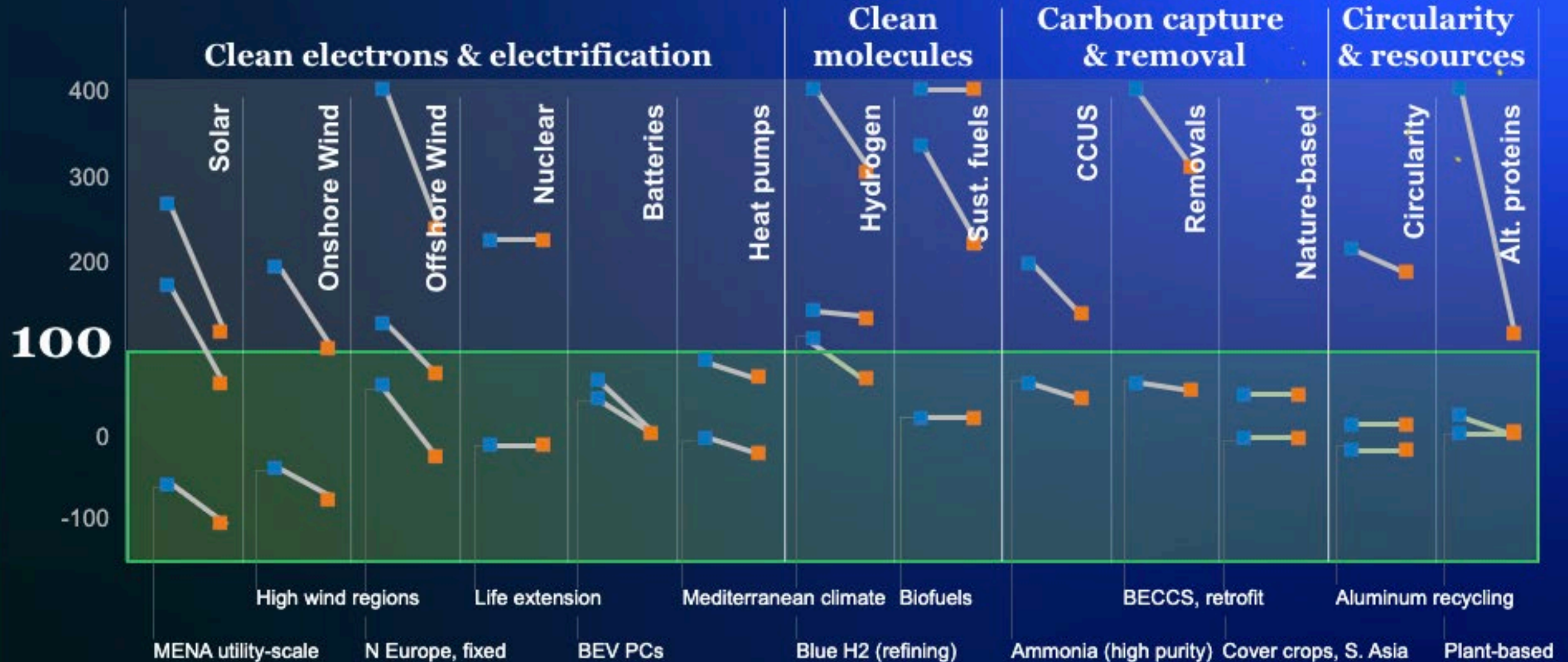
10 % of techs in the money today – steep cost-down to 2030

Estimated abatement costs, USD/tCO₂e



100\$/tCO₂ carbon tax would make most techs competitive

Estimated abatement costs, USD/tCO₂e



25 September 2024

WSJ: "Big Tech Is Rushing to Find Clean Power to Fuel AI's Insatiable Appetite"

by Jennifer Hill and Amrith Ramkumar

AI

News

WSJ

Over time, tech companies say AI could help them limit emissions by, for example, helping utilities more efficiently deploy renewable power. But it isn't clear such benefits would come close to making up for the soaring emissions.

"It's a massive increase that may not be justified by the productivity gains from AI," said Gernot Wagner, a climate economist at Columbia Business School.

gwagner.com/wsai

① Productivity gain to justify CO₂?



gwagner.com/ai (Somehow the most popular page on my personal site: my AI policy)

The AI Revolution Mirrors the Green Transition

The need for massive upfront investments and the likelihood of significant job displacement imply remarkable parallels between the AI buildout and the green transition. In both cases, the state has an important role to play in guiding market forces on behalf of the public good.

AI

Climate tech

Green Growth

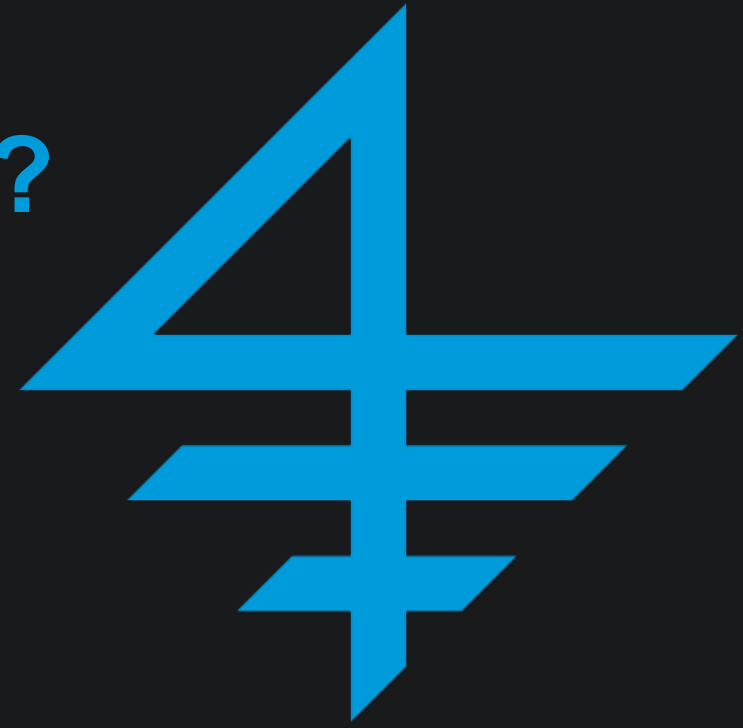
Columns

Project Syndicate

By Adam Michael Bauer and Gernot Wagner

CHICAGO/NEW YORK—The AI race is already generating forces that are transforming the global economy. That makes it surprisingly similar to the green transition, given the potential of both to upend traditional industries, labor markets, and geopolitical balances. Both call for trillions of dollars in upfront investments in exchange for significant benefits over the medium and long term.

- ① Productivity gain to justify CO₂?
- ② CO₂ emissions are/will be up



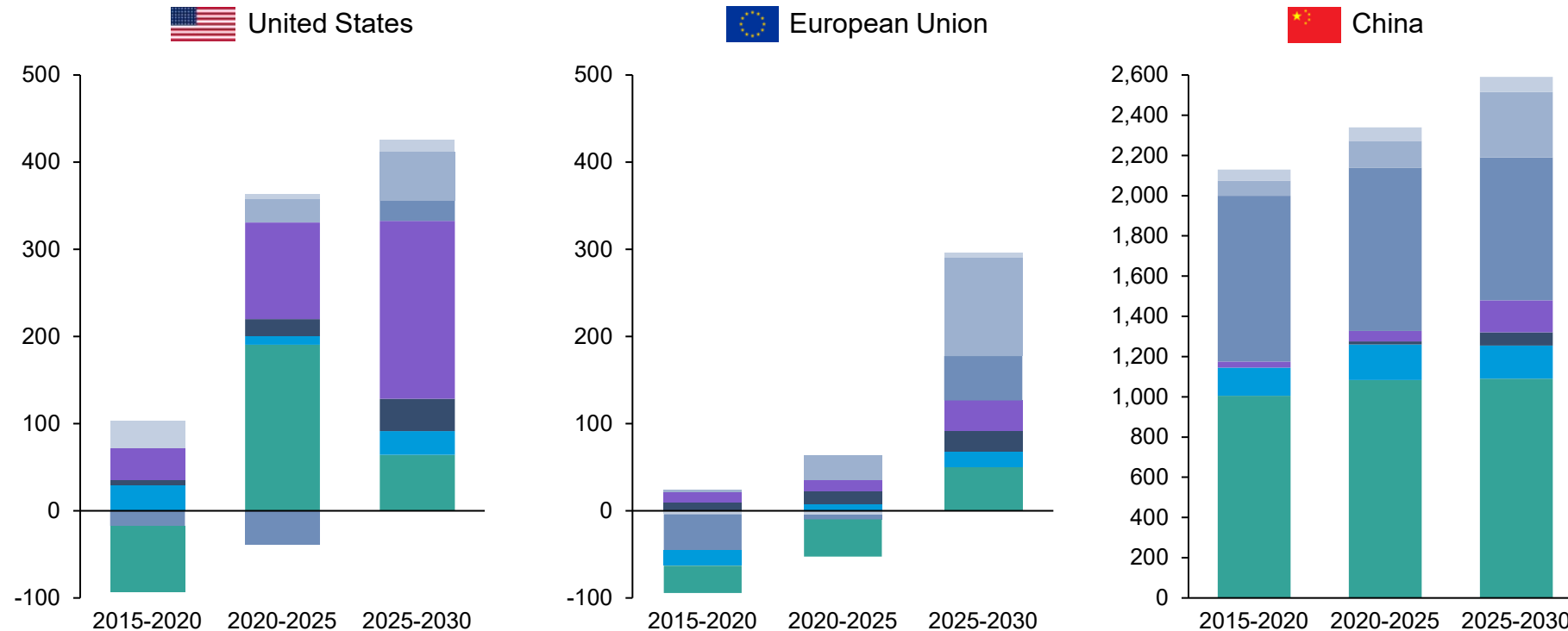
gwagner.com/cki-grids

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

Industry Cooling Heat pumps Data centers Rest of building Transport Other



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 (28 September 2026).

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



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



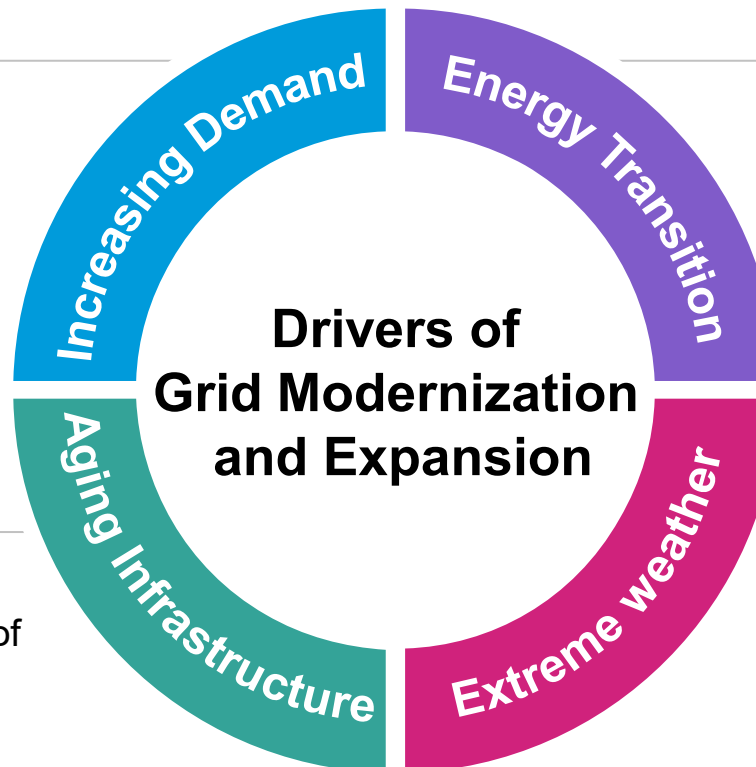
Structural shift in the electricity system

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



Escalating climate & weather events

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

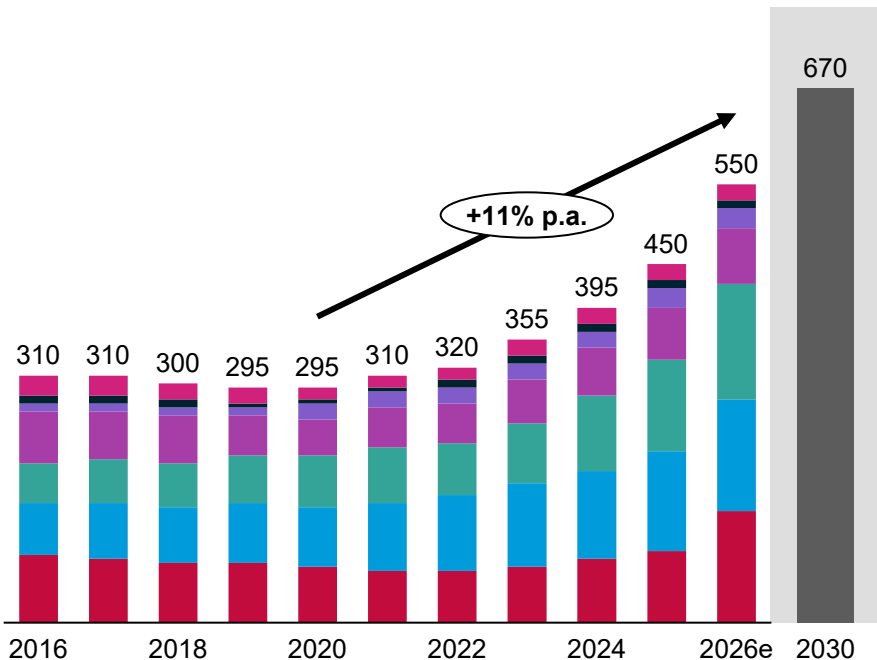


Global grid investment is expected to rise to +\$500B in 2026 and increase through 2030, driven by infrastructure, materials, and labor

Investment grew ~85% over 5 years, targeted to reach \$600B by 2030 in NZE¹

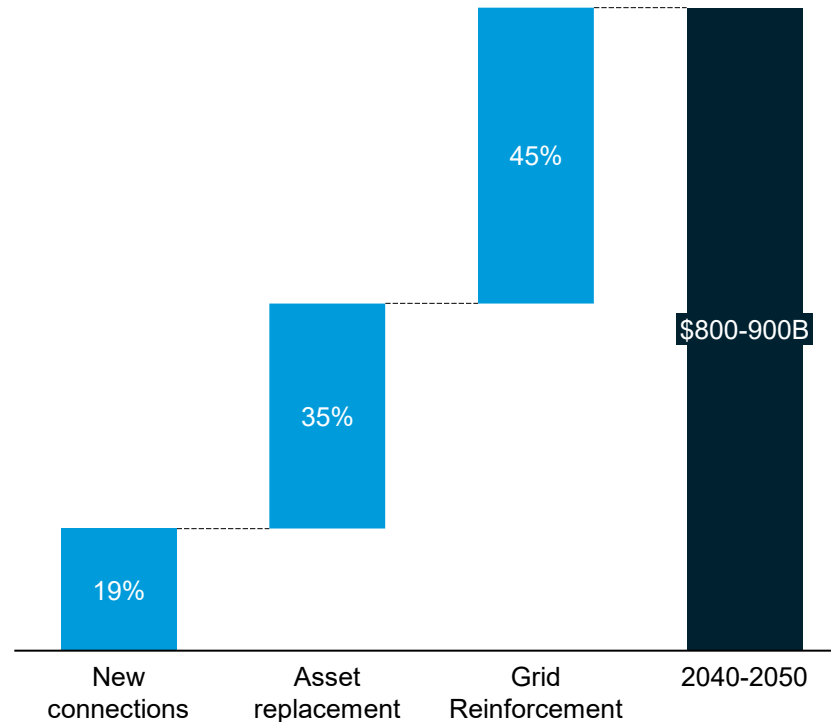
Investment in power grid infrastructure, 2016-2026e USD Billions

■ ROW ■ Central and South America ■ Europe ■ China
■ Africa ■ APAC ex. China ■ North America



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

¹In 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).

- ① Productivity gain to justify CO₂?
- ② CO₂ emissions are/will be up
- ③ AI opportunities to cut CO₂



gwagner.com/cki-grids

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 Profile¹	- 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 Opportunity²	- Estimated \$50-\$150B+/yr from 2030-2035¹ - 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

¹The 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).

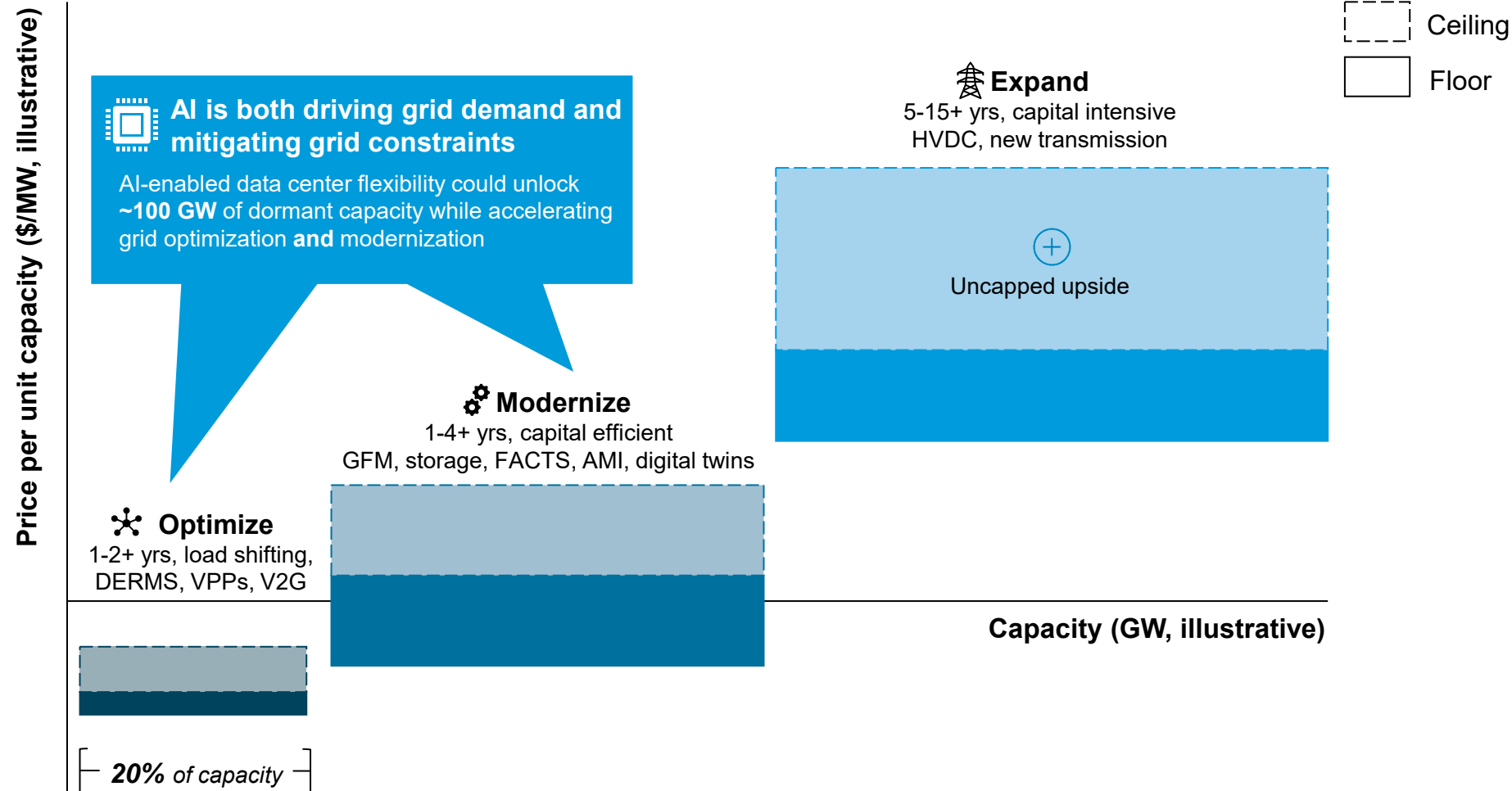
²Investment opportunity is global and based on projected investments for highlighted solutions as defined in each solution area, supplemented by World Energy Investment 2025-2026 reports aligned to STEPS 2030 and BNEF NZE and ETS scenarios. Grid expansion is driven significantly by net-new wires (transmission & 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 (28 September 2026).

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

Illustrative



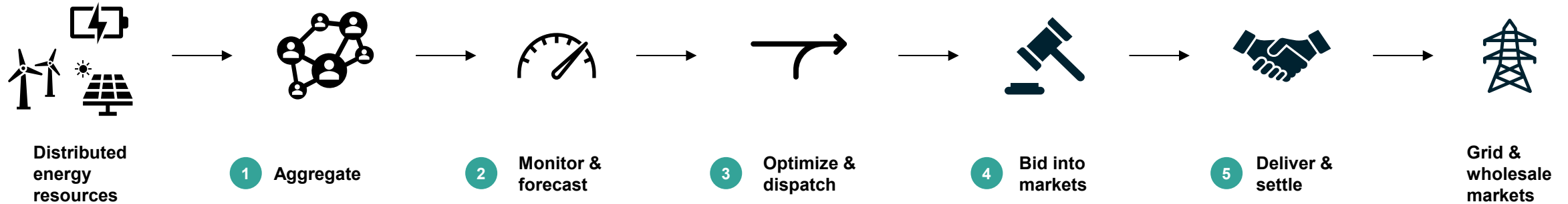
Observations

- AI could 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 Tezcan, Ariela Farchi, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (28 September 2026).

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

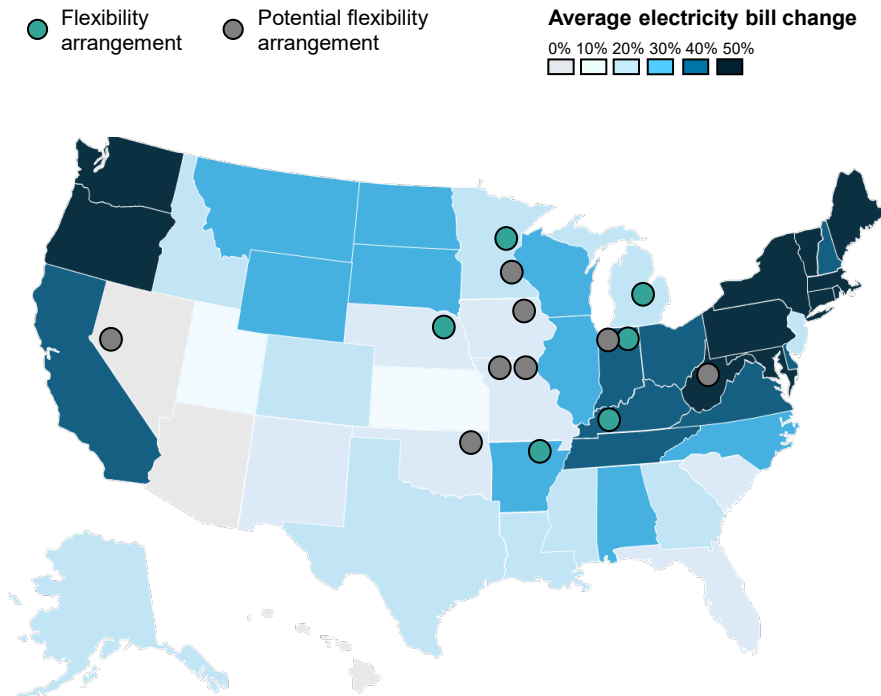
Source: [Pathways to Commercial Liftoff: Virtual Power Plants](#) (US DOE, 2025); [2025 North America VPP Market](#) (Wood Mackenzie, 2025)

Credit: Vincent Sandow-Straesser, Ariela Farchi, and [Gernot Wagner](#). [Share with attribution:](#) Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (28 September 2026).

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

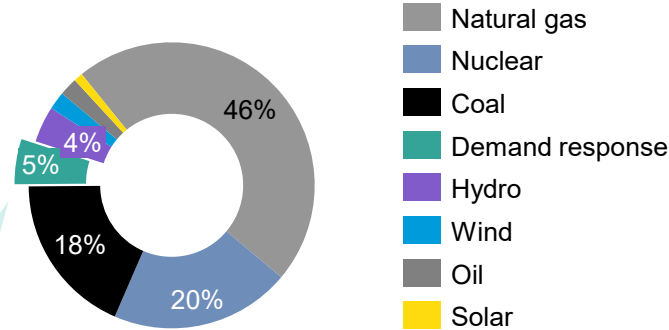
Demand flexibility agreements are in place for data centers across the U.S.

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



Deal Dynamics

- Voltus aggregates 100 MW annually of customer flexibility (batteries, smart thermostats, and other flexible assets) over 3 years in a Google-funded 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

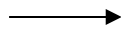
Source: [Large Load Customer Projects and Tariffs](#) (EEI, 2026); [A new framework for DER value in the speed to power era](#) (The Brattle Group, 2026); [How we're making data centers more flexible to benefit power grids](#) (Google, 2025); [Google and Voltus to deliver grid capacity and local economic 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).

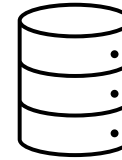
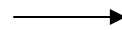
Advanced Metering enables two-way digital communication between utilities and customers, enabling smarter grid operations



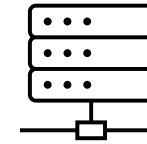
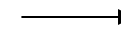
1 Smart meter



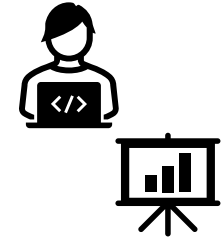
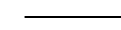
2 Communication tower



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

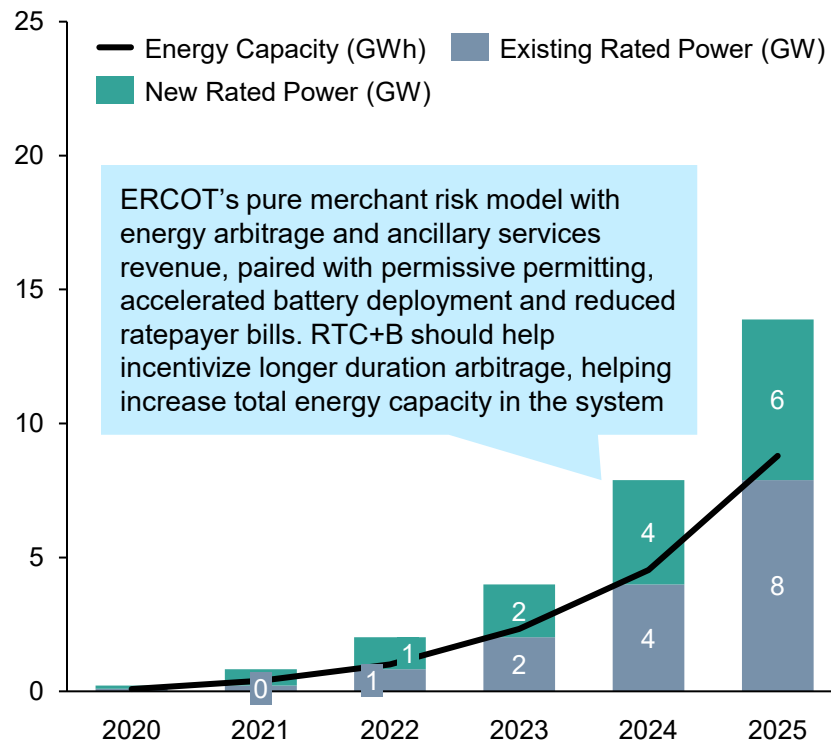
Sources: [Demand Response and Advanced Metering](#) (FERC, 2025); [Electricity Grids and Security Energy Transitions](#) (IEA, 2024); [What is advanced metering infrastructure \(AMI\)](#) (IBM, 2026).

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 (28 September 2026).

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

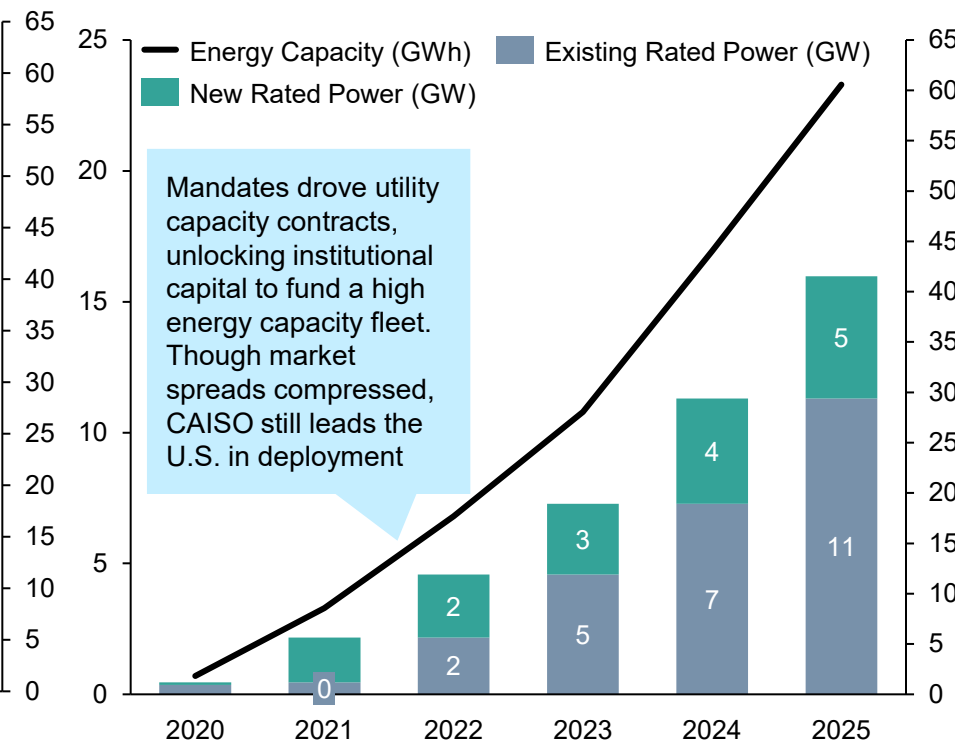
Private investment and arbitrage returns drove high battery deployment in ERCOT

ERCOT Battery Fleet, 2020-2026¹



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

CAISO Battery Fleet, 2020-2026¹



Observations

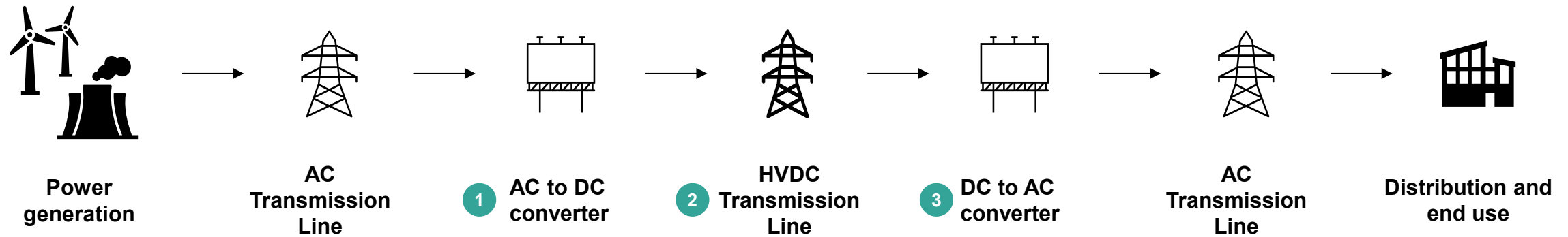
- Battery deployment continues to accelerate as battery cell costs reduce and duration is extended
- The global battery storage market is **expected to exceed \$100B in 2026**, led by grid-connected batteries (~80%)²
- Batteries can help balance the grid, complement renewables, and lower customer electricity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

¹Modo 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



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

¹AC 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 Tilkioglu, 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

	Roles & Responsibilities	Delay hotspot stages				
		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		●			●
Build & Deploy	Finance	Regulate	Demand	● Primary Decision Gate ● Secondary Influence		
				>4 yr median IR-to-COD ¹	~4 yr federal permitting	>2.5 yr ² equipment lead times + constrained EPC capacity

¹Interconnection 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).

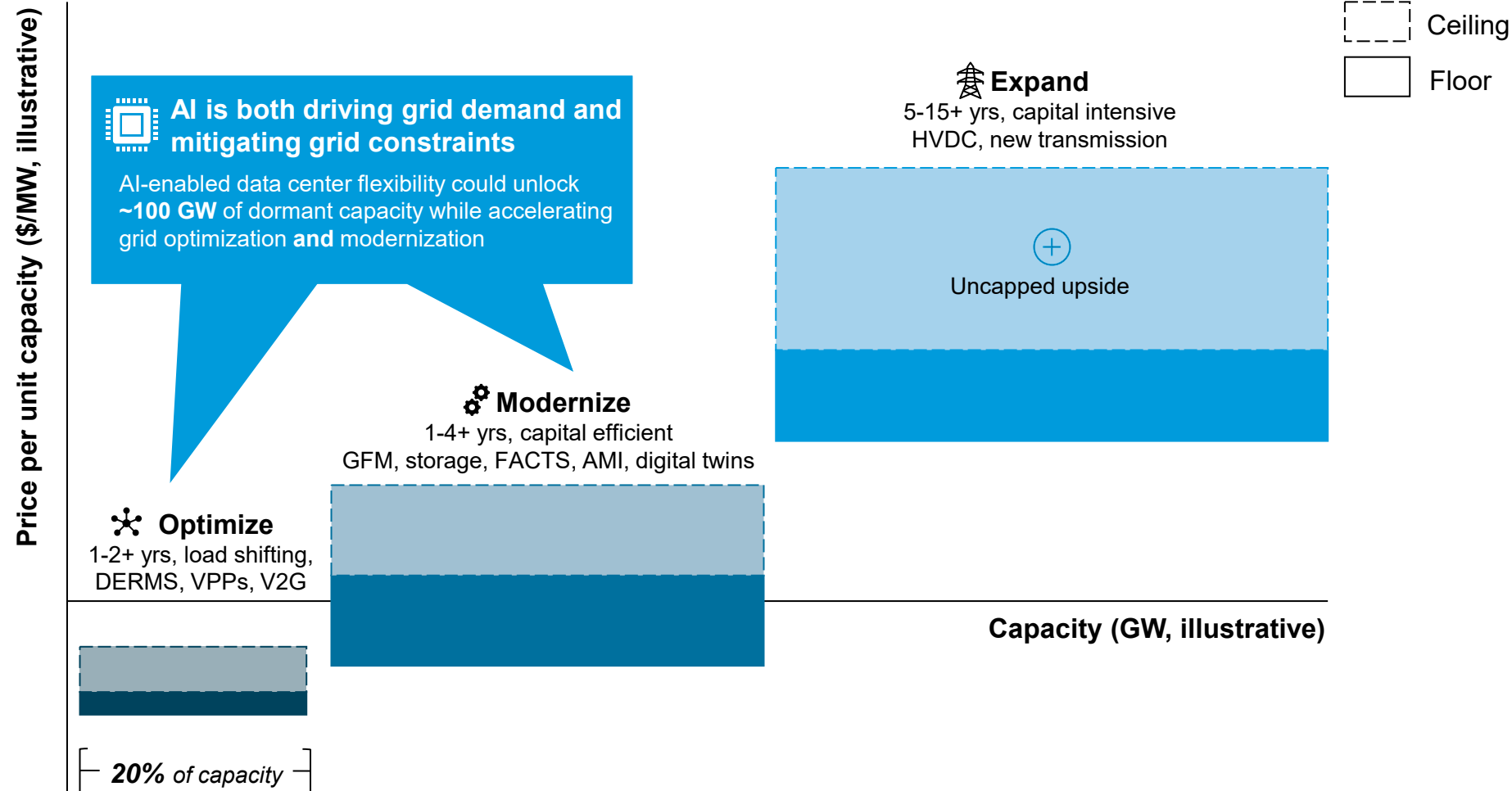
- ① Productivity gain to justify CO₂?
- ② CO₂ emissions are/will be up
- ③ AI opportunities to cut CO₂
- ④ No way around grid expansion



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

Illustrative



Observations

- AI could 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 Tezcan, Ariela Farchi, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Powering Grids," Columbia Business School Climate Knowledge Initiative (28 September 2026).

Powering Grids Executive Summary

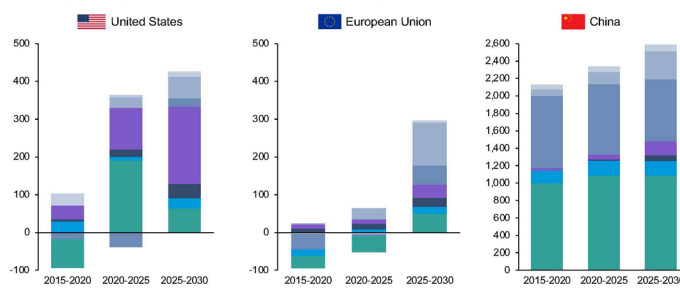
Gernot Wagner, Hasan Alawadhi, Sevgi Helin Tilkicioglu, Dominica Wambold, Ilayda Tezcan, Gunay Kiran, Stephanie Chen, Christy Wong, Ryon Roque, Vincent Sandow-Straesser, Isabel Hoyos, Denis Morrow

Cite as: Wagner et al. "Powering Grids," Columbia Business School Climate Knowledge Initiative (28 September 2026).

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



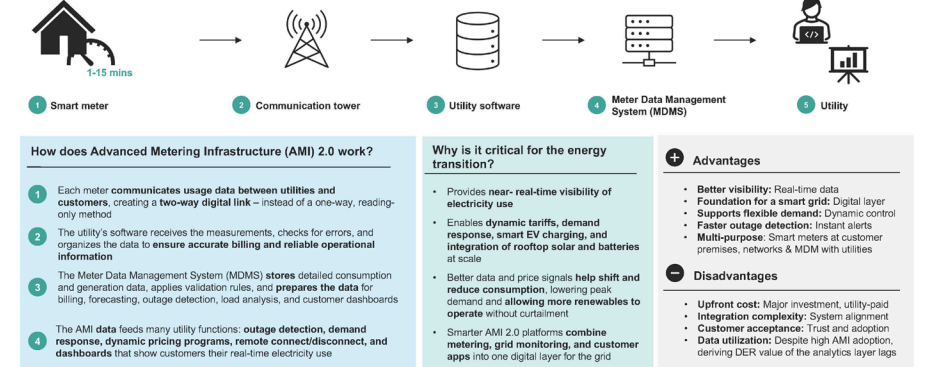
Sources: *Electricity 2026* (IEA, 2026); *World Energy Investment 2026* (IEA, 2026). Credit: Gernot Wagner, Dominica Wambold, Arela Farchi, and [Gernot Wagner](#). Share with attribution: Wagner et al. "Powering Grids," Columbia Business School Climate Knowledge Initiative (28 September 2026).

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

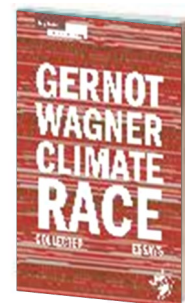
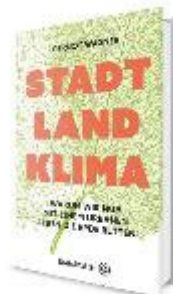
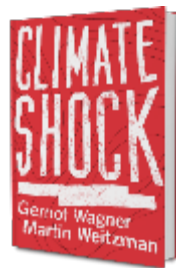
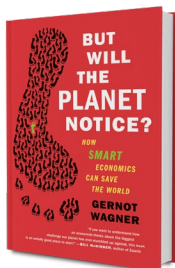
	Optimize grid assets	Modernize and harden the core	Expand grid networks
Definition	Maximize the value of the grid through digital intelligence and demand management	Upgrade and modernize the core with capital efficient physical and technical augmentation	Structurally extend the grid's network to integrate 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 2030-2035¹ - 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

¹The 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).
²Investment 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 the core includes IEA's Power segment of battery storage; the optimize range includes grid modernization and a subset of end-use related charging infrastructure, with savings potential reflecting estimated grid value from demand flexibility.
Sources: *Building the Future Transmission and Distribution* (IEA, 2025); *World Energy Investment* (IEA, 2025); *Electricity 2026* (IEA, 2026); *Energy Storage: Enabling the 100% Renewable Grid* (BNEF, 2026); *Electric Vehicle Charging* (IEA, 2025); *The Value of Demand Flexibility* (IEA, 2025); *Building Grids Faster* (Energy Transitions Commission, 2024); *Electricity Grids and Secure Electricity* (IEA, 2024).

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



Sources: *Demand Response and Advanced Metering* (FERC, 2025); *Electricity Grids and Security* (Energy Transitions (IEA, 2024); *What is advanced metering infrastructure (AMI)* (BMA, 2026). Credit: Sevgi Helin Tilkicioglu, Hasan Alawadhi, Isabel Hoyos, Dominica Wambold, Arela 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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