Climate Risks, Opportunities, and Geopolitics

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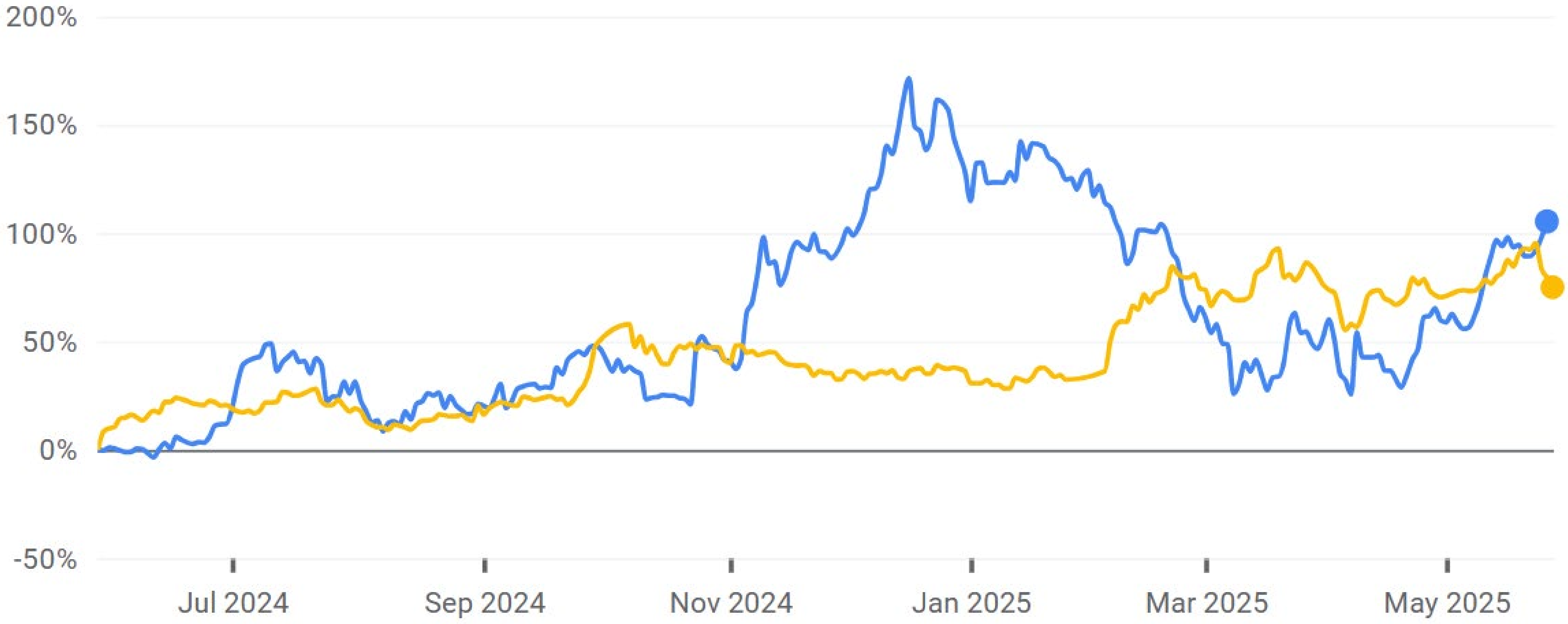
1D 5D 1M 6M YTD 1Y 5Y MAX



Tesla Inc	$362.89	+$186.14	↑105.31%
BYD Ord Shs A	¥362.88	+¥155.50	↑74.98%

Managing the net-zero transition

Climate Risks, Opportunities, and Geopolitics

28 May 2025

1. Climate risk is financial risk
2. Solar
3. Steel
4. Is the goal a high or a low price per tonne of CO_2?

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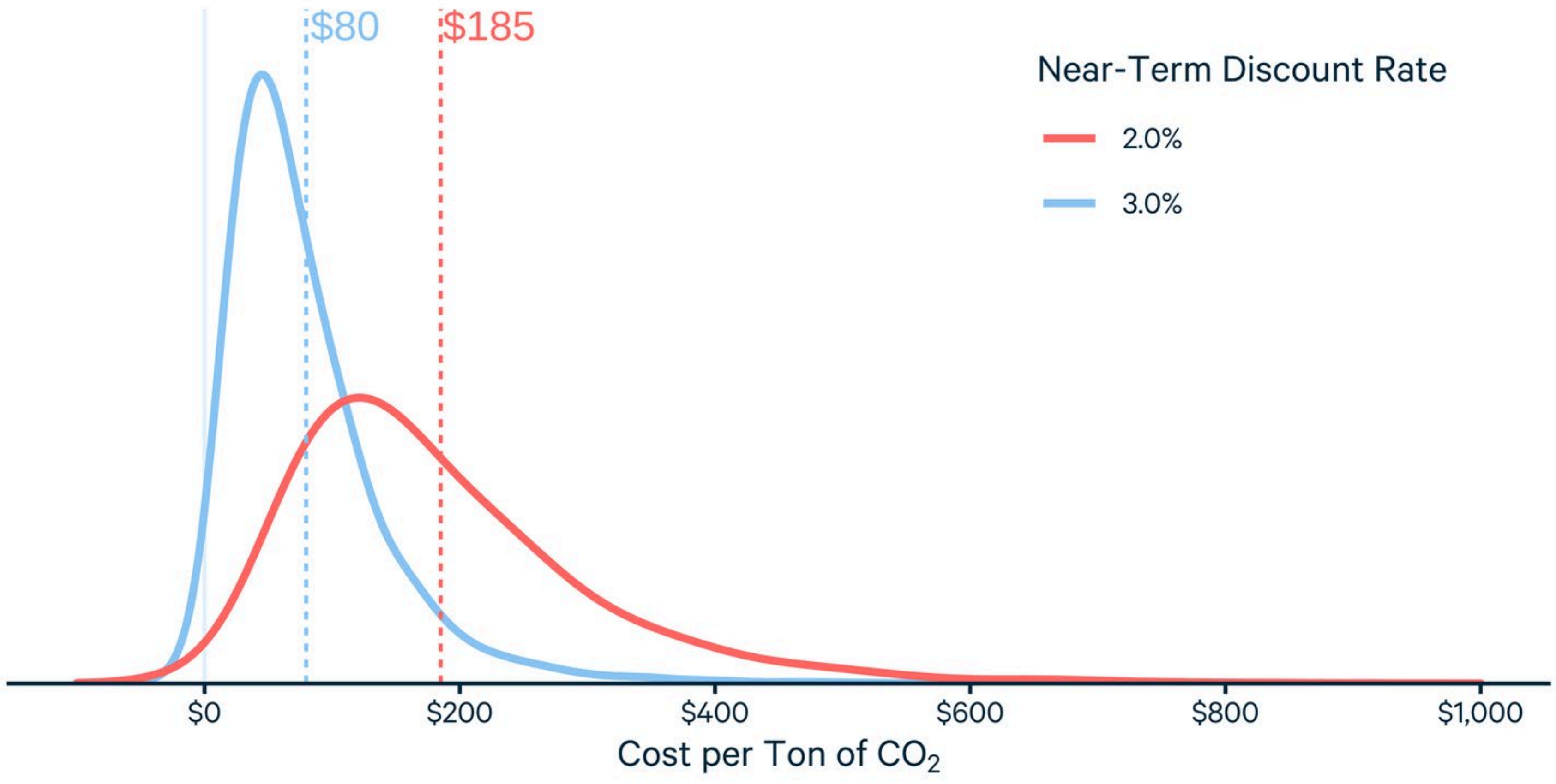
~$200 / tCO_2

~$185 Social Cost of CO_2

Based on 2% constant discount rate, with most of the increase due to discounting



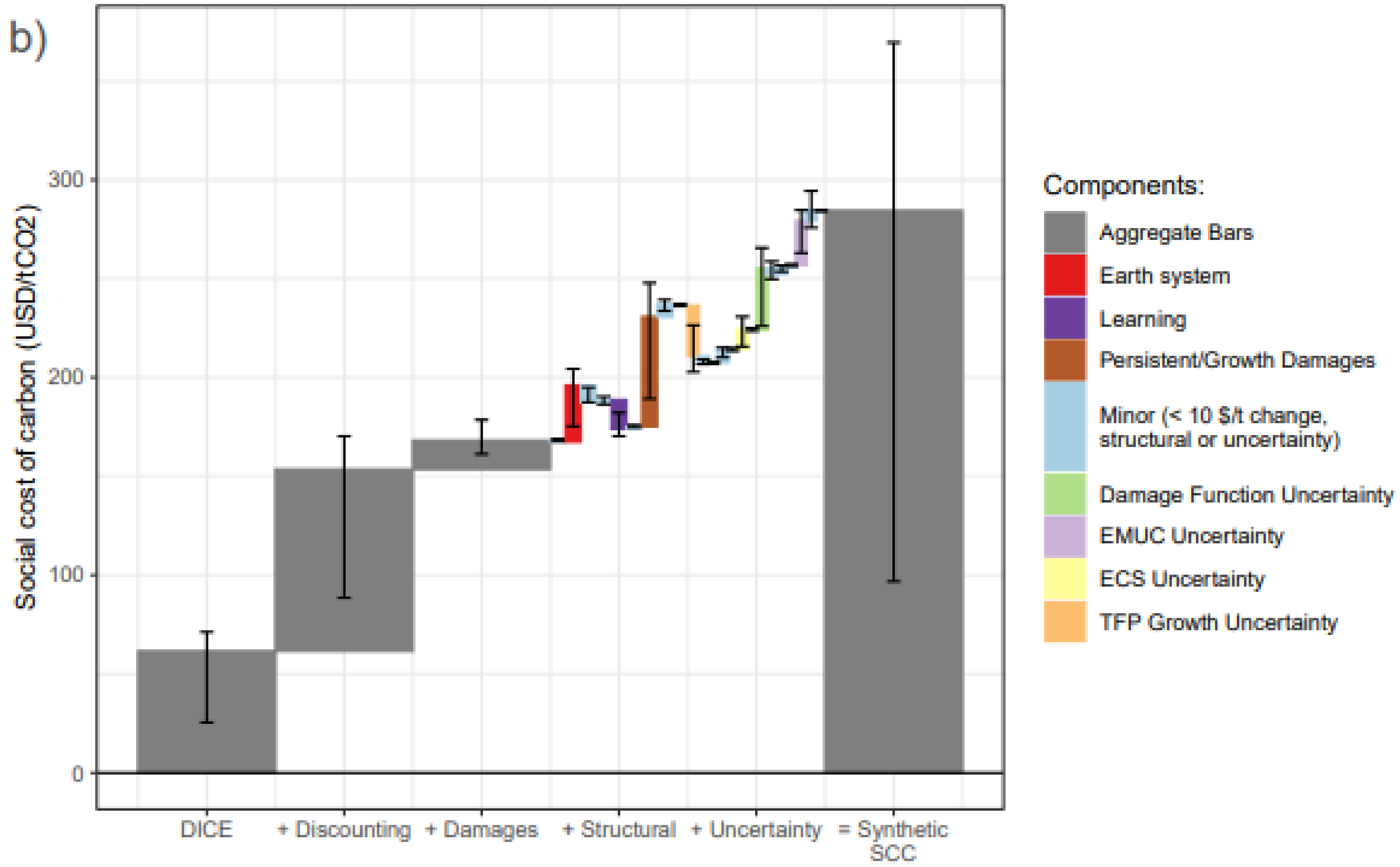
~$50 to ~$80 from updated damages,
~$80 to ~$185 from discounting

Source: Rennert *et al* "Comprehensive Evidence Implies a Higher Social Cost of CO_2" (*Nature*, September 2022).

$> \$200 \; / \; tCO_2$

“Synthetic” Social Cost of Carbon with median = $185 and mean = $284

For 1 tonne of CO_2 emitted in 2020, in $2020, with 5%–95% range of $32–$874(!)

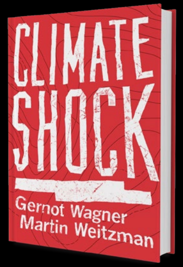


Source: Moore, Drupp, Rising, Dietz, Rudik & Wagner (*2024*), gwagner.com/synthesis-scc

>~$200 / tCO_2 :

Climate damage quantification

including tipping points



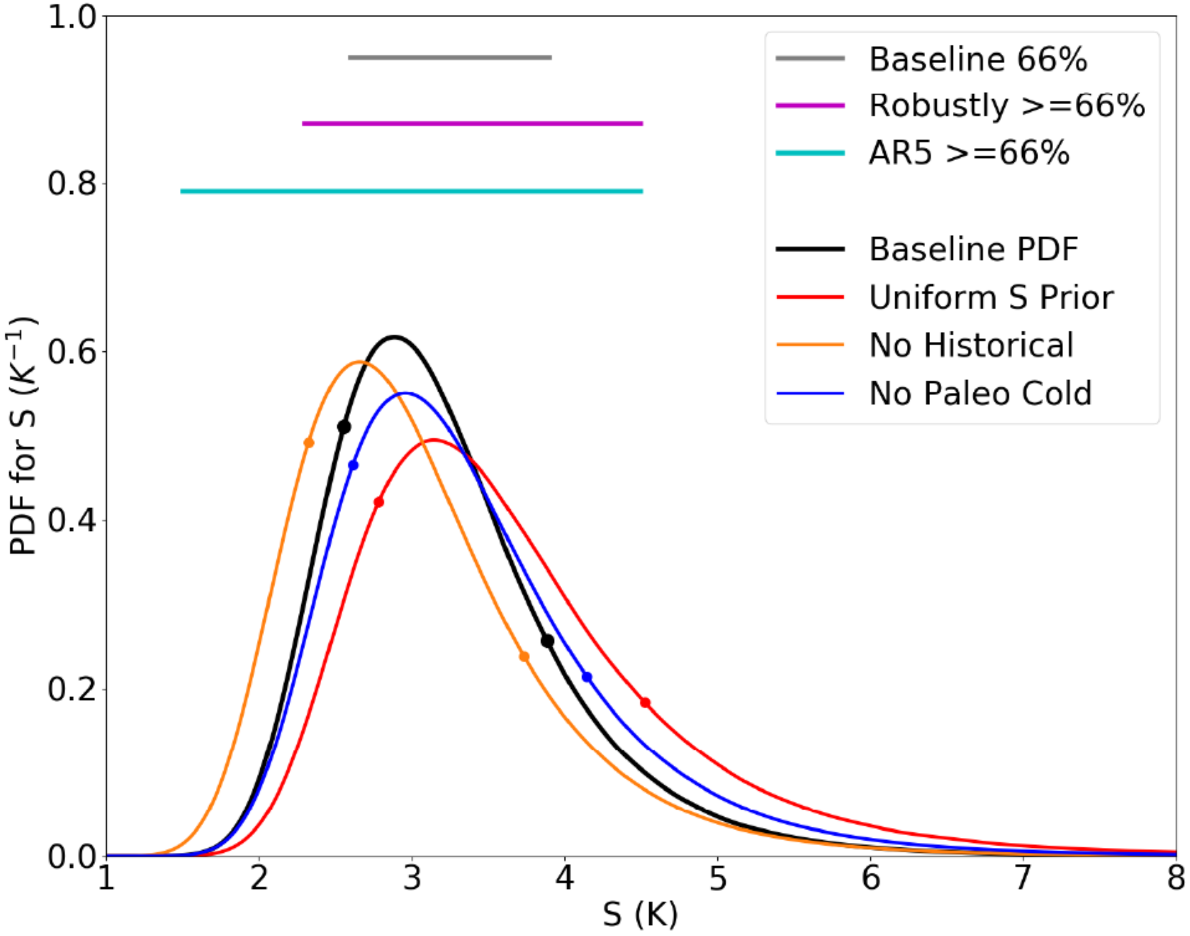
Tail risks

Discounting

Risk calibration, equity, etc.

Climate sensitivity "likely" between ~2-4.5°C

Latest assessment narrows 66% "likely" range from 1.5-4.5°C



Tail risk might dwarf importance of "likely" range

Source: Sherwood et al (2020)

>~$200 / tCO_2 :

Climate damage quantification

including tipping points

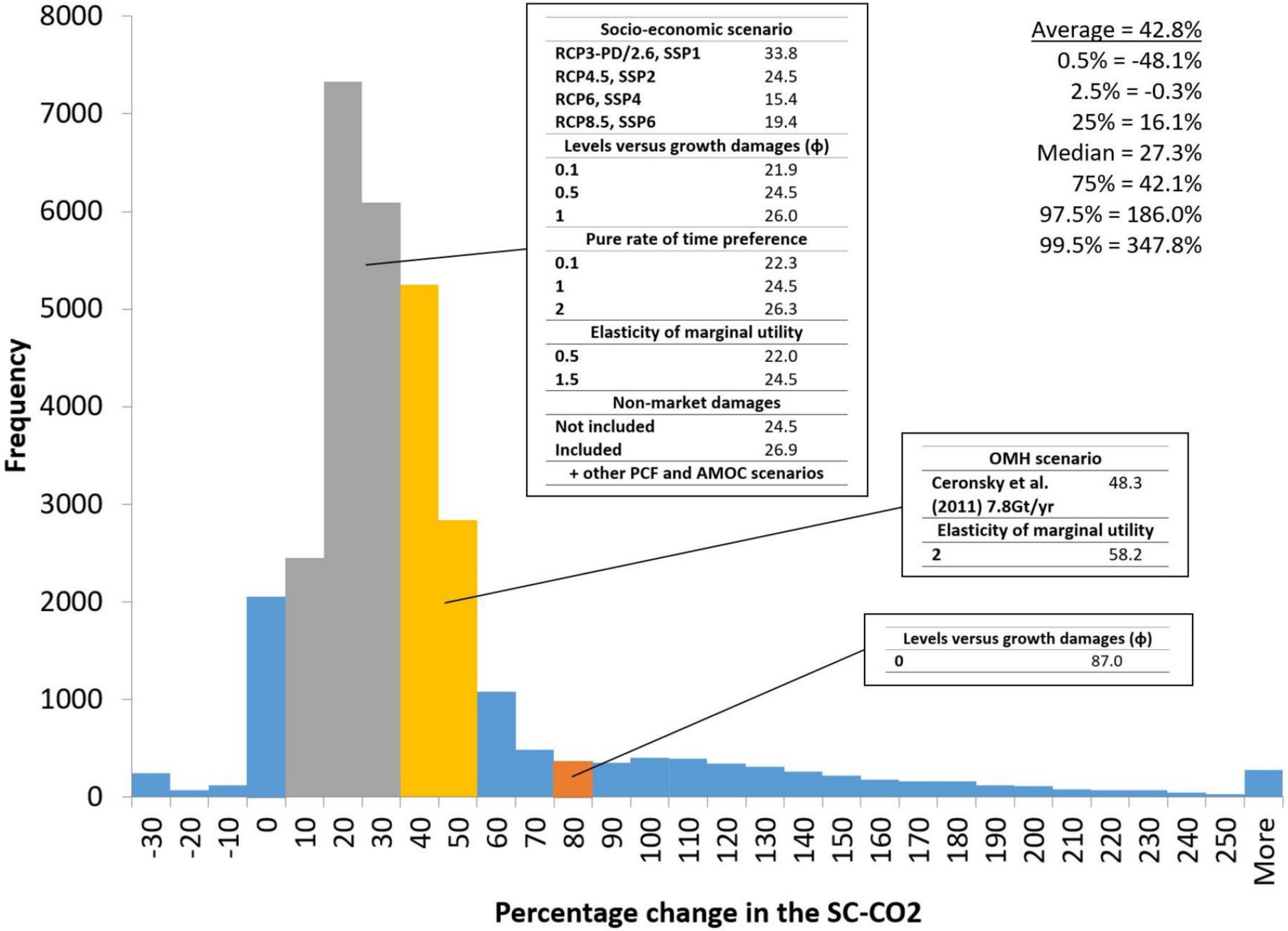
Tail risks

Discounting

Risk calibration, equity, etc.

Economic impacts of tipping points in the climate system

Tipping points increase SCC by between ~27-43%, with large, right-skewed distribution



Source: Dietz, Rising, Stoerk & Wagner (*PNAS* 2021), gwagner.com/tipping-economics

~ \$200 / tCO_2

=

~8-10% of

global GDP

~ $1,000 / tCO_2

=

~50%(!!) of *global* GDP

Source: Bilal & Känzig (NBER, 13 May 2024), nber.org/papers/w32450

> $150 /

car entering NYC*

* Manhattan below 60th Street

The New York Times

There's Only One Way to Fix New York's Traffic Gridlock

June 8, 2023

Congestion pricing is the only durable antidote to persistent traffic congestion. The Columbia University economist and Nobel laureate William Vickrey demonstrated 60 years ago that there's no way out of gridlock without making drivers pay for taking up limited street space. Otherwise, there will always be more car owners wanting to use the available space than there is space to accommodate them.

Komanoff & Wagner, *NYT* (8 June 2023)

The New York Times

There's Only One Way to
York's Traffic Grid

June 8, 2023

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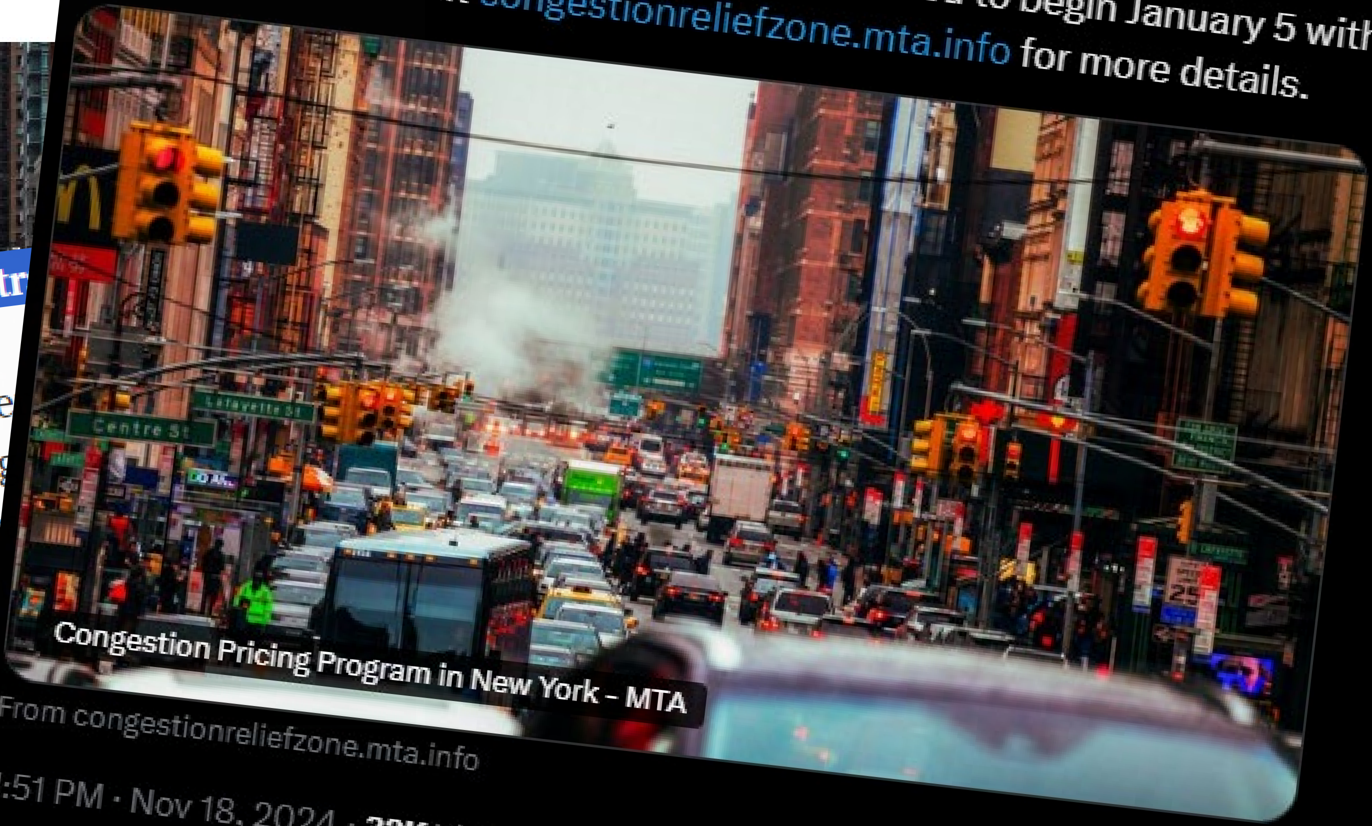
MTA
@MTA

The MTA Board has approved a phase-in approach to the Central Business District Tolling Program, now scheduled to begin January 5 with 40% lower rates. Visit congestionreliefzone.mta.info for more details.



Congestion Pricing Program in New York - MTA

From congestionreliefzone.mta.info

1:51 PM · Nov 18, 2024 · **32K** Views

Komanoff & Wagner, *NYT* (8 June 2023)

The New York Times

Our City Could Become One of the World's Greenest, but It Won't Be Easy

Feb. 7, 2023

The rewards the city reaps will not only be reputational. If New York cracks this decarbonization nut (as it started to do under Mayor Michael Bloomberg with transport and especially bike lanes), the city's hard-to-bear summers, when the asphalt, steel and brick absorb the sun's rays and turn the city into a heat island will mellow. The noise from air-conditioners and boilers will ebb.

It will be a much nicer place to live.

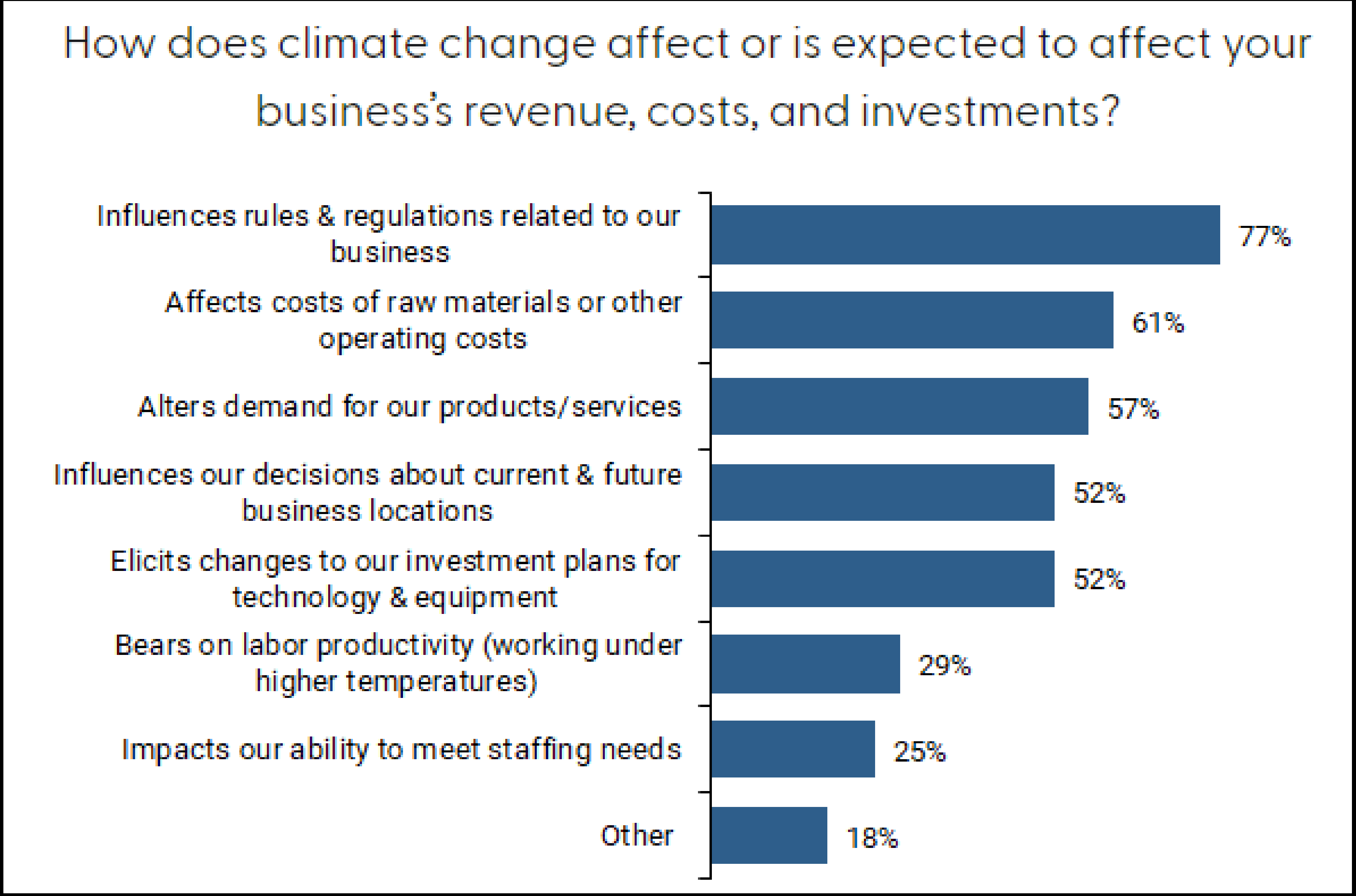
Greenberg & Wagner, *NYT* (7 February 2023)

Risks, uncertainties, unknowns, tails ≻ ‘known knowns’

Climate policy risk ≻ climate risk

Climate Risk
vs
Policy Risk

Climate Risk
&
Policy Risk



Source: San Francisco Fed's Survey on Climate Risk 2021

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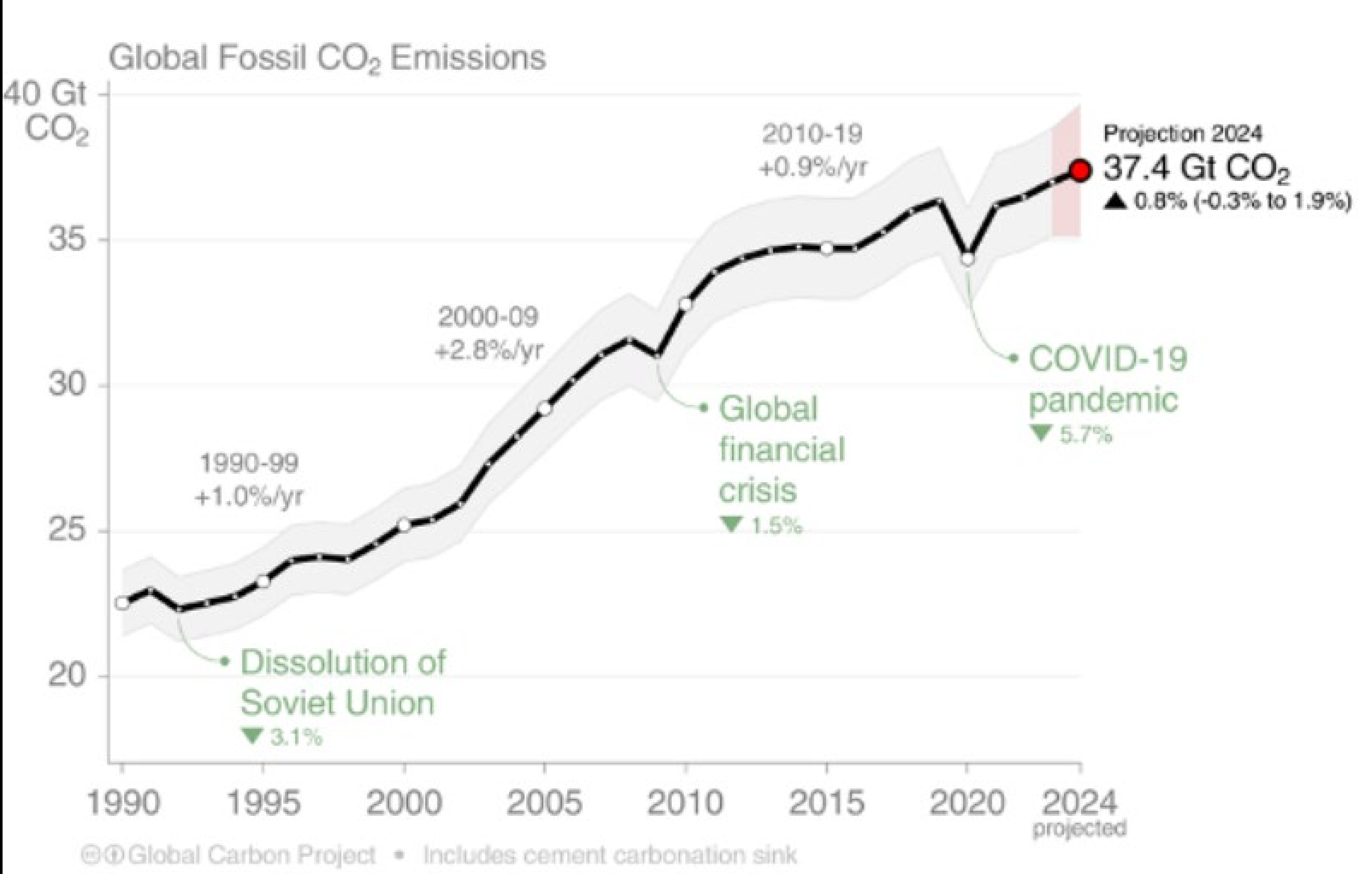
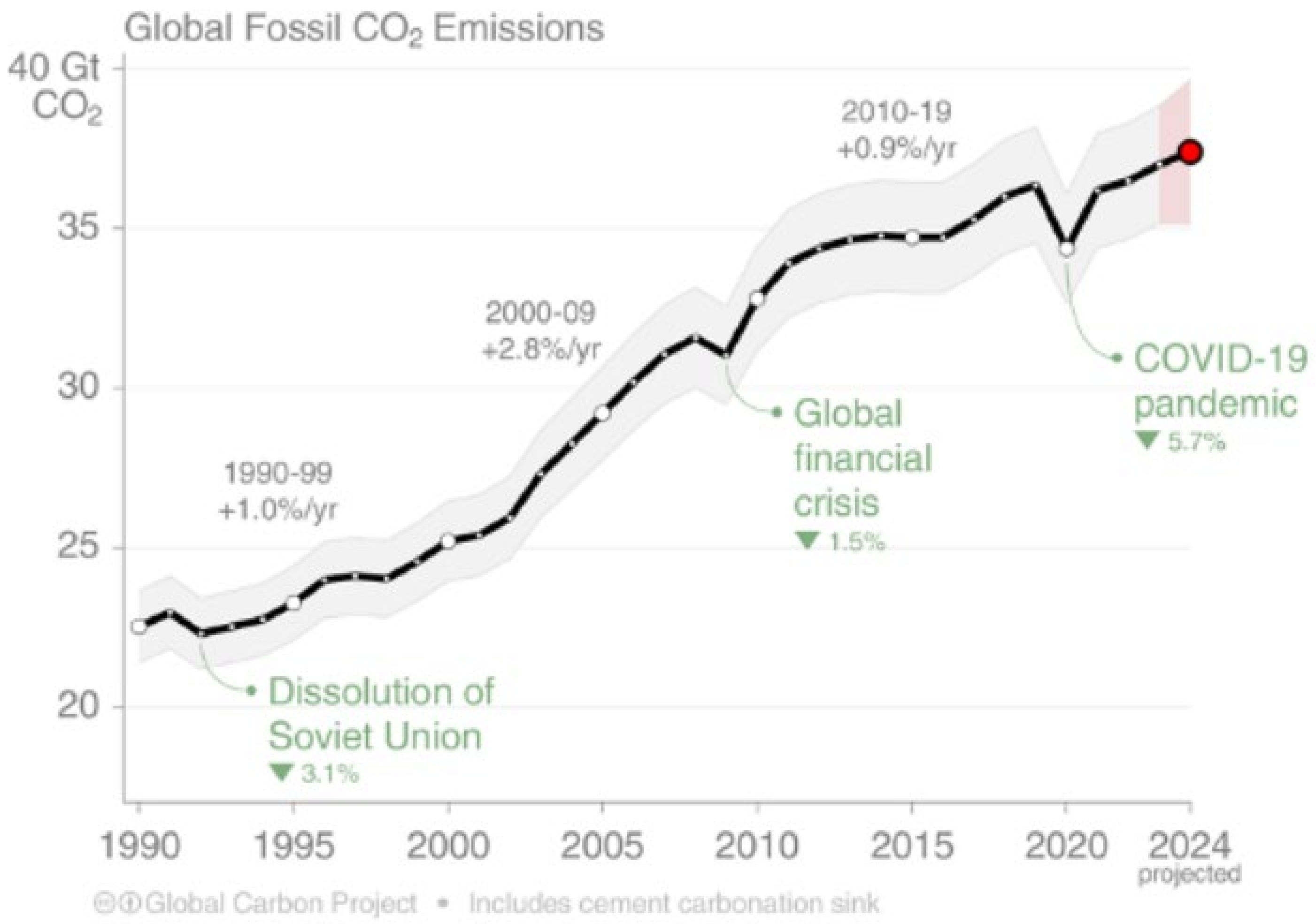
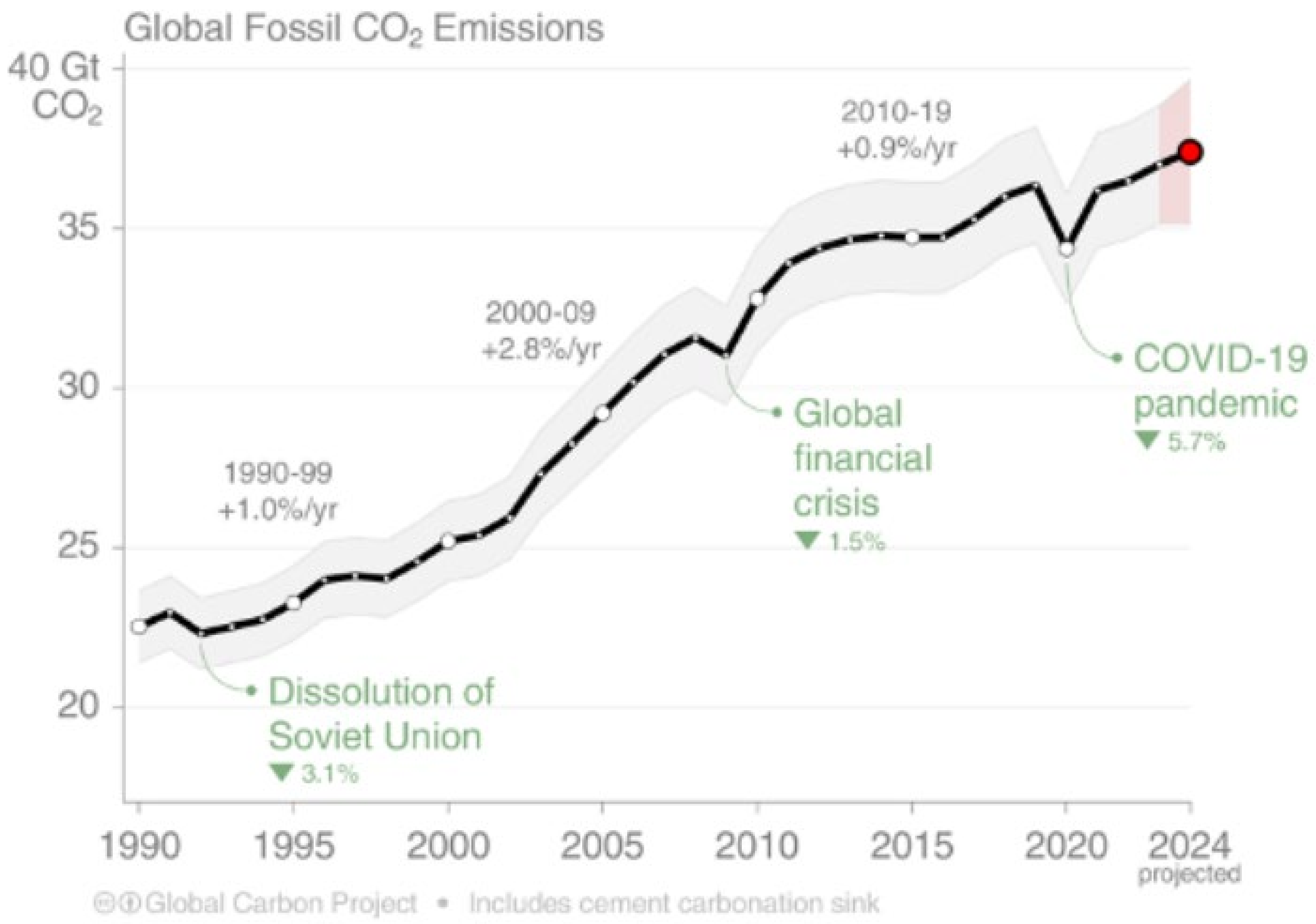


Source: Global Carbon Project (2024)



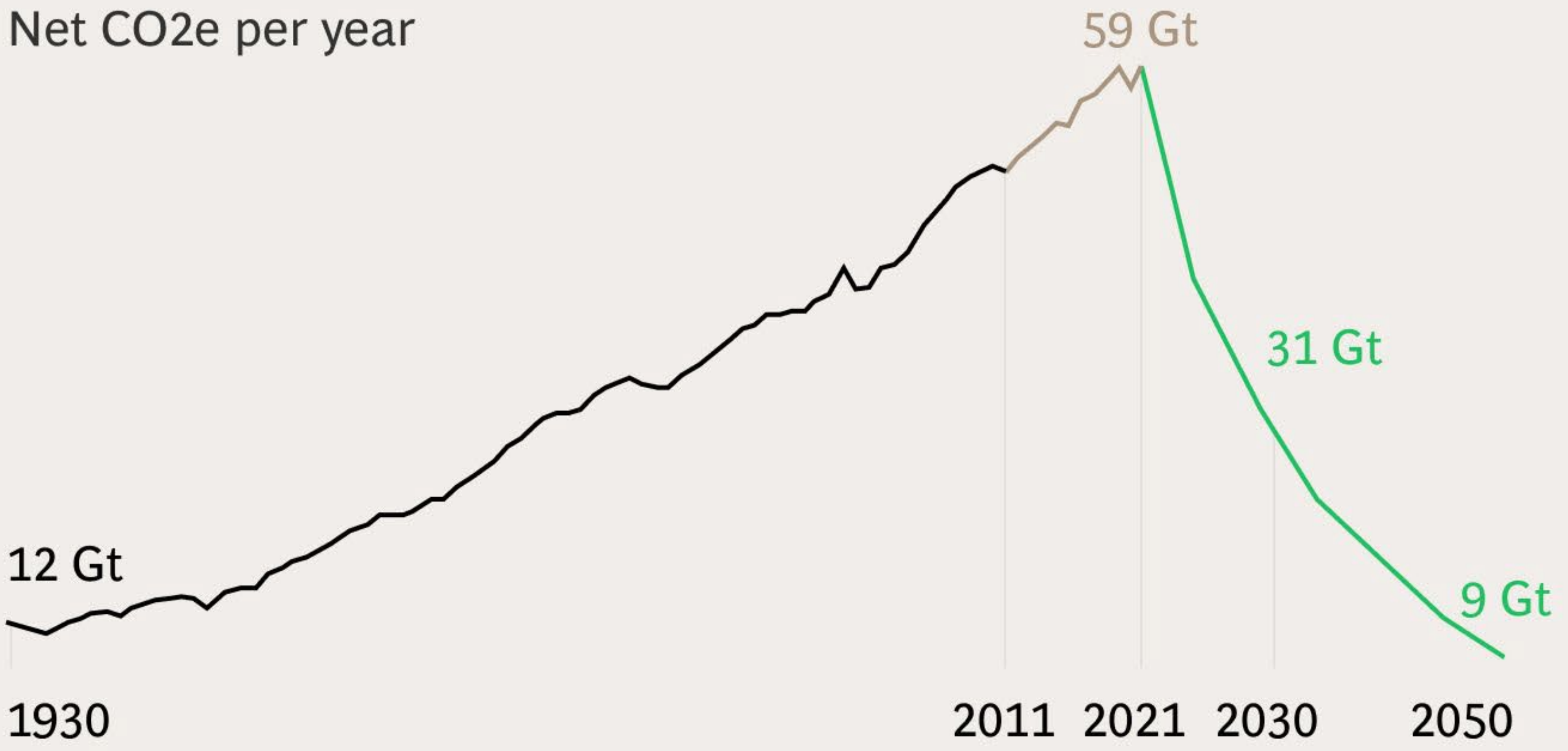
Source: Global Carbon Project (2024)



Source: Global Carbon Project (2024) + umpteen climate-economic model runs

BCG

Major course correction needed to achieve the 1.5°C ambition

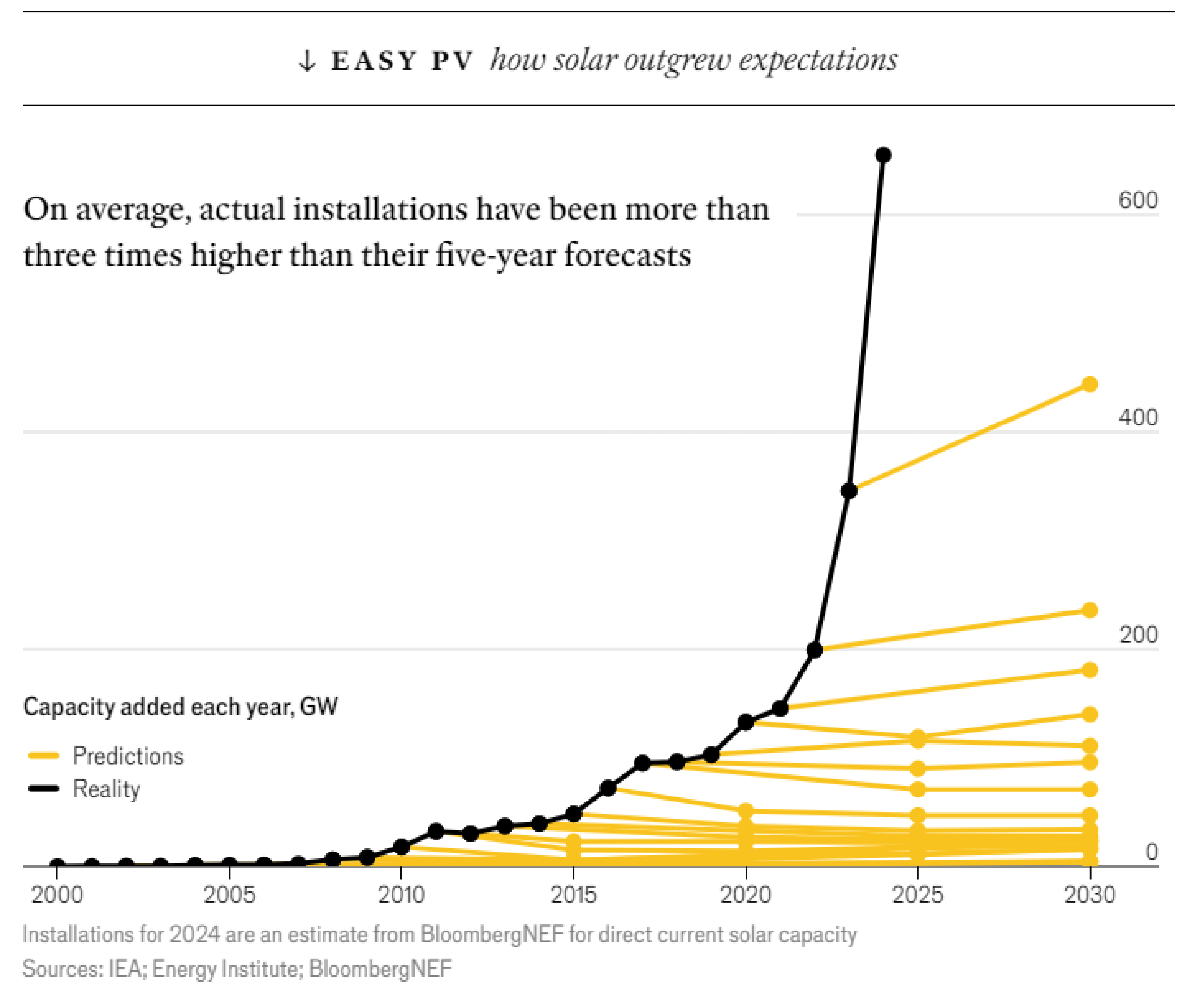


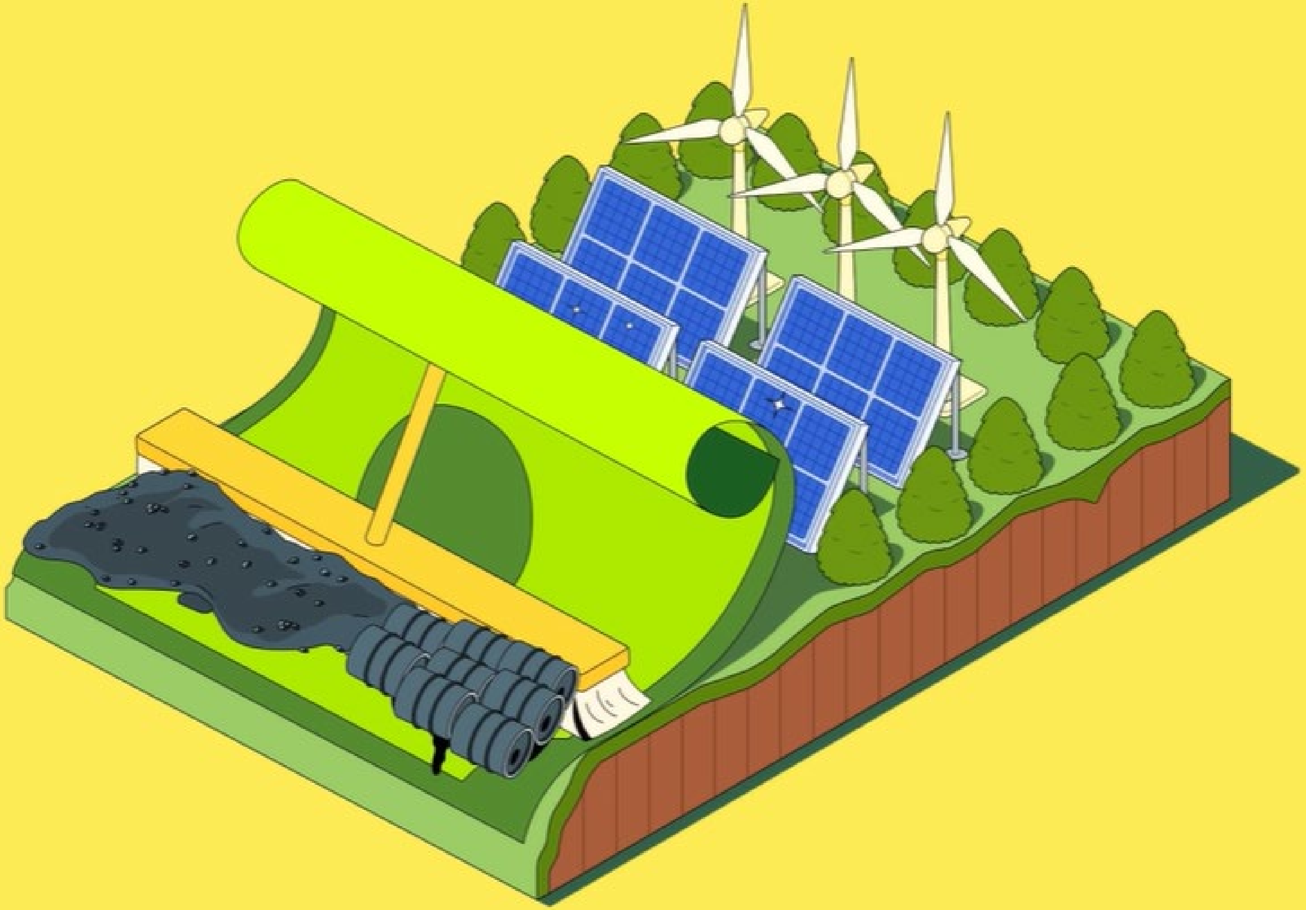
-7%
annual reduction in emissions needed by 2030 to meet the 1.5°C pathway

+1.5%
recent annual increase in emissions from 2011-2021

Sources: IPCC, PIK, BCG analysis


The Economist
AI and war
A report card on Milei's reforms
China in the Arctic
The champagne boom
JUNE 22ND–28TH 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
600
400
200
0
2000
2005
2010
2015
2020
2025
2030
Installations for 2024 are an estimate from BloombergNEF for direct current solar capacity
Sources: IEA; Energy Institute; BloombergNEF



Briefing | Carbon bargain

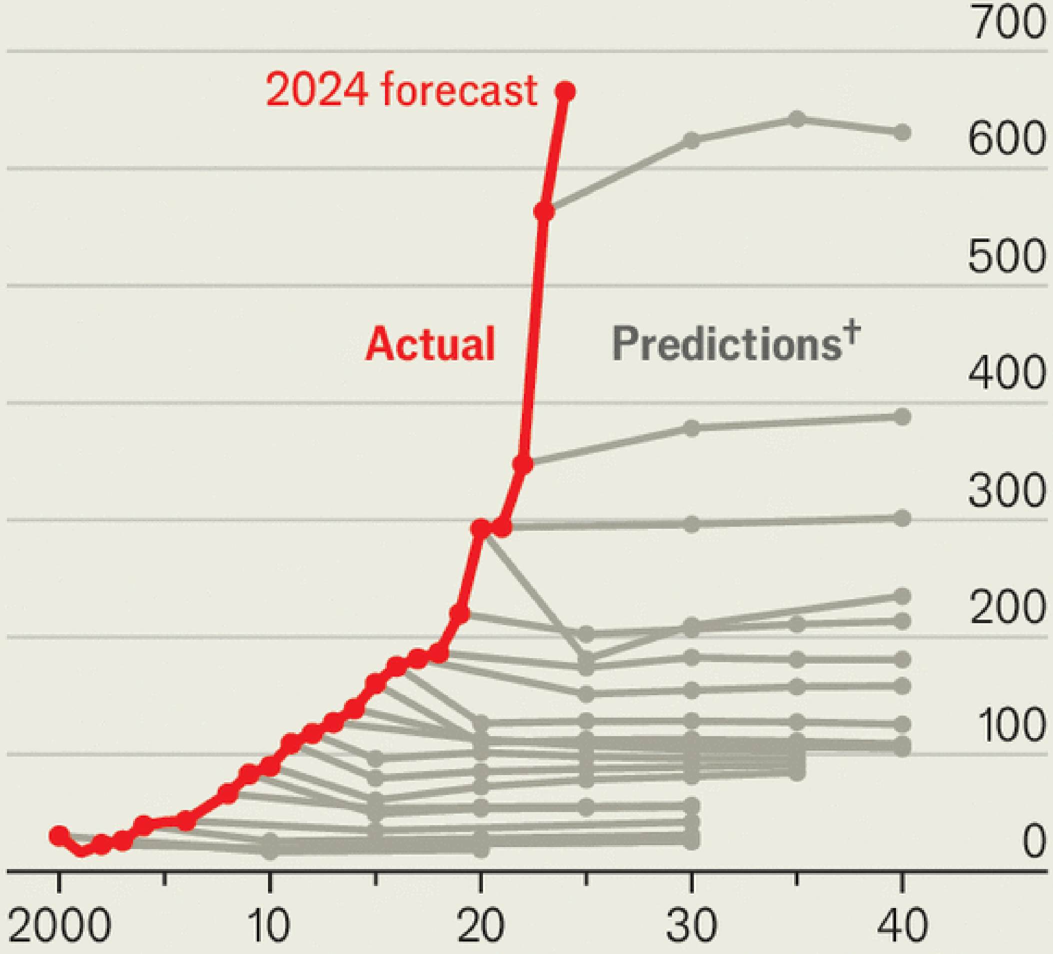
The energy transition will be much cheaper than you think

Most analysts overestimate energy demand and underestimate technological advances

Unshakable pessimism

2

Global renewable energy*, capacity added each year, GW



*Includes solar, wind, hydropower, bioenergy, geothermal and marine †Existing-policies scenario, lower-end estimates

Source: IEA

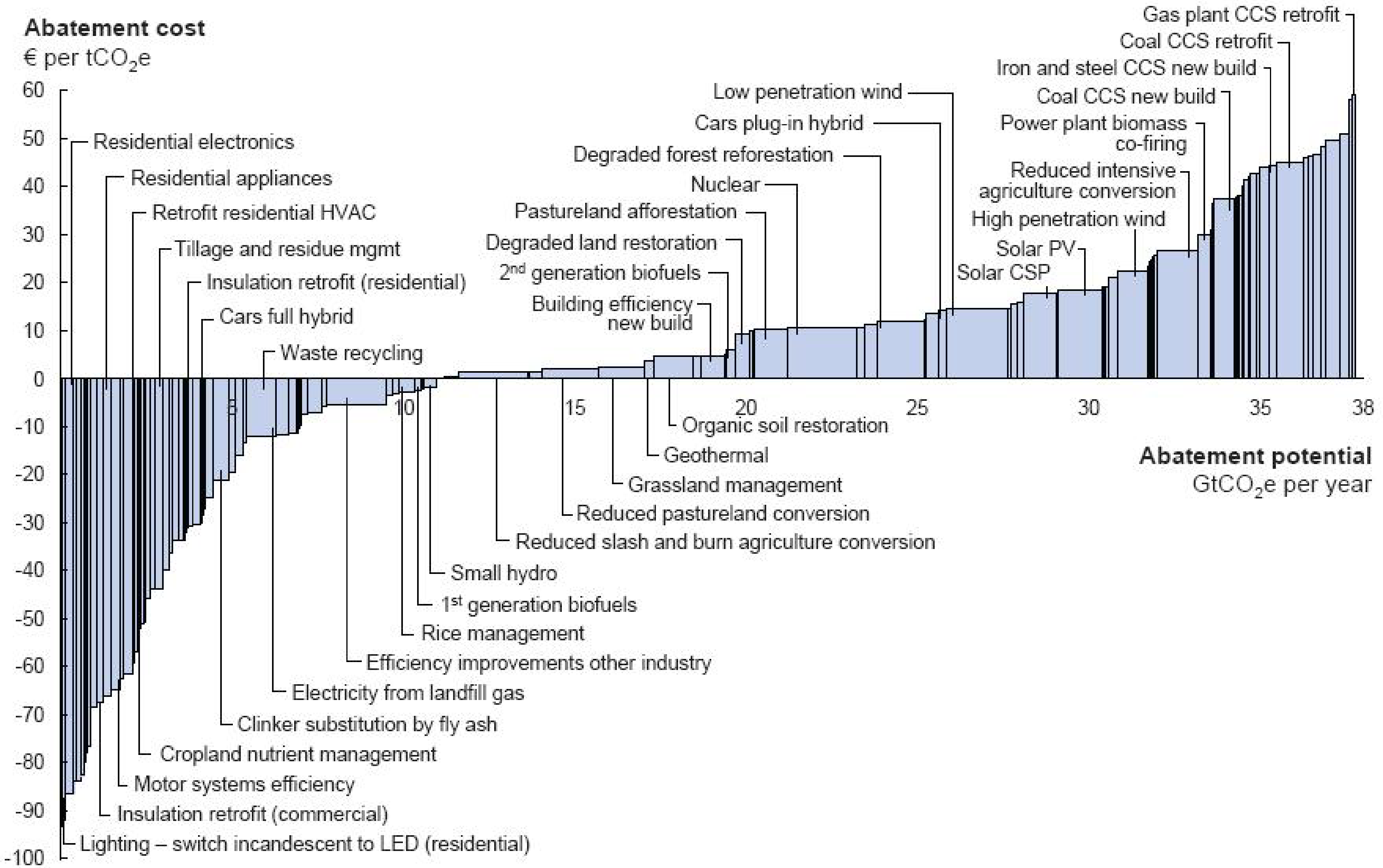
Renewables revolution unstoppable*

and so are climate impacts

* "Trump can and will handicap domestic industries in jockeying for positions in [the global climate race], but he cannot halt it." (What Will Trump's Victory Mean for the Climate?, 9 November 2024)

Large abatement opportunities available at low or no cost

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

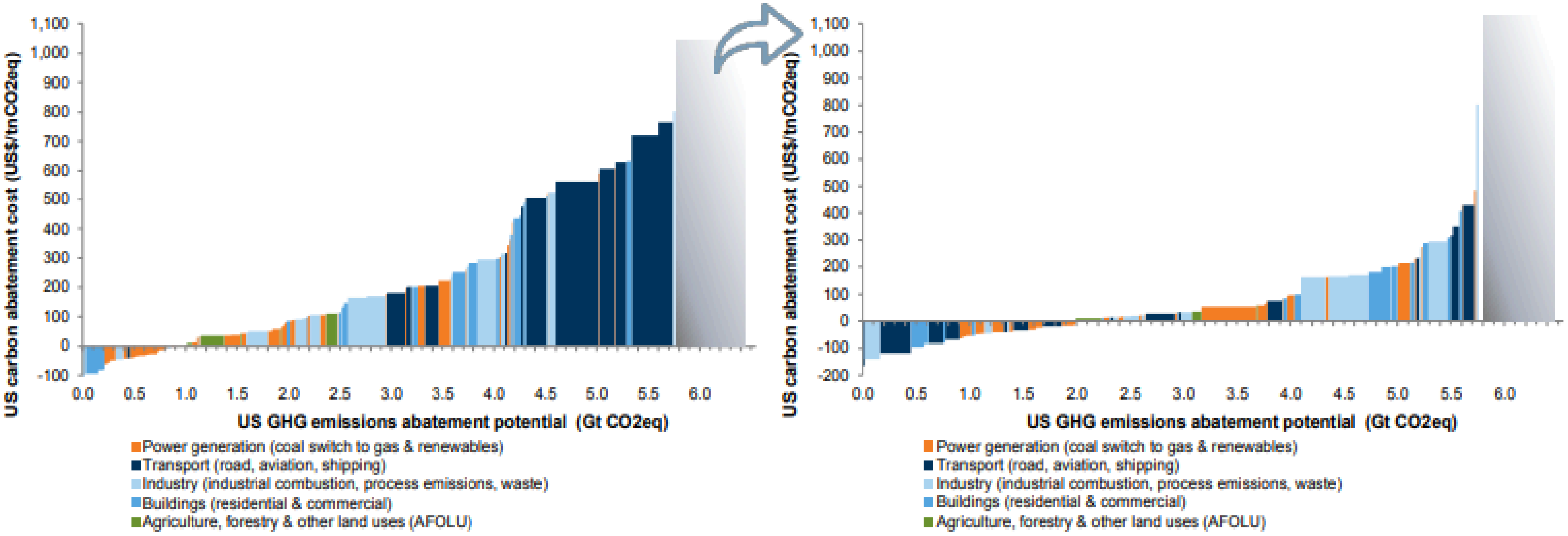


Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO_2e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0

Exhibit 46: The IRA has transformed the cost curve of the US bringing most technologies in the money, especially in the transportation and buildings sectors

US carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and current costs, assuming economies of scale for technologies in the pilot phase prior and after IRA

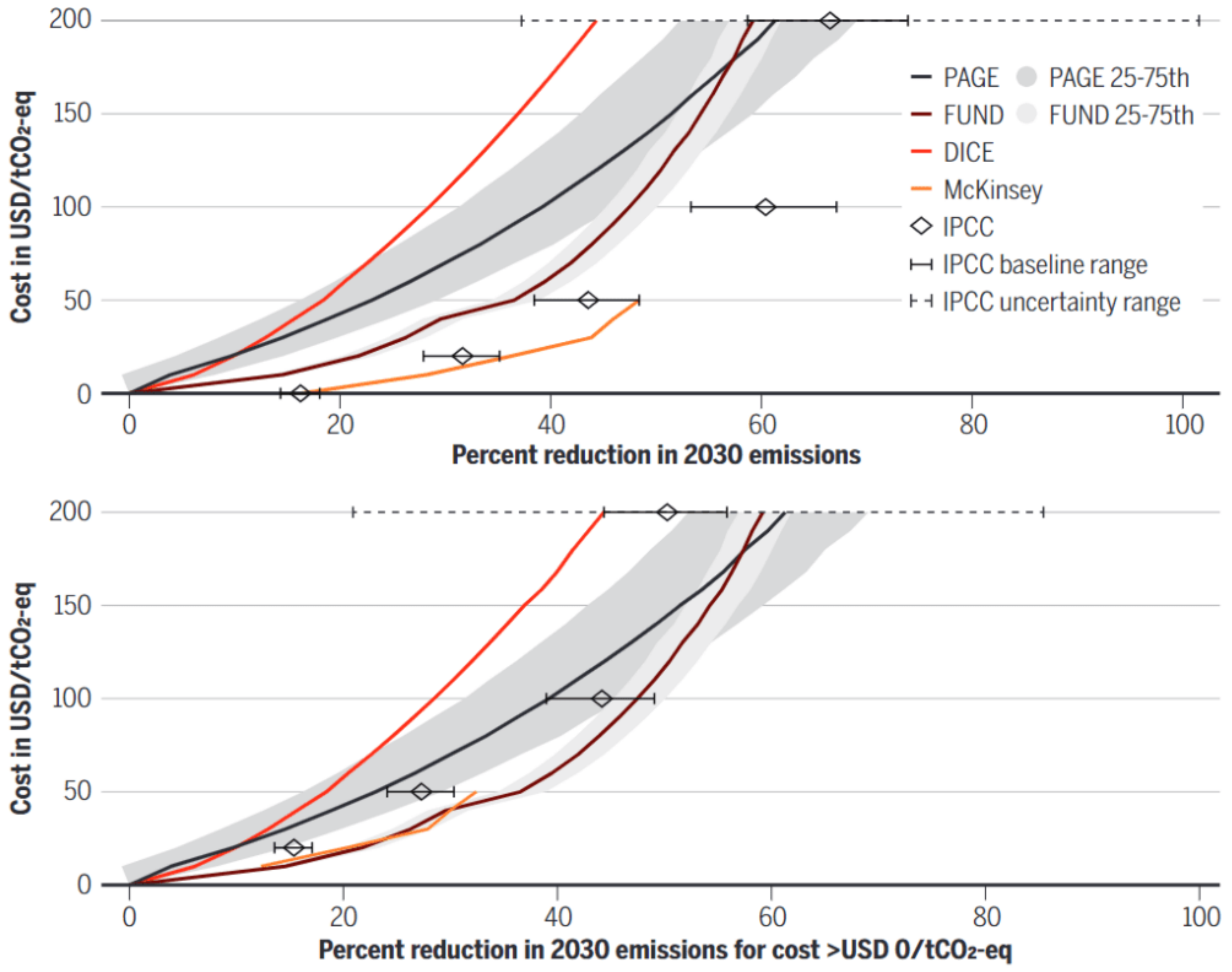


Source: Goldman Sachs Global Investment Research

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.

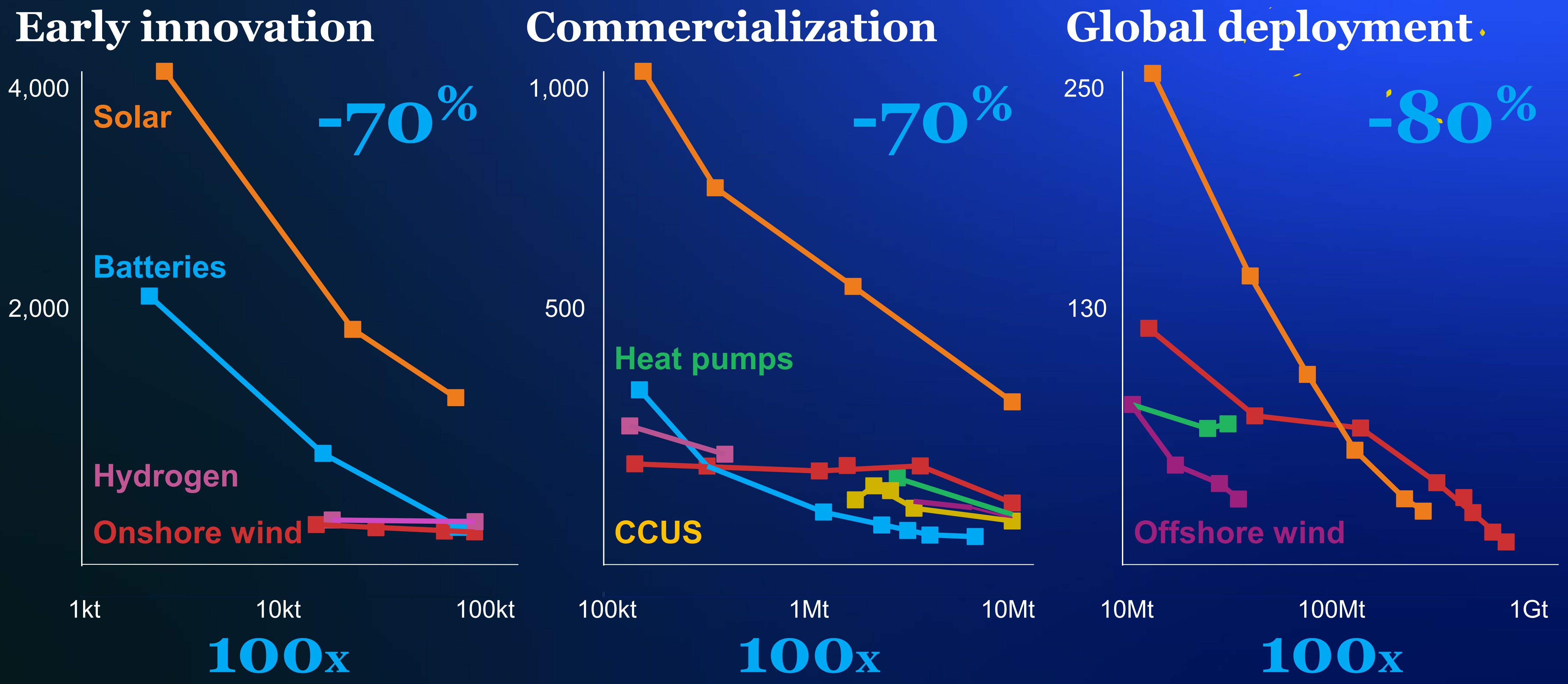


Source: Kotchen, Rising & Wagner. “The costs of “costless” climate mitigation.” *Science* (30 November 2023).

Bernd Heid, Senior Partner, McKinsey, at Columbia Business School, 18 November 2024

“Moore’s Law” of climate technology: 100x scale-up drives 70%+ cost-down

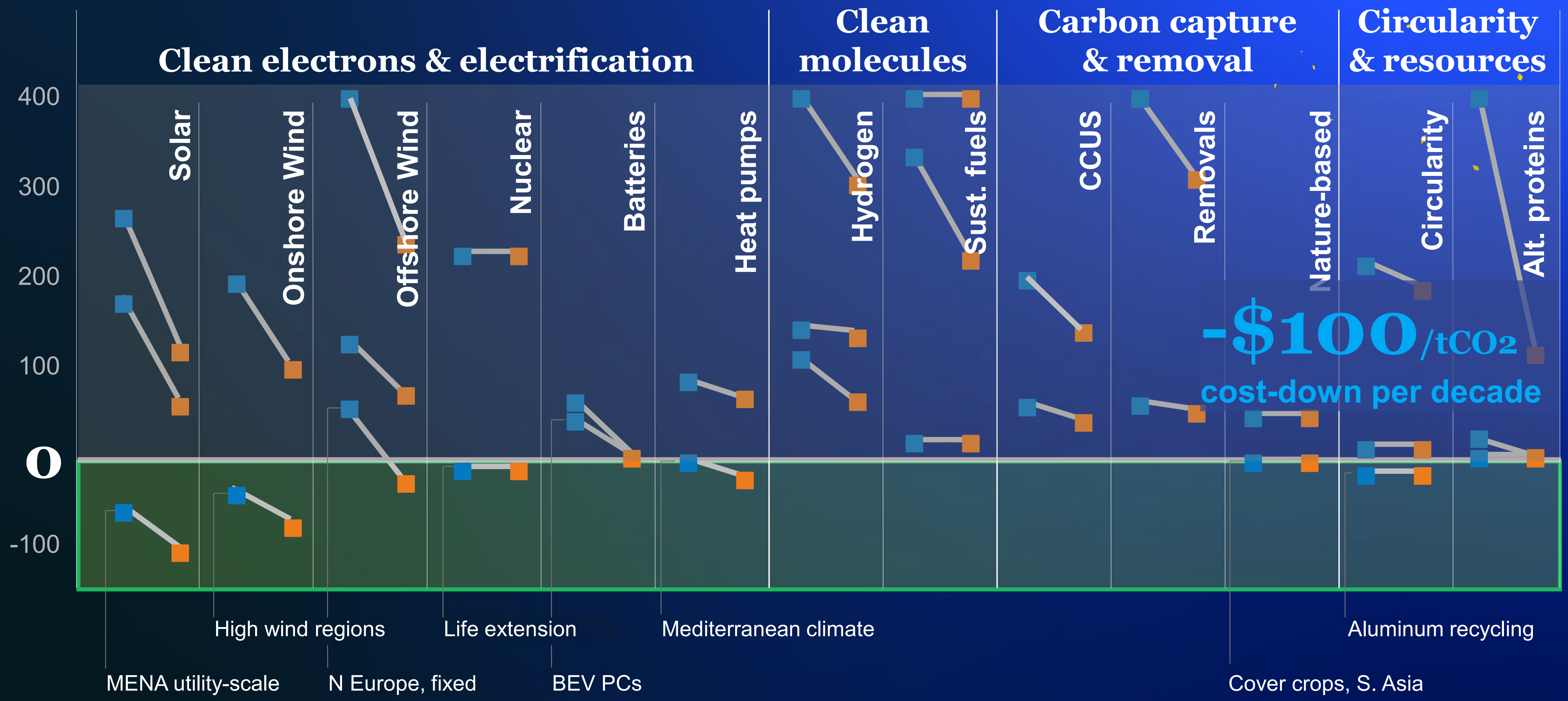
Abatement cost, $/tCO_2$



McKinsey & Company

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

Estimated abatement costs, USD/tCO_2e

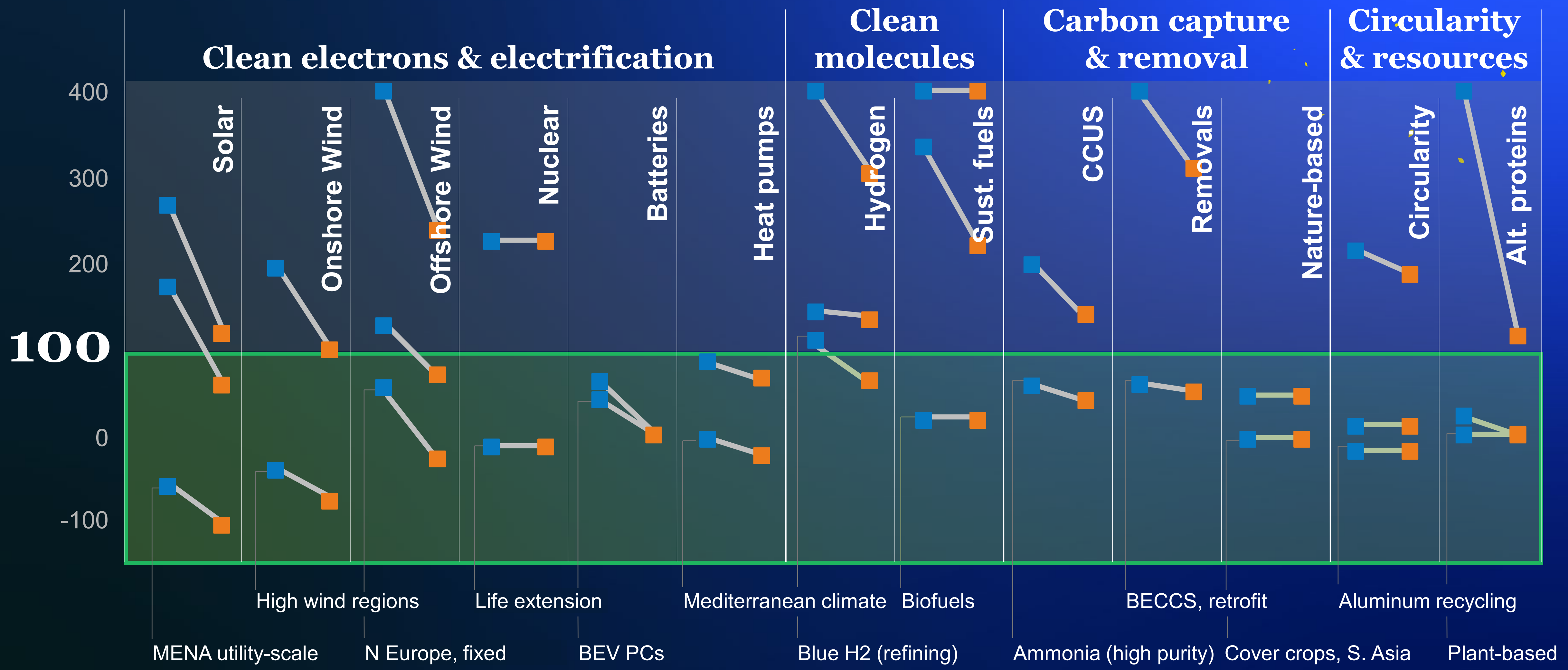


Source: McKinsey Global MACC with regional/product estimations

McKinsey & Company

100$/$tCO_2$ carbon tax would make most techs competitive

Estimated abatement costs, USD/tCO_2e



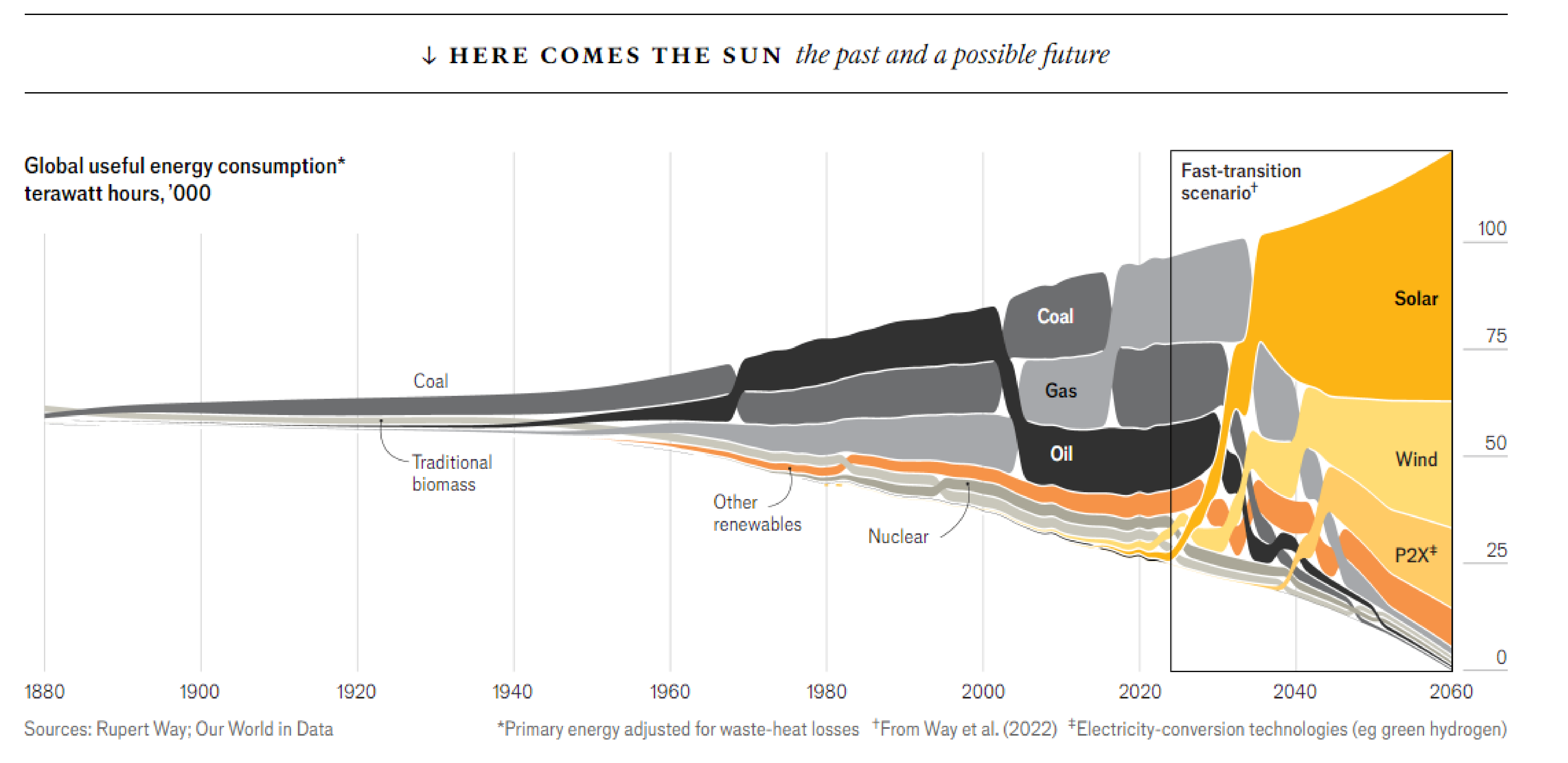
Source: McKinsey Global MACC with regional/product estimations

McKinsey & Company

Columbia Business School
AT THE VERY CENTER OF BUSINESS

Scaling Solar

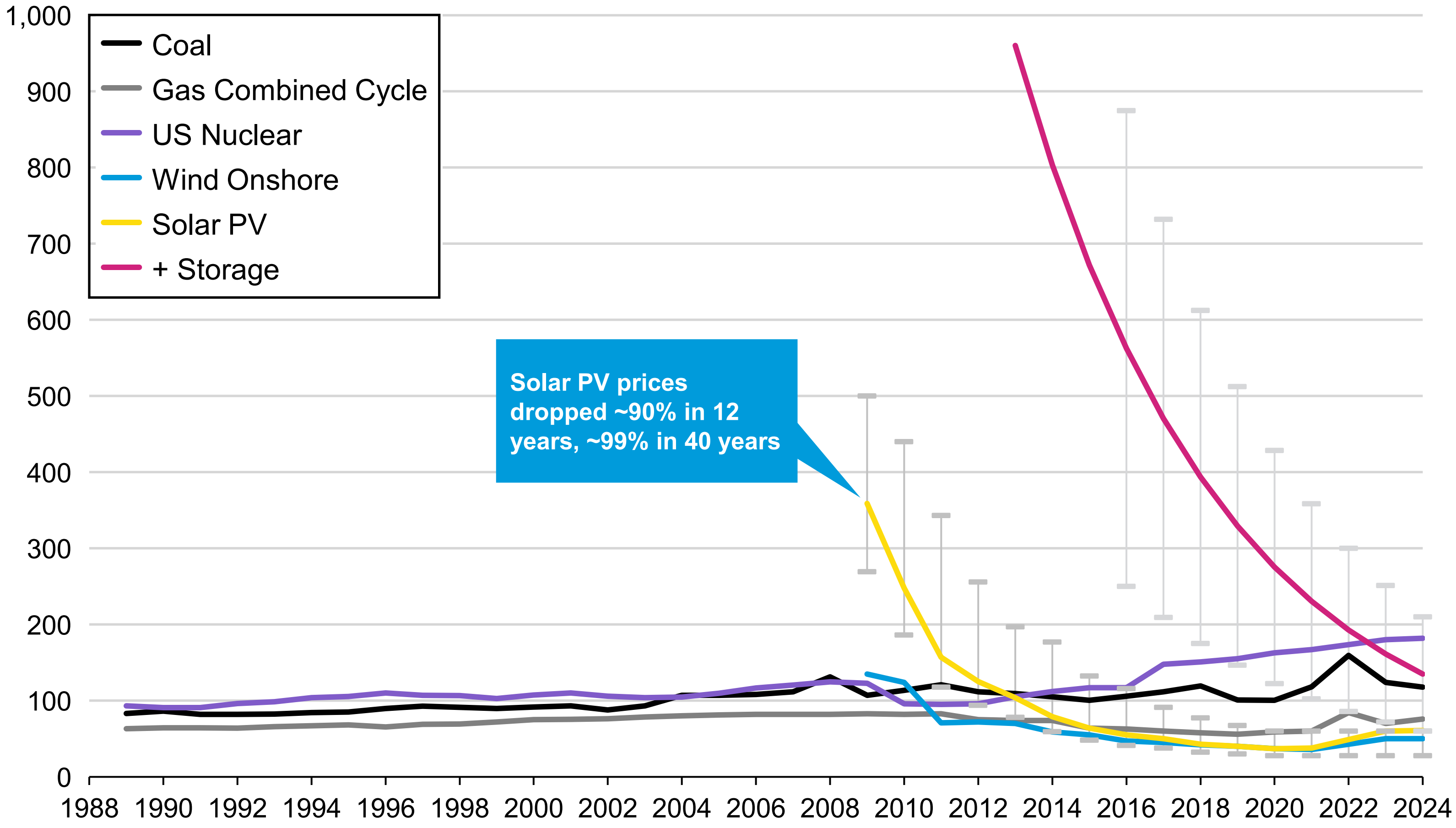
Hyae Ryung Kim, Marcelo Cibie, Max de Boer, Lara Geiger, Isabel Hoyos, Taicheng Jin, Hassan Riaz, and Gernot Wagner



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

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

- **Levelized Cost of Electricity (LCOE) & Storage (LCOS), *US$/MWh***



Observations

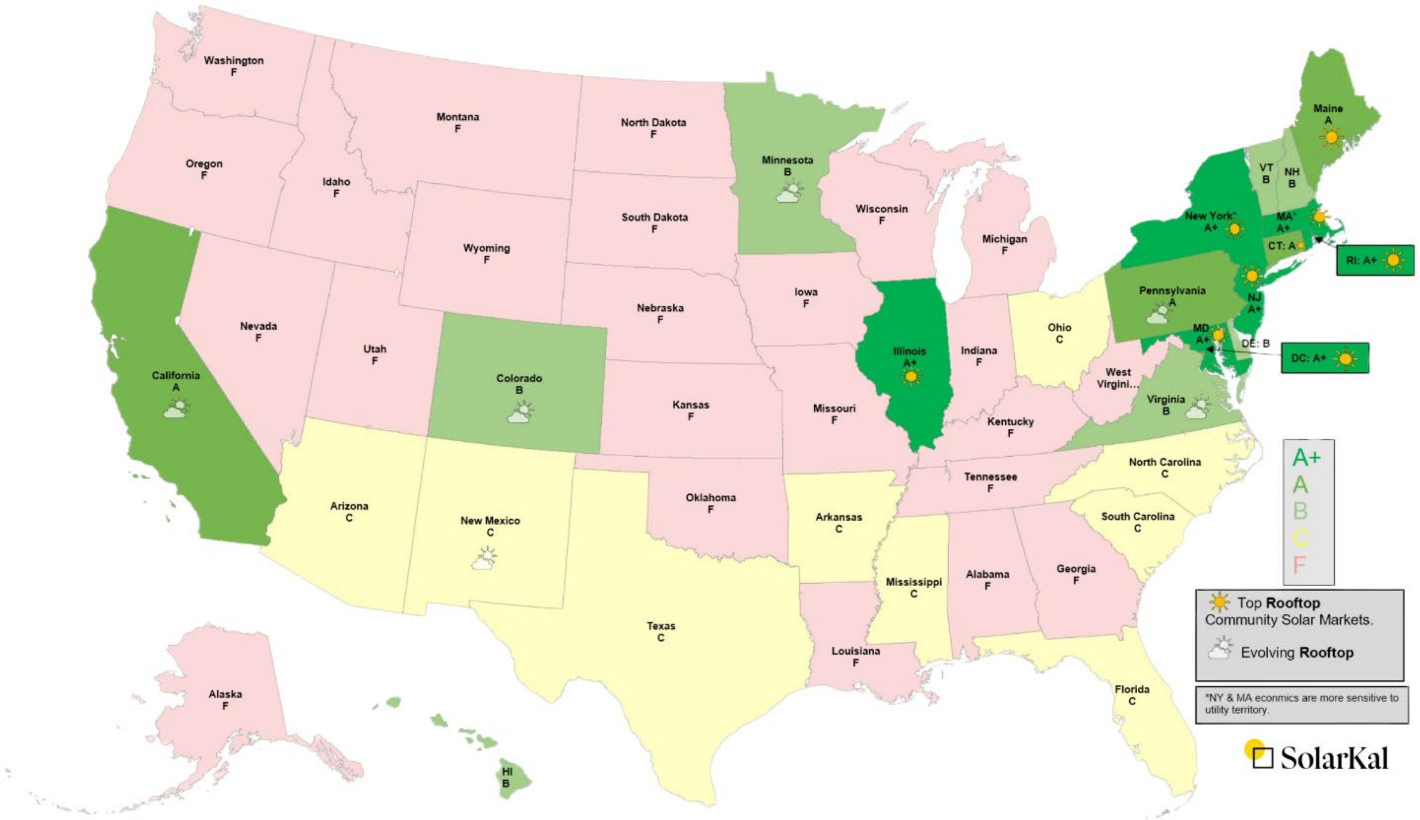
- **Solar photovoltaic (PV) prices dropped ~80% in past decade, wind by ~70%, lithium-ion battery costs by ~90%.**
  - PV price drop primarily driven by **improvements in module efficiency** and **economies of scale** (Kavlak *et al*)
  - Onshore **wind cheap the longest**, now only beaten by PV (Lazard).
  - Lithium-ion **battery costs fell 20% in 2023** alone (BNEF).
- **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 to fall** due to cell manufacturing overcapacity, economies of scale, and switch to lower-cost lithium-iron-phosphate (LFP) batteries.

- Sources: Lazard, LCOE+ (2024); Our World in Data (2024); Energy Institute, Statistical Review of World Energy (2024); BNEF, Battery Price Survey (2024); Kavlak *et al.* (2018).

Credit: Hyae Ryung Kim, Xiaodan Zhu, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (8 April 2025).

Deployment environments differ across states and energy markets, with ISO-NE and CAISO leading in the US

State-level solar receptiveness graded on a letter scale



Observations

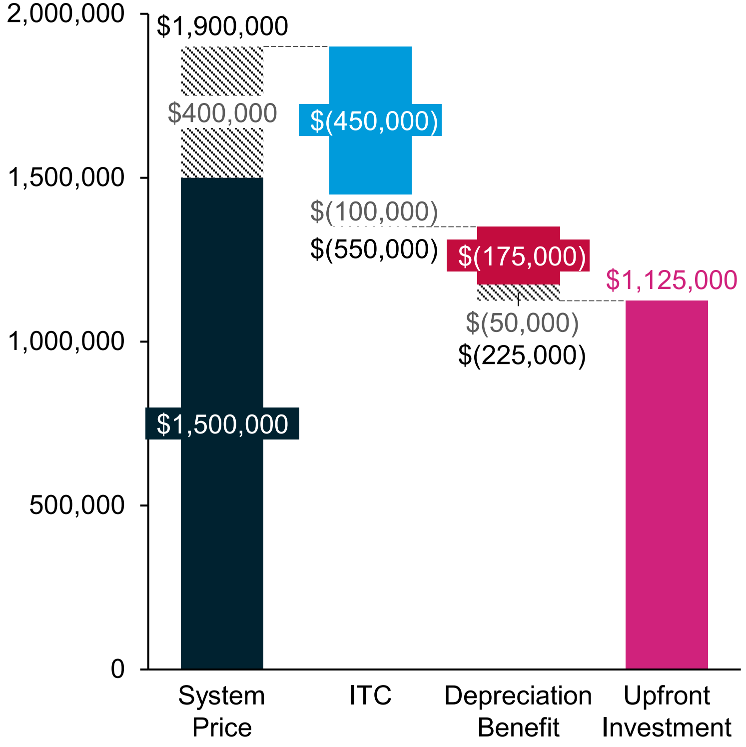
- **A state's solar attractiveness** is principally determined by:
  - **Incentives** including state rebates, SRECs (solar renewable energy certificates), and community solar
  - **Electricity rates** determining energy saving, which make up the bulk of the revenue to repay investment
  - **Net metering rules** setting rates utilities pay for returned solar energy; e.g. "net metering" pays the retail unit energy cost (same a customers pay to receive energy), whereas "net billing" applies wholesale rate, reducing revenue a customer receives
  - **Solar irradiation** measuring how much sunshine an area receives, on average, over a period of time
- **CA and Northeastern states** are the friendliest solar states due to state level incentives like NJ's SREC, PA's elevated electricity rates, or NY's offering of Tax Credit Bridge Loans and VDER net-metering arrangement

Note: CAISO is the California Independent System Operator and ISO-NE is the Independent State Operator North-East.
Sources: SolarKal (2025); NREL; EIA, Electric Power Annual Reports (2024); Berkeley Labs (2024).
Credit: Taicheng Jin, Hassan Riaz, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (20 March 2025).

Federal ITCs and PTCs provide limited relief, but state incentives play a crucial role in pushing projects past investors' hurdle rate

e.g. REC could boost IRR by 7-15% and cut payback by 2-5 years

Waterfall of a 1MW project without state-incentives



Return Profile if based in:

Annual income in New Jersey
(+) Energy Savings: $150,000
(+) REC Revenue: $125,000
Project IRR: 24-26%
Payback Period: 6 Years

Annual income in Florida
(+) Energy Savings: $128,000
Project IRR: 11-13%
Payback Period: 7 Years

Annual income in Texas
(+) Energy Savings: ~$128,000
Project IRR: ~8-16%
Payback Period: ~5-10 Years

* Diagonal represent additional cost/savings for range estimate.
** Assuming a standard 1 MW solar project (BTM/direct ownership): On-site system, behind the meter, for self-consumption; direct ownership provides full control, access to tax incentives, and long-term savings.

Observations

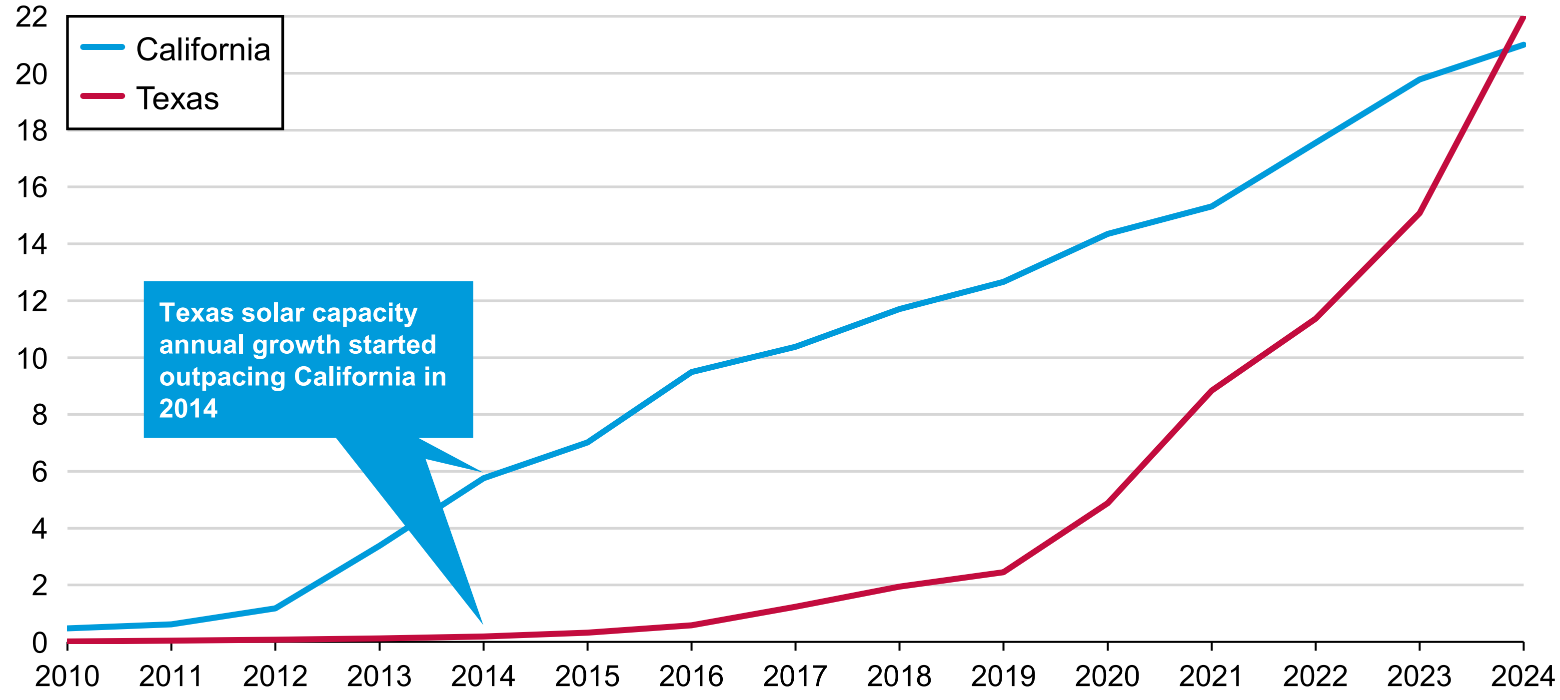
- Federal incentives provide a significant boost, but **strong state-level incentives can push a project over hurdle rate**
  - **Federal level:** ITC, PTC, Accelerated Depreciation
  - **State level:** state Credits, RECs, rebates, state tax exemption, net-metering, renewable portfolio standards (RPS), interconnection standards
  - **County level:** rebates & grants, buildings standards
  - **Community level:** energy-efficient organizations, regional partnerships
- NJ, FL, and TX offer **varying levels of state-incentives**, resulting in different levels of project IRR
  - **New Jersey:** The **Successor Solar Incentive (SuSI)** program rewards solar energy production with **SREC-II certificates**, valued at **$85-$90 per MWh for 15 years**. Solar equipment is exempt from sale and property taxes, and net metering allows generators to sell excess electricity back to the grid.
  - **Florida:** The state exempts added value of solar energy system from **property taxes and sales taxes**. Statewide net metering policy allows full credit on utility bills. Local utilities offer **$2,000-$4,000 rebates** for solar battery installations.
  - **Texas: Several** utilities provide **$2,500-$3,000 rebates** for solar PV of at least 3 kW. Some utilities and retail energy providers offer **solar buyback programs** that provide bill credits or cash for surplus energy fed back into the grid.

Note: Texas has a larger band of uncertainty around buybacks depending on location
Sources: Solar.com's Solar Rebates by State; Forbes (2024); Energysage (2025); Texas Power Guide; DSIRE; Canary Media (2025); Data for solar project IRR models provided by SolarKal.
Credit: Taicheng Jin, Hassan Riaz, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (20 March 2025).

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

Total installed utility-scale solar capacity in Texas and California, *GW*

CAGR '10-'15	CAGR '15-'20	CAGR '20-'24
CA: 71%	CA: 15%	CA: 10%
TX: 87%	TX: 73%	TX: 46%



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" (20 March 2025).

Solar Supply Chain

SiO_2 is refined to produce ingots, which are cut into wafers and then assembled into cells and modules

Polysilicon

- **Polysilicon** from **(Si)** is abundant but **does not occur in pure form**.
- First, **SiO_2**, the second most abundant mineral on earth, is refined to **metallurgical-grade silicon** (98-99% pure).
- Next, met-grade silicon goes through the **Siemens process** to **remove final impurities**.
- The result is **chunks of polysilicon** with **>99.99999% (7-10N) purity**.

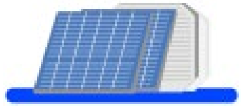
Ingots

- Next, the **chunks of polysilicon** are **melted into ingots**.
- For **poly-Si ingots**, the polysilicon is **simply melted** and **allowed to solidify,** forming **many small polysilicon crystals**.
- **Monocrystalline ingots** are formed using the **Czochralski process**.
  - **A polysilicon seed** is dipped into the molten polysilicon, **slowly lifted, and rotated**.
  - The result is **an ingot** that consists of **one large single crystal cylindrical column**.

Wafers

- **Polysilicon ingots** are then sawn into **wafers** either through **a slurry-based** or **diamond wire** method.
  - In the **slurry method**, the ingot is passed onto **rotating wires** spaced equidistantly and mixed with **silicon carbide solution**.
  - The diamond wire that has been **covered in small diamond particles** is gradually replacing the slurry method.
- The product is a **wafer** that measures **only 200 micrometers thick** – about **2.5x the size of a human hair**.

Cells



- A wafer is **transformed into a solar cell** by applying several steps. The major ones are:
- **Boron** is added to create positive **(p-type)** wafers and **phosphorous** to create negative **(n-type)** wafers in a process called **doping**.
- **Metallic contacts** are applied to the **front and back of the wafer** through which **electricity can flow**.
- An **antireflective coating** is applied to help the cell **absorb more sunlight**.

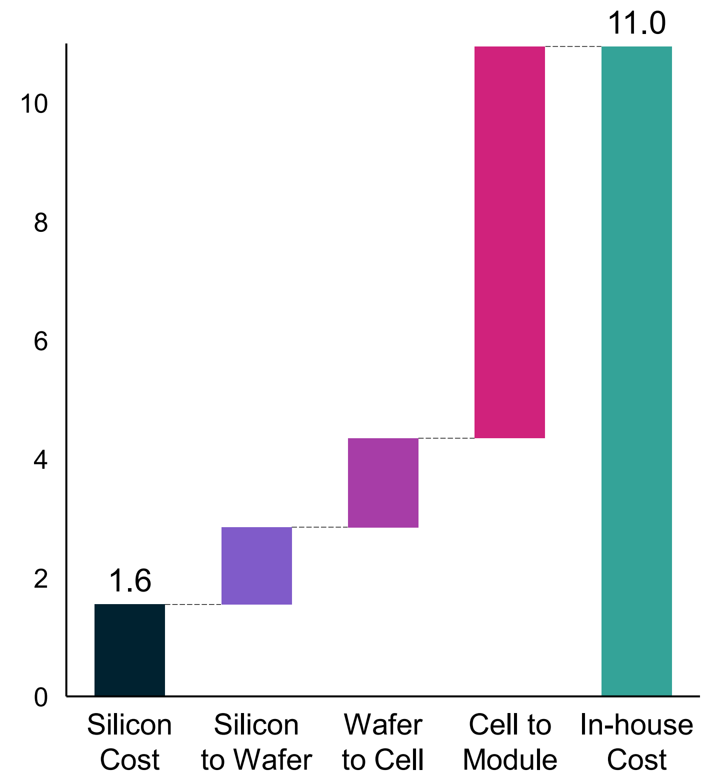
Panels / modules

- In the final step, **multiple solar cells are combined** to form a **single solar panel or module**.
- First, **solar cells are soldered together** to form an array.
- The cells are then **encapsulated in plastic**, and **a separate insulating back sheet** is added.
- Finally, several arrays are **soldered to a metal frame** and a **connector that** connects the panel to the grid is added.

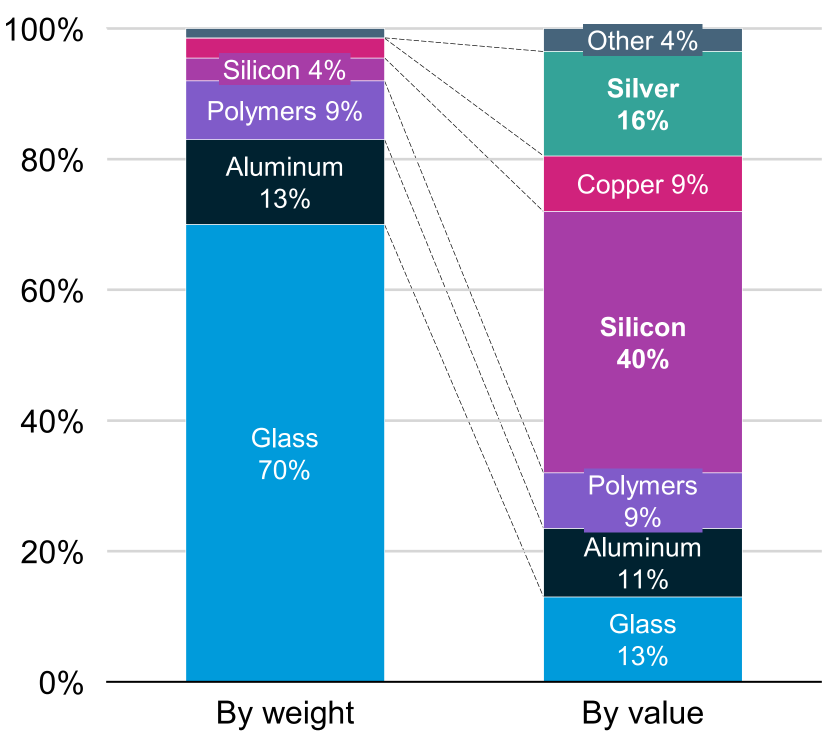
Sources: Pv-Education.org, pv-manufacturing; images from IEA, Solar PV Global Supply Chains
Credit: Taicheng Jin, Hassan Riaz, Max de Boer, Lara Geiger, Marcelo Cibie, Hyae Ryung Kim, and Gernot Wagner (12 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Silicon and silver make up the bulk of material cost; cell-to-module assembly represents the largest chunk of in-house cost (~60%)

Breakdown of total cost (cents per watt) – (Q3, 2023)



Material composition shares of c-Si solar panels (in %) – (world, 2021)



Observations

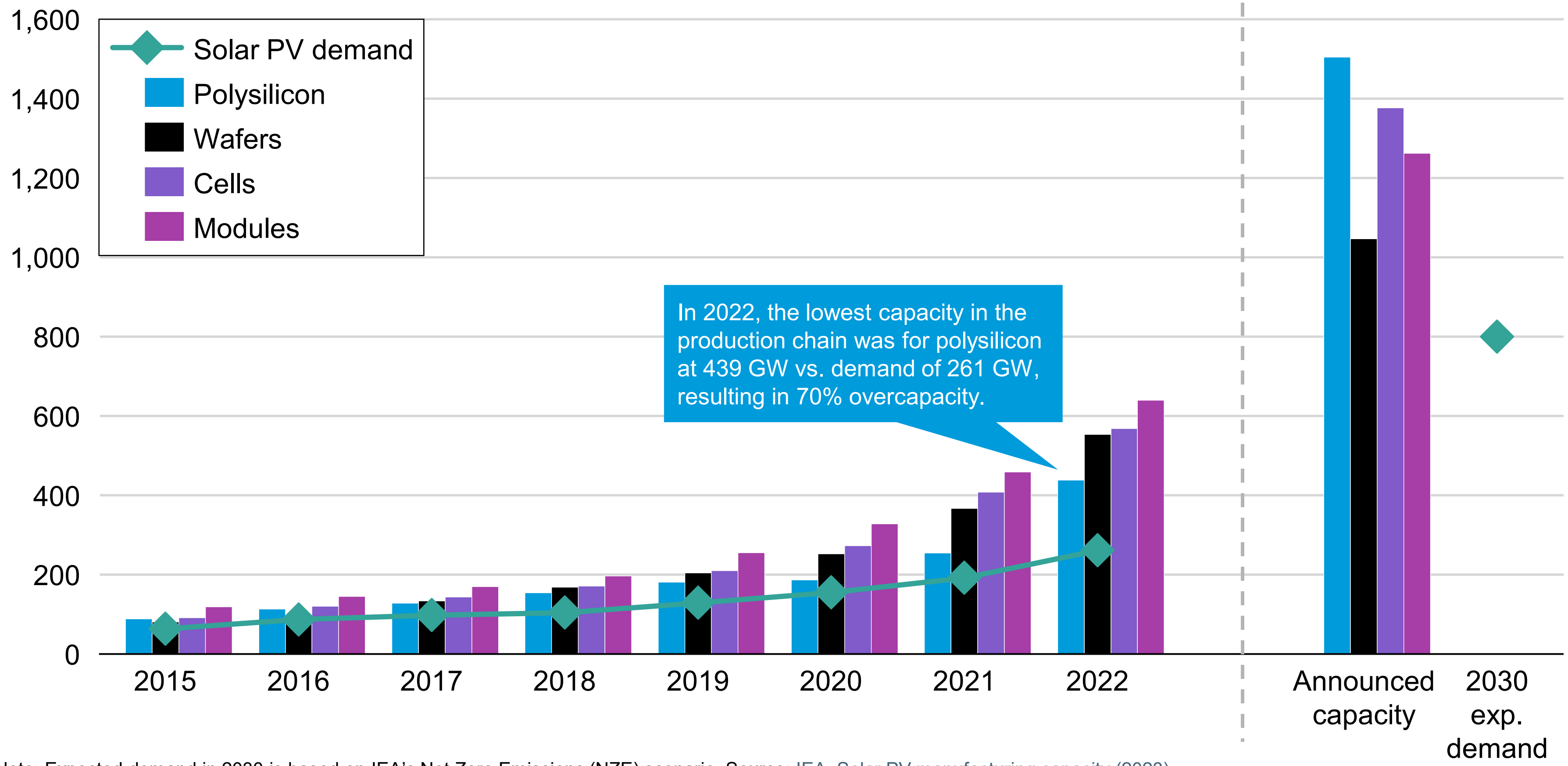
- **Silicon input** accounts for around **15%** of total in-house cost:
  - **Silicon and silver make up >50% of materials costs of solar c-Si panels,** but material use is becoming more efficient.
  - **Polysilicon intensity** for c-Si cells dropped by **more than six times between 2004 and 2020** thanks to cell efficiency improvements.
- Cell to module is nearly **60%** of total in-house cost.
  - Cells are stringed and placed between sheets of EVA (ethylene vinyl acetate) and **laminated**; the structure is then supported with **aluminum frames**.
- **Big, integrated companies** can exert pressure on small players that have less **cost control**.
  - Companies with **cost advantage** and **cash holdings** will end up expanding market share.

Source: Sinovoltaics, adapted from BloombergNEF, data as of Q3 2023. Cash cost assumes in-house production from polysilicon modules to integrated solar makers, D&A, SG&A excluded.
Median used for silicon cost: $6 ~$7/kg, $2.14/g polysilicon, $1=¥7 when referring to mainland China factories.
Note: Material composition percentages are averages. Source: IEA, Solar PV Global Supply Chains; pv-manufacturing.org

Solar PV manufacturing capacity exceeds demand at every step by at least 70%; overcapacity is expected to last at least until 2030s

Since 2017, solar PV manufacturing capacity has outstripped demand

Global solar PV manufacturing capacity along steps of the value chain (in GW)



Observations

- Since 2015, **global solar PV manufacturing capacity** has **consistently exceeded demand**.
- **Global capacity** is expected to **more than double** in the **next five years**, based on **investment announcements** and the **expected impact of industrial policies**:
  - **IRA** – United States
  - **The Green Deal** – EU
  - **Production Linked Initiative** – India
- With **demand in 2030** expected at **800 gigawatts per year**, all currently announced production capacity would result in a **30% overcapacity in 2030**.

Note: Expected demand in 2030 is based on IEA's Net Zero Emissions (NZE) scenario. Source: IEA, Solar PV manufacturing capacity (2023)

Technology

China's Longi says it will lay off about 5% of employees

By **Reuters**

March 18, 2024 10:34 PM EDT · Updated 4 months ago

Bloomberg

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Green

Longi Layoffs Speed Move in Solar Production Away From China

- Most of the job cuts will likely be in China, says Daiwa's Ip
- Chinese firms increasingly looking to move capacity offshore

Climate Risks, Opportunities, and Geopolitics

28 May 2025

1. Climate risk is financial risk
2. Solar
3. Steel
4. Is the goal a high or a low price per tonne of CO_2?

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Columbia Business School
AT THE VERY CENTER OF BUSINESS

26 March 2025

Decarbonizing Steel

Max de Boer, Grace Frascati, Mimi Khawsam-ang,
Hassan Riaz, Hyae Ryung Kim & Gernot Wagner

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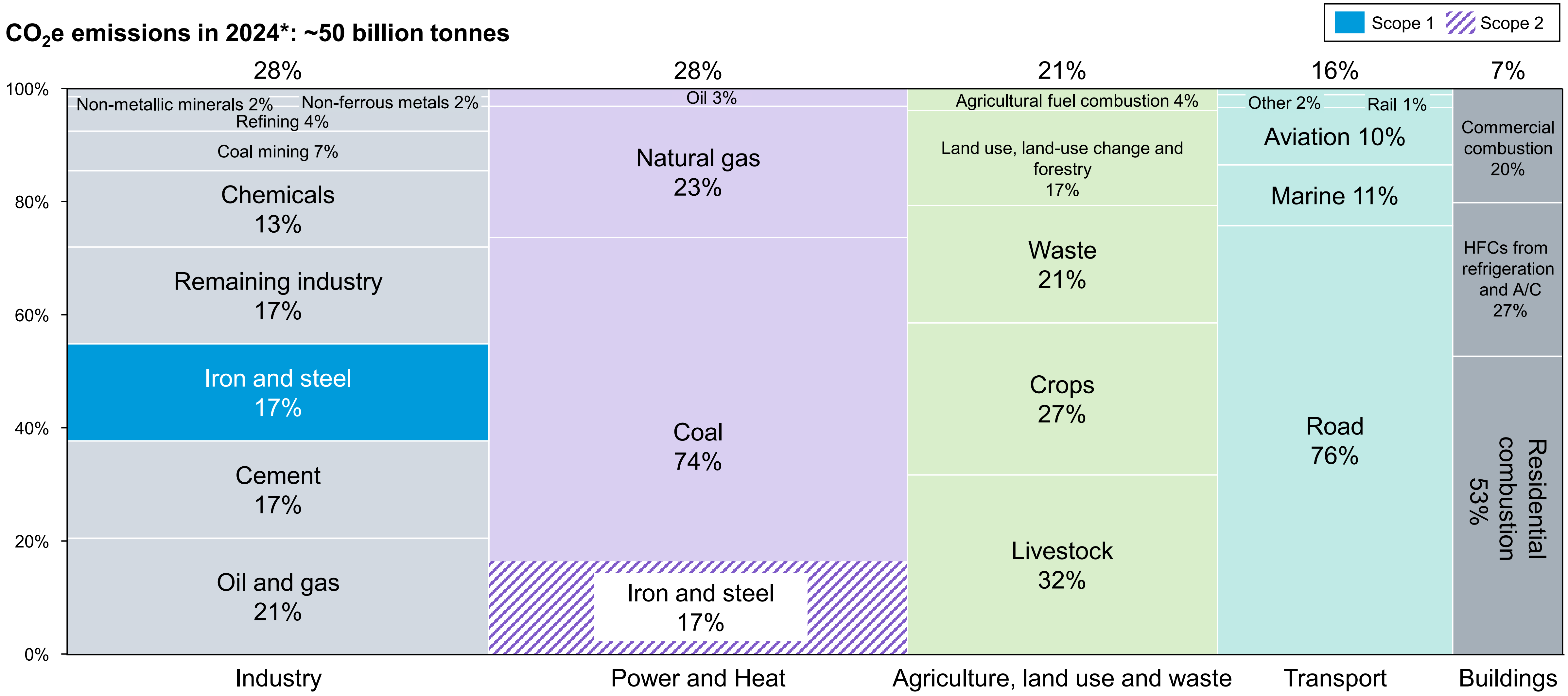
Steel Sector Overview: The Problem

Steel sector Scopes 1 and 2 around 10% of global CO_2e emissions

CO_2e emissions in 2024*: ~50 billion tonnes



Sources: Scope 1 emissions from Rhodium Group ClimateDeck (September 2024); Scope 2 iron and steel estimate from IEA (2023); * 2024 emissions based on projections.
Credit: Theo Moers, Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: De Boer *et al*., "Decarbonizing Steel" (27 September 2025).

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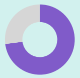
At present, crude steel is produced through three main methods that all emit CO_2: BF-BOF, scrap EAF, and NG DRI-EAF

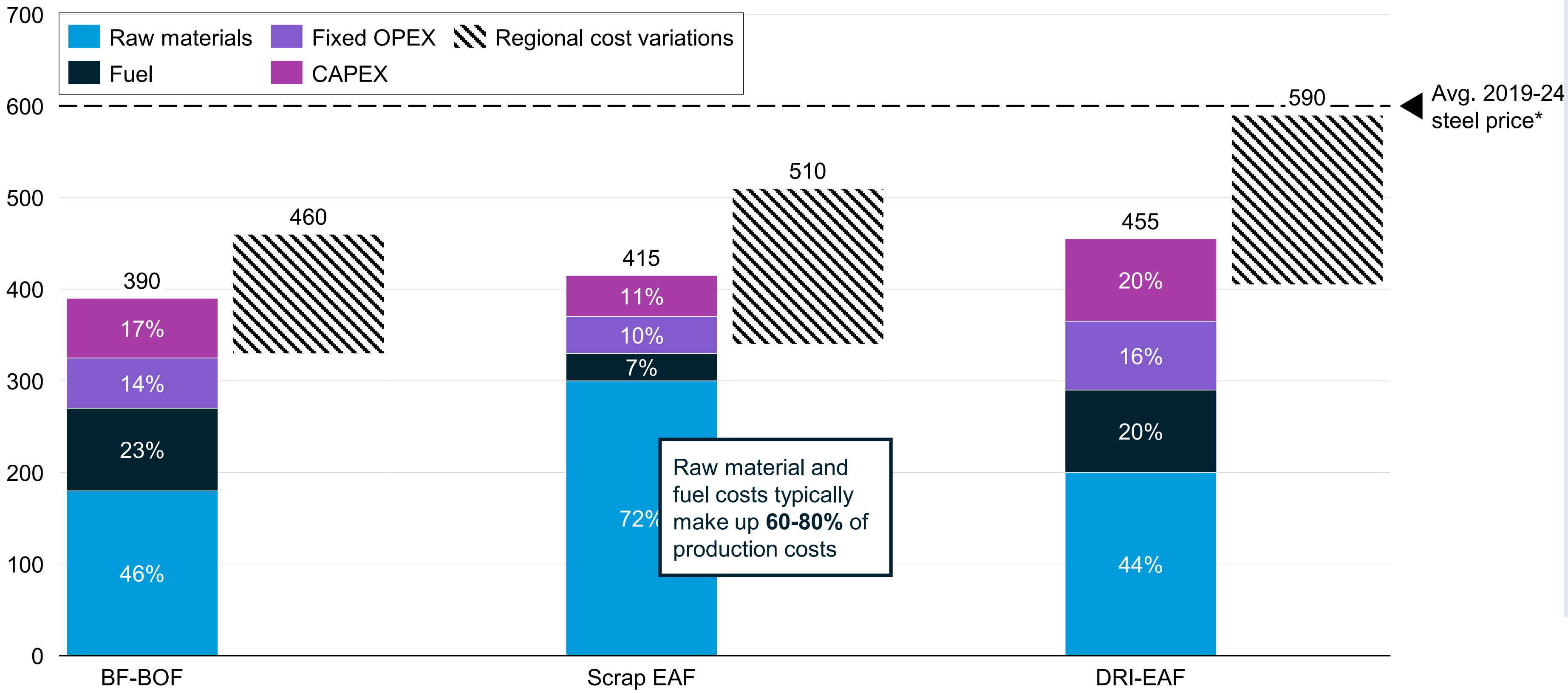
	1	2	3
	Blast Furnace-Basic Oxygen Furnace (BF-BOF)	**Scrap Electric Arc Furnace (Scrap EAF)**	**Natural Gas-Based Direct Reduced Iron – Electric Arc Furnace (NG DRI-EAF)**
Description	**Iron ore, coke, and limestone** produce pure iron in a **blast furnace**, which **is turned into steel in an oxygen furnace**	**Scrap metal** is **melted in an EAF** using **electrical energy**	**Iron ore** is turned **into iron** using **natural gas**, which is then **melted in an EAF** to **produce steel**
Main inputs	**Iron ore, cooking coal**	**Scrap steel, electricity**	**Iron ore, natural gas**
% of global steel production	 72%	 21%	7%
CO2 per tonne of crude steel	**2.4 tonnes**	**0.98 tonnes**	**1.4 tonnes**
Energy intensity per tonne of crude steel	**~24 GJ**	**~10 GJ**	**~22 GJ**
Average cost per tonne of crude steel	**~$390**	**~$415**	**~$455**

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel.
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: De Boer *et al*., "Decarbonizing Steel" (16 September 2024).

BF-BOF is the cheapest production method, but regional cost differences impact margins across production methods

Regional cost differences cause all steel making methods to be competitive

Simplified levelized cost breakdown of crude steel production via conventional routes (in USD per tonne, 2020)



Observations

- **Profit margins** across the industry are slim – the **average EBITDA** margin of steel producers over the **past 10 years** was **8-10%**
- **Raw material** and **fuel prices** can cause **strong fluctuations in margins**, given that these typically make up between **60-80% of total production costs**
  - While **some of these markets are global** (iron ore), **others are more regional** (e.g. electricity, scrap steel) which can **drive regional cost differences**
- **Labor costs**, feeding into fixed OPEX, are typically **higher in advanced economies than** in **emerging economies**
- **CAPEX** for **production equipment** is usually **consistent across regions**. However, **engineering, procurement and construction costs** can **vary significantly**

(*) Average steel price based on Hot Rolled Coil Steel Futures Continuous Contract (HRN00), average of 2019-24 monthly prices. Source: MarketWatch (2019) McKinsey,IEA *Iron and Steel Technology Roadmap* (2020), European Commission Joint Research Centre *Science for Policy Report* (2016).

Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: De Boer *et al.*, "Decarbonizing Steel" (16 September 2024).

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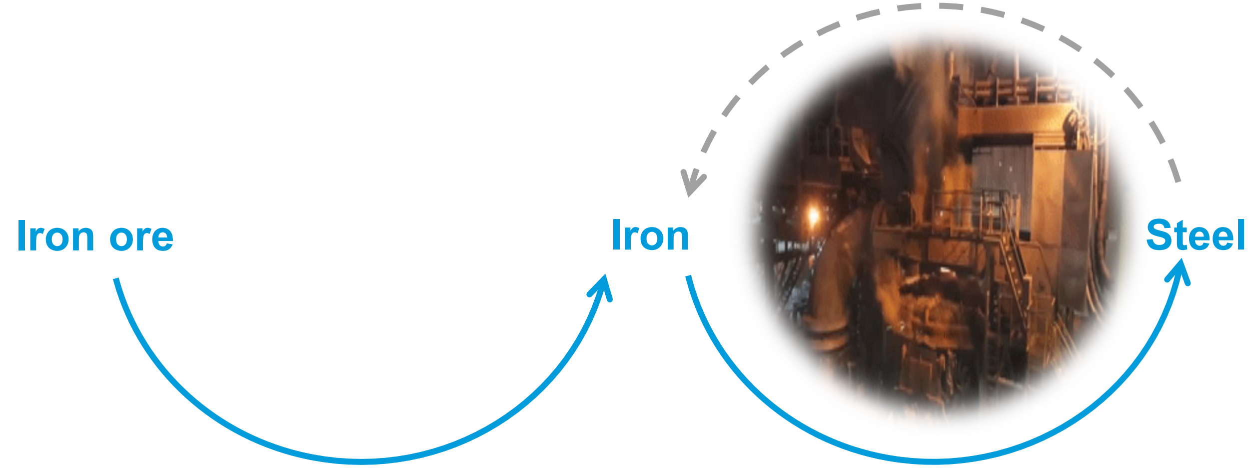
Steel Decarbonization Technologies

1 Green H_2 DRI-EAF is an emerging technology using green hydrogen instead of natural gas as an iron ore reductant with standard electric arc furnaces

Green H_2 direct reduced iron-EAF has an average cited decarbonization potential of ~90%



Renewable electricity is used throughout the production process, including the creation of green hydrogen

Comes at a green price premium

Observations

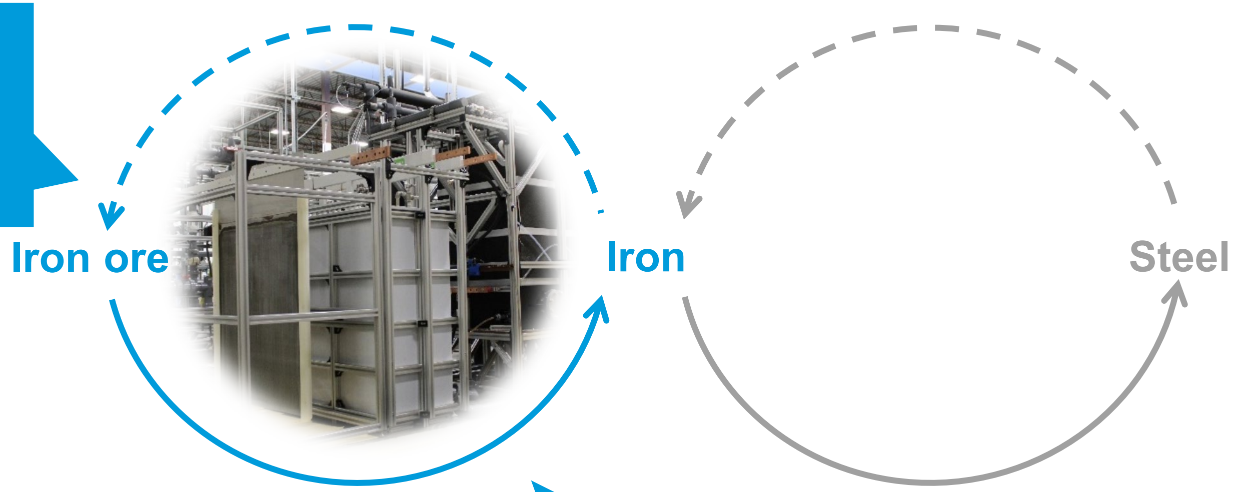
- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace
- **Scrap EAF:** Scrap metal is melted in an EAF using electrical energy
- **NG DRI-EAF:** Iron ore turns into iron using natural gas, which is then melted in an EAF to produce steel
- **Green H_2 DRI-EAF:** Green hydrogen replaces natural gas as an iron ore reductant; byproduct is water vs. CO_2

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel.
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: De Boer *et al*., "Decarbonizing Steel" (16 September 2024).

2 Iron ore electrolysis is an emerging technology that uses an electric current to drive a chemical reaction, producing molten iron or pure solid iron

Iron ore electrolysis has an average cited decarbonization potential of ~97%

Iron is now akin to solid-state battery, allowing for a reversed process that *produces* electricity



Electrowinning-EAF dissolves iron from iron ore in acid, then electrifies it to form pure solid iron; molten oxide electrolysis runs a current through iron ore and liquid electrolyte to split ore into pure molten iron

May be cheaper than conventional processes but has not yet been proven at scale

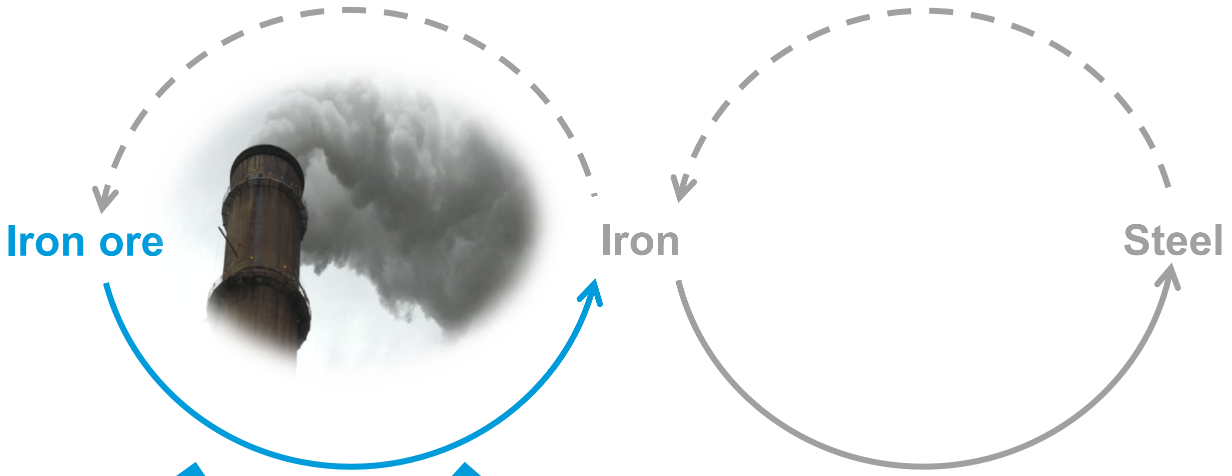
Observations

- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace
- **Scrap EAF:** Scrap metal is melted in an electric arc furnace (EAF) using electrical energy
- **NG DRI-EAF:** Iron ore turns into iron using natural gas, which is then melted in an EAF to produce steel
- **Green H_2 DRI-EAF:** Green hydrogen replaces natural gas as an iron ore reductant; byproduct is water vs. CO_2
- **Iron ore electrolysis:** Molten oxide electrolysis runs a current through iron ore and liquid electrolyte to split ore into pure molten iron; electrowinning-EAF dissolves iron from iron ore in acid, then electrifies it to form solid iron

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel.
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: De Boer *et al.*, “Decarbonizing Steel” (16 September 2024).

3 Carbon capture, utilization, and storage (CCUS) is an emerging technology that reduces steel's carbon footprint by capturing released CO_2

Despite a cited ~90% decarbonization potential, CCUS technology is largely unproven



Less viable for the blast furnace route given difficulty of capturing all carbon released

Capture rates range from 50%-90%, and viability is debated due to the lack of a single capture point

Observations

- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace
- **Scrap EAF:** Scrap metal is melted in an electric arc furnace using electrical energy
- **NG DRI-EAF:** Iron ore turns into iron using natural gas, which is then melted in an EAF to produce steel
- **Green H_2 DRI-EAF:** Green hydrogen replaces natural gas as an iron ore reductant; byproduct is water vs. CO_2
- **Iron ore electrolysis:** Molten oxide electrolysis runs a current through iron ore and liquid electrolytes to split ore into pure molten iron; electrowinning-EAF dissolves iron from iron ore in acid, then electrifies it to form solid iron
- **CCUS:** Equipment is added to existing steel-producing infrastructure to capture emitted CO_2, to then sequester or reuse

Sources: World Steel Association; IEEFA (2022); IEA, Iron and Steel Technology Roadmap (2020); Steel Technology, Basic Oxygen Furnace Steelmaking; Recycling Today, Growth of EAF Steelmaking; Wildsight, Do We Really Need Coal to Make Steel.
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: De Boer *et al.*, "Decarbonizing Steel" (16 September 2024).

Green H_2, electrolysis, and CCUS could reduce steelmaking CO_2 emissions by over 85% if implemented at scale

	1	2	3
	100% Green Hydrogen (H2) DRI-EAF	**Iron Ore Electrolysis**	**Carbon Capture, Utilization, and Storage (CCUS)**
Description	• **Green hydrogen** replaces **natural gas** as an iron ore reductant in DRI shaft; the rest of the process remains the same • Generates **water as a byproduct** instead of CO_2	• **Two different processes** are possible: **Molten oxide electrolysis:** High current runs through mixture of iron ore and liquid electrolyte to split ore into pure molten iron **Electrowinning-EAF:** Iron from iron ore is dissolved in acid. Iron-rich solution is then electrified to form pure solid iron	• **CCUS equipment** can be added to **existing steel-producing infrastructure** to **capture** emitted CO_2 • Captured CO_2 is then **sequestered underground** or **reused**
Real-time sector initiatives	HYBRIT/Stegra 100% fossil fuel-free DRI-EAF production with green H_2 used for DRI	Electra Electrowinning to produce high-purity iron plates ready for EAF input (no DRI or MOE step)	ArcelorMittal Carbalyst® captures carbon from a blast furnace and reuses it as bio-ethanol. However, technology not proven at scale
Applicability to conventional routes	**Applicable to existing DRI-EAF route**, with minor retrofitting	**Full overhaul** of BF-BOF equipment required; **replacement** of DRI shaft in DRI-EAF	**Retrofitting** of capture technology is possible on **conventional BF-BOF and DRI-EAF**
Decarbonization potential (vs. BF-BOF)	**~90%**	**~97%**	**~90%** (Hypothetical best-case scenario)
Estimated production cost (excl. CapEx)	**<$800 per tonne of steel**	**~$215 per tonne of iron + cost of 'stranded' iron ore**	**~$380 – 400 per tonne**

Sources: Columbia Center on Global Energy Policy (2021); IEA, Iron and Steel Technology Roadmap (2020); McKinsey (2020); Mining Technology (2023); Tata Steel; Primetals Technologies; Edie, ArcelorMittal accused of net-zero greenwashing (2023).
Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: De Boer *et al*., "Decarbonizing Steel" (16 September 2024).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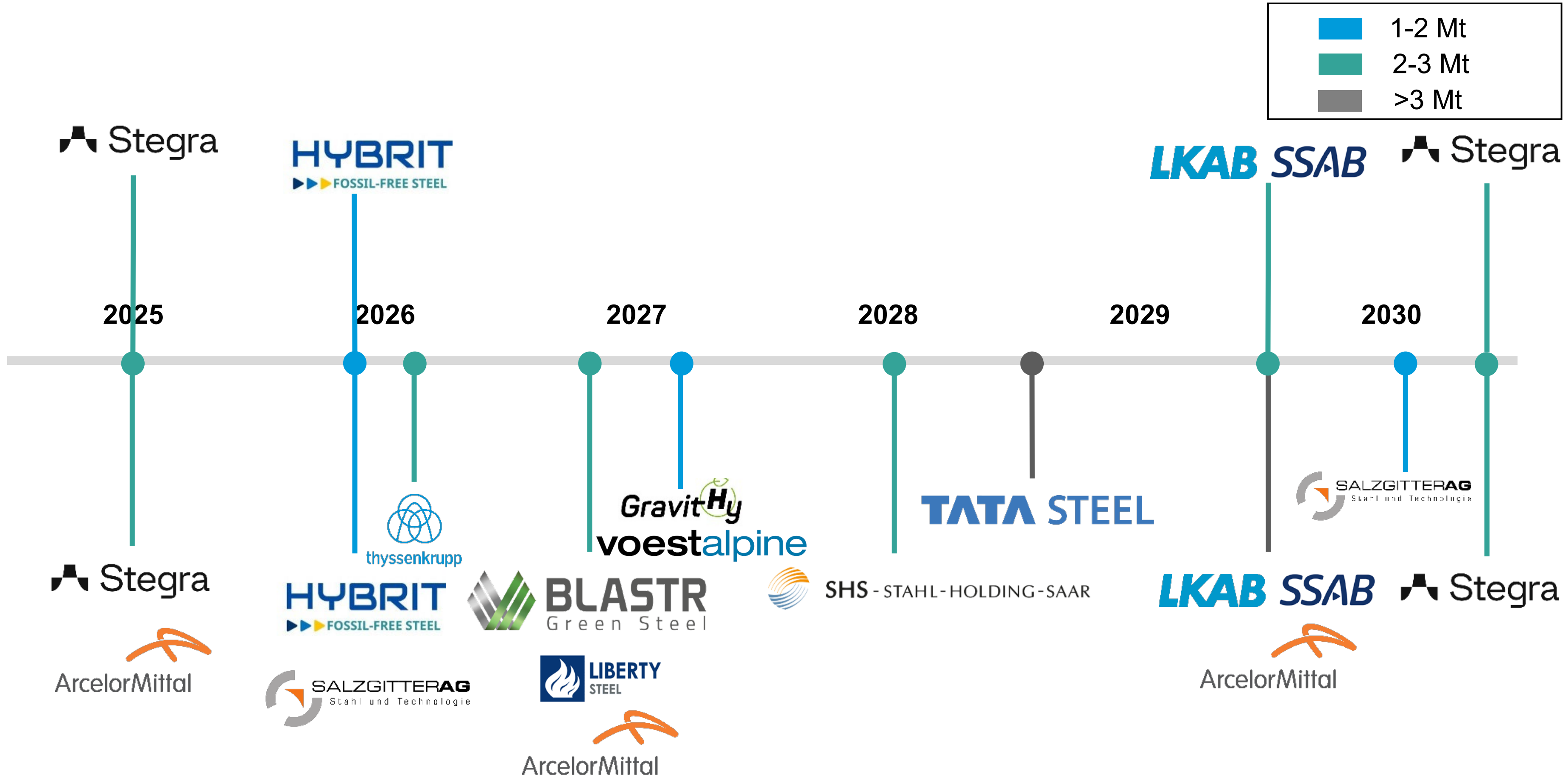
~40 Mt of green steel project announced in Europe by 2023, implying 2-2.4 Mt green H_2 demand

As of 2023, ~40 Mt of green steel projects announced in Europe alone

Four green steel plants announced as of 2021

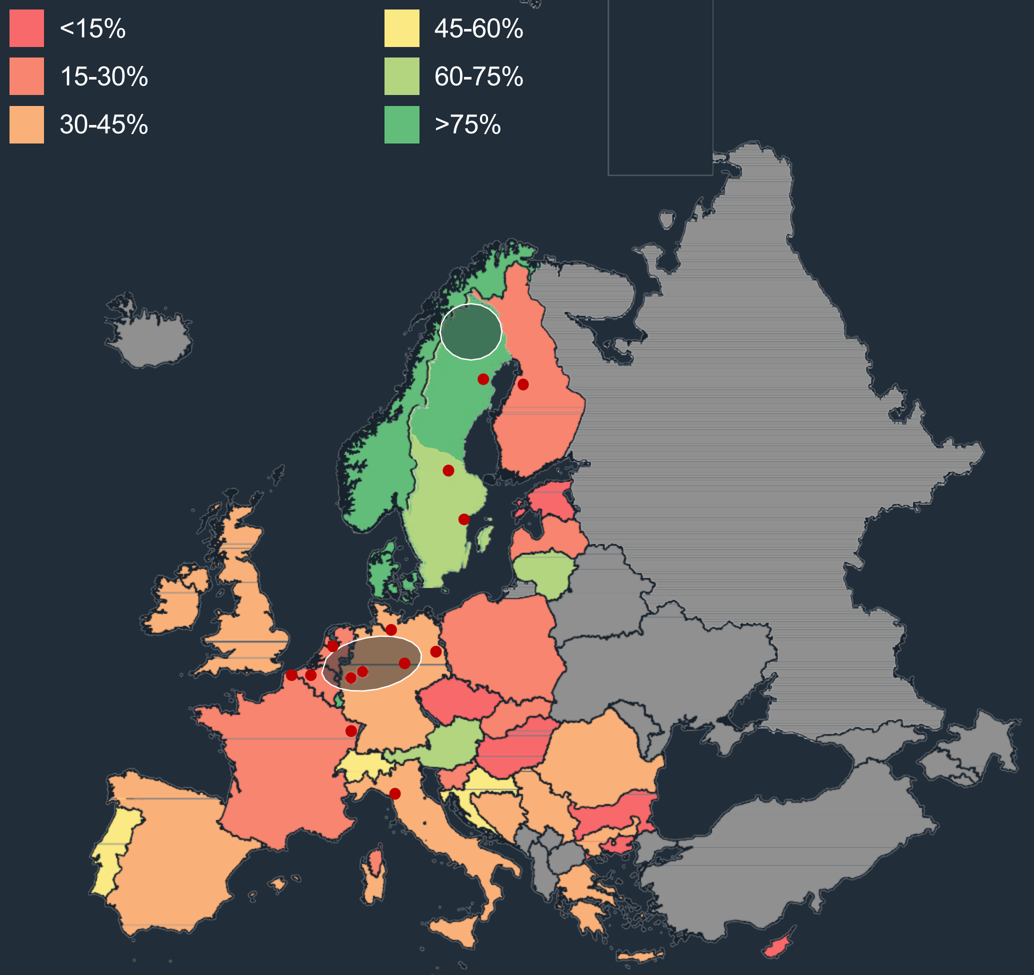
As of 2023, ~40 Mt green steel announced in Europe by 2030



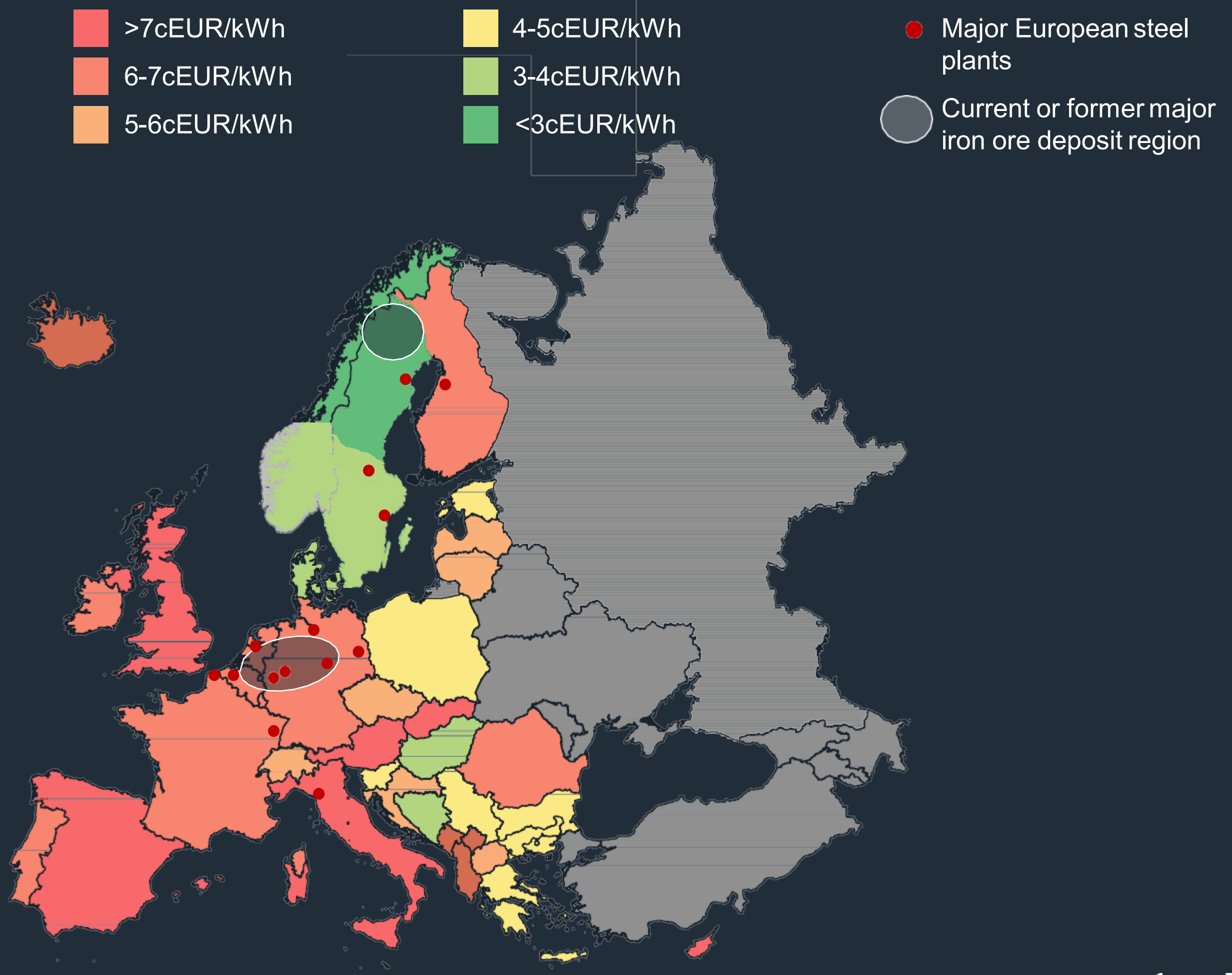
Source: Columbia Business School, H2 Green Steel (2024)
Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and Gernot Wagner (12 December 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Northern Sweden has unique advantages from low-cost renewable electricity and iron ore deposits

Renewable share in electricity production in Europe
2019



Industrial electricity prices in Europe
2019

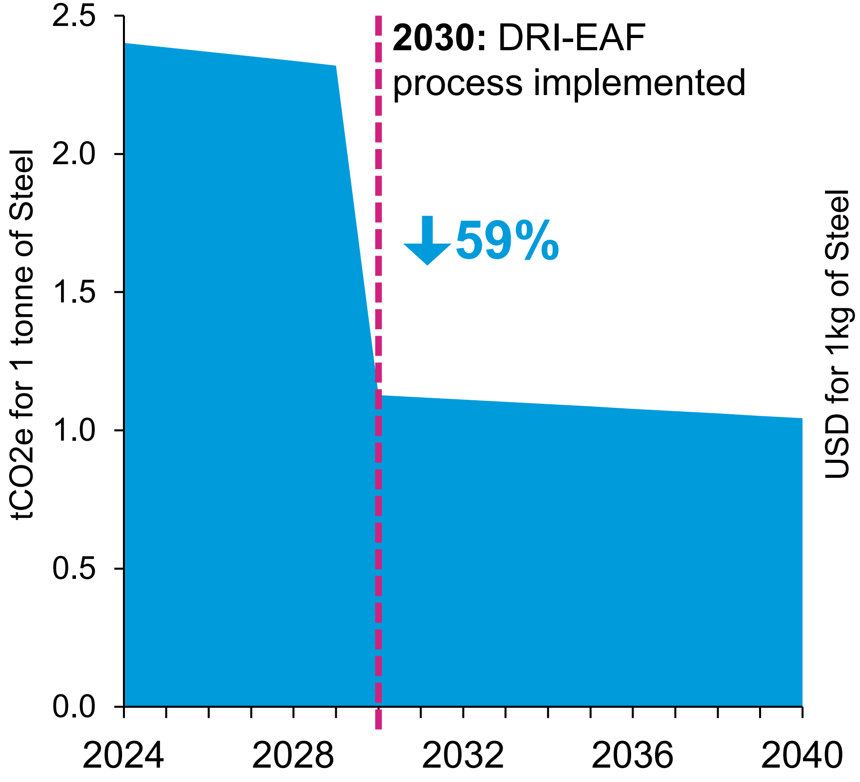


Source: International Energy Agency (IEA); Eurostat; ProMine

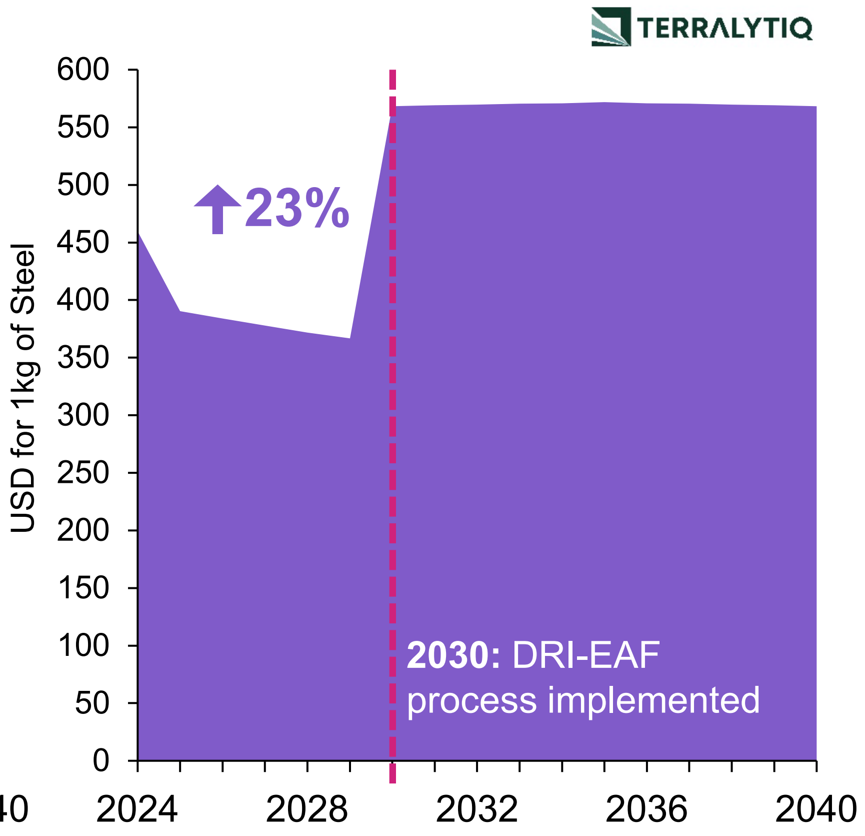
H2greensteel

1 Green H_2 DRI-EAF process uses green electricity will halve carbon intensity but increases production costs by 23%

Reduction in Carbon Footprint



Increase in Production Costs



Observations:

- **Replacing the BF-BOF process with the green hydrogen DRI-EAF process** with green electricity will cut steel production's carbon intensity by **59%**
- This transition i**ncreases production costs by 23%**, driven by required investment costs for implementing the electric arc furnace (EAF)
- **Capital investment of $210 million** is required, with the largest impact stemming from hydrogen adoption and grid decarbonization at the Iron Furnace stage

Source: Terralytiq (2024).
Credit: Theo Moers, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: De Boer *et al.*, "Decarbonizing Steel" (26 March 2025).

The Advanced Manufacturing Production Credit could provide as much as a 60% subsidy for domestic solar production, if the full value chain is on-shored

Impact of IRA on domestic solar value chain

Polysilicon →

Production Credit:
$3.00 / kg

Credit per Watt dc:
$0.02 / W

% of US-produced module price[1]:
6%

Wafer →

Production Credit:
$12.00 / sq m

Credit per Watt dc:
$0.07 / W

% of US-produced module price:
21%

Cell →

Production Credit:
$0.04 / W

% of US-produced module price:
12%

Module

Production Credit:
$0.07 / W

% of US-produced module price:
21%

1) Based on First Solar "average selling price" per module, as per company earnings calls and annual reports

Source: DOE, H.R. 5376 Inflation Reduction Act of 2022, First Solar 2020 10K, Roland Berger

Climate Risks, Opportunities, and Geopolitics

28 May 2025

1. Climate risk is financial risk
2. Solar
3. Steel
4. Is the goal a high or a low price per tonne of CO_2?

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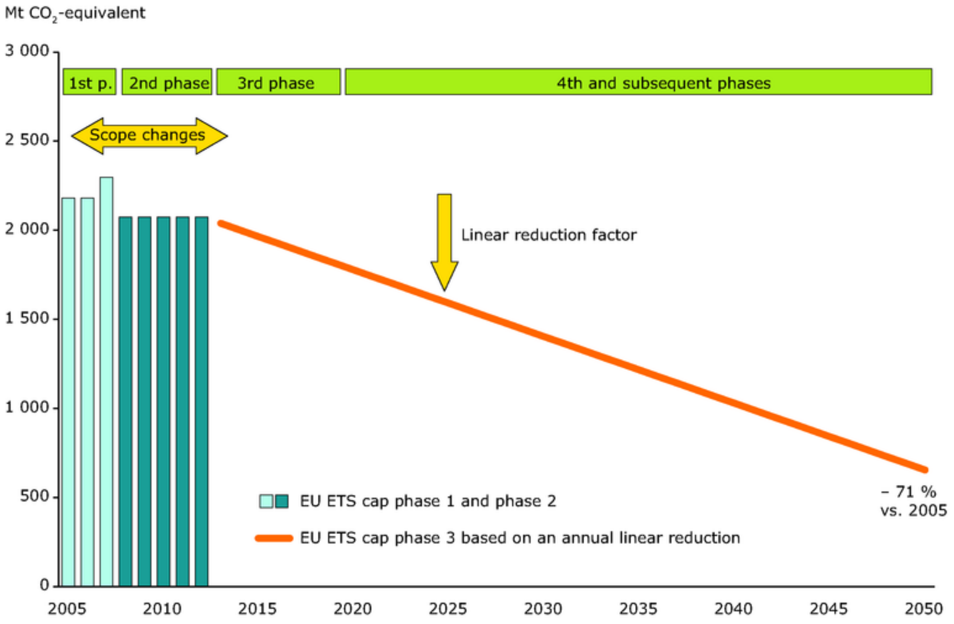
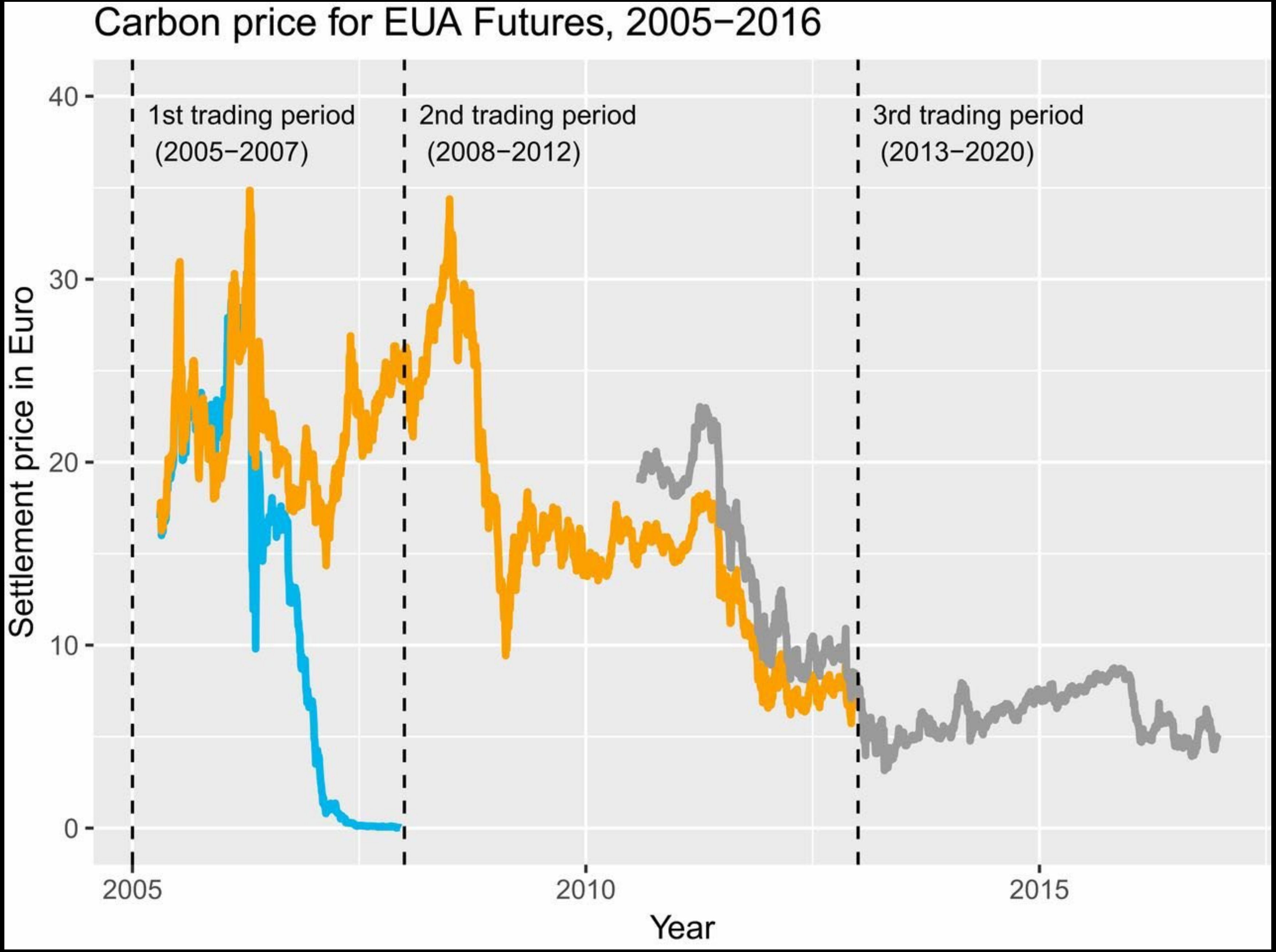
How to judge climate policies

Think "carbon price", explicit or implicit

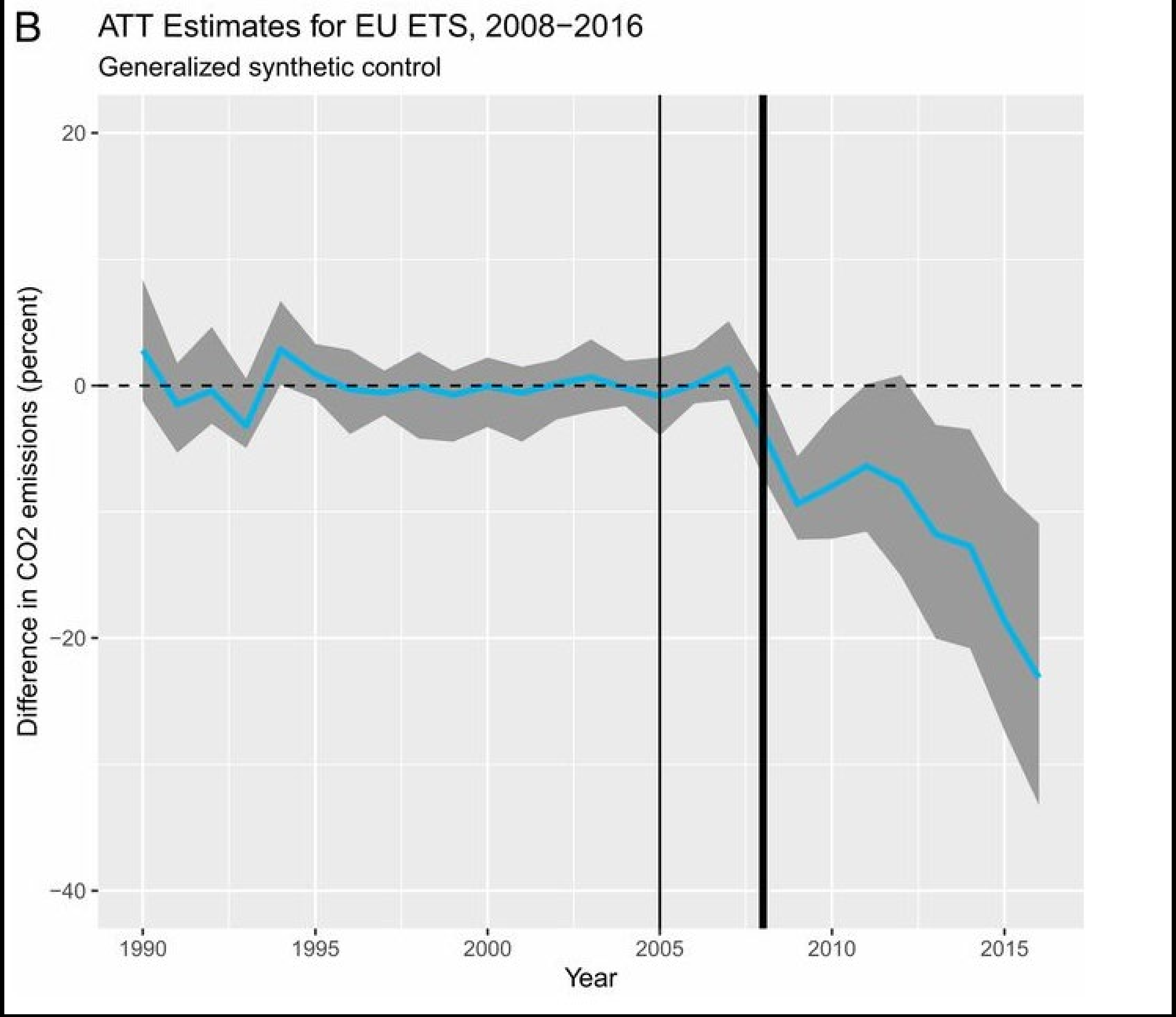
High price and/or(?!) Low cap



Keohane & Wagner "Judge a carbon market by its cap, not its prices" *FT* (2013) & Wagner "Taming Carbon" *Milken Review* (2023)

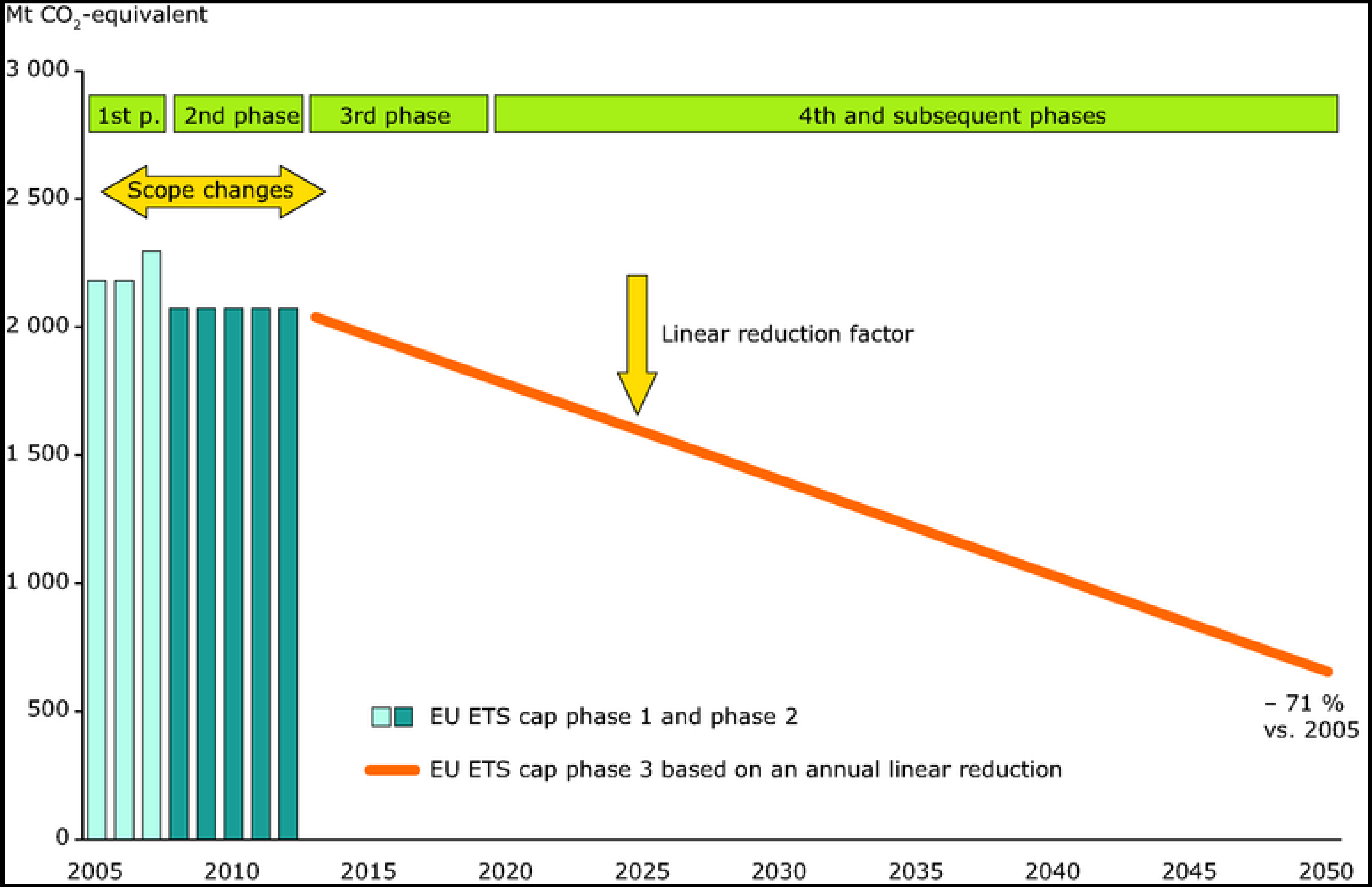


Source: Bayer & Aklin *PNAS* (2020)



Source: Bayer & Aklin *PNAS* (2020)

Source: tradingeconomics.com/commodity/carbon



Source: European Environment Agency

How to judge climate policies

Think “carbon price” or cap, explicit or implicit

- **Low cap = high carbon price**

But also:

- **High price → low CO_2 ‘demand’ → low price**

- **Race between price & cap on one hand, and clean-energy transition on the other**

Does ‘success’ mean a high carbon price *or* a low cap?

Keohane & Wagner “Judge a carbon market by its cap, not its prices” *FT* (2013) & Wagner “Taming Carbon” *Milken Review* (2023)

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