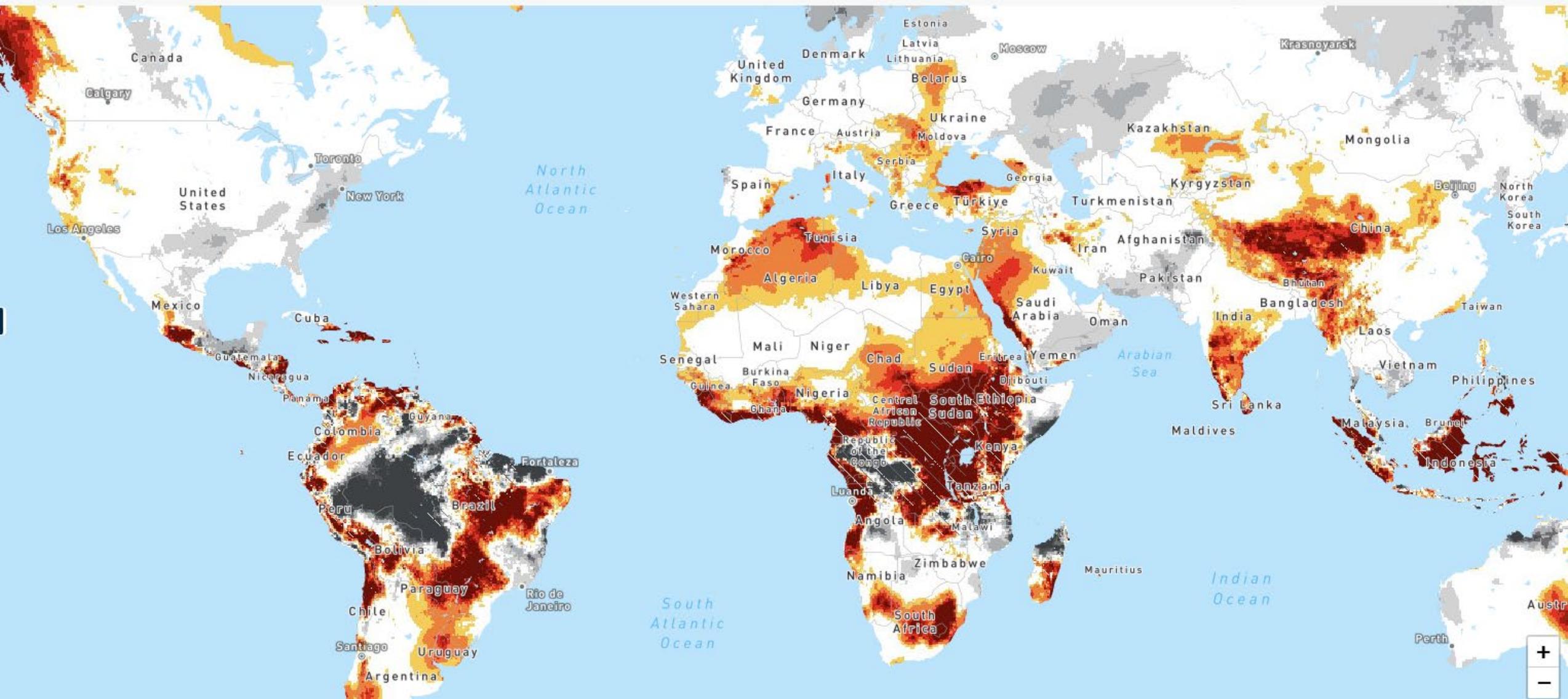


# Climate Shift Index [Learn more...](#)

for average temperatures, Jan 27, 2026

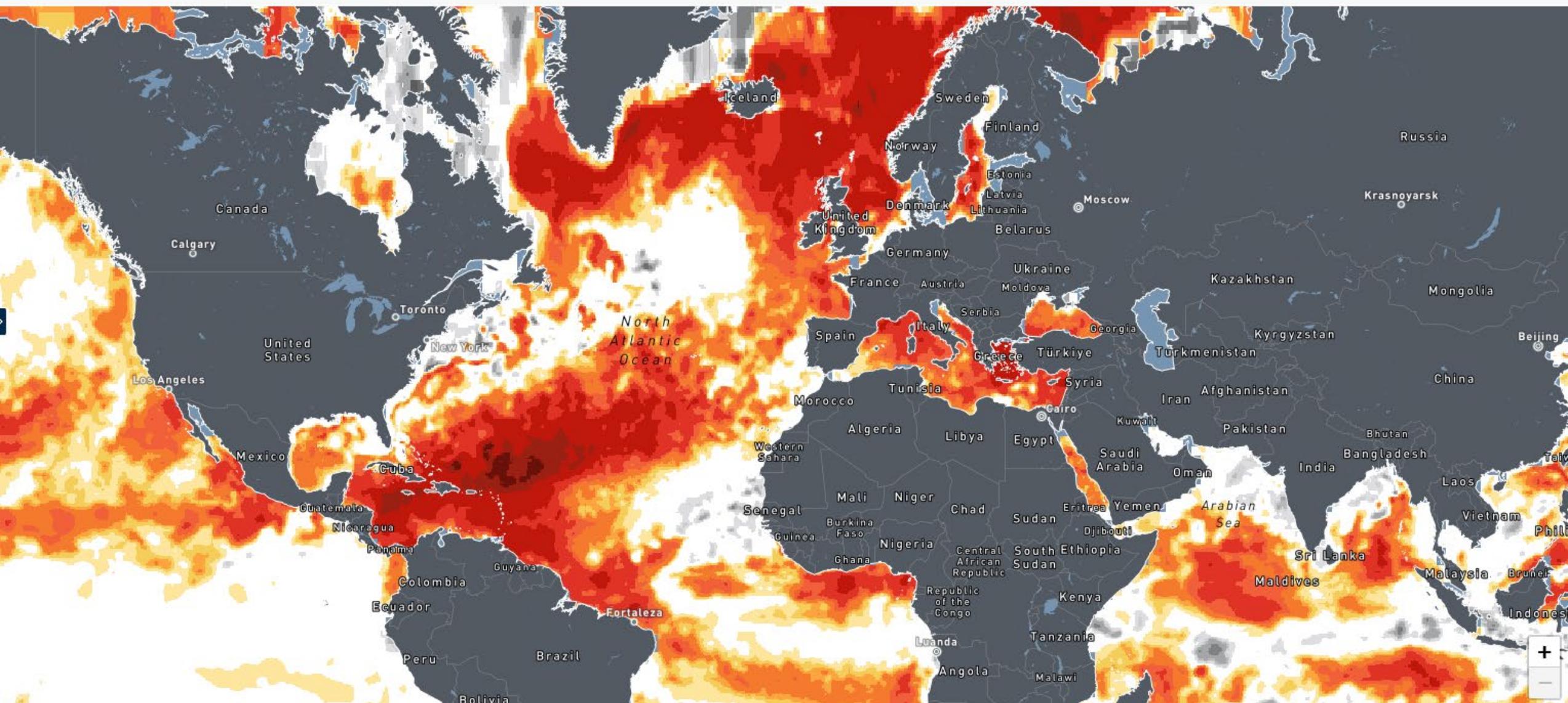
Change in likelihood due to climate change



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

for sea surface temperatures, Jan 22, 2026

Change in likelihood due to climate change



Source: [climatecentral.org/climate-shift-index](https://climatecentral.org/climate-shift-index)

**Not *if*, *when***



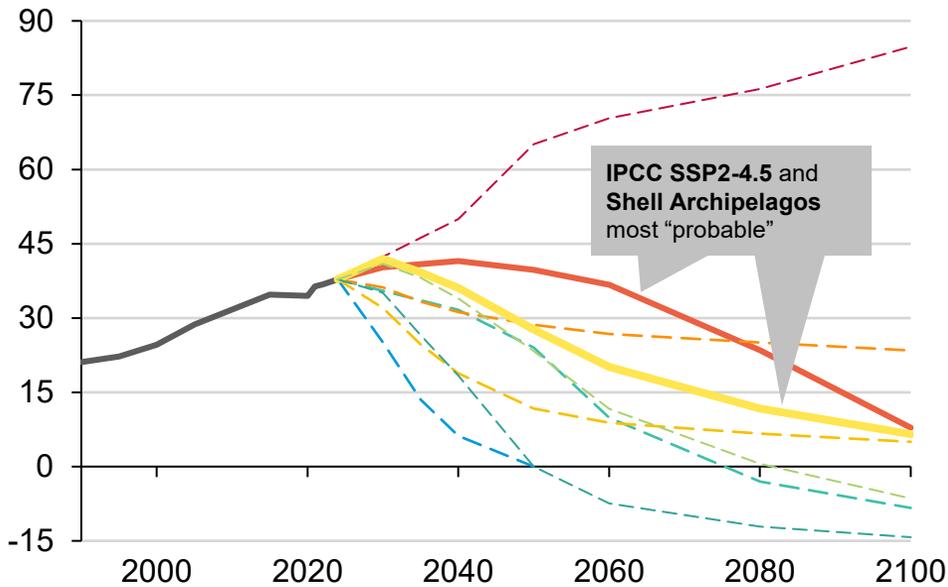
# Early decarbonization investments are key to keeping temperatures within livable range and saving trillions in climate costs

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

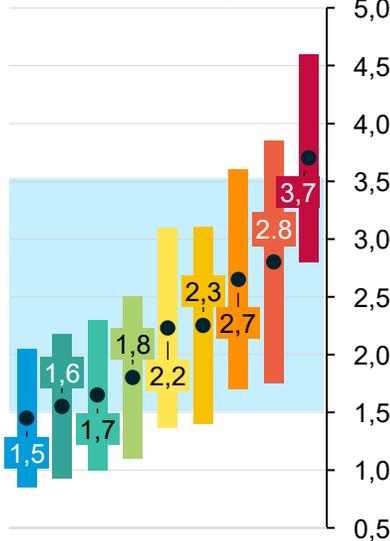
Low-carbon investment has risen rapidly recently, though ~2.5-3.5x gap remains

- 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

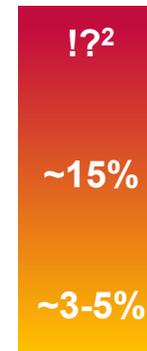
Annual global CO<sub>2</sub> emissions, GtCO<sub>2</sub>



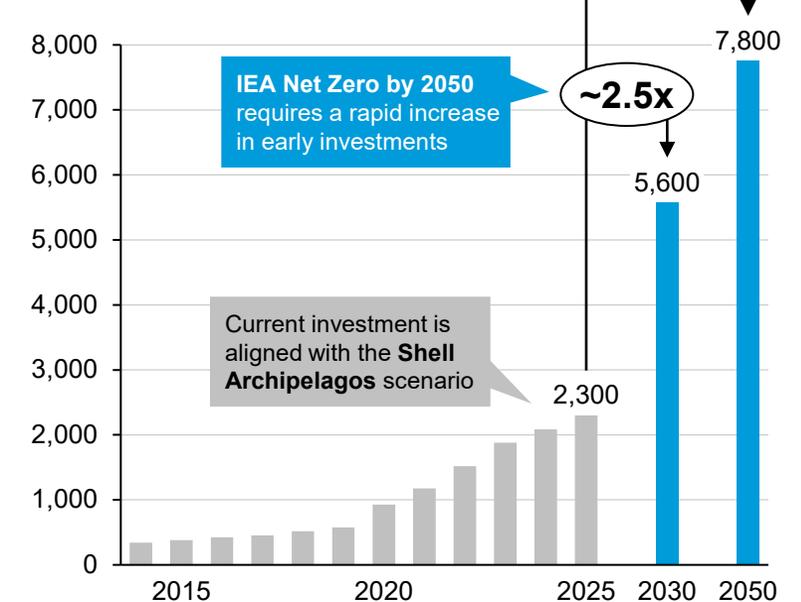
Projected average global warming<sup>1</sup>, °C



Climate impacts, % GDP loss



Annual investments, US\$B



<sup>1</sup> Global warming by 2100 above 1850-1900 average, with 66% “likely” ranges. “Probable” ranges are based on own best estimate of current trends.

<sup>2</sup> 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).

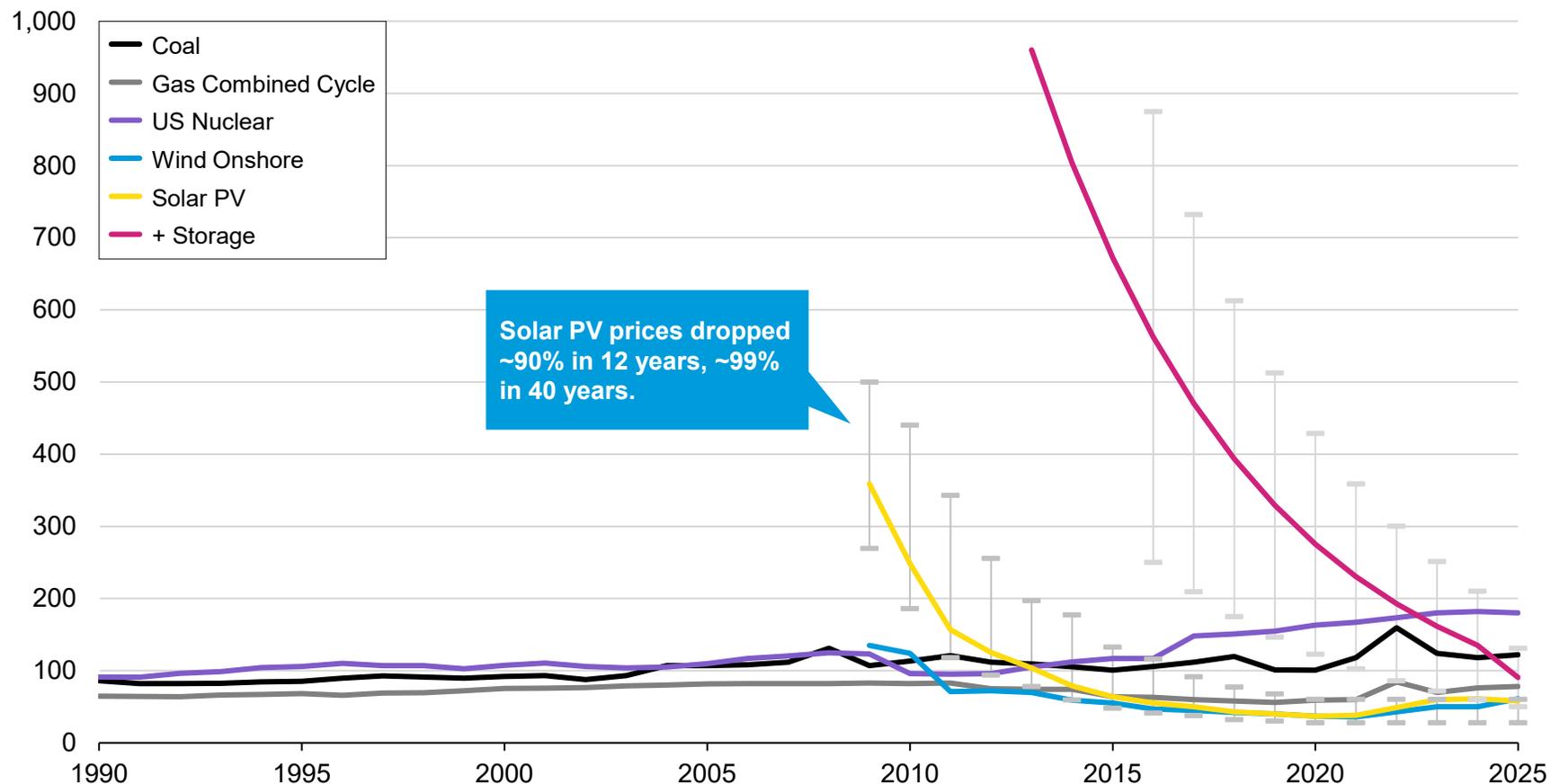
Credit: Anika Behrndt, Zacharia Thurston, Isabel Hoyos, Hyaee Ryung Kim, and Gernot Wagner. Share with attribution: Kim et al., “Probable Climates” (27 January 2026).



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

# 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

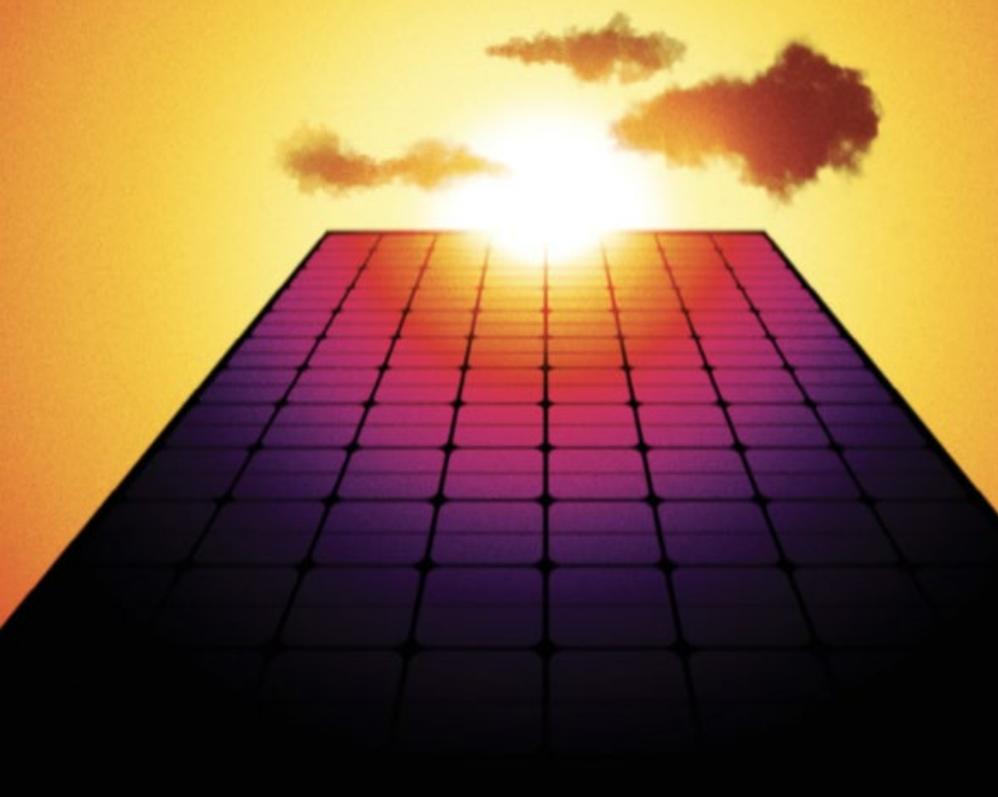
- **Solar photovoltaic (PV) prices dropped by ~80% in the past decade**, wind by ~70%, and lithium-ion battery costs by ~90%.
  - PV price drop primarily driven by **improvements in module efficiency and economies of scale.**
  - **Onshore wind** remained the cheapest for the longest, **now beaten by 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” \(14 August 2025\).](#)

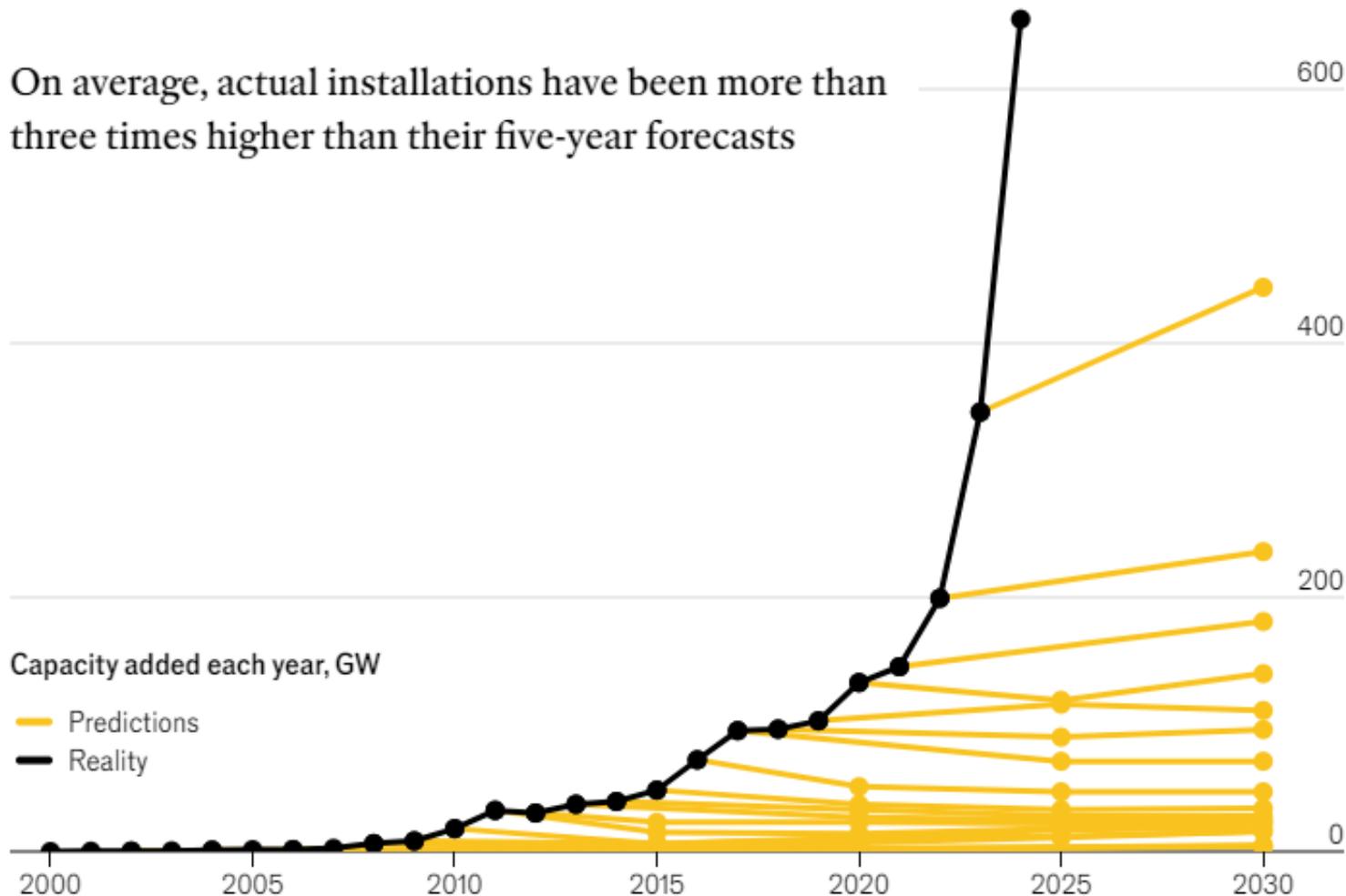
## DAWN OF THE SOLAR AGE

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

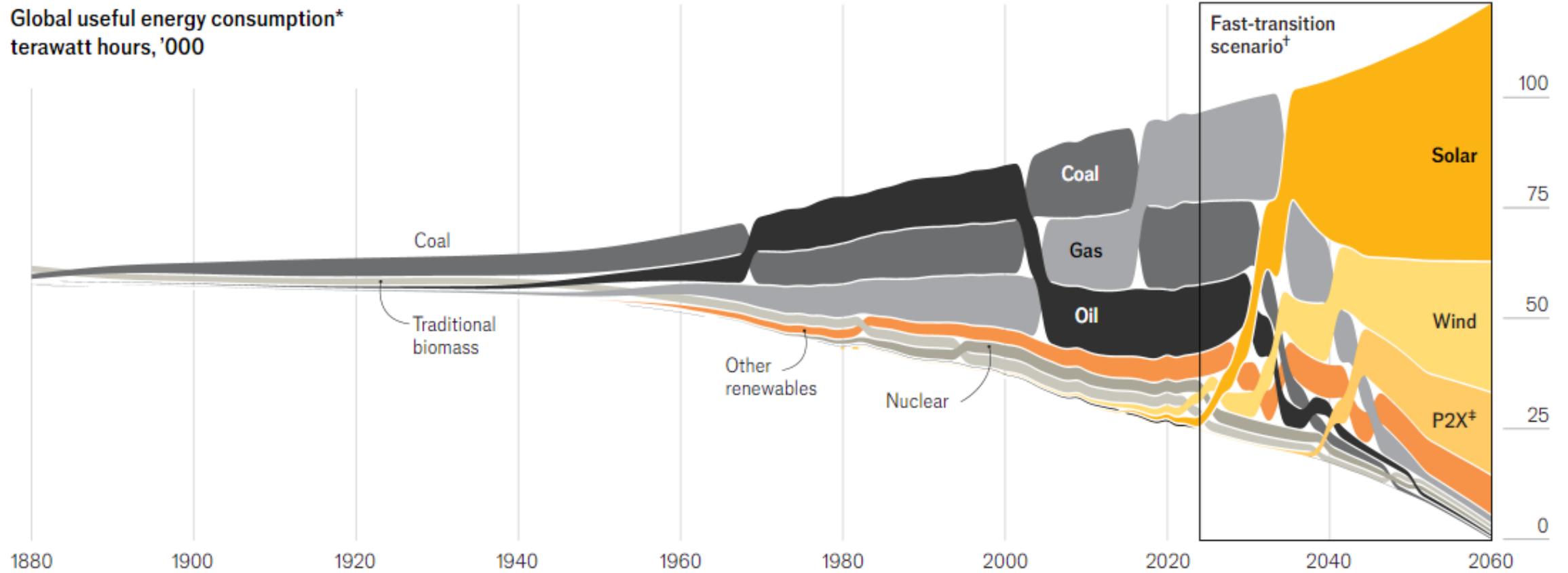


Installations for 2024 are an estimate from BloombergNEF for direct current solar capacity

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)

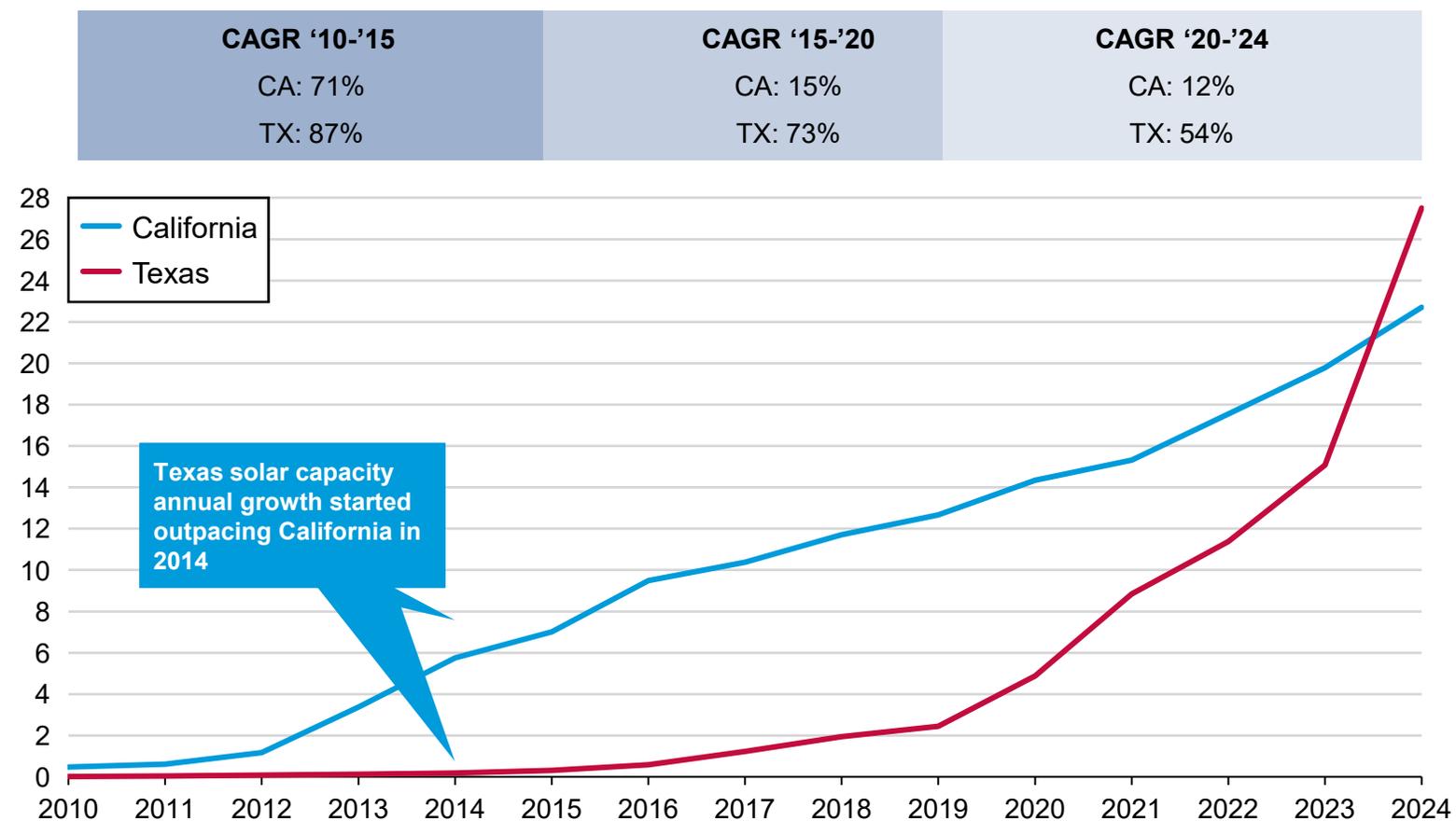
# One Big Beautiful Bill Act phases out incentives for solar & wind, biggest impacts on EV adoption and US manufacturing

Technology	IRA Incentives (2022-2025) vs OBBBA Policy Changes (2025 onward)	Industry Outlook <sup>2</sup> in the U.S. with OBBBA
Solar & Wind	 <ul style="list-style-type: none"> <li>• 48E and 45Y credits available until 2033</li> <li>• Phased out after 2027<sup>1</sup>; sourcing rules tightened (FEOC)</li> </ul>	 <ul style="list-style-type: none"> <li>• Continued growth trend through 2030, significant slow-down by 2035<sup>3</sup></li> <li>• Overall higher electricity end-user prices</li> </ul>
Green Hydrogen	 <ul style="list-style-type: none"> <li>• 45V credit available until 2033</li> <li>• Phased out by 2028</li> </ul>	 <ul style="list-style-type: none"> <li>• Deployment undermined by weak demand, loss of incentives, and sourcing restrictions</li> </ul>
Electric Vehicles	 <ul style="list-style-type: none"> <li>• 30D, 25E, and 45W credits for EVs; 30C for charging infrastructure</li> <li>• Phased out by 2026 (30D/25E/45W by Oct 2025, 30C by Jul 2026)</li> </ul>	 <ul style="list-style-type: none"> <li>• Consumer adoption hit by loss of credits and policy uncertainty</li> </ul>
Manufacturing	 <ul style="list-style-type: none"> <li>• 45X and 28C credits support clean tech supply chain</li> <li>• 45X phased out after 2027 (wind) and 2028 (solar/storage); 48C compromised by sourcing rules</li> </ul>	 <ul style="list-style-type: none"> <li>• Clean energy manufacturing hit by loss of credits and supply chain constraints</li> <li>• Subsidy loss threatens existing investments</li> </ul>
Carbon Capture	 <ul style="list-style-type: none"> <li>• 45Q credit available until 2033</li> <li>• Preserved; EOR provisions enhanced</li> </ul>	 <ul style="list-style-type: none"> <li>• Growth in oil and gas CCS, challenged by foreign entity restrictions</li> </ul>
Energy Storage	 <ul style="list-style-type: none"> <li>• 48E credit available until 2033</li> <li>• Preserved in full</li> </ul>	 <ul style="list-style-type: none"> <li>• Preserved credits support growth, challenged by foreign entity restrictions</li> </ul>
Biofuels	 <ul style="list-style-type: none"> <li>• 45Z credit available until 2027</li> <li>• Extended to 2029; feedstock sourcing rules tightened; capped SAF</li> </ul>	 <ul style="list-style-type: none"> <li>• Slow adoption, challenged by foreign entity restrictions</li> </ul>
Geothermal	 <ul style="list-style-type: none"> <li>• 48E and 45Y credits available until 2033</li> <li>• Preserved in full</li> </ul>	 <ul style="list-style-type: none"> <li>• Moderate growth from low baseline</li> <li>• R&amp;D support for superhot geothermal</li> </ul>
Nuclear	 <ul style="list-style-type: none"> <li>• ITC/PTC for new, 45U for existing plants available until 2033</li> <li>• Preserved in full; fuel sourcing rules apply after 2028</li> </ul>	 <ul style="list-style-type: none"> <li>• Challenges remain for large ~1GW reactors</li> <li>• More optimistic outlook for SMRs, XMRs</li> </ul>
Oil, Gas	 <ul style="list-style-type: none"> <li>• No support</li> <li>• Gains tax breaks, public land access, and regulatory rollbacks</li> </ul>	 <ul style="list-style-type: none"> <li>• Stable or rising share, as renewables face disadvantage</li> </ul>

(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).

# 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

The logo consists of the letters 'PS' in a stylized, serif font.

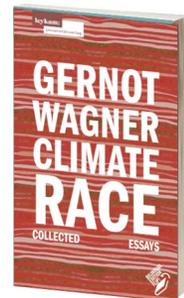
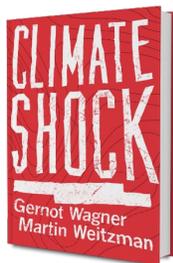
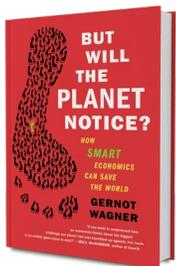
Longer Reads

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.



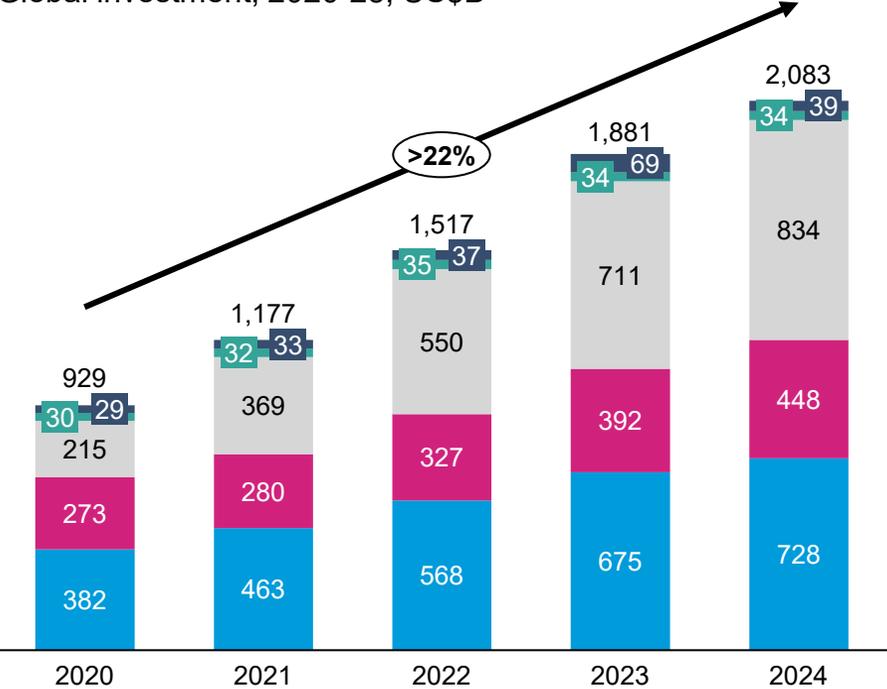
**Gernot Wagner**  
gwagner@columbia.edu  
gwagner.com

# Global clean energy investment grew at >22% CAGR from 2020 to 2024, with renewables deployment in Asia leading the charge

**Electrification overtakes renewables as global clean energy investments accelerate**

Renewables    Electrification    Other emerging technologies  
 Grid & storage    Nuclear

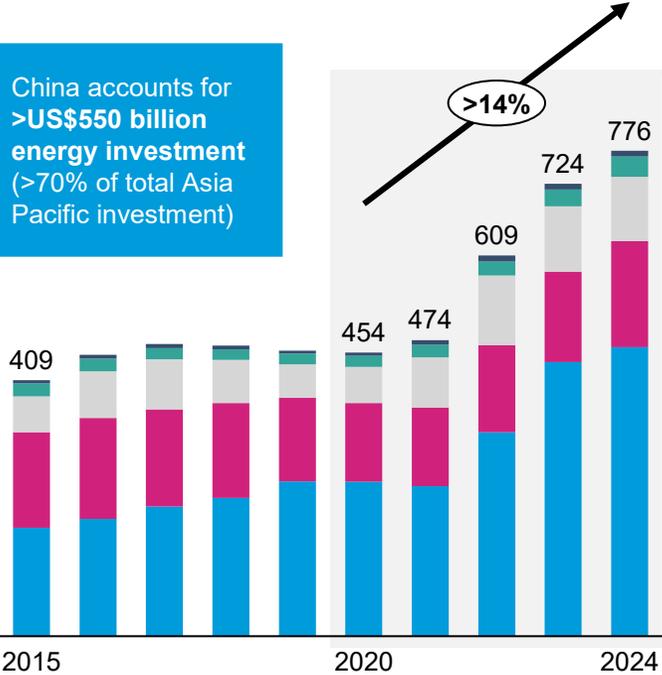
Global investment, 2020-25, US\$B



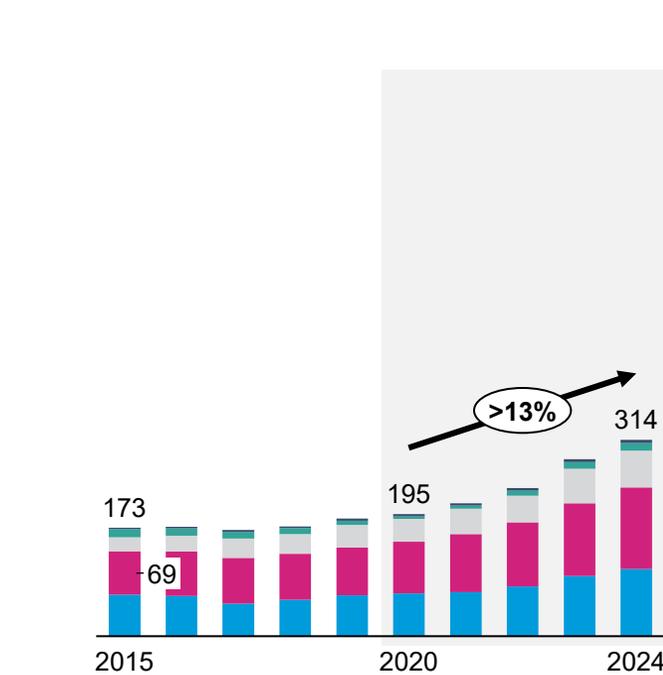
**Asia heavily and rapidly investing in renewables (>10% CAGR, 2015-25); North America investing steadily, focused on renewables, grids, and storage**

Renewables    Grid & storage    Electrification    Nuclear    Other emerging technologies

Asia investment, 2015-25, US\$B



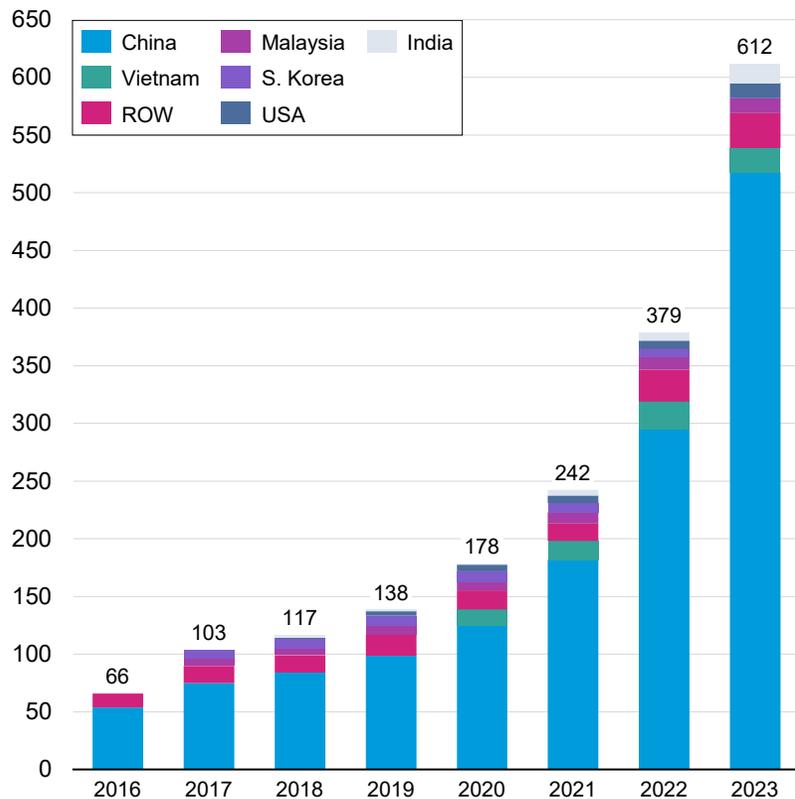
North America investment, 2015-25, US\$B



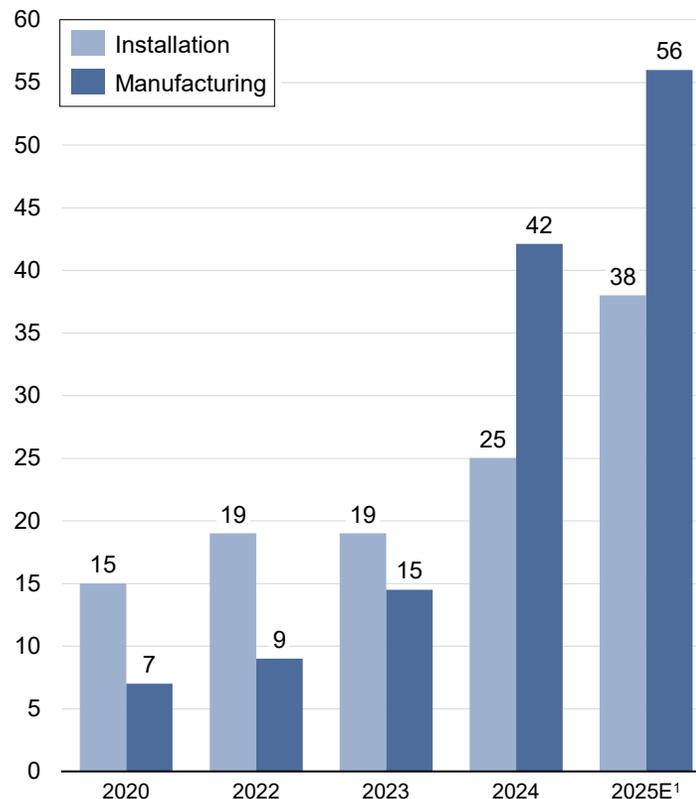
Note: BloombergNEF technology categories were consolidated into five broader sectors: (1) renewables, (2) grid & storage, (3) electrification of end-use sectors (transport, heat), (4) other emerging solutions (clean industry, hydrogen, CCUS), and (5) nuclear. Grouping was based on primary function within the energy-transition value chain. The regional investment breakdown is based on IEA data, with electrification extrapolated from the "Other end uses" section. The share of electrification (92%) of other end uses and emerging technologies is based on the Bloomberg NEF proxy. Sources: IEA, [World Energy Investment 2025](#) (2025); BloombergNEF, [Energy Transition Investment Trends](#) (2025). Credit: Zacharia Thurston, Isabel Hoyos, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Kim et al., "Probable Climates" (9 September 2025).

# Bolstered by the IRA, the United States' solar PV manufacturing capacity grew ~50% annually since 2020

Global solar PV panel production (GW)



US PV manufacturing & installation capacity (GW)



## Observations

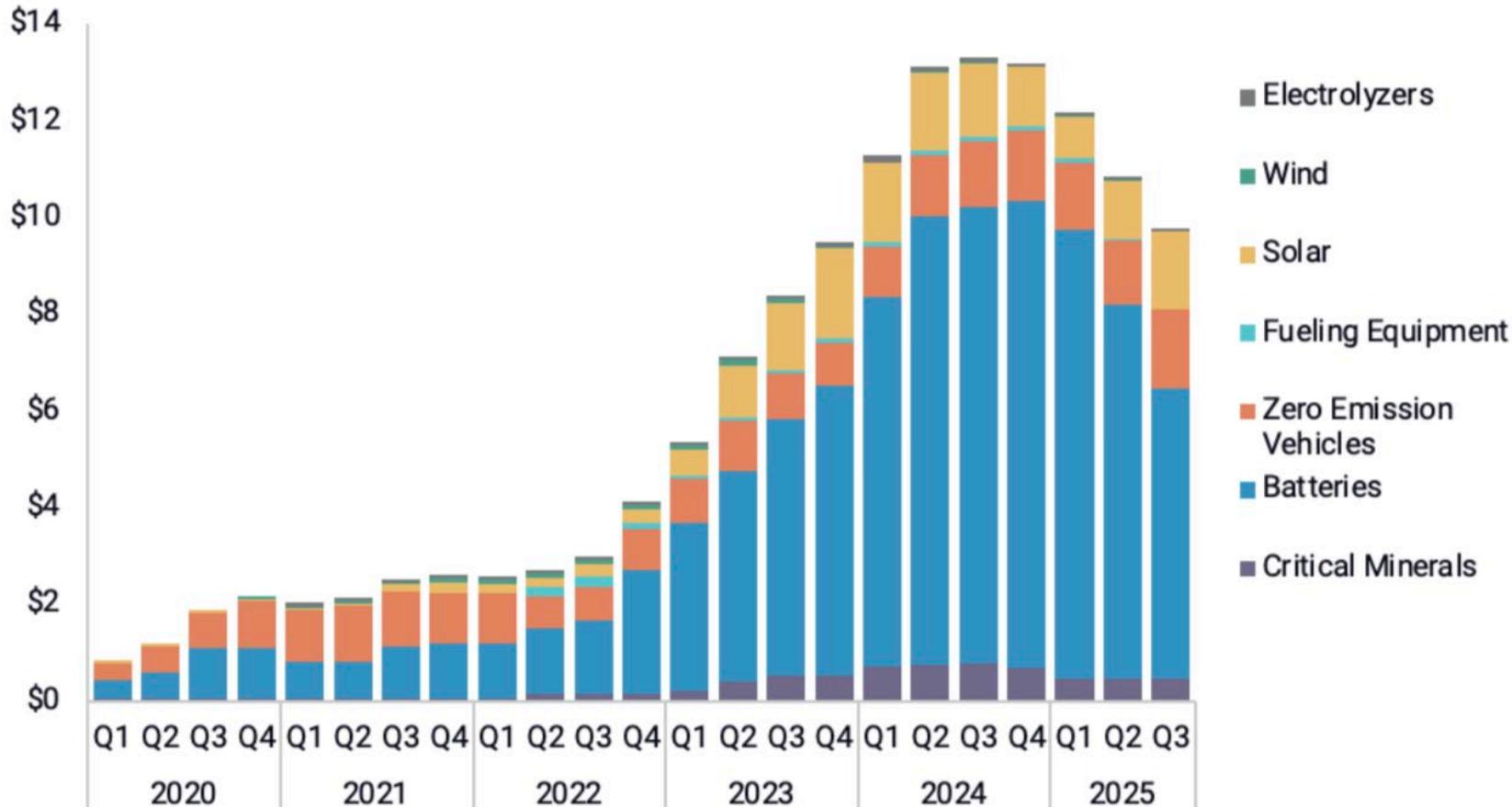
- **China still dominates the global market:**
  - As of 2025, China's manufacturing capacity exceeds 1,200 GW/year which accounts for **80-90% of the global supply** across key stages (polysilicon, wafers, cells, modules).
  - China has aggressively increased **solar module production** along with producing in countries in APAC region such as Vietnam, Malaysia, and S. Korea.
  - China benefits from **economies of scale, vertically integrated supply chains and low production costs**.
- **US manufacturing capacity is growing rapidly:**
  - US module manufacturing capacity grew from ~7 GW in 2020 to over 56 GW as of May 2025.
  - The **IRA was a game changer** unlocking billions in public and private investment.
- **China's market faces headwinds** as overcapacity and price crashes in 2024/2025 are pressuring Chinese manufacturers.
- While the **US cannot match China's scale**, the country strategically built high-quality, incentivized and politically supported capacity from 2022 to 2025, starting to **position itself as a strategic alternative supplier in the West to mitigate geopolitical and supply chain risks**.

(1) US solar PV manufacturing & installation capacity as of May 2025 (SEIA, 2025)  
 Source: SEIA, [Solar Industry Research Data](#) (2025); IEA PVPS, [Trends in Photovoltaic Applications 2024](#) (2024); IRENA, [Stats Tool](#) (2025).  
 Credit: Yosafat Partogi, Heonjae Lee, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. [Share with attribution: Kim et al., "Scaling Solar" \(14 August 2025\).](#)

# Rapid drop in US manufacturing investments, driven by batteries

## Manufacturing investment by technology

Billion 2024 USD



Source: Rhodium Group/MIT-CEEPR Clean Investment Monitor

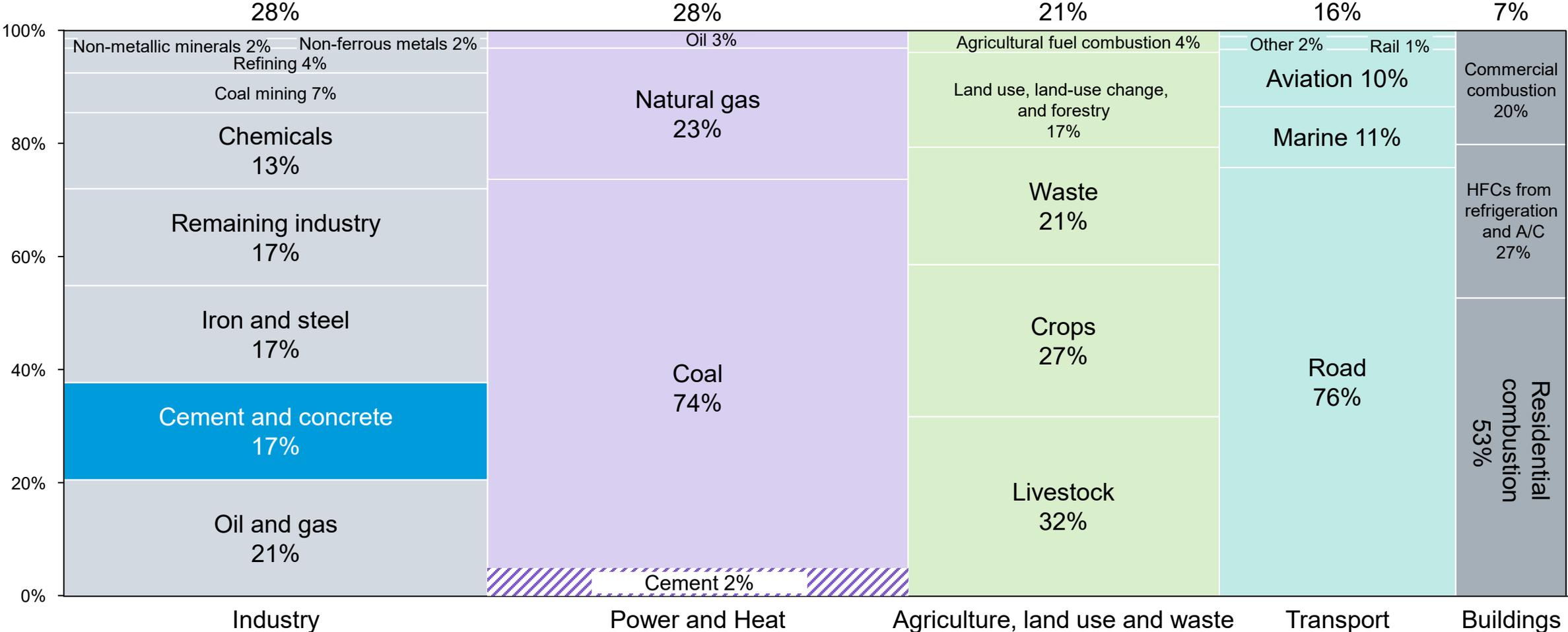
12 January 2026

# Decarbonizing Cement

Hyae Ryung Kim, Jessica Cong, Nicolas Herrera, Isabel Hoyos,  
Ariela Farchi, Shailesh Mishra, Hoshi Ogawa, Hassan Riaz,  
Sho Tatsuno, Adele Teh, Soraya van Beek, and Gernot Wagner

# Cement and concrete sector CO<sub>2</sub> emissions account for ~5 to 8% of global total, mostly Scope 1

CO<sub>2</sub>e emissions in 2024\*: ~50 billion tonnes



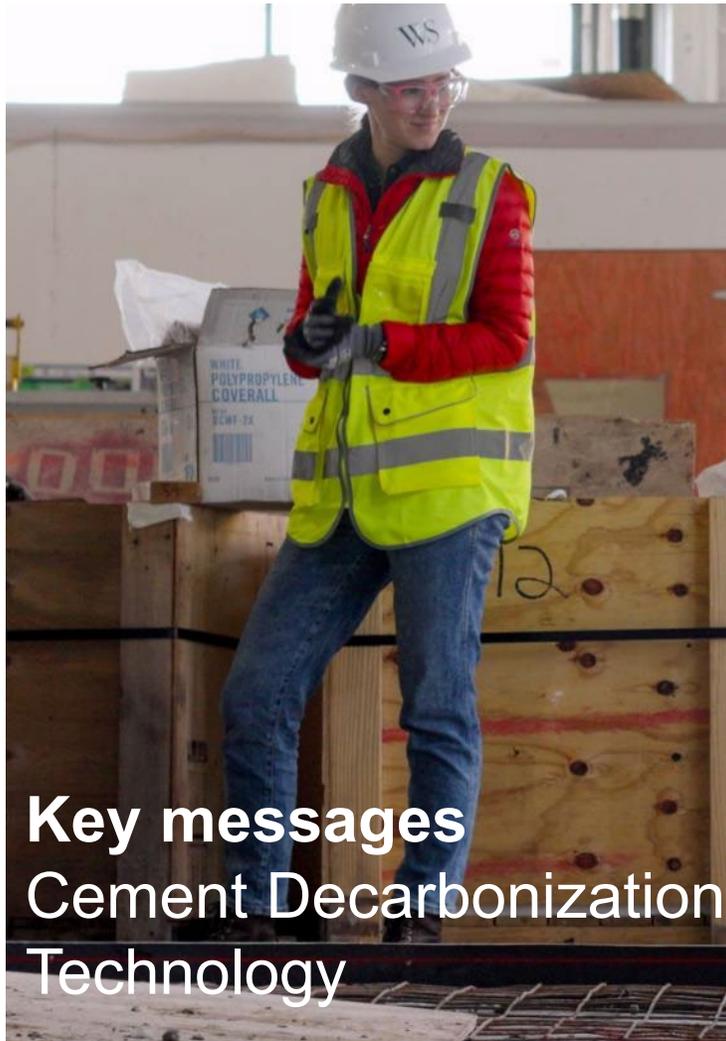
\* 2024 emissions based on projections.

Sources: Scope 1 emissions from [Rhodium Group ClimateDeck](#) (September 2024); Scope 2 cement emissions estimated assuming indirect emissions from electricity are 10% of total emissions, [IEA](#) (2023).

Credit: Theo Moers, Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Kim *et al.*, "Decarbonizing Cement" (12 January 2026).



# Cement Decarbonization Technologies



## Key messages Cement Decarbonization Technology

Cement production remains **emission-intensive**, demanding innovation beyond incremental efficiency.

- **~90%** of emissions stem from **limestone calcination and the high heat needed for clinker production**.
- Decarbonization requires **combining process efficiency, fuel switching, and clinker substitution with emerging production routes**.

Deployable solutions can abate up to **~45% of emissions through efficiency, fuel, and clinker substitution**.

- **Energy efficiency** measures are retrofit-ready, delivering **~10 to 15%** abatement at negative to low cost (~50 \$/tCO<sub>2</sub>).
- **Alternative fuels** such as bioenergy and waste-derived fuels can **replace up to 50% of fossil fuels**.
- **Substituting clinker with SCMs and LC3** can reduce emissions by **~15 to 40%**, with modest process adjustments and cost savings.

Emerging technologies can unlock deep decarbonization but require new infrastructure and capital investments.

- **Thermal batteries** can replace fossil fuel kilns with electric heat at up to 40% abatement, contingent on low-cost clean electricity.
- **Alternative feedstocks and electrochemical production** can eliminate up to **90% of process CO<sub>2</sub>** but face **high CapEx and power intensity**.

**Carbon capture, utilization, and storage (CCUS) serves as a transitional and complementary pathway** to retrofit existing assets and reach near-zero emissions.

- **Carbon capture can mitigate up to 60% of emissions**, serving existing clinker plants and bioenergy systems.
- **High costs (\$60 to \$190/tCO<sub>2</sub>) and limited storage access** constrain adoption, yet CCUS is critical for legacy plants and hard-to-abate clinker lines.

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

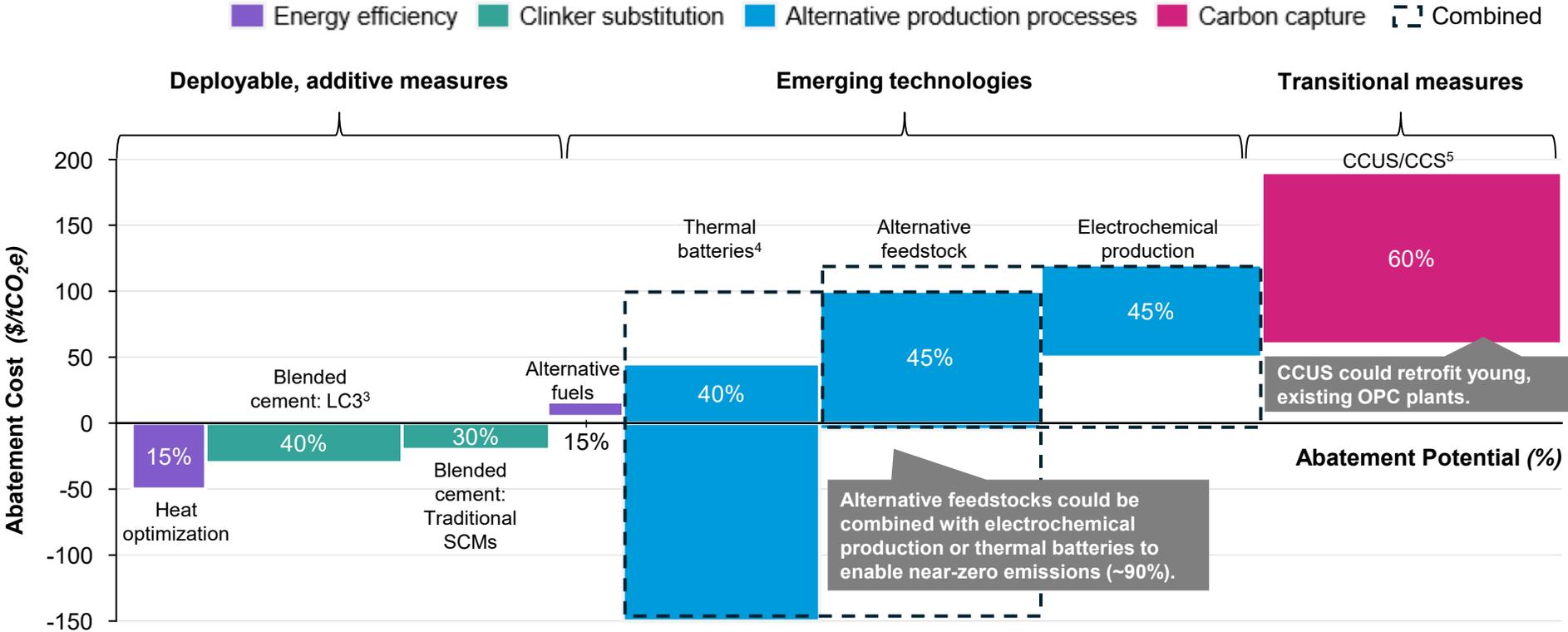
○ R&D/Lab stage    ◐ Pilot plant stage    ◑ Ready for commercialization    ● Mature and commercialized

	Energy efficiency		Clinker substitution		Alternative production technologies			Carbon capture
	Heat optimization	Alternative fuels	Blended cement: Traditional SCMs	Blended cement: LC3	Thermal batteries <sup>6</sup>	Alternative feedstock	Electrochemical production	CCUS/CCS
Description	Levers include: <ul style="list-style-type: none"> <li>Vertical mills or high-pressure grinding rolls</li> <li>Kiln preheaters and improved insulation</li> <li>Waste heat use</li> <li>Digital process control</li> </ul>	<ul style="list-style-type: none"> <li>Using biomass and waste as heat sources lowers thermal emissions.                             <ul style="list-style-type: none"> <li>Current kiln heat supply is fossil-fuel dominated (70% coal, 25% oil and gas).</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>Supplementary cementitious materials (SCMs)</li> <li>Can partially replace clinker in blended cements.</li> <li>SCMs include fly ash, steel furnace slag, and natural pozzolans.</li> </ul>	<ul style="list-style-type: none"> <li>Limestone calcined clay cement (LC3)</li> <li>Blended cement that uses limestone and calcined clay</li> <li>Can replace more clinker than traditional SCMs.</li> </ul>	<ul style="list-style-type: none"> <li>High-temperature thermal batteries, powered by cheap electricity, can replace fossil-fueled rotary kilns.</li> <li>Can be connected to the grid or powered by off-grid renewables.</li> </ul>	<ul style="list-style-type: none"> <li>Non-carbonate rocks can replace limestone as feedstock.</li> <li>Can avoid the chemical emissions of limestone calcination.</li> </ul>	<ul style="list-style-type: none"> <li>Electrochemistry can break down limestone instead of high-heat kilns.</li> <li>Combined with non-carbonate feedstock, it can fully decarbonize cement production.</li> </ul>	<ul style="list-style-type: none"> <li>Retrofitting plants with carbon capture can remove CO<sub>2</sub> released during clinker production.</li> <li>Captured CO<sub>2</sub> can serve as feedstock, fuels, or building materials.</li> </ul>
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	●	●	●	● <sup>5</sup>	◐	◑	◐	◐
Abatement potential <sup>1</sup>	10-15%	~15%	~15-30%	~30-40%	~30-40% <sup>2</sup>	~30-45%	~30-45% <sup>2</sup>	~61% <sup>4</sup>
Abatement cost, \$/tCO <sub>2</sub> e	-50-0	10-15	-20-0	-30-0	-150-45 <sup>3</sup>	-5-100 <sup>3</sup>	50-120 <sup>3</sup>	60 –190 <sup>3</sup>

1) Unconstrained theoretical abatement potential for a given tonne of cement produced for each approach in isolation. 2) Assumes clean energy source. 3) Abatement cost of emerging technologies is based on estimates and has high uncertainty. 4) Reflects the approximate emissions gap after other measures, not a fixed technical limit. 5) Despite TRL9, market penetration remains minimal due to slow standards adoption, limited supply chain coordination, and conservative procurement practices. 6) Thermal 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: Nicolas Herrera, Soraya Van Beek, Isabel Hoyos, Hyae Ryoung Kim, and [Gernot Wagner](#). Share with attribution: Kim *et al.*, “[Decarbonizing Cement](#)” (12 January 2026).

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

Abatement cost<sup>1</sup> vs. abatement potential<sup>2</sup> for key decarbonization pathways

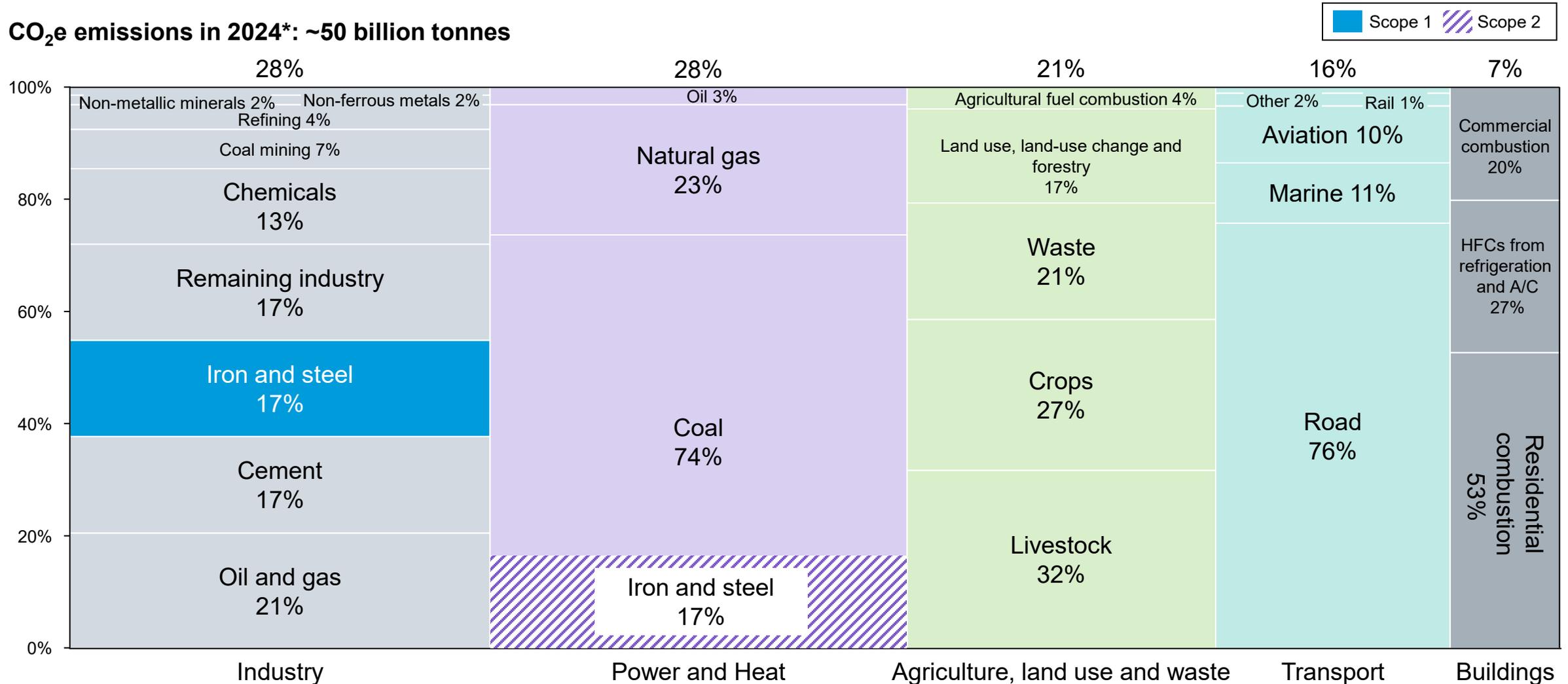


**Observations**

- 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" (12 January 2026).

# Steel sector Scopes 1 and 2 around 10% of global CO<sub>2</sub>e emissions



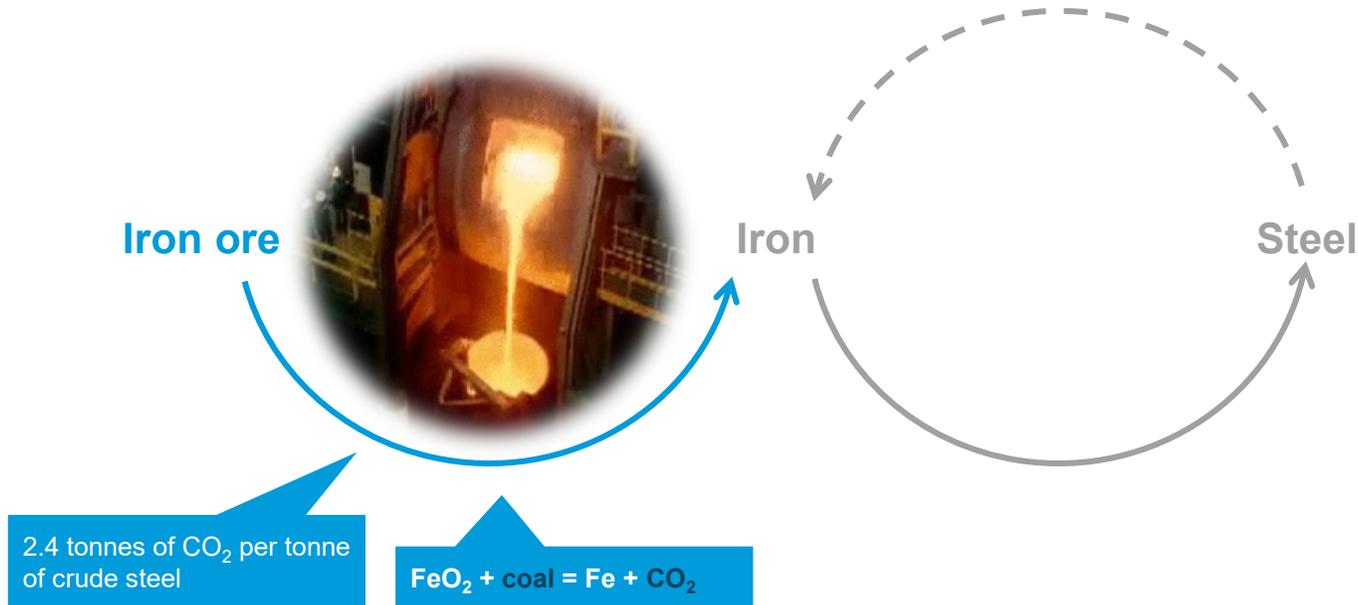
Sources: Scope 1 emissions from [Rhodium Group ClimateDeck](#) (September 2024); Scope 2 iron and steel estimate from [IEA](#) (2023). \* 2024 emissions based on projections.  
 Credit: Theo Moers, Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hyaee Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#):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

# 1 Of three main steelmaking methods, blast furnace-basic oxygen furnace (BF-BOF) is the cheapest, most popular, and most polluting

**BF-BOF ~73% of global steel production and ~80% of iron and steel CO<sub>2</sub> emissions**

## Observations

- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace

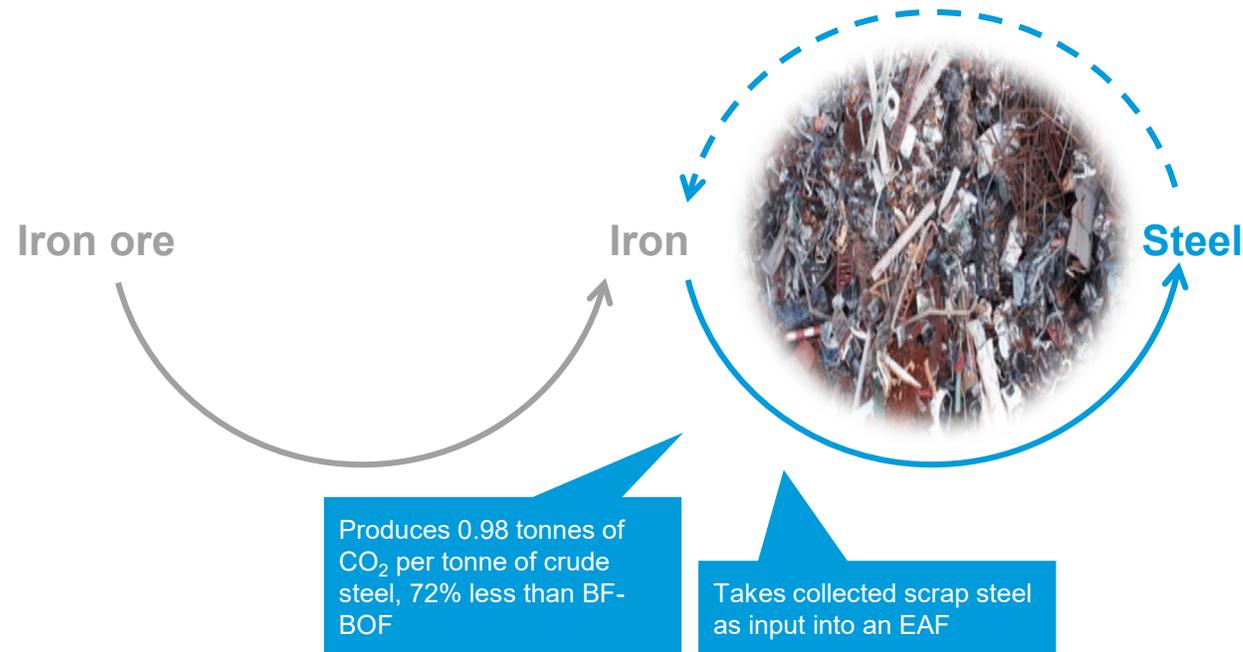


Sources: [World Steel Association](#); [IEEFA](#) (2022); IEA, [Iron and Steel Technology Roadmap](#) (2020); Steel Technology, [Basic Oxygen Furnace Steelmaking](#); Recycling Today, [Growth of EAF Steelmaking](#); Wildsight, [Do We Really Need Coal to Make Steel](#).

Credit: Mimi Khawsam-ang, Max de Boer, Grace Frascati, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): De Boer *et al.*, "[Decarbonizing Steel](#)" (6 May 2025).

## 2 Of the three main steelmaking methods, scrap electric arc furnace (EAF) is the cleanest, though limited by the scarcity of scrap material

More than 80% of steel recycled; scrap EAF accounts for ~22% of global steel production



### Observations

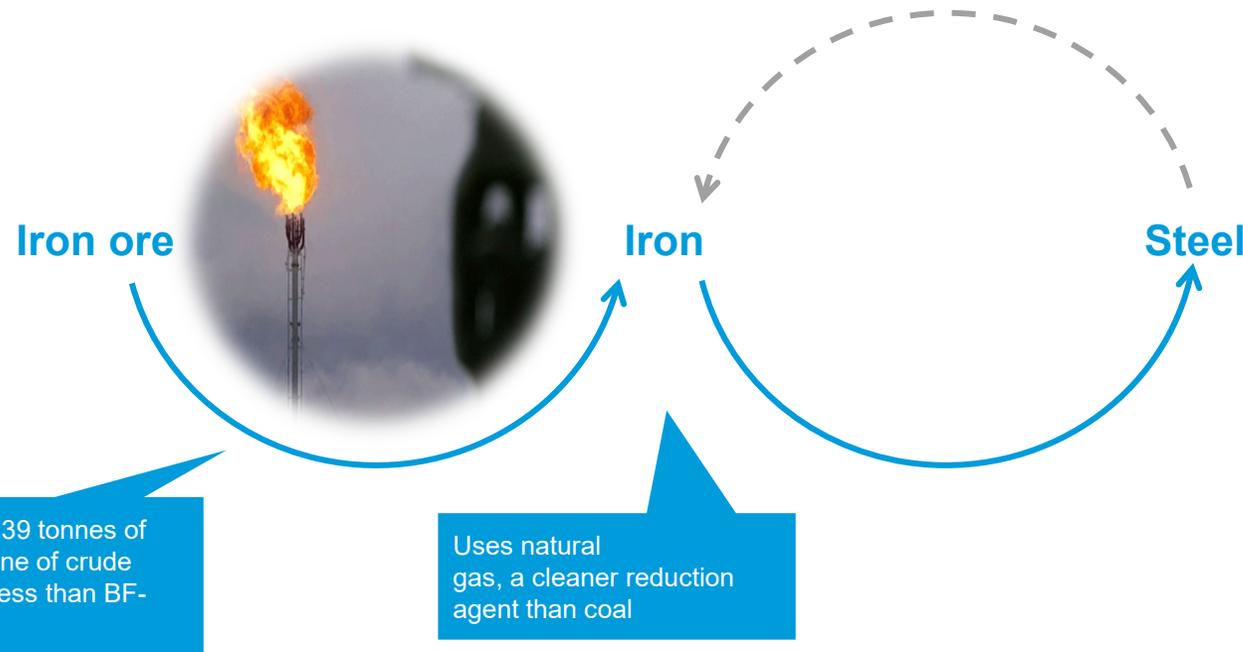
- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace
- **Scrap EAF:** Scrap metal is melted in an EAF using electrical energy

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 Of the three main steelmaking methods, natural gas-based direct reduced iron-electric arc furnace (NG DRI-EAF) is the most expensive and least used

NG DRI-EAF ~7% of global steel production and 4% of iron and steel CO<sub>2</sub> emissions



#### 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

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, Hassan Riaz, Hyaee Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): De Boer *et al.*, "Decarbonizing Steel" (16 September 2024).

# At present, crude steel is produced through three main methods that all emit CO<sub>2</sub>: BF-BOF, scrap EAF, and NG DRI-EAF

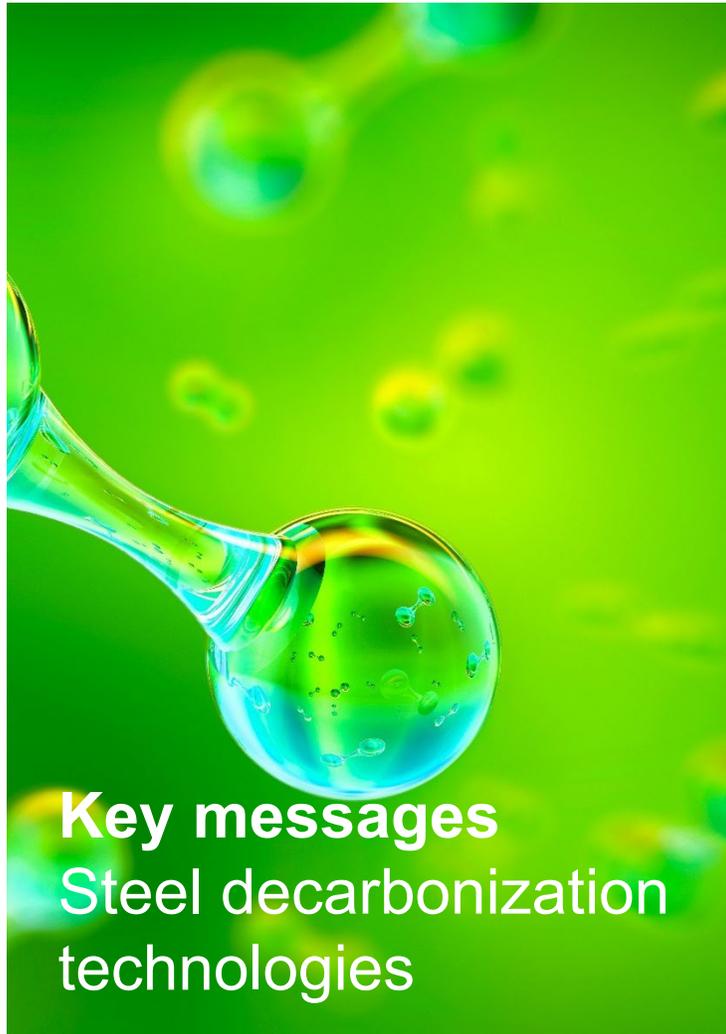
	1	2	3
	<b>Blast Furnace-Basic Oxygen Furnace (BF-BOF)</b>	<b>Scrap Electric Arc Furnace (Scrap EAF)</b>	<b>Natural Gas-Based Direct Reduced Iron – Electric Arc Furnace (NG DRI-EAF)</b>
Description	Iron ore, coke, and limestone produce pure iron in a blast furnace, which is turned into steel in an oxygen 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%
CO <sub>2</sub> 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).



# Steel Decarbonization Technologies



### Three main **deep decarbonization steelmaking technologies**:

- **Green hydrogen DRI-EAF**: Hydrogen produced using zero-carbon electricity is used as iron ore reductant instead of natural gas; second step uses an Electric Arc Furnace (EAF).
- **Iron ore electrolysis**: Use of electricity to split pure iron from iron ore. Two technologies:
  - > **Molten Oxide Electrolysis (MOE)**: A high current is run through a mixture of iron ore and a liquid electrolyte, which causes the iron ore to split into oxygen and molten iron.
  - > **Electrowinning-EAF (EF-EAF)**: Iron from iron ore is dissolved in an acid; the iron-rich solution is electrocuted to form pure solid iron, which is melted in an EAF.
- **Carbon Capture, Utilization and Storage (CCUS)**: BF-BOF or DRI-EAF retrofitted with point capture equipment. Captured carbon is then used or stored.

These technologies produce steel with **over 90% fewer CO<sub>2</sub> emissions** compared to conventional processes. However, **green hydrogen DRI-EAF** and **CCUS BF-BOF / DRI-EAF** come at a **green price premium**. **CCUS is also less viable for BF route**, given **difficulty of capturing all released carbon**. **Electrolysis** may be **cheaper** than conventional processes but **has not been tested at scale**.

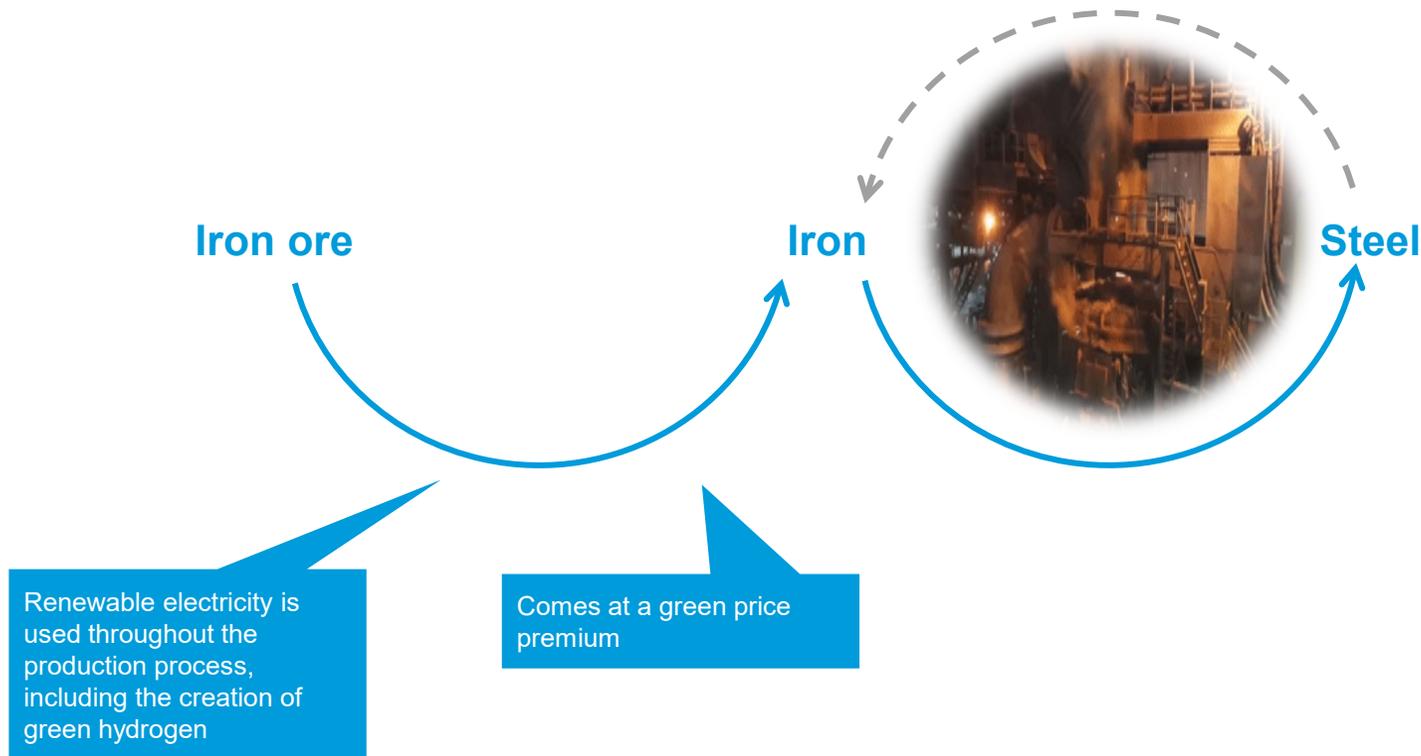
There are also some **emerging transitional steelmaking technologies** with **decarbonization potential of ~10-50%**:

- **Modifications to existing BF-BOF and DRI-EAF**: using biomass as input, switching to zero-carbon electricity, partial green hydrogen injections.
- **Different production process**: Smelting Reduction-BOF (SM-BOF).

**Transitional technologies** may be appropriate in **specific circumstances**, but despite lower overall decarbonization potential, they often still come with a **considerable green premium**.

# 1 Green H<sub>2</sub> 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<sub>2</sub> direct reduced iron-EAF has an average cited decarbonization potential of ~90%



## 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<sub>2</sub> DRI-EAF:** Green hydrogen replaces natural gas as an iron ore reductant; byproduct is water vs. CO<sub>2</sub>

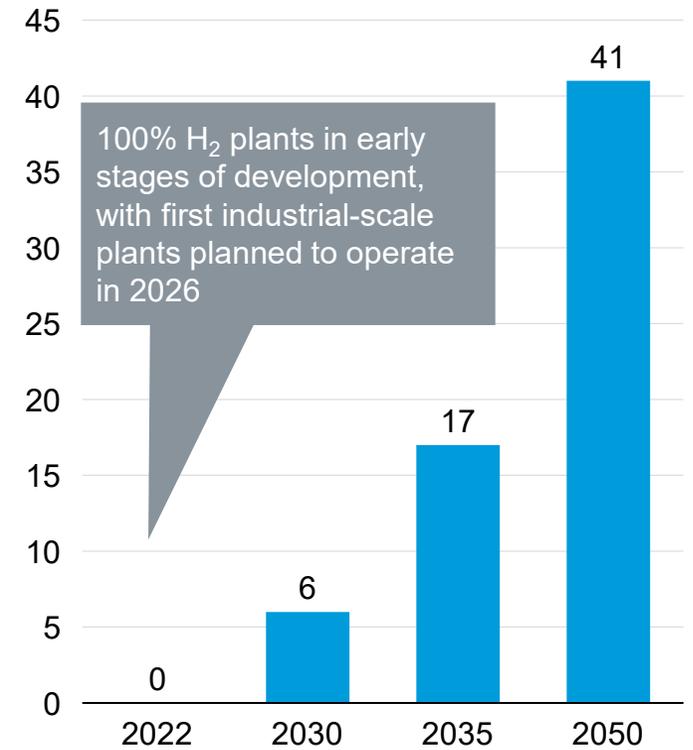
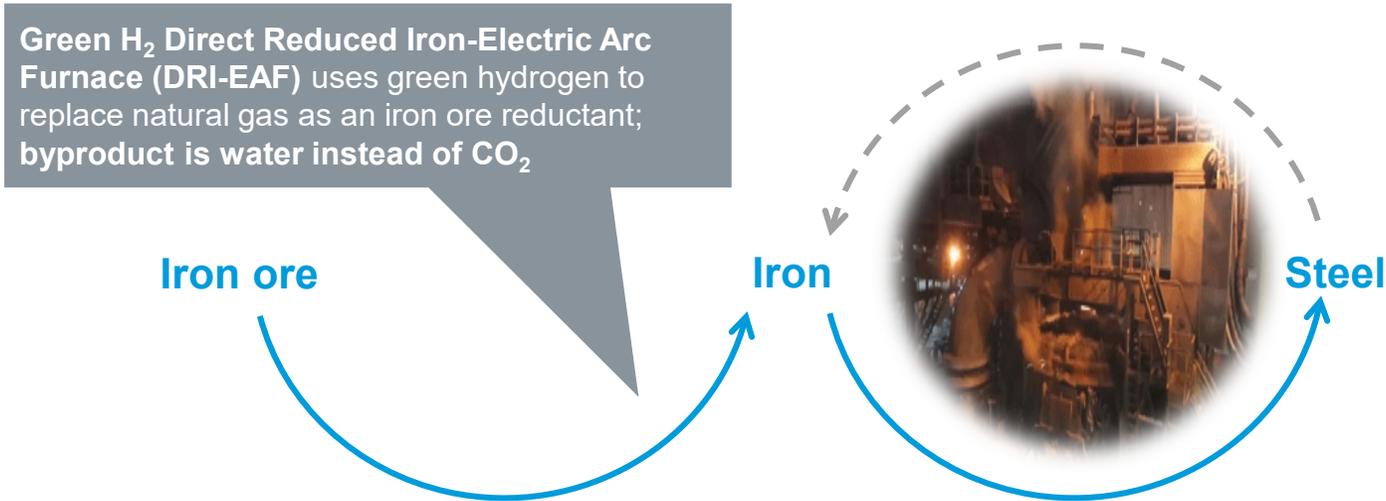
Sources: [World Steel Association](#); [IEEFA](#) (2022); IEA, [Iron and Steel Technology Roadmap](#) (2020); Steel Technology, [Basic Oxygen Furnace Steelmaking](#); Recycling Today, [Growth of EAF Steelmaking](#); Wildsight, [Do We Really Need Coal to Make Steel](#).

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 steel production possible key driver for green H<sub>2</sub> demand, with each tonne of Green H<sub>2</sub> DRI-EAF steel requiring ~50-60kg H<sub>2</sub>

**Green H<sub>2</sub> direct reduced iron with decarbonization potential of ~90% compared to now dominant Blast Furnace-Basic Oxygen Furnace (BF-BOF)**

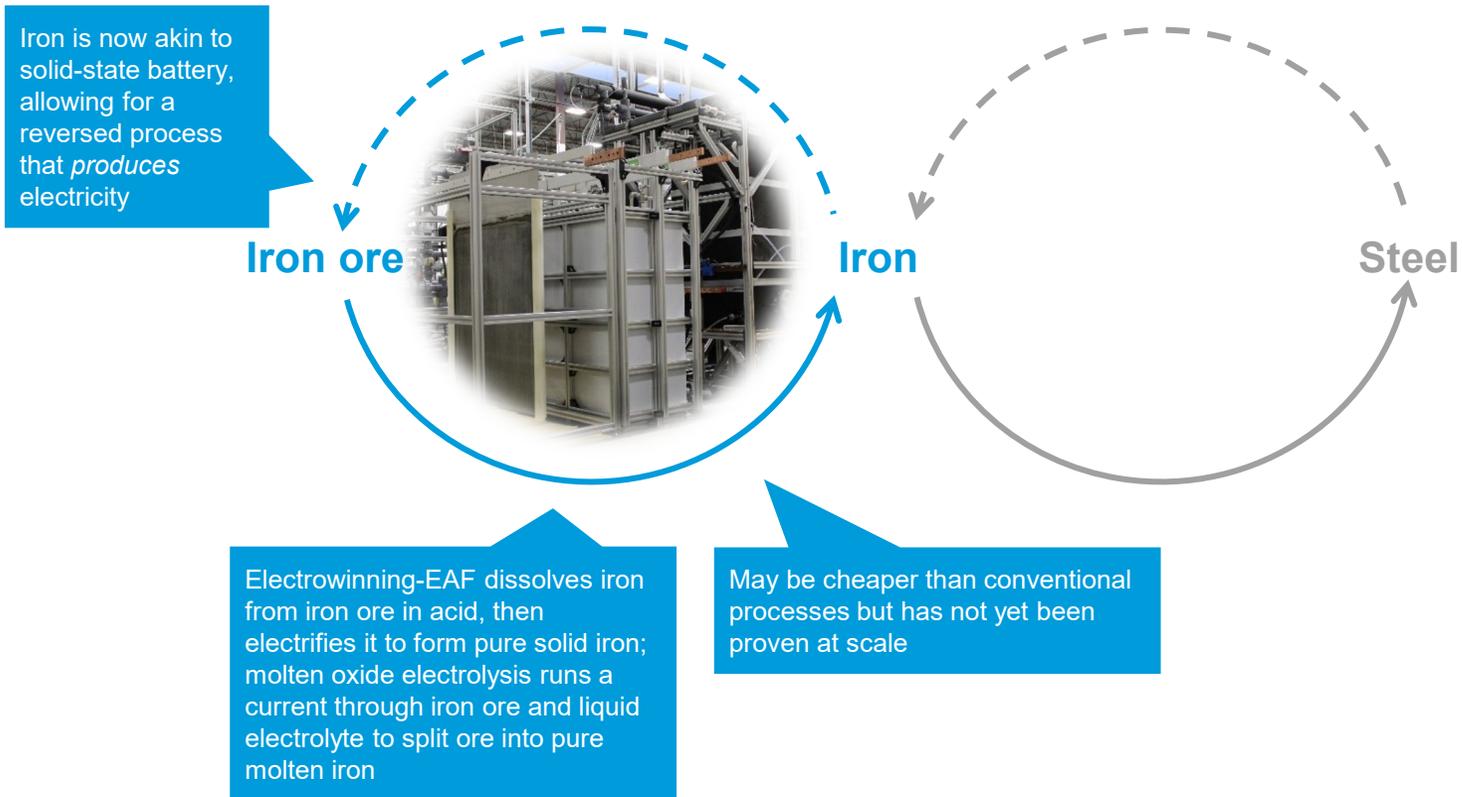
**H<sub>2</sub> demand for steel (Mt)**



Sources: Center on Global Energy Policy at Columbia University, [Low-Carbon Production of Iron & Steel](#) (2021); IEA, [Iron and Steel Technology Roadmap](#) (2020); IEA, [Net-zero scenario hydrogen outlook](#) (2023); McKinsey, [Decarbonization challenge for steel](#) (2020); BNEF, [Scaling Up Hydrogen](#) (2024)  
 Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Sayn-Wittgenstein *et al.*, "Greening Hydrogen" (12 December 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%



### Observations

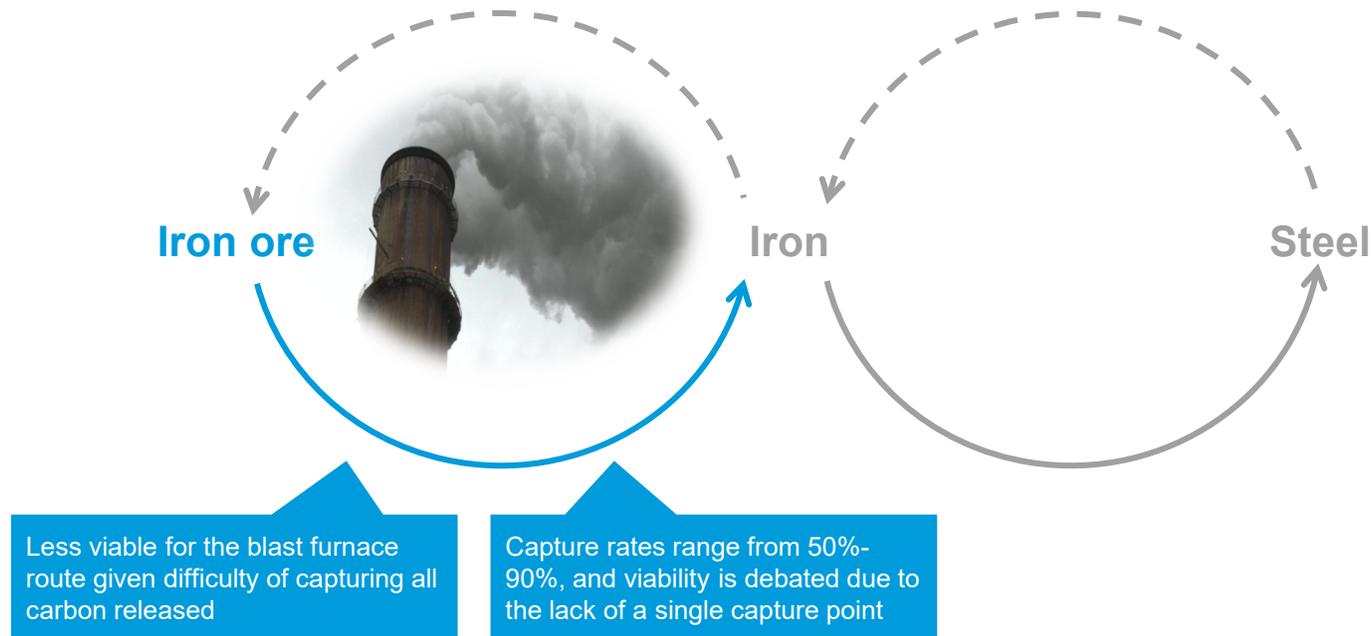
- **BF-BOF:** Iron ore, coke, and limestone produce iron in a blast furnace, which is turned into steel in an oxygen furnace
- **Scrap EAF:** Scrap metal is melted in an electric arc furnace (EAF) using electrical energy
- **NG DRI-EAF:** Iron ore turns into iron using natural gas, which is then melted in an EAF to produce steel
- **Green H<sub>2</sub> DRI-EAF:** Green hydrogen replaces natural gas as an iron ore reductant; byproduct is water vs. CO<sub>2</sub>
- **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<sub>2</sub>

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



#### 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<sub>2</sub> DRI-EAF:** Green hydrogen replaces natural gas as an iron ore reductant; byproduct is water vs. CO<sub>2</sub>
- **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<sub>2</sub>, 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<sub>2</sub>, electrolysis, and CCUS could reduce steelmaking CO<sub>2</sub> emissions by over 85% if implemented at scale

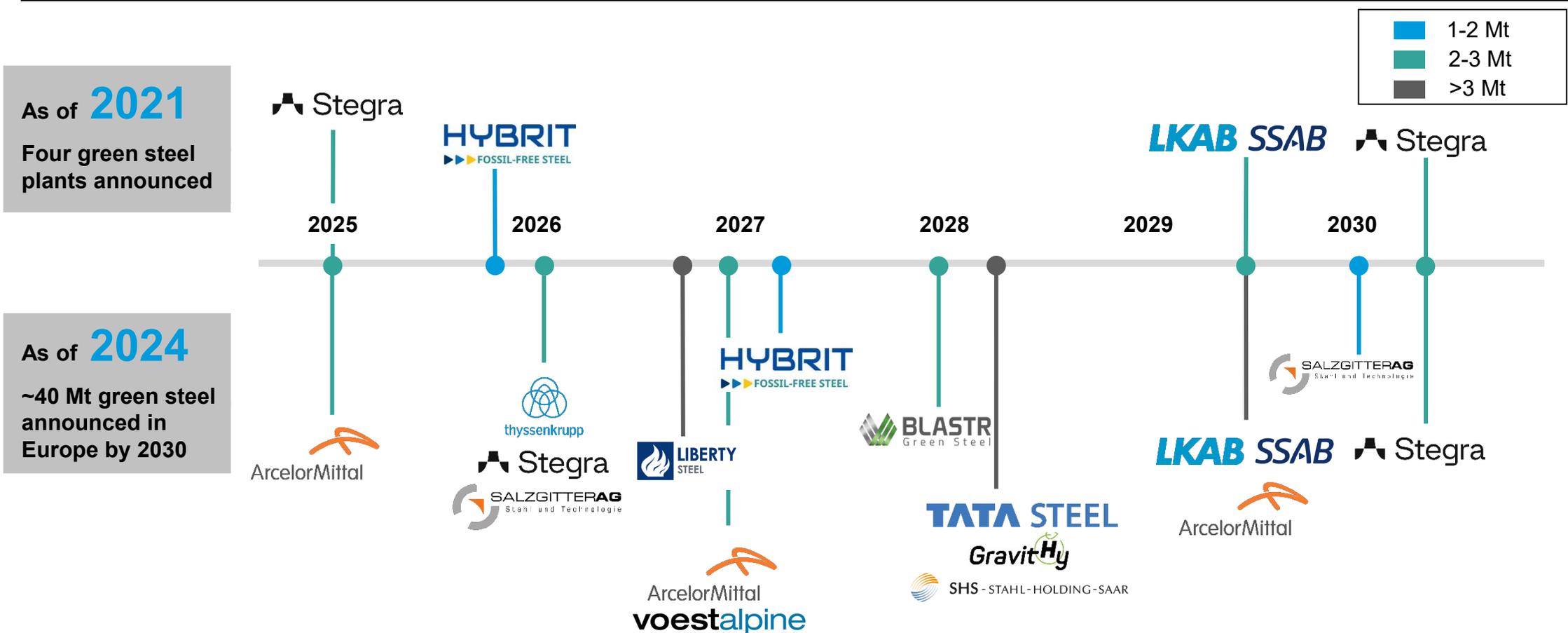
	1	2	3
<b>Description</b>	<p><b>100% Green Hydrogen (H<sub>2</sub>) DRI-EAF</b></p> <ul style="list-style-type: none"> <li>Green hydrogen replaces natural gas as an iron ore reductant in DRI shaft; the rest of the process remains the same</li> <li>Generates water as a byproduct instead of CO<sub>2</sub></li> </ul>	<p><b>Iron Ore Electrolysis</b></p> <ul style="list-style-type: none"> <li>Two different processes are possible:           <ul style="list-style-type: none"> <li><b>Molten oxide electrolysis:</b> High current runs through mixture of iron ore and liquid electrolyte to split ore into pure molten iron</li> <li><b>Electrowinning-EAF:</b> Iron from iron ore is dissolved in acid. Iron-rich solution is then electrified to form pure solid iron</li> </ul> </li> </ul>	<p><b>Carbon Capture, Utilization, and Storage (CCUS)</b></p> <ul style="list-style-type: none"> <li>CCUS equipment can be added to existing steel-producing infrastructure to capture emitted CO<sub>2</sub></li> <li>Captured CO<sub>2</sub> is then sequestered underground or reused</li> </ul>
<b>Real-time sector initiatives</b>	<p><a href="#">HYBRIT/Stegra</a> 100% fossil fuel-free DRI-EAF production with green H<sub>2</sub> used for DRI</p>	<p><a href="#">Electra</a> Electrowinning to produce high-purity iron plates ready for EAF input (no DRI or MOE step)</p>	<p><a href="#">ArcelorMittal</a> Carbalyst® captures carbon from a blast furnace and reuses it as bio-ethanol. However, technology not proven at scale</p>
<b>Applicability to conventional routes</b>	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
<b>Decarbonization potential (vs. BF-BOF)</b>	~90%	~97%	~90% <span style="background-color: #0070C0; color: white; padding: 2px;">Hypothetical best-case scenario</span>
<b>Estimated production cost (excl. CapEx)</b>	<\$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).

# ~40 Mt of green steel project announced in Europe by 2024, implying 2-2.4 Mt green H<sub>2</sub> demand

As of 2024, ~40 Mt of green steel projects announced in Europe alone



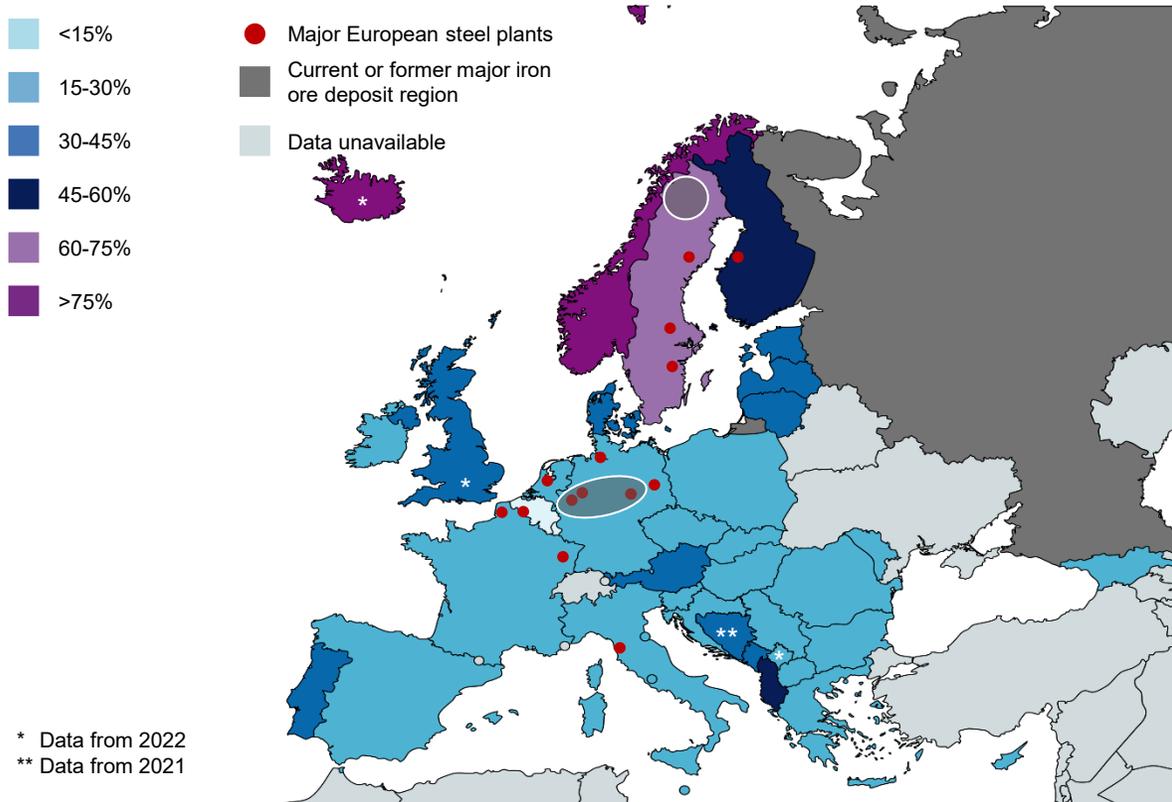
Source: Columbia Business School, [H2 Green Steel](#) (2024).

Credit: Friedrich Sayn-Wittgenstein, Ellie Valencia, Nadine Palmowski, Pia Doris Morrow, Hyae Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): De Boer *et al.*, "Decarbonizing Steel" (6 May 2025).

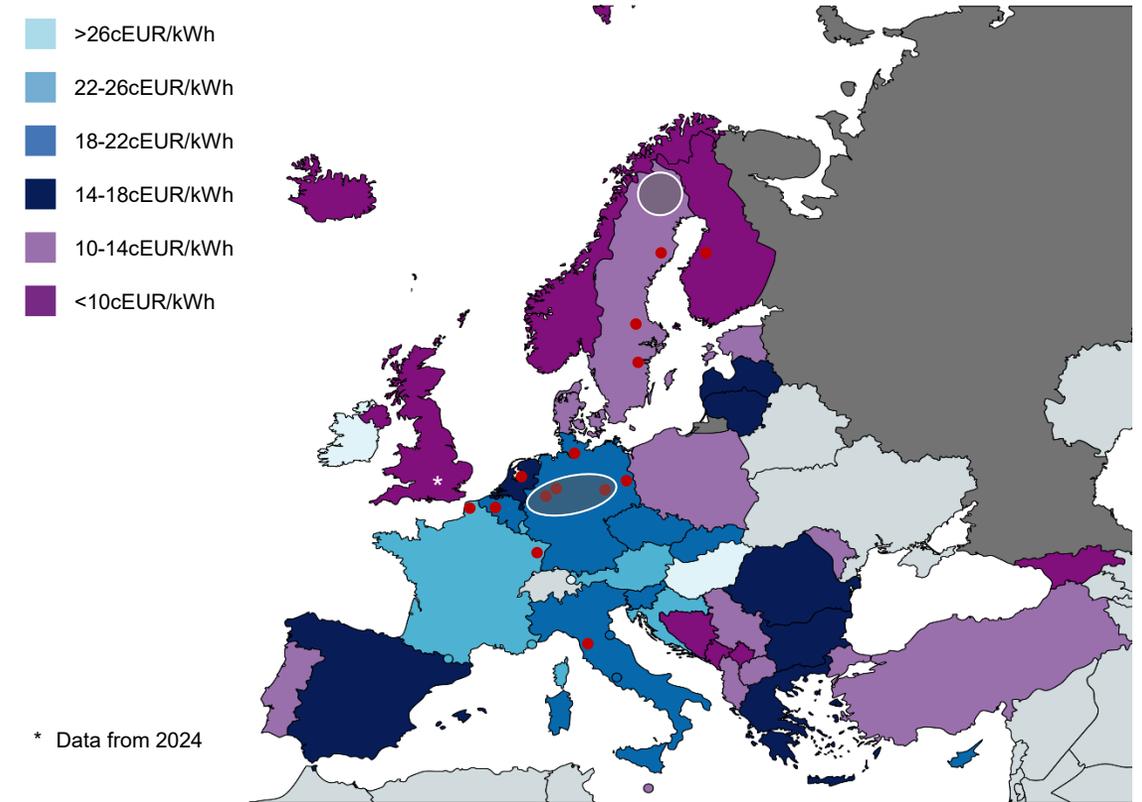
# Low-cost renewable electricity and iron ore deposits gives Northern Europe a unique advantage for steel production

## Renewable electricity production and prices throughout Europe

Share of energy from renewable resources in Europe (2023)



Non-consumer electricity prices in Europe (2023)



Source: International Energy Agency (IEA); Eurostat; ProMine; Stegra (2024), [EuroStat I](#) (2024); [Eurostat II](#) (2024); [UK Statistics Authority](#) (2023); [British Steel](#) (2024)  
 Credit: Pia Doris Morrow, Hyae Ryung Kim, and [Gernot Wagner](#). Share with attribution: De Boer *et al.*, "Decarbonizing Steel" (6 May 2025).