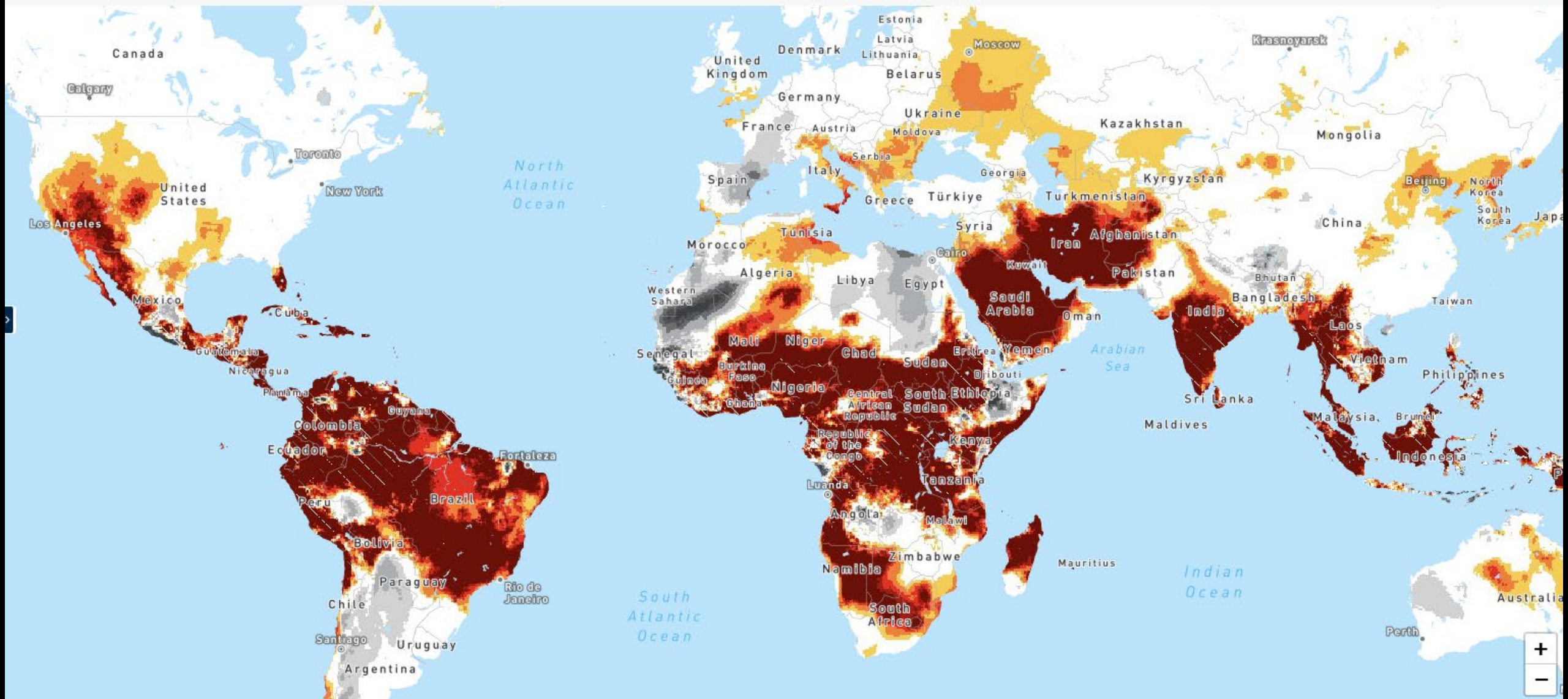


Climate Shift Index [Learn more...](#)

for average temperatures, Oct 9, 2026

Change in likelihood due to climate change



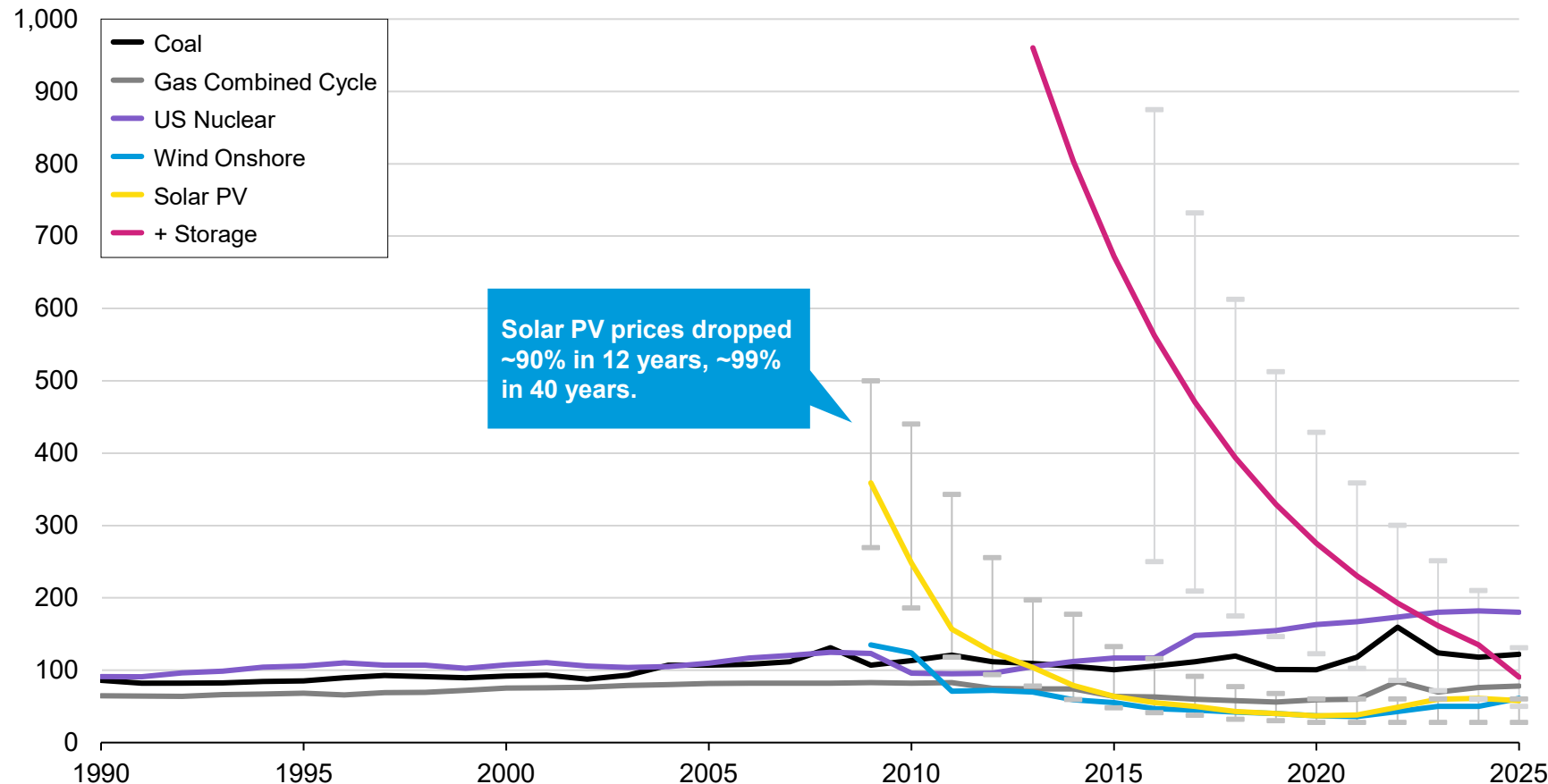
Source: climatecentral.org/climate-shift-index

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

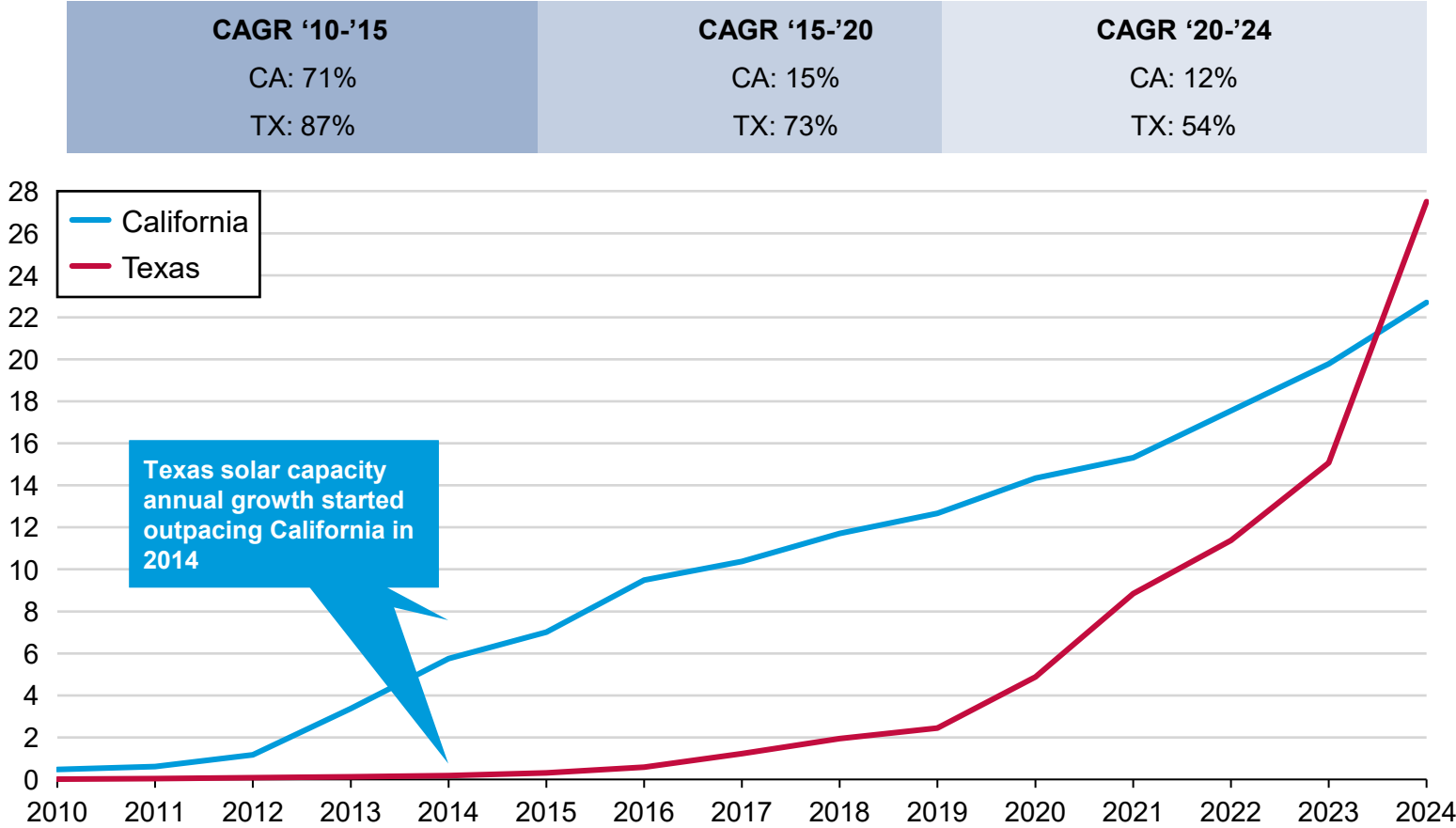
- **Solar photovoltaic (PV) prices dropped by ~80% in the past decade**, wind by ~70%, and lithium-ion battery costs by ~90%.
 - PV price drop primarily driven by **improvements in module efficiency** and **economies of scale**.
 - **Onshore wind** remained the cheapest for the longest, **now beaten 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).

One Big Beautiful Bill Act phases out incentives for solar & wind, biggest impacts on EV adoption and US manufacturing

Technology	IRA Incentives (2022-2025) vs OBBBA Policy Changes (2025 onward)		Industry Outlook ² in the U.S. with OBBBA	
Solar & Wind		48E and 45Y credits available until 2033 - Phased out after 2027¹; sourcing rules tightened (FEOC)		- Continued growth trend through 2030, significant slow-down by 2035³ - Overall higher electricity end-user prices
Green Hydrogen		45V credit available until 2033 - Phased out by 2028		Deployment undermined by weak demand, loss of incentives, and sourcing restrictions
Electric Vehicles		30D, 25E, and 45W credits for EVs; 30C for charging infrastructure - Phased out by 2026 (30D/25E/45W by Oct 2025, 30C by Jul 2026)		Consumer adoption hit by loss of credits and policy uncertainty
Manufacturing		45X and 28C credits support clean tech supply chain 45X phased out after 2027 (wind) and 2028 (solar/storage); 48C compromised by sourcing rules		- Clean energy manufacturing hit by loss of credits and supply chain constraints - Subsidy loss threatens existing investments
Carbon Capture		45Q credit available until 2033 - Preserved; EOR provisions enhanced		Growth in oil and gas CCS, challenged by foreign entity restrictions
Energy Storage		48E credit available until 2033 - Preserved in full		Preserved credits support growth, challenged by foreign entity restrictions
Biofuels		45Z credit available until 2027 - Extended to 2029; feedstock sourcing rules tightened; capped SAF		Slow adoption, challenged by foreign entity restrictions
Geothermal		48E and 45Y credits available until 2033 - Preserved in full		- Moderate growth from low baseline - R&D support for superhot geothermal
Nuclear		- ITC/PTC for new, 45U for existing plants available until 2033 - Preserved in full; fuel sourcing rules apply after 2028		- Challenges remain for large ~1GW reactors - More optimistic outlook for SMRs, XMRs
Oil, Gas		- No support - Gains tax breaks, public land access, and regulatory rollbacks		Stable or rising share, as renewables face disadvantage

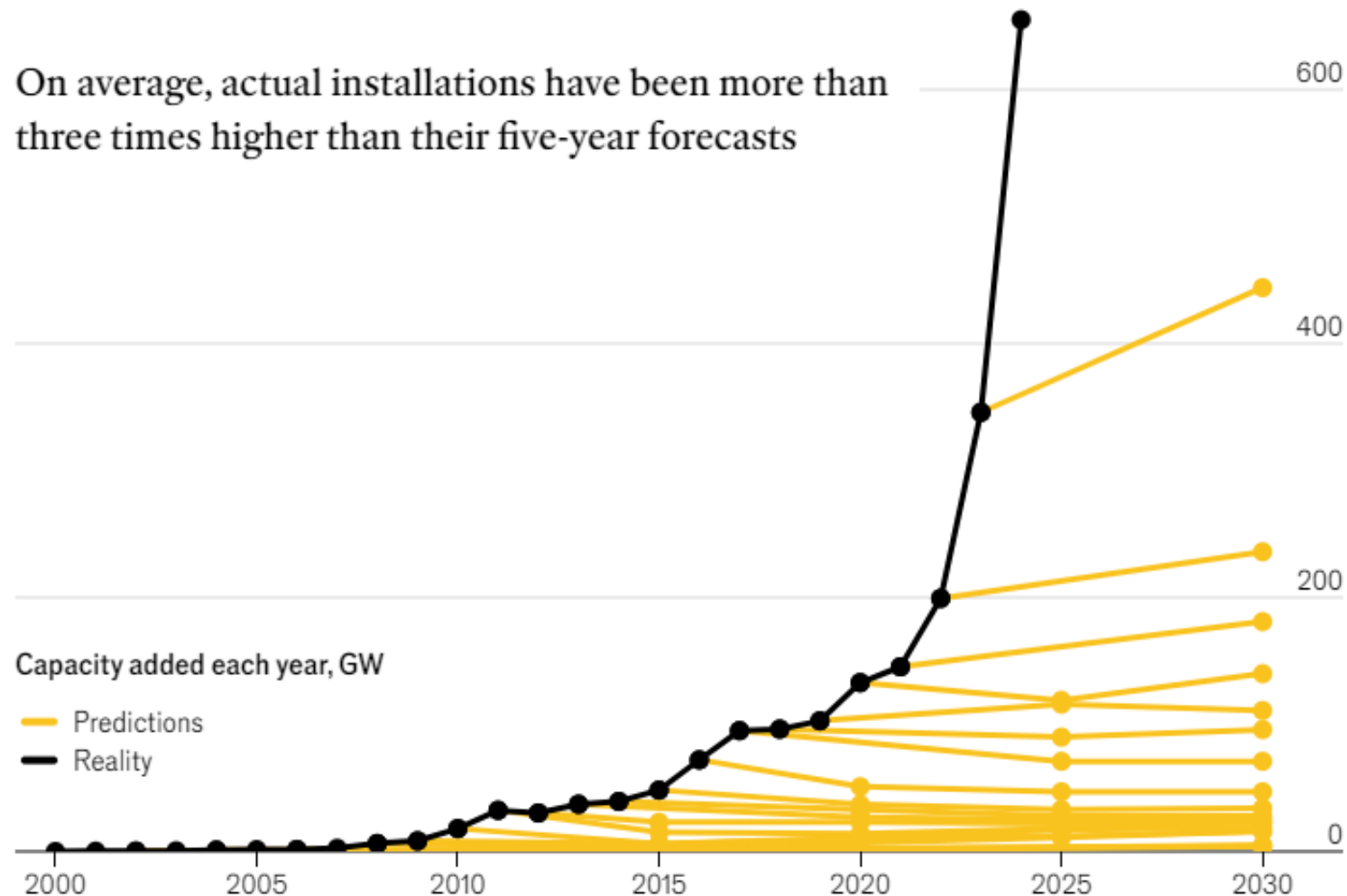
(1) Construction by 4 July 2026 = 4 years to completion, after = in service before 2028. (2) EV, Carbon Capture, Energy Storage, Biofuels, Hydrogen and Oil, Gas & Coal's Outlook use EIA's reference case and alternative transportation case. (3) Outlook expectations for solar and wind based on EIA's 2025 AEO, using "Reference" Case and "High Zero-Carbon Technology Cost" Case. Sources: Congress, [One Big Beautiful Bill Act](#) (2025); DOE, [Inflation Reduction Act](#) (2022); Norton Rose Fulbright, [Effects of "One Big Beautiful Bill" On Projects](#) (2025); CKI Analysis (2025). Credit: Mariana Castaño, Ariela Farchi, Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Castaño et al, "Climate Impact of One Big Beautiful Bill Act" (15 July 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

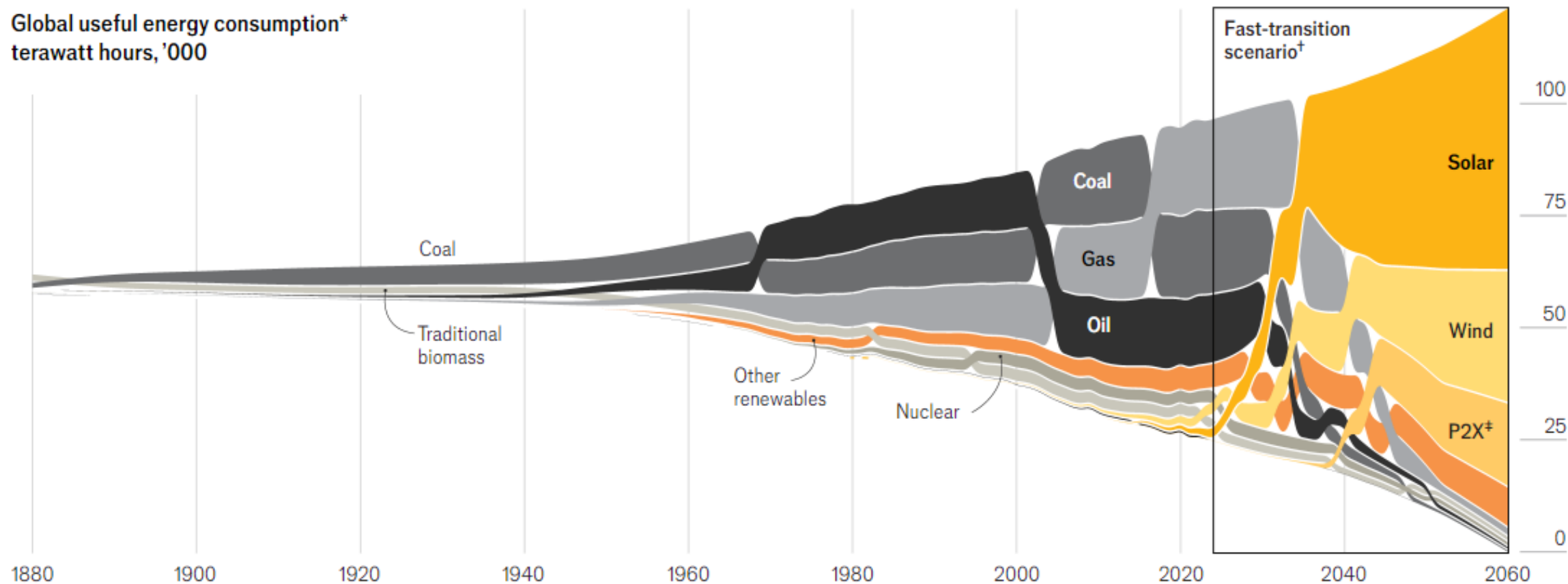


Installations for 2024 are an estimate from BloombergNEF for direct current solar capacity

Sources: IEA; Energy Institute; BloombergNEF

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

Global useful energy consumption*
terawatt hours, '000

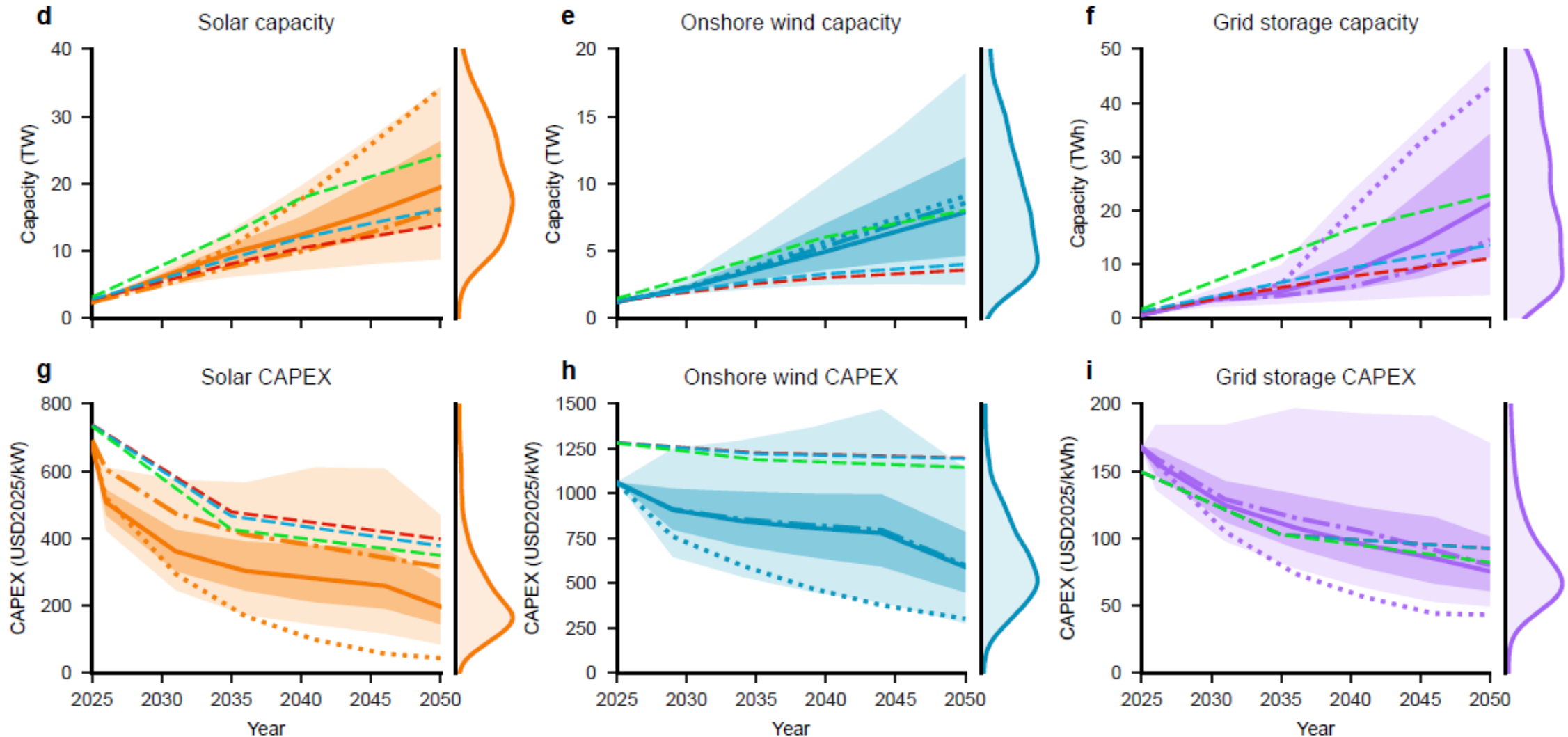


Sources: Rupert Way; Our World in Data

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

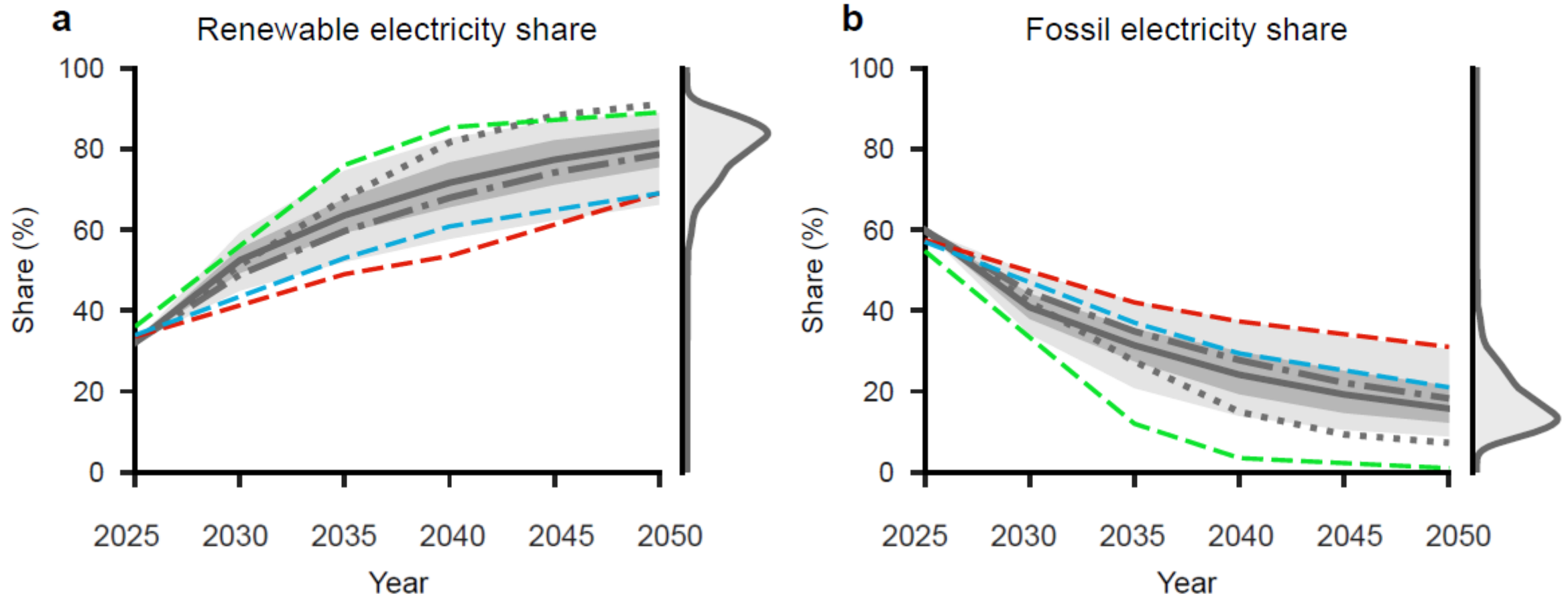
Source: *Economist* "[Sun Machines](#)" (20 June 2024)

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



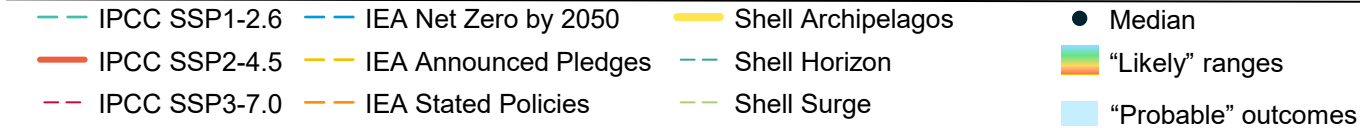
Consistently high (>75%) renewables share by 2050

Correspondingly low fossil electricity share (<20%)

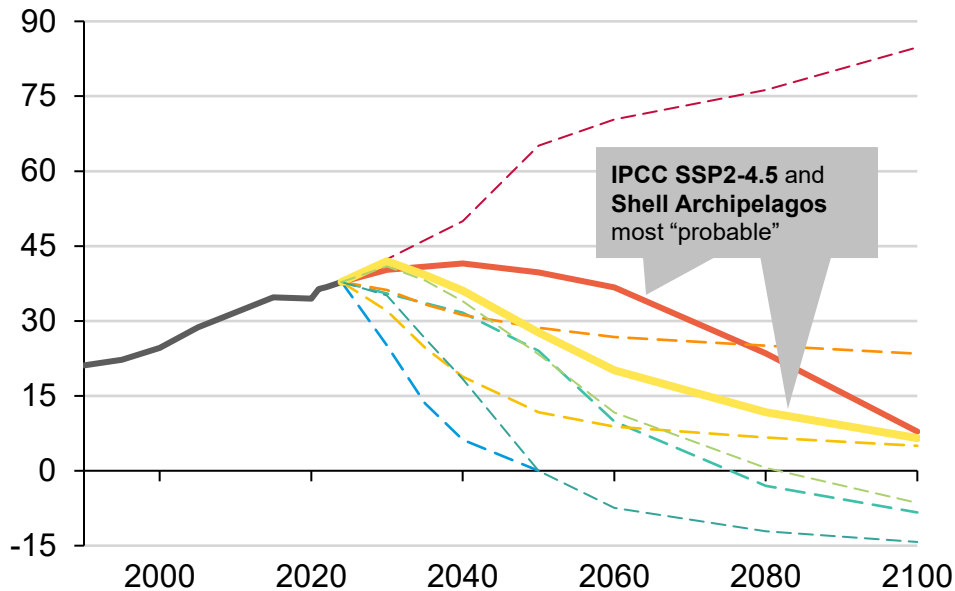


Early decarbonization investments are key to keeping temperatures within livable range and saving trillions in climate costs

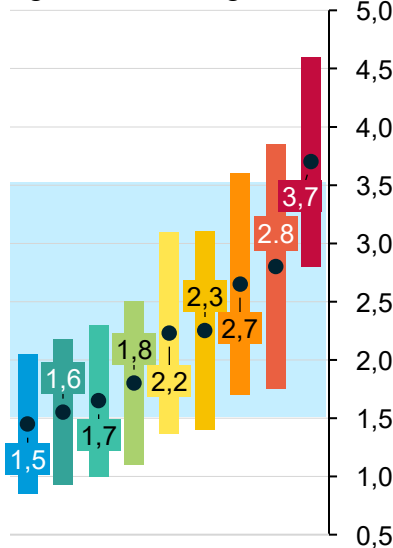
Even the least-ambitious Shell scenario reaches near-zero emissions by 2100, but speed is essential to avoid the worst climate impacts and runaway economic costs



Annual global CO₂ emissions, GtCO₂



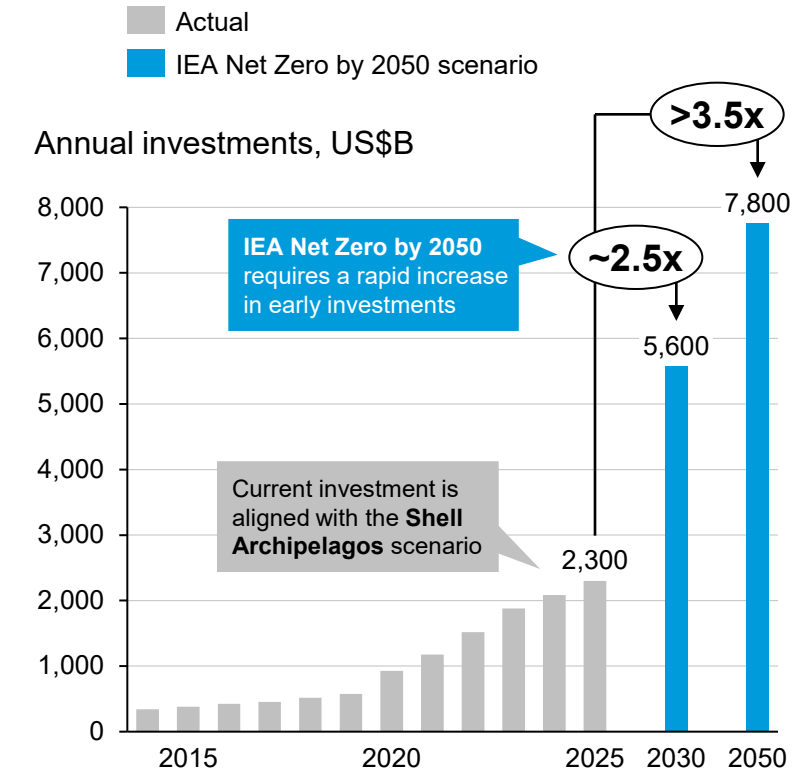
Projected average global warming¹, °C



Climate impacts, % GDP loss



Low-carbon investment has risen rapidly recently, though ~2.5-3.5x gap remains



¹ Global warming by 2100 above 1850-1900 average, with 66% "likely" ranges. "Probable" ranges are based on own best estimate of current trends.

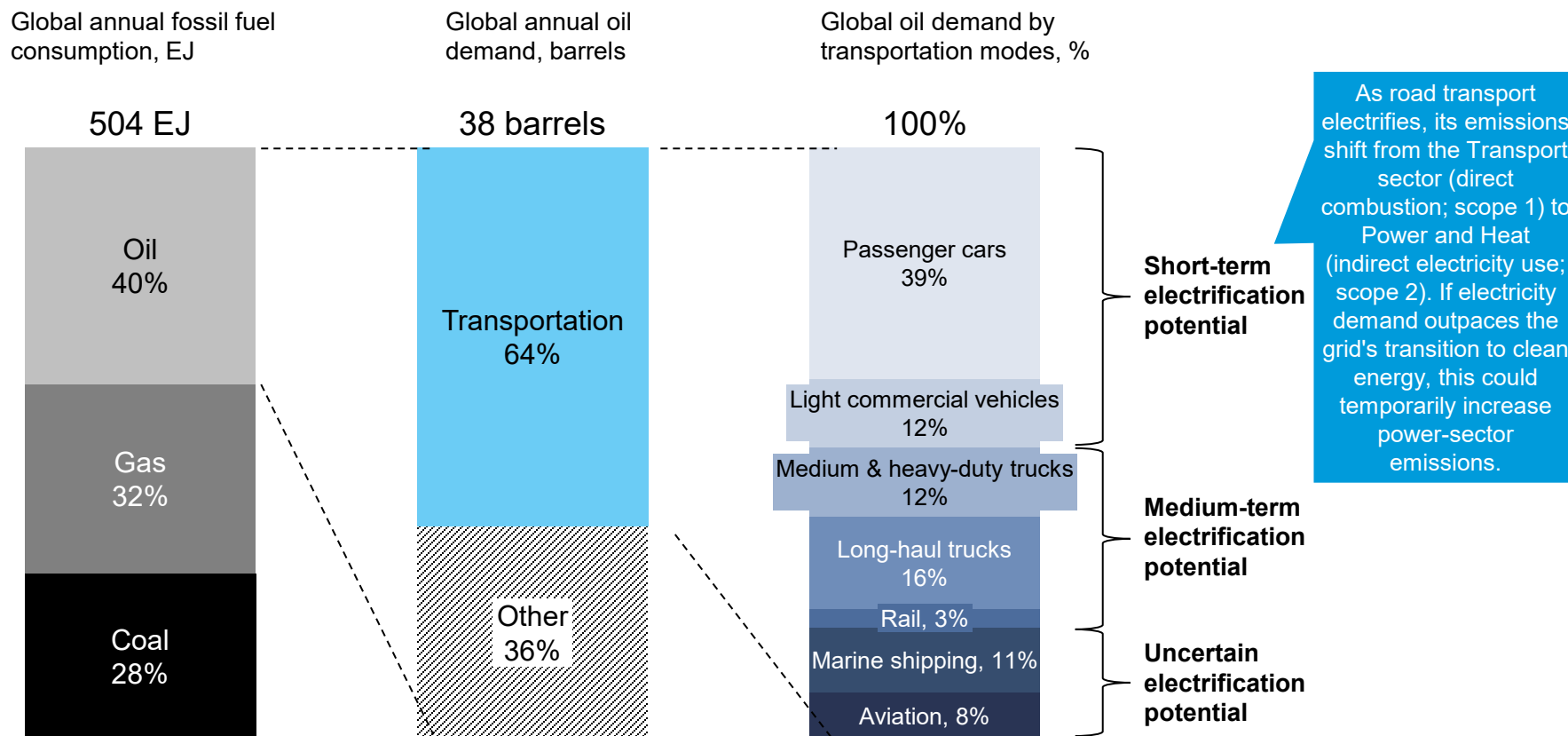
² Global warming of >2°C is expected to trigger tipping points with large, highly uncertain costs — e.g., Moore et al., [PNAS](#) (2024); Dietz et al., [PNAS](#) (2021).

Sources: IPCC, [Climate Change Synthesis Report](#) (2023); Shell, [The Energy Security Scenarios](#) (2025); IEA, [World Energy Outlook](#) (2024); Nature, [Emissions – the 'business as usual' story is misleading](#) (2020); BNEF, [Energy Transition Investment Trends](#) (2026).

Credit: Anika Behrndt, Zacharia Thurston, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). Share with attribution: Wagner et al., "Probable Climates" (27 January 2026).

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

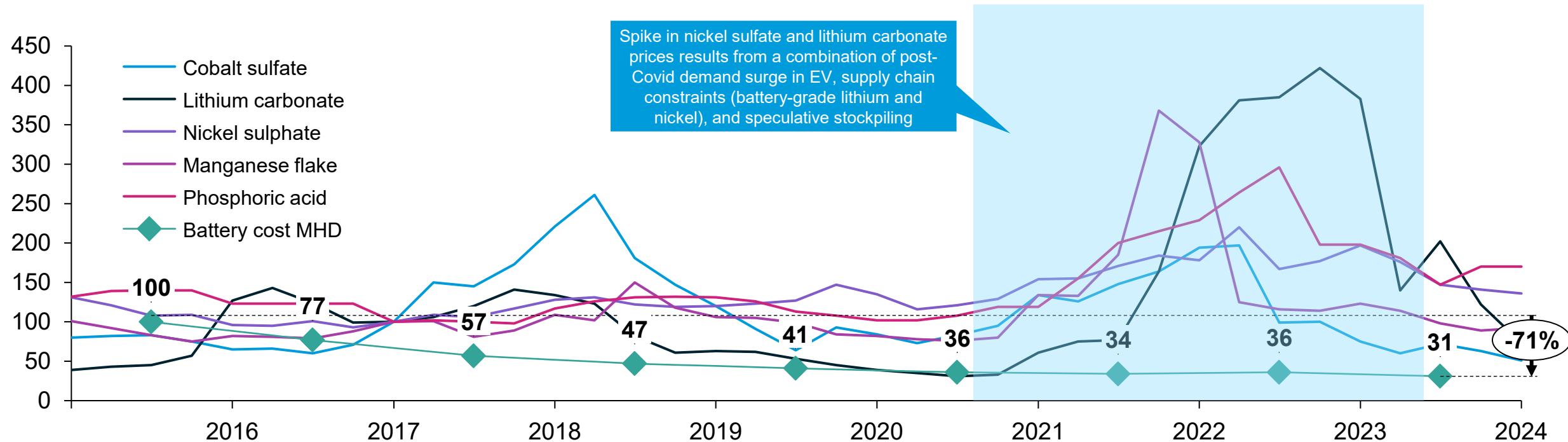


Observations

- 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

Battery prices are falling, strengthening the case for electrified medium trucks, though input costs remain volatile

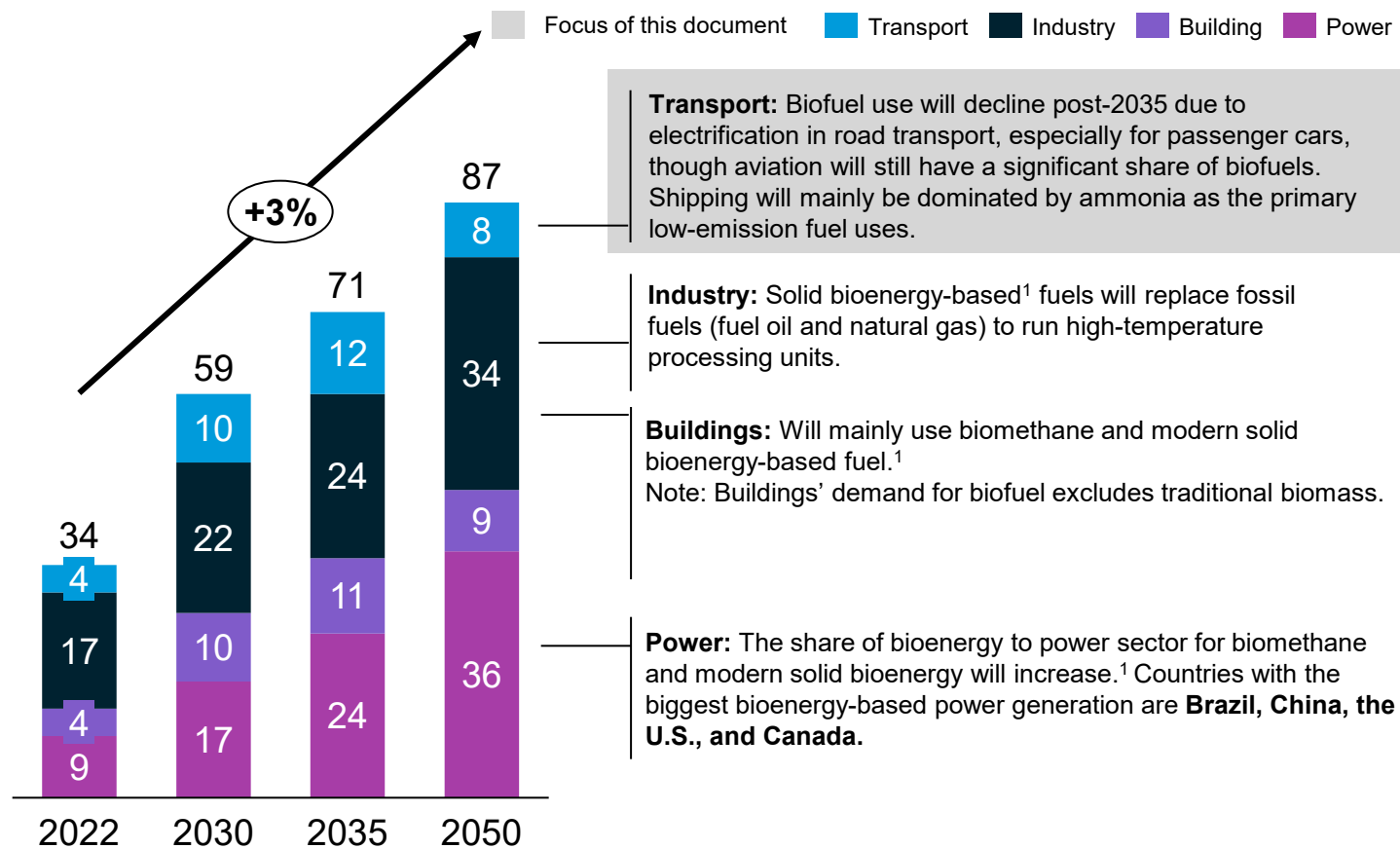
Price of select battery materials relation with battery cost of medium trucks, USD between 2015 and 2024



Global battery prices are projected to fall to ~ \$80/kWh by 2026, nearly a 50% drop from 2023 levels, and mainly driven by technological advancements such as **30% higher energy density** cells. While innovations like that reduce the TCO of LDV and **smallest medium-duty trucks (class 3-6)**, this doesn't extend to heavy-duty trucks (class 7-8) immediately, whose battery cost is projected to remain above \$100/kWh by 2026 in the U.S., even under an aggressive technological progress.

Biofuels rapidly expanding in heavy trucking, with long-term growth in power, industry, aviation, and maritime

Global biofuels demand projection in NZE scenario, EJ



Observations

Power generation will account for a major share of biofuel production toward net-zero emissions, mainly from biomethane and advanced fuels from biomass feedstock, which will comprise ~60% of total bioenergy.

Hard to abate industries (e.g., cement) will gradually shift to bioenergy, in addition to increasing efficiency and expanding electrification and carbon capture efforts.

Transport: Biofuel growth in the transport sector is significantly **influenced by the expansion of electric vehicles** in road transport and the **cost competitiveness of hydrogen.**

Road transport: Biofuels remain the dominant pathway for avoiding oil demand in the diesel segments. EVs outpace biofuels in the gasoline segment, leading to the potential decline of biofuel post-2035.

Aviation: Biofuel and hydrogen-based (synfuel) sustainable aviation fuel will have the majority share. Synfuel share is expected to pick up by 2035, as the technology is maturing.

Shipping: Biodiesel currently holds a small share in the bunker market but is expected to reach ~20% by 2050, with hydrogen and ammonia accounting for the remainder.

¹) Includes charcoal, fuelwood, dung, agricultural residues, wood waste, and other solid biogenic wastes — except the traditional use of biomass.

Sources: IEA, [Net Zero Roadmap](#) (2023); IEA, [Transport biofuels](#) (2023); Boston University, [What Countries Have the Greatest Bioenergy Power Capacity?](#) (2023).

Credit: Birru Lucha, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Lucha et al., ["Biofueling Transport"](#) (19 November 2025).

SAF is the only near-term option for aviation emissions abatement, but production capacity remains insufficient and uncompetitive

Types of SAF



R&D / pilot scale



Ready for commercialization



Mature and commercialized

	1	2	3	4
Fuel products	Fischer-Tropsch (FT)	HEFA ²	Alcohol to Jet (AtJ)	Power to Liquid (PtL)
Use in Aviation	Aviation (drop-in SAF)	Aviation (drop-in SAF)	Aviation (drop-in SAF)	Aviation (drop-in SAF)
Technology	Gasification	Hydrotreating	Alcohol to Jet	Power-to-Liquid (DAC and Renewable Electricity)
Technology maturity				
Max Blend % (ASTM)	Up to 50%	Up to 50%	Up to 50%	Up to 50%
Est. Cost (USD/gal)	~\$5.00–9.00	~\$4.00–6.00	~\$3.00–8.00	~\$6.00–12.00
CO ₂ Reduction	~60–80%	~60–80%	~50–85% (depends on feedstock & tech)	>90% (if powered with 100% renewable electricity)
Challenges	Depends on renewable feedstock	Feedstock availability	Tech complexity, feedstock scale	Cost, electricity need, carbon source purity

Observations

- **HEFA is leading** SAF deployment due to technical maturity, wide feedstock base (e.g., UCO, animal fats), and ASTM certification (Annex A2). However, **feedstock scarcity may limit scale**
- **Advanced SAF and FT**, offers **diverse feedstocks** and higher potential CO₂ reductions, but technologies face **complex scale-up and cost challenges**
- **Power-to-Liquid (PtL)** has the **highest climate benefit**, but is currently **cost-prohibitive**, highly energy-intensive, and depends on **availability of green electricity and pure CO₂ streams**
- **Policy frameworks like CORSIA³, ReFuelEU, and the U.S. SAF Grand Challenge** are accelerating commercialization, but **infrastructure, incentives, and mandates** are still needed to bridge the cost gap

¹ Sustainable Aviation Fuel (SAF) refers to non-fossil-derived aviation fuels that meet strict technical and sustainability criteria; ²HEFA: Hydrotreated Esters and Fatty Acids.

SAF can be "drop-in," meaning it can be used in existing aircraft engines and infrastructure with no modifications, while reducing lifecycle CO₂ emissions by up to 90% compared to conventional Jet-A.

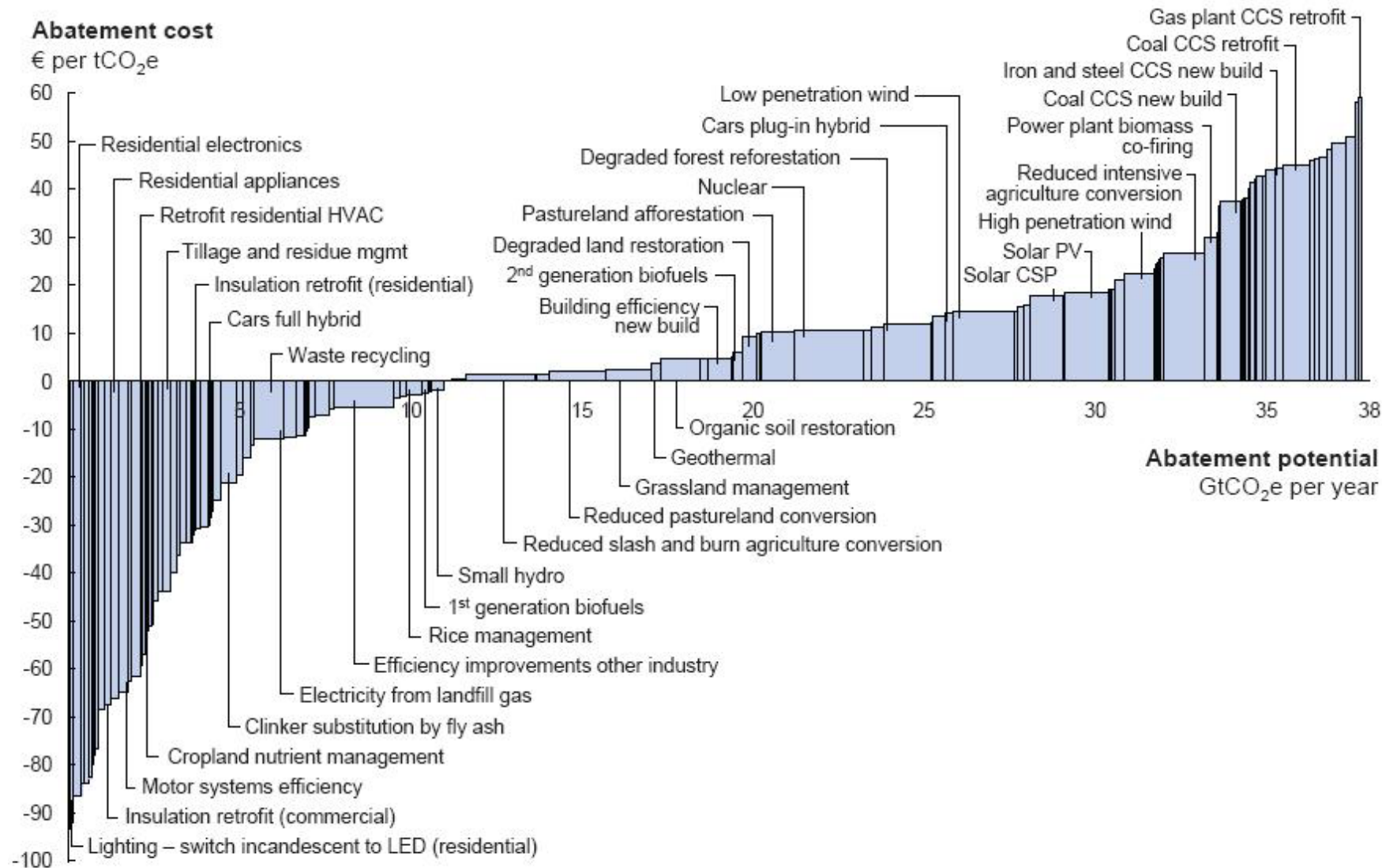
³Carbon Offsetting and Reduction Scheme for International Aviation.

Sources: IEA, [Net Zero Roadmap](#) (2023); IEA, [Transport Biofuel](#) (2023); ICCT, [Fact Policies](#) (2024).

Credit: Augusto Agazzi, Andrea Castro, and Gernot Wagner. [Share with attribution](#): Wagner et al. "Decarbonizing Transport" (8 May 2026).

Large abatement opportunities available at low or no cost

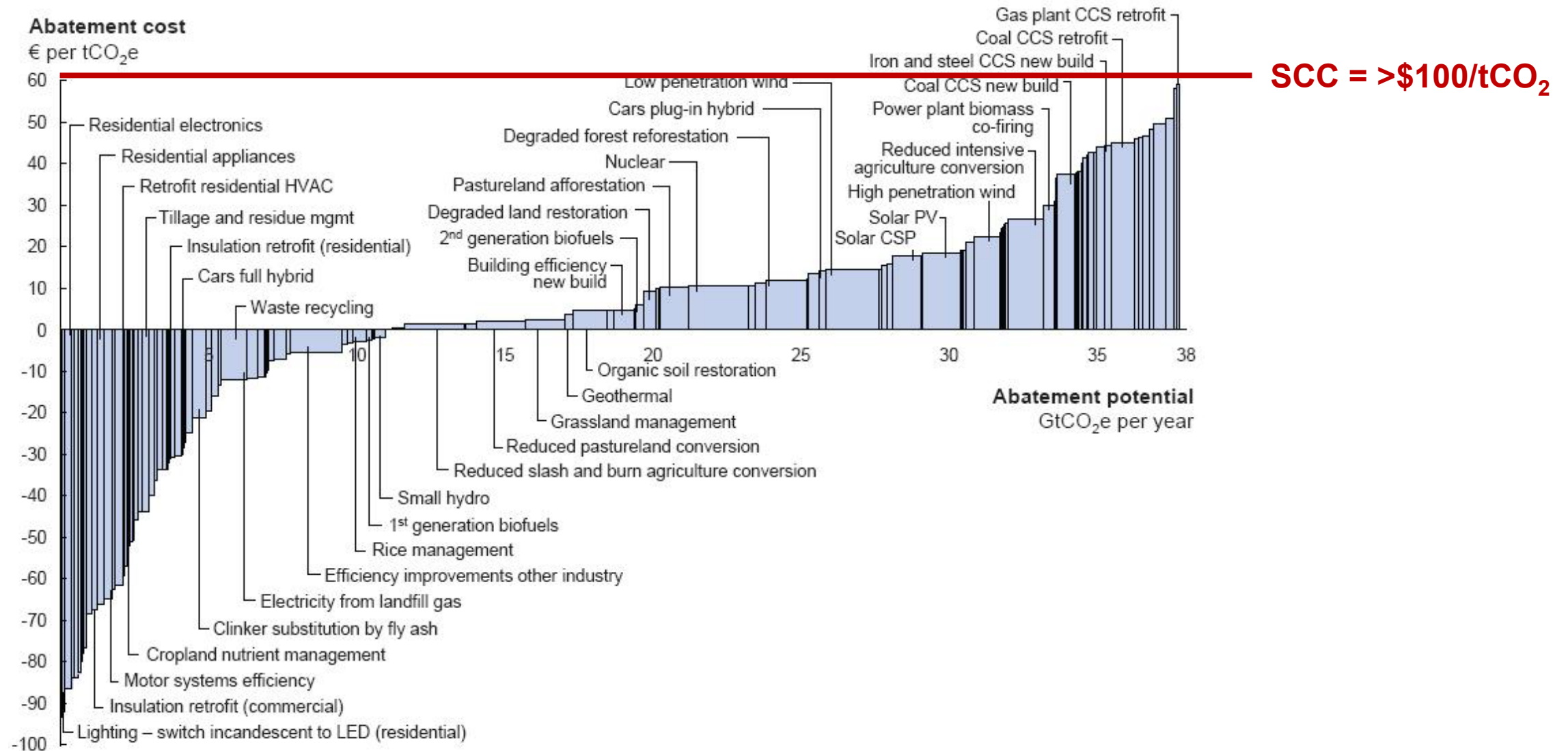
McKinsey Global v2.0 effort in 2009 identified 38 GtCO₂e abatement potential in 2030



Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO₂e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

Large abatement opportunities available at low or no cost

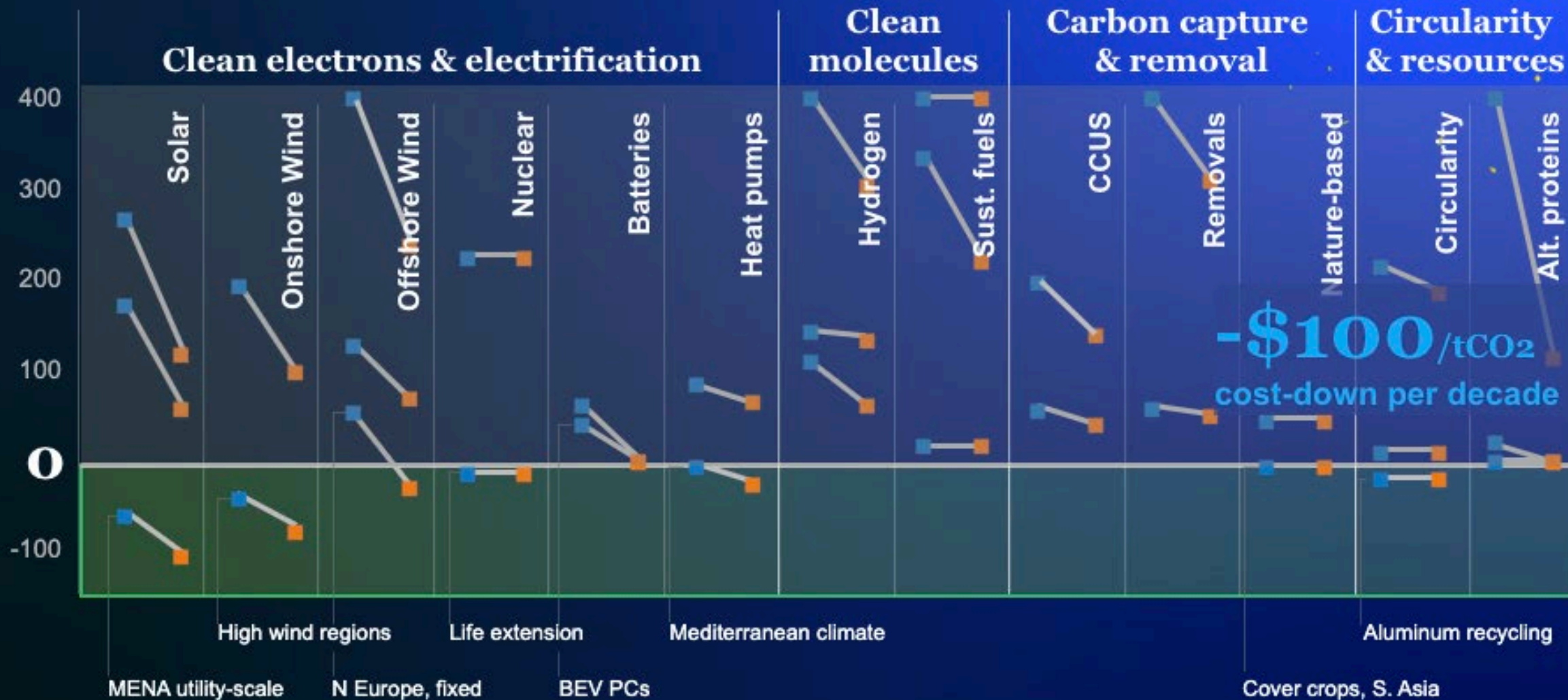
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Source: Global GHG Abatement Cost Curve v2.0

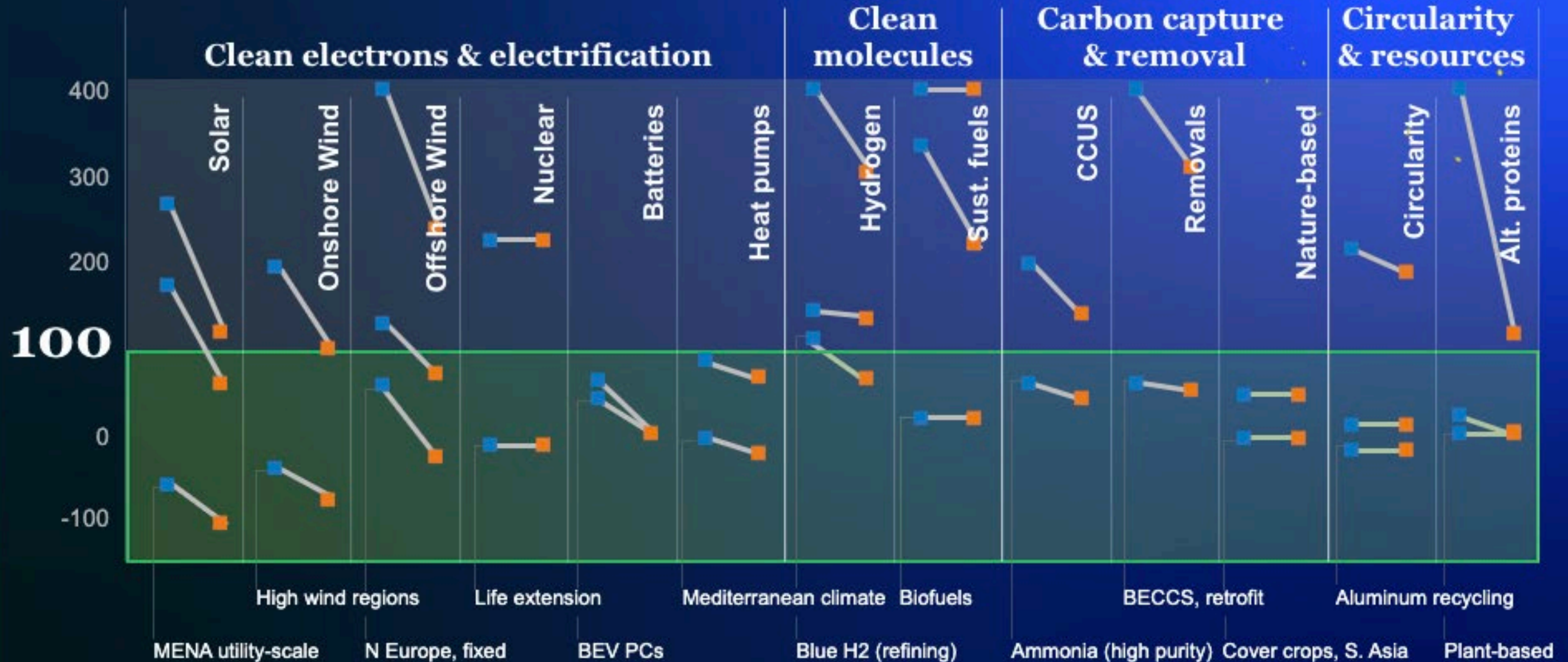
10 % of techs in the money today – steep cost-down to 2030

Estimated abatement costs, USD/tCO₂e



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

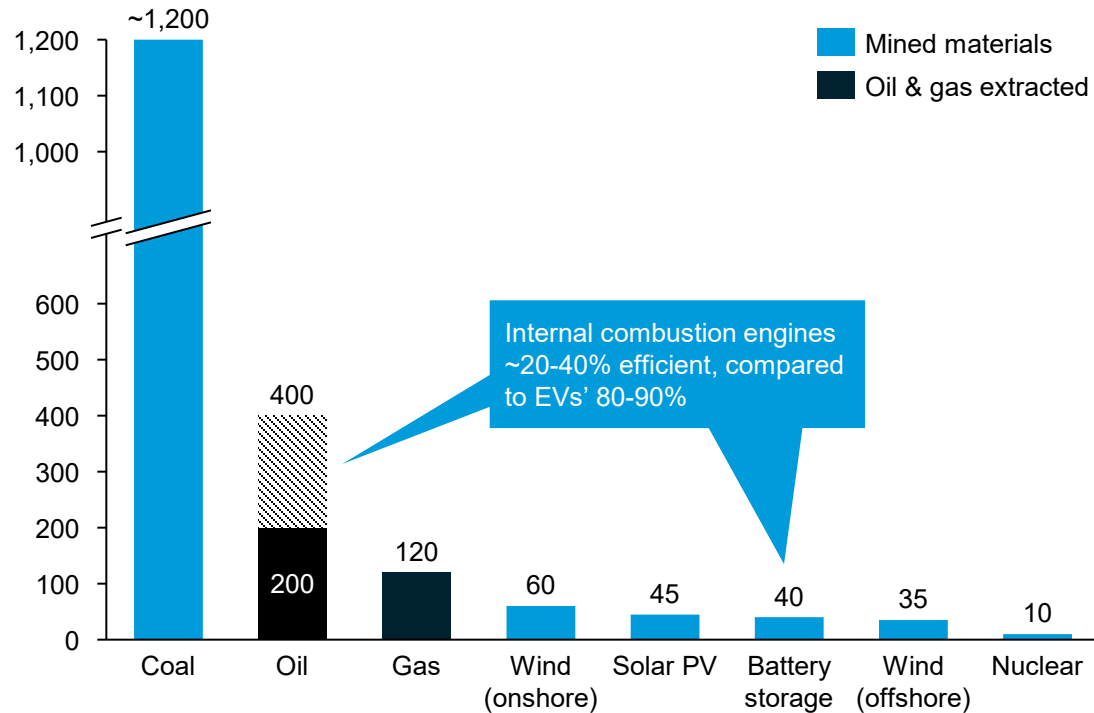
Estimated abatement costs, USD/tCO₂e



Despite its dependence on critical minerals, energy transition's material footprint lower than that of the fossil-fuel economy

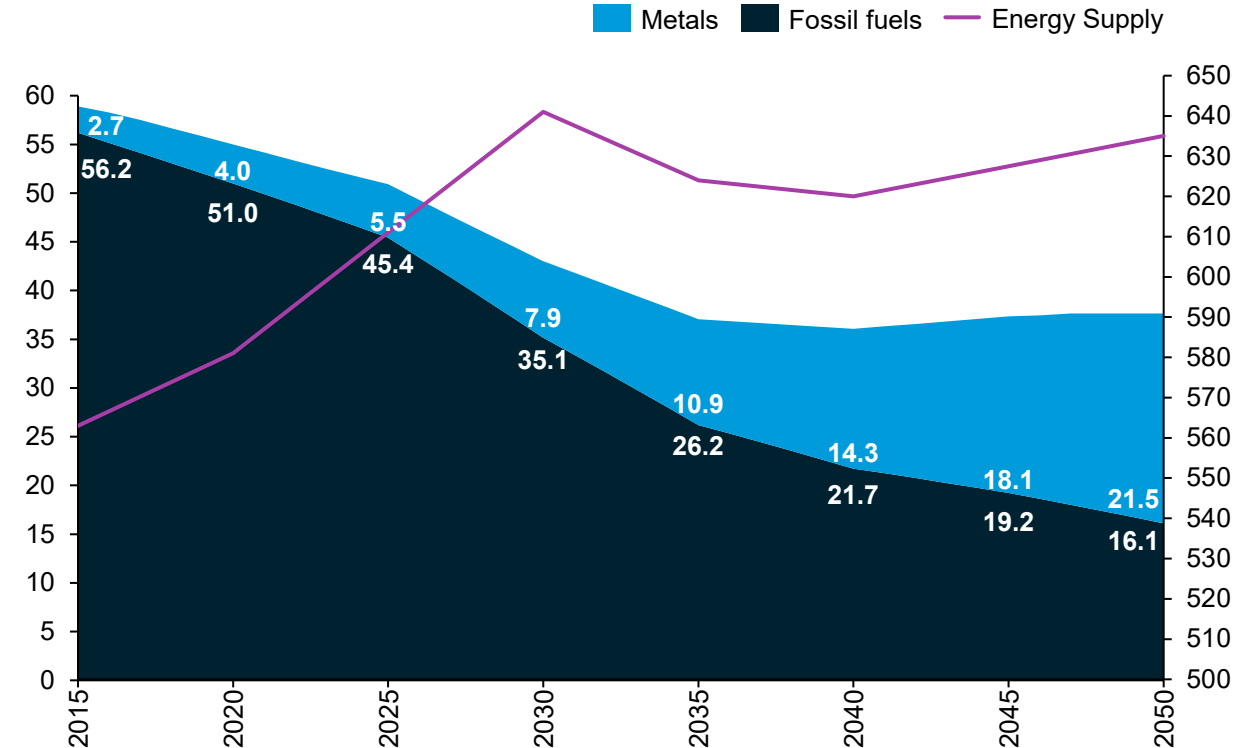
Fossil fuels have higher material intensity and, unlike renewables, require continuous mining & extraction

Mining requirements for energy sources, *tonnes of material/GWh*



The energy transition will increase mineral demand, but decrease total material footprint, despite growing energy supply

Material requirements of the energy transition (electricity and transport) v. growing global energy supply¹, 2015-2050, *Gt/year v. EJ/ year*



¹ Based on the IEA scenario keeping temperature rise to 1.75°C by 2100.

Sources: Wurmsdobler, [Mineral Resource Usage for the Energy Transition](#) (2025); [Sustainable Energy Transitions Require Enhanced Resource Governance](#) (Journal of Cleaner Production, 2021);

[Energy Outlook 2025](#) (IEA, 2024).; Mining for Electricity (Our World in Data, 2022).

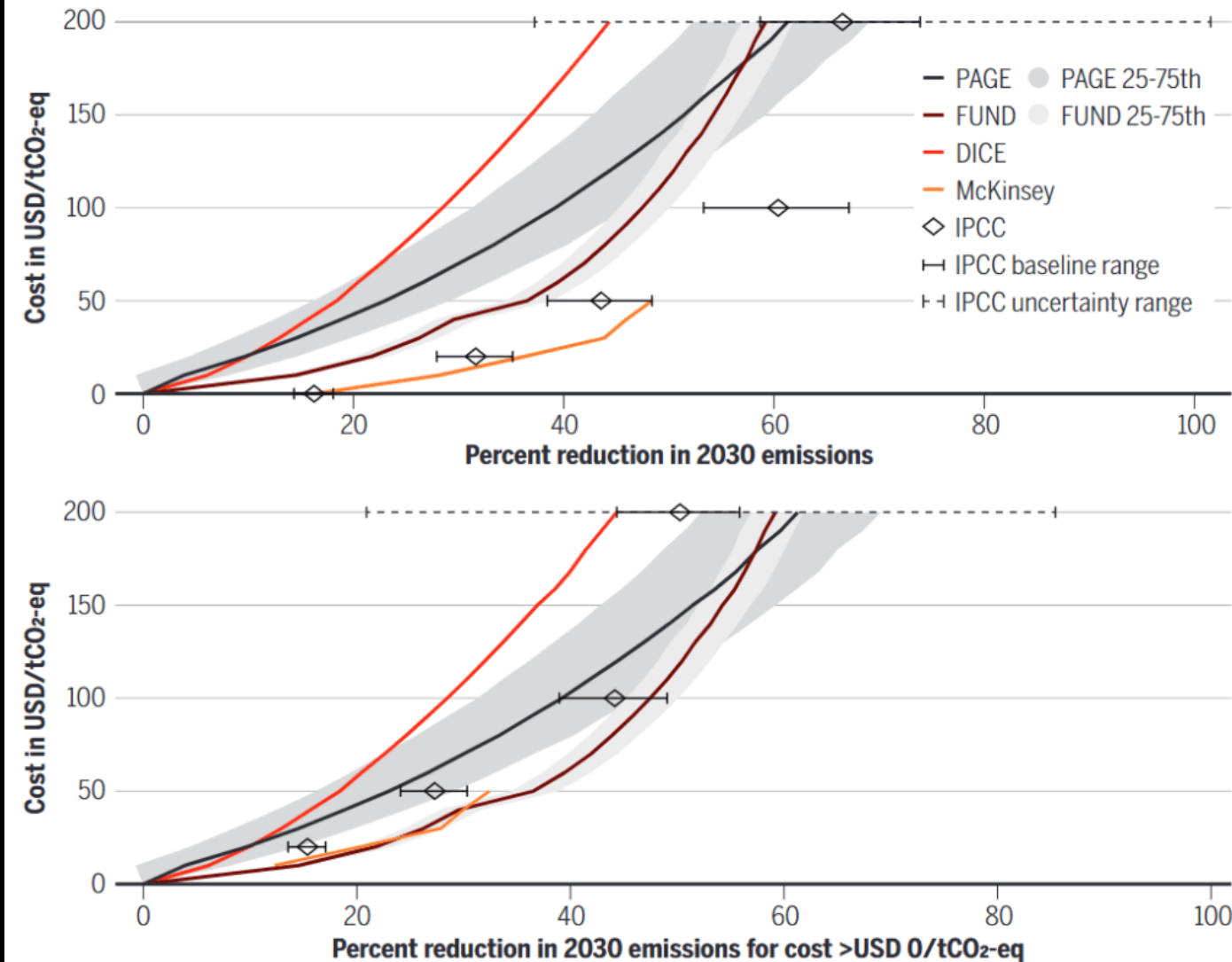
Credit: Leo Gordon, Isabel Hoyos, Ariela Farchi, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Mining for the Energy Transition" (10 April 2026).

How costly, or costless, is climate emissions mitigation? p. 1001



Comparison of global mitigation potentials at different costs

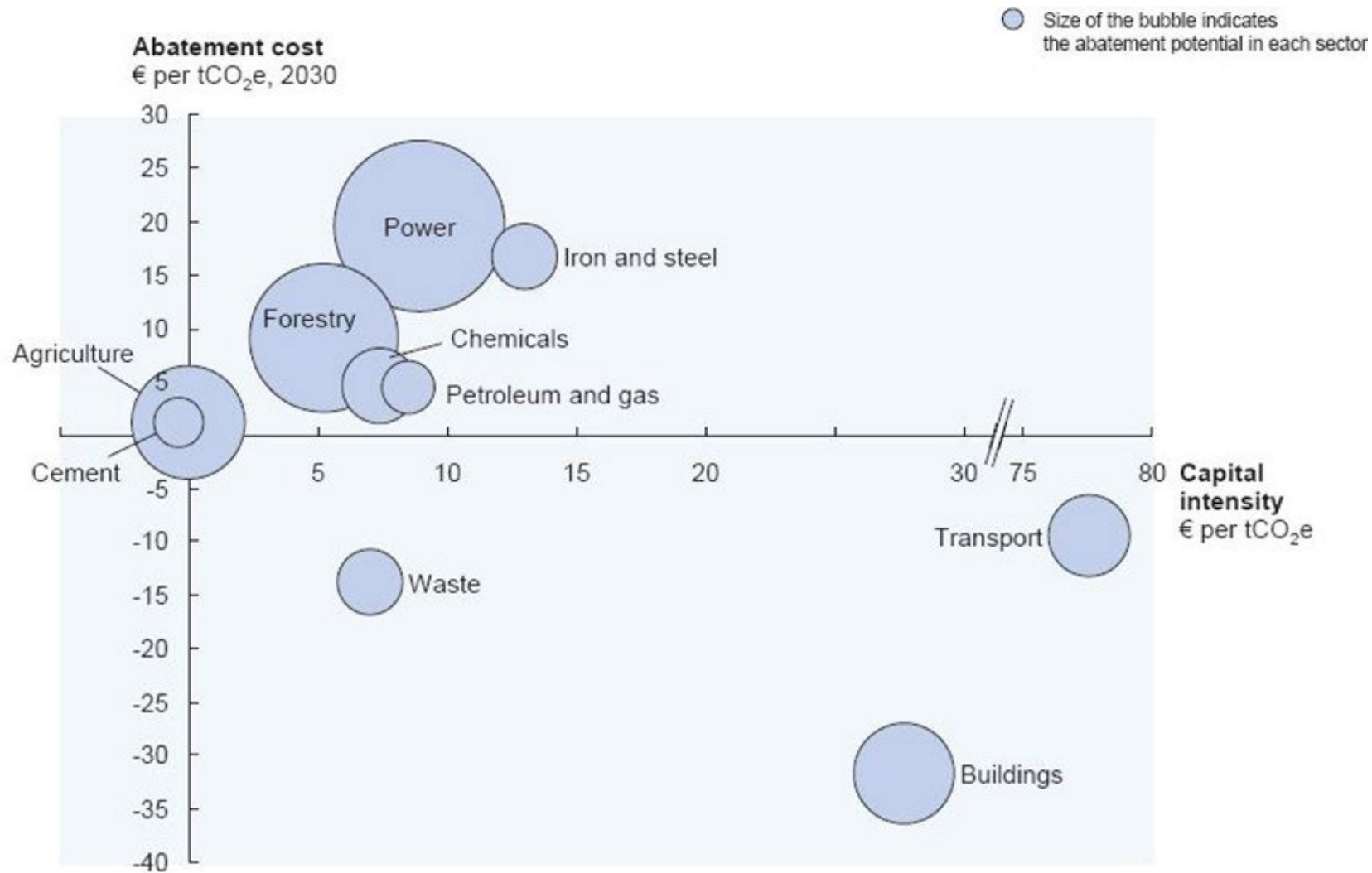
The IPCC results use different baseline emissions to calculate the range of mitigation potentials. The top panel reports the full set of results, and the bottom panel reports only the mitigation potentials with costs $> \$0$ per tonne of CO_2 equivalent ($\text{tCO}_2\text{-eq}$). USD reported in 2020 dollars. See supplementary materials.



Source: Kotchen, Rising & Wagner. "The costs of "costless" climate mitigation." *Science* (30 November 2023).

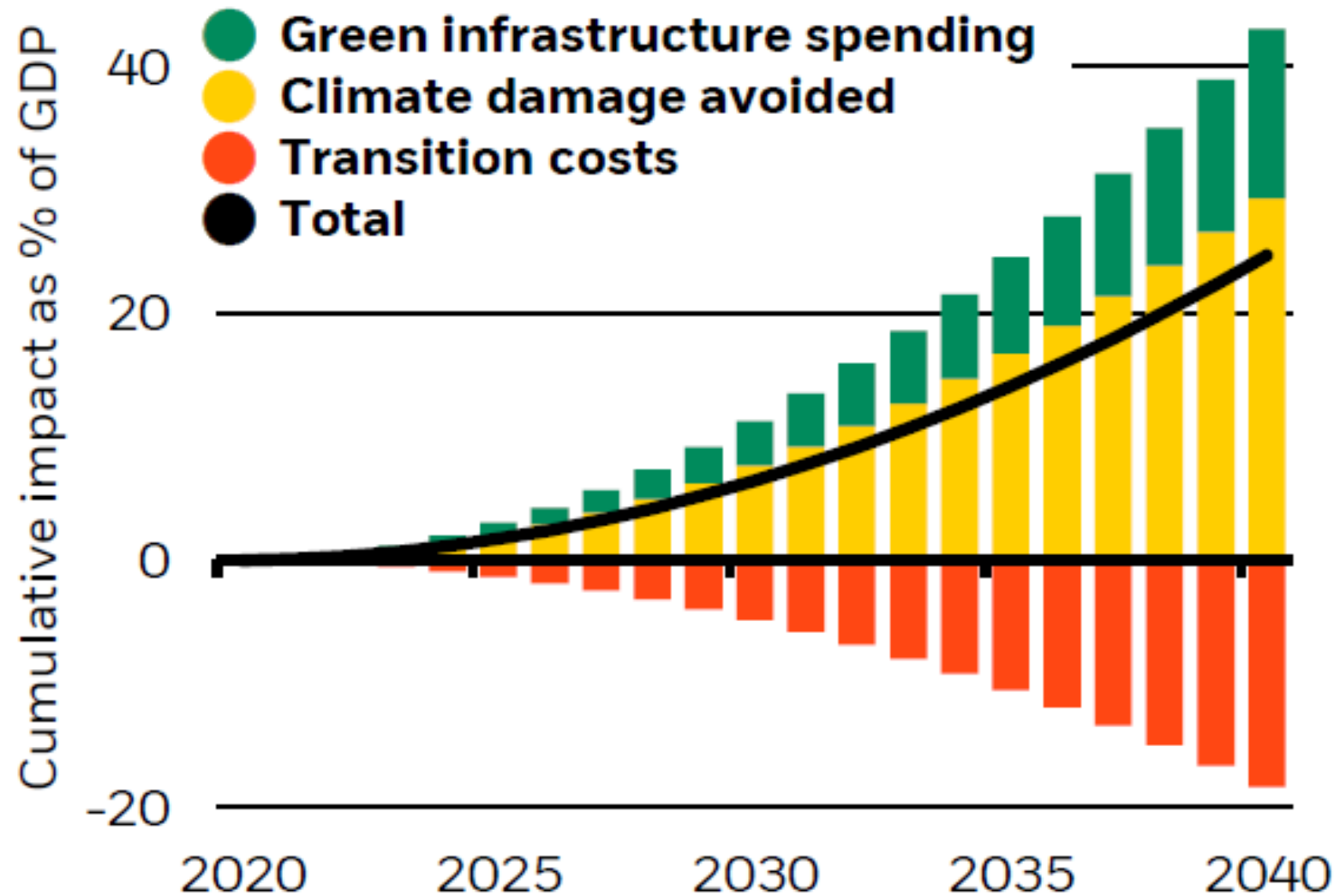
Capital intensity varies widely across sectors

Transport and buildings with largest up-front capital expenditure requirements



Transition results in net economic gain

Estimated cumulative GDP impact of transition, 2020-40



Cost-effective, deployable solutions can partially abate cement emissions; full decarbonization requires emerging technologies

○ R&D/Lab stage ◐ Pilot plant stage ◑ Ready for commercialization ● Mature and commercialized

	Energy efficiency		Clinker substitution		Alternative production technologies			Carbon capture
	Heat optimization	Alternative fuels: biomass/waste	Blended cement: Traditional SCMs	Blended cement: LC3	Thermal batteries ⁶	Alternative feedstock	Electrochemical production	CCUS/CCS
Description	Levers include: - Vertical mills or high-pressure grinding rolls - Kiln preheaters and improved insulation - Waste heat use - Digital process control	- Using biomass and waste as heat sources can lower thermal emissions. - Current kiln heat supply is fossil-fuel dominated (70% coal, 25% oil and gas).	- Supplementary cementitious materials (SCMs) - Can partially replace clinker in blended cements. - SCMs include CCR, steel furnace slag, and natural pozzolans.	- Limestone calcined clay cement (LC3) - Blended cement that uses limestone and calcined clay - Can replace more clinker than traditional SCMs.	- High-temperature thermal batteries, powered by cheap electricity, can replace fossil-fueled rotary kilns. - Can be connected to the grid or powered by off-grid renewables.	- Non-carbonate rocks can replace limestone as feedstock. - Can avoid the chemical emissions of limestone calcination.	- Electrochemistry can break down limestone instead of high-heat kilns. - Combined with non-carbonate feedstock, it can fully decarbonize cement production.	- Retrofitting plants with carbon capture can remove CO₂ released during clinker production. - Captured CO₂ can serve as feedstock, fuels, or building materials.
Addressed emissions	Thermal	Thermal	Thermal and chemical	Thermal and chemical	Thermal	Chemical	Thermal	Thermal and chemical
Limiting factor	CapEx	Feedstock availability and cost	Material availability and depletion	Retrofit and CapEx	New tech, CapEx, energy cost	New tech, CapEx	New tech, CapEx, energy cost	High CapEx, infrastructure
TRL	●	●	●	● ⁵	◐	◐	◐	◐
Abatement potential ¹	~9% (2030) ~19% (2050)	~4% (2030) ~27% (2050)	~12% (2030) ~39% (2050)	~8% (2030) ~32% (2050)	~4% (2030) ² ~12% (2050)	~4% (2030) ~11% (2050)	~15-20% (2030) ² ~70-80% (2050)	~19% (2030) ~69% (2050) ⁴
Abatement cost, \$/tCO ₂ e	-46.3 / 39 (2030) -26.9 / 14 (2050)	-80 / -40 (2030) -25.4 / -8 (2050)	-97.7 / -35 (2030) -48.2 / -19 (2030)	-82.7 / -32.2 (2030) -33.2 / -11.5 (2050)	159 / 414 (2030) ³ 37 / 132 (2050)	-44.2 / 9 (2030) ³ -15.4 / 2 (2050)	287 / 593.4 (2030) ³ 74 / 152 (2050)	167 / 364 (2030) ³ 46.3 / 101 (2050)

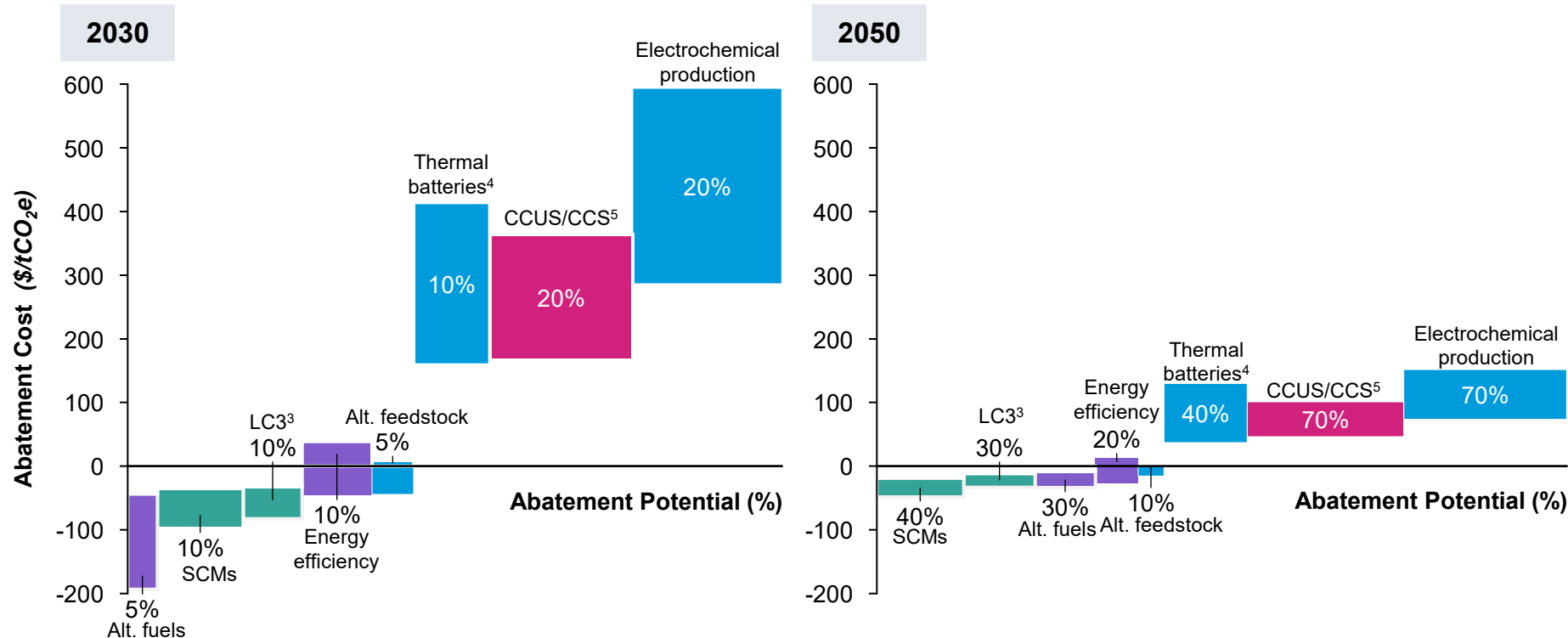
¹Unconstrained theoretical abatement potential for a given tonne of cement produced for each approach in isolation. ²Assumes clean energy source. ³Abatement cost of emerging technologies is based on estimates and has high uncertainty. ⁴Reflects the approximate emissions gap after other measures, not a fixed technical limit. ⁵Despite TRL9, market penetration remains minimal due to slow standards adoption, limited supply chain coordination, and conservative procurement practices. ⁶Thermal batteries abatement potential and cost are based on off-grid renewables.

Sources: DOE, [Liftoff Report](#) (2023); Mission Possible, [Net-zero concrete and cement](#) (2023); CATF, [Recasting the Future](#) (2025); ACA, [Roadmap to Carbon Neutrality](#) (2021); GCCA, [Concrete Future](#) (2022); ClimateWorks Foundation, [Low-carbon cement](#) (2023); Energies, [Alternative Fuels and Energy Efficiency in Cement](#) (2023); International Journal of Greenhouse Gas Control, [BioCCS in cement](#) (2023); IEA, [Bioenergy Annual Report](#) (2022); RMI, [The Business Case for LC3](#) (2024); Energy Innovation, [Industrial Thermal Batteries](#) (2023).

Credit: Camilo Avilés, Nicolas Herrera Isaza, Soraya Van Beek, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., “[Decarbonizing Cement](#)” (20 July 2026).

Emerging technologies like thermal batteries, alternative feedstock, and electrochemistry are key to achieving full decarbonization

Abatement cost¹ vs. potential² for key decarbonization pathways by 2030 vs. 2050



Observations

- Currently deployable measures can deliver up to **30% emission reductions** through energy efficiency, alternative fuels, and blended cement (conventional SCMs and LC3).
- Alternative feedstock and electrochemical production can virtually eliminate cement production emissions, but require significant technological advancements and transformational changes to production process.
- Thermal batteries' successful deployment depends heavily on **low-cost and low-carbon electricity**.
- Electrochemistry faces challenges including **high energy demand and competition for feedstock**.
- CCS costs vary widely depending on carbon **transportation and storage infrastructure**.

¹Abatement cost of emerging technologies is based on estimates and has high uncertainty. ²Abatement potential is calculated as unconstrained and theoretical for each approach in isolation.

³Despite TRL 9, market penetration of LC3 remains low due to slow standards adoption, limited supply chain coordination, and conservative procurement practices. ⁴Thermal batteries' abatement potential and cost are based on off-grid renewables; see slide 28 for grid power. ⁵CCUS/CCS calculations reflect the approximate emissions gap after other measures, not a fixed technical limit.

Sources: DOE, [Liftoff Report](#) (2023); Mission Possible, [Net-zero concrete and cement](#) (2023); CATF, [Recasting the Future](#) (2025); ACA, [Roadmap to Carbon Neutrality](#) (2021); GCCA, [Concrete Future](#) (2022); ClimateWorks Foundation, [Low-carbon cement](#) (2023); Energies, [Alternative Fuels and Energy Efficiency in Cement](#) (2023); International Journal of Greenhouse Gas Control, [BioCCS in cement](#) (2023); IEA, [Bioenergy Annual Report](#) (2022); RMI, [The Business Case for LC3](#) (2024); Energy Innovation, [Industrial Thermal Batteries](#) (2023).

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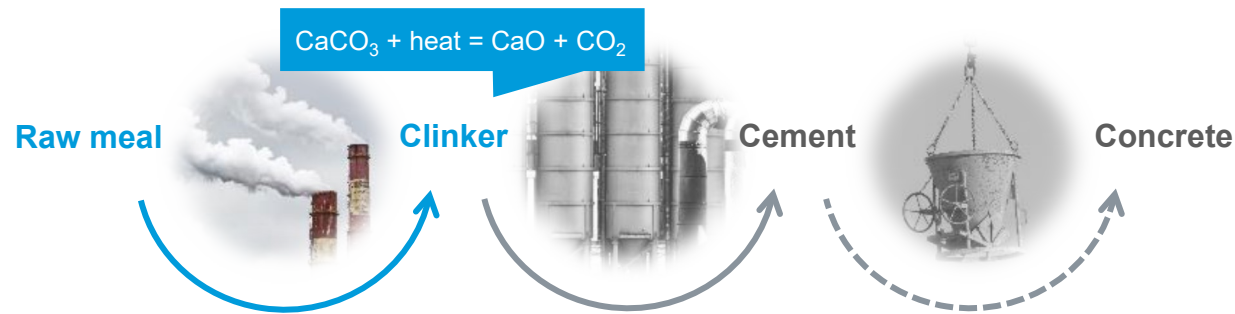
① Not if, *when*



Wagner, “[Who pays for cutting carbon out of making cement?](#)” (*Financial Times*, 19 May 2025)

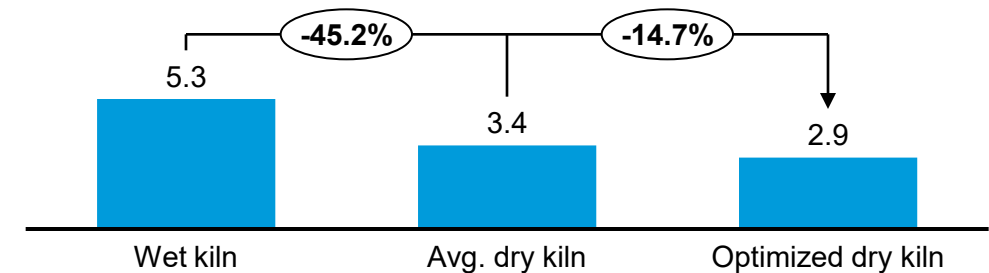
Clinker production ~85% of cement emissions; dry kiln adoption has led to significant efficiency gains

Clinker production is the first step in concrete production¹



Dry kilns have replaced wet kilns for clinker production

Kilns energy efficiency, GJ/ton clinker



1 Preheat

- Vertical cyclones with exhaust gases from the kiln are heated at ~900°C.
- Raw meal of crushed limestone and other minerals go in.

2 Precalcining

- Limestone is partially decomposed into lime in a combustion chamber before entering the kiln.

3 Melting clinker

- Precalcined meal enters the rotary kiln heated to 1,450°C with fossil fuels combustion.
- Clinker is produced.

Observations

- Calcination of limestone and combustion of fuels used to bring limestone to the required temperature account for **~90% of clinked production emissions**.
- The industry is rapidly shifting to adopt dry kilns**, with over 80% of global and 90% of European clinker production now using dry kilns. This shift reflects a clear willingness and capacity to change best practices to favor efficiency.
 - In dry kilns, raw materials are ground into a fine powder to form a raw meal; in wet kilns, raw materials are mixed with water to form a slurry.
 - The wet process is relatively **less energy efficient and more resource intensive**, with more energy required to evaporate the water in the slurry.

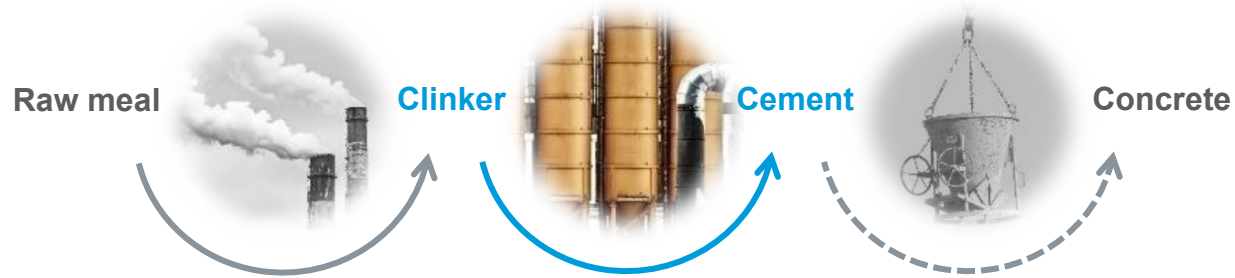
¹ The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.

Sources: Environmental Development, [Energy conservation and emission reduction for cement](#) (2022); Portland Cement Association (2024); CEMBUREAU, [Cement manufacture fact sheet](#) (2021); Mission Possible, [Making net-zero concrete and cement possible](#) (2023).

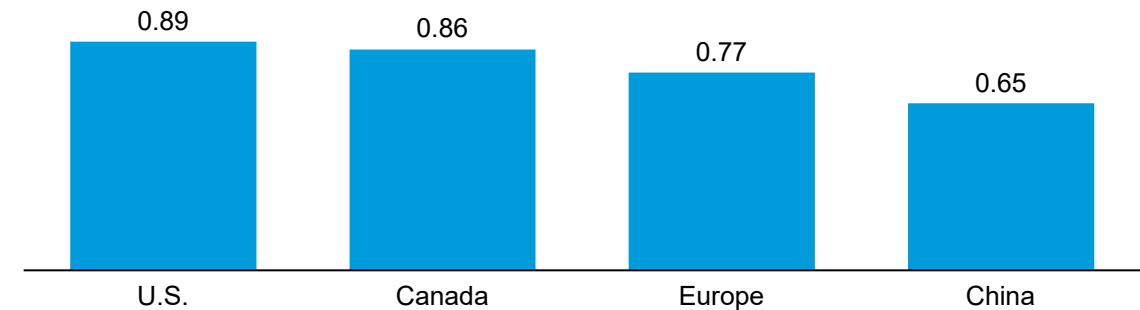
Credit: Nicolas Herrera Isaza, Jessica Cong, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., ["Decarbonizing Cement"](#) (20 July 2026).

Clinker production ~85% of cement emissions; lower clinker-to-cement ratio can drive marginal emissions reductions

Clinker-to-cement production process¹



Clinker-to-cement ratios vary considerably by region



Observations

- Energy emissions from **cement grinding account for ~5% of the sector's emissions**.
- The higher clinker-to-cement ratio in the U.S. (0.88 versus 0.76 world average) is due to the U.S.'s use of a lower proportion of SCMs than other countries.
- Ordinary Portland cement (OPC) can contain up to 95% clinker.
- Blended cements, which partially replace clinker with SCMs, are a deployable and cost-effective technology, though they have struggled to gain market share.

1 Cooling

- Hot clinker is rapidly cooled to 100°C with air blowers powered by electricity.

2 Grinding and blending

- Clinker is mixed with 4-5% gypsum.
- In some cases, it is mixed with other supplementary cementitious materials (SCMs) (e.g., slag, CCR, clay).
- The mixture is ground and blended into cement.

¹ The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.

Sources: CEMBUREAU, [Net-zero roadmap](#) (2024); [Portland Cement Association](#) (2024); CEMBUREAU, [Cement manufacture fact sheet](#) (2021); Mission Possible, [Making net-zero concrete and cement possible](#) (2023).

Credit: Nicolas Herrera Isaza, Jessica Cong, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "[Decarbonizing Cement](#)" (20 July 2026).

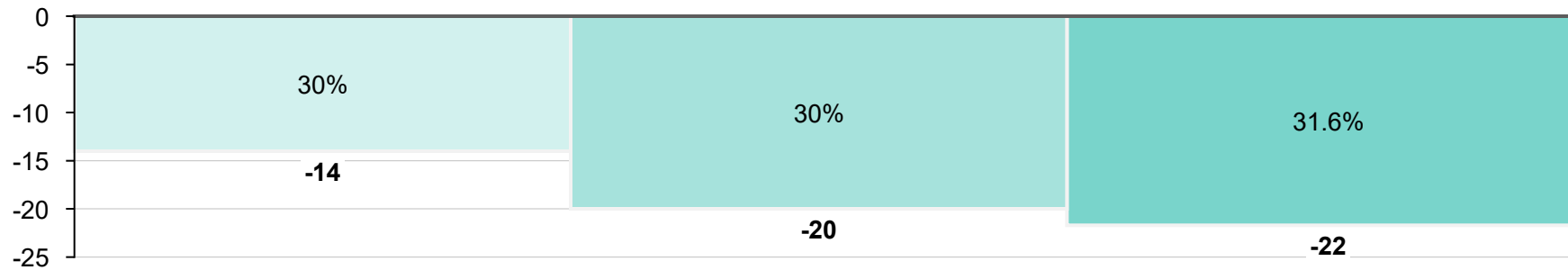
Blended cements partially replace clinker, reducing emissions with minor changes to production process or added costs

	Clinker	Furnace slag (GGBFS)	Coal combustion residuals (CCR)	Calcined clay (LC3)
Replacement potential	N/A	30-50% ¹	30-35%	30-40%
Availability	3.8 billion Mtpa	520-680 Mtpa	500-800 Mtpa	3.5-5 Mtpa
Availability-adjusted replacement potential	N/A	~10-18%	~10-20%	1-2%
Emissions reduction potential ²	N/A	~15-30%	~15-30%	~30-40%
Price \$/ton	~65-75	~51	~45	~20-35

Observations

- Global clinker production is ~3.8 Gt/year. Replacing 50% of global clinker would require SCM supply far above today's ~500-600 Mt/year of usable materials; only LC3 offers long-term scalable supply.
- At the product level, furnace slag has the potential to replace up to 50% of clinker, but global availability limits slag-based substitution.
- coal combustion residuals (CCR) cements can substitute 30-35% at the plant level but globally only ~10-20% due to limited supplies of high-quality CCR as coal plants retire.
- LC3 can deliver 30-40% clinker reduction, but current industrial capacity is small (~1-2% of global cement), and significant new calcination and production infrastructure is required.

Abatement cost³ (\$/tCO₂e) vs. emission abatement potential (% tCO₂e)



¹ 30-50% replacement in CEM II/B-S or CEM III/A; up to 60-70% in CEM III/B. ² The % CO₂ reduction achieved if the full technical replacement potential is used. ³ Cost relative to clinker. Source: CKI analysis; DOE, [Liftoff Report](#) (2023); RMI, [The business case for LC3](#) (2024); IEA, [Net Zero by 2050](#) (2023); GCCA, [Concrete Future Roadmap](#) (2021). Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). Share with attribution: Wagner et al., "[Decarbonizing Cement](#)" (20 July 2026).

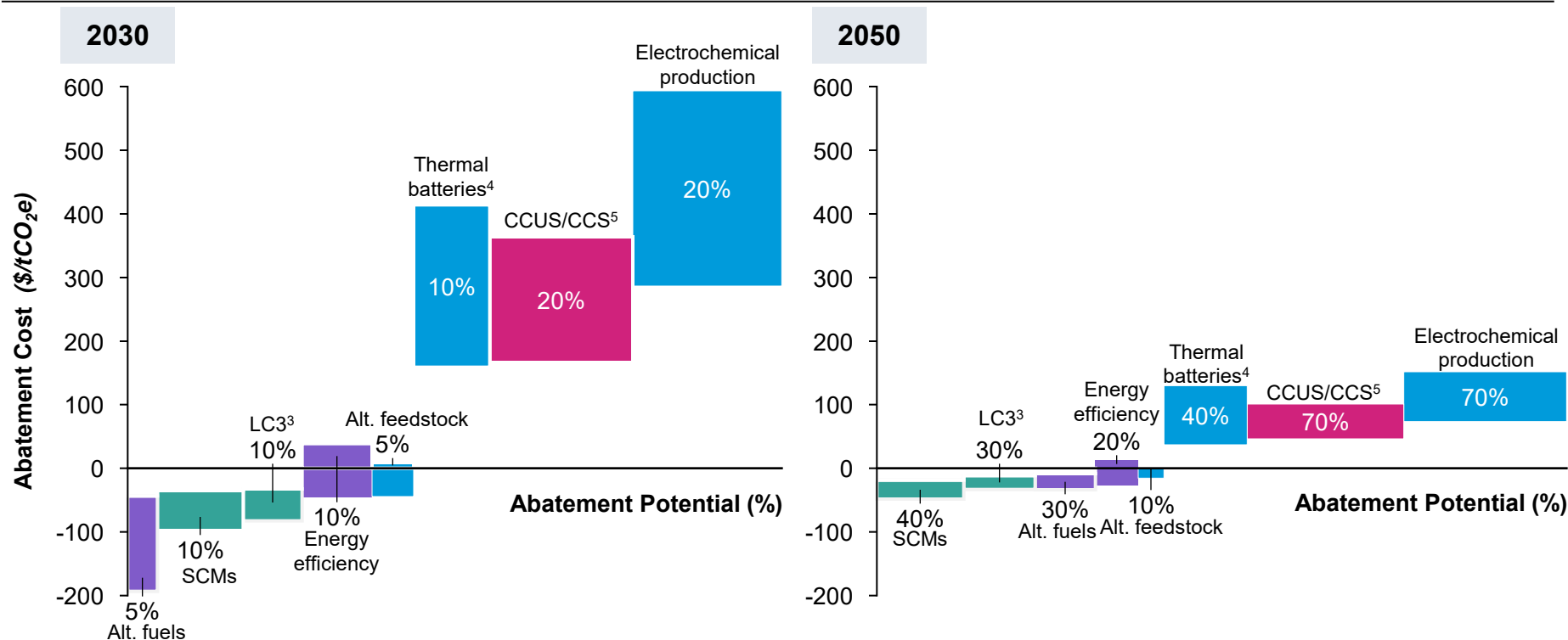
- 1 Not if, *when*
- 2 Innovator's Dilemma



Wagner, “[Who pays for cutting carbon out of making cement?](#)” (*Financial Times*, 19 May 2025)

Emerging technologies like thermal batteries, alternative feedstock, and electrochemistry are key to achieving full decarbonization

Abatement cost¹ vs. potential² for key decarbonization pathways by 2030 vs. 2050



Observations

- Currently deployable measures can deliver up to **30% emission reductions** through energy efficiency, alternative fuels, and blended cement (conventional SCMs and LC3).
- Alternative feedstock and electrochemical production can virtually eliminate cement production emissions, but require significant technological advancements and transformational changes to production process.
- Thermal batteries' successful deployment depends heavily on **low-cost and low-carbon electricity**.
- Electrochemistry faces challenges including **high energy demand and competition for feedstock**.
- CCS costs vary widely depending on carbon **transportation and storage infrastructure**.

¹Abatement cost of emerging technologies is based on estimates and has high uncertainty. ²Abatement potential is calculated as unconstrained and theoretical for each approach in isolation.

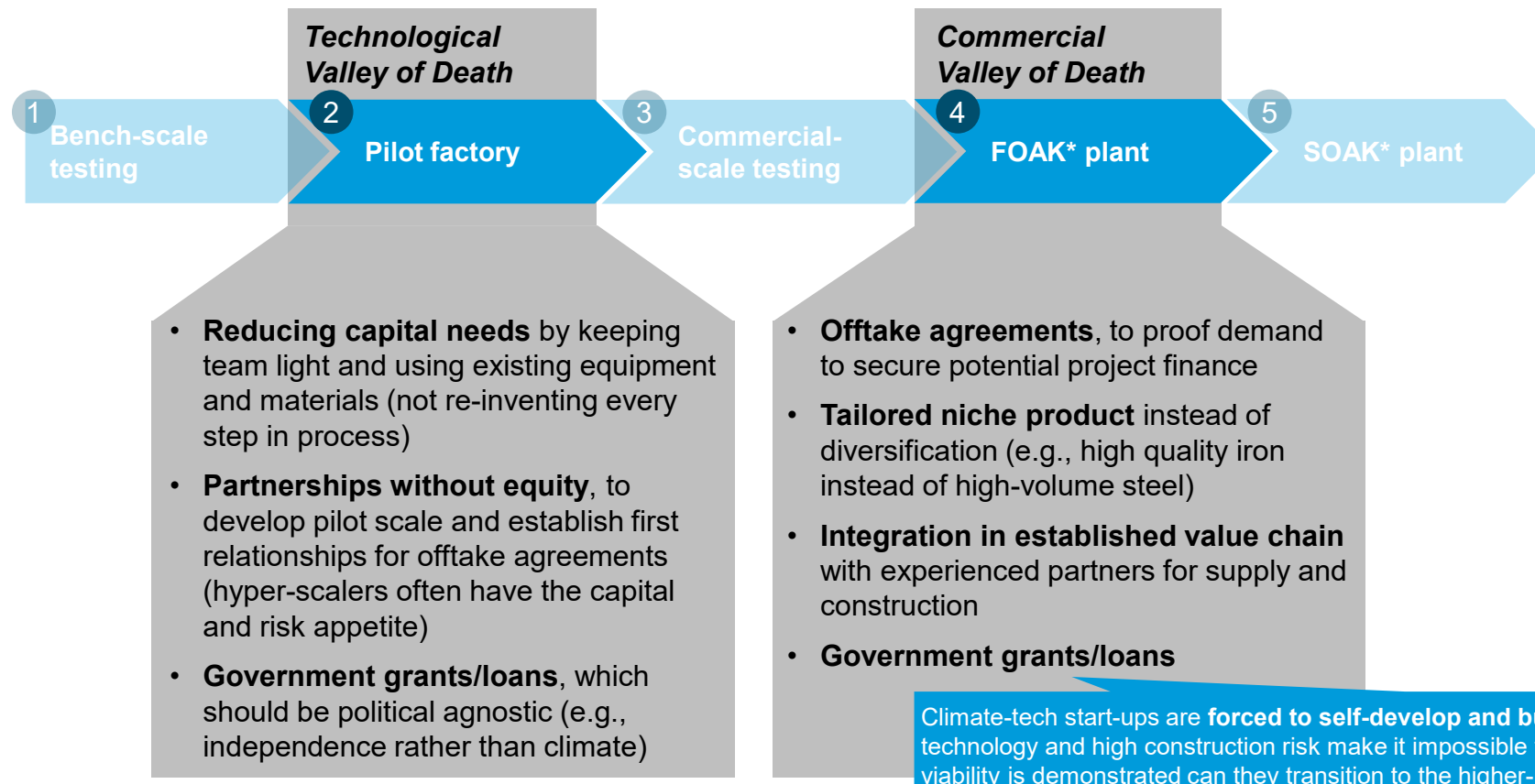
³Despite TRL 9, market penetration of LC3 remains low due to slow standards adoption, limited supply chain coordination, and conservative procurement practices. ⁴Thermal batteries' abatement potential and cost are based on off-grid renewables; see slide 28 for grid power. ⁵CCUS/CCS calculations reflect the approximate emissions gap after other measures, not a fixed technical limit.

Sources: DOE, [Liftoff Report](#) (2023); Mission Possible, [Net-zero concrete and cement](#) (2023); CATF, [Recasting the Future](#) (2025); ACA, [Roadmap to Carbon Neutrality](#) (2021); GCCA, [Concrete Future](#) (2022); ClimateWorks Foundation, [Low-carbon cement](#) (2023); Energies, [Alternative Fuels and Energy Efficiency in Cement](#) (2023); International Journal of Greenhouse Gas Control, [BioCCS in cement](#) (2023); IEA, [Bioenergy Annual Report](#) (2022); RMI, [The Business Case for LC3](#) (2024); Energy Innovation, [Industrial Thermal Batteries](#) (2023).

Credit: Camilo Avilés, Nicolas Herrera Isaza, Soraya Van Beek, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Decarbonizing Cement" (20 July 2026).

Capital efficiency key to overcoming technological “Valley of Death”; risk transfer across value chain key for commercial one

Climate-tech startups must de-risk demand and often leverage public, concessional, or philanthropic capital to finance FOAK* commercial plants



Observations

- The Technological valley solutions are primarily about capital efficiency: reducing what you need to spend; the Commercial valley solutions are about risk transfer: shifting risk onto counterparties (offtakers, value chain)
- Government grants are equally critical at the Commercial valley: DOE/EU funding has been an enabler of FOAK project debt in recent cases (e.g. Stegra, LanzaJet)
- "Tailored niche product" is a highest-risk commercial strategy: it narrows the customer base, but protects margin if it works
- High-risk construction often leads to companies turning to in-house development
- The two solution sets are sequentially dependent

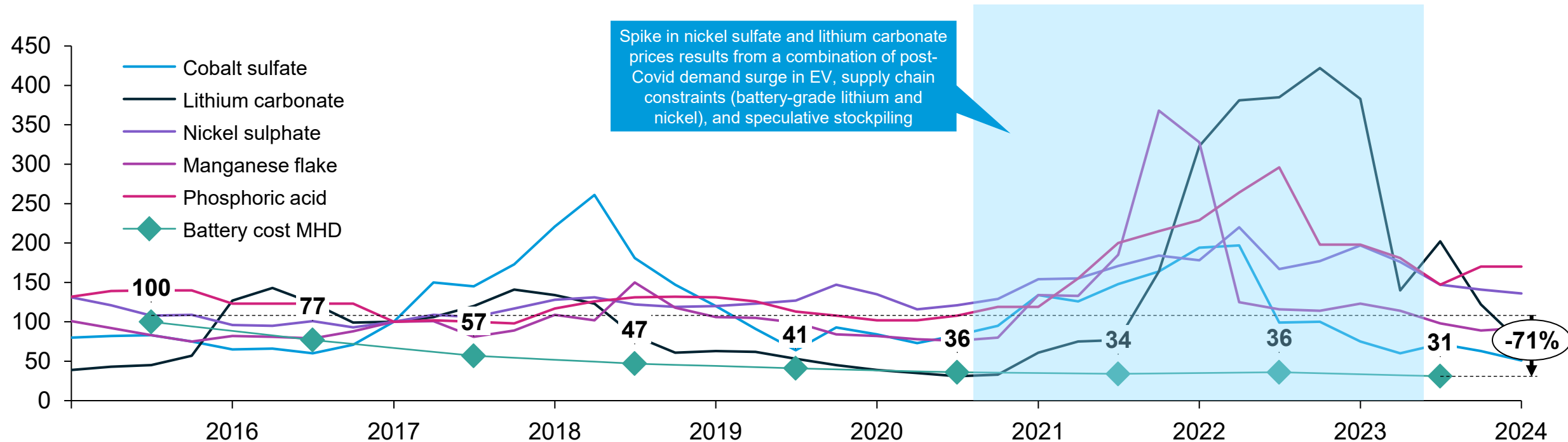
¹FOAK = First Of A Kind; SOAK = Second Of A Kind; ²Capital costs refer to construction CAPEX only; excludes OPEX, financing costs, and pre-FID development expenditure

Sources: DOE, [Learning from Case Studies: Financing and Development Approaches from Recent First-of-a-Kind Projects](#) (2024); Sightline Climate, [Meet the FOAK folks](#) (2025); Extantia Capital, [The FOAK Question: Essential Insights for Financing and Planning First-Of-A-Kind plants](#) (2023).

Credit: Soraya van Beek, Isabel Hoyos, and Gernot Wagner. [Share with attribution](#): Wagner et al., "Decarbonizing Cement" (20 July 2026).

Battery prices are falling, strengthening the case for electrified medium trucks, though input costs remain volatile

Price of select battery materials relation with battery cost of medium trucks, USD between 2015 and 2024



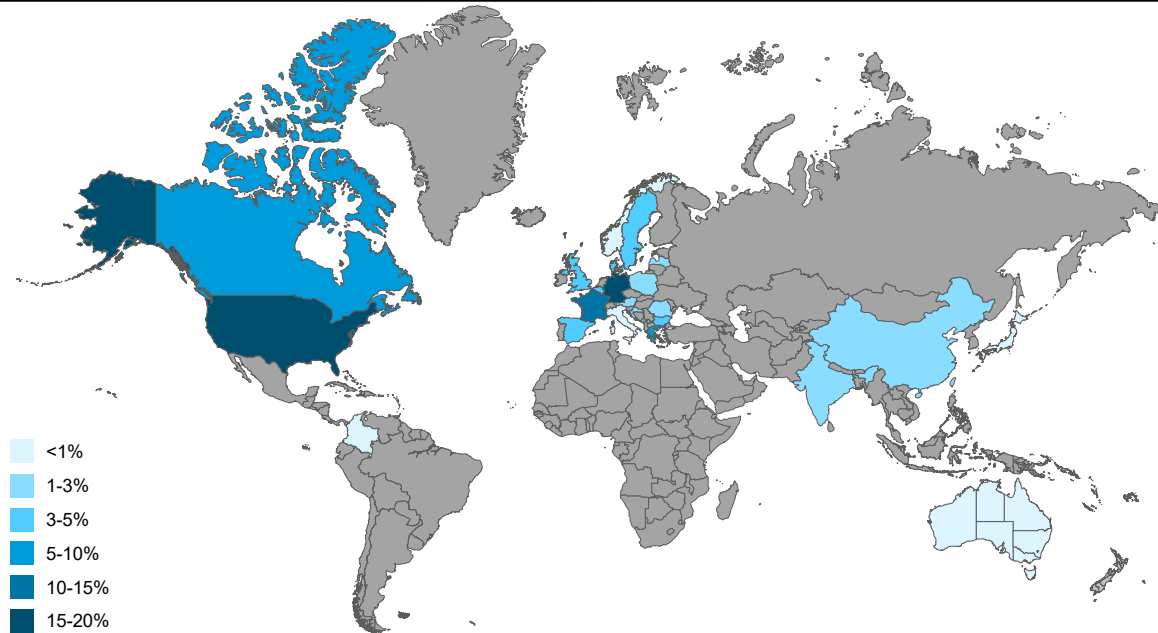
Global battery prices are projected to fall to ~ \$80/kWh by 2026, nearly a 50% drop from 2023 levels, and mainly driven by technological advancements such as **30% higher energy density** cells. While innovations like that reduce the TCO of LDV and **smallest medium-duty trucks (class 3-6)**, this doesn't extend to heavy-duty trucks (class 7-8) immediately, whose battery cost is projected to remain above \$100/kWh by 2026 in the U.S., even under an aggressive technological progress.

- 
- 1 Not if, *when*
 - 2 Innovator's Dilemma
 - 3 Who pays?

Wagner, "[Who pays for cutting carbon out of making cement?](#)" (*Financial Times*, 19 May 2025)

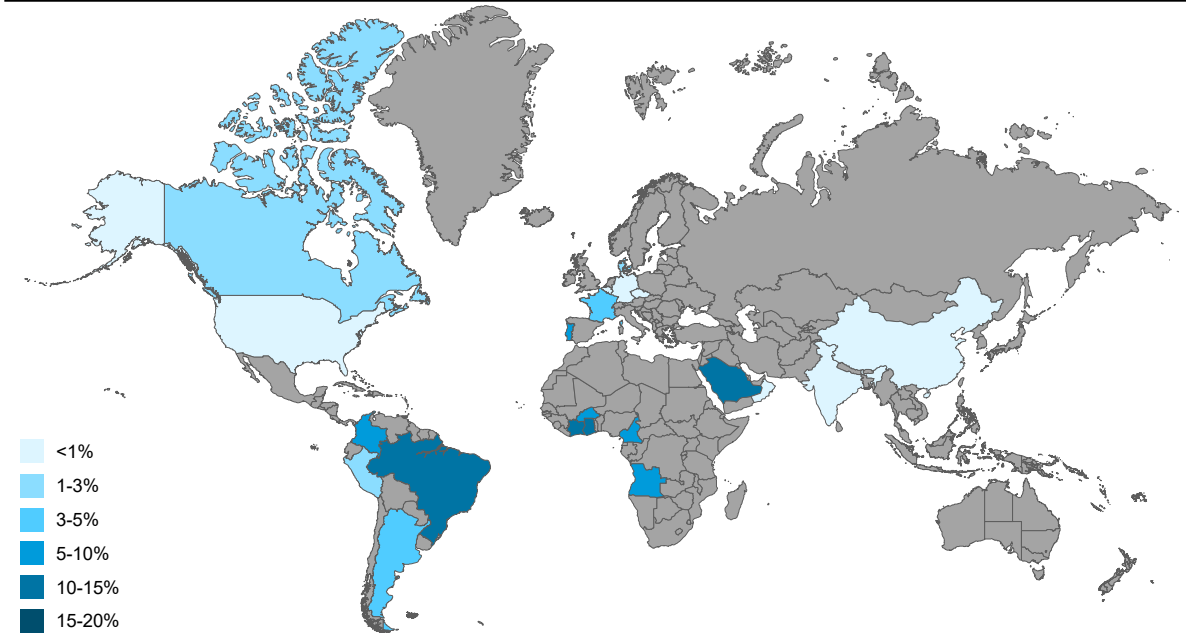
Investment capacity and infrastructure drive CCUS in Global North; clay reserves and capital constraints drive LC3 in South

Cement CCUS capacity¹, global distribution, Dec. 2024



- **North America and the EU account for 92%** of stated capacity from announced cement CCUS projects.
- **High capital needs and strong policy support** (e.g., U.S. 45Q tax credit) drive CCUS deployment in high-income countries.
- **Existing oil and gas infrastructure** in developed markets (e.g., pipelines, storage facilities, geological data) enable faster rollout. For example, Norway's Northern Lights project uses existing North Sea oil infrastructure to store CO₂.

Clay calciner capacity¹, global distribution, Dec. 2024



- **Africa accounts for 44%** of stated capacity from announced clay calciner projects.
- Clay calcination kilns are **less capital-intensive** and easily integrated into existing cement plants than CCUS installations, making them a more attractive option for countries with limited industrial investment capacity.
- Many developing countries have **abundant clay reserves** but rely on imported clinker due to the scarcity of high-grade limestone. Clay-based alternatives offer a **cost-effective solution** to meet rising cement demand amid rapid urbanization in developing countries.

¹ Expected at full operation based on stated disclosed carbon capture capacity for CCUS and stated disclosed installed capacity for clay calciner

Source: GCCA and LeadIT, [Green Cement Technology Tracker](#) (2024).

Credit: Adele Teh, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al., "Decarbonizing Cement" (20 July 2026).

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.

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

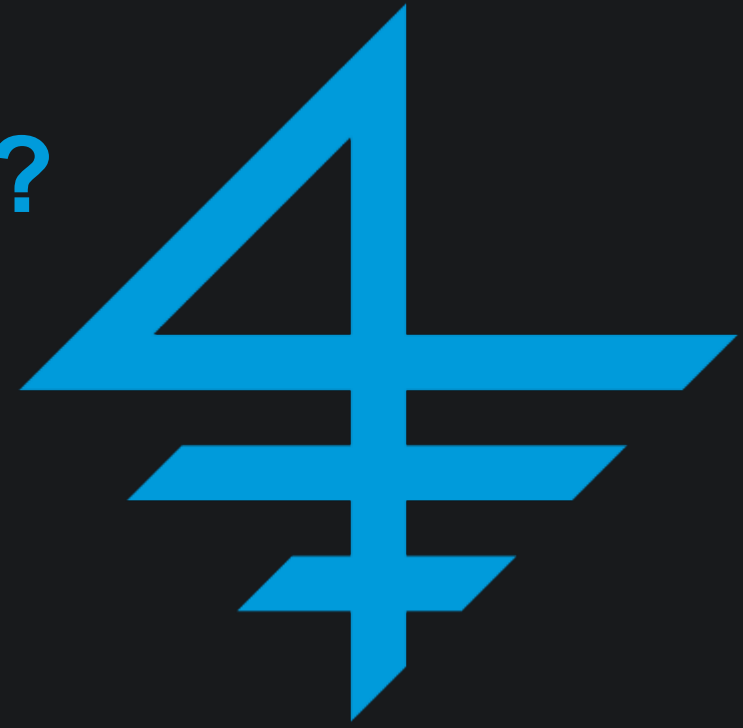
Columns

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



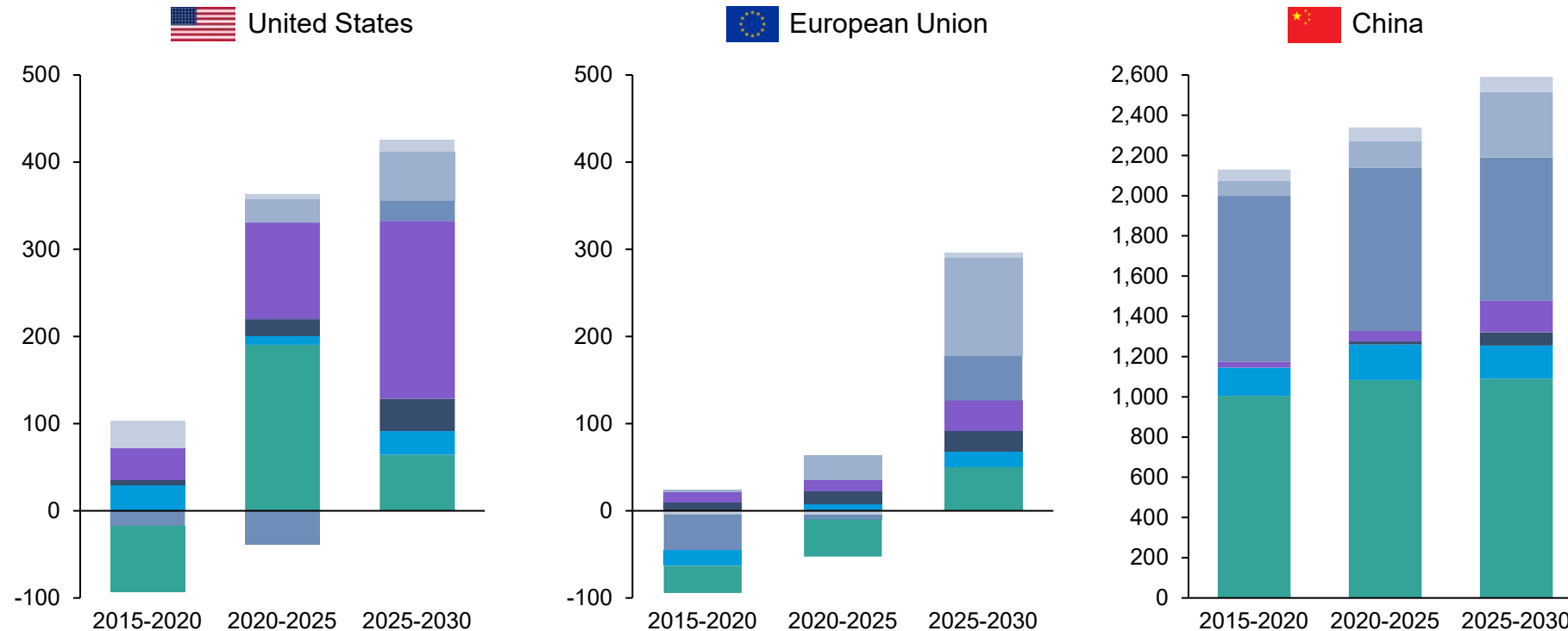
gwagner.com/cki-grids

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



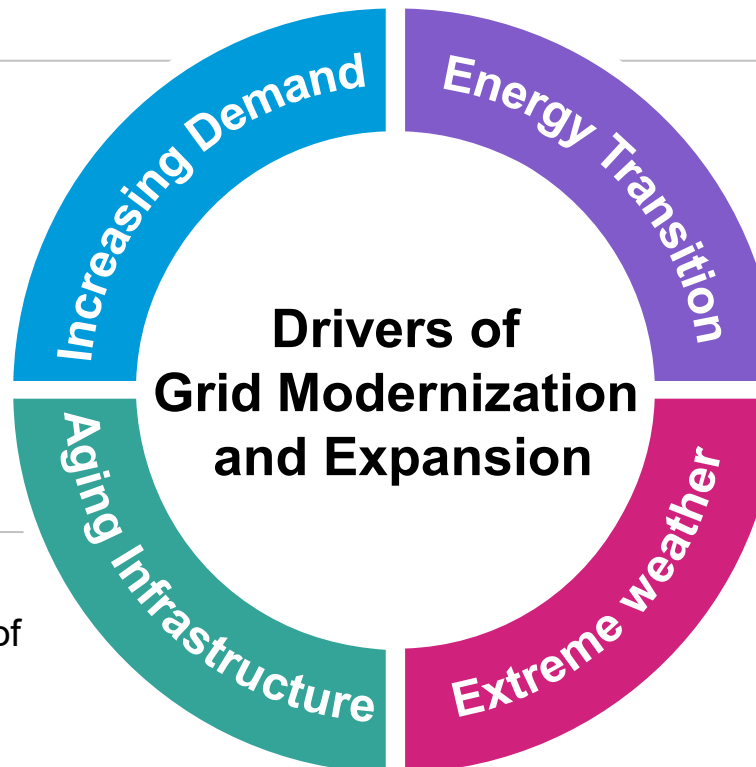
Structural shift in the electricity system

- 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

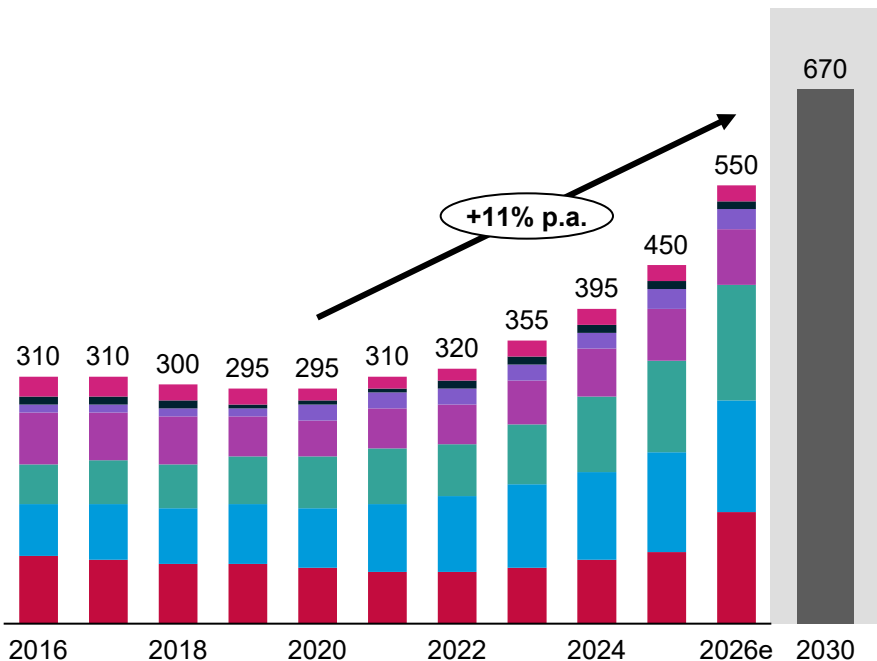


Global grid investment is expected to rise to +\$500B in 2026 and increase through 2030, driven by infrastructure, materials, and labor

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

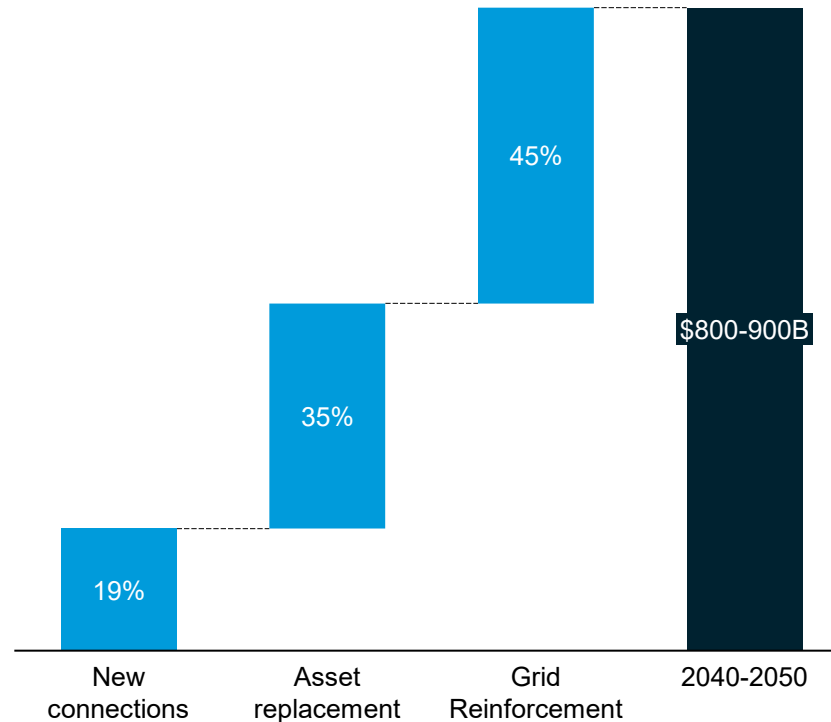
Investment in power grid infrastructure, 2016-2026e USD Billions

■ 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).

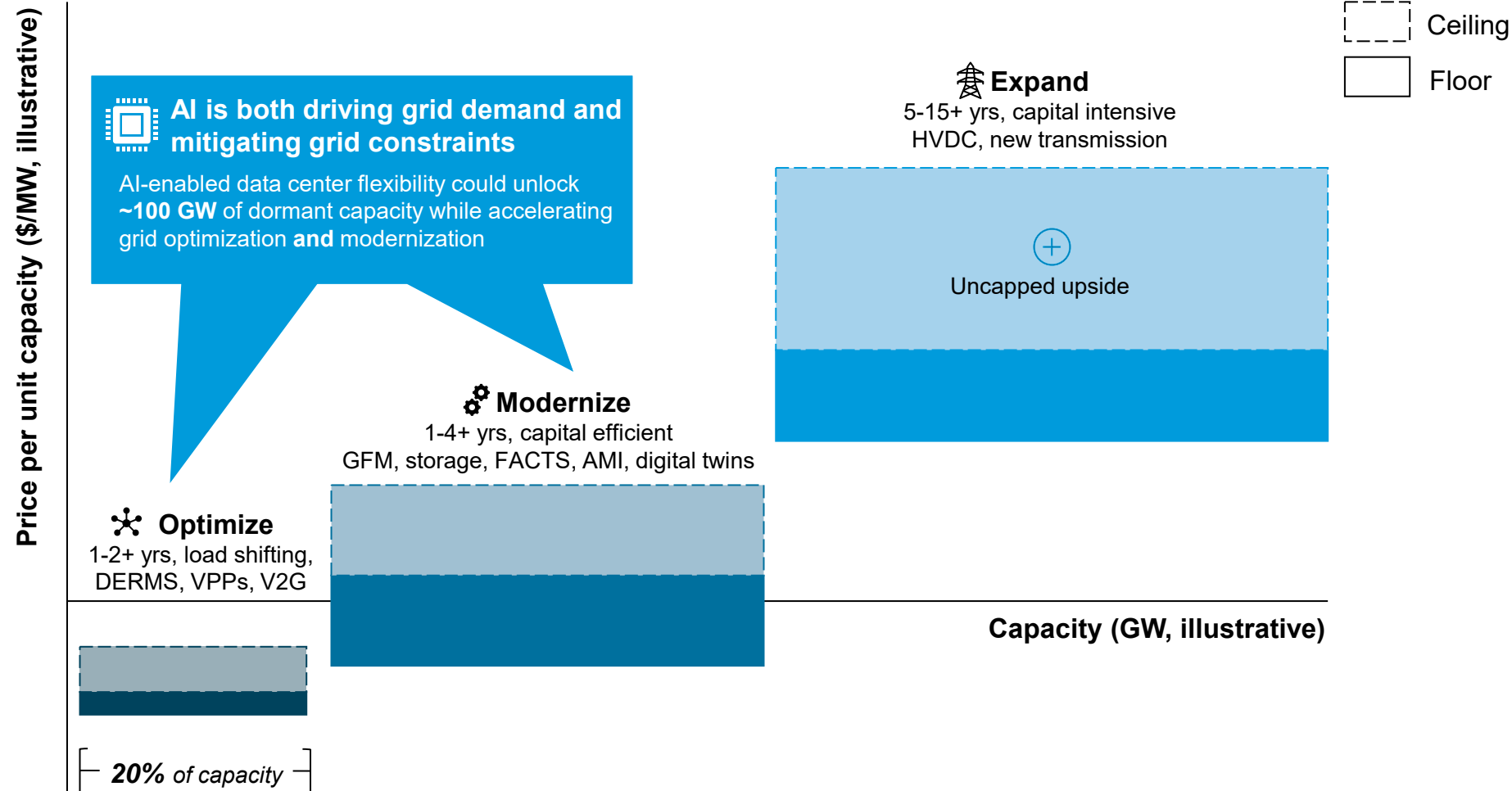
²Investment opportunity is global and based on projected investments for highlighted solutions as defined in each solution area, supplemented by World Energy Investment 2025-2026 reports aligned to STEPS 2030 and BNEF NZE and ETS scenarios. Grid expansion is driven significantly by net-new wires (transmission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



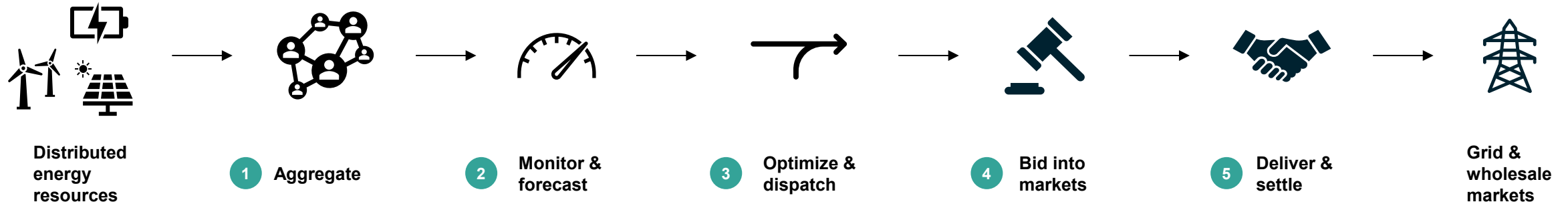
Observations

- 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

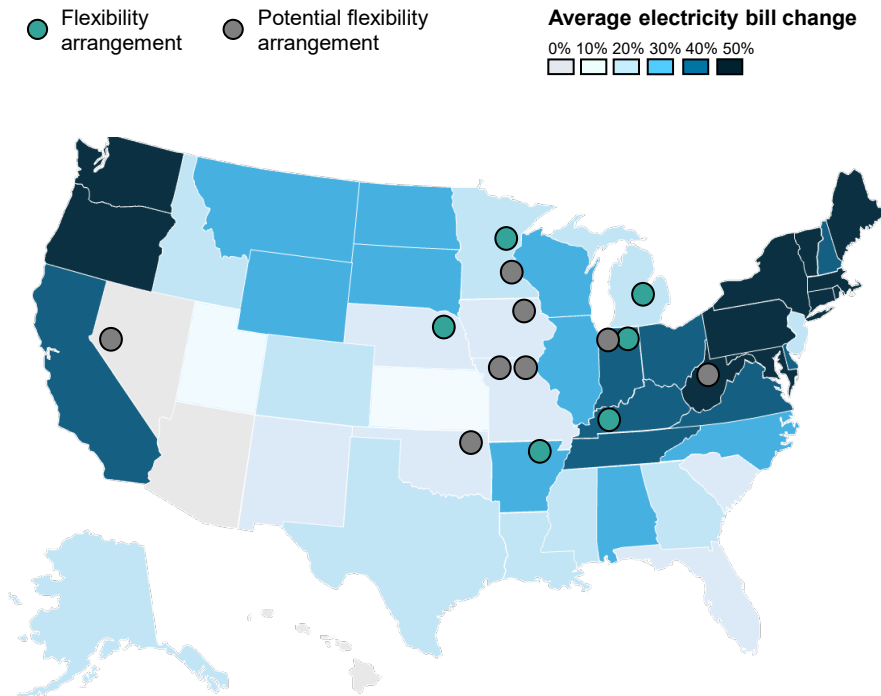
Source: [Pathways to Commercial Liftoff: Virtual Power Plants](#) (US DOE, 2025); [2025 North America VPP Market](#) (Wood Mackenzie, 2025)

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

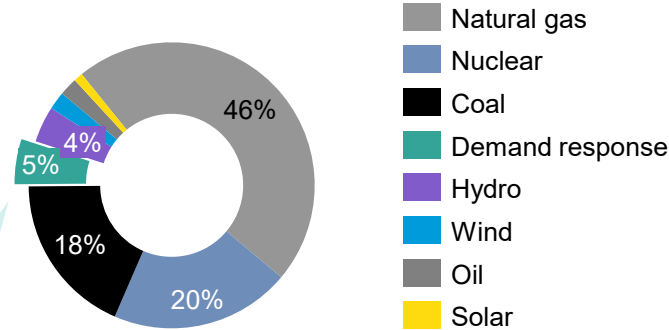
Demand flexibility agreements are in place for data centers across the U.S.

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

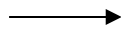
Source: [Large Load Customer Projects and Tariffs](#) (EEI, 2026); [A new framework for DER value in the speed to power era](#) (The Brattle Group, 2026); [How we're making data centers more flexible to benefit power grids](#) (Google, 2025); [Google and Voltus to deliver grid capacity and local economic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

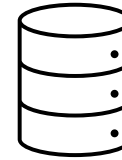
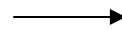
Advanced Metering enables two-way digital communication between utilities and customers, enabling smarter grid operations



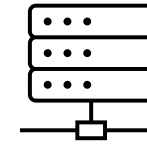
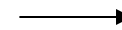
1 Smart meter



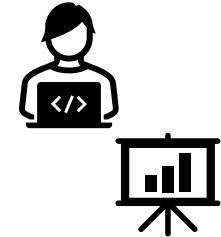
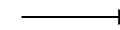
2 Communication tower



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

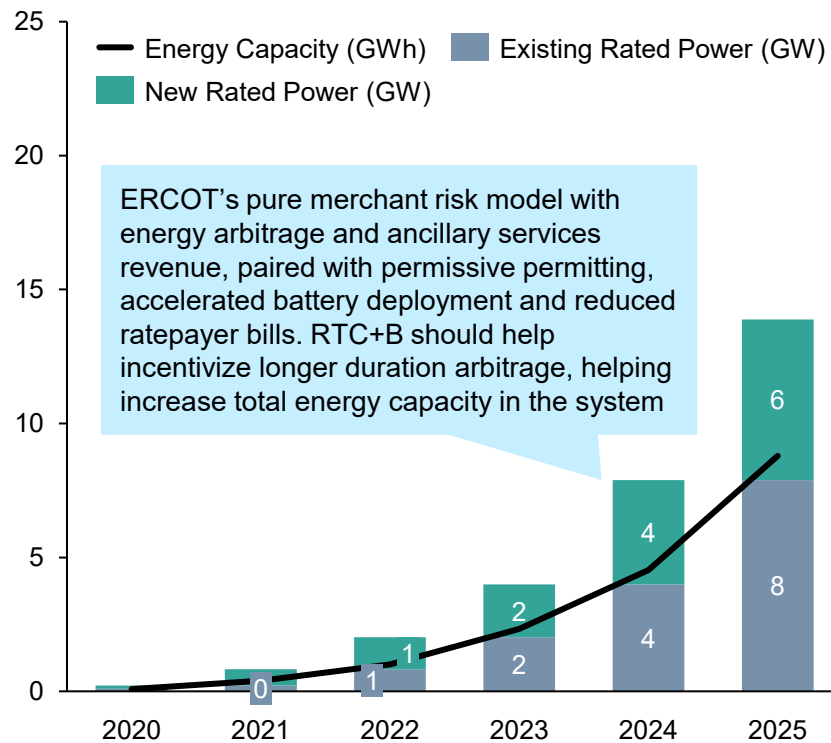
Sources: [Demand Response and Advanced Metering](#) (FERC, 2025); [Electricity Grids and Security Energy Transitions](#) (IEA, 2024); [What is advanced metering infrastructure \(AMI\)](#) (IBM, 2026).

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

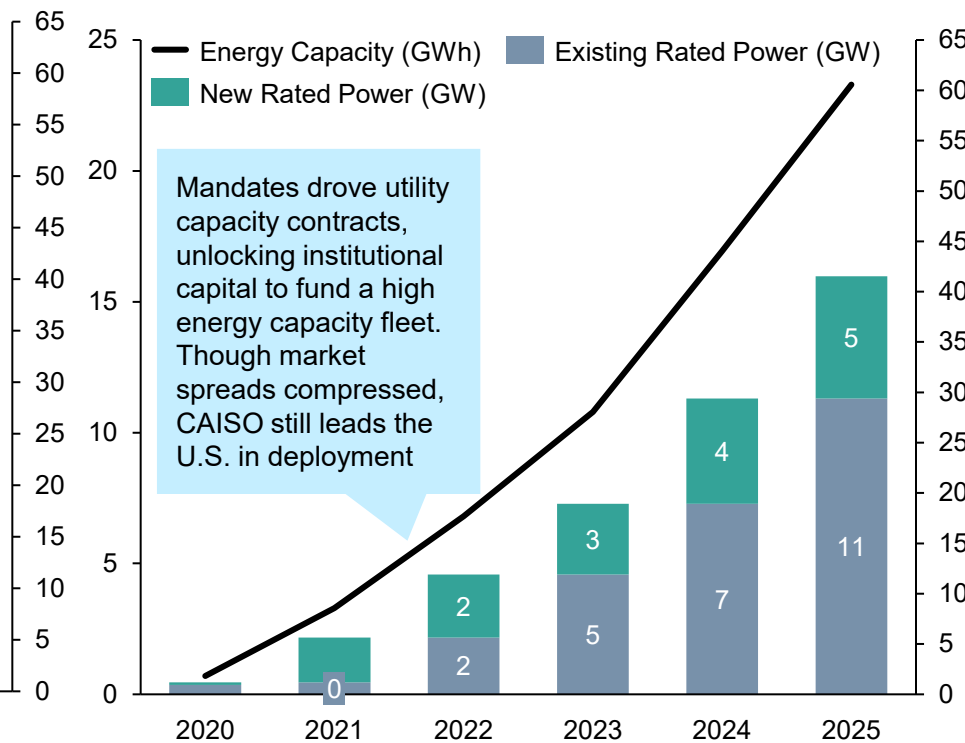
Private investment and arbitrage returns drove high battery deployment in ERCOT

ERCOT Battery Fleet, 2020-2026¹



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

CAISO Battery Fleet, 2020-2026¹



Observations

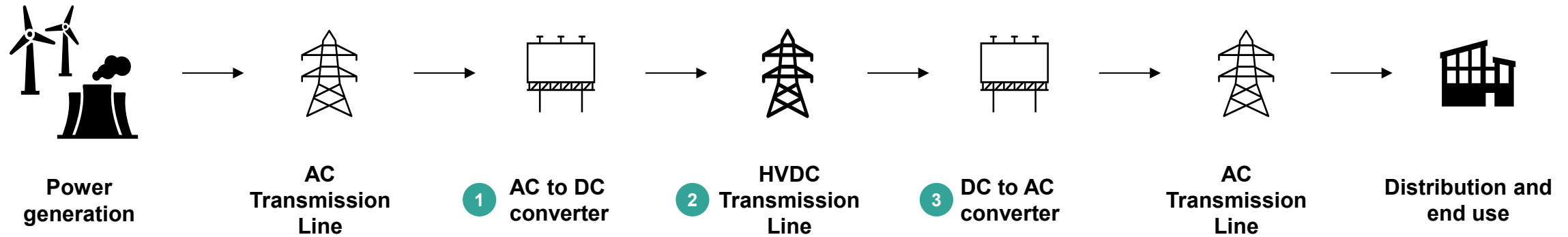
- Battery deployment continues to accelerate as battery cell costs reduce and duration is extended
- The global battery storage market is **expected to exceed \$100B in 2026**, led by grid-connected batteries (~80%)²
- Batteries can help balance the grid, complement renewables, and lower customer electricity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

				Delay hotspot stages		
	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		●			●
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
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).						

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).

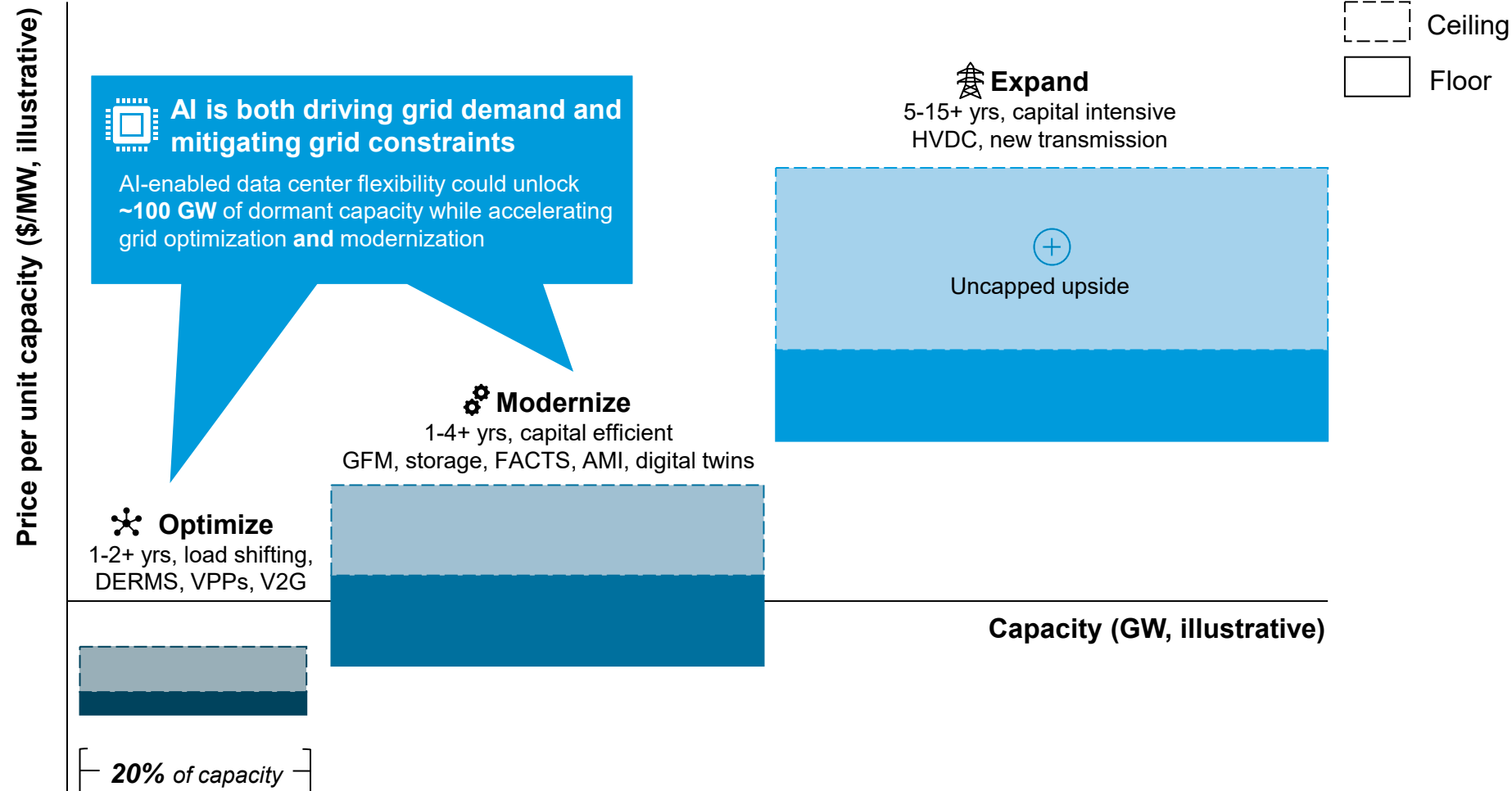
- ① Productivity gain to justify CO₂?
- ② CO₂ emissions are/will be up
- ③ AI opportunities to cut CO₂
- ④ No way around grid expansion



gwagner.com/cki-grids

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

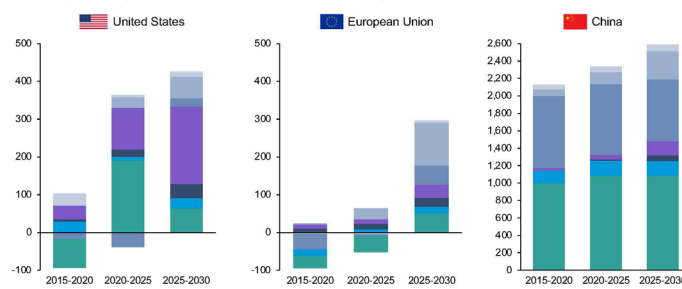
Gernot Wagner, Hasan Alawadhi, Sevgi Helin Tilkicioglu, Dominica Wambold, Ilayda Tezcan, Gunay Kiran, Stephanie Chen, Christy Wong, Ryon Roque, Vincent Sandow-Straesser, Isabel Hoyos, Denis Morrow

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



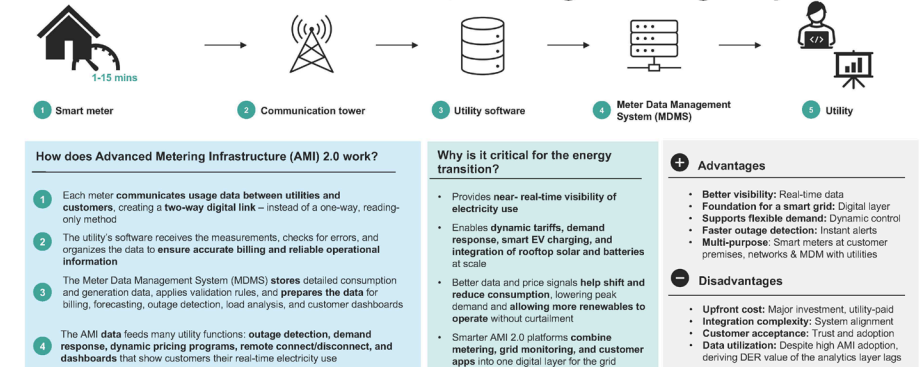
Sources: *Electricity 2026* (IEA, 2026); *World Energy Investment 2026* (IEA, 2026). Credit: Gernot Wagner, Dominica Wambold, Arela Farchi, and [Gernot Wagner](#). Share with attribution: Wagner et al. "Powering Grids," Columbia Business School Climate Knowledge Initiative (28 September 2026).

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

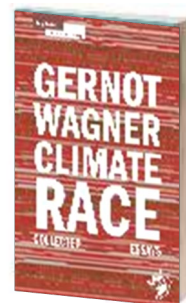
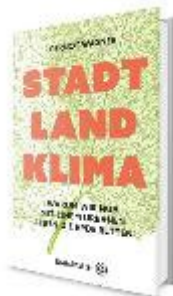
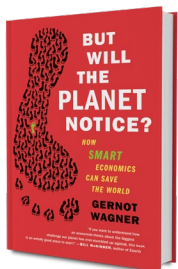
	Optimize grid assets	Modernize and harden the core	Expand grid networks
Definition	Maximize the value of the grid through digital intelligence and demand management	Upgrade and modernize the core with capital efficient physical and technical augmentation	Structurally extend the grid's network to integrate available and emerging generation
Physical and Capital 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 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* (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, 2026).

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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