

Innovation uncertainty shapes divergent pathways toward decarbonization*



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How does uncertainty in clean-technology learning shape the cost, timing, and emissions of decarbonization pathways?

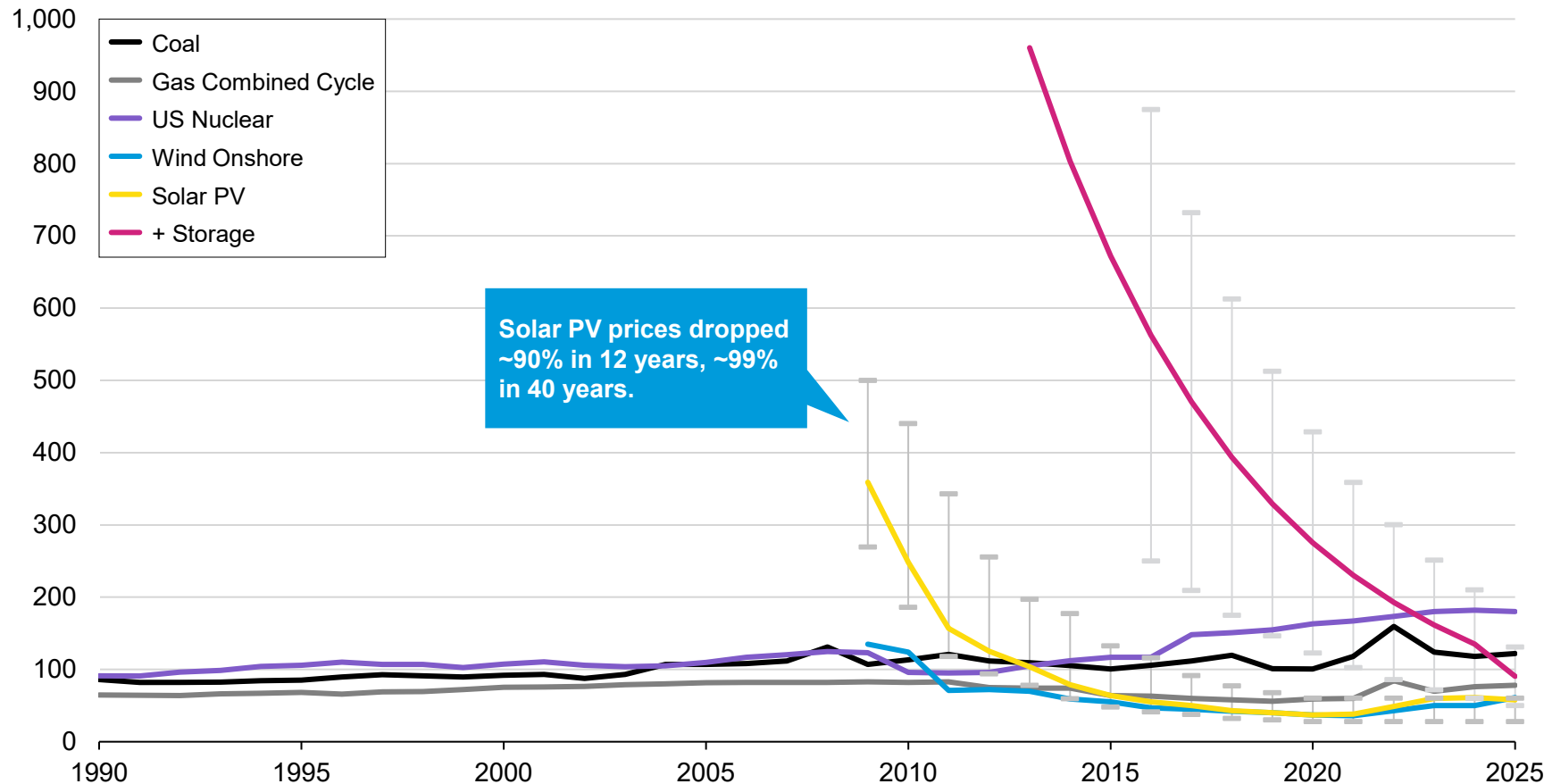


Not *if*, *when*



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

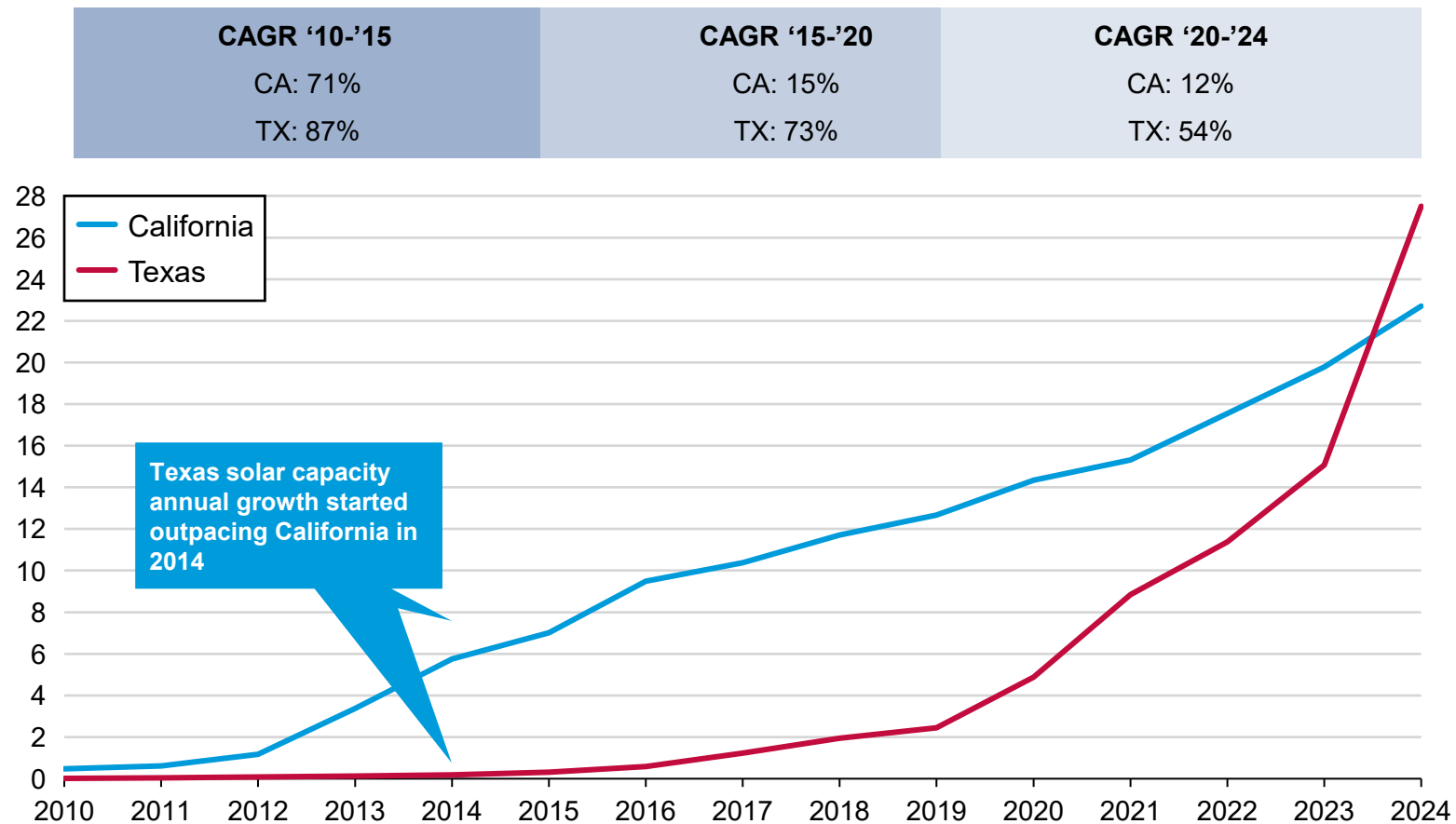
- **Solar photovoltaic (PV) prices dropped by ~80% in the past decade**, wind by ~70%, and lithium-ion battery costs by ~90%.
 - PV price drop primarily driven by **improvements in module efficiency and economies of scale.**
 - **Onshore wind** remained the cheapest for the longest, **now beaten by PV.**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



PS

Longer Reads

Gernot Wagner

The Green Key to Germany's Economic Recovery

It is tempting to look to Texas, which has become the North Star of electricity-market liberalization. The state recently surpassed California in total solar-power deployment. On most days, a live view of its grid shows that wind, solar, and battery storage provide the majority of electricity – and at rock-bottom rates. After accounting for nuclear, which provides around 10% of baseload power, the state's power grid often has a smaller relative carbon footprint than those in California or Germany.

One answer is an explicitly two-tiered electricity pricing system – one for renewables, and one for fossil electricity generation. Solar, wind, and, increasingly, batteries promise to be the cheapest sources of electricity. Making this a reality requires market reform, while keeping appropriate incentives for the necessary investments.



Wagner, [“The Climate Policy Pendulum”](#) (16 January 2025)

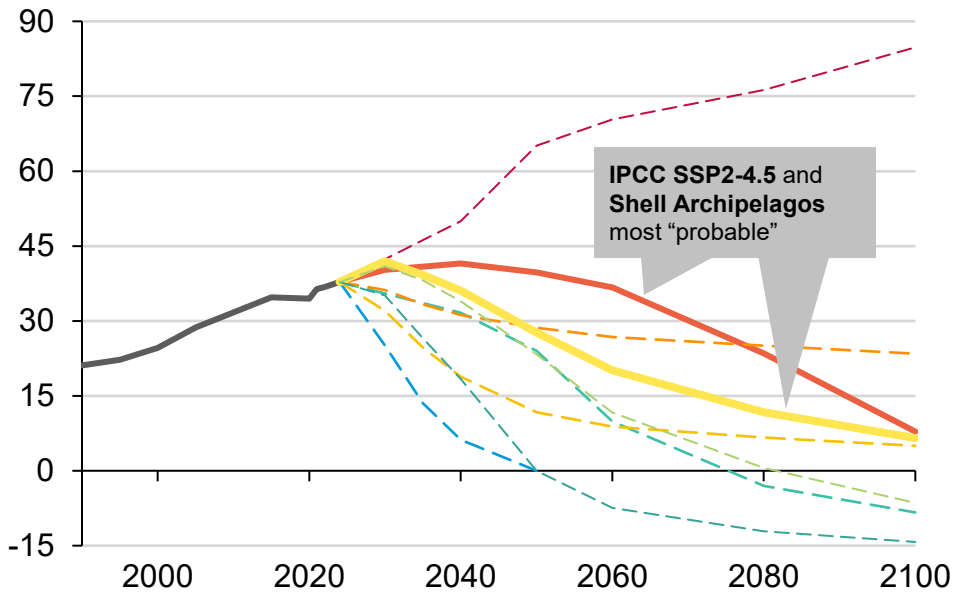
Early decarbonization investments are key to keeping temperatures within livable range and saving trillions in climate costs

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

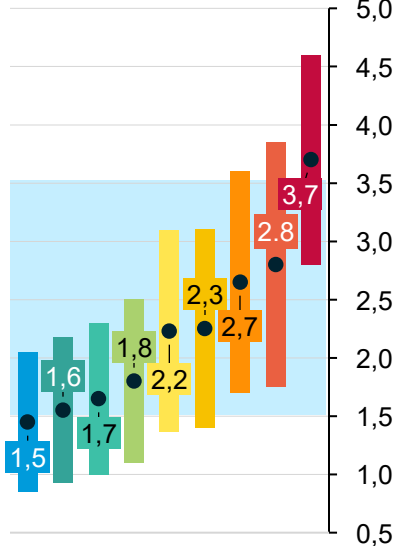
Low-carbon investment has risen rapidly recently, though ~2.5-3.5x gap remains

- IPCC SSP1-2.6 — IEA Net Zero by 2050 — Shell Archipelagos ● Median
- IPCC SSP2-4.5 — IEA Announced Pledges — Shell Horizon ■ “Likely” ranges
- IPCC SSP3-7.0 — IEA Stated Policies — Shell Surge ■ “Probable” outcomes

Annual global CO₂ emissions, GtCO₂



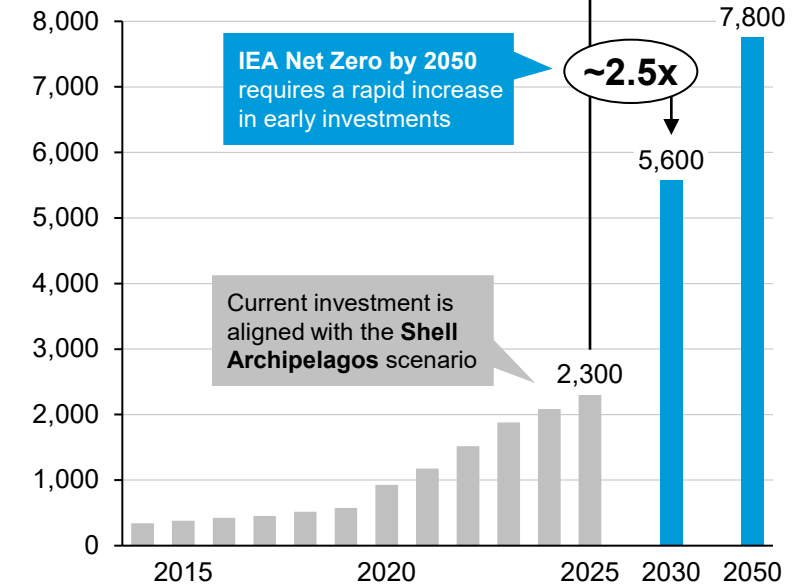
Projected average global warming¹, °C



Climate impacts, % GDP loss



Annual investments, US\$B



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, Hyaee Ryung Kim, and Gernot Wagner. Share with attribution: Kim et al., “Probable Climates” (27 January 2026).

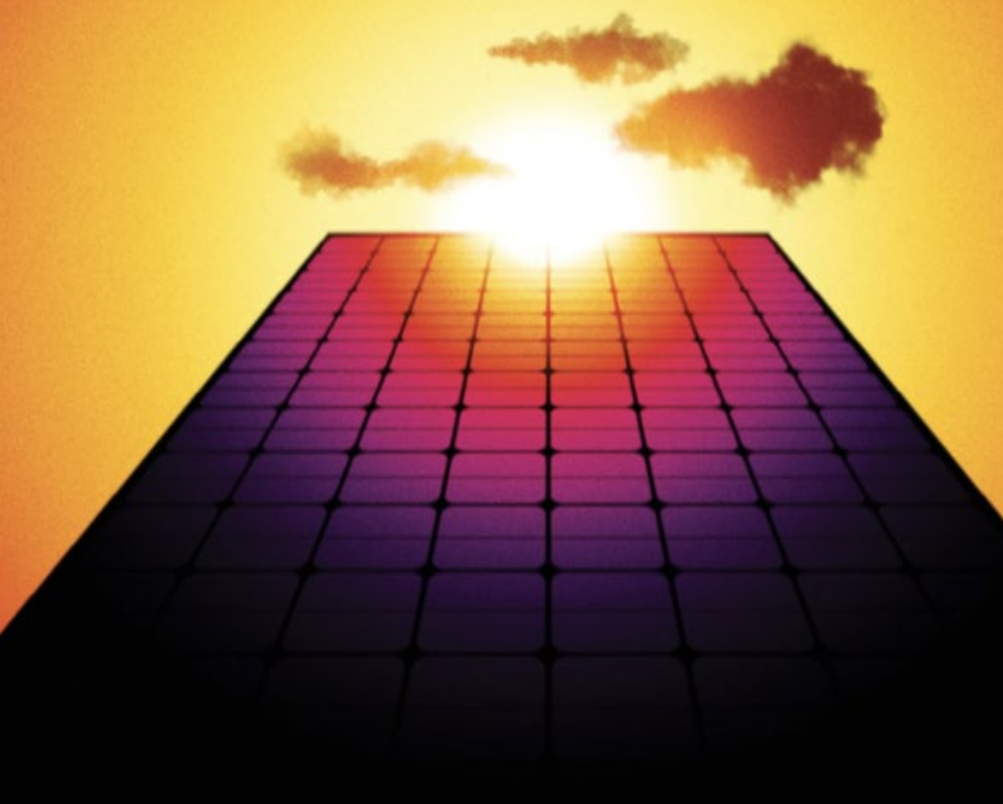
→ Power sector 'solved'



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

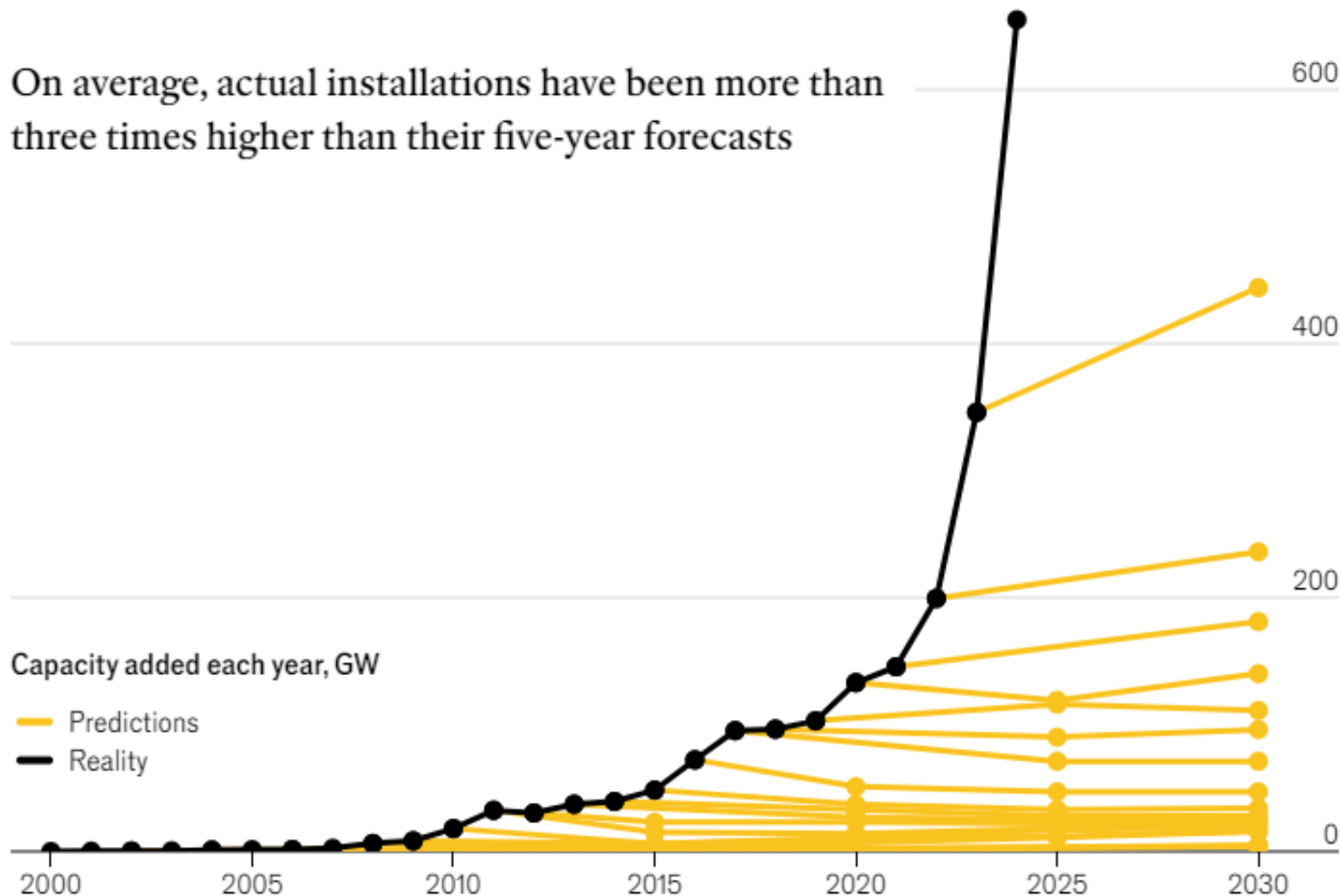
DAWN OF THE SOLAR AGE

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



Capacity added each year, GW

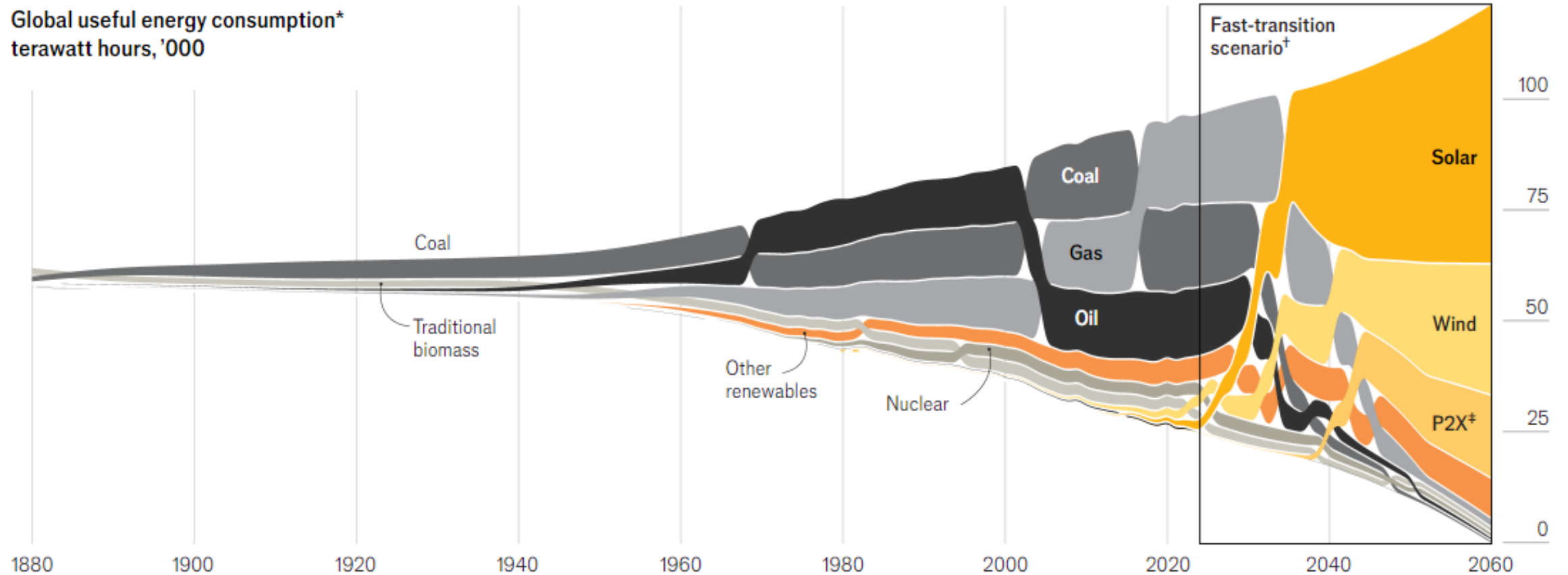
— Predictions
— Reality

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)

Power sector 'solved'

→ 'Missing profits'



Christophers, "The Price is Wrong: Why Capitalism Won't Save the Planet" (Verso, 2024)

China's world-beating solar industry is in turmoil

The Gulf war won't save it

Save Share AI Summary



PHOTOGRAPH: GETTY IMAGES

It all makes for a gloomy outlook. Already, more than 40 Chinese solar firms have gone bankrupt, been acquired or delisted from stock exchanges since 2024. One-third of the workforce of the country's five biggest solar-industry firms has been laid off, according to Reuters, a news agency. But the biggest wave of consolidation has yet to break, says Jessica Jin of S&P Global, a research firm. Solar-panel prices have nudged up in recent months, but the panels still sell at less than their average production costs. The share prices of LONGi Green Energy Technology, Tongwei, Jingko Solar and Trina Solar, the biggest producers, are all hovering well below half their peaks of a few years ago.

Business school teaching case study: how should solar-panel makers respond to falling prices?

China's Longi was a pioneer. Now commodification is forcing a dilemma over how to expand



Heading for the sun: a cell wafer undergoes checks at a Longi plant in China before

Gernot Wagner

A virtuous cycle is under way in which rising manufacturing capacity leads to lower costs and increased demand. Everyone benefits — except for the solar-panel makers.

What is a dominant first mover, such as Longi, to do?

Vertical vs horizontal expansion

Power sector ‘solved’

‘Missing profits’

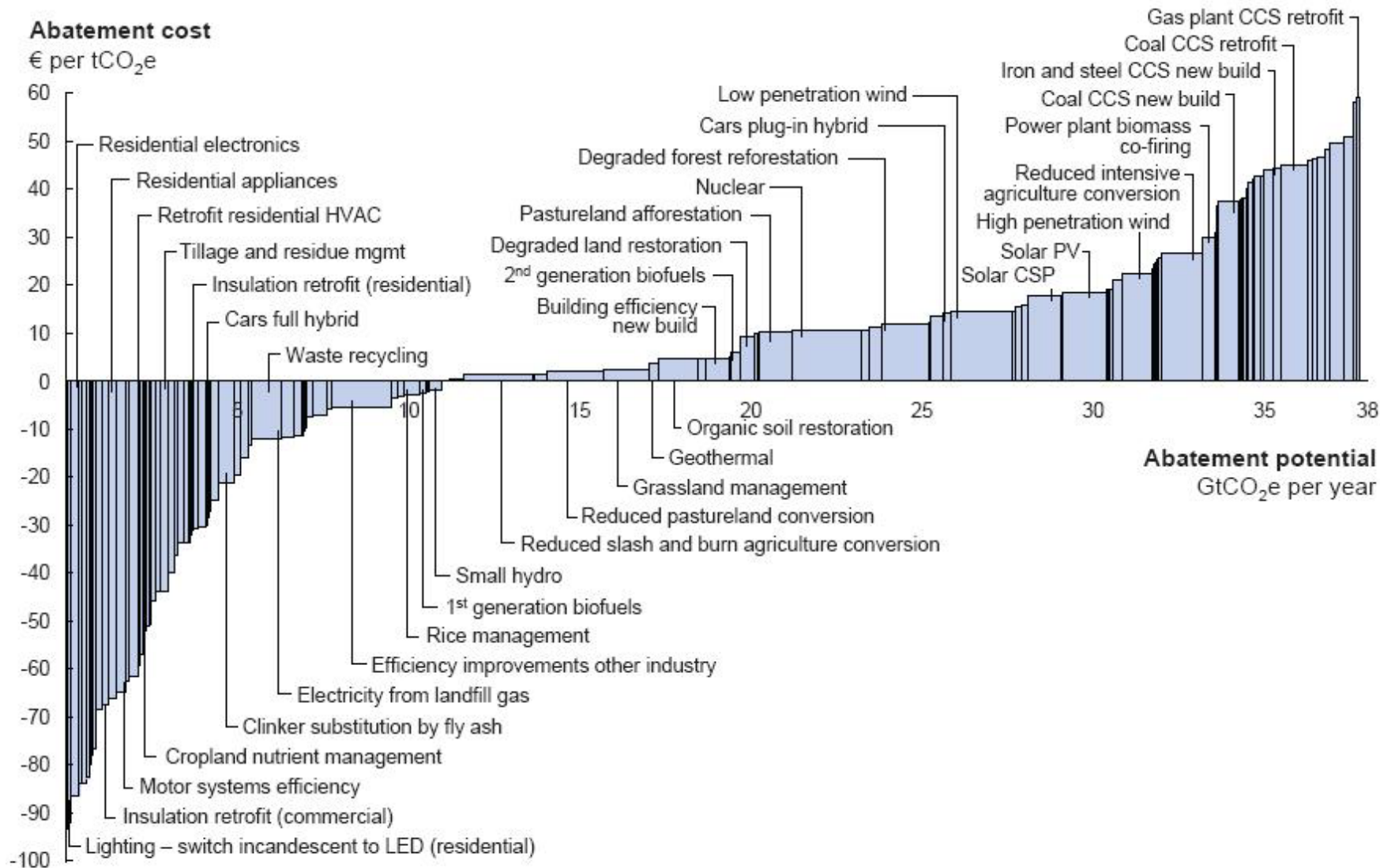
→ Cost of ‘costless’ mitigation



Kotchen, Rising & Wagner. [“The costs of “costless” climate mitigation.”](#) *Science* (30 November 2023).

Large abatement opportunities available at low or no cost

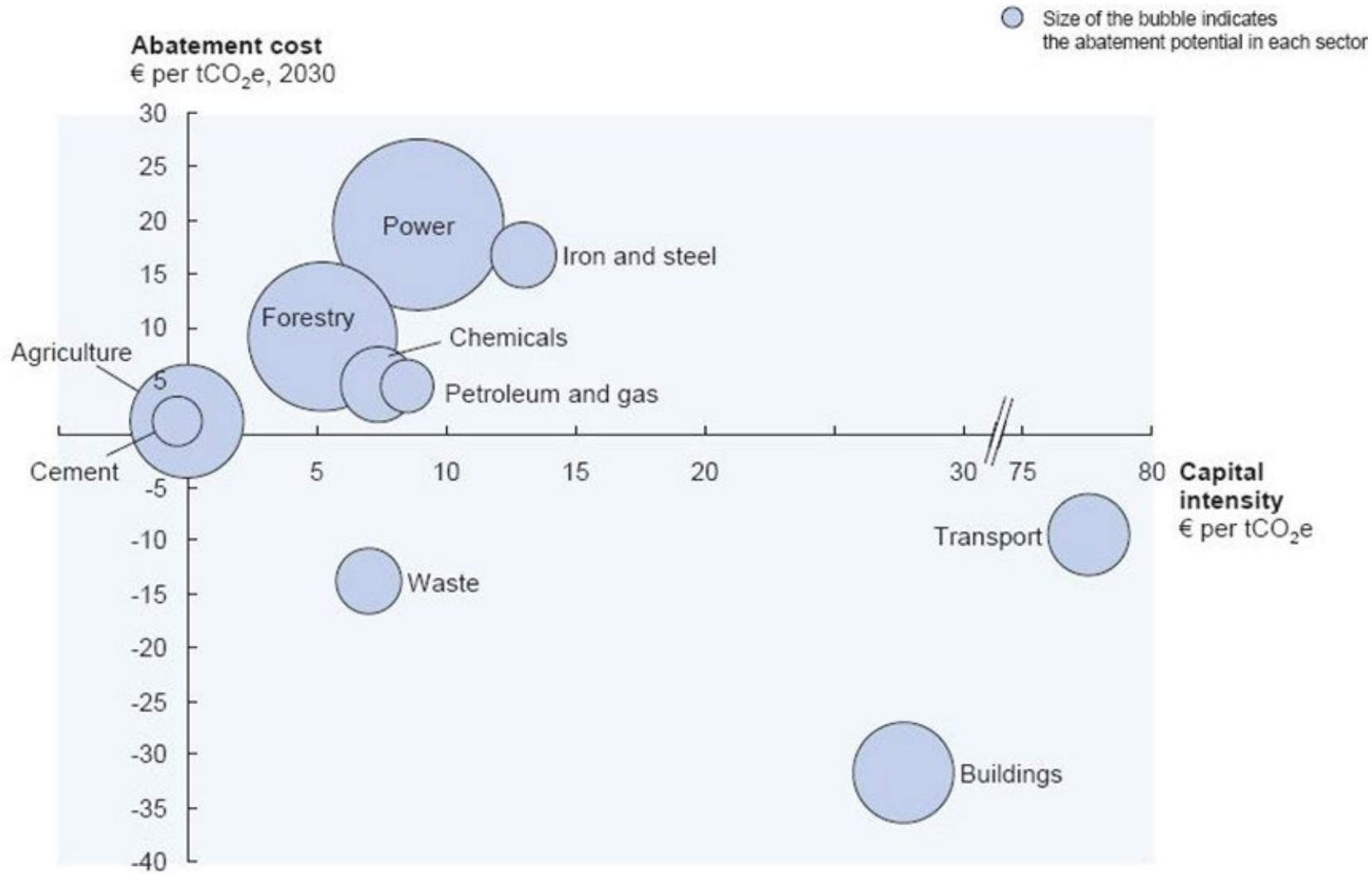
McKinsey Global v2.0 effort in 2009 identified 38 GtCO₂e abatement potential in 2030



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

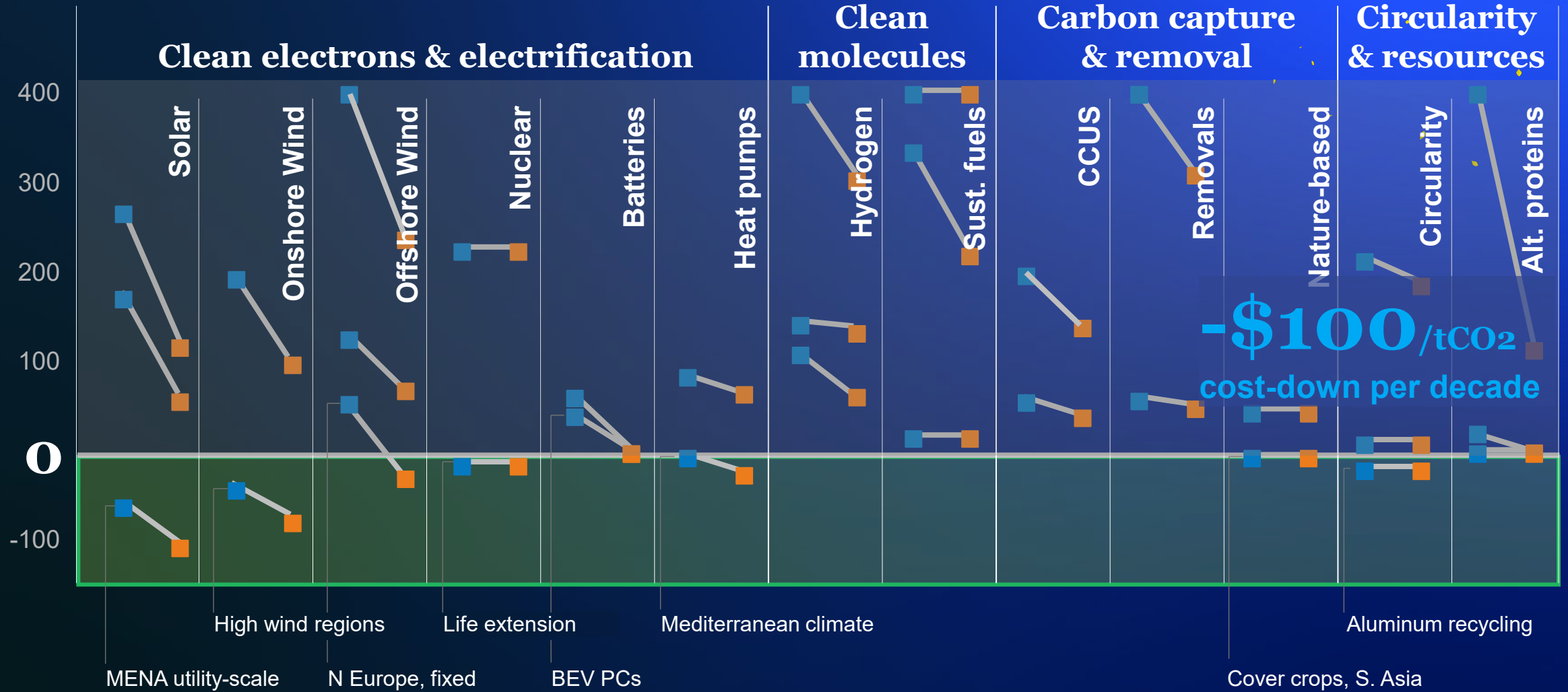
Capital intensity varies widely across sectors

Transport and buildings with largest up-front capital expenditure requirements



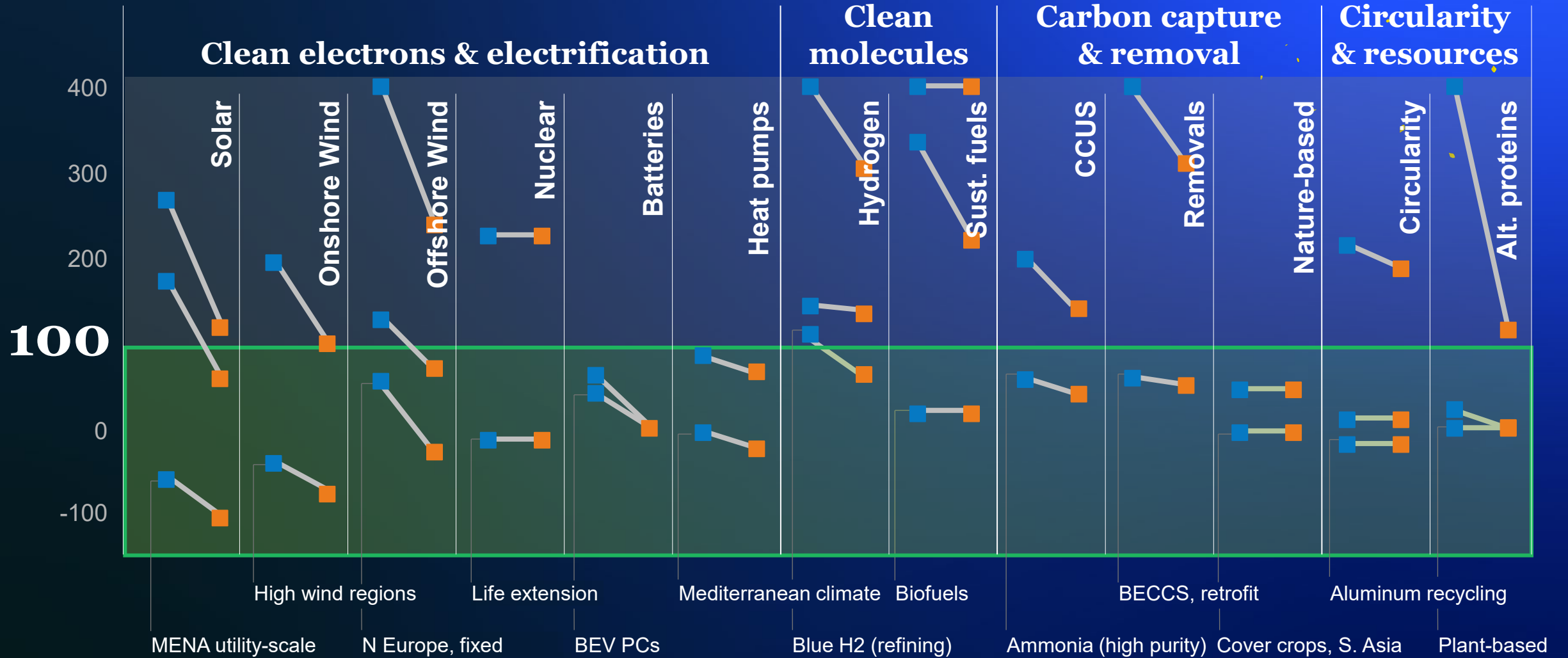
10 % of techs in the money today – steep cost-down to 2030

Estimated abatement costs, USD/tCO_{2e}



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

Estimated abatement costs, USD/tCO_{2e}

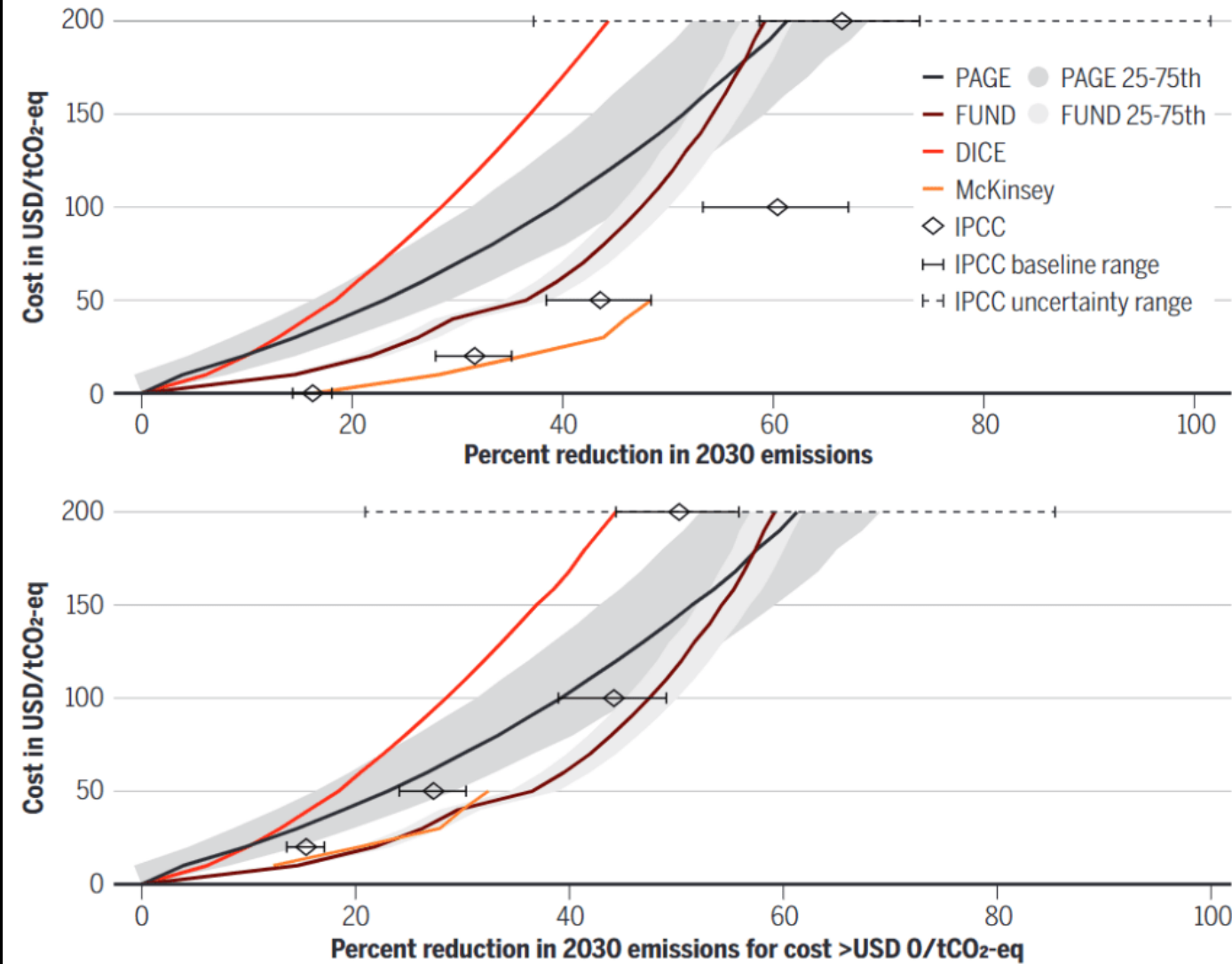


How costly, or costless, is climate emissions mitigation? p. 1001



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 CO₂ equivalent (tCO₂-eq). USD reported in 2020 dollars. See supplementary materials.



Source: Kotchen, Rising & Wagner. [“The costs of “costless” climate mitigation.”](#) *Science* (30 November 2023).

Power sector ‘solved’

‘Missing profits’

Cost of ‘costless’ mitigation

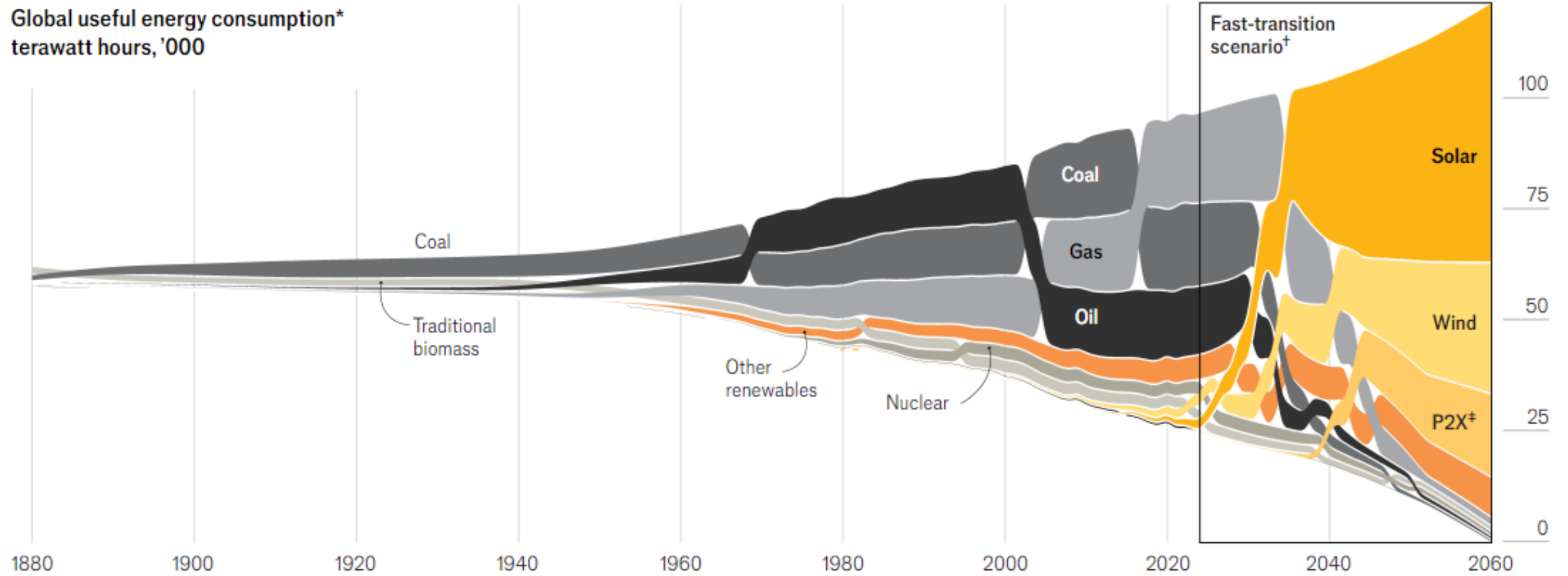
→ Transition matters



Moers, Fioriti & Wagner, “Innovation uncertainty shapes divergent pathways toward decarbonization,” *Mimeo* (31 May 2026)

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

Global useful energy consumption*
terawatt hours, '000



Sources: Rupert Way; Our World in Data

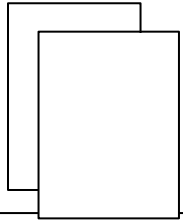
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Source: *Economist* "[Sun Machines](#)" (20 June 2024)

How does uncertainty in clean-technology learning shape the cost, timing, and emissions of decarbonization pathways?



Literature: Technology dynamics in transition models



Energy-economy models

- Mainstream energy-economy models often treat technological change as exogenous or deterministic (e.g. Way et al., 2022)
- Scenario tools have repeatedly underestimated renewable cost declines and diffusion speeds (e.g. IEA WEO; Creutzig et al 2017)



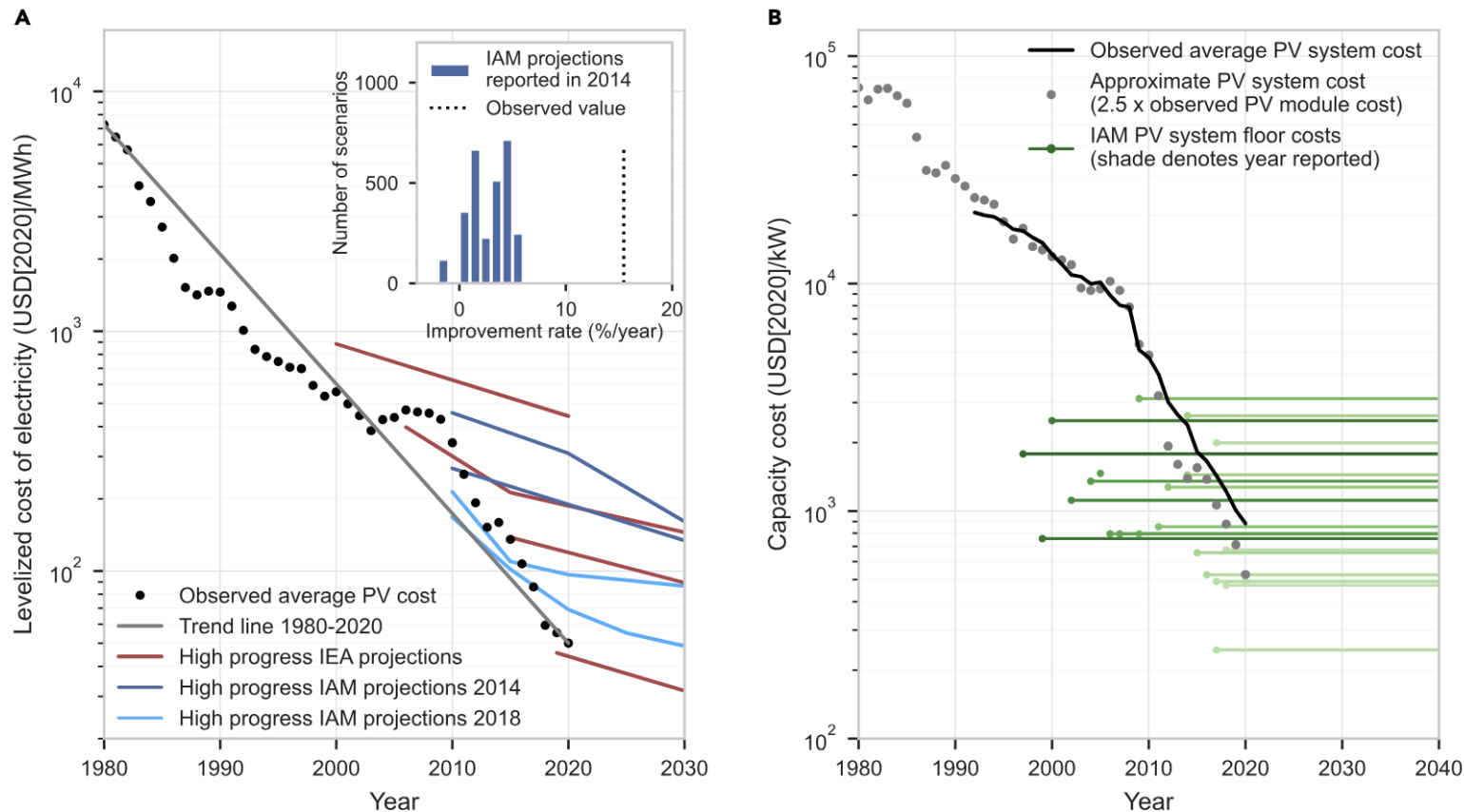
Empirical learning and forecasting

- Empirical work shows large heterogeneity, uncertainty, and structural breaks in learning rates (e.g. Goksin et al 2017, 2025; Trancik 2021)
- Vast endogenous learning literature (e.g. Acemoglu et al 2012; Coppens, Dietz & Venmans 2025)
- Probabilistic forecasting increasingly used for energy & climate outcomes, but rarely coupled to high-resolution models (e.g. Trancik et al 2025)

→ Combine empirically disciplined innovation uncertainty with high-resolution energy system model (PyPSA-Earth)

Forecast error is an economic problem

Historical PV cost projections

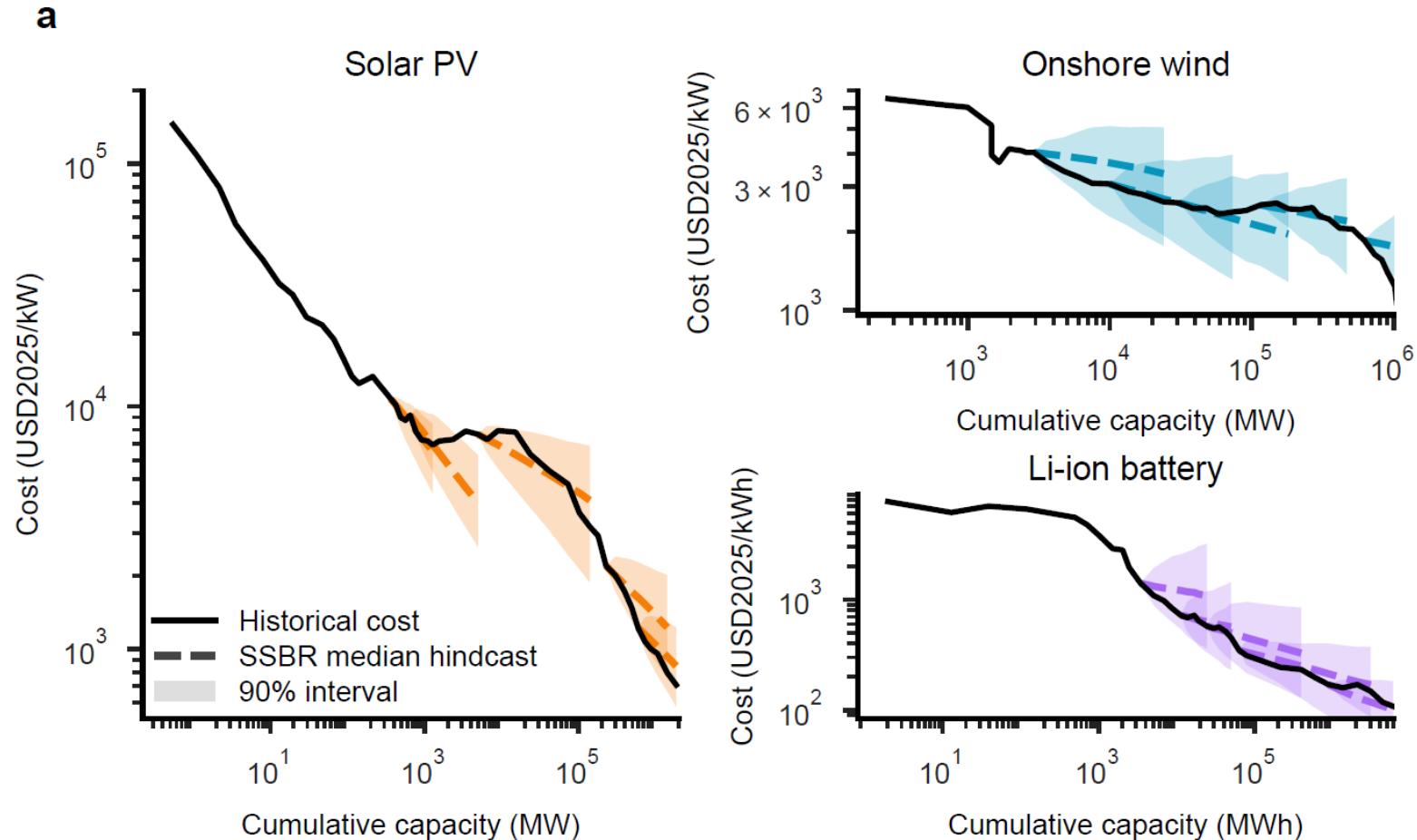


Source: Way et al., (2022)
 Moers, Fioriti & Wagner, "Innovation uncertainty shapes divergent pathways toward decarbonization," Mimeo (31 May 2026)

- Solar, wind & batteries have repeatedly become cheaper faster than expected
- Cost assumptions shape **investments, policy trade-offs, and *perceived* feasibility** (Trancik *et al.*, 2025)
- Too pessimistic: mitigation looks unnecessarily slow & expensive
- Too optimistic: institutional, grid, and deployment frictions disappear by assumption

Methodology: Empirical calibration

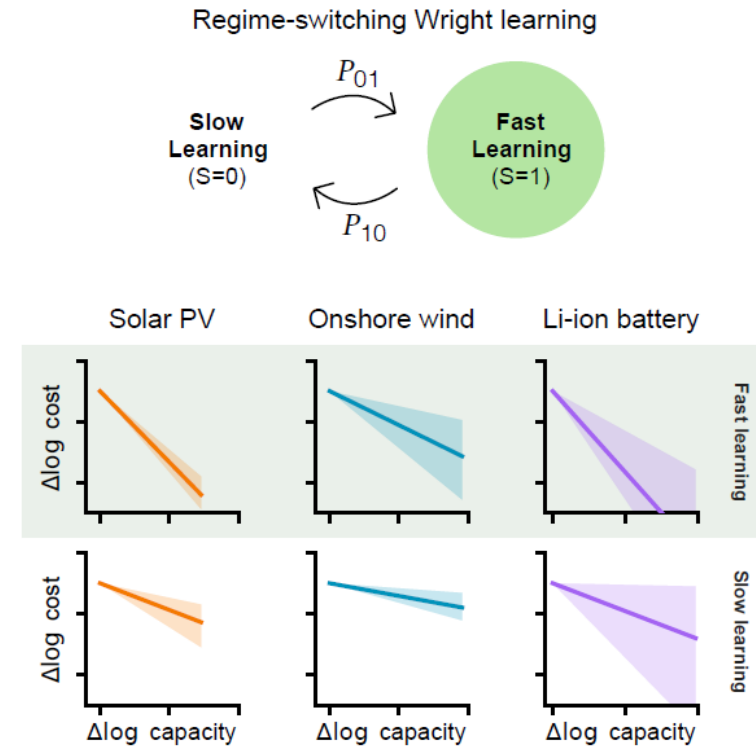
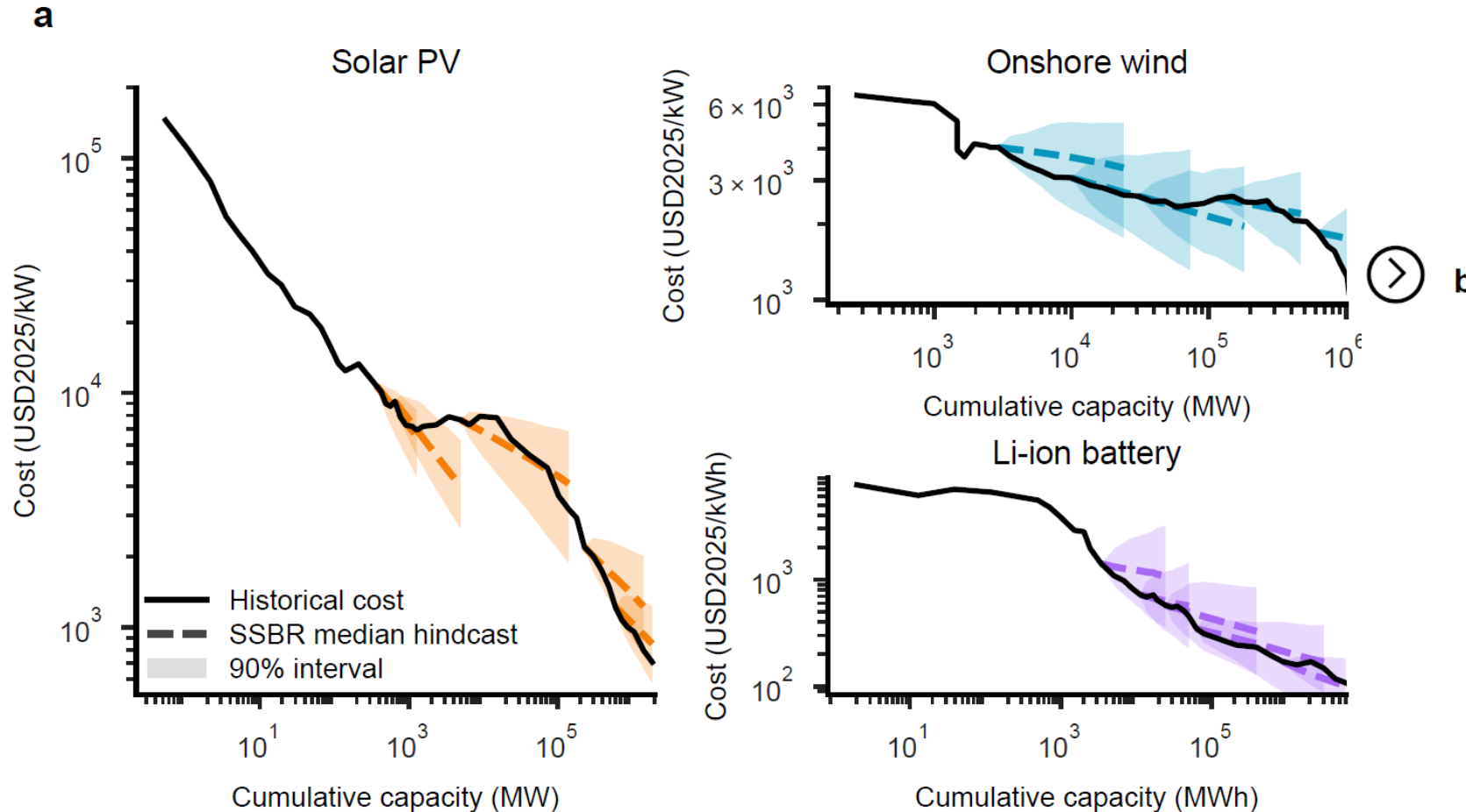
Shared-State Bayesian Regime-learning Wright model hindcasts



Methodology: Empirical calibration + Stochastic learning model

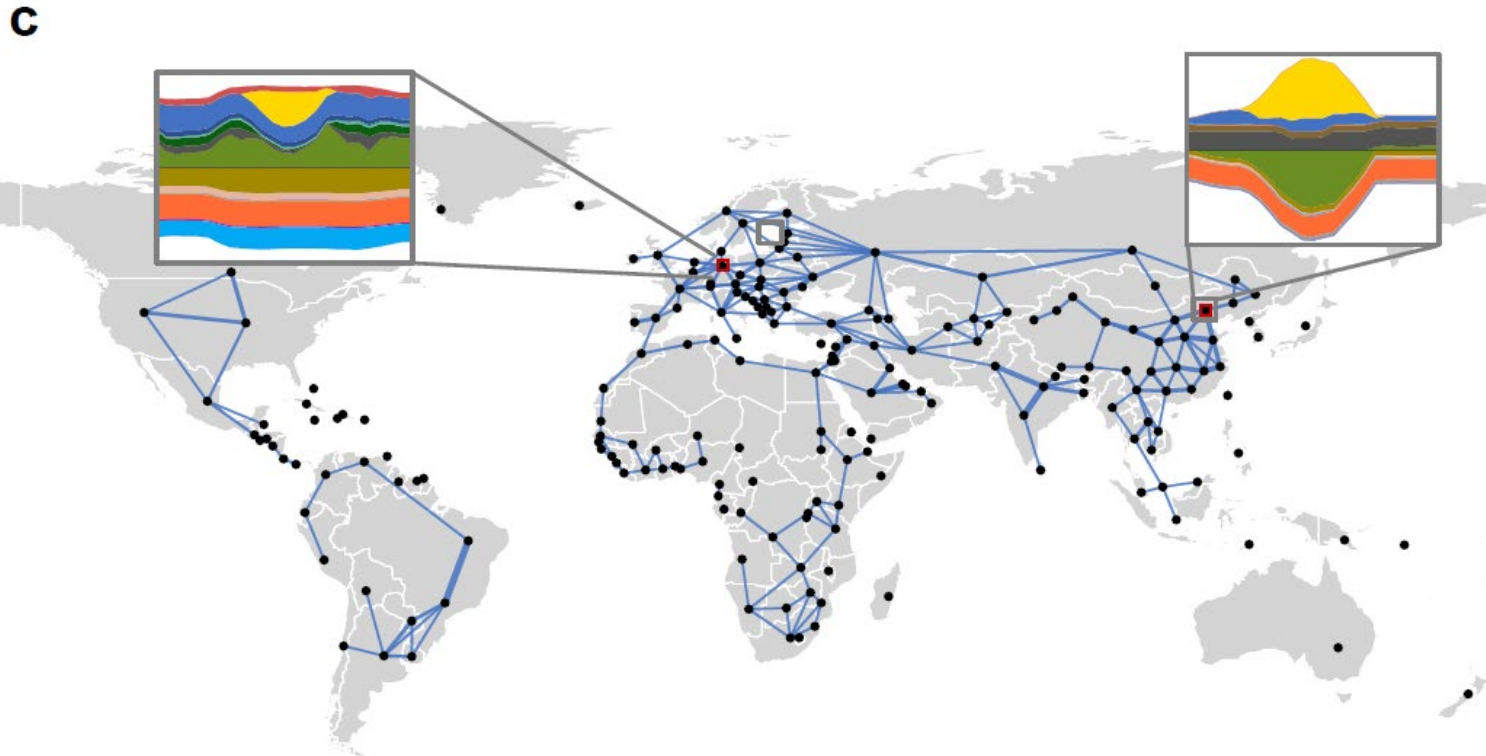
Shared-State Bayesian Regime-learning Wright model hindcasts

Learning Model



Global PyPSA-Earth Power Sector model

Energy System Model



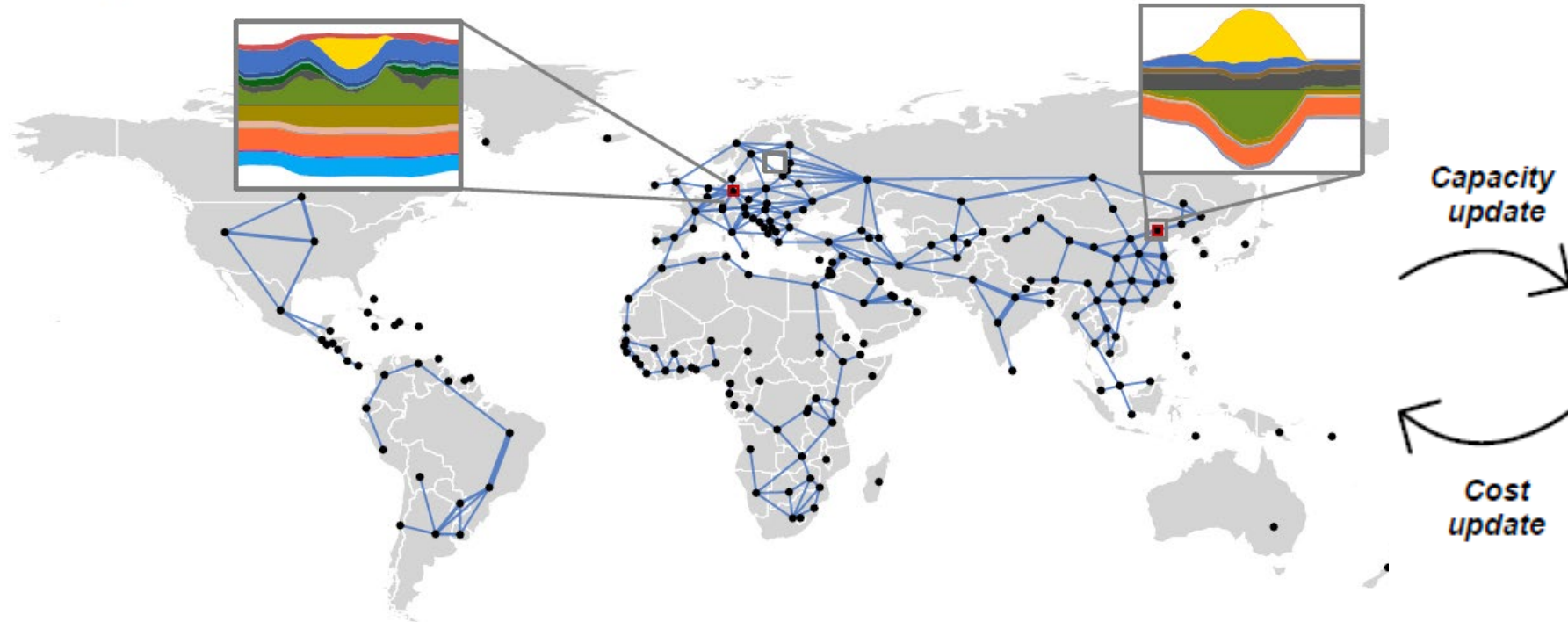
- High-resolution, open-source, linear model that minimizes system costs
- 200 regions, 10 typical days, 5-year steps
- Sector-coupled model; our focus on power sector
- No emissions constraint in baseline

Global PyPSA-Earth Power Sector model

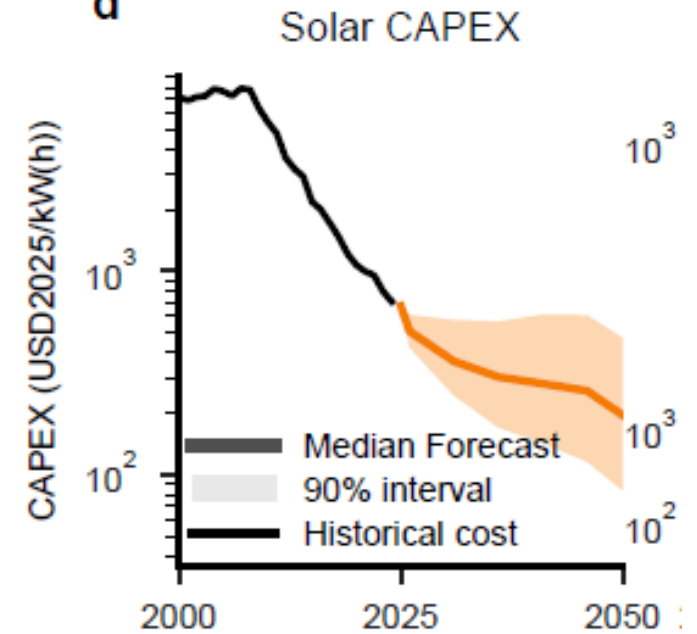
Energy System Model

Learning Model

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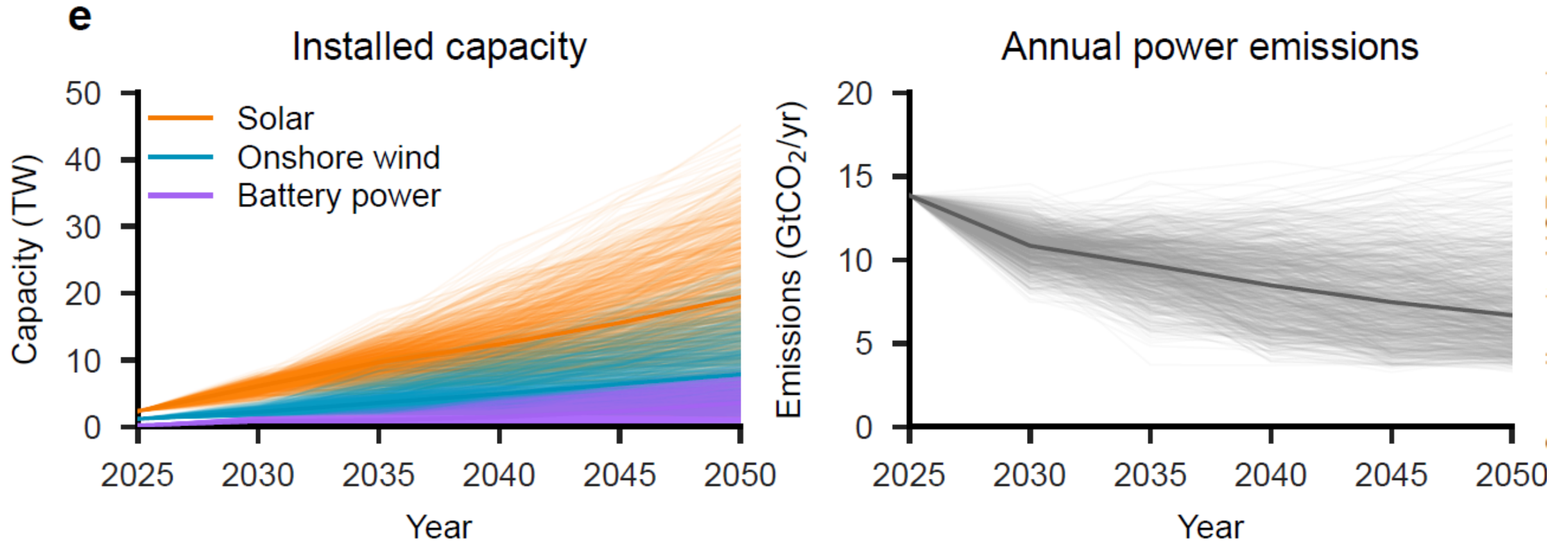


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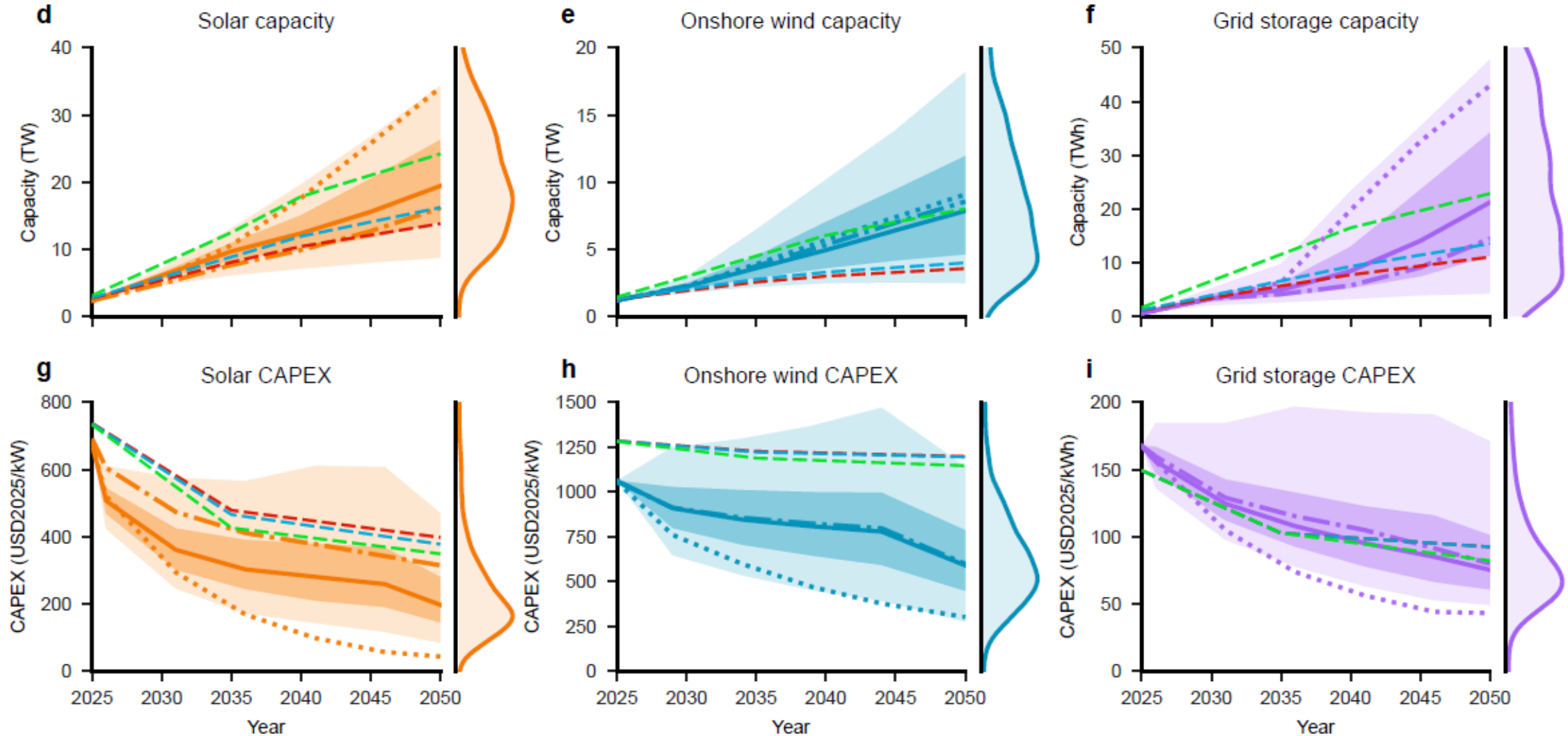


Large pathway uncertainty(?!)

Distribution of feasible energy-system states

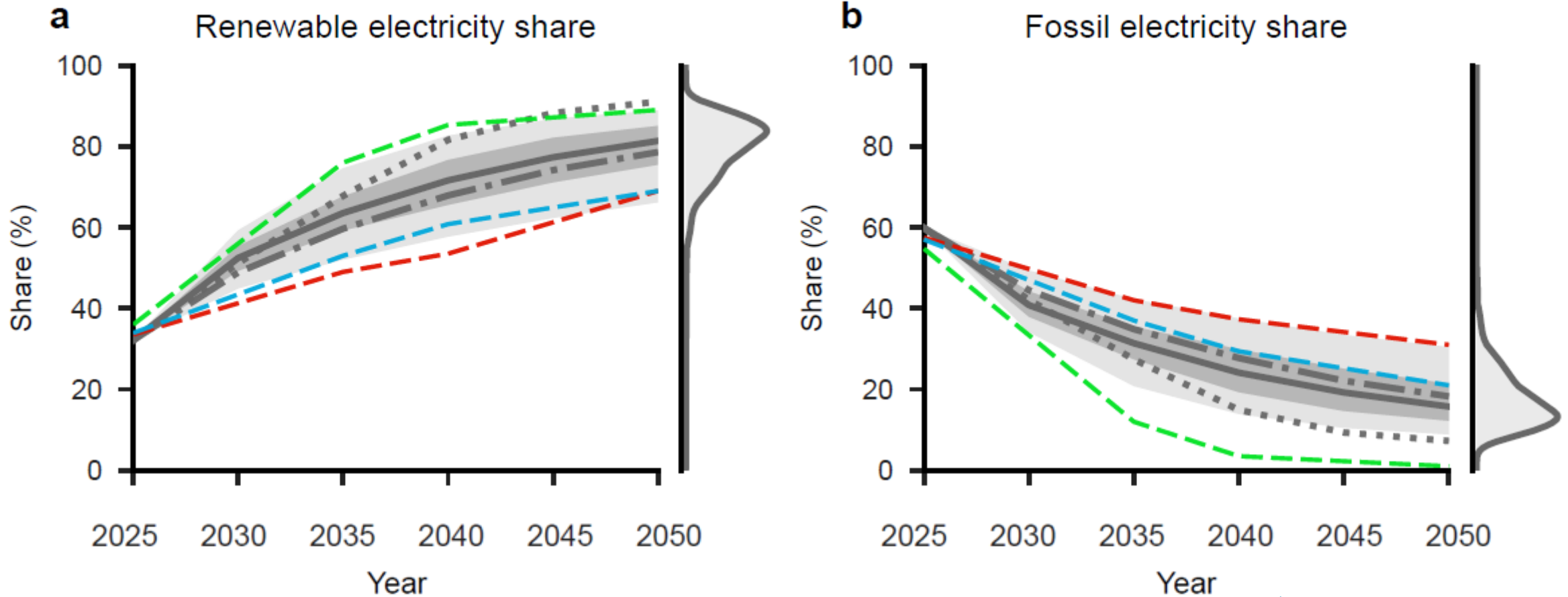


Large spread of solar, wind, and grid storage pathways...



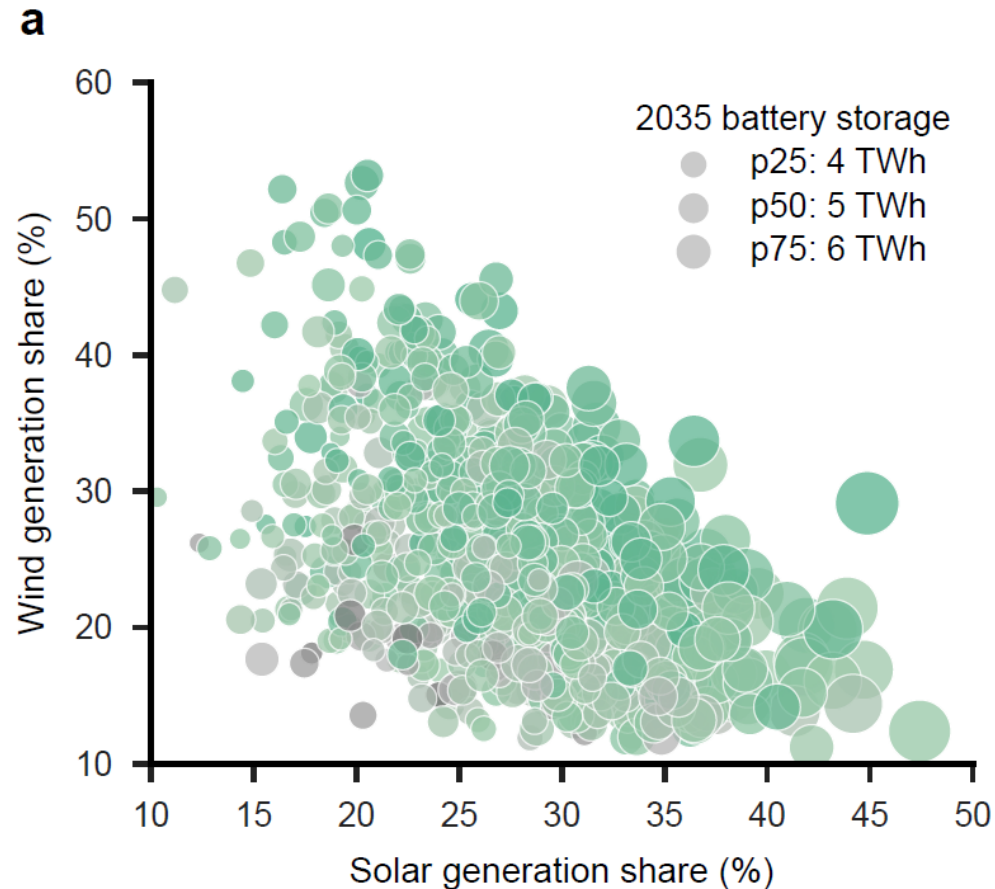
Consistently high (>80%) renewables share by 2050

Correspondingly low fossil electricity share (<20%)

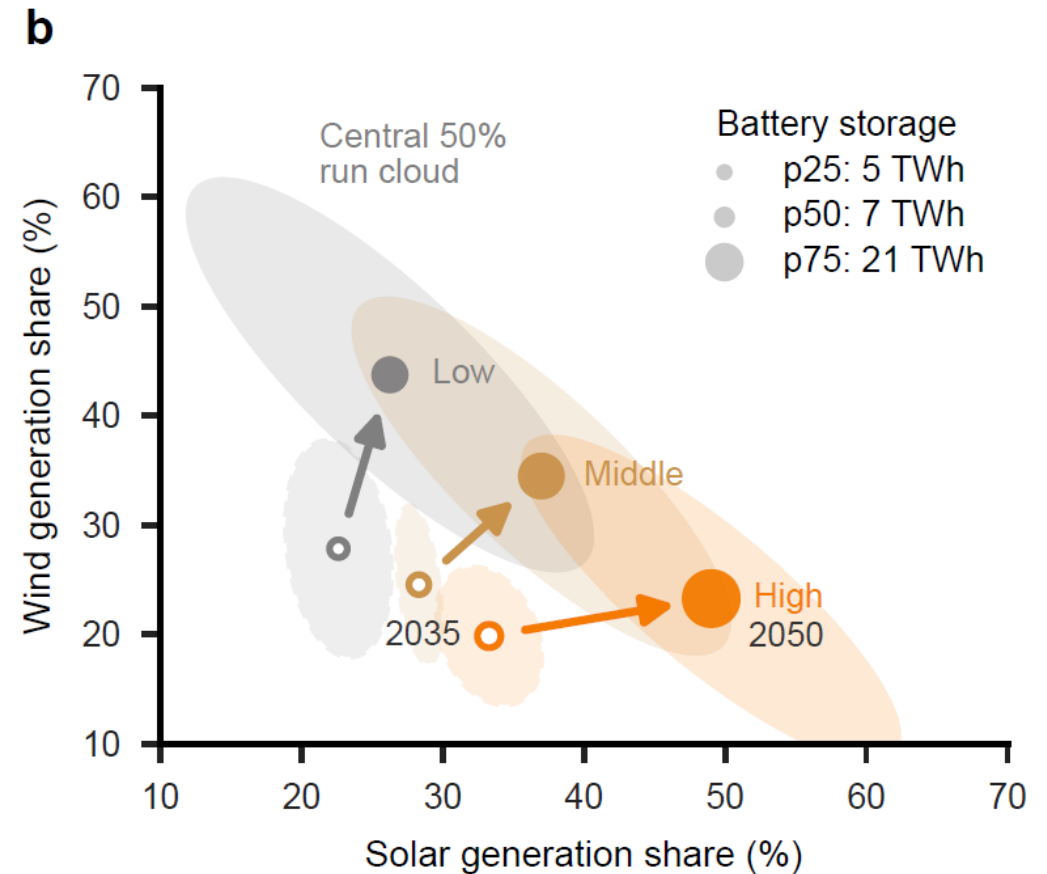


Power systems sort into distinct renewables architectures

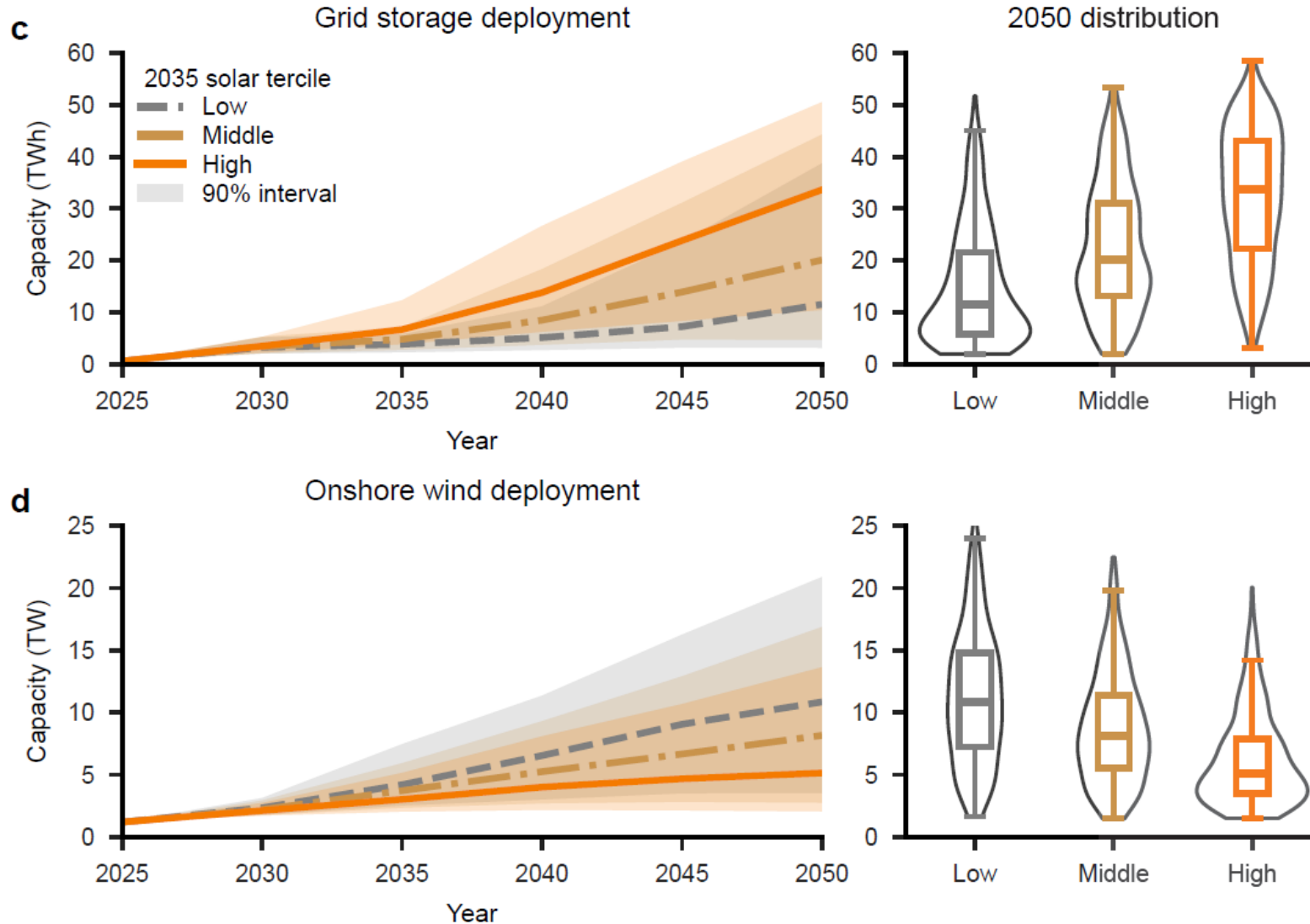
2035 wind versus solar shares



Large path dependencies between 2035 & 2050

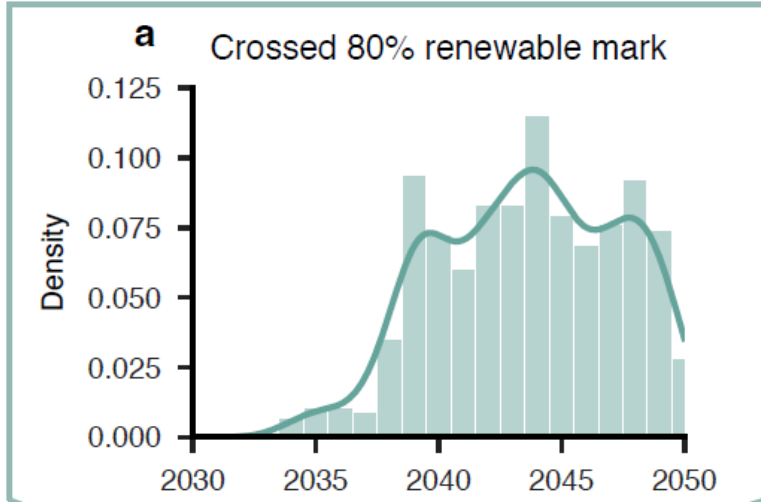


High 2035 solar share → high solar (+ battery) share by 2050



- By 2035, runs sort into distinctive renewables architectures
- High solar share = high grid storage share
- Fossil shares remain similar across high and low solar deployment, with wind as ‘substitute’
- 2035 fossil share less indicative of architecture than solar and wind shares

Early high renewable systems save significant emissions...

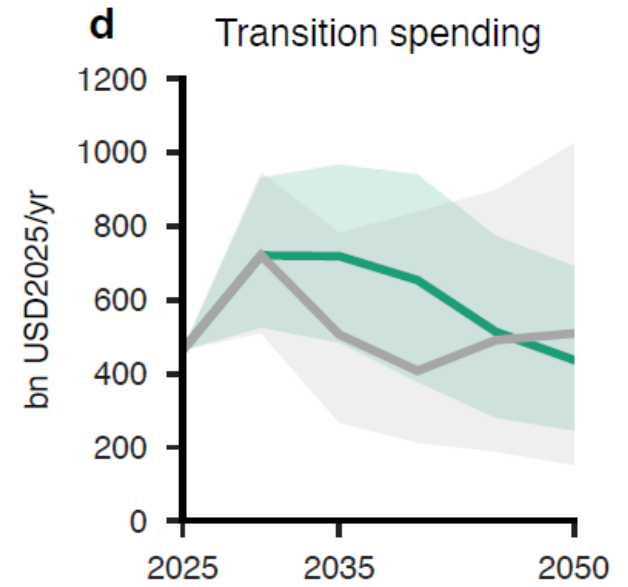
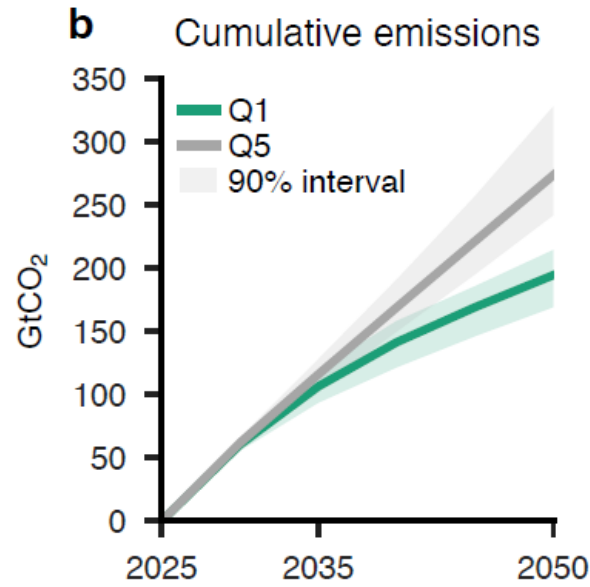
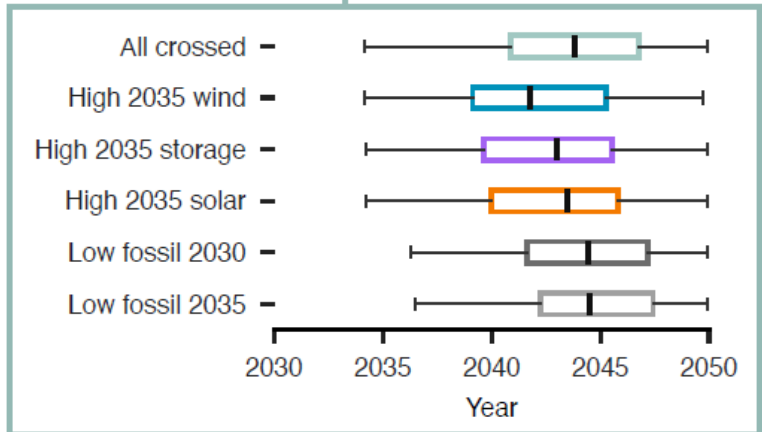


Partition runs by when they cross 80% renewables threshold

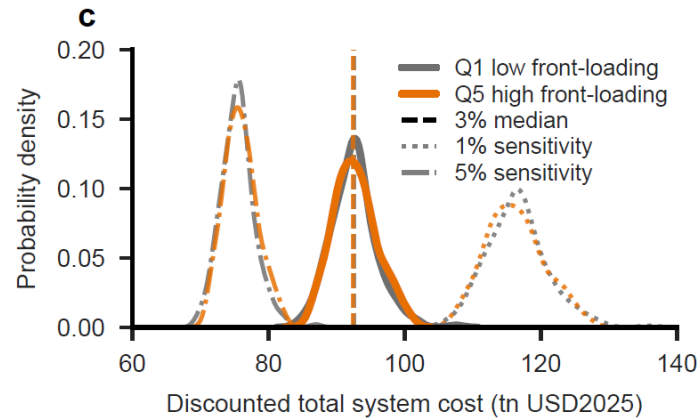
Outcome	Earliest quintile	Latest quintile
Cumulative emissions	193.3 GtCO ₂	278.5 GtCO ₂
2050 annual emissions	4.81 GtCO ₂ /yr	10.79 GtCO ₂ /yr
2050 renewable share	86.4%	68.1%
2050 fossil share	11.2%	28.4%

Crossed 80%
56.5%

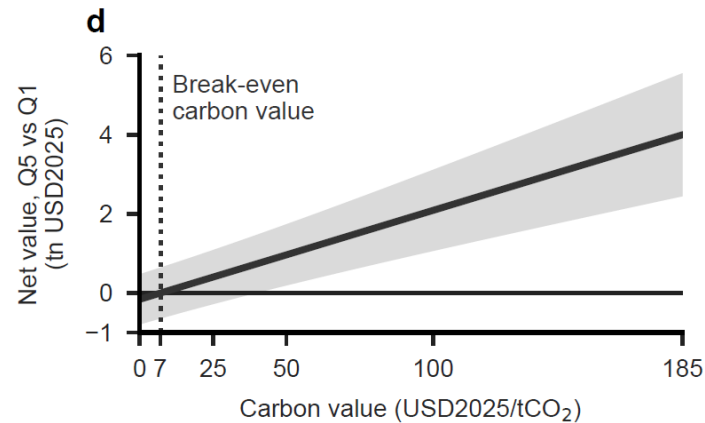
Did not cross
43.5%



... without increasing system costs significantly



Outcome	Low front-loading	High front-loading
Probability of lowest-emissions quintile	5.0%	32.5%
Mean cumulative emissions	22.47 GtCO ₂ lower in high front-loading	
Mean total system cost	0.16 trillion USD higher, $p = 0.62$	
Median total system cost	92.55 trillion USD	92.41 trillion USD



Carbon value	Net value of high front-loading
Break-even	7.13 USD/tCO ₂
50 USD/tCO ₂	0.96 trillion USD
100 USD/tCO ₂	2.09 trillion USD
185 USD/tCO ₂	4.00 trillion USD

Net value of early investment
 = avoided emissions
 x carbon value
 – change in system costs

What innovation can and cannot do

Innovation can

- Lower clean-technology costs
- Expand feasible transition pathways
- Create self-reinforcing deployment dynamics
- Reduce expected transition spending

Innovation may not be able to

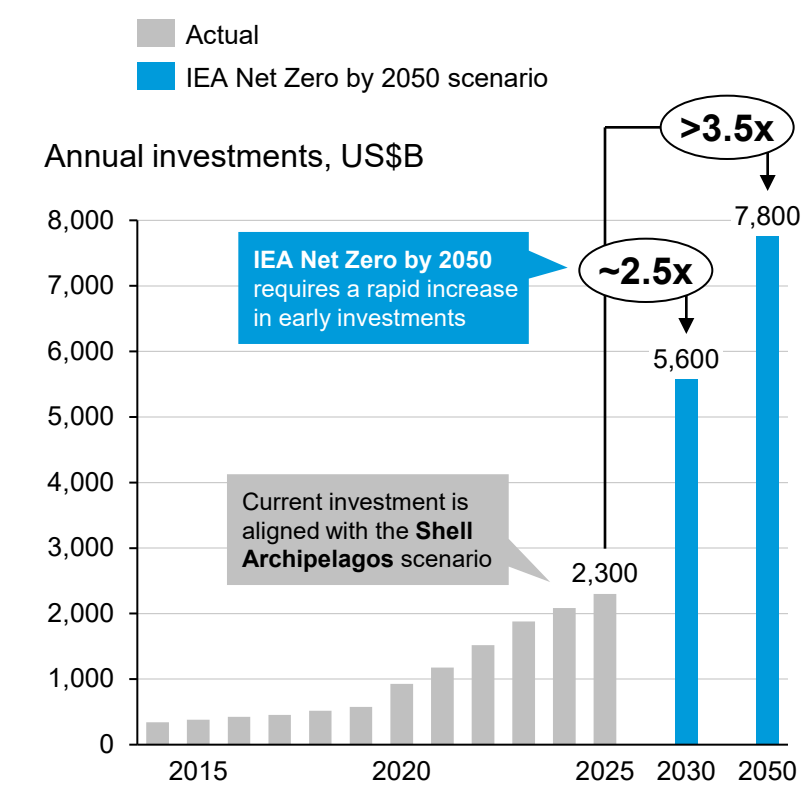
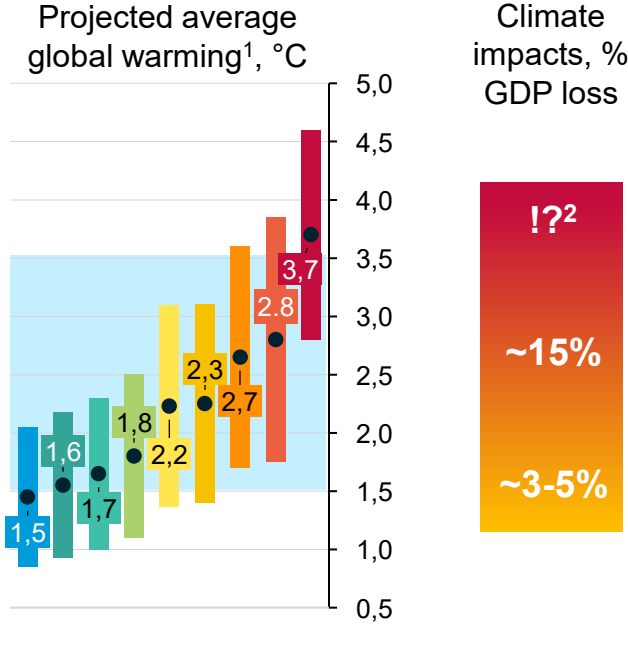
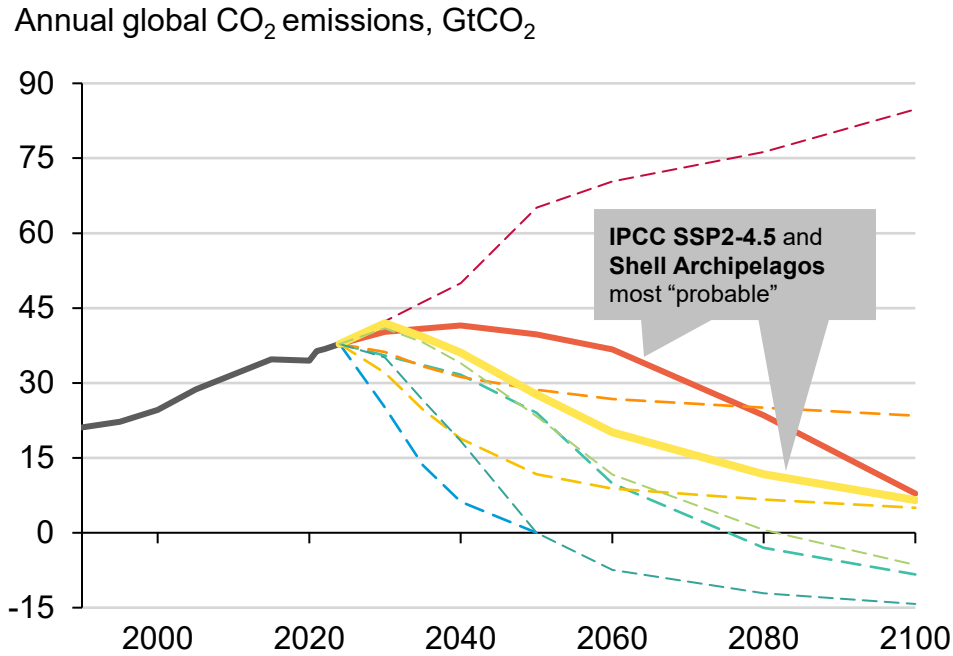
- Retire some residual coal and gas
- Resolve grid and permitting frictions
- Guarantee full decarbonization (by 2050)
- Manage distributional and political constraints

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

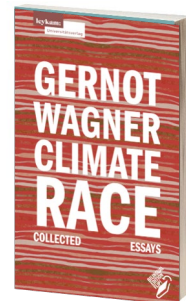
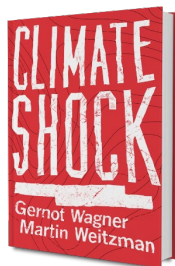
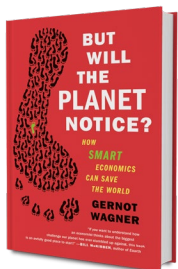
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 Credit: Anika Behrndt, Zacharia Thurston, Isabel Hoyos, Hyaee Ryung Kim, and Gernot Wagner. Share with attribution: Kim et al., “Probable Climates” (27 January 2026).



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