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❶ Not if, *when*

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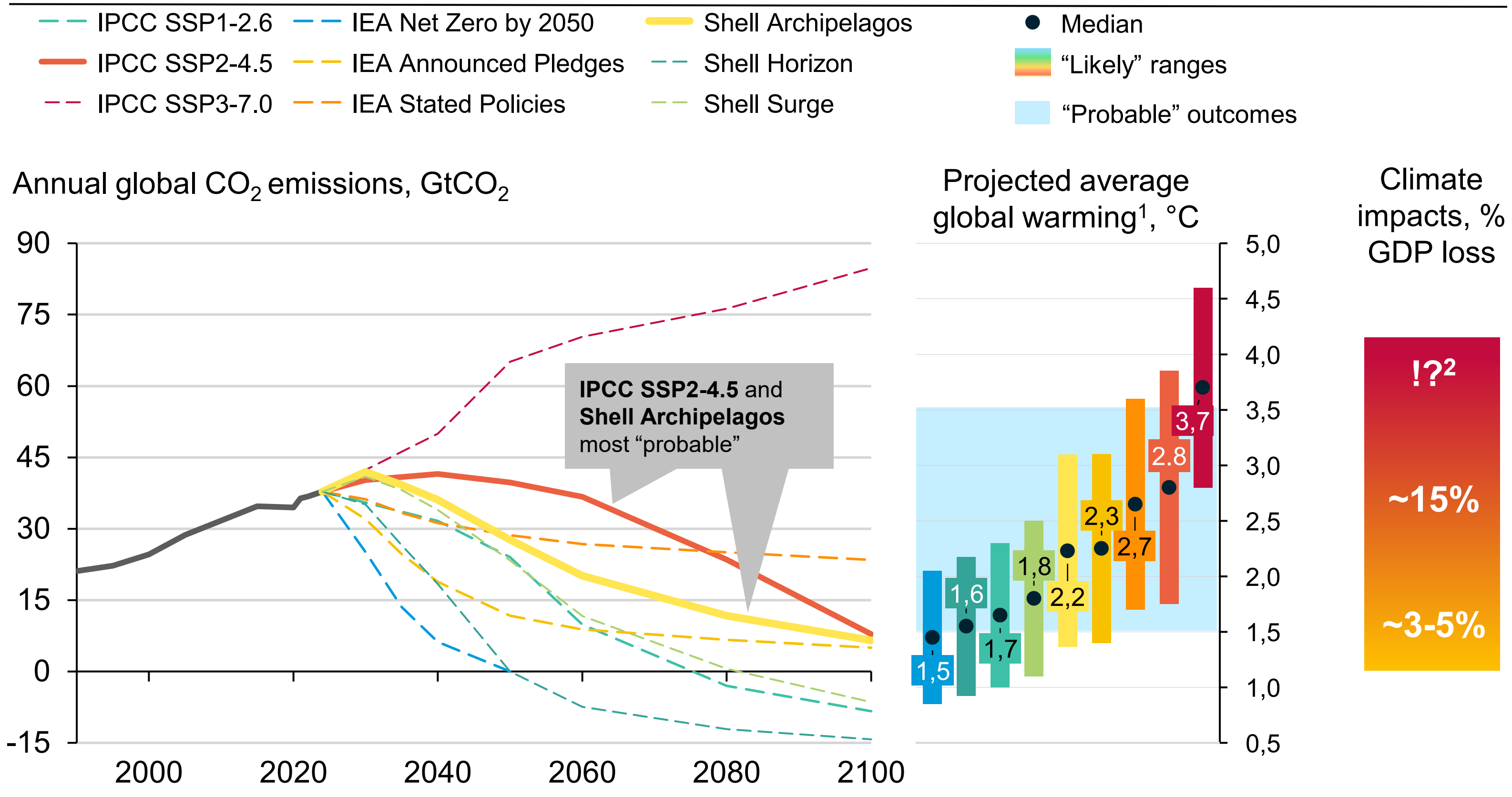
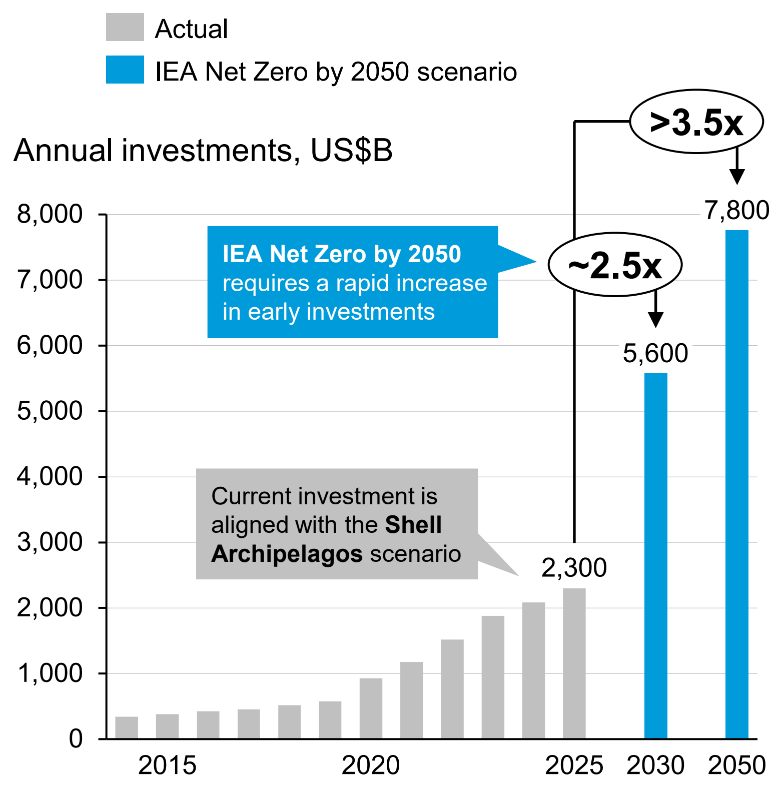
Early decarbonization investments are key to keeping temperatures within livable range and saving trillions in climate costs

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



[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: Kim et al., "Probable Climates" (27 January 2026).

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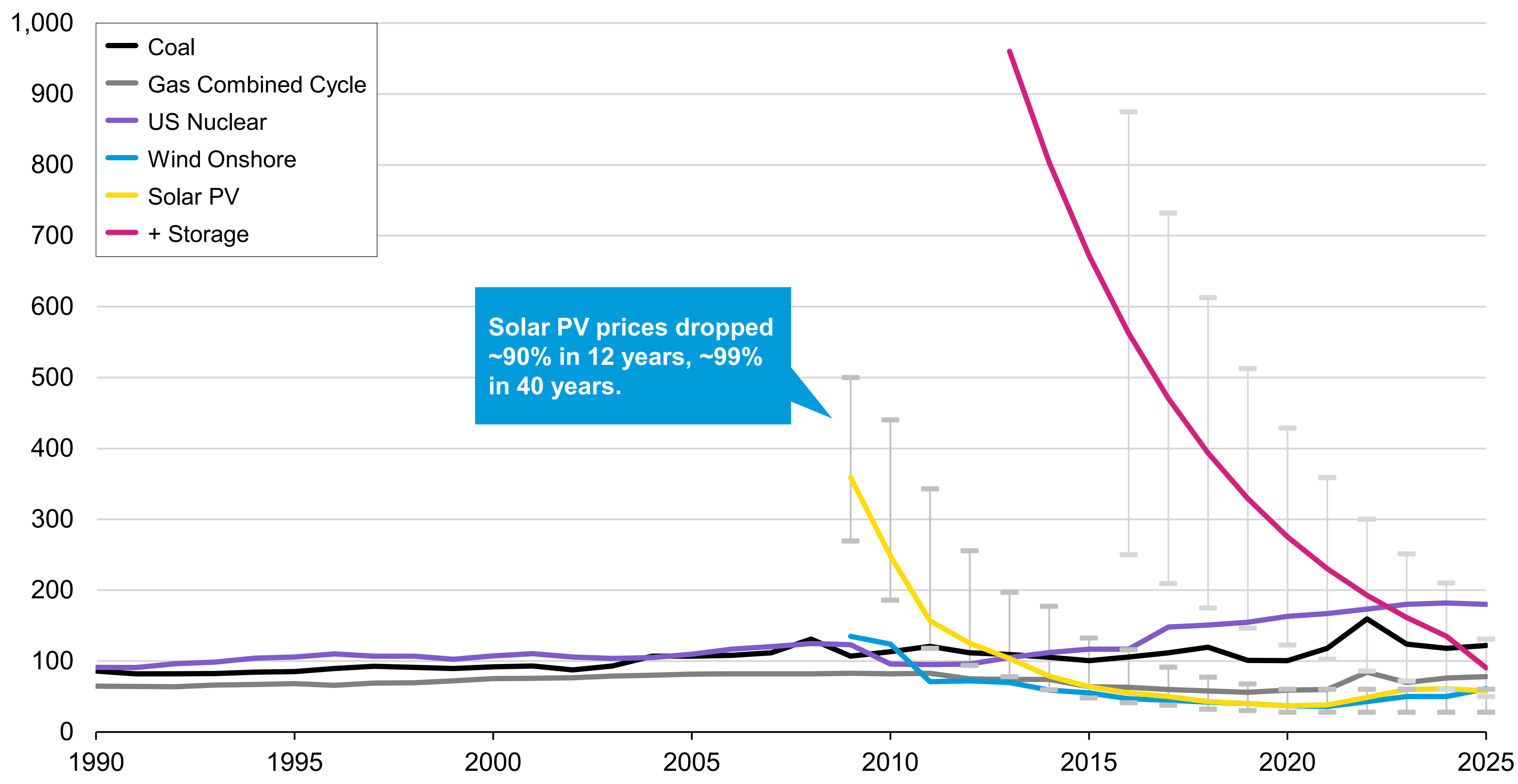
Utility-scale solar and wind now cheaper than fossil fuels, battery storage costs not far behind and falling fast

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).

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A personal take on science and society

World view

By Gernot Wagner

Why more fossil fuels won't fix the Iran energy crisis

Climate-friendly technologies are the best way to stymie rising inflation – and will get better and cheaper over time.

Spend any time discussing solar and wind power as a solution to climate change, and you are sure to encounter someone who asks about reliability. The Sun does not shine at night and the wind does not always blow, so fossil fuels will be needed forever as a back-up, they argue.

But how reliable are fossil fuels? In the past two months, conflict in Iran has created an energy crisis – the latest in a series. Oil prices spiked within days of the start of US, Israeli and Iranian bombing in the Gulf region on 28 February. Fuel prices remain high and volatile, and the ripple effects are set to increase inflation in the coming months. Isabel Schnabel, a member of the European Central Bank's executive board, memorably named this effect fossilflation in the aftermath of Russia's invasion of Ukraine in 2022.

There was, and is, one clear winner: renewables and other low-carbon technologies, from batteries to electric vehicles (EVs) and heat pumps. That is what distinguishes this Middle East oil and gas crisis from the Arab oil embargoes of the 1970s. Then, renewables were mostly unavailable, and industrial decarbonization was on few people's radars. Solar power cost at least 500 times more than it does today, and EVs, heat pumps and induction stoves were a pipe dream.

Ditching fossil fuels is not all smooth sailing. In 2022, European natural-gas prices spiked to ten times their levels before the Ukraine invasion, resulting in long waiting times for solar panels and heat pumps. Prices for these rose as demand outpaced supply, an effect Schnabel dubbed greenflation. She used a third term, climateflation, to describe the economic effects of climate-induced weather extremes, such as food-price rises from crop failures (M. Kotz *et al. Commun. Earth Environ.* **5**, 116; 2024).

Thus, abandoning fossil fuels might cause some temporary greenflation, but the solution is the same for all three drivers: produce more of the climate technologies that will move the world off fossil fuels faster.

That point typically raises two more objections. One is what energy scholars Emily Grubert and Sara Hastings-Simon call the mid-transition. Arguably, the current geopolitical uncertainties are part of this shift away from fossil fuels.

Oil is still the main source of energy for mobility: internal combustion engines account for more than 60% of global oil consumption today. But oil's days are numbered. Around half of it goes into cars, a sector in which the ascendancy of EVs is unstoppable. Norway shows the way.

> "Nations should invest in a rapid, orderly transition instead of waiting for the collapse of the fossil-fuelled economy."

Gernot Wagner is a climate economist at Columbia Business School, New York City, New York, USA. e-mail: gwagner@columbia.edu

All but a handful of specialized vehicles registered there so far this year were fully electric. Lots of older petrol cars are still on the roads, but the direction is clear. So is the messy nature of the transition.

Maintaining two sets of infrastructure – one with petrol stations and garages for internal combustion engines, and another with charging stations and repair specialists for an electric fleet – is expensive. At some point, it will be cheaper for companies or the state to buy the last remaining petrol vehicles in exchange for EVs. Such 'cash-for-clunkers' incentives are part of the policy toolkit for an orderly energy transition. At what point might it make sense to abandon internal combustion engines entirely?

Norway has all but banished petrol cars from dealerships while maintaining its status as a leading oil exporter. It profits from others buying its oil, and uses some of the proceeds to decarbonize its own car fleet and economy. Other oil-exporting nations and companies should follow Norway's lead: invest in a rapid, orderly transition instead of waiting for the collapse of the fossil-fuelled economy.

The second big objection to moving off fossil fuels typically involves China and its control of the climate technology supply chain. Chinese dominance extends to the kind of critical and rare-earth minerals needed in solar panels, batteries and other technologies. Developing these capacities from mines to manufacturing is important, and resiliency demands investment in globally diversified supply chains. But that's no excuse to delay getting off fossil fuels.

Building an EV needs around six times the minerals that making a petrol car does, but that misses the huge physical footprint of fossil fuels required to propel the latter. Although the oil-to-power comparison is fraught with caveats, oil takes some 200–400 tonnes of material to produce one gigawatt hour of energy, compared with less than 50 tonnes for solar power or batteries (see go.nature.com/4vp8wjk).

Another crucial difference between fossil fuels and low-carbon technologies is that fuels need to continue to flow, whereas technologies such as solar, geothermal and batteries involve largely capital investments, and are thus infrastructure. No more oil shipments through the Strait of Hormuz means a physical impasse that reverberates throughout global commodity markets. Yet once a solar panel is installed, it delivers electricity for years even if the physical supply chain for more panels gets cut.

Shifting to technologies that can only get cheaper and better over time is an investment in geopolitical and price stability. Former US president Joe Biden's Inflation Reduction Act (IRA) was derided at the time for its opportunistic name, to say nothing of his successor's assailing of most of its contents since. History will judge both the IRA's name and policies kindly.

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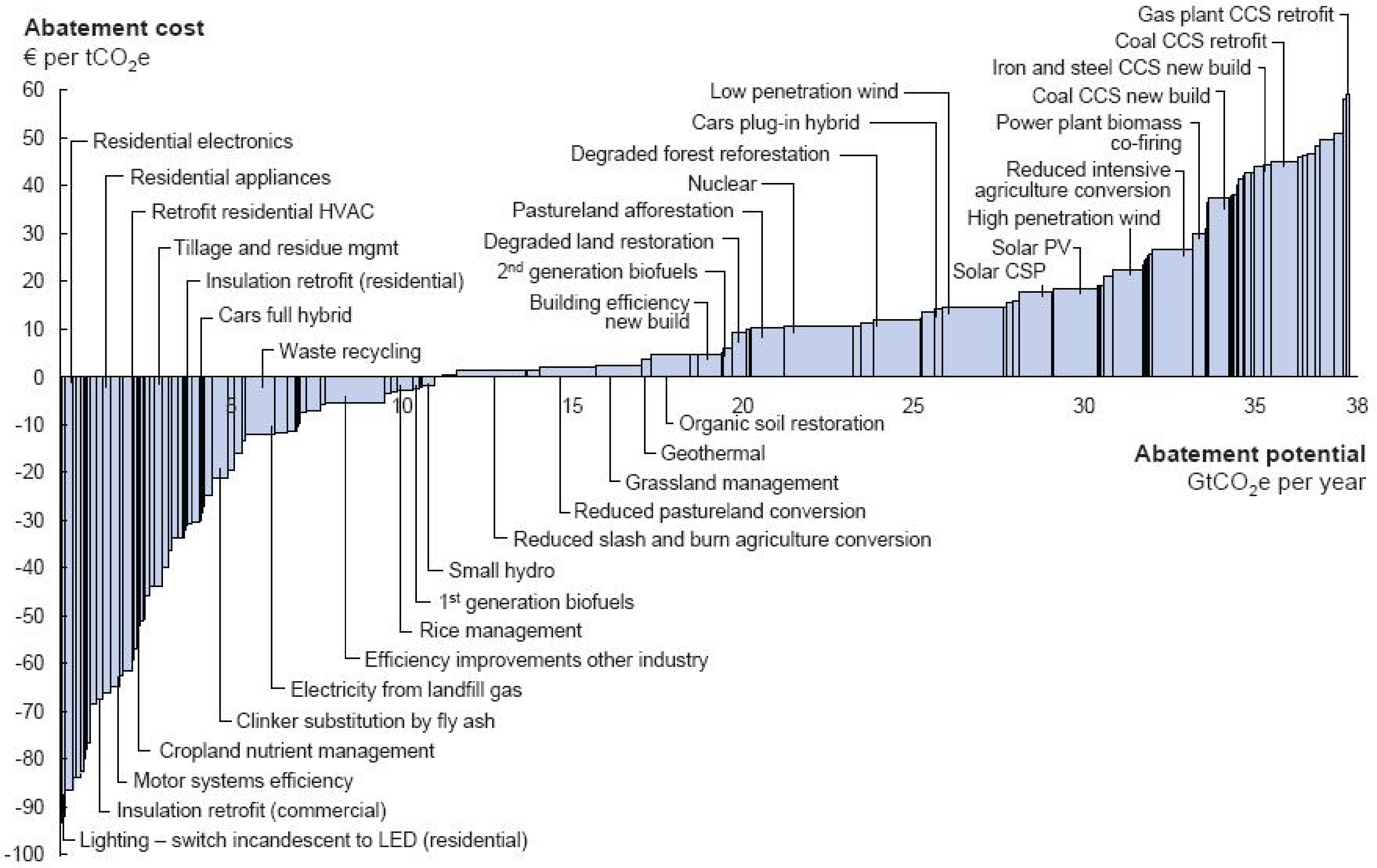
Nature (16 April 2026)

Large abatement opportunities available at low or no cost

McKinsey Global v2.0 effort in 2009 identified 38 $GtCO_2e$ abatement potential in 2030



Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO_2e 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

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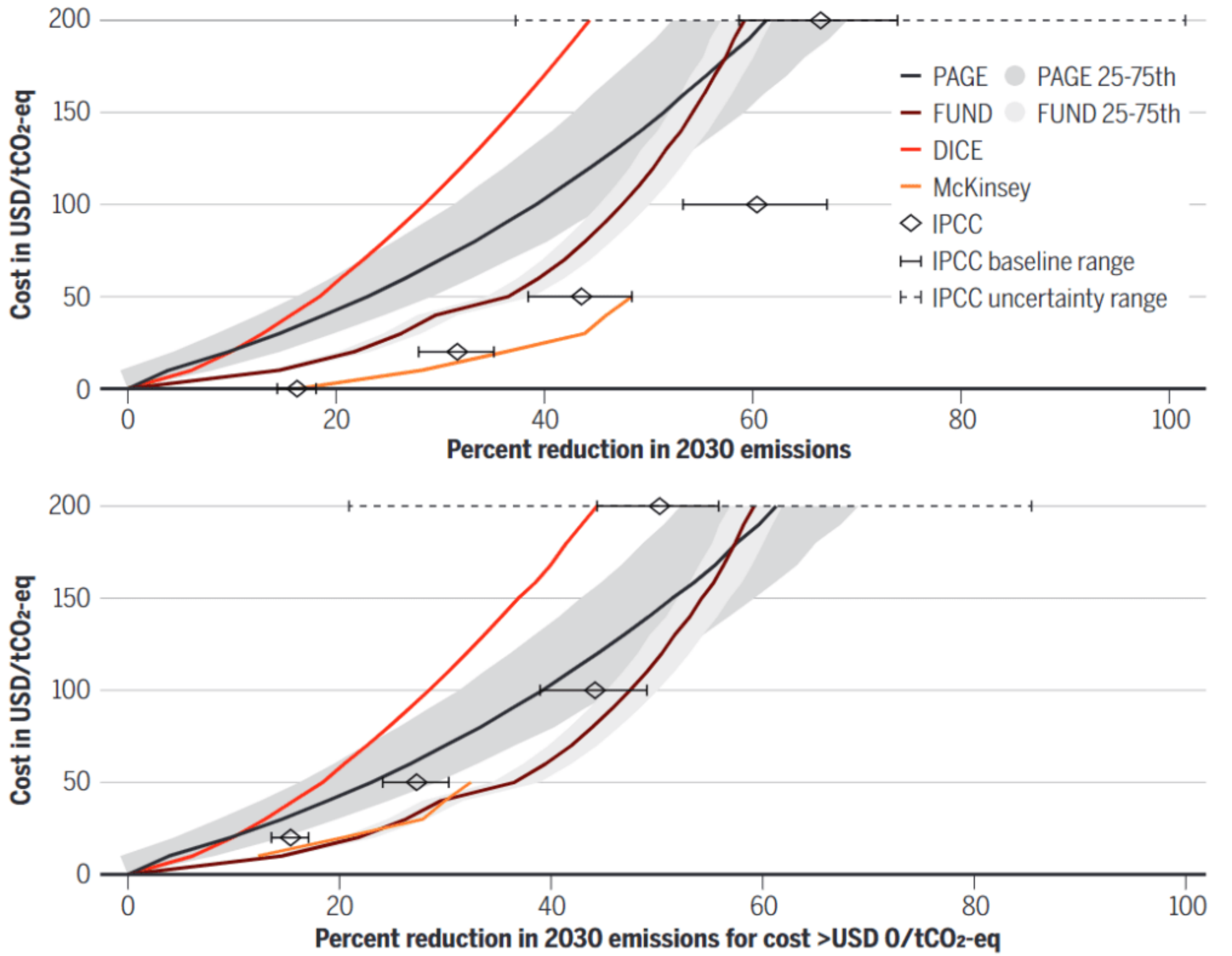
How costly, or costless, is climate emissions mitigation? p. 1001

Comparison of global mitigation potentials at different costs

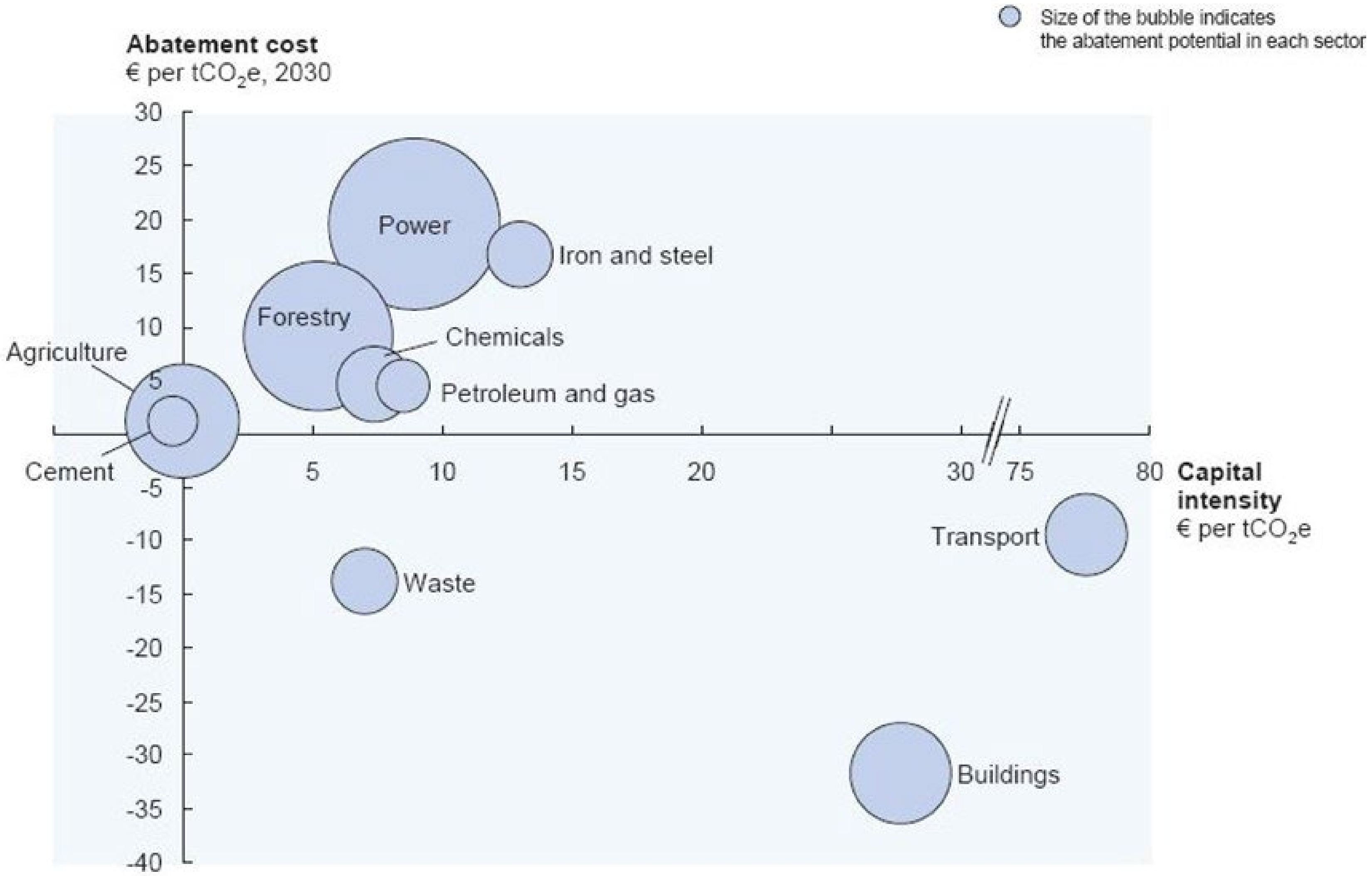
The IPCC results use different baseline emissions to calculate the range of mitigation potentials. The top panel reports the full set of results, and the bottom panel reports only the mitigation potentials with costs >$0 per tonne of CO_2 equivalent (tCO_2-eq). USD reported in 2020 dollars. See supplementary materials.



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

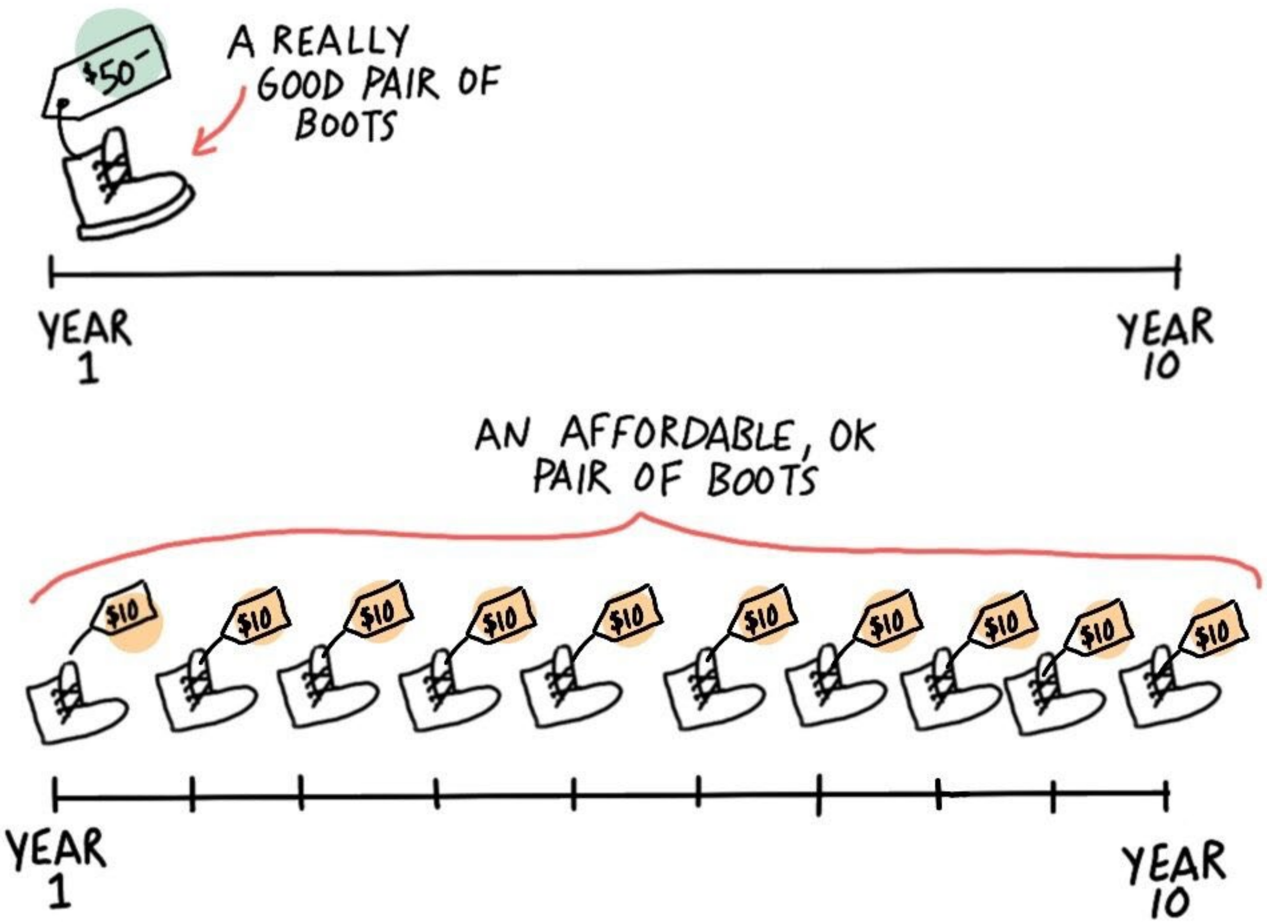
Capital intensity varies widely across sectors

Transport and buildings with largest up-front capital expenditure requirements



Source: Global GHG Abatement Cost Curve v2.0

THE BOOTS THEORY OF SOCIOECONOMIC UNFAIRNESS



@thehellyeahgroup

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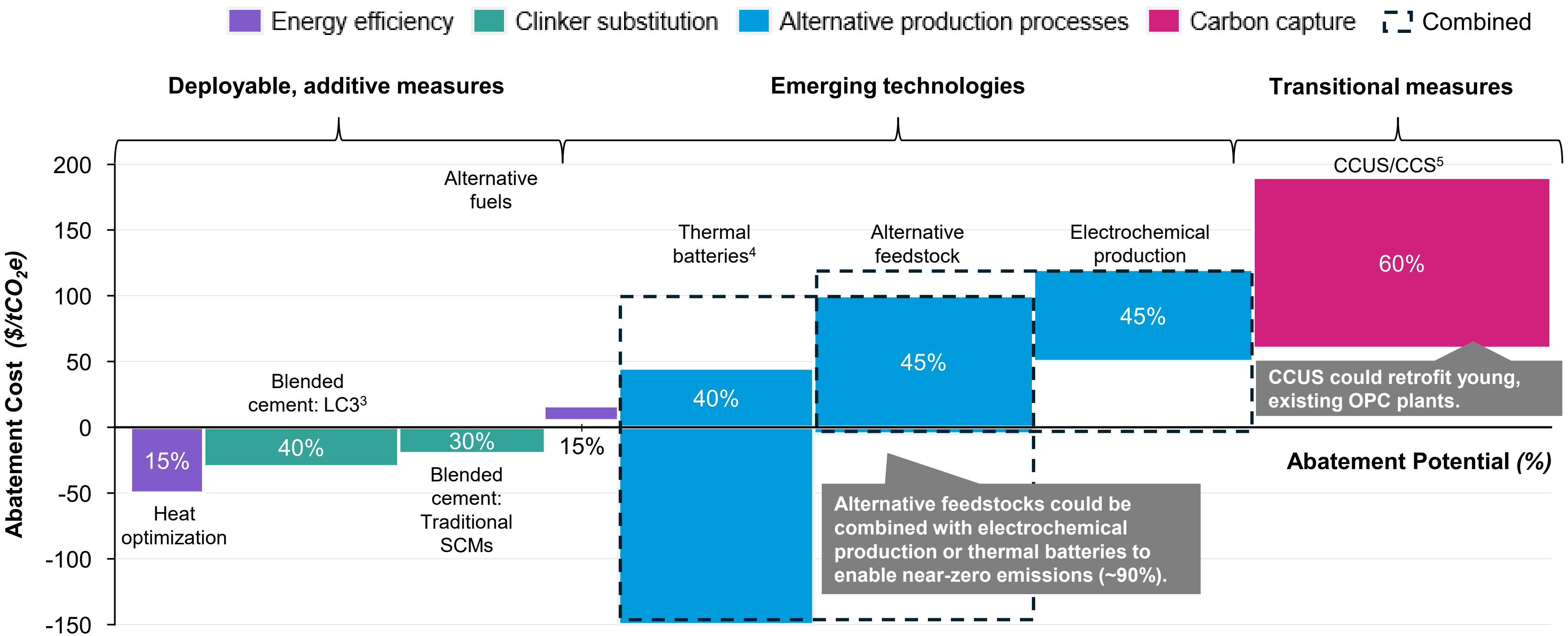
Emerging technologies like thermal batteries, alternative feedstock, and electrochemistry key to cement decarbonization

Abatement cost[1] vs. abatement potential[2] for key decarbonization pathways



Observations

- Currently deployable measures can deliver up to **40% emission reductions** through energy efficiency, alternative fuels, and blended cement (conventional SCMs and LC3).
- Alternative feedstock and electrochemical production can eliminate cement production emissions by up to **~90%** but require **step changes in technology, CapEx, and infrastructure.**
- Thermal batteries' successful deployment depends heavily on **low-cost and low-carbon electricity.**
- Electrochemistry faces challenges including **high energy demand and competition for mineral feedstock.**
- CCS costs vary widely depending on carbon **transportation and storage infrastructure.**

1) Abatement cost of emerging technologies is based on estimates and has high uncertainty. 2) Abatement potential is calculated as unconstrained and theoretical for each approach in isolation. 3) Despite TRL 9, market penetration of LC3 remains low due to slow standards adoption, limited supply chain coordination, and conservative procurement practices. 4) Thermal batteries' abatement potential and cost are based on off-grid renewables; see slide 28 for grid power. 5) CCUS/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: Nicolas Herrera Isaza, Soraya Van Beek, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Decarbonizing Cement" (30 April 2026).

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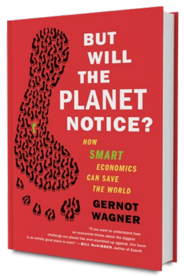

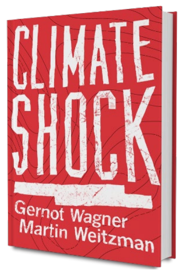

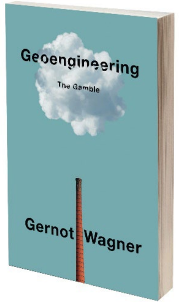

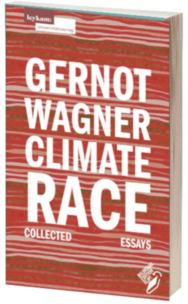

Gernot Wagner
gwagner@columbia.edu
gwagner.com