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Capturing Carbon

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Capturing Carbon: The Opportunity

CCUS overview: Carbon capture, utilization, and storage (CCUS) involves capturing CO_2 from industrial facilities or directly from the atmosphere, known as direct air capture (DAC), then utilizing or storing it.

Role in net-zero emissions (NZE): CCUS is essential for reaching NZE by 2050, with the potential to abate 6 Gt of CO_2 in select subsectors depending on the scenario.

Types of carbon capture:

- **Point-source capture (99%):** Industrial facilities or bioenergy with carbon capture storage (BECCS)
- **Ambient carbon removal (<1%):** DAC, field weathering, mineralization, ocean removal, and ocean alkalinity enhancement

Current CCUS adoption: As of 2024, CCUS captures 50 $MtCO_2$ per year (0.1% of global emissions), with growth projected to expand by 130x by 2050.

Global market trends: ~50 operational CCUS projects are expected to capture 440 Mt CO_2 by 2030 but remain 60% behind 2050 NZE goals. The top five facilities account for 56% of current capacity.

Challenges and regional growth: High costs are the main barrier to CCUS adoption. North America leads in capacity, while Europe and APAC are expected to see the highest growth, with over 15 Mt per year of new capture capacity currently under construction in China and the Middle East. Government funding is crucial to scaling global deployment.

Source: GMI, Europe Carbon Capture and Storage Market, (2024).
Credit: Maitreyi Menon, Michelle Priscilla, Anda Wang, Yosafat Partogi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim et al., “Capturing Carbon” (7 November 2025).

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CCUS, a retroactive CO_2 abatement lever, used for hard-to-abate emissions not addressed by renewable power and alternative fuels

Focus of deck (2) — NON-EXHAUSTIVE

	1 Renewable power	2 Capturing carbon (CCUS)	3 Alternative fuels
Description	• There has been a shift toward **low-carbon and/or clean power sources** such as renewables. • Wind and solar will **double their share to 25% of global electricity** by 2028. • Solar, wind, and hydro costs have decreased, making renewables competitive.	• CCUS is **tech that captures CO_2**, generally from large point sources like power generation and industrial facilities or directly from air. • CCUS can **either store** CO_2 in geologic formations or **reuse** it to create valuable products.	• The remaining emissions that cannot be electrified will be replaced with **cleaner fuels** • Primary use case has been in transportation and industrials • Biofuels and hydrogen for road transport, SAF for airplanes, ammonia for shipping
Progress to date	• Renewables **surpassed coal as the largest electricity source** in 2025. • **Investment imbalances** exist across regions; emerging and developing markets account for only 16%.	• Today, CCUS facilities capture **~50 $MtCO_2$ annually.** • Cost per CO_2 ton captured varies **from \$25 to \$340** depending on sector and technology.	• Biofuel for road is more **price competitive** as countries regulate biofuel usage in transportation • SAF and gaseous fuels remain **costly due to low adoption**
Impact (potential abatement)	• **Emissions reduction:** Transitioning the U.S. power grid to 100% clean electricity by 2035 could cut economywide emissions by 62% compared with 2005 levels.	• **Retrofitting fossil plants:** CCUS could reduce emissions from existing coal and gas plants by >90%, preventing lock-in of legacy infrastructure. • CCUS facilities can adjust operations in response to electricity supply and demand, helping **balance the grid** as intermittent renewables are integrated.	• **Biofuel and H_2:** By 2031, biodiesel production supported by U.S. tax credits could reduce emissions by 31 MMT and 48 MMT for clean hydrogen annually

Notes: Hard-to-abate emissions are those that are difficult to eliminate due to inherent process emissions in sectors like cement (calcination), steel (coal-based reduction), and chemicals (process-related CO_2 release). Carbon capture is essential to address these emissions.

Sources: IAE, Renewables (2024); IAE, CCUS (2024); IAE, Levelized cost of CO_2 (2024); DoE, Pathways to Commercial Liftoff: Clean Hydrogen (2024).

Credit: Maitreyi Menon, Michelle Priscilla, Anda Wang, Yosafat Partogi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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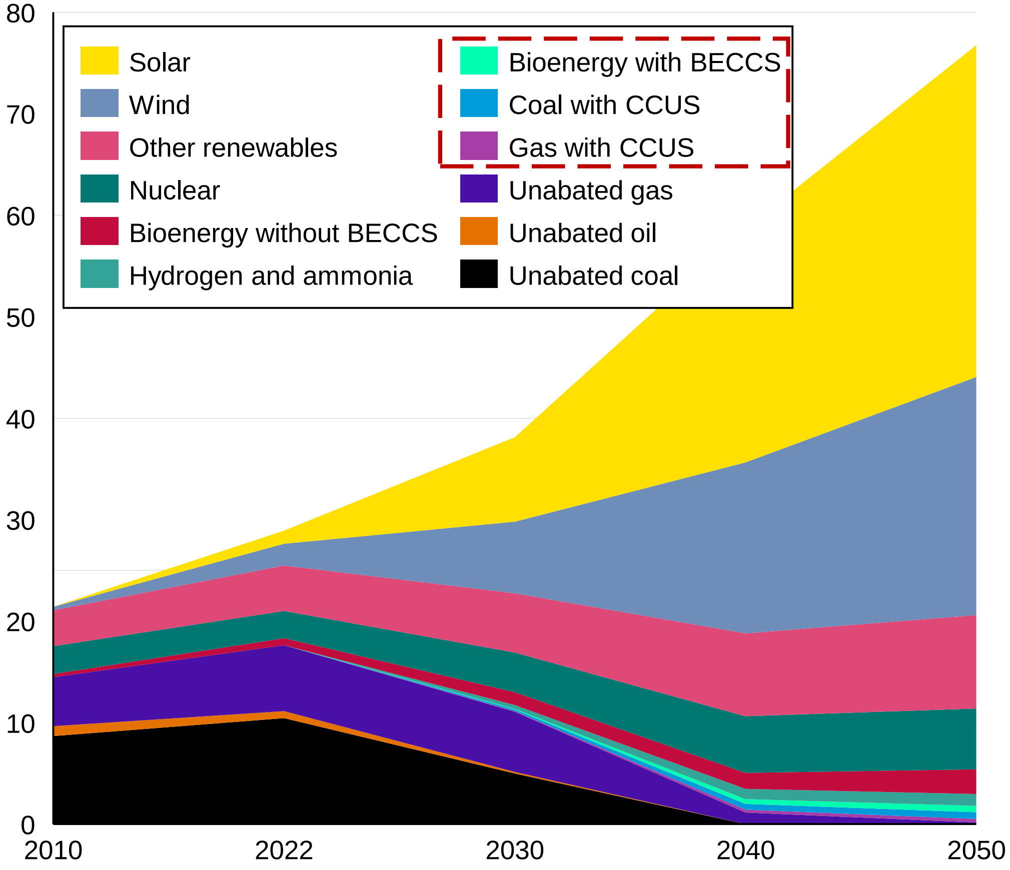
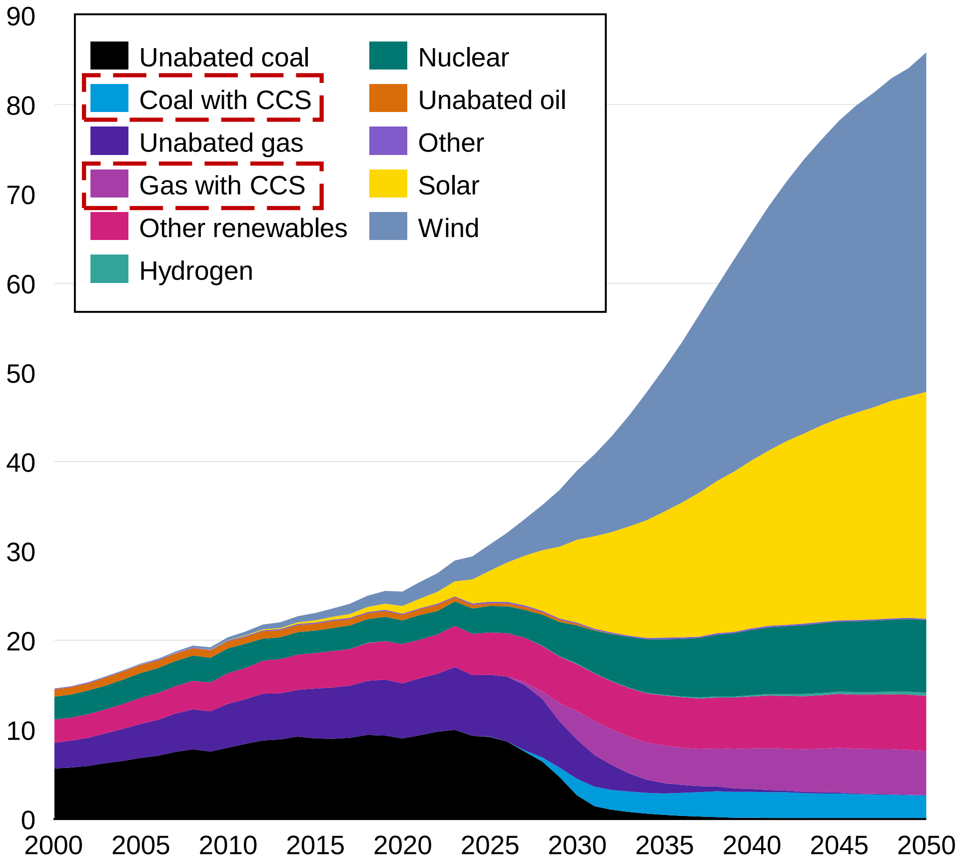
CCUS to play small role in energy sector abatement in net-zero scenarios (NZS) with widespread renewables adoption

NZS from IEA (in thousands of TWh)



NZS from BNEF (in thousands of TWh)



Observations

- Under the **IEA scenario**, aim is to capture **1 Gt of CO_2 annually by 2030**, compared with capture capacity in 2023 of ~50 Mt of CO_2.
- Under the **BNEF scenario**, capturing and storing carbon removes **97 Gt of CO_2 by 2050.**
- **Unabated fossil fuels will decline by 5.6% annually** between 2022 and 2050; IEA projects that **fossil fuels equipped with carbon capture** will grow by **31% annually** from 2022 to 2030.

Sources: IEA, Net Zero Roadmap: A Global Pathway to keep the 1.5°C Goal in Reach (2023); BNEF, New Energy Outlook (2024).
Credit: Michelle Priscilla, Anda Wang, Shaurir Ramanujan, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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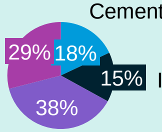
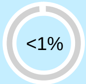
Two key categories of carbon management — point source and ambient — differ based on the origin and dispersal of emissions

	1 **Point-source capture**	2 **Ambient carbon removal**
Description	Separation and entrapment of CO_2 before it is released from **large stationary sources** (e.g., industrial plants)	**Removal of CO_2 already in the atmosphere or from biomass energy** by targeting diffuse CO_2 concentrations rather than capturing emissions at the source
Examples	Applications to iron & steel, cement, freight, blue hydrogen & ammonia 	Direct air capture (DAC), field weathering, mineralization, direct ocean removal, ocean alkalinity enhancement
% share of total CO_2 captured using carbon capture technologies, by method	 Vast majority of current capture is industrial point source.	
Current CO_2 absorption (per year)	**~50 $MtCO_2$**	**<1 $MtCO_2$**
Technological readiness level	**High with immediate scalability**	**Low to medium with limited scalability;** *DAC is medium while others are relatively low*
Cost of CCUS per ton of CO_2	**$21-$210** depending on industry	**DAC:** $135-$345 **Enhanced weathering:** $50-$200 **Ocean methods:** $50-$150

Sources: IEA, CCUS (2025); IEA, BECCS (2023); IEA, DAC (2022); DoE, Pathways to Commercial Liftoff: Industrial Decarbonization, (2023).
Credit: Maitreyi Menon, Michelle Priscilla, Anda Wang, Yosafat Partogi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., “Capturing Carbon” (7 November 2025).

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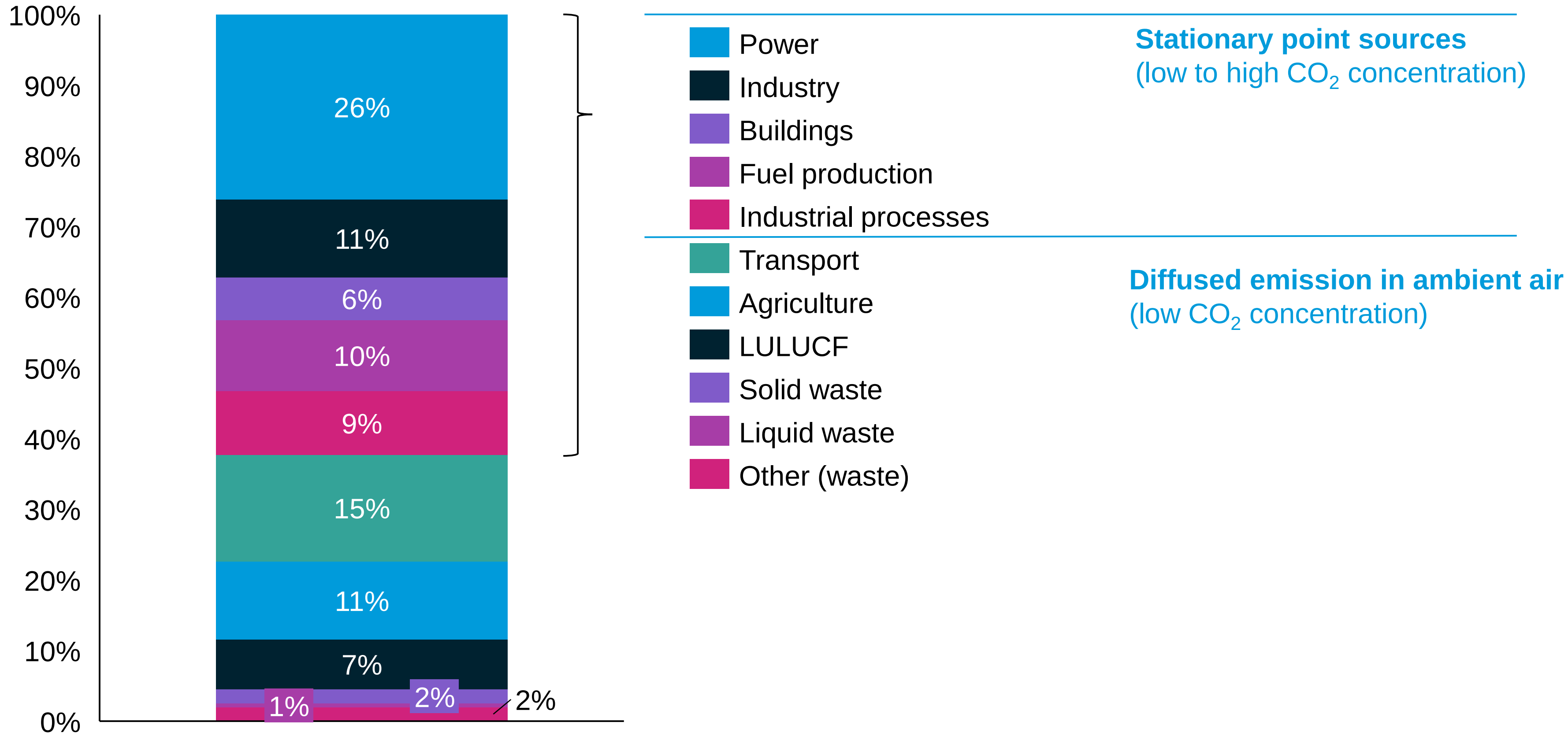
Carbon capture to play key role in abating the ~30% global GHG emissions from industrial sources through retrofitting

Global GHG emissions by sector (2023, %)



Observations

- CO_2 emissions **originate from stationary point sources or are diffused in ambient air.**
- The **stationary nature of industrial facilities** — such as cement, steel, and chemical and petrochemical plants — makes them **well-suited for carbon capture retrofitting.**
- **Stationary power sources** (e.g., coal and gas plants) could **also be retrofitted**; however, current projections indicate they will be **phased out in parallel with the adoption of clean energy and carbon capture**, **limiting the long-term role of retrofitting** in this segment.

Sources: Rhodium Group, Climate Action and Competitiveness (2023); IPCC, Special Report on Carbon Dioxide Capture and Storage; UNEP, UN Emissions Gap Report (2024).
Credit: Michelle Priscilla, Anda Wang, Grace Frascati, Shaurir Ramanujan, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

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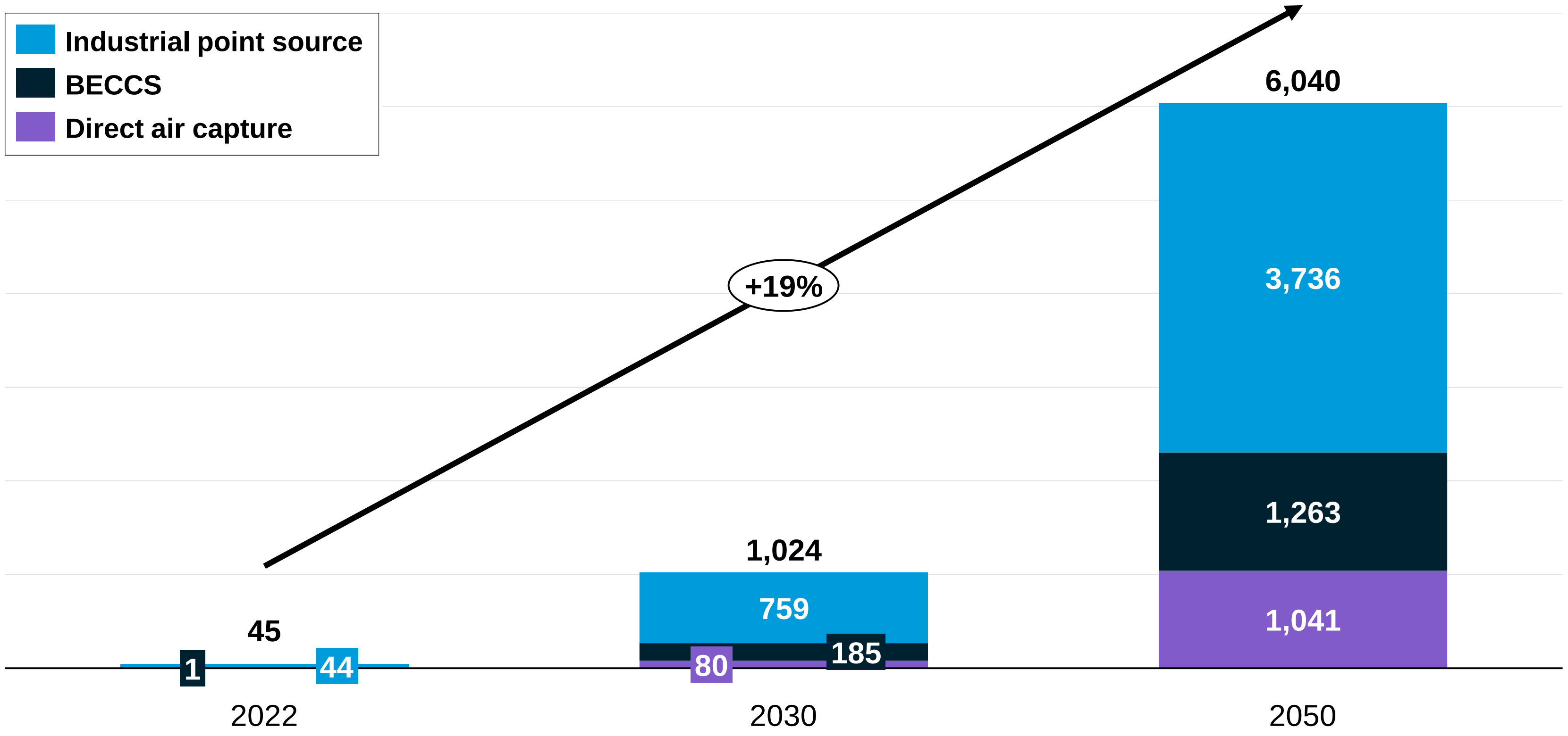
Capturing carbon currently removes 0.1% of emissions per year; NZE would require a 130x increase in total CO_2 capture by 2050

CO_2 capture potential is expected to grow by 19% year over year

Total CO_2 captured by technology ($MtCO_2$ per year)



Observations

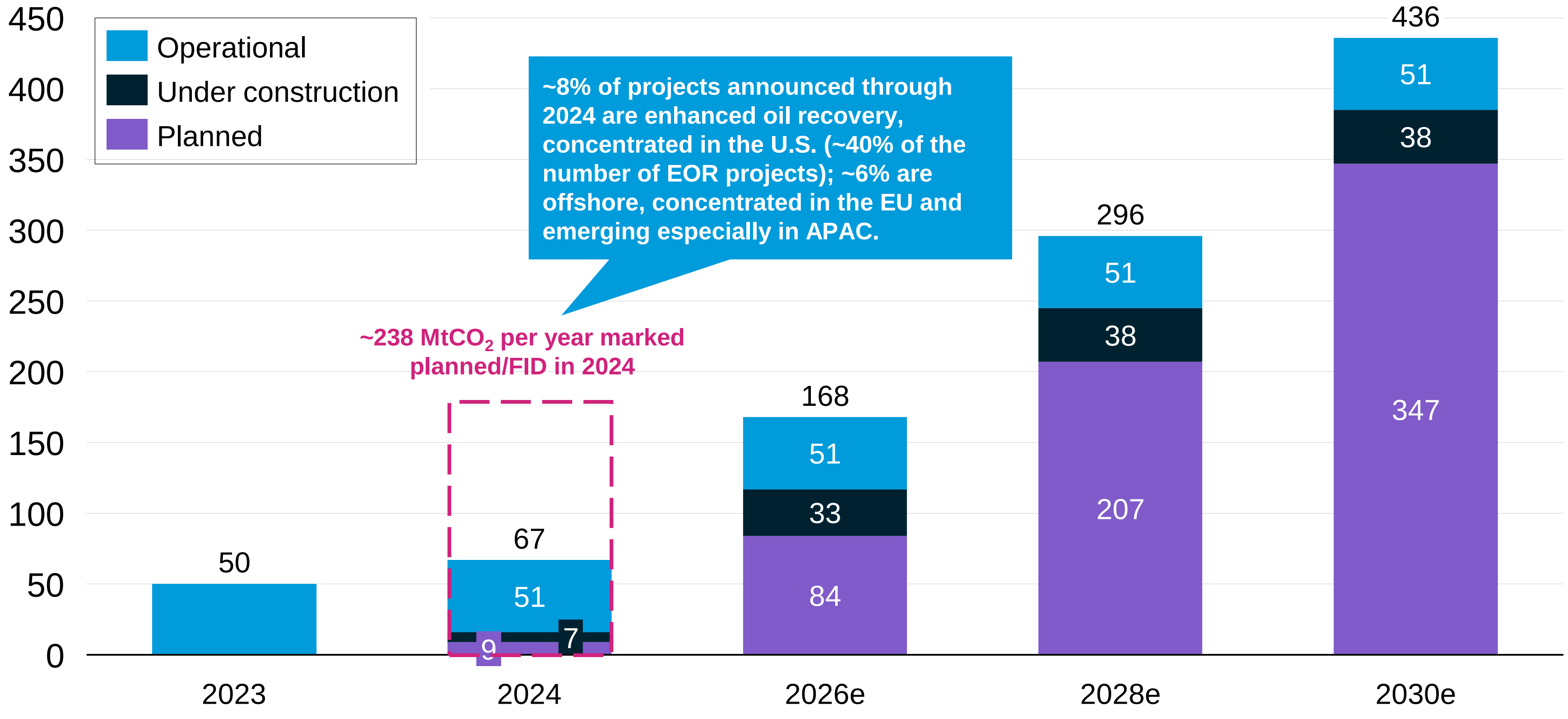
- As of 2024, CCUS technology captures **~50 Mt of CO_2 per year.**
- Over **98%** of current CO_2 capture occurs **from industrial processes and fuel transformation.**
- CCUS is **expected to capture 1,024 $MtCO_2$ by 2030** and **6,040 $MtCO_2$ by 2050.**
- **66% of total announced CO_2 capture capacity** occurs in **developing countries** and **emerging markets.**
- **Operational** captured capacity **lags significantly** behind **announced capture capacity.**
- **Completion** of planned CCUS projects **would increase capacity** by **8x by 2030.**

Source: IEA, Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach (2023).
Credit: Michelle Priscilla, Anda Wang, Shaurir Ramanujan, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

51 operational CCUS projects projected to reach ~440 Mt of global CO_2 capacity by 2030 but still 60% behind 2050 net-zero emissions

Operational and planned capture capacity expected to increase ~6x from 2024-30e

Operational and planned capture capacity ($MtCO_2$ per year)



Observations

- **>60% of the current 50.4 Mt of CCUS capacity is used for natural gas processing,** and **significant growth** is **expected for power** (64% CAGR 2023-30), **iron and steel** (51%), and **hydrogen** (43%).
- ~**436 Mt of captured CO_2 in 2030 is ~40% of the ~1 Gt CO_2 p.a. captured in the NZE by 2030 scenario.**
- While **most current capacity uses point-source technology**, **DAC is on the rise**, with **~61 Mt of 2030 capacity expected to be DAC** (~16 Mt NZE gap).
- Of the current and planned facilities, 34 **(~5%)** are DAC; the **main technology in place remains industrial point-source** capture (ready today with the potential to capture large volumes of CO_2 from hard-to-abate industries).

Sources: IEA, CCUS Projects Explorer (2024); IEA, Direct Air Capture (2022); McKinsey, Global Energy Perspective: CCUS Outlook (2023) and Scaling CCUS (2022).
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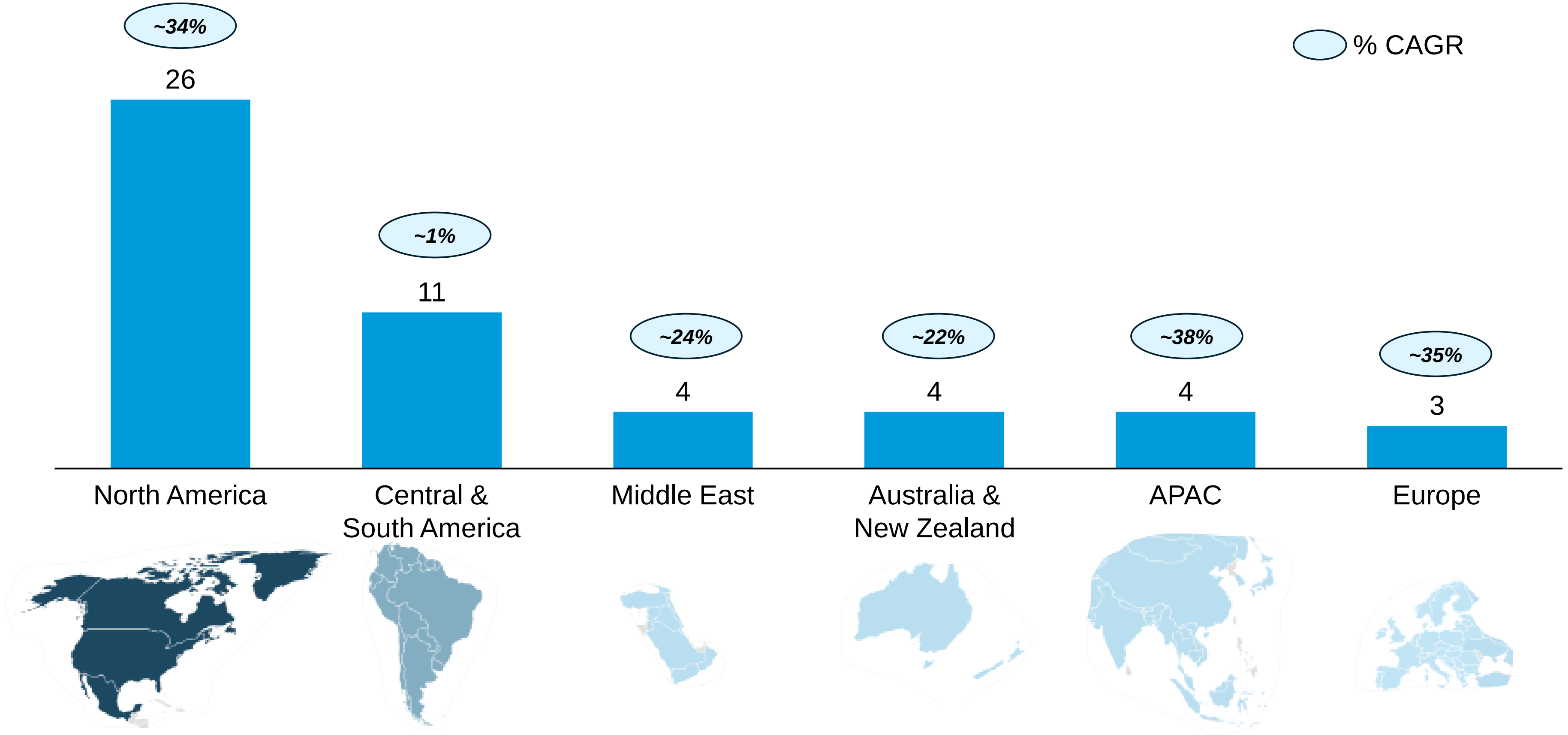
Current projects are concentrated in North America with density of 26 $MtCO_2$ per year; growth is expected in Europe and APAC

While the highest capture capacity is in North America, APAC is expected to see the highest CAGR (38%)

Operational and planned capture capacity, shaded by approximate density (in $MtCO_2$ per year), with 2023-30 CAGR



Observations

- **~50% of the current capacity comes from North America**; **significant growth is expected in Europe** (35% CAGR 2023-30), **Asia Pacific** (38%), and **North America** (34%).
- Development in **China, India, Latin America, the Middle East, and Africa is limited by a lack of firm policy and regulatory frameworks.**
- Geographic expansion is fueled by funding and **cross-border initiatives:**
  - The **Carbon Management Challenge** introduced a joint call to action for **governments to accelerate the deployment of tech.**
  - Denmark, Belgium, the Netherlands, and Sweden signed a **CO_2 transport and storage agreement** with Norway.

Sources: IEA, CCUS Projects Explorer (2024); IEA, CCUS (2024); Wood Mackenzie, CCUS: US$196bn Investment Opportunity (2024); ABI Research, The Future of Industrial Decarbonization (2024).
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Top 5 facilities today comprise 56% of the current capture capacity, indicating concentrated and slow-to-deploy projects

Major CCUS facilities are concentrated in developed countries

	Description	Country	Established	Facility industry	Type of storage	Capture capacity	Current capture
Petrobras Santos Basin Pre-Salt Oil Field	First CCUS project in ultra-deep waters and among the fastest growing	Brazil	2013	Natural gas processing	Enhanced oil recovery	14.2 Mtpa CO_2	~14.2 Mtpa CO_2
ExxonMobil Shute Creek Gas	Made controversial after report finding a venting of unsold CO_2 back into the atmosphere	U.S.	1986	Natural gas processing	Enhanced oil recovery	7.0 Mtpa CO_2	~7.0 Mtpa CO_2
Chevron Gorgon	Largest single-resource development in Australia with 40+ years of production lifespan	Australia	2019	Natural gas processing	Dedicated geological storage	4.0 Mtpa CO_2	~3.0 Mtpa CO_2
Great Plains Synfuels Plant	Converts coal into synthetic natural gas and has captured CO_2 for decades for EOR	U.S.	2000	Synfuels/ gasification	Enhanced oil recovery	3.0 Mtpa CO_2	~3.0 Mtpa CO_2
Sleipner	First in the world to inject CO_2 into a dedicated geological storage formation	Norway	1996	Natural gas processing	Dedicated geological storage	1.0 Mtpa CO_2	~1.0 Mtpa CO_2

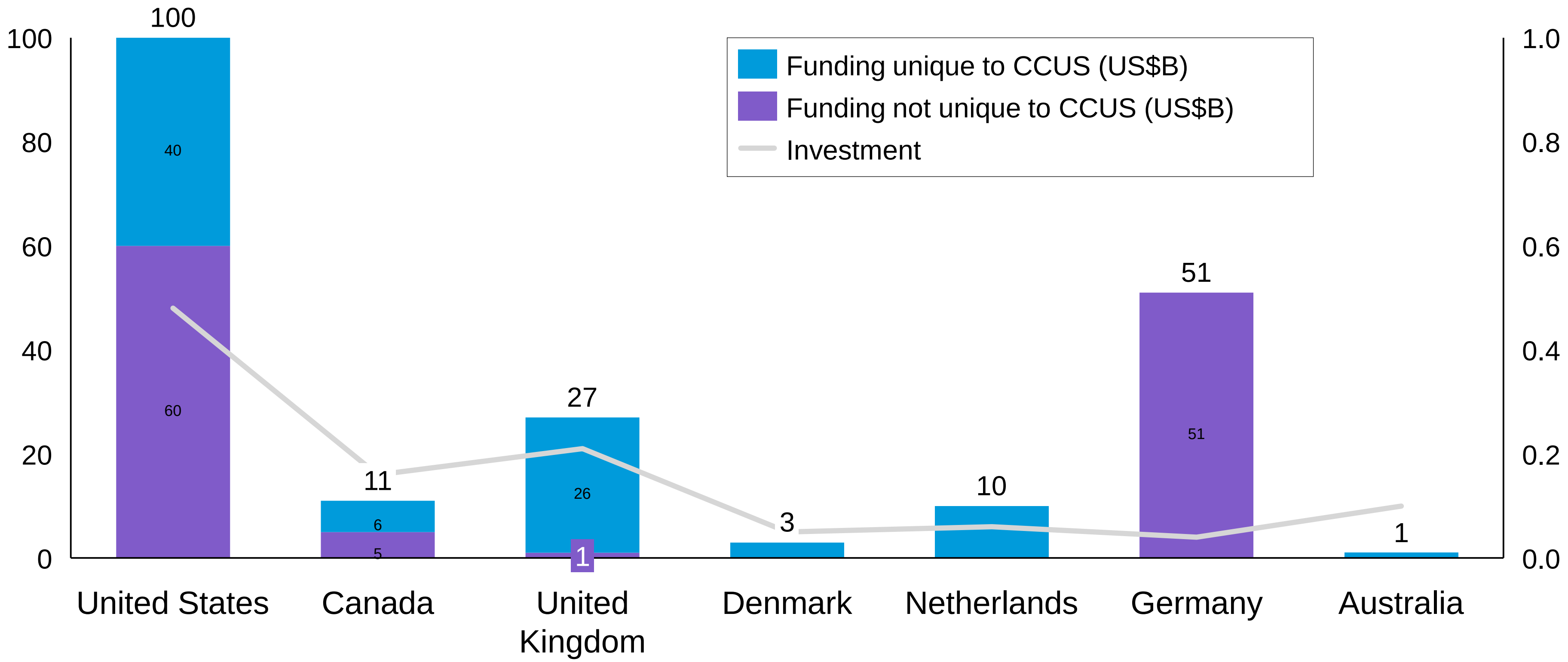
Future projects are still **anticipated to be megaprojects (>$1B),** meaning they inherently face risks and thus require robust planning, communication, stakeholder alignment, and committed project management teams.

Notes: Difference in Mt per year between this and prior slide is due to different figures/pathways (i.e., it is not additive) for CCUS vs. CCS.
Sources: BR Petrobas, Petrobas Santos Basin (2023); Catalyst Group, Lessons Learned (2024); Chevron, Evolution of the Gorgon Project; E&E News, The Kemper Project just collapsed. What it signifies for CCS (2021); ExxonMobil, ExxonMobile to expand carbon capture and storage at LaBarge, Wyoming, facility (2022); Geos, Processing plant details (2021); Global CCUS Institute, Global Status of CCUS (2024); IEEFA, Shute Creek (2022); Oil & Gas, Stuck at 1/3 Capacity (2023); S&P Global, CCUS in decarbonization (2021); Wolf Midstrream, Carbon (2024); Petrobras, News (2024); Equinor, Intro (2024).
Credit: Michelle Priscilla, Anda Wang, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Government funding of CapEx required influences geographical dispersion of carbon capture facilities

About 70% of global CCUS investment stems from Europe and North America

CCUS: Government funding and 10-year investment outlook in key countries



Observations

- **Country progress stems mostly from government funding.**
  - In the U.S., **$1.7B is allocated for demo projects** and **$1.2B for DAC hubs** under the 2021 Infrastructure Investment and Jobs Act.
  - **The U.S. leads funding** at **50% of the total,** followed by the **UK at 33% and Canada at 10%.**
  - Australia is investing AU$1.7B via ARENA to scale net-zero tech and AU$32.6M over four years to establish CCUS regulations.
- **Government funding for CCUS across key countries** – including the U.S., Canada, the U.K., Denmark, and Australia – **amounts to ~$80B.**

Notes: “Funding unique to CCUS” refers to government funds that have been set aside or the amount of revenue foregone in the case of tax incentives for any part of the CCUS value chain — capture, transport, utilization, and storage. “Funding not unique to CCUS” also supports decarbonization technologies beyond CCUS.
Source: Wood Mackenzie, CCUS: US$196 billion investment opportunity (2024).
Credit: Michelle Priscilla, Anda Wang, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., “Capturing Carbon” (7 November 2025).

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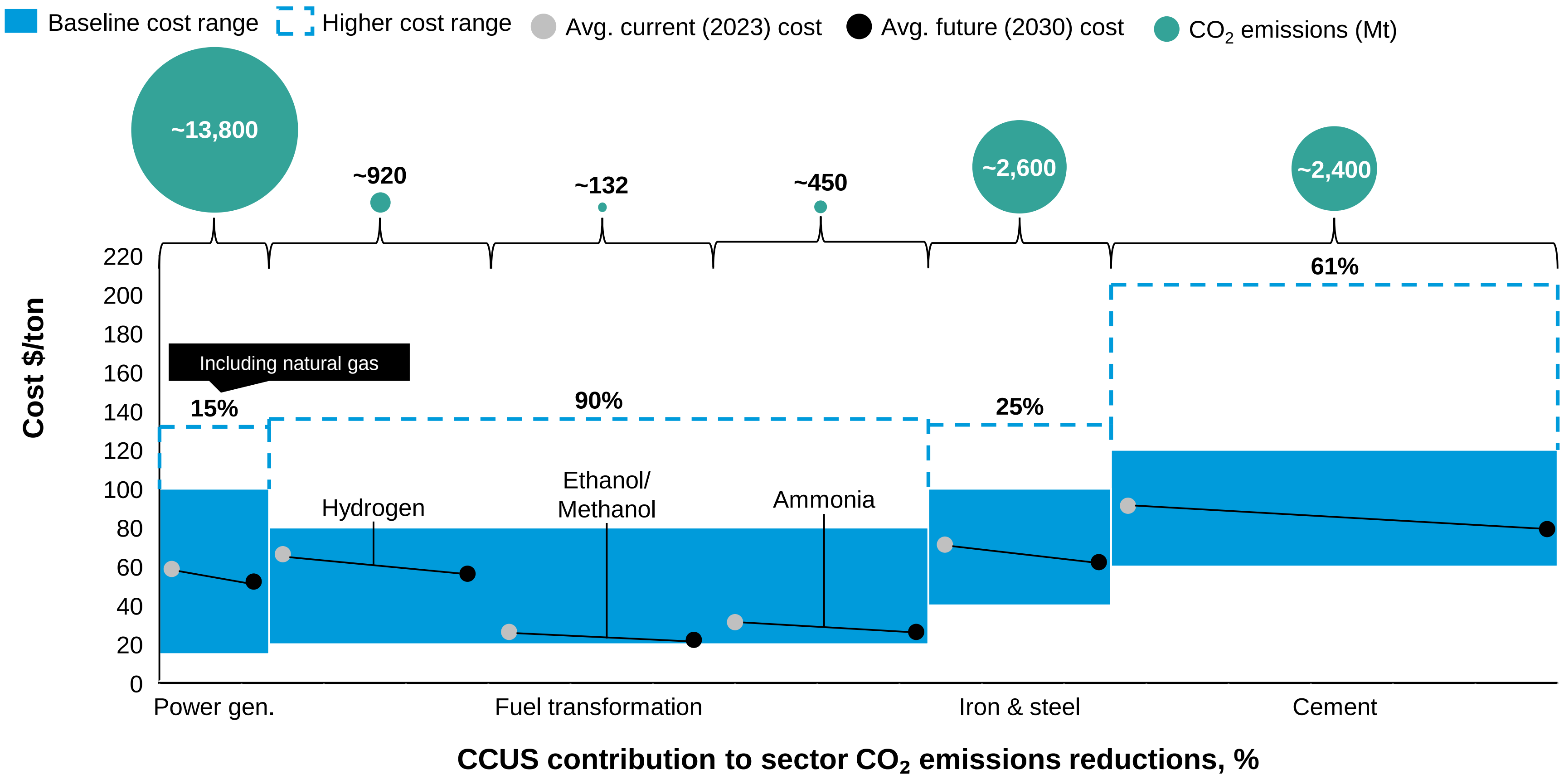
Carbon capture favors fuel transformation for 90% abatement and competitive costs over constrained heavy industry applications

Levelized cost of CO_2 capture across sectors (in US$/ton)



Observations

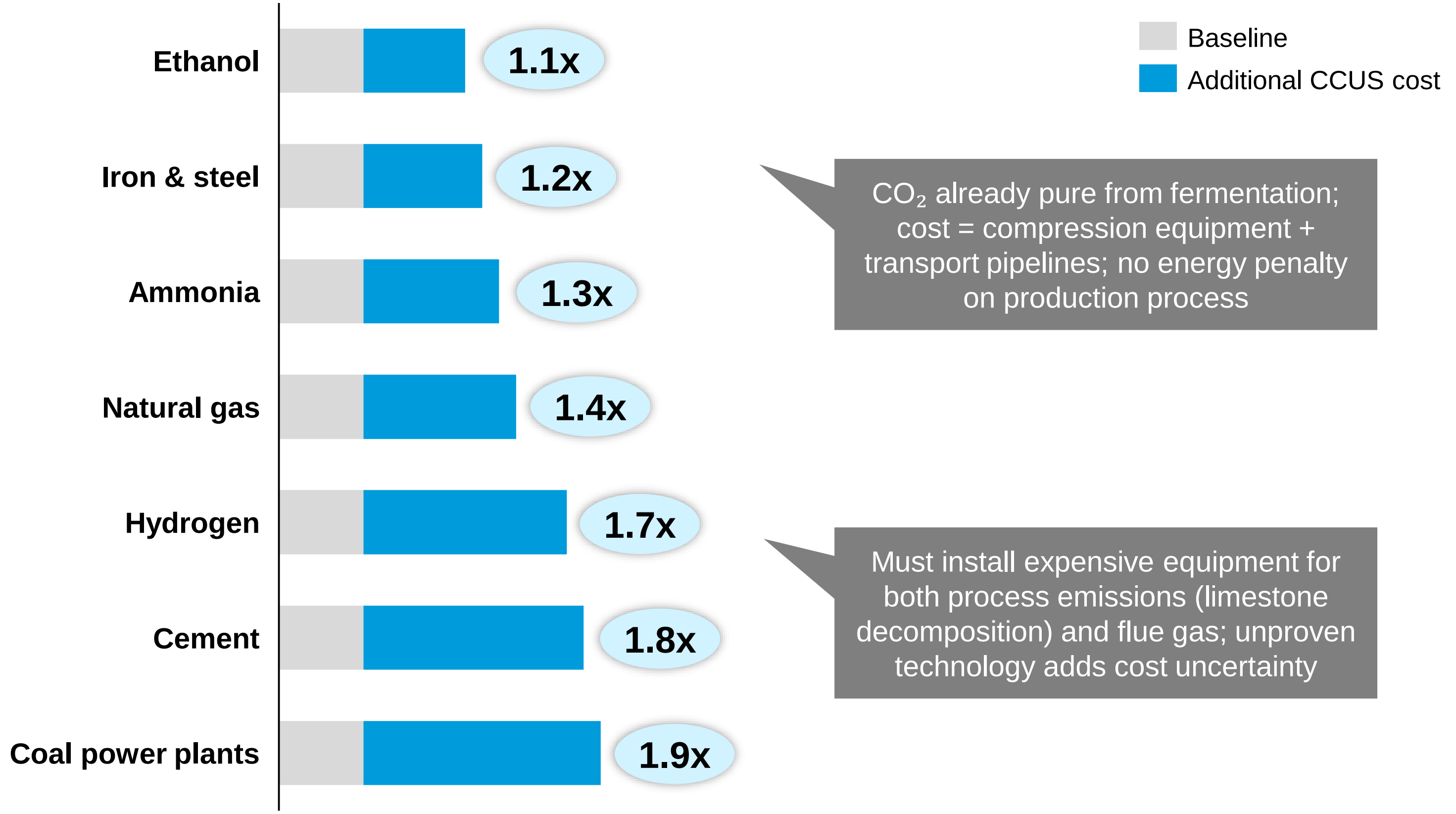
- **Fuel transformation sectors (hydrogen, ethanol/methanol, ammonia) achieve ~90% abatement at low cost ($20-$60 per ton)** with tight uncertainty bands. These process-constrained sectors benefit from pure CO2 streams in chemical processes, making abatement both high and predictable.
- **Power generation shows limited abatement potential (15%) despite low costs ($20-$60 per ton)** due to competition with renewables; the physics ceiling determines the economic floor rather than technology constraints.
- **Heavy industry sectors (iron and steel, cement) face high costs with massive uncertainty.** Iron and steel shows 25% abatement with moderate costs but wide uncertainty ranges, while cement achieves 61% abatement at the highest costs ($60-$200+ per ton) with the greatest uncertainty — retrofit complexity amplifies both cost and risk.

Sources: IEA, CCIS in Clean Energy Transitions (2020); IEA, Levelized Cost of CO2 Capture by Sector (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs US Context (2022); IEA, Biofuels (2023); IEA, Electricity (2025); IEA, Global Hydrogen Review (2024); IEA, Iron and Steel Technology Roadmap (2020); Farmdoc Daily, CO2 Production by the U.S. Ethanol Industry and the Potential Value of Sequestration (2024); CaptureMap, Ethanol – A Great Starting Point For Carbon Capture? (2023); IEA, Cement (2023); IEA, Ammonia Technology Roadmap (2021).

Credit: Maitreyi Menon, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Industrial decarbonization costs vary 6x by sector; pure CO_2 streams enable low-cost capture

Additional CCUS cost index compared with baseline cost



Observations

- **No CCUS application is cost competitive today.** Even best-case ethanol represents a **1.1x cost increase** — a margin-destroying burden for commodity industries operating on 3-8% EBITDA margins.
- **Current economics require permanent subsidization: 45Q credits** essentially function as production subsidies, not transition support.
- **Stream purity creates winner-takes-all economics:** Ethanol's **99% pure streams** require simple compression versus steel's **15% streams,** which need energy-intensive separation.
- **Process integration determines viability: High-purity sectors** benefit from integrated capture while **dilute sectors** require bolt-on solutions with **20-40% energy penalties.**
- **Ethanol's CCUS success relies on pure CO_2 streams, but its impact is small** (~110 $MtCO_2$ per year, just 2% of what's needed for industrial decarbonization).

Sources: IEA, CCIS in Clean Energy Transitions (2020); IEA, Levelized Cost of CO2 Capture by Sector and Initial CO2 Concentration (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs US Context (2022).
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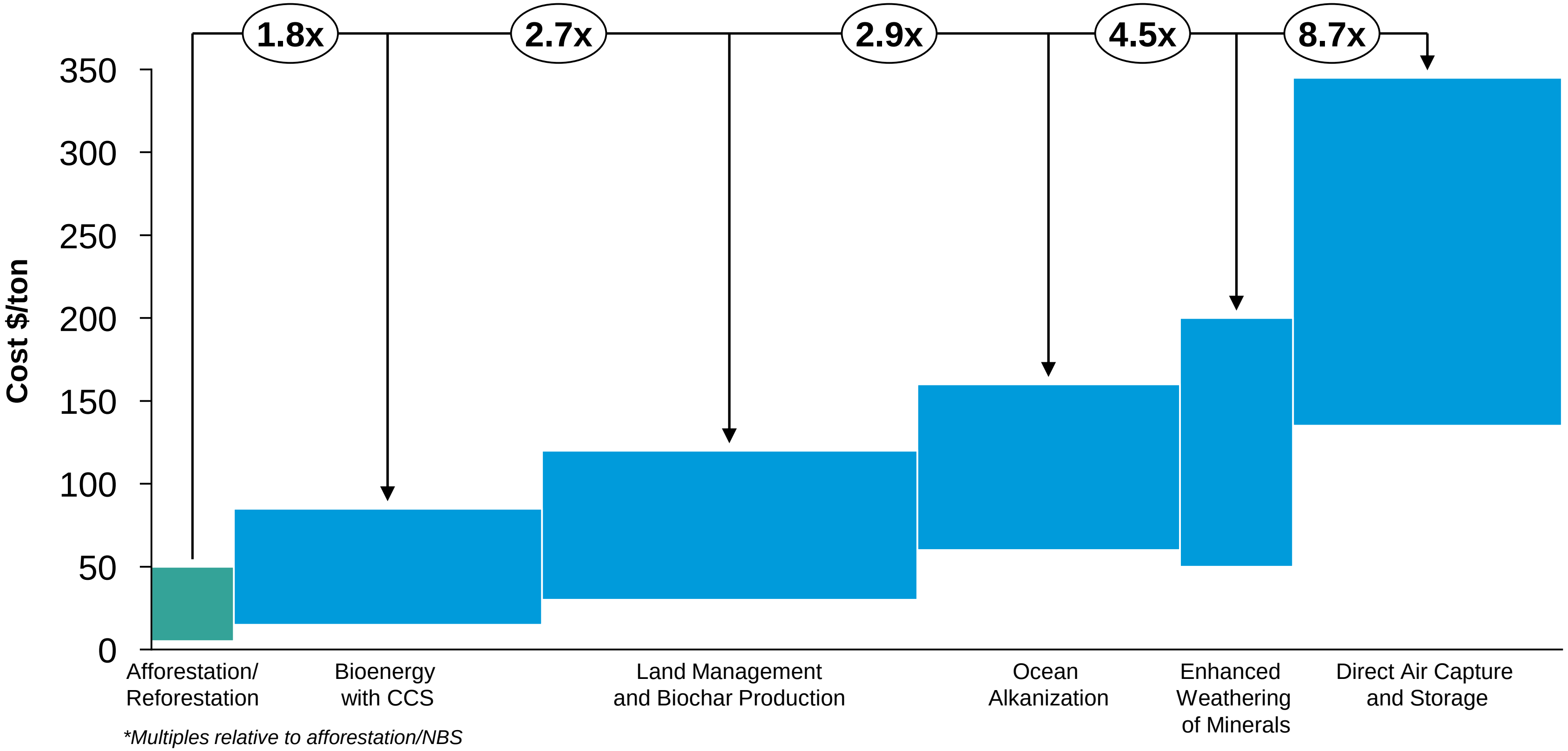
Cost premium of 10x separates temporary, nature-based solutions from permanent, engineered removal

CO_2 capture cost across carbon removal approaches and technologies (in US$/ton)



Multiples relative to afforestation/NBS

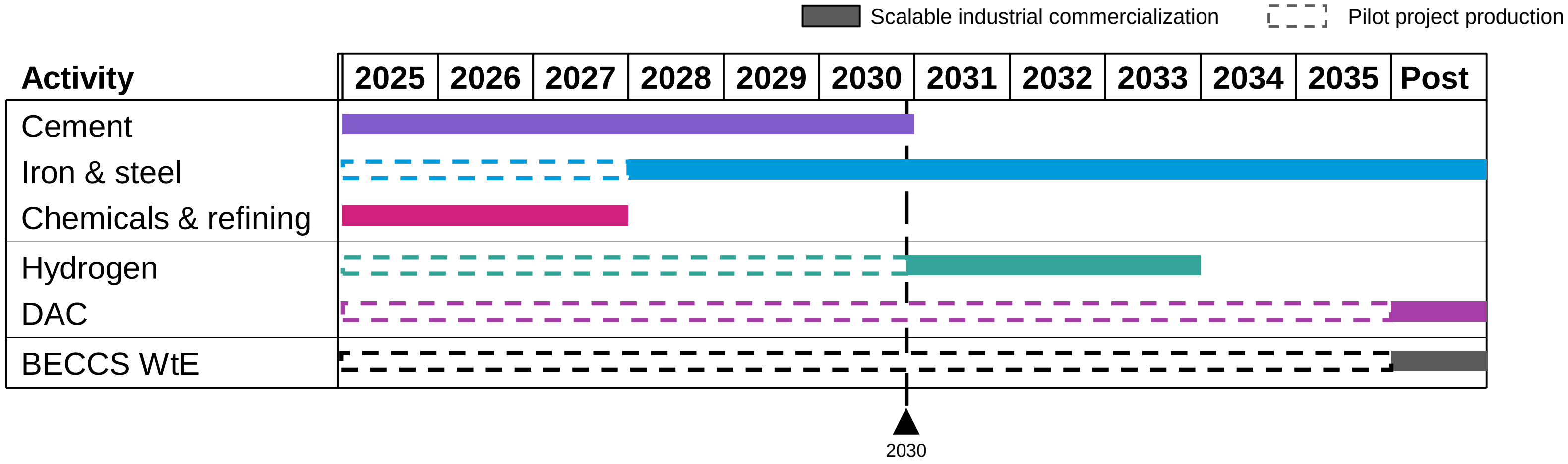
Observations

- **Nature-based removal is ready now** (**TRL 9**). It's cheap at **$5 to $50 per ton**, but the carbon storage is temporary.
- **The 10x-plus cost premium for DAC buys permanent, millennium-scale storage.** It's an earlier technology (**TRL 7-8**), but its potential to scale is massive.
- **Co-products and revenue streams complicate the cost analysis:** BECCS generates dispatchable low-carbon power, biochar improves soil health and agricultural yields, and enhanced weathering can act as a fertilizer.
- These co-products have distinct economic value, meaning the *net cost* of carbon removal is highly specific to each project's business model.
- **Shared infrastructure creates powerful synergies:** While the front-end capture methods for technologies like BECCS and DAC are different, they ultimately depend on the exact same back-end infrastructure for CO_2 transport and geological storage.

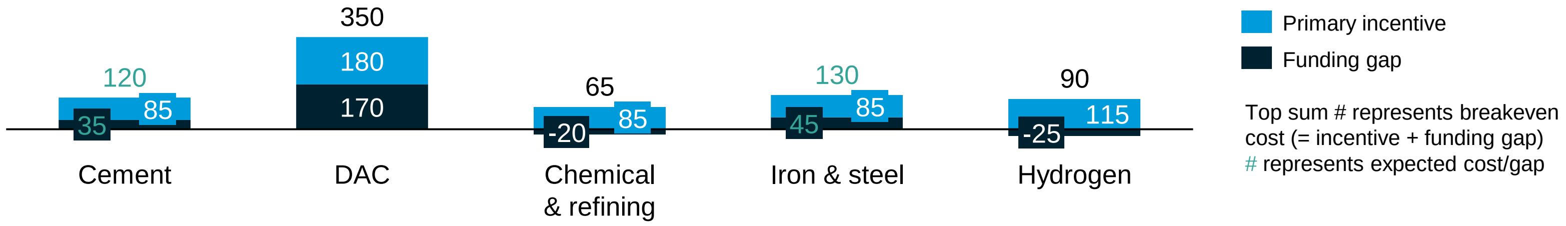
Sources: IEA, CCIS in Clean Energy Transitions (2020); IEA, Levelized Cost of CO2 Capture by Sector and Initial CO2 Concentration (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs US Context (2022).
Credit: Maitreyi Menon, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

CCUS commercialization is phased, viable now for high-purity sectors, entering a critical 2025-30 demonstration

Commercialization timelines for carbon capture techs (development stage, 2025-35+)



Comparative economic viability of decarbonization pathways ($/ton CO_2, 2025 estimates)



Observations

- The cost chart highlights a clear economic divide: CCUS for chemicals and hydrogen is profitable now with a funding surplus, while DAC's $170/ton funding gap presents the largest economic challenge.
- **Chemicals and refining:** Leads in maturity, entering scalable commercialization now (2025-27) with proven, replicable projects.
- **Hydrogen (blue):** Major projects underway; the ~2030 scalable timeline reflects the long construction lead time for essential large-scale infrastructure.
- **Iron and steel:** In an early demonstration phase, with foundational projects starting ~2026. A long proving period pushes scalable deployment to 2028-30+.
- **Cement:** Entered its critical demonstration phase in mid-2025 with the Brevik plant. Scalable commercialization is not expected until after 2030.
- **Direct air capture (DAC):** Enters a crucial demonstration phase with the Stratos plant commissioning in late 2025, which is key to proving reliability for post-2030 deployment.
- **BECCS WtE:** Timeline mirrors DAC, with key demonstration projects starting in 2026 (Ørsted, Celsio) to prove the model for post-2030 commercialization.

Source: BCG, Cement's Carbon Footprint Doesn't Have to Be Set in Stone (2024); World Economic Forum, Net-Zero Industry Tracker (2024); Environmental Science & Technology Letters, Aqueous-Phase Single-Electron Transfer Calculations for Carbonate Radicals Using the Validated Marcus Theory (2023); Worley, Making CCUS viable for cement: The role of integration and partnership (2025) ; IDTechEx, Early Opportunities: Which Industries Will Embrace CCUS First? (2024); IEA, CCUS technology innovation (2024); UK Department for Energy Security & Net Zero, Hydrogen production and industrial carbon capture business models (2023).
Credit: Michelle Priscilla, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Closing gaps in investment, acceptance, and readiness is essential to scaling CCUS deployment globally

Financing gaps

- **Investment has significantly increased, tripling to $6.4 billion by 2024.** Also, the first project-financed CCUS initiative has occurred.
- **Investable revenue streams (e.g., ETS, carbon pricing) and de-risking mechanisms** — including U.S. Department of Energy support through Bipartisan Infrastructure Law (BIL) funding — are critical to scaling carbon capture projects.

Lack of shared infrastructure

- Without common-use CO_2 transport and storage, **projects risk inefficiency and duplication.**
- **DOE is supporting shared infrastructure** development through **BIL funding** to help reduce costs.

Regulatory/market uncertainty

- **Voluntary carbon markets are unpredictable**, with uncertain long-term prices and volumes, making financing for carbon dioxide removal projects risky.
- **Greater transparency, regulatory backing, and demand-driven technology premiums** are needed to stabilize funding.
- China and the Middle East have strengthened their policy commitments. The problem persists, but there are now **examples of progress.**

Sources: DOE, Pathways to Commercial Liftoff: Carbon Management (April 2023); Energy Research & Social Science, Establishing Leadership in Bringing CCUS to Scale (2025).
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Carbon Capture Technology

Key messages
Carbon Capture Technology

Carbon capture: Involves capturing CO_2, methane, and nitrous oxide, focusing on hard-to-abate sectors like cement, iron, and steel. The capture technology constitutes ~70% of total project costs.

Cost breakdown: Key components are carbon capture (70%), transportation (10%), storage (15%), and utilization (5%). Research aims to reduce costs and enhance scalability.

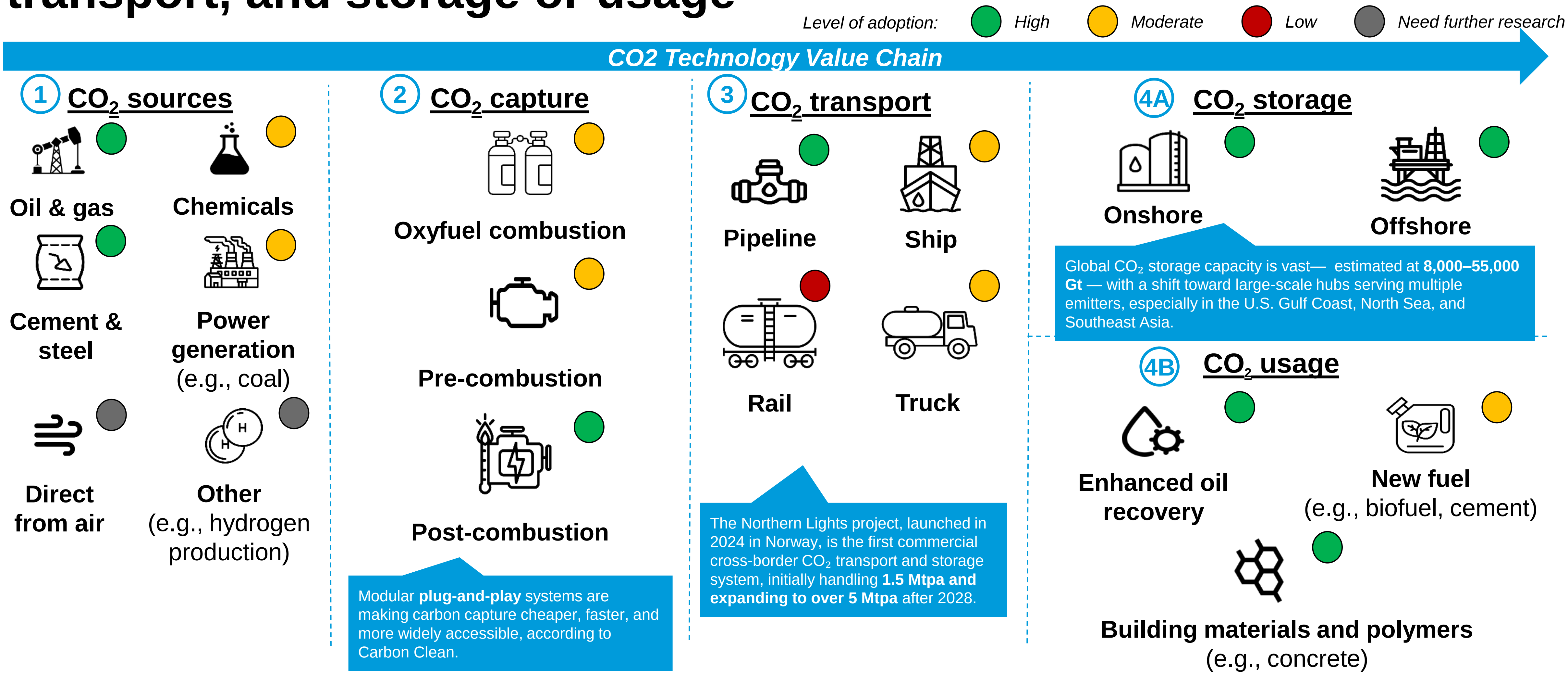
Value chain development: Industrial CCUS technologies are moving from demonstration to commercialization, with integration challenges. Pipelines are the primary CO_2 transport method, with alternatives like truck, rail, and ship for specific regions.

Storage and utilization: Global storage capacity is sufficient to store the forecasted 220 Gt of CO_2 from 2020 to 2070. Currently, **onshore geological storage** accounts for two-thirds of the world's carbon capture capacity and will **continue to play a critical role** in storing captured carbon, while enhanced oil recovery (EOR) leads in utilization at ~75% globally within the oil and gas sector. Other uses, like carbon-based fuels and materials, face technological hurdles.

From an industry deep-dive point of view, cement and ammonia production may be the most promising industries for carbon capture using point-source technology, as their technological readiness has reached the commercialization level and is cost efficient provided that financial incentives remain available (i.e., Inflation Reduction Act).

Industries like iron and steel, freight transport, and blue hydrogen are still in niche stages, focused on R&D and pilot projects. High installation and operational costs make these solutions economically unviable, as the estimated LCOC per ton remains high, even with incentives.

CO_2 capture value chain is comprised of CO_2 sources, capture, transport, and storage or usage



Sources: Land & Climate Review, Capturing and storing problems (2022); MIT, How efficient is carbon capture and storage? (2021); CATF, Project track records (2024); CECO, Barriers to successfully implementing CCUS (2024); WRI, 7 Things to Know about CCUS (2023).
Credit: Christian Sandjaja, Sean Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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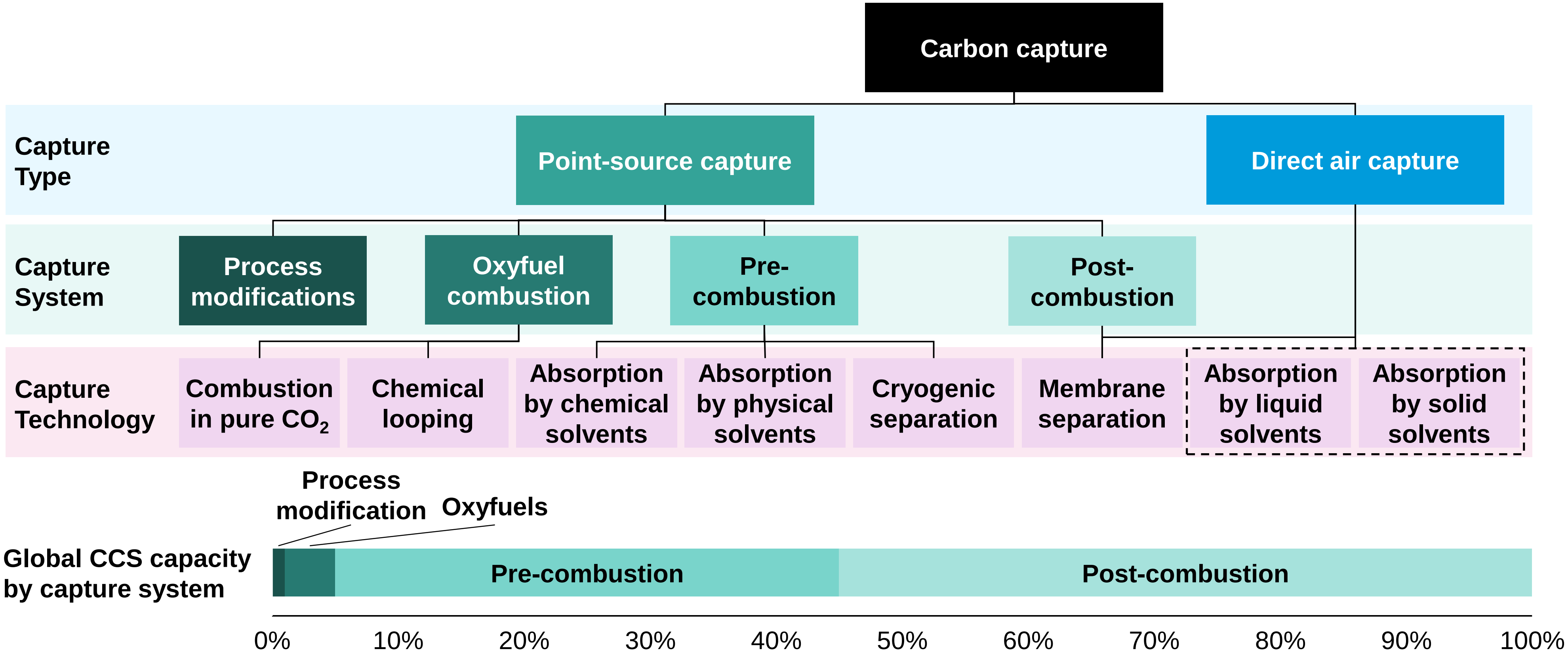
Carbon capture technologies can be classified by capture type, system design, technology used, and separation process

Carbon capture technologies



Observations

- **Post-combustion is the most widely used capture system**, representing the largest share of global CCS capacity.
- **Pre-combustion is the second most adopted system**, indicating its significant role in current CCS deployment.
- **Absorption by chemical solvents is used in both major systems,** showing its broad applicability across capture methods.

Sources: Energy Transition Committee, Carbon Capture, Utilisation, & Storage in the Energy Transition: Vital but Limited (2022); Concawe Review, Technology Scouting–Carbon Capture: From Today's to Novel Technologies (2021).
Credit: Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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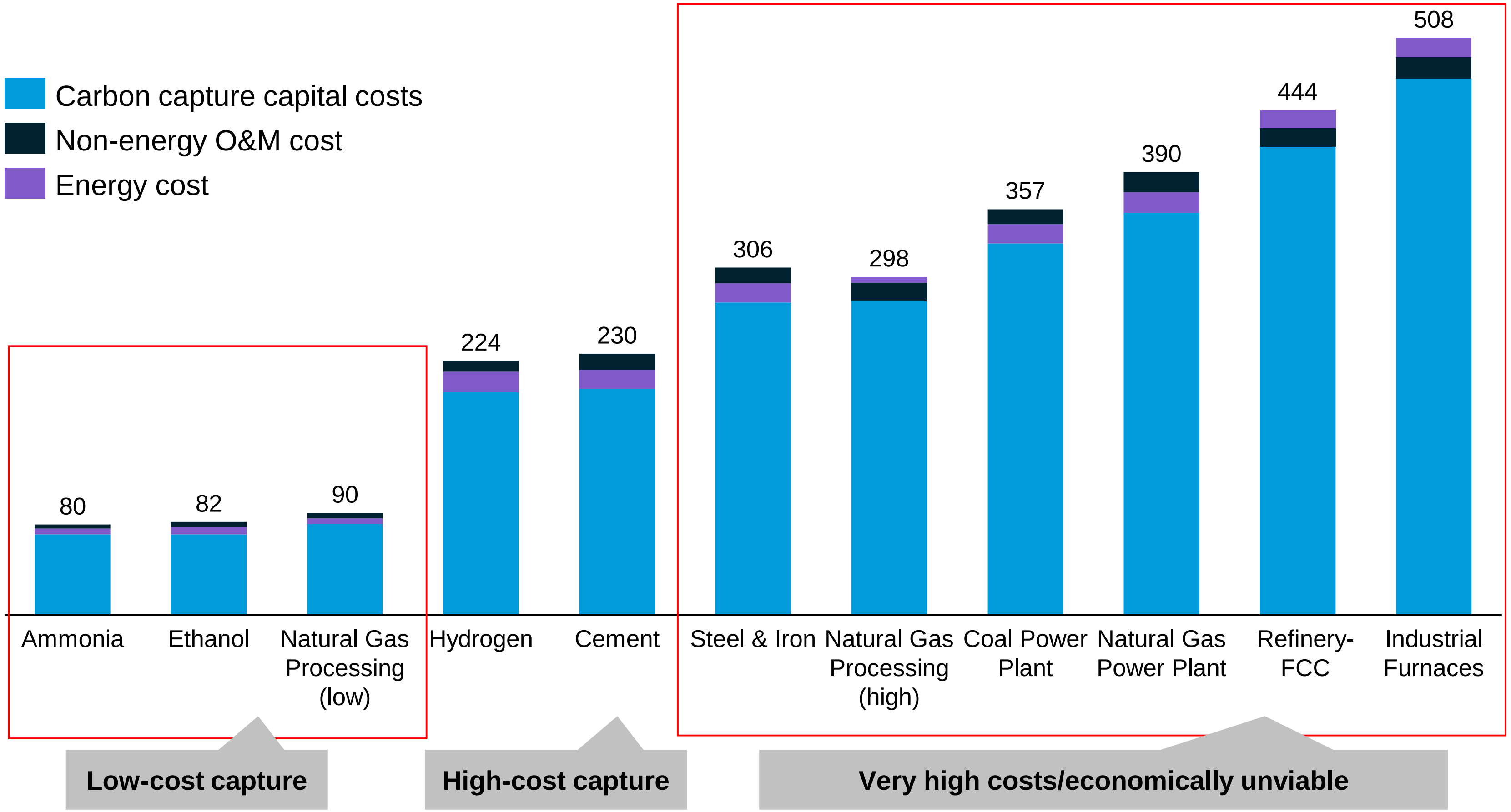
Capital and operating costs of capturing carbon varies by industry, technology, and energy costs

Cost breakdown for capturing carbon by industry, US$/ton



Observations

- **Technology readiness varies significantly across pathways,** but all require substantial development.
- **Energy intensity of** CO_2 conversion due to chemical inactivity **creates a cost disadvantage** — economics depend on "affordable, renewable energy" availability.
- **Commercial timeline spans two decades to develop and commercialize** for most CO_2-use technologies.
- **Current costs exceed conventional alternatives:** CO_2-derived products face a cost disadvantage and must compete with less-expensive non-CO_2-based routes.
- **Scale remains suboptimal:** Existing commercial CO_2 use facilities operate at significantly smaller scale than traditional production plants, limiting cost competitiveness.

Source: DOE, Meeting the Dual Challenge (2019).
Credit:, Maitreyi Menon, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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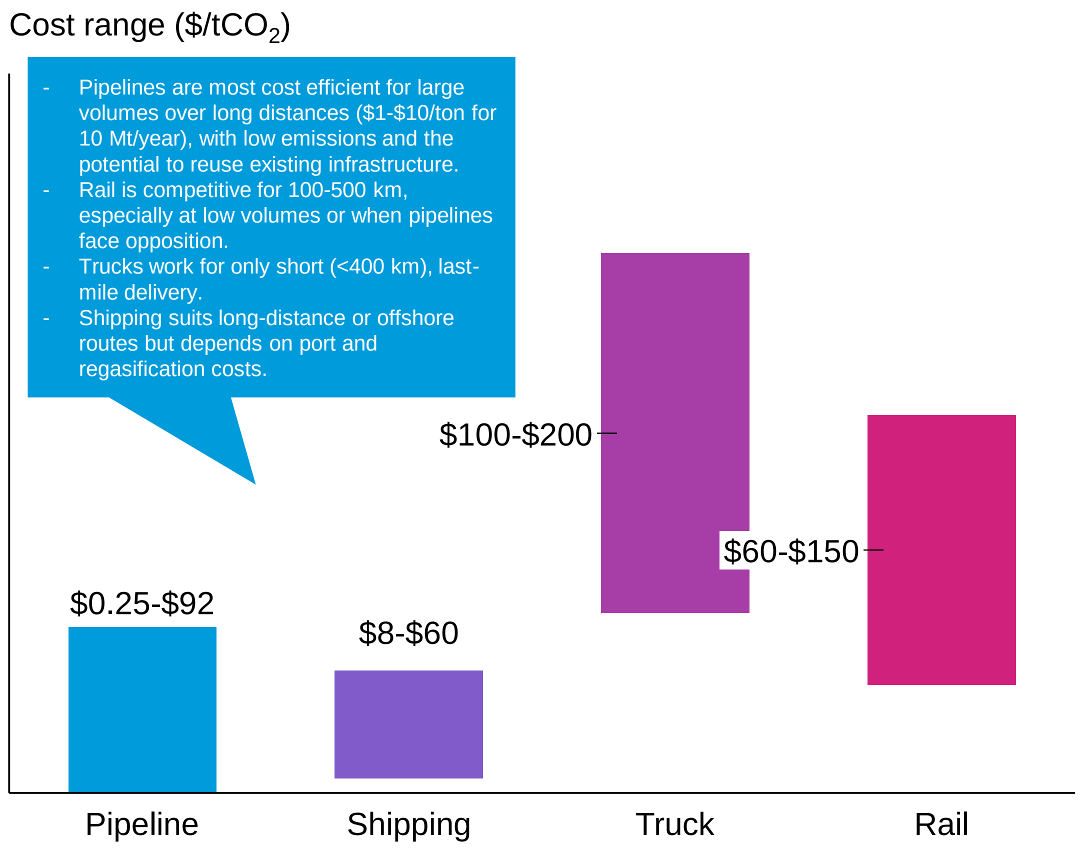
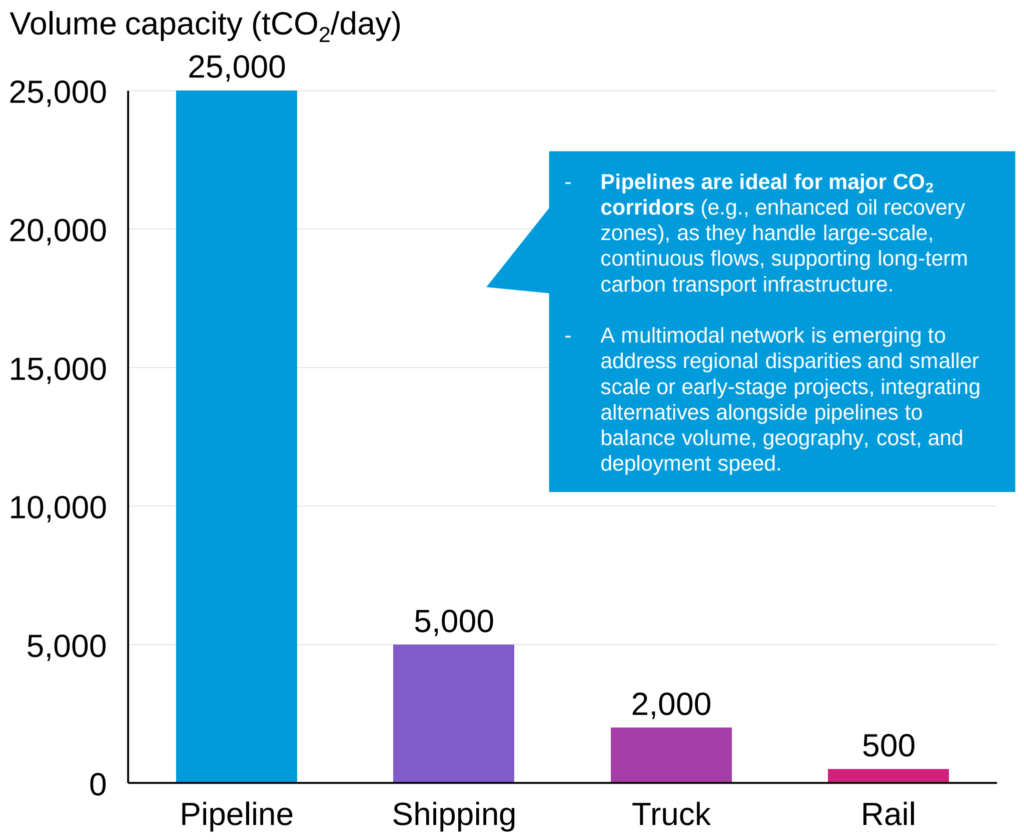
Pipelines are most cost-efficient option for high-volume CO_2 transport, though alternatives offer essential flexibility

Pipeline remains the most cost-efficient solution



Pipeline enables stable, high-volume transport



Sources: Energies, B3, Pipeline Infrastructure for CO2 Transport (2024); MIT, Cost of CO2 transport and storage (2021); Energies, Systematic Review of CCUS (2023); Wood Mackenzie, What's shaping CCUS project costs? (2023); Nature Climate Change, A proposed global layout for CCUS (2021); Energy Procedia, Understanding the economic feasibility of ship transport (2014).
Credit: Shaurir Ramanujan, Grace Frascati, Christian Sandjaja, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Coordinated expansion of onshore and offshore storage infrastructure required to meet rising CO_2 storage needs

Theoretical global CO_2 storage capacity

~63%

About two-thirds of global storage capacity is onshore, driven by favorable cost effectiveness, proximity of lower cost of operation, and existing infrastructure.

Onshore storage

Sample: Alberta Carbon Trunk Line Project – active CO_2 onshore storage site

~37%

Offshore storage

Sample: Northern Lights Project – active CO_2 offshore storage site

Observations

- There is **enough storage** (8,000-55,000 Gt) around the world to store forecasted 220 Gt of CO_2 from 2020 to 2070.
- **80% of current operational storage is associated with EOR,** while the remainder is dedicated to geological storage which is expanding rapidly and is expected to reach roughly half of global capacity.
- **Onshore storage is likely to dominate in the near term;** but offshore storage is expected to expand rapidly over the medium to long term.
- Large-scale CO_2 storage has demonstrated that **risks of leakage are small and can be managed effectively,** with **careful storage site selection and appraisal.**

Sources: IEA, Capacity and need to store CO2 (2021); IEA, CO2 Transport and Storage; University of Oxford, Onshore geological carbon storage has potential in the UK, but key knowledge and regulatory gaps remain (2024).
Credit: Michelle Priscilla, Christian Sandjaja, Sean Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., “Capturing Carbon” (7 November 2025).

Enhanced oil recovery is currently the only profitable application of captured CO_2, offers minimal net climate benefit (1/2)

Captured CO_2 application	Definition and environmental impact	Cost (estimated $/ton)
EOR 	• **Utilizes captured CO_2 to inject into mature oil fields,** increasing oil extraction efficiency while simultaneously storing CO_2 underground. • Environmental impact: o **Reduced carbon footprint:** EOR oil produces 37% less CO_2 than conventional oil. o **Prolonged fossil fuel dependence:** EOR extends the lifespan of oil fields and the fossil fuel industry.	Variable but can be profitable with oil prices and incentives; net $55/tCO2 to provider (e.g., North Dakota EOR project)
Production of drop-in fuels 	• **Converts captured CO_2 into liquid fuels** that are chemically identical to conventional hydrocarbons, enabling direct use in existing engines and infrastructure without modification. • Environmental impact: o **Reduced carbon footprint:** Reduces 83% emission compared with conventional fuel.	Very high; e-kerosene $50-$80/GJ; synthetic gasoline needs electricity at <$0.03/kWh to compete
Building materials and polymers 	• **Utilizes captured CO_2 as a feedstock** to create sustainable concrete, carbon-based building materials, and polymers, reducing emissions and enhancing material performance. • Environmental impact: o **Reduced carbon footprint:** Reduces building products' raw material greenhouse gas emissions by 30-50%.	Wide range: $77-$102/tCO2 avoided (slag/wollastonite); some routes cheaper than CCS; aggregates $8-$11/t product

Sources: Environmental Technology & Innovation, A review of progress made on DAC (2022); Environmental International, Enhanced oil recovery: Environmental issues and state regulatory programs (2003); IEA, CO_2 Capture and Utilization; Iowa Capital Dispatch, Using Co2 to extract oil is ultimately worse for the environment (2024); WEF, What is CCUS? (2024); IEA, CO_2 Transport and storage; Clean Air Task Force, Carbon capture and storage in the United States power sector (2019); Pipeline Fighters Hub, CO_2 EOR issues (2024); Coryton, Sustainable Fuels Myths vs. Truths (2022); RMI, The Hidden Climate Impact of Residential Construction (2023).
Credit: Grace Frascati, Christian Sandjaja, Maitreyi Menon, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Enhanced oil recovery is currently the only profitable application of captured CO_2, offers minimal net climate benefit (2/2)

Captured CO_2 application	Advantages and concerns
EOR 	⊕ Considered **both a form of storage and utilization** ⊕ **Currently most economically feasible use of CO_2,** allowing companies to store CO_2 in geological formations (depleted oil fields) while pushing out additional oil that can be **extracted to generate revenue and offset capture costs** ⊖ **Raises several environmental concerns,** such as pollution of land and surface water from chemical and oil leakages ⊖ Early-on projects are carbon-negative, then go carbon-positive six to 18 years into operations as oil production declines
Production of drop-in fuels 	⊕ Generates feedstock for methanol and synthetic fuels **that are compatible with existing infrastructure** (largely focusing on sustainable aviation fuel) ⊕ Helps **reduce reliance on fossil fuels** and closes carbon loop ⊖ Many technologies are in early development
Building materials and polymers 	⊕ Converts CO_2 into carbonates used in cement and concrete production and can also be used to create plastics and other chemical and polymer materials ⊕ Building materials derived from CO_2 products are the only use case that counts as **permanent sequestration** ⊖ Only a handful of projects focus on this use due to lack of profitability

Sources: Environmental Technology & Innovation, A review of progress made in DAC of CO_2 (2022); Environment International, EOR environmental issues (2003); IEA, CO_2 Capture and Utilization; Iowa Capital Dispatch, Using CO2 to extract oil is ultimately worse for the environment (2024); WEF, What is CCUS? (2024); IEA, CO_2 Transport and Storage (2024); MDPI, Energies, Environmental and Operational Performance of CO2-EOR as a CCUS Technology (2019).
Credit: Grace Frascati, Christian Sandjaja, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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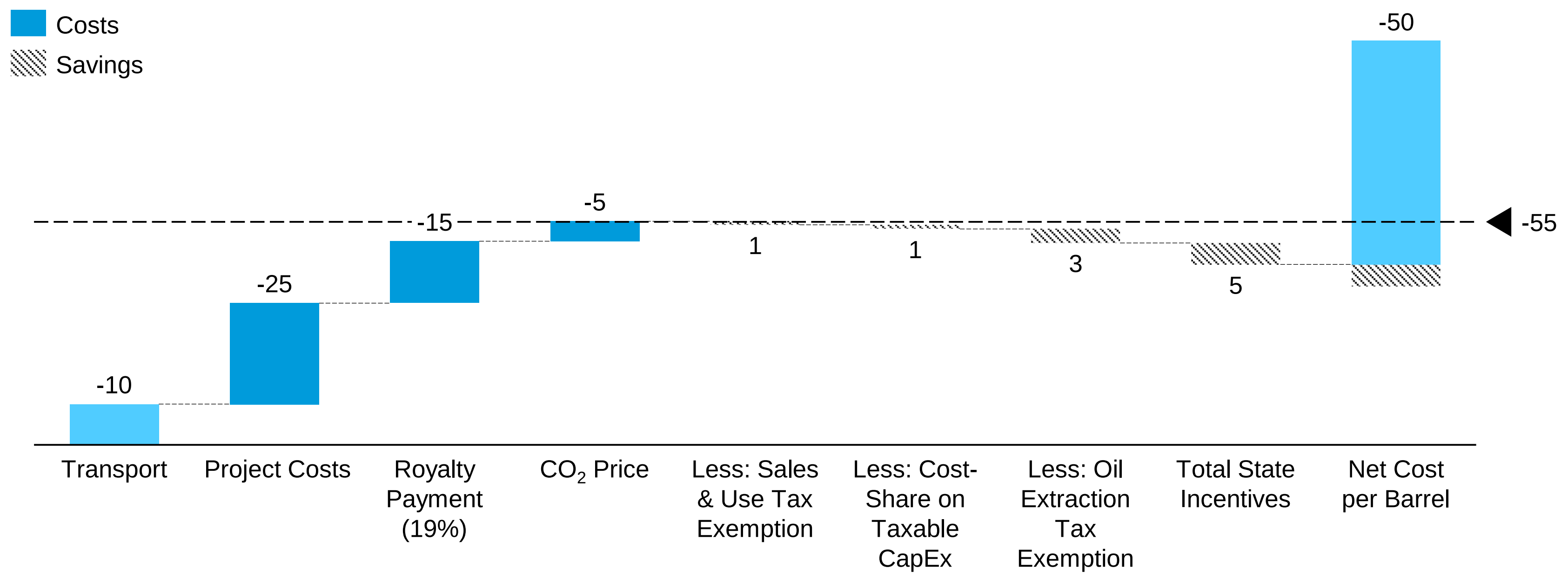
North Dakota state subsidies for EOR incentivize oil extraction instead of CO_2 sequestration, undermining abatement potential

Cost model for single-well EOR project in North Dakota (November 2024)



Assumptions

- Oil price fixed at $80/BBL; all calculations in $/BBL
- CO_2 utilization = 3 barrels of oil per ton injected
- Costs and incentives converted from $/t$CO_2$ to $/BBL
- Tax benefits reflect statutory rates: 19% royalty, 5% extraction tax (86.5% exempt), 5% sales tax
- State incentive values derived from Pelton (2025) model, applicable to typical Bakken CO_2-EOR project

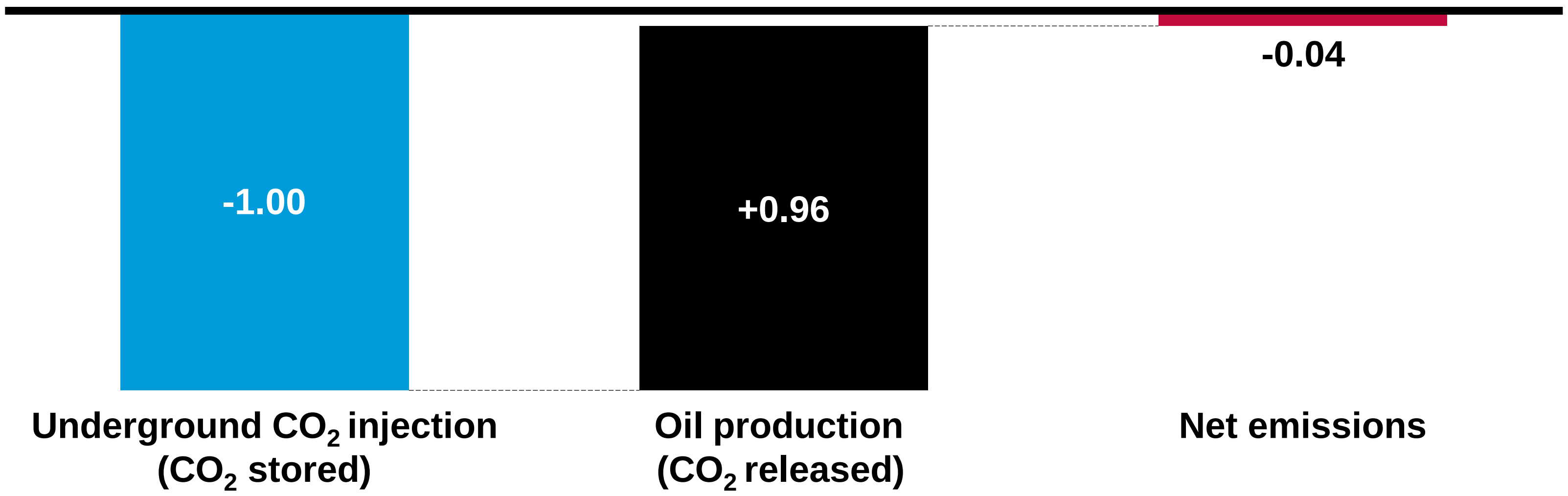
Observations

- State subsidies are misaligned with climate objectives, **fueling increased oil production instead of incentivizing carbon sequestration.**
- At $80-per-barrel oil, producers earn nearly $50 net per barrel, making EOR with CO_2 highly attractive.
- Full Bakken deployment could generate $3B-$9B in oil-linked state revenue over 10 years, **reinforcing extraction over sequestration.**
- North Dakota's policy stack (tax holidays, infrastructure relief) is the most aggressive in the U.S., significantly tilting economic viability toward EOR.

Sources: Office of the North Dakota Tax Commissioner, North Dakota CO2-EOR Financial Analysis (2024).
Credit: Maitreyi Menon, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Even when made with sequestered carbon, EOR delivers minimal net climate benefit and can promote increased oil production

Lifecycle carbon emissions of CO_2-EOR (ton CO_2e/ton CO_2 injected)



For every ton of CO_2 injected into an oil reservoir for EOR production, operators can claim permanent storage.

That same ton of injected CO_2 enables production of ~3 barrels of oil, releasing 0.96 tons of CO_2e when burned.

Once both storage and combustion are counted, **the net negative emissions are just 0.04 ton CO_2e.** This doesn't account for potential storage leaks.

Observations

- **Enhance oil recovery is often promoted as carbon-negative, but lifecycle analysis (CATF, IEA, NETL) shows it is still a source of emissions,** typically 25-40% less per barrel than conventional oil, not zero.
- The apparent benefit relies on perfect, permanent CO_2 storage and assumes the oil produced displaces other oil rather than adding to the total supply.
- For every ton of CO_2 injected, roughly three barrels of oil are produced**, releasing around 0.96 tons of CO_2e when extracted and burned.** If these barrels are additional to global supply, **total emissions increase and the process becomes a net climate harm.**
- At scale, even small per-barrel emission gaps can add up to hundreds of millions of tons of CO_2, offsetting storage gains if demand stays high. **Subsidizing EOR risks locking in fossil fuel infrastructure, prolonging oil use, and delivering minimal emissions cuts.**

Source: Office of the North Dakota Tax Commissioner, North Dakota CO2-EOR Financial Analysis (2024).
Credit: Maitreyi Menon, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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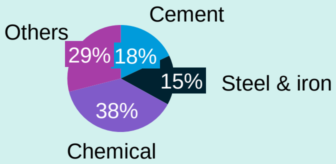
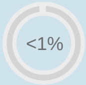
Technology Deep Dive

Two key categories of carbon management — point source and ambient — differ based on the origin and dispersal of emissions

	1 Point-source capture	2 Ambient Carbon Removal
Description	Separation and entrapment of CO_2 before it is released from **large stationary sources** (e.g., industrial plants)	**Removal of CO_2 already in the atmosphere or from biomass energy** by targeting diffuse CO_2 concentrations rather than capturing emissions at the source
Examples	Applications to iron & steel, cement, freight, blue hydrogen & ammonia 	DAC, Field Weathering, Mineralization, Direct Ocean Removal, Ocean Alkalinity Enhancement
% share of total CO_2 captured using carbon capture technologies, by method	 The majority of current capture is industrial point source.	
Current CO_2 absorption (per year)	**~50 $MtCO_2$**	**<1 $MtCO_2$**
Technological readiness level	**High with immediate scalability**	**Low to Medium with limited scalability;** *DAC is medium while the others are relatively low*
Cost of CCUS per ton of CO_2	**$21-$210** depending on industry	**DAC:** $135-345 **Enhanced Weathering:** $50-200 **Ocean Methods:** $50-150

Sources: IEA, CCUS (2025); IEA, BECCS (2023); IEA, DAC (2022); DOE, Pathways to Commercial Liftoff: Industrial Decarbonization (2023).
Credit: Maitreyi Menon, Michelle Priscilla, Anda Wang, Yosafat Partogi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

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Cement production may be the most promising industry for carbon capture application (1/2)

○ R&D/pilot scale ◑ Ready for commercialization ● Mature and commercialized

	1 Iron & steel	2 Cement
Description	• **BF-BOF** or **DRI-EAF** retrofitted with point capture equipment • Captured CO_2 is then **sequestered underground** or **reused**	• Captures CO_2 from limestone decomposition process and subsequently either: • **Sequesters it underground or** • **Reuses it** in the production of low-carbon cement
Technology readiness level	○	◔
Estimated LCOC ($/ton)	**$40-$100**	**$60-$120**
Challenges	**Viability hotly contested** due to **absence of a single, harnessable carbon egress point** and the scarcity of pure carbon	Variety of expensive technologies that are **costly to retrofit and scale across plants**
Future outlook	Continued **technological advancements** to make **effective** and **cost efficient**	Continued **technological advancements** to make **effective** and **cost efficient**
Real-time sector initiatives	ArcelorMittal Carbalyst® captures carbon from a blast furnace and reuses it as bioethanol; tech has **moved beyond "not proven at scale" to being operational** at an industrial demonstration scale	Brevik CCS (Heidelberg) Construction completed; project start operational May 2025

Sources: IEA, Iron and Steel Technology Roadmap (2020); IEA, Is carbon capture too expensive? (2021); Heidelberg, First CO_2 captured in Brevik as part of ramp-up phase (2025); ArcelorMittal, ArcelorMittal announces the first industrial production of ethanol (2023); IEA, Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019 (2020).
Credit: Maitreyi Menon, Michelle Priscilla, Anda Wang, Grace Frascati, Shaurir Ramanujan, Sean Lee, Yosafat Partogi, Christian Sandjaja, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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Ammonia production considered another promising industry for carbon capture application (2/2)

○ R&D/pilot scale ◐ Ready for commercialization ● Mature and commercialized

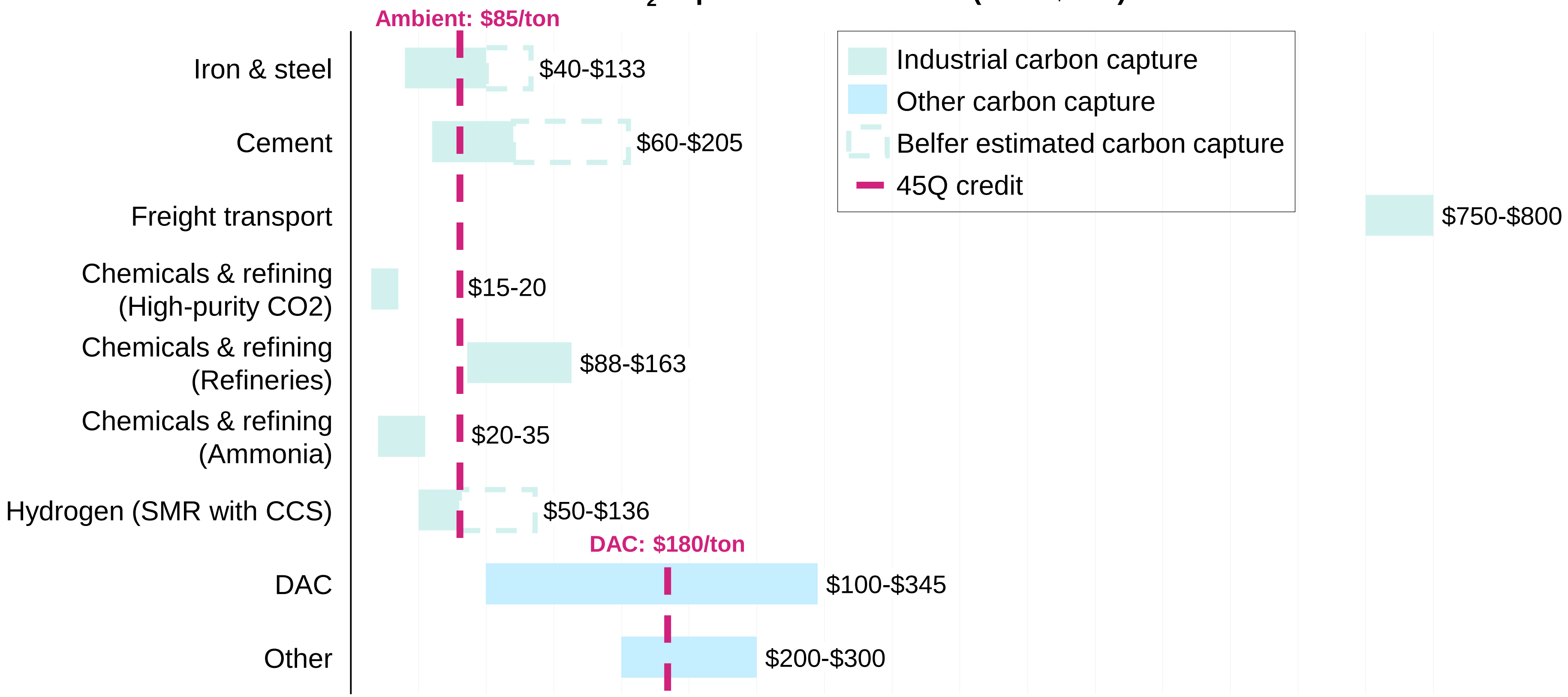
	3 Freight transport	4 Chemicals – blue ammonia and blue hydrogen
Description	• **Shipping:** Onboard CCS with ~90% emission reductions; post-combustion system uses chemical adsorption and advanced cryogenic capture • **Trucking:** Mobile system uses metal-organic frameworks with emissions reductions of ~50%	Fossil-based routes with CCS technology are in various stages: • SMR with CCS (steam methane reforming) – ~60% CO_2 capture for ammonia (blue ammonia) • ATR with CCS (autothermal reforming) – emerging for both ammonia and blue hydrogen **Ammonia** production seen as **more mature**; **blue hydrogen** still **developing**
Technology readiness level	○	◐ For blue ammonia ○ For blue hydrogen
Estimated levelized cost ($/ton)	N/A (marginal abatement cost but not reliable)	$25-$35 for ammonia, $50-$80 for blue hydrogen
Challenges	**Costly installation and operating process, lack of** storage and utilization **infrastructure**, **energy intensive**, discharge **safety issues**	**High associated costs with electrolysis and CCS**; **reliance on natural gas** for feedstock; **lower CO_2 capture** rates for some blue hydrogen processes
Future outlook	Continued technological and policy advancement to **enhance energy, cost, and space efficiency**	- Technological improvements in CCS to reduce costs **- Ammonia: Commercially viable** today **- Blue hydrogen: Transitional solution** until green hydrogen scales
Real-time sector initiatives	Shipping: Value Maritime Filtree System Trucking: Research and MOF design by Pezella and Sarathy	- Nutrien's Redwater Nitrogen Facility in Alberta is producing blue ammonia (conventional ammonia with CCUS) - Moving more firmly into **"ready for commercialization"** for many large-scale industrial applications

Sources: IEA, Iron and Steel Technology Roadmap (2020); Is carbon capture too expensive? (2021); Nutrien, Environmental Performance (2024); DOE, Pathways to Commercial Liftoff: Clean Hydrogen (2024); IEA, Levelised cost of CO2 capture by sector and initial CO2 concentration (2020).
Credit: Maitreyi Menon, Michelle Priscilla, Anda Wang, Grace Frascati, Shaurir Ramanujan, Sean Lee, Yosafat Partogi, Christian Sandjaja, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Cost is an overarching challenge of CO_2 capture, with cost effectiveness the primary focus across industry sectors

Levelized cost of capture is highest for DAC, lowest for other industries

Levelized cost of CO_2 capture across sectors (in US$/ton)



Observations

- High cost is **one of the most frequently cited reasons slowing CCUS adoption.**
- The graph reflects hypothetical capture costs; the **cost of transport and storage also greatly varies** depending mostly on CO_2 volumes, transport distances, and storage conditions.
- In the real world, **Climeworks has achieved a cost of $1,000/ton** and **aims to hit $250-$350/ton by 2030.**
- It can be **more cost effective to retrofit existing facilities with CCUS** than to build new low-carbon production capacity with alternative technologies.
- CCUS is the **cheapest emission reduction option for some chemicals** (~20-40% more expensive than unabated, compared with ~50-115% for higher electrolytic H_2).

Sources: Canary Media, CO_2 Removal (2024); Carbon180, DAC (2024); Eisneramper, 45Q Credit (2023); Lazard, LCOE (2023); IEA, Is carbon capture too expensive? (2021); IEA, Levelized Cost of CO2 (2020); DOE, Pathways to Commercial Liftoff (2024); IEA, Levelized Cost of CO2 Capture by Sector and Initial CO2 Concentration (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs in the U.S. Context (2022).
Credit: Grace Frascati, Anda Wang, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., “Capturing Carbon” (7 November 2025).

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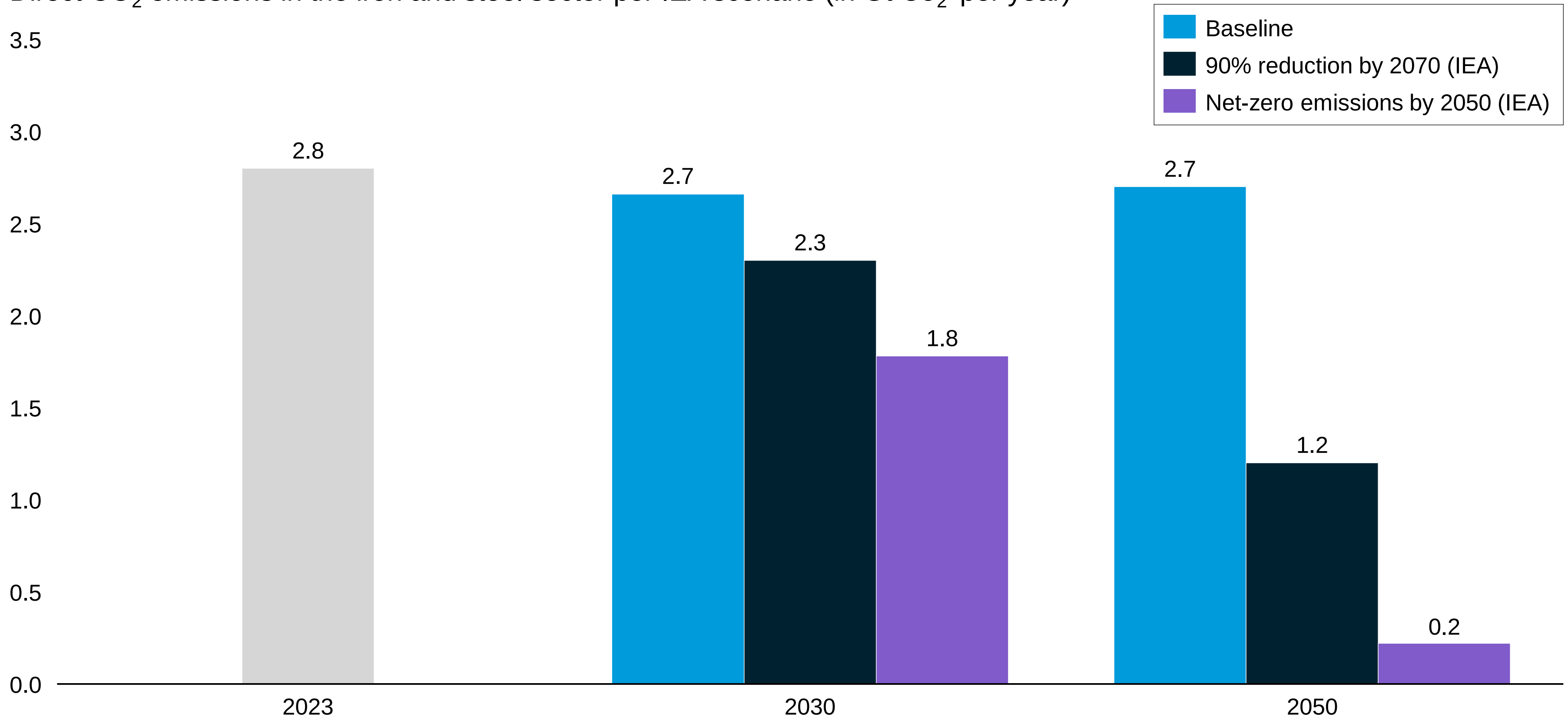
Iron and steel emissions expected to rise without intervention; future reduction scenarios require drastic cuts

Only with intervention will CO_2 from iron and steel decline into 2050

Direct CO_2 emissions in the iron and steel sector per IEA scenario (in Gt Co_2 per year)



Observations

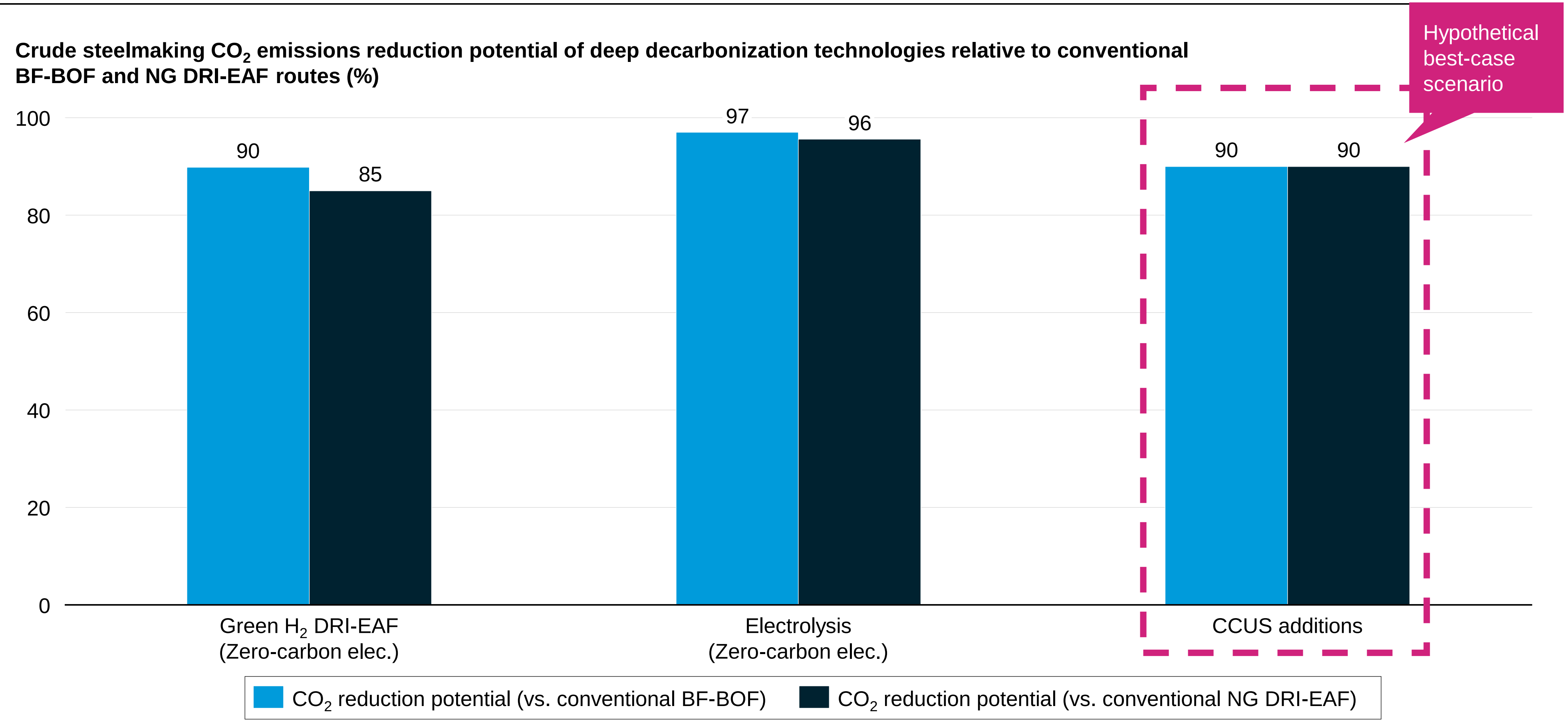
- If no action is taken, **global emissions** from the iron and steel sector are **expected to peak at 2.7 gigatons per year in 2050.**
  - The increase in emissions is attributable **to growing steel demand from emerging economies.**
- **IEA** has developed several possible pathways for the steel industry:
  - In **the 90% reduction by 2070** pathway, emissions would still need to drop by **50% by 2050.**
  - In the net-zero emissions by 2050 pathway, emissions would already need to drop by **25% by 2030** and **drop to close to zero by 2050.**
- **BF-BOF, the cheapest** and **most efficient steelmaking process,** is also the **most polluting.**

Notes: The baseline scenario reflects the policies and implementing measures that have been adopted as of September 2022; NZE = net-zero emissions.
Sources: IEA, Direct CO2 emissions in the iron and steel sector by scenario, 2019-2050 (2020); IEA, Net Zero by 2050 (2021); IEA, Iron and Steel Technology Roadmap (2020); McKinsey, The resilience of steel: Navigating the crossroads (2023); World Economics Forum, Steel industry net-zero tracker (2024).
Credit: Grace Frascati, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Carbon capture with potential to reduce steelmaking emissions by ~90% if scaled, comparable to green H_2 and electrolysis

CCUS retroactively decreases emissions compared with other zero-carbon tech

Crude steelmaking CO_2 emissions reduction potential of deep decarbonization technologies relative to conventional BF-BOF and NG DRI-EAF routes (%)



Observations

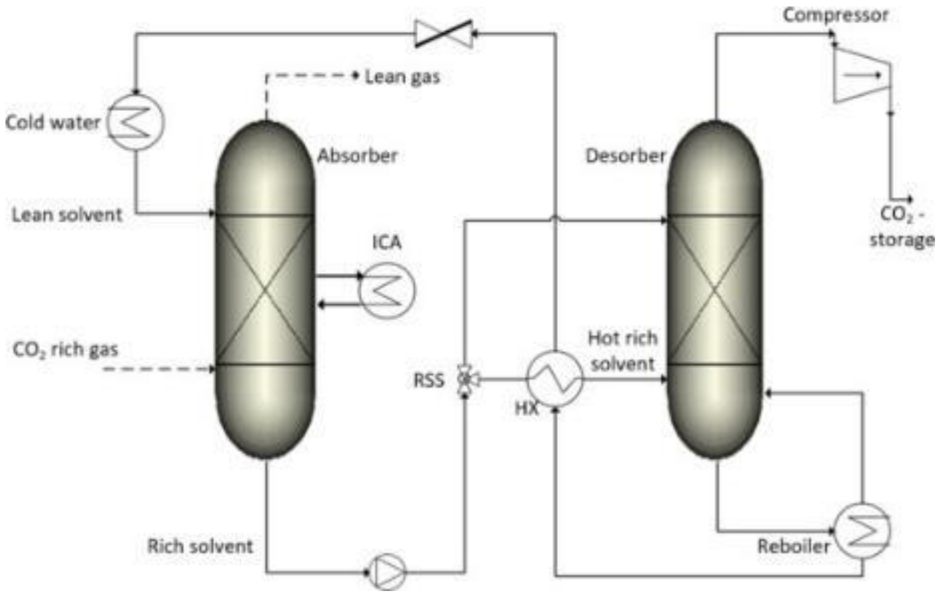
- The 90% CO_2 reduction for CCUS is a **hypothetical best-case scenario,** which at present **has not been proven at scale.**
- Compared with other decarbonization technologies requiring new systems (e.g. DRI-EAF), **carbon capture equipment can be retrofitted** to existing equipment, increasing accessibility; at the same time, it **continues reliance on fossil fuels** (unlike, for example, electrolysis, which proactively decreases fossil fuel needs).

Sources: Columbia Center on Global Energy Policy, Low Carbon Production of Iron & Steel (2021); American Institute of Chemical Engineers, Catalyzing Commercialization: Producing Green Iron with a Zero-Carbon Electrochemical Process (2023); Electra; Boston Metal, Decarbonizing steelmaking for a net-zero future; Midrex, Impact of Hydrogen DRI on EAF Steelmaking (2021); International Journal of Greenhouse Gas Control, A techno-economic analysis and systematic review of carbon capture and storage (2017); Mission Possible Partnership, Net-Zero Steel Sector Transition Strategy (2021).

Credit: Michelle Priscilla, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

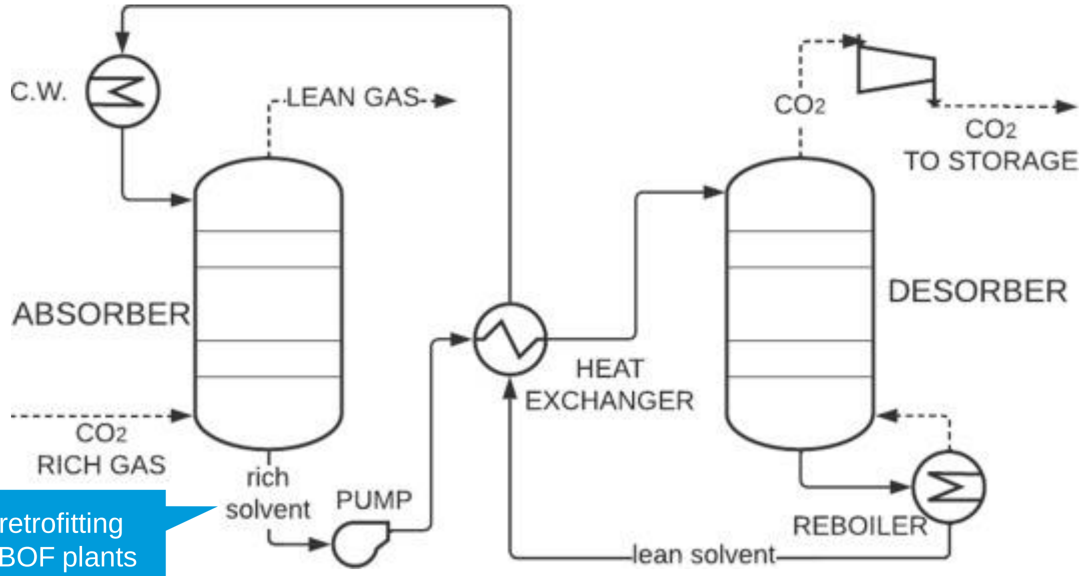
Iron and steel carbon capture possible both pre- and post-combustion

Pre-combustion capture



- **CO_2-rich gas is sent into absorber**, where it interacts with a liquid amine **solvent that absorbs CO_2.**
- **The rich solvent is preheated** by a heat exchanger **before entering the desorber.** Here, **heat** (provided by the reboiler) **separates CO_2 from the solvent.** Pure **CO_2 is sent to storage** or for further **utilization.**

Post-combustion capture



Suitable for retrofitting existing BF-BOF plants

- **CO_2-rich gas is sent to an absorber, where** a **liquid chemical solvent absorbs the CO_2** from the gas, while the remaining gas (low in CO_2) exits the absorber.
- **The CO_2-laden solvent is transported to a desorber for CO_2 separation;** here, heat from the reboiler raises the temperature, causing the **CO_2 to separate from the solvent.**
- **CO_2 is collected** as a concentrated gas and sent to **storage/utilization.**

Sources: Center on Global Energy Policy, Low-Carbon Production (2021); Fuel, Integration of Carbon Capture Tech (2023).
Credit: Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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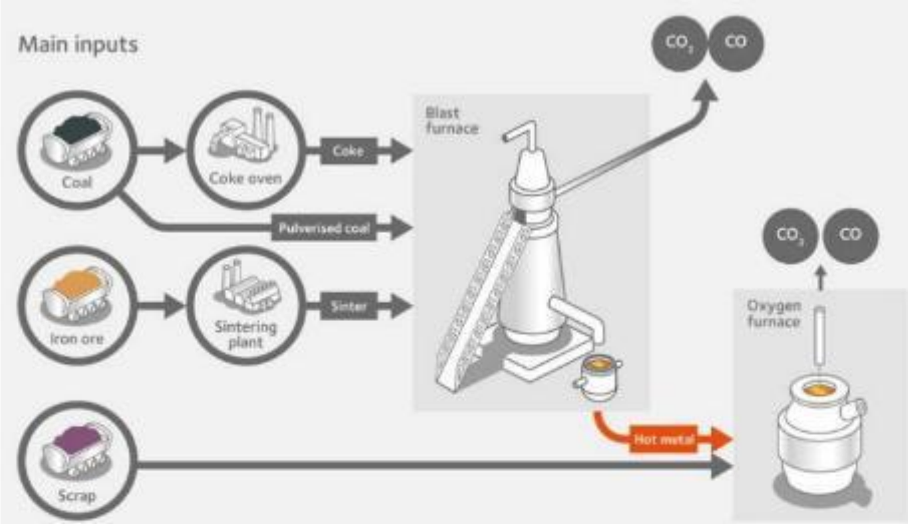
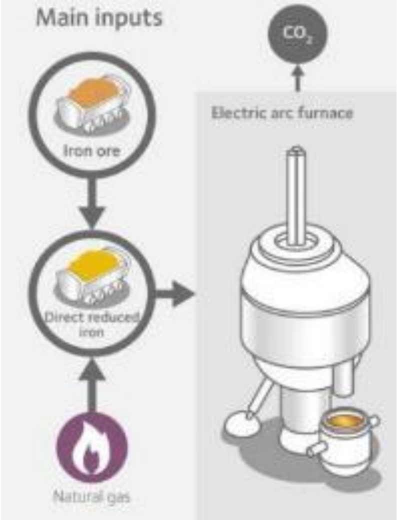
Iron and steel carbon capture can be implemented with BF-BOF or NG DRI-EAF

Blast furnace-basic oxygen furnace (BF-BOF)



- BF-BOF **requires metallurgical coal to be coked first,** with coke oven gases either vented, burned in the BF-BOF, or used in cogeneration. The BF-BOF process **uses coal and carbon monoxide as the heat source and reductant.**
- **Exhaust gases from the process are approximately 20%** but have an unpredictable mix of co-contaminants, complicating CCUS separation.
- While IEA cites $40-$100/ton, a more feasible range may be **$85-$157/ton once (or if) commercialized.**

Natural gas-based direct reduced iron – electric arc furnace (NG DRI-EAF)



- Methane-based DRI **exposes iron ore to H_2 and CO syngas at a lower temperature of 900°C.**
- When using an autothermal process (e.g., Tenova) instead of steam methane reforming (standard Midrex), the **resulting CO_2 is nearly pure.**
- This approach could potentially reduce CO_2 costs to **$40-$80/ton** once commercialized.

Sources: Midrex, Impact of Hydrogen DRI on EAF Steelmaking (2021); ArcelorMittal, Climate Action Report 2 (2021), World Steel Association (2021); Wiley, Physical and policy pathways to net-zero emissions industry (2019); IEEFA, Fact Sheet (2022); IEA, Iron and Steel Technology Roadmap (2020).
Credit: Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., “Capturing Carbon” (7 November 2025).

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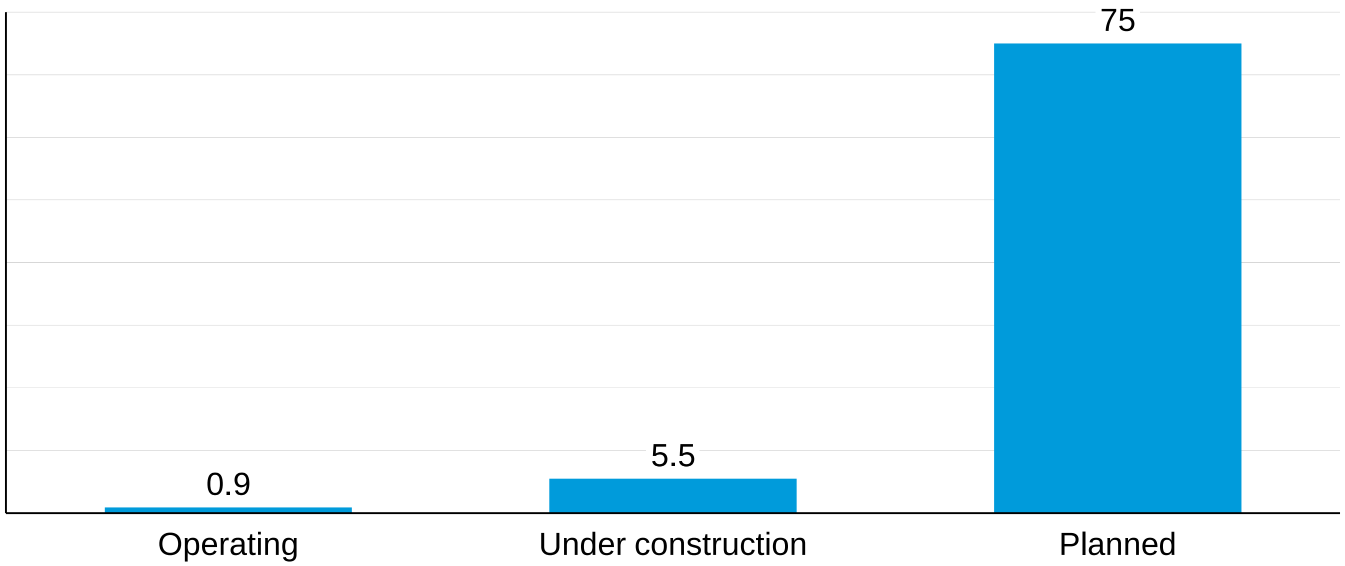
Technological potential for iron and steel CCS exists but is not yet proven at scale

Capture facilities available today

Estimated CCUS capture capacity
in 2025, in Mtpa CO_2



CCUS facilities: **2** (Operating), **3** (Under construction), **50+** (Planned)

- Operating: Baotou Steel and Emirates Steel
- Under construction: ArcelorMittal and Tata Steel

Considerations

Pros

- Offers potential for **considerable emission reduction** of this **heavy-emitting, hard-to-abate sector.**
  - If done successfully, could serve as a **case study for other hard-to-abate sectors.**
- Can be used with **existing equipment through retrofits.**
- Captured CO_2 **can be used for enhanced oil recovery**, **increasing the efficiency of oil extraction** and providing an **additional revenue stream.**

Cons

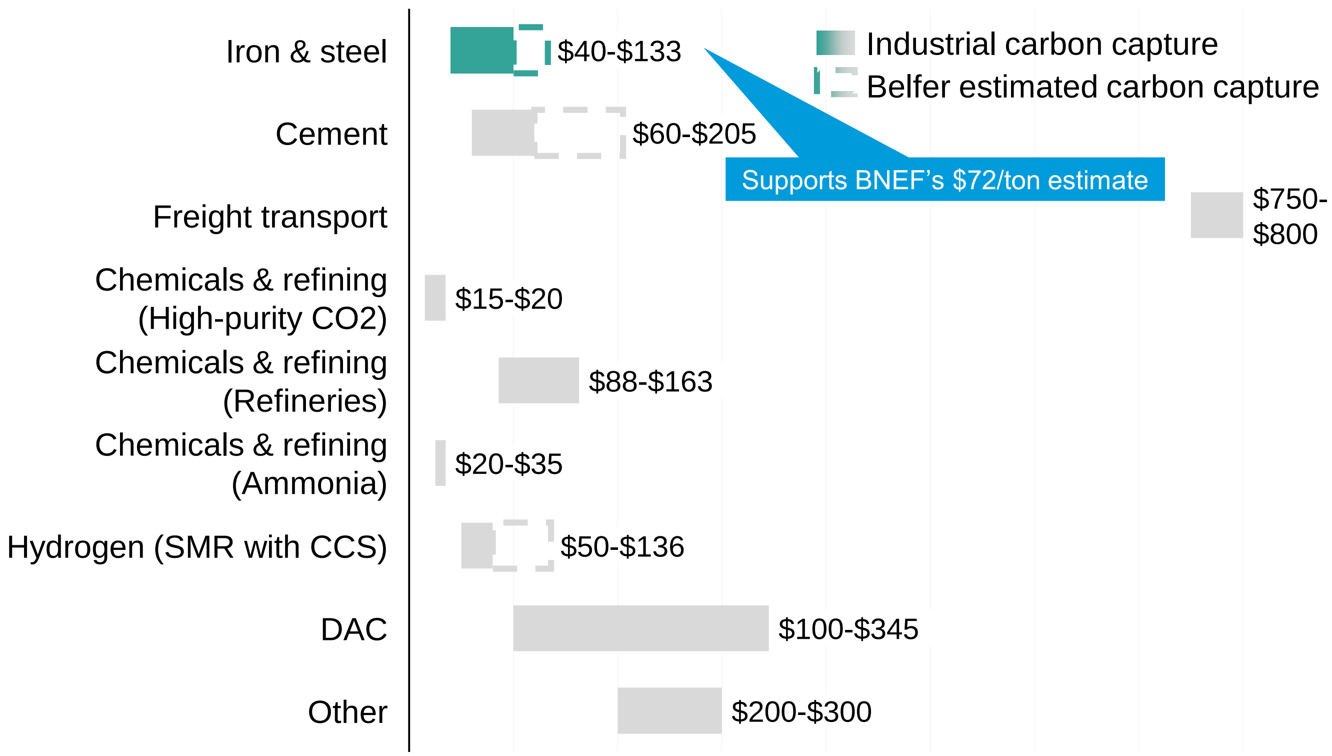
- **Technology is not yet proven at scale**, making it **difficult to secure conviction and funding.**
- **Costs are significant** with **no guarantee of effectiveness**, making for **risky** investments.
- Does **not remove reliance on fossil fuels** in steel-making.

Sources: AZO Cleantech, The Advantages and Disadvantages of Carbon Capture (2022); Center on Global Energy Policy, Low-Carbon Production of Iron and Steel (2021); IEA, Iron and Steel Technology Roadmap (2020); IEA, Is carbon capture too expensive? (2021); LETA, CCUS case studies (2025); Global CCS Institute, Facilities Database (2025).
Credit: Michelle Priscilla, Anda Wang, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Capture costs in iron and steel indicate $40-$159/ton CO_2, though total CCUS cost is much higher and range from use of scrap

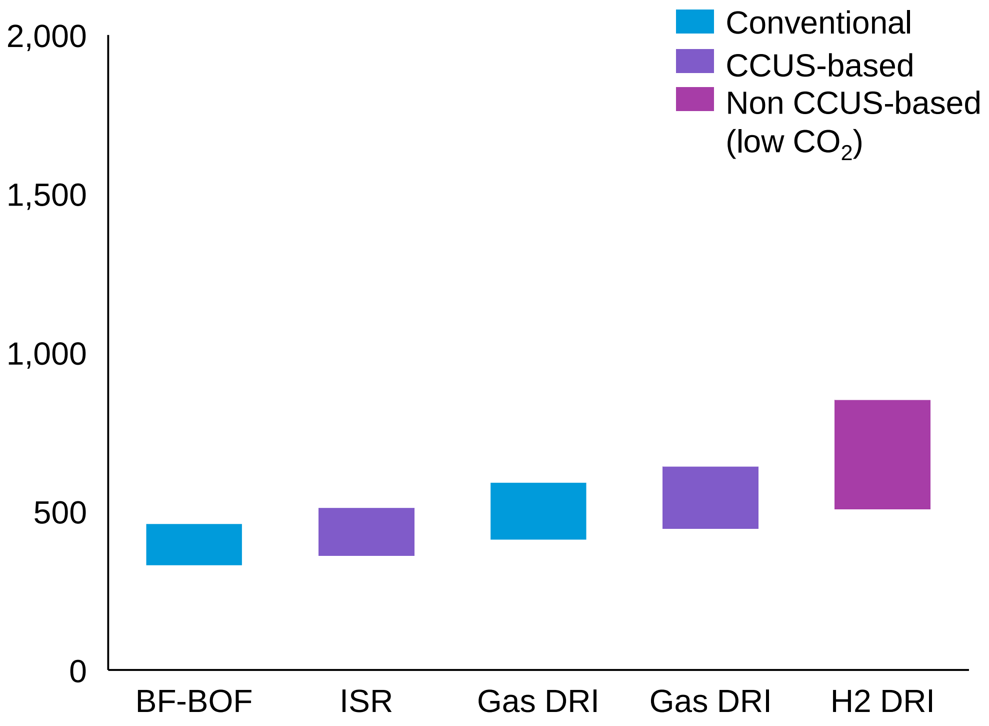
Iron and steel levelized cost is on the lower end of overall industry range

Levelized cost of CO_2 capture across sectors (in US$/ton)



CCUS adds to cost consideration but is cheaper than hydrogen-based DRI

Simplified levelized cost of competing low-carbon tech in steel production

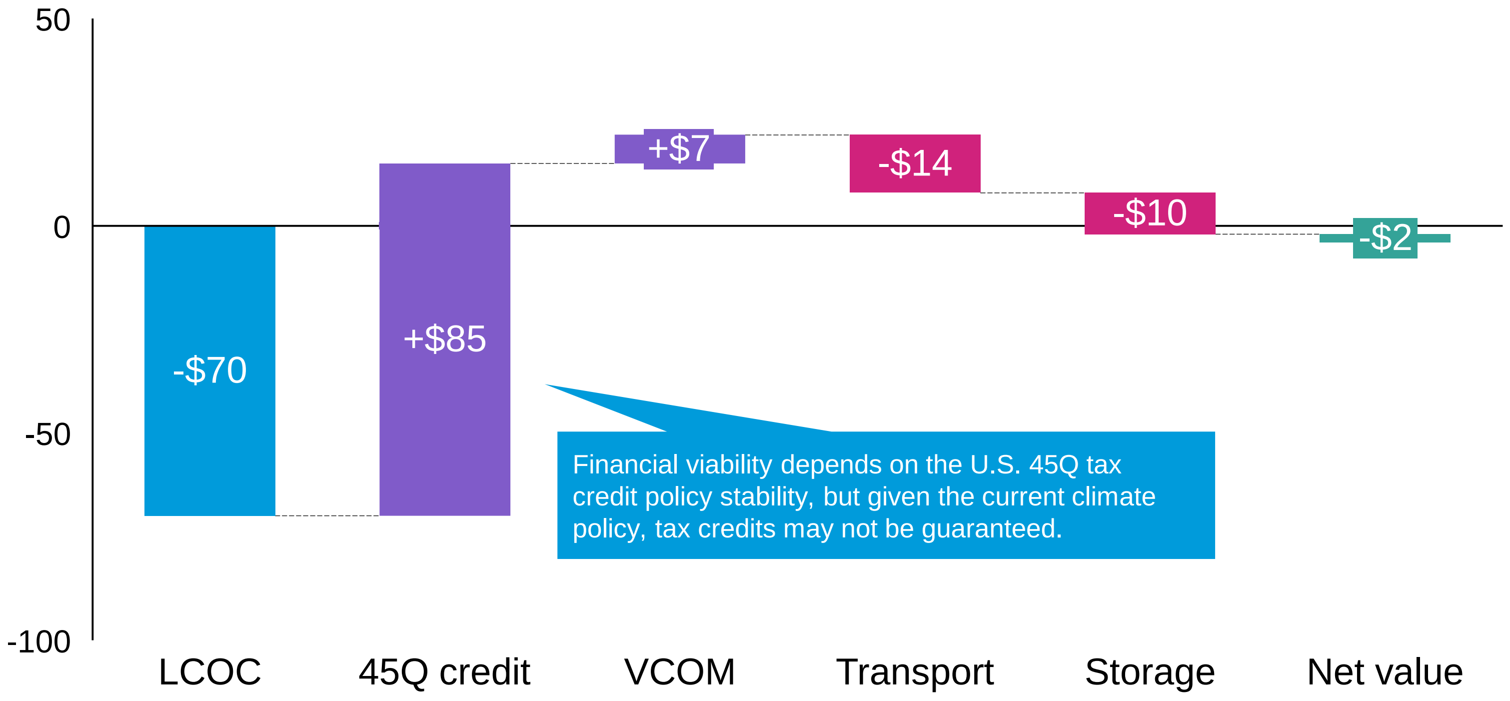


Note: Iron and steel recycling incorporates scrap steel. Sources: Arcelor Mittal, LanzaTech partnership (2021); Bloomberg, CCUS market (2023); IEA, CCUS Projects Explorer (2024); IEA, Iron and Steel Technology Roadmap (2020), IEA, Is carbon capture too expensive? (2021); Masdar, CCUS at Emirates Steel (2012); DOE, Pathways to Commercial Liftoff (2024); IEA, Levelized Cost of CO2 Capture by Sector and Initial CO2 Concentration (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs US Context (2022).
Credit: Grace Frascati, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Carbon capture for iron and steel continues to face economic hurdles, even with current credits

Even with the 45Q credit, CCUS for iron and steel may not be economically feasible

Permanent storage + 45Q tax credit monetization, in $/ton CO_2



Observations

- ArcelorMittal's Steelanol project has received **funding from various sources, including from the European Union's Horizon 2020 program, the European Investment Bank, and the Belgian and Flemish governments** (details not disclosed).
- While specific funding details are not readily available, **Emirates Steel's CCUS project** is supported by major organizations (Masdar and ADNOC).
  - **Funding has been fueled by a lack of other viable options** for addressing this hard-to-abate sector (BF-BOF is a very efficient process, though carbon intensive).
- Otherwise, capturing carbon in the iron and steel industry benefits from the **same generic subsidies (e.g., 45Q tax credit).**

Note: Uses $70, the average from prior slide, as LCOC. Uses $14 and $10 transport and storage costs, on the higher end of general (i.e., non-iron and steel specific) IEA estimates, for a more conservative approach; ~$7 VCOM is also a general figure.

Source: ArcelorMittal, LanzaTech partnership (2021); Bloomberg, CCUS market (2023); IEA, Iron and Steel Technology Roadmap (2020); IEA, Is carbon capture too expensive? (2021); Masdar, CCUS at Emirates Steel (2012).

Credit: Grace Frascati, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Case study: ArcelorMittal, one of only two operational projects in the industry, uses LanzaTech to capture carbon-rich waste gases

Plant overview

- **Carbalyst®,** also known as **Steelanol,** uses technology developed by **LanzaTech to capture carbon-rich waste gases** emitted from the blast furnace during the steelmaking process and **convert them into recycled carbon chemicals.**

- The project is an **industrial-scale demonstration plant** at ArcelorMittal's steelworks **in Ghent, Belgium.**

CCS expansion

- **Proven effective reduction of hard-to-abate emissions:** Cuts steel production emissions, advancing ArcelorMittal's 2050 NZE goal.
- **Establishes company as a sustainability leader:** By repurposing captured CO_2, ArcelorMittal promotes sustainability and leads CCUS adoption in steel.

Key statistics

Reduces CO_2 emissions by…

125,000 tons of CO_2 per year

Produces bioethanol at a rate of...

80M liters per year

Received funding to help finance the...

€180M project from the European Union's Horizon 2020 program, European Investment Bank, and Belgian and Flemish governments (details not disclosed)

LanzaTech received investment of…

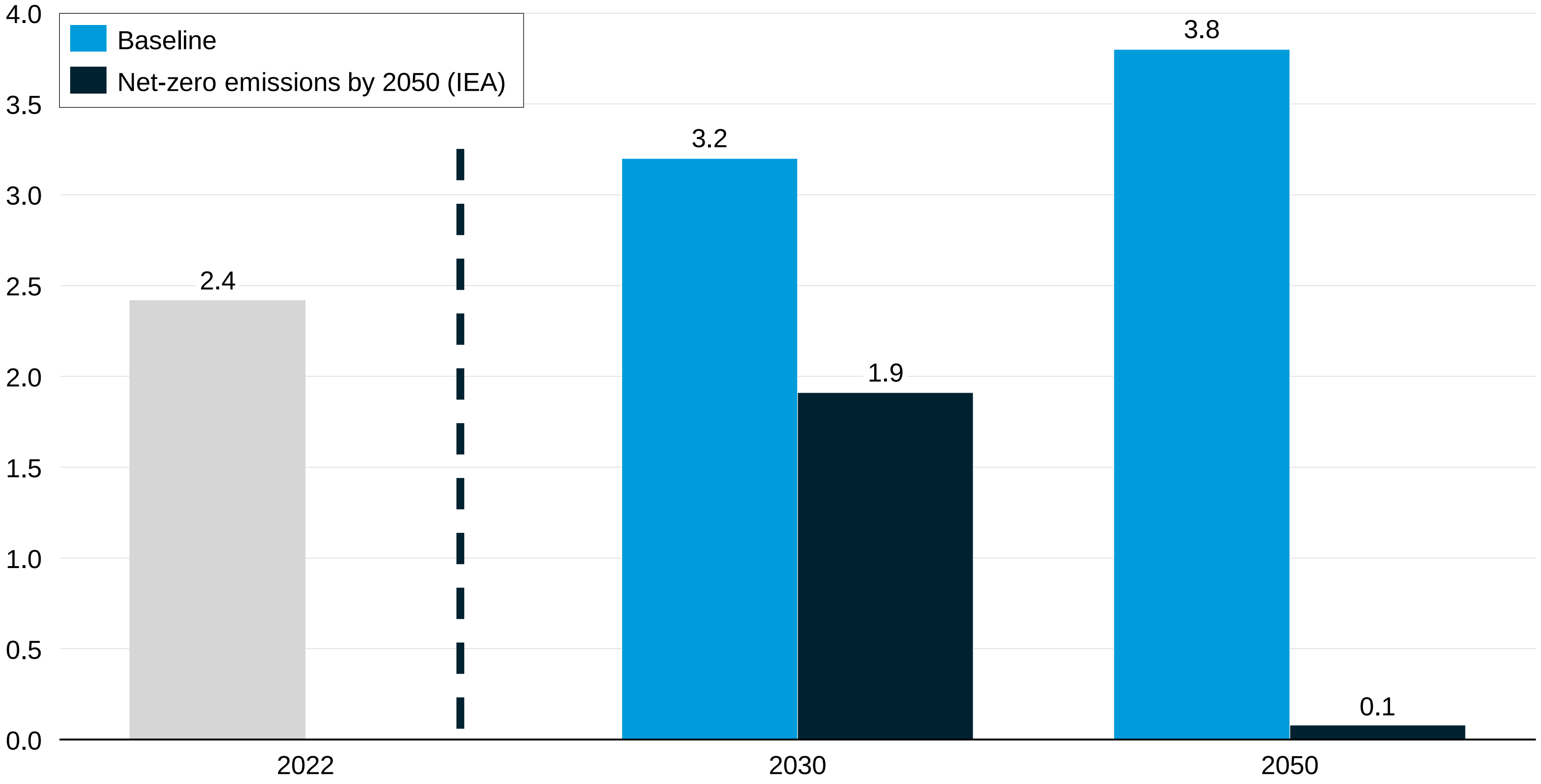
$30M from ArcelorMittal's XCarb Innovation Fund (most funding is private)

Sources: ArcelorMittal, Carbalyst, LanzaTech (2021); Georgeault, ArcelorMittal (2022).
Credit: Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Cement emissions expected to rise dramatically absent scaling carbon abatement technology, particularly in China

Only with intervention will CO_2e from cement decline into 2050

Direct CO_2 emissions in the cement sector per IEA scenario (in Gt CO_2 per year)



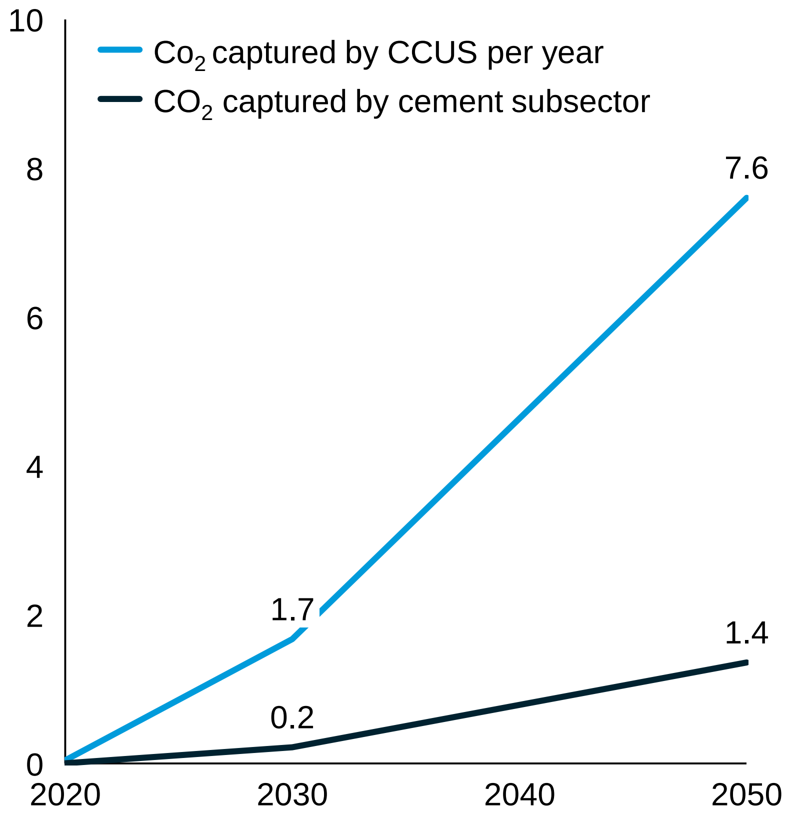
Observations

- If no abatement measures are taken, **global emissions** from the cement sector are **expected to peak at 3.8 gigatons per year in 2050.**
  - Increase in emissions attributable **to growing construction from emerging economies** with **increased population and infrastructure needs**
- **IEA** has developed a net-zero pathway for the cement industry that assumes the following:
  - A 30- to 40-year lifetime for cement kilns
  - Hydrogen and CCUS playing an outsized role in achieving emissions reductions
  - **Bioenergy** accounting for **30% of energy demand in cement production by 2050**
- Most projections assume a **linear rise in alternative fuels** and **minimal changes in fundamental kiln structure.**

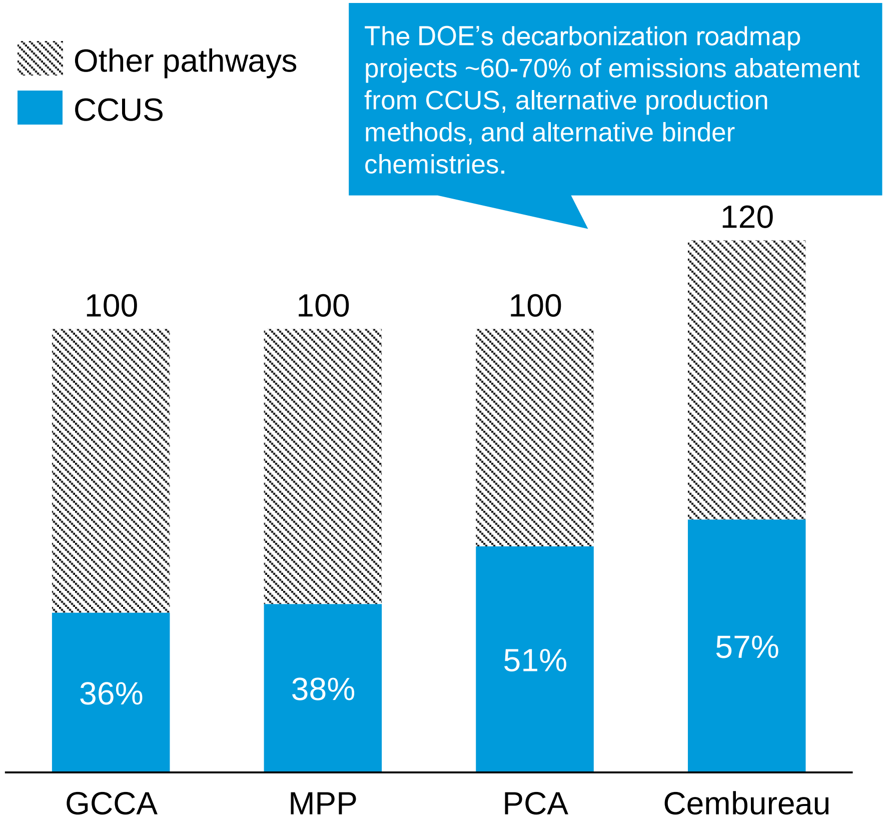
Sources: IEA, Net Zero by 2050 (2021); BCG, Cement's Carbon Footprint Doesn't Have to be Set in Stone (2024); Nature Communications, Projecting future carbon emissions from cement production in developing countries (2023).

Carbon capture, utilization, and storage projected to abate cement sector emissions not abated by other technologies

IEA targets for CO_2 captured, 2020-50
Gt CO_2



Abatement from CCUS by decarbonization roadmap, 2050
Percentage



Observations

- **~55% of the cumulative emissions reductions from CCUS** will rely on technologies that are currently at the demonstration or prototype stage.
- Heidelberg received Norwegian government funding in 2020 to build a **full-scale carbon capture and storage facility** at its factory in Brevik. Completed in 2024, the project anticipates reducing emissions by **400,000 tons of CO_2 annually.** The project is in the **final commissioning phase** and is expected to be fully operational in the second half of 2025.
- In 2018, China-based Anhui Conch invested $10 million in a carbon capture project to capture **50,000 tons of CO_2 annually;** however, it is a "loss maker," as there is a **limited local market** for the captured CO_2.

Sources: IEA, Net Zero by 2050 (2021); IEA, Cement (2023); Global Cement Magazine, CCUS (2024); International Cement Review, China starts CCUS focus (2024); Heidelberg, First global net-zero carbon capture and storage facility in the cement industry (2024); GCCA, Concrete Future (2021); Mission Possible Partnership (2023); PCA, Roadmap to Carbon Neutrality (2024); DOE, Low Carbon Cement (2023), Cembureau, From Ambition to Deployment (2024).
Credit: Michelle Priscilla, Anda Wang, Shaurir Ramanujan, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Despite policy uncertainty, a broad range of instruments have been implemented to decarbonize cement manufacturing

Enabler	Policy type	Policy instrument	Key examples	Impact
Risk management	Risk-sharing	Financial certainty to innovators (through subsidies and incentives)	• EU Carbon Contracts for Difference • U.S. DOE Industrial Demonstration Program	Provides financial certainty to innovators by sharing investment risks in early-stage low-carbon technologies, incentivizing adoption and de-risking the transition to decarbonization solutions
Technology	Incentive-based	R&D direct funding	• EU Innovation Fund	Grant funding provided for **20+ cement CCUS projects** in **eight countries**
		Supporting regulations	• EU Net-Zero Industry Act	Strengthens regulations and creates targets and permitting environment to boost CCUS technology investments; **entered into force in July 2024**
	Market-based	Carbon price	• EU Emissions Trading System (ETS) • California ETS • China ETS (expand the ETS to include the cement sector)	Incentivizes cement producers to reduce emissions by trading credits
		Border adjustment tariff	• CBAM (full implementation in **2026**) • Prove It Act (under discussion)	Emission-intensive cement exporters to the EU face a cost escalation of up to 100%; needs to be complemented by transparent carbon accounting standards
Demand	Incentive-based	Green public procurement (GPP)	• GPP concrete product policies in Germany, the Netherlands, the UK, and Sweden • Federal Buy Clean Initiative in the U.S.	Creates a viable market for low-emission cement through GPP commitments
	Mandate-based	Building/end-use product codes and standards	• Embodied carbon limit policies in the Netherlands, Sweden, France, and Germany • U.S. General Services Administration low embodied carbon concrete standards in the U.S.	Provides a clear market signal to low-emission cement production
Infrastructure	Incentive-based	CCUS infrastructure direct funding	• Public funding of CCUS hubs in the EU • CCUS hubs provision under Bipartisan Infrastructure Law	Over **$15 billion** committed to develop CCUS hubs in the U.S. and the EU
Capital	Incentive-based	Tax credits/subsidies	• CCUS tax credits under Inflation Reduction Act	**20-30%** reduction in costs to deploy CCUS in cement plants; extended 45Q credit results in a CCUS cost of **$15-$65/ton** in cement plants

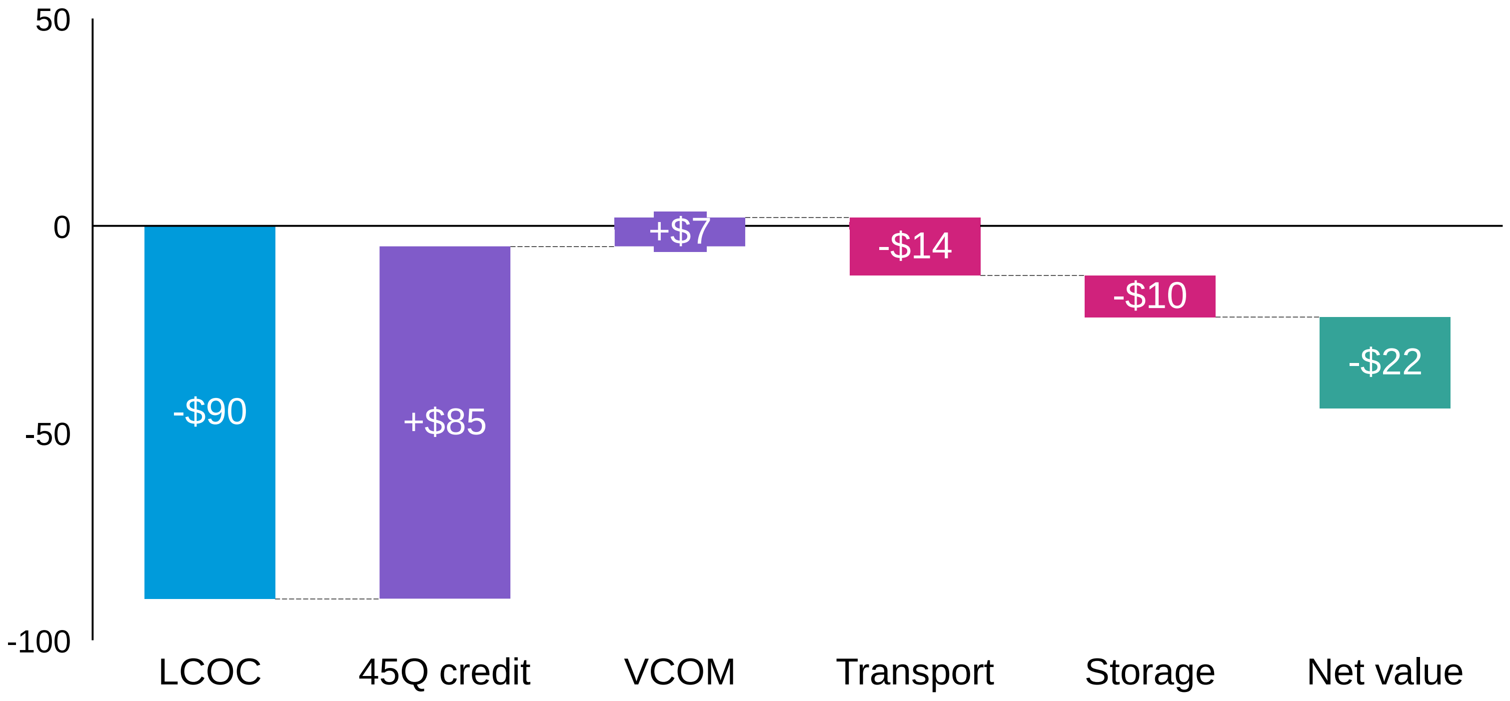
Sources: WEF, Net-Zero Industry Tracker (2023); Climate Bond, Cementing the global net-zero transition (2023); EC, EU Innovation Fund (2024); Global Policy Watch, EU Net-Zero Industry Act (2024); EC, EU ETS (2024); ICAP, California ETS (2024); EC, EU CBAM (2024); UNIDO, GPP Pledge (2023); Office of the Federal Chief Sustainability Officer, Federal Buy Clean Initiative (2024); S&P Global IRA 45Q (2023); CATF, EU CCfDs (2024); DOE, DOE's Industrial Demonstrations Program (2023); EC, EU Innovation Fund projects (2025).

Credit: Shaurir Ramanujan, Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Significant reduction in LCOC and stronger financial incentives key to achieving economically feasible cement CCUS projects

Even with the 45Q credit, CCUS for cement is not currently economically feasible

Permanent storage + 45Q credit monetization, in \$/ton CO_2



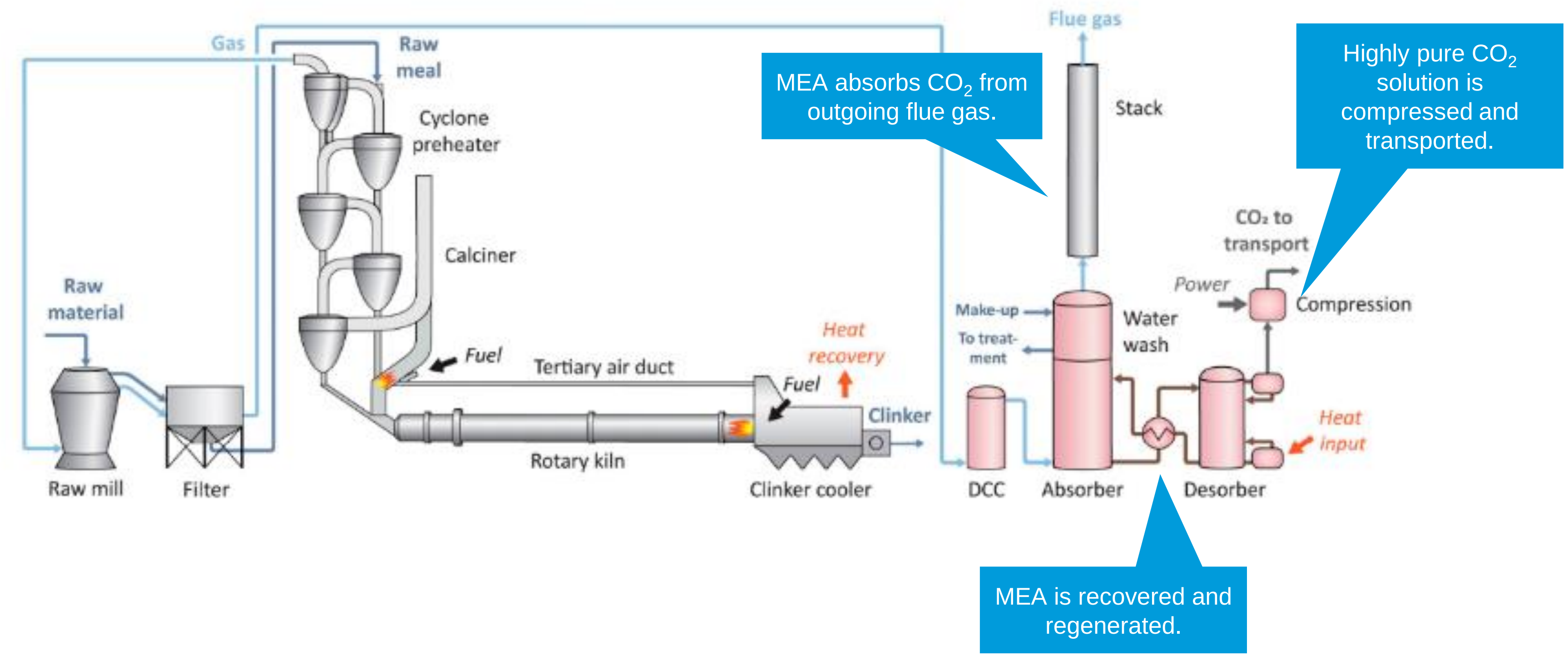
Observations

- Heidelberg has enjoyed generous funding from the **Norwegian government** for its **Brevik plant.**
- In January 2025, the U.S. Department of Energy offered **\$101 million** in funding for **five projects** to build new CCUS testing centers at cement plants.
  - Another Cemex plant project in Germany, estimated to capture **1.3 million MtCO$_2$** annually, received **\$164 million** from the EU Innovation Fund in October 2024.
- Otherwise, capturing carbon in the cement industry benefits from the **generic subsidies (e.g., the 45Q tax credit).**

Notes: Uses \$90, the industry average, as LCOC. Uses \$14 and \$10 transport and storage costs, on the higher end of general (i.e., non-iron and steel specific) IEA estimates, for a more conservative approach; ~\$7 VCOM is also a general figure. Sources: DOE, Industrial Demonstrations Program (2024); Businesswire, EU backs pioneering CO_2 capture project at Cemex's Rüdersdorf Cement Plant (2024); Agg-Net, Cemex cement plant chosen for US DOE-funded CCUS project (2025); ArcelorMittal, LanzaTech partnership (2021); Bloomberg, CCUS market (2023); IEA, Iron and Steel Technology Roadmap (2020); IEA, Is carbon capture too expensive? (2021).
Credit: Shaurir Ramanujan, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Capturing carbon in the hard-to-abate cement industry done by retrofitting post-combustion technology

Carbon capture process



Observations

- Hot limestone is transformed into **Portland cement clinker**, providing cement with cohesive properties.
- **Two-thirds of emissions are from reactions in the chemical process of heating limestone**, making CCS an attractive abatement solution.
  - Process emissions associated with the decomposition of calcium carbonate are **non-fossil fuel emissions that only CCS can resolve.**
- While there are many early-stage technologies to retrofit existing processes with CCS, the most common reference point is using **monoethanloamine (MEA)** a solvent that **filters and absorbs CO_2 from flue gas.**
- **Captured CO_2 is subsequently compressed and stored** in a separate facility or underground.

Sources: MDPI, Energies, Comparison of Technologies for CO_2 Capture from Cement Production – Part 1: Technical Evaluation (2019); Scientific American, Solving Cement's Massive Carbon Problem (2023).
Credit: Shaurir Ramanujan, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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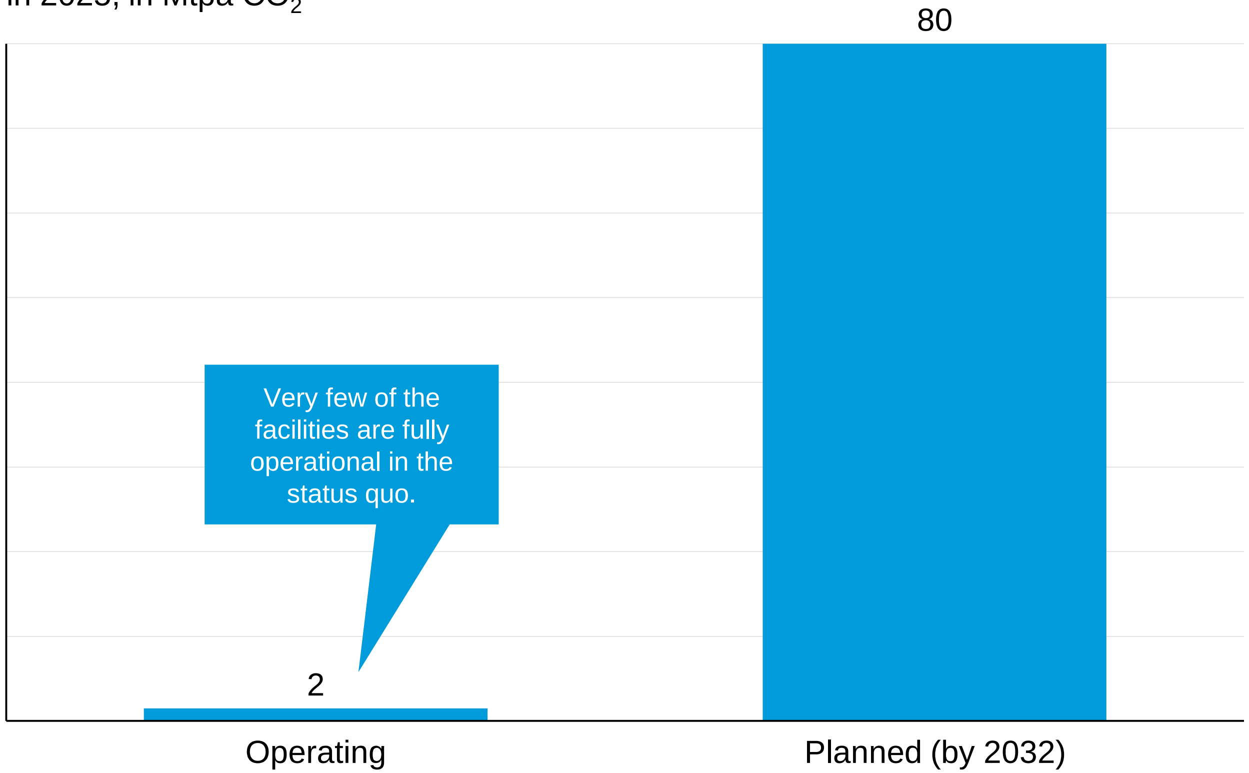
Climate Knowledge Initiative

Despite immense potential for GHG reduction in cement, CCUS remains untapped because results are largely unproven

Capture facility available today

Estimated CCUS capture capacity
in 2025, in Mtpa CO_2



Considerations

Pros

- Provides feasible emissions abatement alternative for **hard-to-abate industry with limited cost-efficient options.**
- A portfolio of technologies should be used for **retrofitting existing plants,** with a preference for post-combustion technology.
- Some industry plants may inject captured CO_2 to be **permanently stored in cement,** a process known as **carbon mineralization.**

Cons

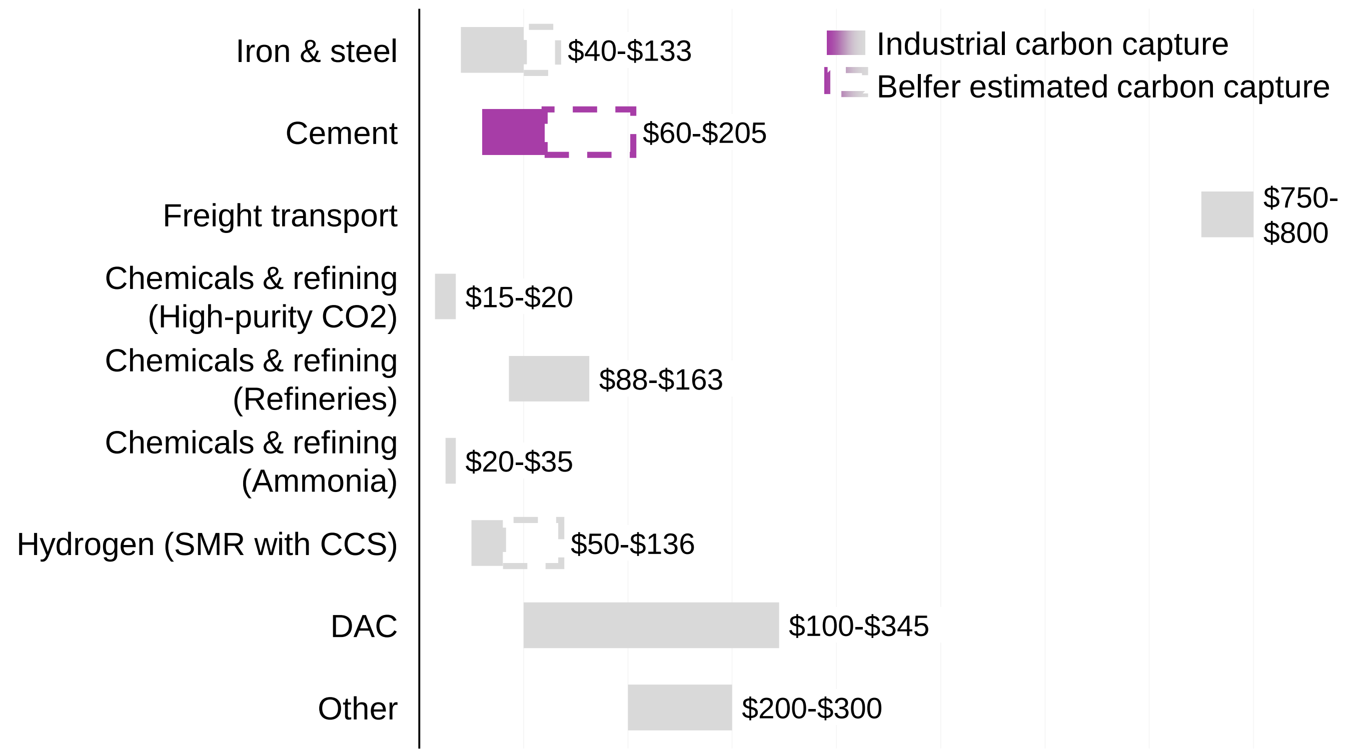
- **Many projects will not be operational until or beyond 2030**, thereby making it an unreliable solution to implement at scale.
- Most projects are announced in **Europe, North America, and Australia,** though **58% of cement is produced in China and India** alone.
- The effects of **oceanic carbon storage** on marine ecosystems remains unclear.

Sources: IEA, CCUS Projects Database (2024); BBC, The environmental cost of China's addiction to cement (2024); IPCC, Ocean storage (2018); IEA, Is carbon capture too expensive? (2021); Global CCS Institute, Facilities Database (2025).
Credit: Michelle Priscilla, Anda Wang, Shaurir Ramanujan, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

The cost of capturing carbon in the cement industry ranges from $60-$134 US$/ton

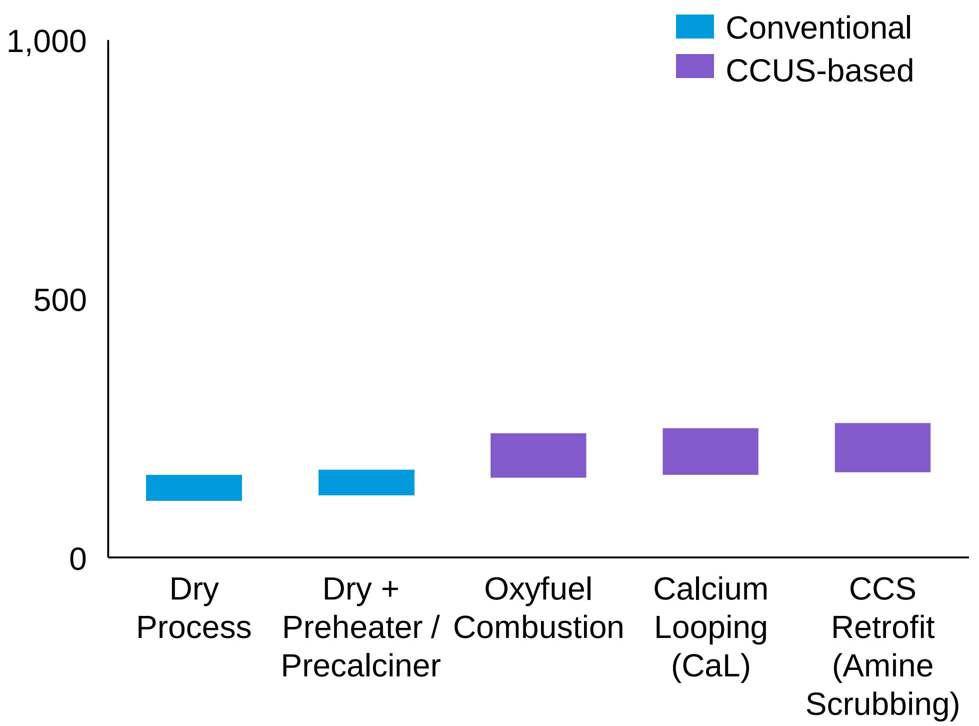
Cement levelized cost is on the lower end of the overall industry range

Levelized cost of CO_2 capture across sectors (in US$/ton)



CCUS-based cement technologies can double production cost vs. conventional methods

Simplified levelized cost of competing low-carbon tech in cement production



Sources: IEA, Is carbon capture too expensive? (2021); IEA, CCUS in Clean Energy Transitions (2020); Carbon Capture Coalition, Primer: 45Q Tax Credit for Carbon Capture Projects (2023); WRI, U.S. Investment in Abating Cement Emissions (2024); MDPI, Energies, Comparison of Technologies for CO2 Capture from Cement Production – Part 2: Cost Analysis (2019); DOE, Pathways to Commercial Liftoff (2024); IEA, Demand and Supply Measures for the Steel and Cement Transition (2024); IEA, Levelized Cost of CO2 Capture by Sector and Initial CO2 Concentration (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs US Context (2022).
Credit: Shaurir Ramanujan, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Case study: Heidelberg Materials’ Norcem plant scheduled to have the largest CCS operation by 2025

Plant overview

- The project directly captures the same amount of CO_2 emissions as **80,000 cars**, which is then stored and pumped a mile beneath the **seabed of the North Sea.**
- Announced in 2020 and mechanically completed in December 2024, the project is an **industrial-scale plant** at Heidelberg’s cement plant **in Brevik, Norway.**

CCS expansion

- **Effective reduction of hard-to-abate emissions:** Cutting cement production emissions allows the company to work toward its goal of saving 10 million tons of CO_2 by 2030.
- **Heidelberg as a product innovator:** New evoZero cement brand provides an opportunity to leverage CCS as a first mover in providing verifiable net-zero products.

For context, China’s 13 CCUS-equipped power and cement plants captured 856,000 tons of CO_2 per year as of 2022.

Key Statistics

Reduces CO_2 emissions by

400,000 tons per year

Reduces plant emissions by

50% per year

Heidelberg is investing…

€1.5B in CCUS projects by 2030

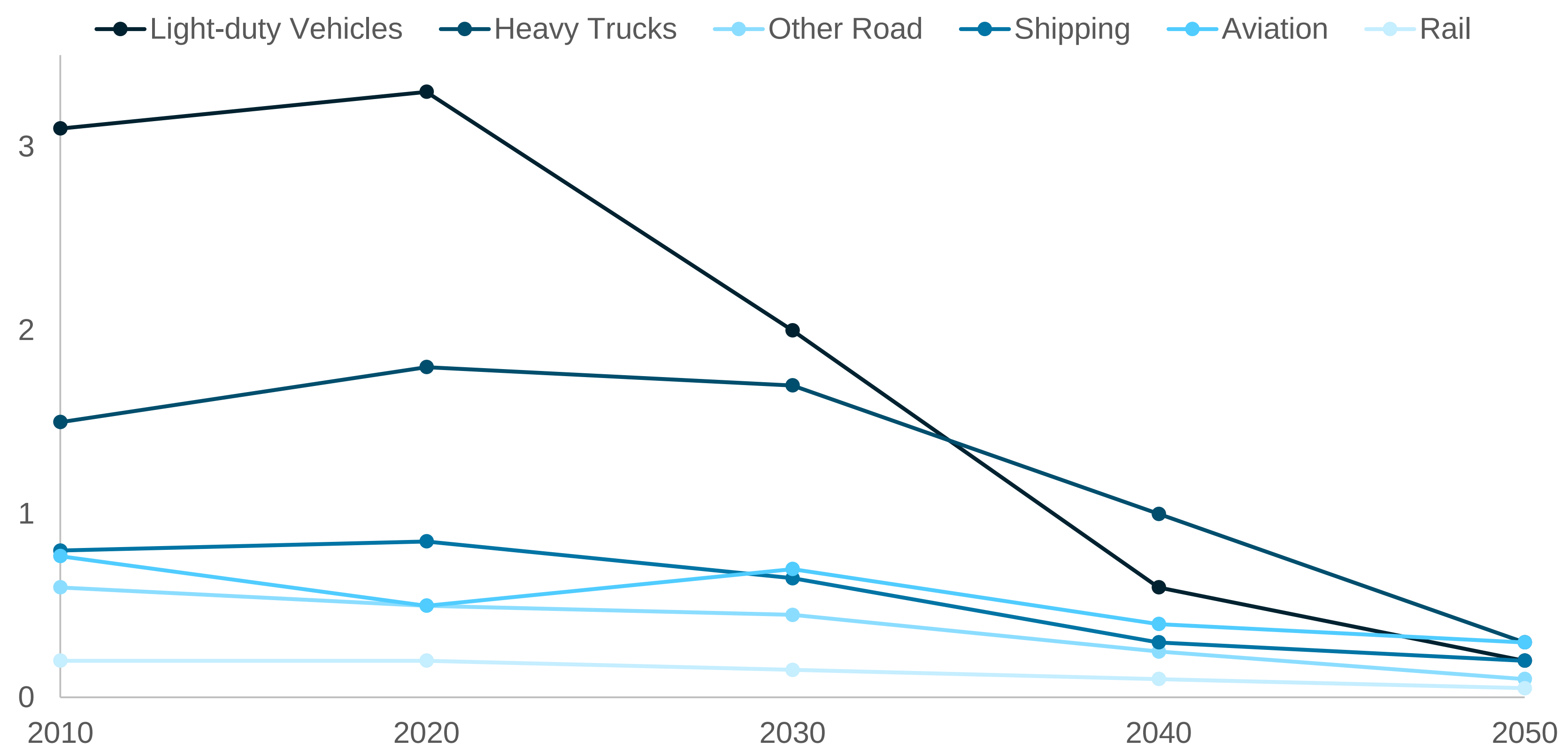
Received investment through a…

$2.6B cost-sharing initiative launched by the Norwegian government in 2020 to advance industry-wide CCS development

Sources: Heidelberg Materials, Brevik CCS (2024); Bloomberg, Norway Carbon-Capture Plant Hits Longship Project Milestone (2024); World Cement, Heidelberg Materials has launched the worlds first net-zero cement (2023); Norwegian government, Longship goes into operation (2025); Liu et al., China’s pathways of CCUS under carbon neutrality vision 2060 (2022).
Credit: Shaurir Ramanujan, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., “Capturing Carbon” (7 November 2025).

Freight transport emissions are high and only increasing; CCUS is a critical intermediary solution necessary to meet NZE scenarios

Global CO_2 transport emissions are set to decline but only with abatement



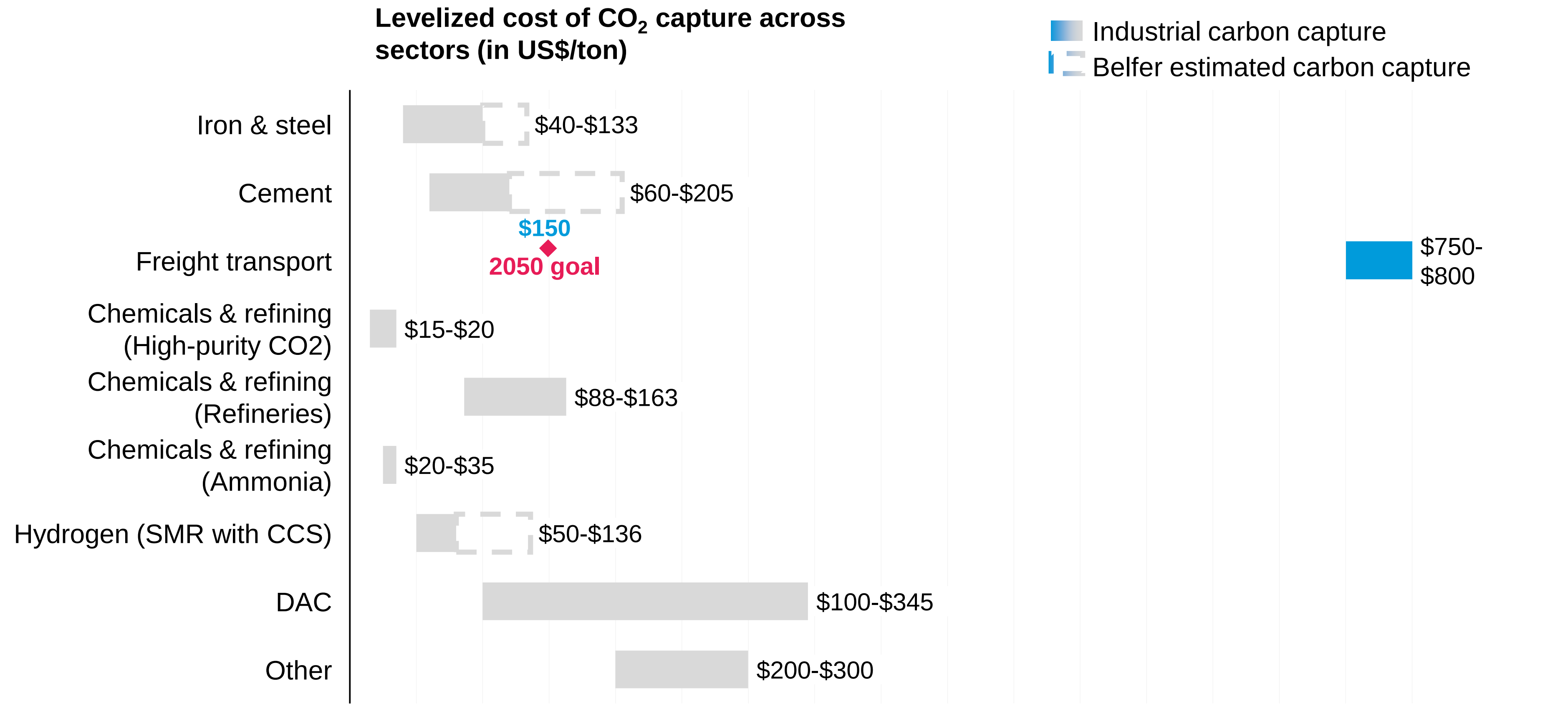
Observations

- Under the NZE scenario, CO_2 emissions from **transport are projected to drop to ~0.7 Gt by 2050.**
- Freight transportation **represents 8% global GHG emissions** (11% with warehouse and port emissions).
  - Demand for freight will increase 3x by 2050, which will **increase GHG emissions 2x** and cause freight to be the **highest emitting sector** by 2050, without intervention.
- Ships represent the majority of cargo, but trucks and vans are 65% of freight emissions; **ships are more energy efficient, but road transport is the faster growing subsector.**

Sources: IEA, Net Zero by 2050 Report (2021); MIT Climate Lab, Freight Transportation (2023); Lloyd's Register, Carbon capture in maritime energy transition (2023).
Credit: Michelle Priscilla, Sean Lee, Petr Jenicek, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Cost of capturing carbon in the freight transport industry is extremely high; current prototypes are at $769 per ton of CO_2

Freight transport levelized cost is far beyond industry standards



Observations

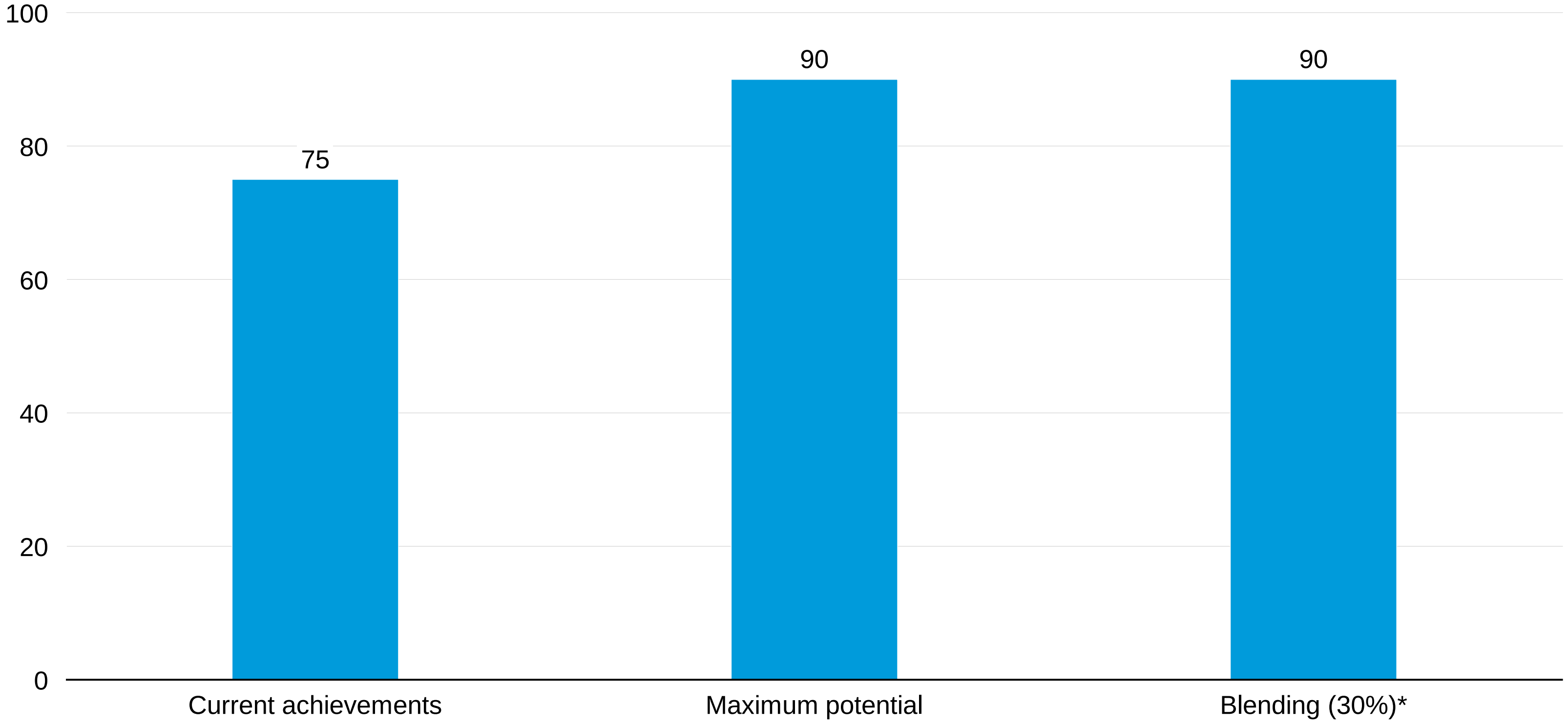
- Due to logistical and technological constraints, **freight transport CCUS costs are very high and expected to stay at the top end of industry average.**
- **Technology is currently nascent**; CCUS for shipping is ahead of road transport CCUS with first prototypes developed.
- The first shipping CCUS prototype was tested by the Oil & Gas Climate Initiative together with cargo ship operator Stena Bulk.
- **The first prototype had very high costs, $769/ton,** due to high CapEx, low efficiency, and high fuel penalty (10%).
- **Costs of onboard CCUS for cargo ships is expected to decrease to $150/ton by 2050, remaining at the top end of expected CCUS costs** across industries.

Sources: IEA, Net Zero by 2050 Report (2021); MIT Climate Lab, Freight Transportation (2023); Lloyd's Register, Carbon capture in maritime energy transition (2023); OCGI, Engineering study charts potential of carbon capture technology to help decarbonize shipping (2024); IEA, Levelized Cost of CO2 Capture by Sector and Initial CO2 Concentration (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs US Context (2022).
Credit: Sean Lee, Petr Jenicek, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Shipping: Onboard carbon capture and storage (OCCS) decreases emissions significantly, suffers from cost and energy constraints

In shipping, CCUS can achieve up to 90% reductions and net zero with blending

Shipping onboard carbon capture and storage (OCCS) CO_2 emissions reduction potential relative to conventional shipping (in %)



Observations

- Onboard technologies have the potential to capture **~90% of all CO_2 emitted** by ships at sea, and **net-zero or even negative lifecycle emissions** with blending.
- **Post-combustion capture** is the best fit for maritime travel, as it does not require large changes to engine design and reduces costs.
- Several shipping and manufacturing companies, such as Dutch Value Maritime, have **installed OCCS tech on vessels.**
- However, OCCS systems are costly, **adding ~25% to ships' annual expenses** due to installation and operational fees, in addition to fuel penalties, loss of cargo capacity, and carbon discharge costs.
- **Pricing of carbon** and **development of the value chain** are critical to adoption decisions, which are altered by fossil fuel and green fuel prices and policy factors.

*Potential for negative lifecycle greenhouse gas emissions when blending combustible fuels with at least 30% green fuels; with baseline 100%, applying biofuel leading to $30 reduction, CO_2 captured: 70 tons * 0.90 = 63 tons of CO_2. CO_2 remaining (slipped): 70 tons - 63 tons = 7 tons of CO_2.

Sources: ShipNerd News, Carbon Capture Systems Cost – Revealed (2021); Lloyd's Register, Carbon capture's role in maritime energy transition (2023); Maritime Impact, What are the key considerations of onboard carbon capture? (2024); DNV, Onboard Carbon Capture and Storage on Ships (2024); Wärtsilä, Wärtsilä Unveils Commercial Carbon Capture System for Ships (2025).

Credit: Sean Lee, Petr Jenicek, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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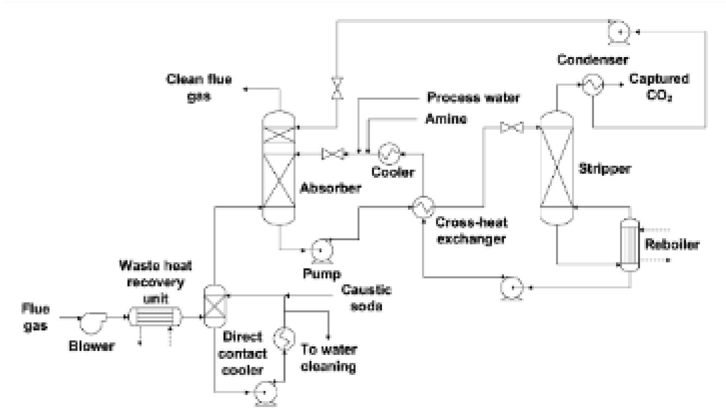
Shipping: Chemical adsorption by amine scrubbing and advanced cryogenic carbon capture are most feasible

Chemical absorption by amine scrubbing (AS)



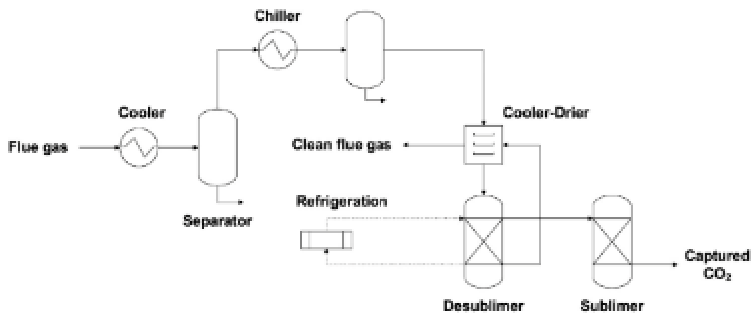
Pros

- Technology is mature and use cases exist
- Captured CO_2 has high purity
- Given onboard energy requirements, application is feasible

Cons

- Increased hazard levels on ship due to solvent used
- High cost of raw material inputs

Advanced cryogenic carbon capture (A3C)



Pros

- Captured CO_2 is high purity
- Allows for simultaneous CO_2 and water removal
- Feasible given onboard energy requirements
- Higher cost effectiveness
- Lack of solvents makes it safer than AS

Cons

- Extremely energy intensive, leading to higher energy penalties and more negative environmental impact
- High capital costs

Observations

- The two strategies highlighted, AS and A3C, are the **most feasible solutions in development** considering fuel penalties and onboard energy requirements.
- AS is the **most effective short-term solution** from a sustainability and cost perspective:
  - Displaces only 4% of ship volume
  - Additional equipment can boost performance and abatement rates
  - **Does not exceed capture cost of $290/ton* of CO_2**
- Although research is in early stages, **costs of cryogenic separation can be ~70% lower** than conventional adsorption processes (A3C specifically).

*Based on a euro-U.S. dollar exchange rate of €1 to US$1.05.

Sources: Journal of Cleaner Production, Onboard carbon capture and storage (OCCS) for fossil fuel-based shipping: A sustainability assessment (2024); Mærsk Mc-Kinney Møller Center, The Role of Onboard Carbon Capture in Maritime Decarbonization (2022).

Credit: Sean Lee, Petr Jenicek, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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Value Maritime's Filtree OCCS system reduces emissions and extends the lifetime of ships, among many other incentives

Technology overview

- The gas cleaning system **eliminates sulfur, particulate matter, and carbon dioxide** from tanker exhausts using liquid storage.
  - Results in 99% reductions in particulate matter and **up to a 30% reduction in CO_2 emissions.**
- Filtree is a modular **plug-and-play system that can be retrofitted** on small and medium-sized ships with engine sizes from 3MW to 15MW.

Key benefits

- Stores CO_2 on board at ambient temperatures, **making the technology more energy efficient** by avoiding the need for cooling or compression processes and **allowing for easy discharge of CO_2 at ports.**
- Filters its own wash water, **preventing ocean acidification.**
- Improves vessels' carbon intensity indicator (CII) ratings from D/E categories to higher classifications, **extending the longevity of ships by decades.**
  - Provides ship users with significant cost savings and makes their operations more sustainable.
  - **Complies with** the International Maritime Organization's **0.1% sulfur cap.**

Current adoption

As of early 2025, Value Maritime has secured orders for **over 30 Filtree systems.**

Ardmore Shipping Corp. has agreements to install the system on all suitable tankers in their fleet.

Ardmore Shipping

Sources: Lloyd's Register, LR award AiP for Value Maritime's Carbon Capture and Storage System (2022); Value Maritime, Filtree transforms low-performing vessels (2023); Carbon Herald, Value Maritime Wins Funding For Onboard Carbon Capture (2025).
Credit: Sean Lee, Petr Jenicek, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Trucking: Mobile CCS is currently in research stages, showing promising emissions reductions, but far from commercialization

Role of CCUS in trucking

- CCUS plays an important role in **short- to medium-term decarbonization of trucks,** as electrification is infeasible and alternative fuels are still in development.
  - Battery-powered trucks **would not be able to carry as much payload** and could travel only short distances.
  - They depend on a grid that still draws energy from majority fossil fuels.
- Trucks and vans make up a **significant portion of transport and global emissions:**
  - Road transport can emit **>100 times as much CO_2 as ships** but is the fastest growing sector and consumes significant amounts of fossil fuels.
- Capturing emissions from moving vehicles is **difficult due to energy requirements, limited space on vehicles, and changing engine conditions in vehicles,** but novel solutions are being developed.

Example CCUS technologies in trucking

Metal organic frameworks (MOF)

- MOFs are microscopic compounds that can store CO_2 in a cage-like structure.
  - Little energy is required to separate gas from the chemical structure.
- Systems are designed using MOFs that can **capture 50% of emissions at 98% purity.**
  - **Requires only 7.6% extra engine power**
  - Occupies less than 1.5 cubic meters of volume
- **Costs are undetermined,** as MOFs are newer technologically and cannot currently be created using industrial processes.

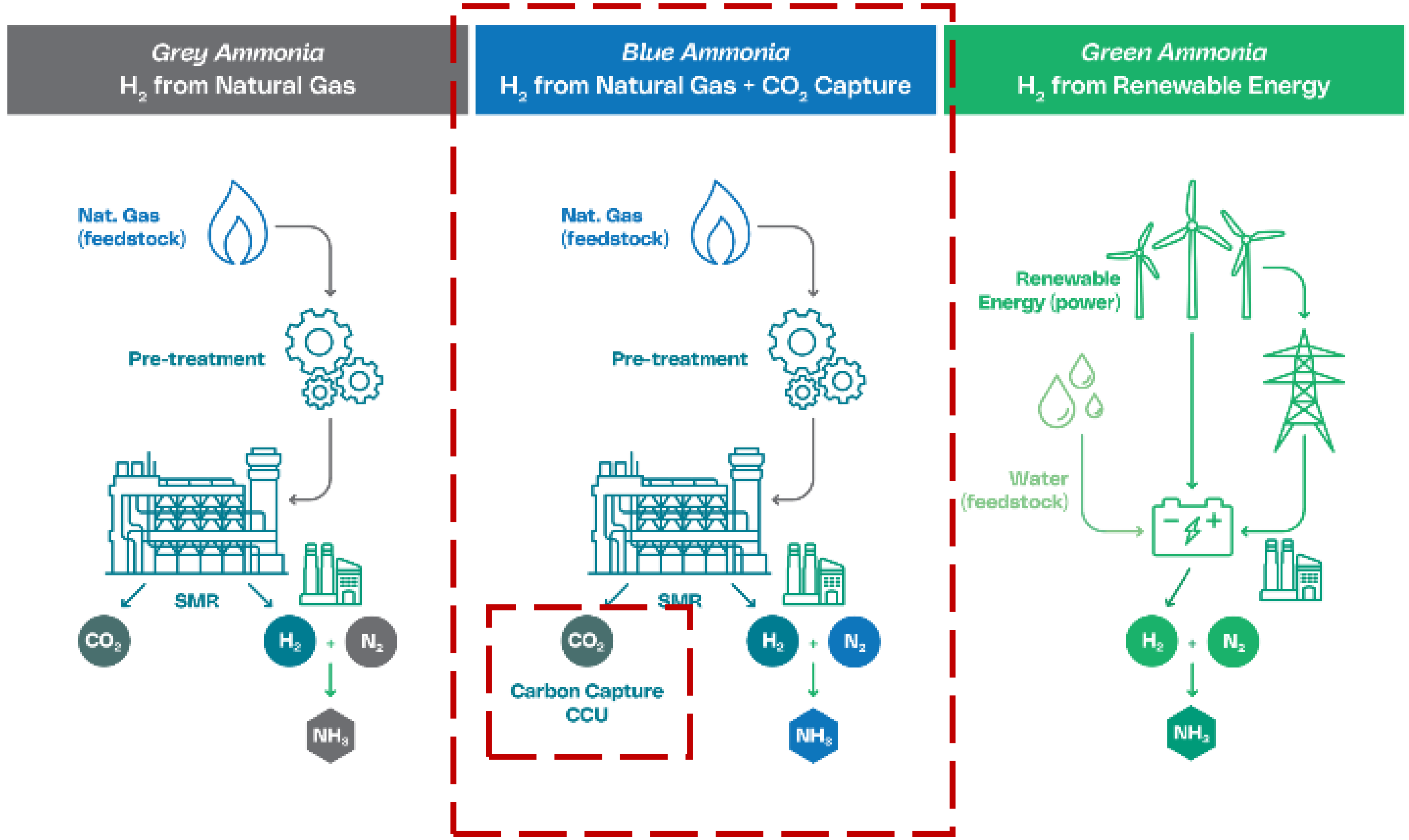
Remora CCUS for semitrucks

- Draws CO_2 directly from the exhaust using a **modular and repeatable model** for Class 8 tractors.
- Uses zeolite to filter out CO_2 and uses heat from the exhaust itself to release captured CO_2.
- **Captures 90% of carbon from tailpipes.**
- Has raised a $5.5 million seed round from venture capital and other tech players.

Sources: Anthropocene, Capturing carbon on moving vehicles (2023); Trellis, Remora is ready to roll with carbon capture for trucks (2021); Remora, Carbon Capture for Vehicles (2025).
Credit: Sean Lee, Petr Jenicek, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

From grey to blue: How CCUS transforms hydrogen and ammonia production

Carbon capture technologies can **transform grey hydrogen and ammonia** (produced from fossil fuels) **into** their low-carbon **blue counterparts by capturing carbon in the production process**



Observations

- The color of **ammonia production** depends directly on the **source of hydrogen.**
- If the hydrogen is **blue**, the resulting ammonia is **blue**; if hydrogen is **green**, the ammonia is **green.**
- **CCUS** enables the shift from **grey to blue hydrogen** by capturing CO_2 during steam methane reforming.
- This makes blue ammonia a **lower-emission alternative** while leveraging existing fossil-based infrastructure.
- Compared with green pathways, **blue hydrogen and ammonia offer a more immediate solution** for emission reduction at scale.

Sources: National Grid, Hydrogen Color Spectrum (2023); IEEFA, Blue hydrogen: not clean, not low carbon, not a solution (2023); SCI, How green is blue hydrogen? (2021); Green Hydrogen Organisation, Mirage of blue hydrogen fading (2022); Journal of CO2 Utilization, Blue hydrogen production from natural gas reservoirs (2023); Energy Education, Types of hydrogen fuel (2024); Hydrogen Tech World, Green ammonia, right where you need it (2024).
Credit: Xiaodan Zhu, Sean Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Scaling blue hydrogen and CCUS to enable near-term emission reductions

Technology overview

Overview

- **Blue hydrogen** is produced from natural gas through **steam methane reforming** or **autothermal reforming** combined with **carbon capture and storage.**
- This process generates CO_2 as a byproduct, but **up to 90% of emissions can be captured** through CCUS technologies.
- **Captured CO_2** can be stored or utilized, enabling the use of **existing fossil fuel infrastructure** for faster and more cost-effective decarbonization.

Current status

- **Less than 1%** of global hydrogen production uses CCUS (blue hydrogen).
- **Production cost: \$2-\$5 per kg H_2.**
- **Energy intensity:** Approximately **60 kWh** per kg H_2 produced.
- **Deployment is limited** to pilot projects; commercial adoption is early stage.
- **High operational and infrastructure costs** continue to constrain scalability.
- **Risk of methane leakage** during upstream natural gas extraction remains a concern.
- **CCUS** transforms conventional hydrogen into a viable low-carbon solution, accelerating industrial decarbonization **toward net zero.**

Role in decarbonization

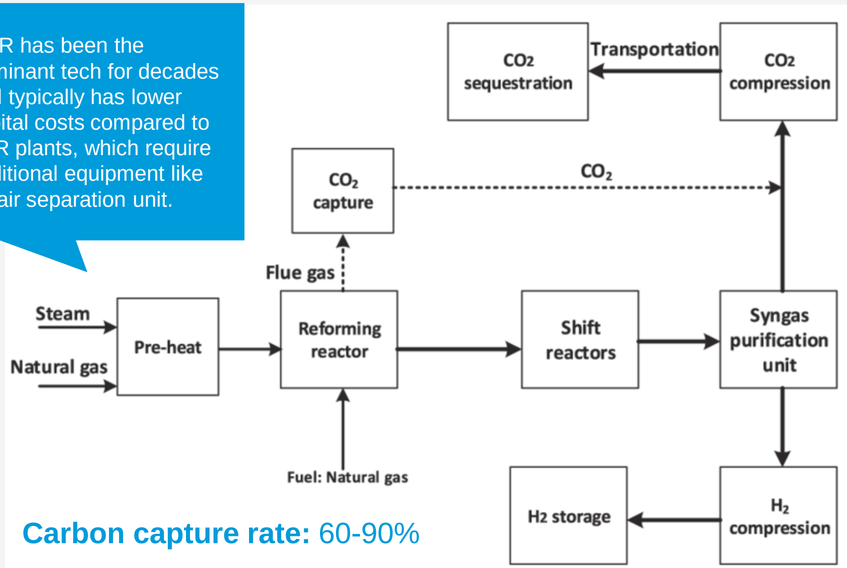
- **Blue hydrogen leverages CCUS to cut emissions by up to 90%,** reducing CO_2 output to **0.2-3.2 kg per kg of H_2** compared with **11-13.7 kg** for grey hydrogen.
- **CCUS is essential** to make hydrogen production from natural gas compatible with **net-zero emissions** goals.
- **Provides a scalable near-term solution** by utilizing **existing infrastructure,** addressing the cost and deployment barriers green hydrogen faces.
- **Acts as a transitional technology,** supporting decarbonization today, while renewable-based green hydrogen scales for the future.

Sources: National Grid, Hydrogen Color Spectrum (2023); IEEFA, Blue hydrogen: not clean, not low carbon, not a solution (2023); SCI, How green is blue hydrogen? (2021); Green Hydrogen Organisation, Mirage of blue hydrogen fading (2022); Journal of CO2 Utilization, Blue hydrogen production from natural gas reservoirs (2023); Energy Education, Types of hydrogen fuel (2024).
Credit: Xiaodan Zhu, Sean Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

SMR leads today, but ATR is gaining momentum with superior carbon capture efficiency

Steam methane reforming (SMR) with CCS

SMR has been the dominant tech for decades and typically has lower capital costs compared to ATR plants, which require additional equipment like an air separation unit.

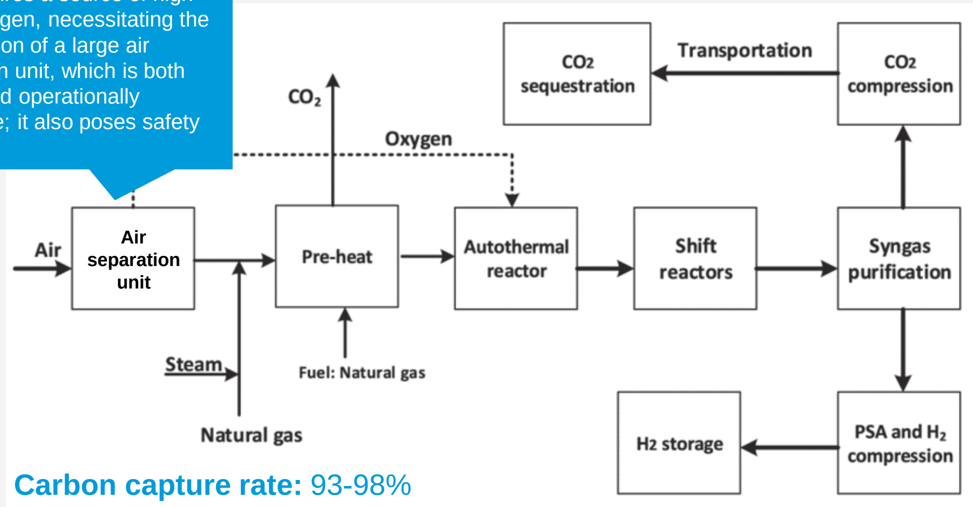


Carbon capture rate: 60-90%

- **Reaction mechanism:** SMR uses hydrocarbons, typically methane with steam.
- **Heat requirement:** SMR is an endothermic reaction (requiring external heat input).
- **CO_2 concentration:** SMR concentrates 60% of CO_2 in the process gas stream, with the remainder in flue gas.

Autothermal reforming (ATR) with CCS

ATR requires a source of high-purity oxygen, necessitating the construction of a large air separation unit, which is both capital and operationally expensive; it also poses safety concerns.



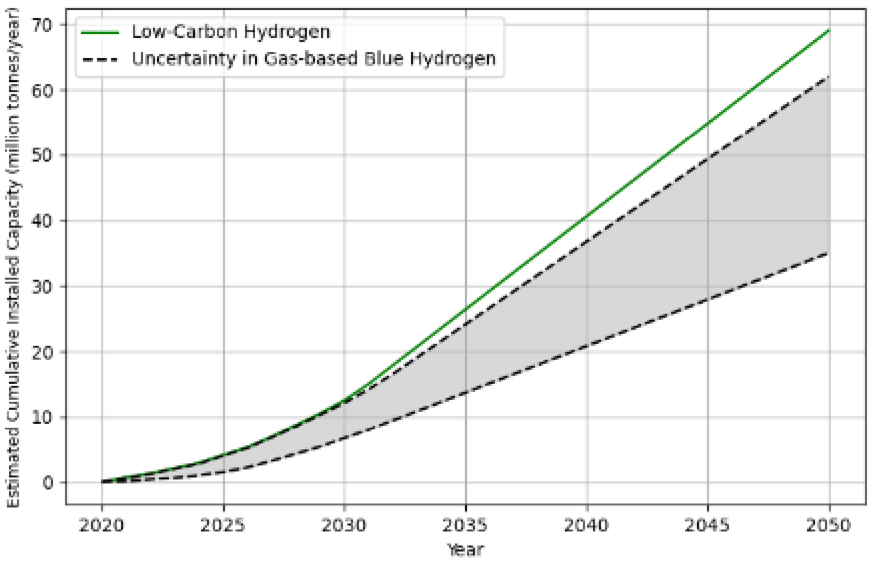
Carbon capture rate: 93-98%

- **Reaction mechanism:** ATR uses the reaction of methane with oxygen and either carbon dioxide or steam.
- **Heat requirement:** ATR is exothermic, generating heat within the process.
- **CO_2 concentration:** ATR concentrates about 90% of CO_2 in the process stream, making capture easier.

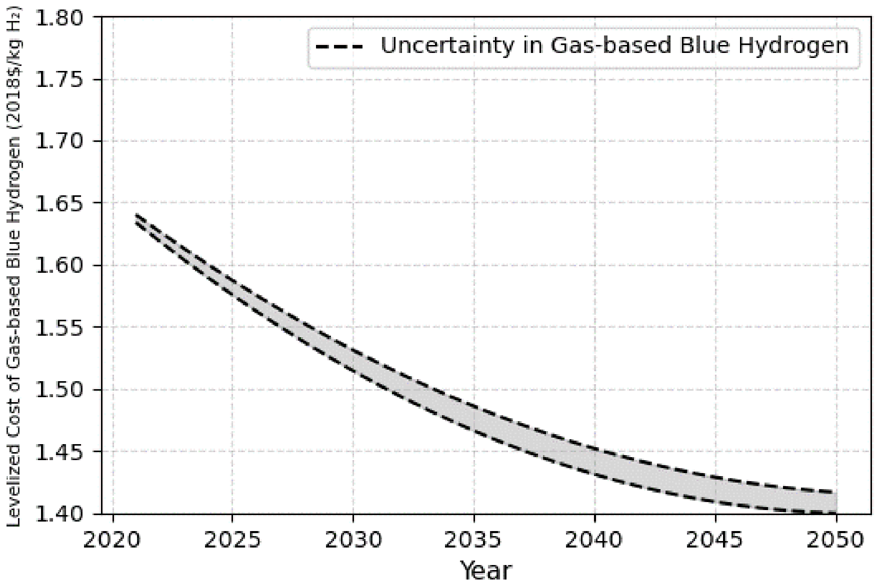
Sources: ScienceDirect, Comparative Assessment of Blue Hydrogen from SMR and ATR (2022); Digital Refining, Blue Hydrogen a Low-Carbon Energy Carrier (2024).
Credit: Yosafat Partogi, Xiaaodan Zhu, Michelle Priscilla Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Blue hydrogen expected to grow, but cost remains a major challenge to achieving net-zero emissions

Diffusion of cumulative installed capacity



Learning curve of blue hydrogen production cost



While cost reductions for blue hydrogen are expected over time, achieving the U.S. cost target of **$1/kg by 2030 is highly unlikely**. Even by 2050, blue hydrogen may struggle to compete on price with alternative energy sources.

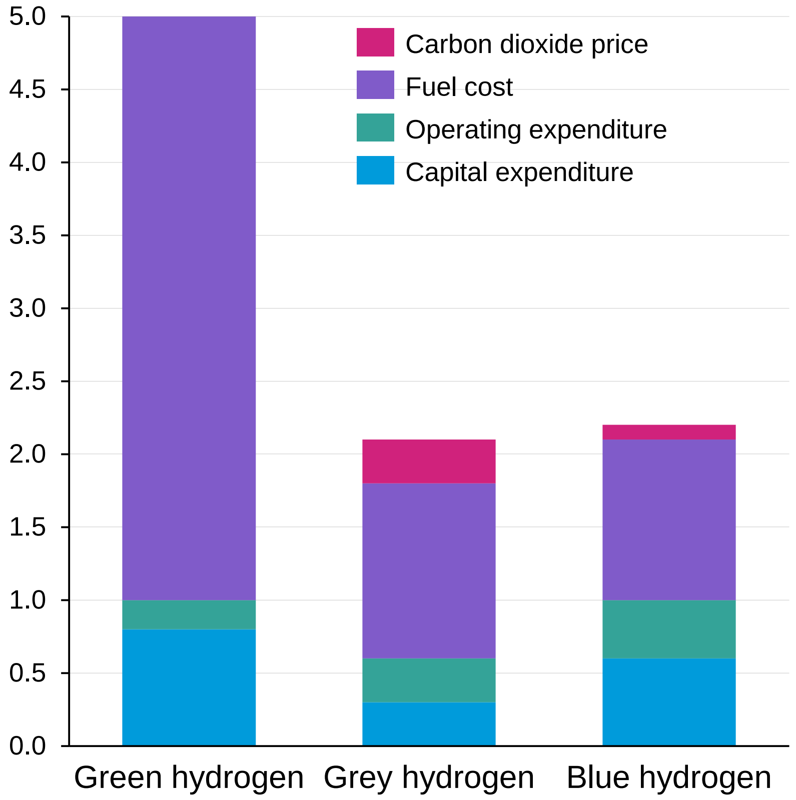
Observations:

- Growing role of blue hydrogen: As achieving net-zero emissions is **urgent**, **the share of blue hydrogen** in total low-carbon hydrogen capacity **will increase significantly over the next few decades.**
- **Green hydrogen is too expensive** for large-scale adoption in the short term.
- **Blue hydrogen** is the more **practical option** to meet decarbonization targets so far.
- To facilitate a cost-effective transition, policymakers and industries must support blue hydrogen deployment while continuing to drive innovation and cost reductions.

Sources: National Grid, Hydrogen Color Spectrum (2023); IEEFA, Blue hydrogen: not clean, not low carbon, not a solution (2023); SCI, How green is blue hydrogen? (2021); Green Hydrogen Organisation, Mirage of blue hydrogen fading (2022); Journal of CO2 Utilization, Blue hydrogen production from natural gas reservoirs (2023); Energy Education, Types of hydrogen fuel (2024); Nature Communications, Technological evolution of large-scale blue hydrogen production toward the U.S. Hydrogen Energy Earthshot (2024).
Credit: Xiaodan Zhu, Sean Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Blue H_2 is financially attractive provided CCUS costs decrease and policy incentives continue

Cost breakdown of H_2 production, $/kg H_2



Finance analysis

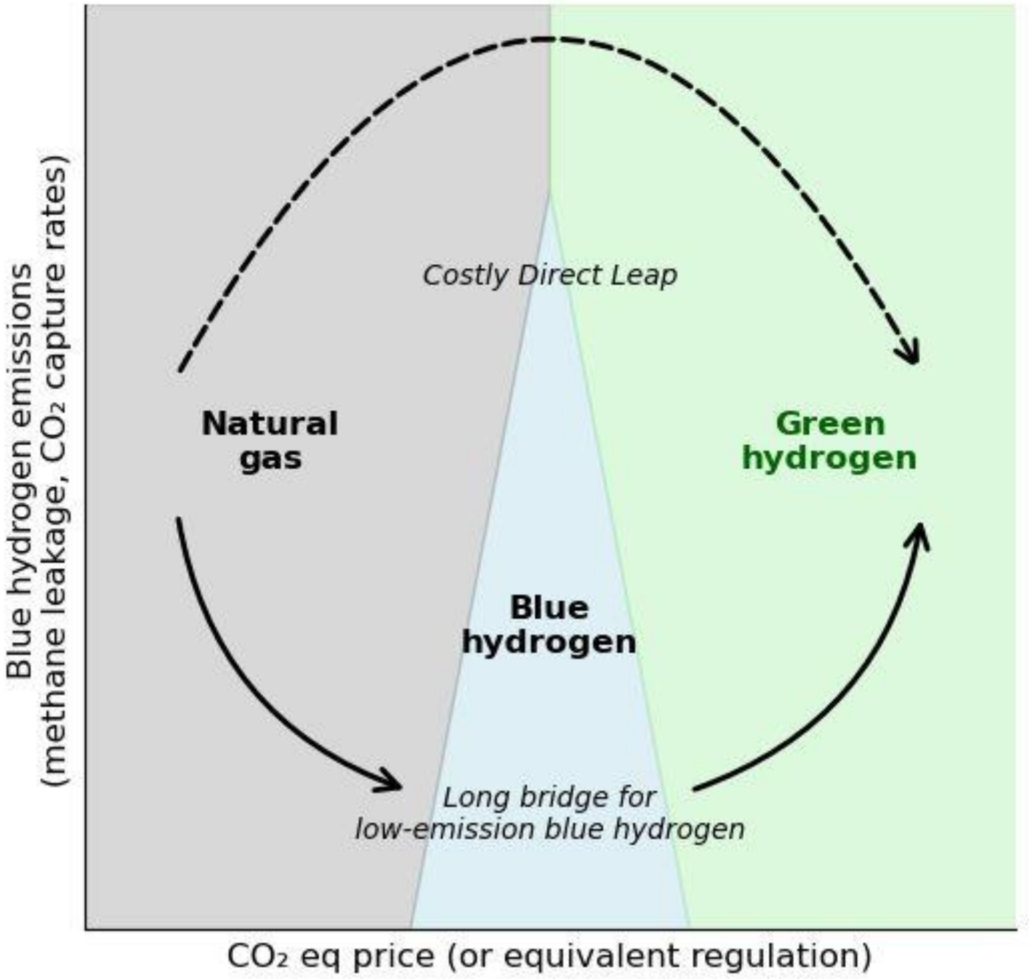
- **Blue hydrogen** is slightly costlier than **grey hydrogen** but much cheaper than **green hydrogen.**
- **Fuel costs** dominate grey and blue hydrogen, with **CCUS capital expenditure** making blue hydrogen more expensive.
- **Green hydrogen** is the most expensive due to **high fuel and capital costs (e.g., renewable electricity).**
- **CCUS increases upfront costs**, reducing short-term financial appeal despite lower emissions.
- **Blue hydrogen is a transition option**, but its viability depends on **policy, carbon pricing, and CCUS cost reductions.**
- Blue hydrogen can **improve energy security,** leveraging existing natural gas infrastructure and reducing reliance on imported fuels.

Policy incentives

- The Inflation Reduction Act provides the 45V tax credit to clean hydrogen projects, ranging from **$0.6-$3 per kg of H_2.**
- The 45V clean hydrogen production tax credit now requires facilities to begin construction before January 1, 2028 (accelerated from the original 2032 deadline).
- OBBBA does not apply foreign entity of concern (FEOC) rules to section 45V, unlike many other clean energy credits.
- The 45Q tax credit on carbon utilization and storage:
  - **$85** per metric ton of CO_2 stored in saline reservoirs; **$60** per metric ton of CO_2 used for enhanced oil recovery
- The DOE confirmed it was considering reducing or eliminating funding for four of the seven selected hubs in March 2025 — those based in California, the Mid-Atlantic, the Pacific Northwest, and the Midwest — representing nearly 60% of the $7 billion in federal support initially committed.
- Companies are advised, "Hydrogen and CCUS projects must move quickly — and entities with complex ownership should review eligibility."

Sources: Shell Catalysts, The Shell blue hydrogen process (2025); Frazier & Deeter, Final rules for the production of clean hydrogen and energy credit (2025); Nature Communications, Technological evolution of large-scale blue hydrogen production toward the U.S. Hydrogen Energy Earthshot (2024); Barnes & Thornburg, Shifting Energy Priorities Are Reshaping the H2Hubs Program (2025).
Credit: Xiaodan Zhu, Michelle Priscilla, Sean Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Future of H_2 within the energy transition to determine importance of CCUS technology within the industry



Potential benefits of blue hydrogen

- **Leverages existing infrastructure** – Utilizes current natural gas pipelines and facilities, minimizing new investments.
- **Lower emissions than natural gas** – Blue hydrogen production technology enables the capture of **up to 90%** of CO_2 emissions through CCUS.
- **Scalability potential** – Can serve as a bridge until green hydrogen and renewables become more viable.
- **Under current circumstances, blue hydrogen will be the inevitable path toward the renewables.**

Limitations and challenges

- Not at scale: No large-scale blue hydrogen production exists.
- Low capture rates: Even at 90%, not enough for net-zero goals.
- Slows progress: Diverts resources from nearly zero-carbon green H2.

Real-world example: Blue hydrogen's economic viability in question

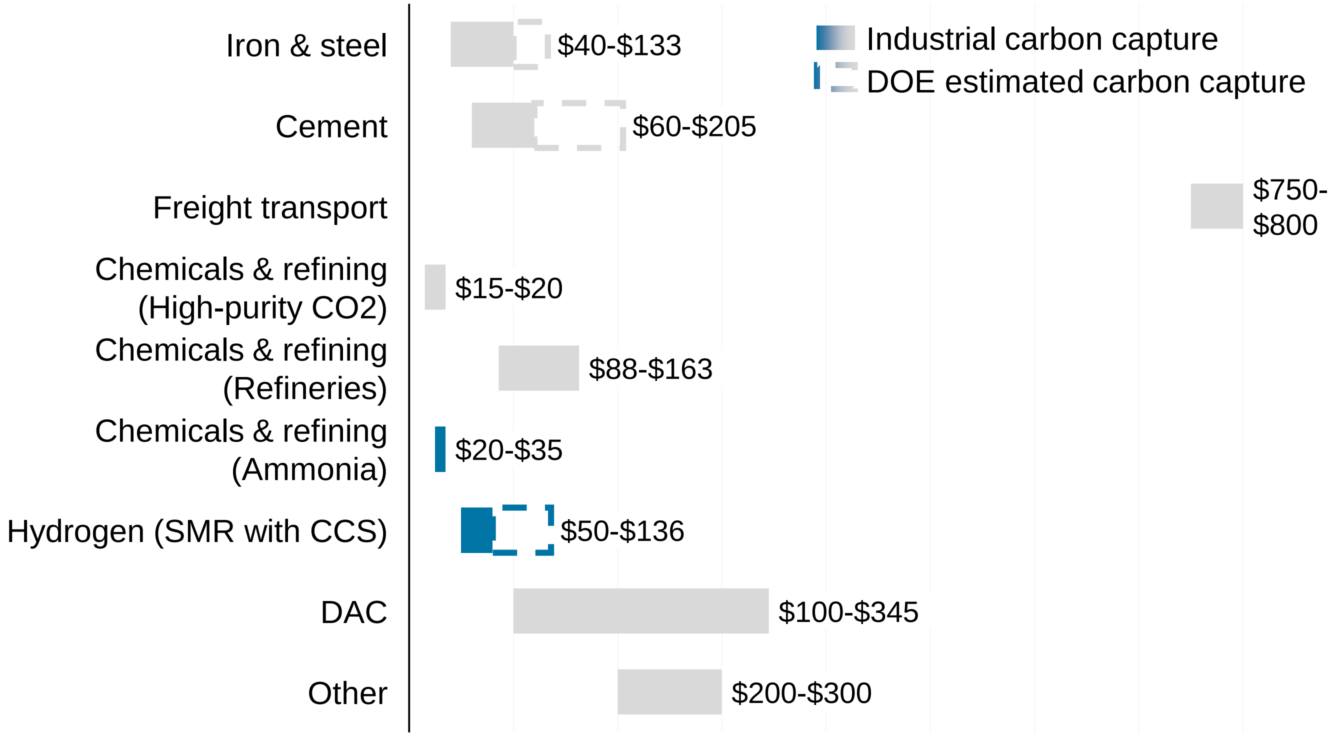
- Shell canceled its blue hydrogen project in Norway (Aukra Hydrogen Hub) due to weak demand and high costs.
- Equinor scrapped a similar project, citing economic challenges.
- This highlights the uncertainty surrounding blue hydrogen's role in the energy transition.

Sources: National Grid, The hydrogen colour spectrum (2023); IEEFA, Blue Hydrogen: Not clean, not low carbon, not a solution (2023); SCI, How green is blue hydrogen? (2021); Green Hydrogen Organisation, The mirage of blue hydrogen is fading (2022); Journal of CO2 Utilization, Blue hydrogen production from natural gas reservoirs: A review of application and feasibility (2023).
Credit: Michelle Priscilla, Xiaodan Zhu, Sean Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Ammonia production enables more cost-effective carbon capture than standalone hydrogen

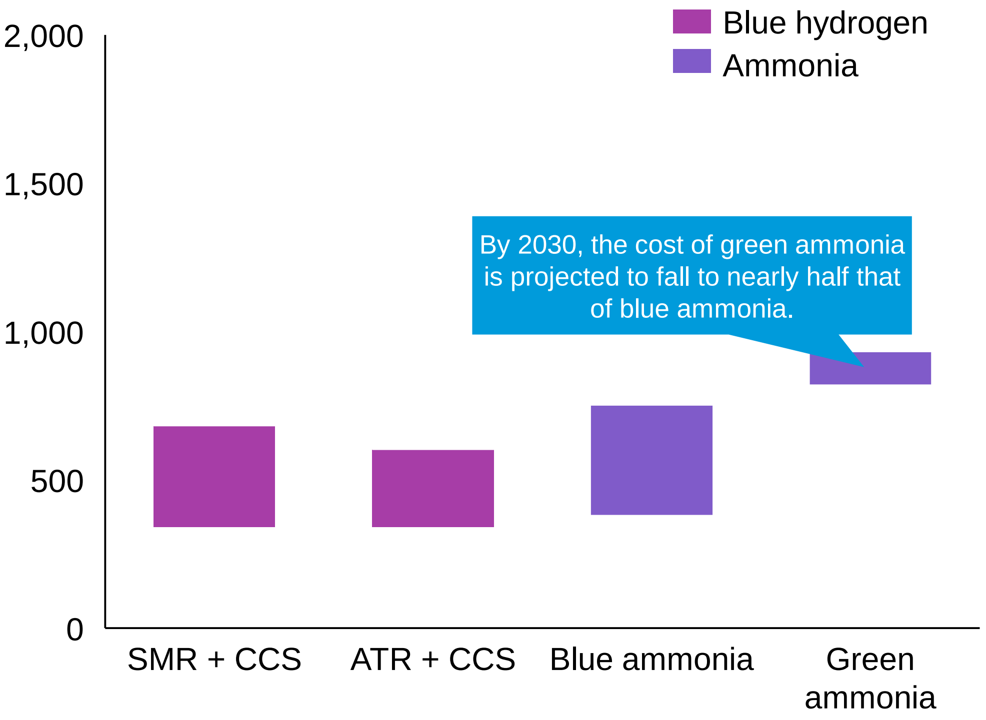
Hydrogen and ammonia levelized cost is on the lower end of the overall industry range

Levelized cost of CO_2 capture across sectors (in US$/ton)



Blue ammonia production offers lower cost pathway than green ammonia

Simplified levelized cost of competing low-carbon tech in blue hydrogen and ammonia production



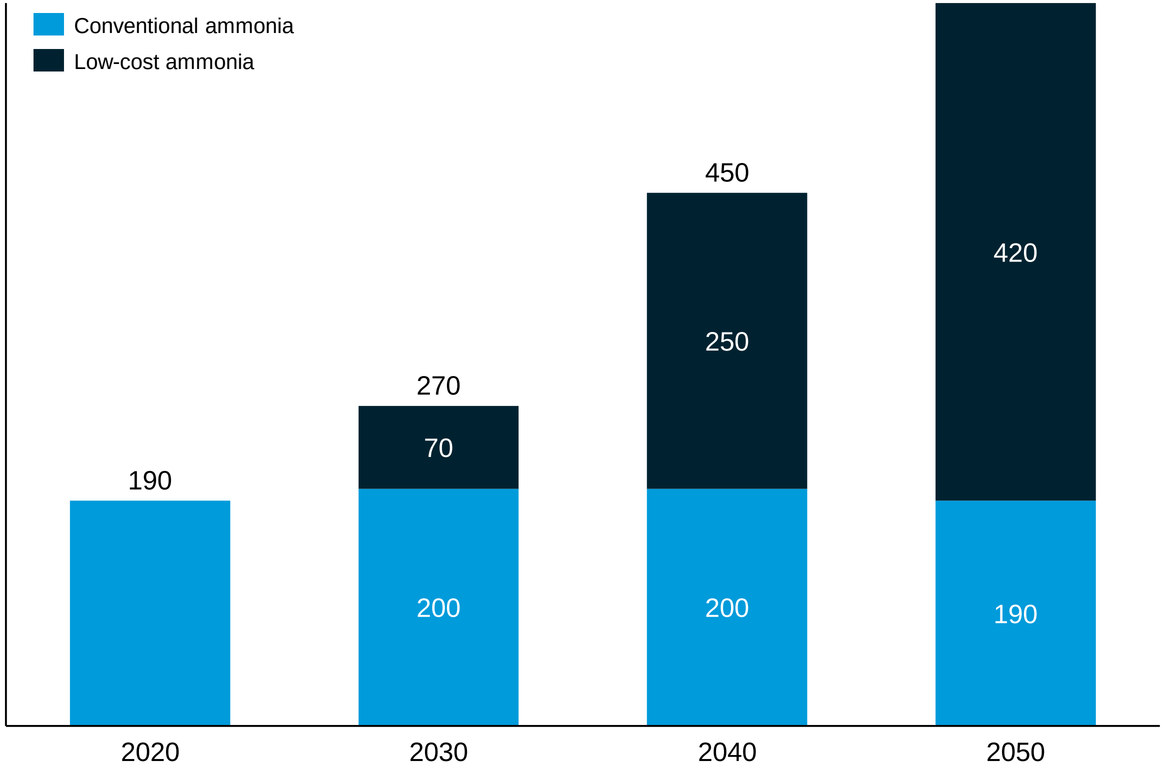
Sources: IEA, Ammonia Technology Roadmap (2021); IRENA, Innovation Outlook Renewable Ammonia (2022); DOE, Pathways to Commercial Liftoff (2024); S&P Global, Global Blue Ammonia Prices Edge Lower, Europe Falls 10% MOM (2025); CRS, Hydrogen Production: Overview and Issues for Congress (2024); Montel, Hydrogen Production Cost Trends 2025 (2025); Argus, Argus Launches EU Low-Carbon Ammonia Benchmark (2025); IEA, Levelized Cost of CO2 Capture by Sector (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs US Context (2022).

Credit: Yosafat Partogi, Michelle Priscilla Xiaodan Zhu, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Ammonia sustains agriculture but remains emissions intensive, requiring a shift to low-carbon supply

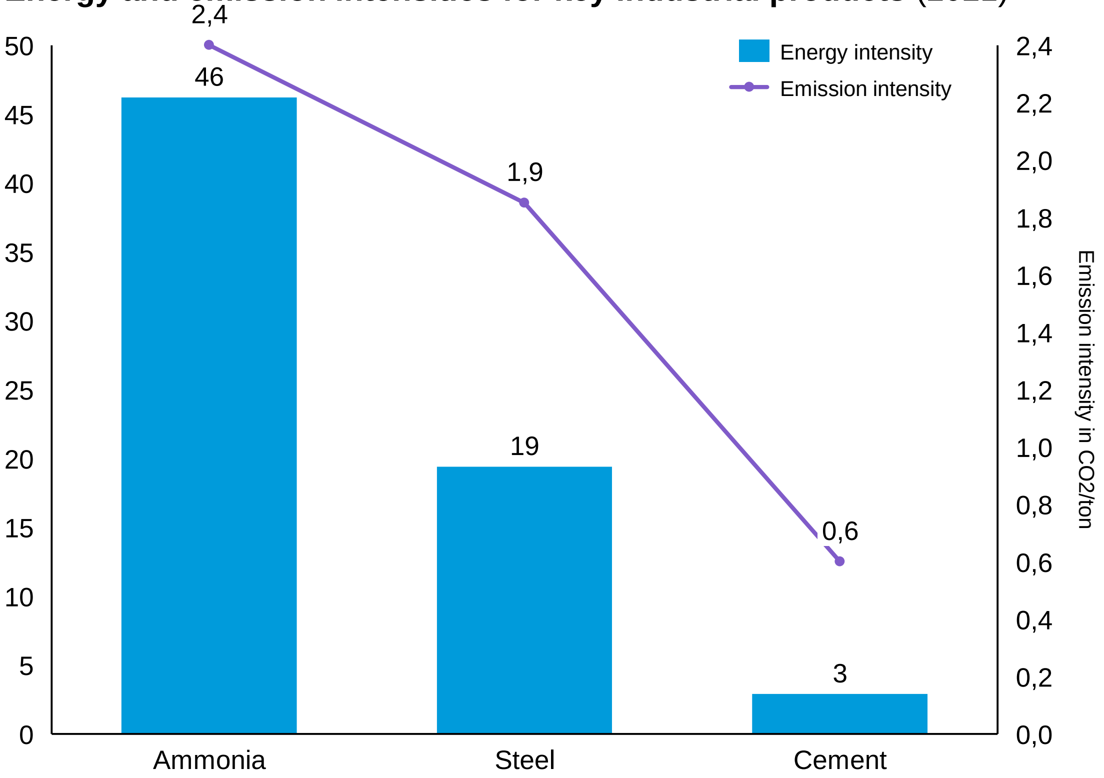
Global ammonia demand expected to triple, fueled by low-carbon supply, with fertilizer as its dominant application

Projected global ammonia demand (Mt)



Ammonia industry consumes more energy and emits more CO_2 emissions than steel and cement industries combined

Energy and emission intensities for key industrial products (2021)

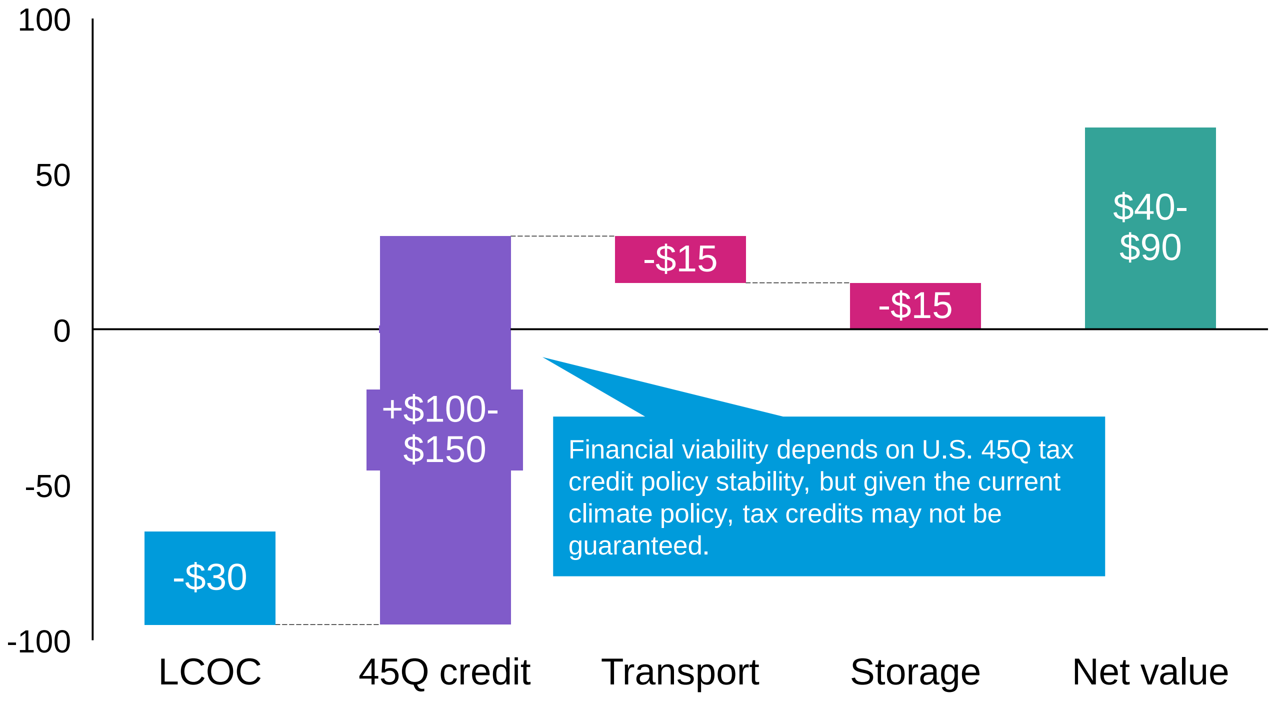


Sources: S&P Global, Global ammonia projection (2024); IEA, Energy and emission intensity for key industries (2021).
Credit: Yosafat Partogi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Ammonia with CCUS generates net financial benefits of \$40-\$90 per ton CO_2 on paper when tax credits are applied in the U.S.

Blue ammonia is economically viable with 45Q credits

Ammonia with CCUS and 45Q credit monetization, in \$/ton CO_2



Observations

- For ammonia production, which typically involves storing captured CO_2, the \$100-\$150/ton credit can effectively offset most or all the capture, transport, and storage costs.
- If total CCUS costs are \$40-\$60 per ton CO_2, the \$100-\$150/ton credit results in a net gain of \$40-\$90 per ton CO_2 captured and stored.
- All in all, CCUS in ammonia production is economically viable and can even generate net financial benefits when tax credits are applied.
- This makes it a practical near-term solution for decarbonizing ammonia production while renewable hydrogen technologies continue to mature.

Notes: Higher end estimate of carbon capture cost in ammonia production is \$35/ton per previous slide and regarded as LCOC. 45Q credit of \$85/ton is baseline.
Sources: IEA, Ammonia Technology Roadmap (2021); IRENA, Innovation Outlook Renewable Ammonia (2022).
Credit: Yosafat Partogi, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., “Capturing Carbon” (7 November 2025).

Blue ammonia's viability depends on stable policy, CCS infrastructure, and low-carbon mandates

Although blue ammonia is economically viable with IRS, its adoption remains limited despite financial incentives

Policy uncertainty

- The OBBBA was relatively kind to clean fuel producers, and it was mostly positive for 45Q and the carbon-capture industry.
- **45V Clean Hydrogen Credit:** The termination date was accelerated to January 1, 2028 (instead of 2032), but no prohibited foreign entity restrictions apply.
- **45Q Carbon Capture Credits:** Enhanced from $60/Mt to $85/Mt for both CCS and CCUS/EOR, establishing rate parity.

Demand-side gaps

- Tax credits target **production,** not consumption.
- Industries like steel and shipping **lack binding mandates to adopt low-carbon ammonia,** creating the chicken-and-egg market dilemma.

Infrastructure hurdle

- Capturing 90-95% of CO_2 form SMR plants using CCS requires **retrofitting existing facilities, which entails high upfront cost.**
- Blue ammonia's carbon footprint hinges on reducing methane emissions across the gas supply chain. **Verified leakage rates remain inconsistent,** complicating tax credit claims.

Competition with LNG

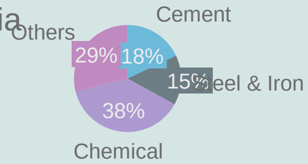
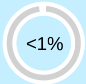
- U.S. gas exporters prioritize LNG because it has established infrastructure and higher margins. Blue ammonia must compete for feedstock (natural gas) and investment.

Innovation delays

- **Project cancellations: Nutrien** scrapped a 1.2 Mtpa blue ammonia plan in Louisiana in 2023 due to rising capital costs and uncertain demand.
- Proprietary constraint: **Key CCS and ammonia synthesis technologies are held by private firms,** slowing knowledge-sharing and standardization.

Sources: Wood Mackenzie, US LNG export restrictions underline case for blue ammonia (2024); Climate Portal, Implications of IRA on deployment of low-carbon ammonia (2023).
Credit: Yosafat Partogi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

The two key categories of carbon management – point source and ambient – differ based on the origin and dispersal of emissions

	1 Point Source Capture	2 Ambient carbon removal
Description	Separation and entrapment of CO_2 before it is released from **large stationary sources** (e.g., industrial plants)	**Removal of CO_2 already in the atmosphere or from biomass energy** by targeting diffuse CO_2 concentrations rather than capturing emissions at the source
Examples	Applications to Iron & Steel, Cement, Freight, Blue Hydrogen & Ammonia 	DAC, field weathering, mineralization, direct ocean removal, ocean alkalinity enhancement
% share of total CO_2 captured using carbon capture technologies, by method	 Vast majority of current capture is industrial point source	
Current CO_2 absorption (per year)	**~50 $MtCO_2$**	**<1 $MtCO_2$**
Technological readiness level	**High with immediate scalability**	**Low to medium with limited scalability;** *DAC is medium while the others are relatively low*
Cost of CCUS per ton of CO_2	**\$27-\$150** depending on industry	**DAC:** \$135-\$345 **Enhanced weathering:** \$50-\$200 **Ocean methods:** \$50-\$150

Sources: IEA, CCUS (2025); IEA, BECCS (2023); IEA, DAC (2022); DOE, Pathways to Commercial Liftoff: Industrial Decarbonization, (2023).
Credit: Yosafat Partogi, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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Of other carbon technologies, all of which remain nascent, mineralization may be most economical (1/2)

	1 Direct air capture (DAC)	2 Enhanced weathering	3 Mineralization
Description	**Captures CO_2 directly from ambient air** and sequesters it underground or reuses it.	**Spreads crushed silicate rocks** such as basalt or olivine on fields to **accelerate natural CO_2 absorption** from the atmosphere, enhancing soil health and long-term carbon storage.	**Converts CO_2 into stable carbonates by reacting with minerals,** locking carbon permanently in rocks, concrete, or underground formations.
Current carbon capture market share	**Low**	**Low**	**Low**
Estimated $/ton	**$100-$345**	**$50-$200** depending on type of rock used (dunite $60 per ton while basalt $200 per ton)	**$10-$30**
Challenges	**Expensive technology**, **energy-intensive process**, **and scalability issues**	Lack of public perception and awareness, scalability, and infrastructure; verification and monitoring of carbon removal at large scale remains a challenge	**Metal contamination** from enhanced rock weathering, high water consumption for in situ methods, and increased mining demands
Leaders	**Climeworks** is a pioneer in DAC, developing modular CO_2 collectors that extract carbon from the atmosphere, with captured CO_2 permanently stored underground using **Carbfix's mineralization technology.**	**Project Vesta** – Spread ground olivine sand along coastlines **Terradot** – Spread crushed basalt over farmland	Carbfix – Large-scale terminals in locations with favorable rock formations for industrial and DAC

Sources: USGS, Making minerals (2019); World Resources Institute, 5 Things to Know About Carbon Mineralization (2023); UArctic, Enhanced weathering (on land) (2024).
Credit: Yosafat Partogi, Xiaodan Zhu, Grace Frascati, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Emerging carbon removal pathways remain early-stage with high cost uncertainty (2/2)

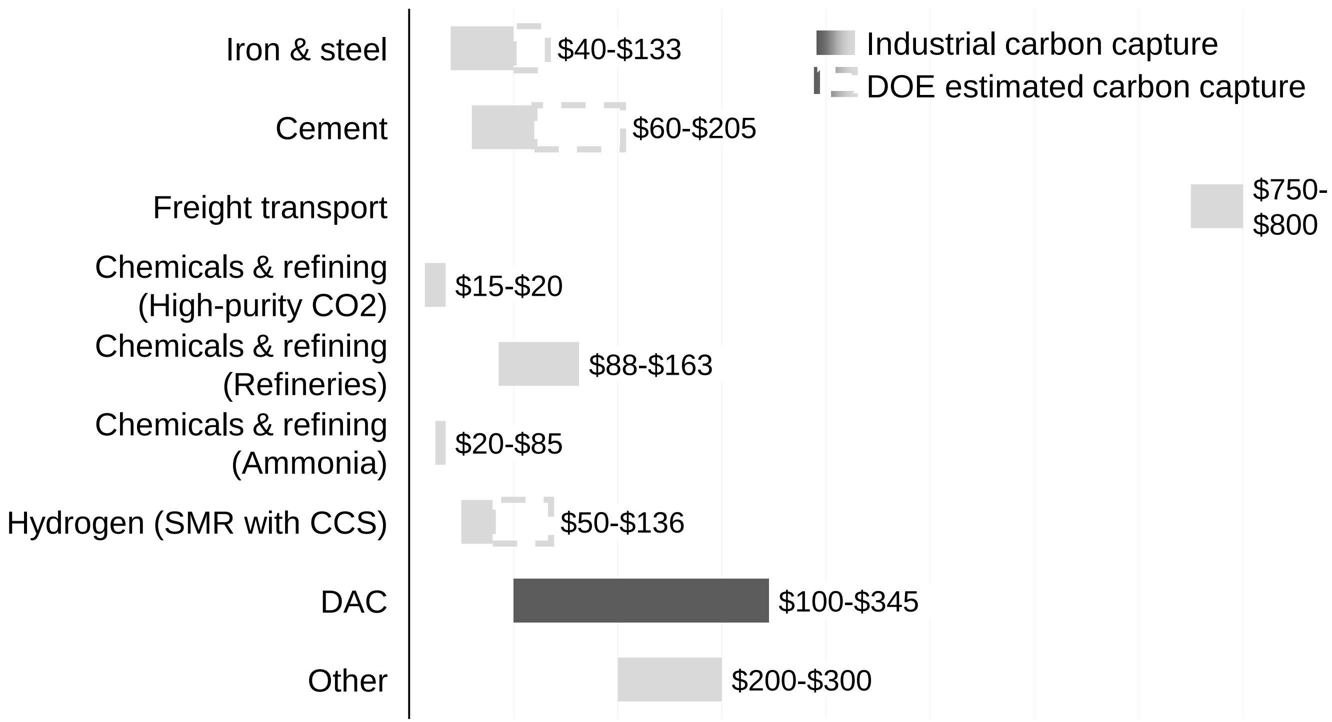
	4 Direct ocean removal	5 Biomass carbon removal and storage	6 Ocean alkalinity enhancement
Description	**Extracts CO_2 directly from seawater,** enhancing the ocean's natural ability to absorb atmospheric carbon, reducing overall CO_2 levels.	**Uses plants to remove carbon dioxide** from the air and store it.	Adds alkaline minerals to seawater to boost its capacity to absorb CO_2 while counteracting ocean acidification and improving marine ecosystems.
Current carbon capture market share	**Low**	**Low**	**Low**
Estimated $/ton	**$55-$200**	**$15-$85**	**$70-$120**
Challenges	**High energy demand and upfront cost; potential disruption to marine life and ecosystems**	**Lack of data and standards to quantify and verify permanent carbon removal**	**Mineral sourcing**, **supply chain infrastructure**, and **adverse environmental impacts**
Leaders	**Captura** utilizes an electrochemical process to extract CO_2 directly from seawater, leveraging renewable energy sources to enhance scalability while minimizing emissions.	**Drax Group-Elimini** focuses on large-scale carbon removal by utilizing bioenergy with carbon capture and storage technology, aiming to generate renewable electricity while actively pulling carbon dioxide from the atmosphere.	**Equatic** and **Planetary Technologies** are key OAE players, but technology is limited to smaller scale testing.

Sources: USGS, Making Minerals (2019); World Resources Institute, 5 Things to Know about Carbon Mineralization (2023); UArctic, Enhanced weathering (on land) (2024).
Credit: Yosafat Partogi, Grace Frascati, Xiaodan Zhu,Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Capturing carbon directly from the air is the most expensive method of carbon capture, at $100-$600 per ton

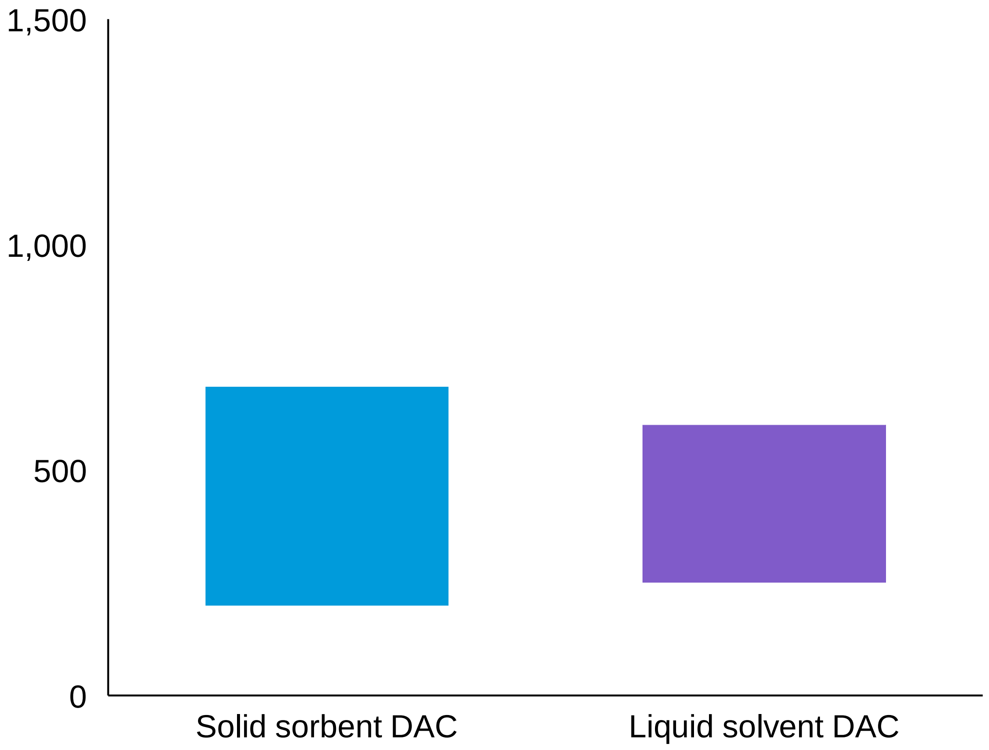
DAC levelized cost is on the lower end of the overall industry range

Levelized cost of CO_2 capture across sectors (in US$/ton)



Liquid solvent DAC shows lower current cost trajectory than solid sorbent DAC

Simplified levelized cost of competing DAC low-carbon tech



Sources: ArcelorMittal, LanzaTech partnership (2021); IEA, CCUS Projects Explorer (2024); IEA, Iron and Steel Technology Roadmap (2020); IEA, Is carbon capture too expensive? (2021); Masdar, CCUS at Emirates Steel (2012); Carbon180, DAC (2025); DoE, Pathways to Commercial Liftoff (2024); Carbon Engineering, Research Round-Up: Evaluating Direct Air Capture Pathways (2022); WRI, 6 Things to Know About Direct Air Capture (2022); DSpace@MIT, Direct Air Capture as a Carbon Removal Solution (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs US Context (2022).

Credit: Christian Sandjaja, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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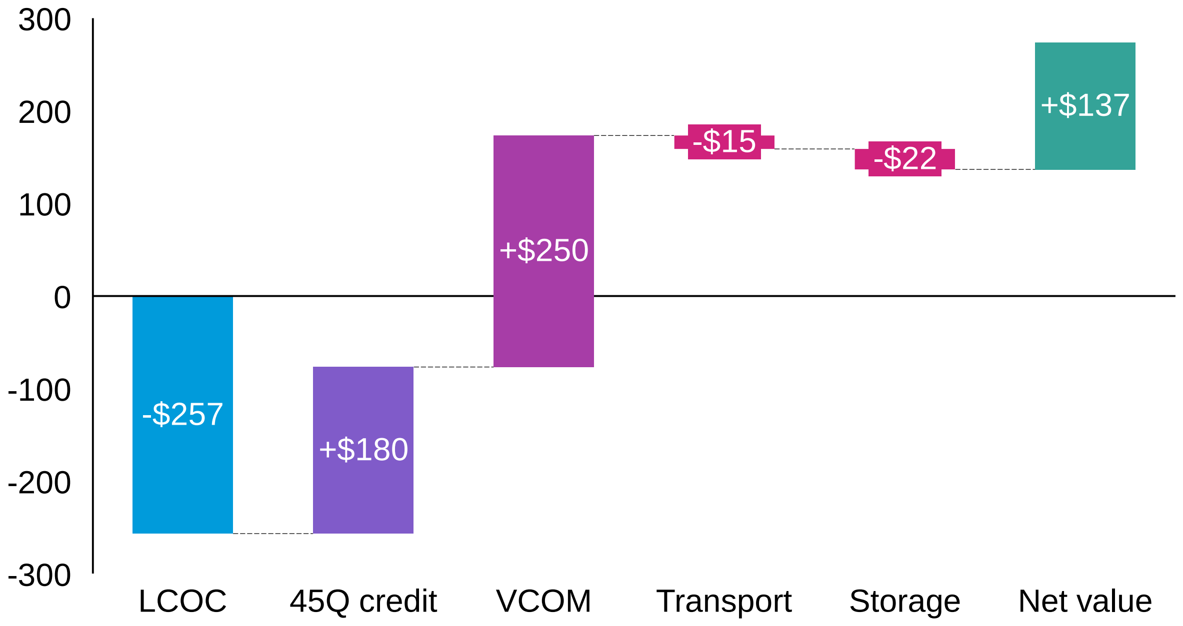
Significant reduction in LCOC and financial incentives key to achieving economically feasible DAC projects

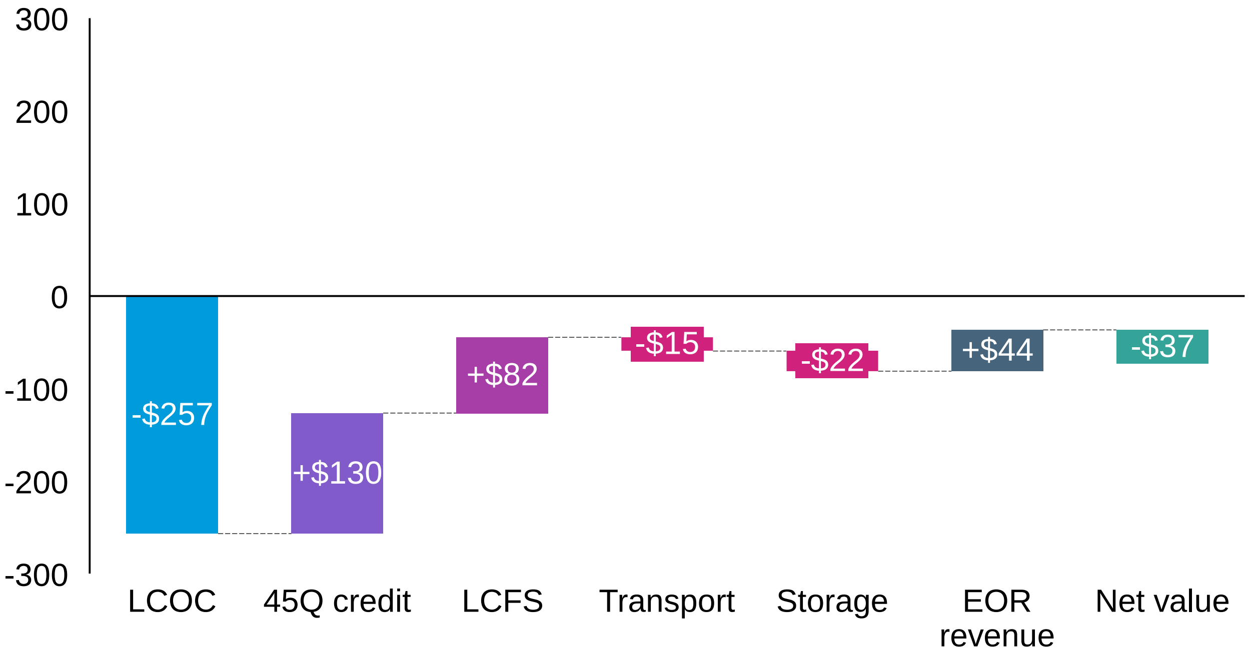
The 'pure play' DAC for permanent storage, combined with a voluntary carbon market, presents a positive value proposition

Permanent storage and VCOM monetization, in \$/ton CO_2



EOR and California's Low Carbon Fuel Standard (LCFS) on their own do not provide a viable pathway for value creation

EOR and LCFS monetization, \$/ton CO_2



Notes: Under the 45Q tax credit, DAC facilities are eligible for up to \$130/MT for captured QCO used in EOR.
Source: Pickering Energy Partners, Getting to Know Direct Air Capture (DAC) (2023).
Credit: Christian Sandjaja, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Future technology developments expected to drive DAC LCOC to <$300 per ton CO_2 in 2030

Companies project a substantial LCOC reduction

	Carbon Engineering	climeworks
LCOC before (2024)	**$600-$1,000/tCO_2**	**$600/t$CO_2$**
LCOC after (future)	**$341/t$CO_2$**	**$250-$300/tCO_2 by 2030**
Key technology (innovation)	KOH-based air contactor, pellet reactor, and calciner loop	Gen 3 modular DAC with 2x capacity, 50% less energy, 3x sorbent life
R&D improvement	Optimize solvent regeneration and thermal integration	Develop high-stability solid sorbents and modular collectors
Air contractor design	Cooling tower-style structure for large air throughput	Compact modular collectors with higher capture efficiency
Scale strategy	Large modular plants with centralized calciner/slaker	Standardized megaton DAC blocks (e.g., Mammoth)
Energy source	Natural gas or waste heat for calciner	100% renewable (mainly geothermal)
Funding & support	Backed by 1PointFive (Occidental), U.S. DOE, 45Q tax credit	$650M funding, Microsoft and Stripe offtake, Swiss government support

Observations

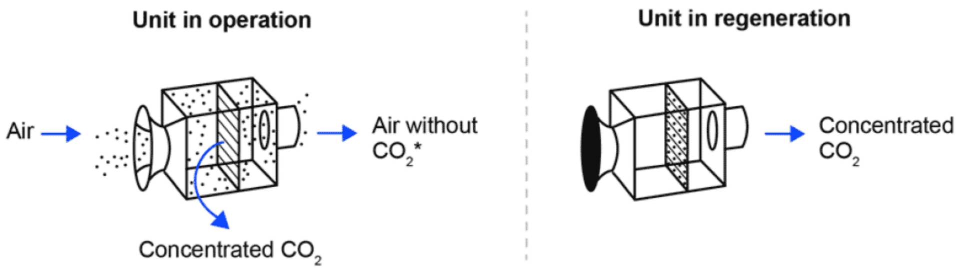
- Achieving <$300/t$CO_2$ will require **better capture materials, efficient system designs, large-scale deployment, clean energy integration, and steady funding.**
- Carbon Engineering is advancing its **KOH-based liquid solvent process** with **centralized regeneration units** to cut costs, supported by industrial partners, U.S. DoE funding, and 45Q incentives.
- Climeworks is scaling **Gen 3 solid-sorbent modules** that boost capacity, lower energy use, and extend material life, backed by $650M in funding, renewable power, and long-term offtake deals.

Sources: Carbon Herald, New Study Places Future Direct Air Capture Costs in a $230-$540 Range (2024); Climeworks, Next generation tech powers Climeworks' megaton leap (2024).
Credit: Michelle Priscilla, Christian Sandjaja, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

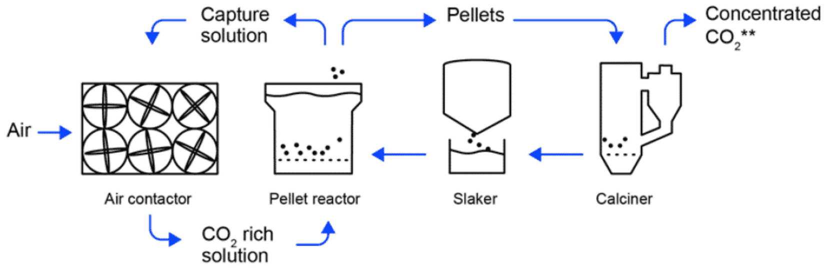
DAC leverages solid or liquid filtration technologies to extract CO2 from the atmosphere

Air capture process

Solid-DAC



Liquid-DAC



	Solid-DAC	Liquid-DAC
Description	Uses **solid filters or sorbents to capture CO_2**; filters are heated to release concentrated CO_2.	**A liquid chemical solution**, typically potassium hydroxide, absorbs CO_2, which is **then released through high-temperature processing.**
Energy consumption	7.2-9.5 KWh	5.5-8.8 KWh
Capture capacity	Modular (e.g., 50 tCO_2/year per unit)	Large-scale (e.g., 0.5-1 $MtCO_2$/year)
Land requirement (km2/$MtCO_2$)	1.2-1.7	0.4
Estimated levelized cost ($/ton)*	$100-$600	$95-$230

L-DAC is more efficient in energy consumption and land use.

*Notes: Levelized costs are estimates. Cost divergence reflects the wide range in estimated $/ton values due to differences in technology, plant scale, energy input, and capital cost.
Sources: Carbon Credits, How Direct Air Capture Works and 4 Important Things About It (2023); DOE, Pathways to Commercial Liftoff (2023).
Credit: Christian Sandjaja, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

S-DAC leads current market due to its modularity, while L-DAC expected to lead in the future due to its scalability

Air capture process

Solid-DAC (e.g., Project Orca – Climeworks)	**Liquid-DAC** (e.g., Project Squamish – Carbon Engineering)
	

Solid-DAC

- ⊕ **Lower energy requirements:** Operates at lower temperatures (80-120°C), allowing waste heat and utilization of renewable sources.
- ⊕ **Modular design:** Systems allow for flexible scaling and placement of capture units.
- ⊕ **Lower water usage:** Advantageous in water-scarce regions.
- ⊖ **Sorbent regeneration:** Solid sorbent materials can be energy intensive and may require frequent replacement.
- ⊖ **Scaling challenges:** While modular, scaling up still presents engineering and cost challenges.

Liquid-DAC

- ⊕ **Higher capture efficiency:** Capture rates per unit volume can reach up to 98%.
- ⊕ **Well-established technology:** Use of liquid solvents for gas separation is a more mature technology, with applications in natural gas processing.
- ⊖ **High energy requirements:** Requires higher temperatures (~900°C) to release captured CO_2, which translates to greater energy consumption.
- ⊖ **Water intensity:** Systems have higher water requirements, which can be a significant drawback in water-scarce regions.
- ⊖ **Complexity:** Involves more complex chemical processes and equipment, potentially increasing operational costs and maintenance requirements.

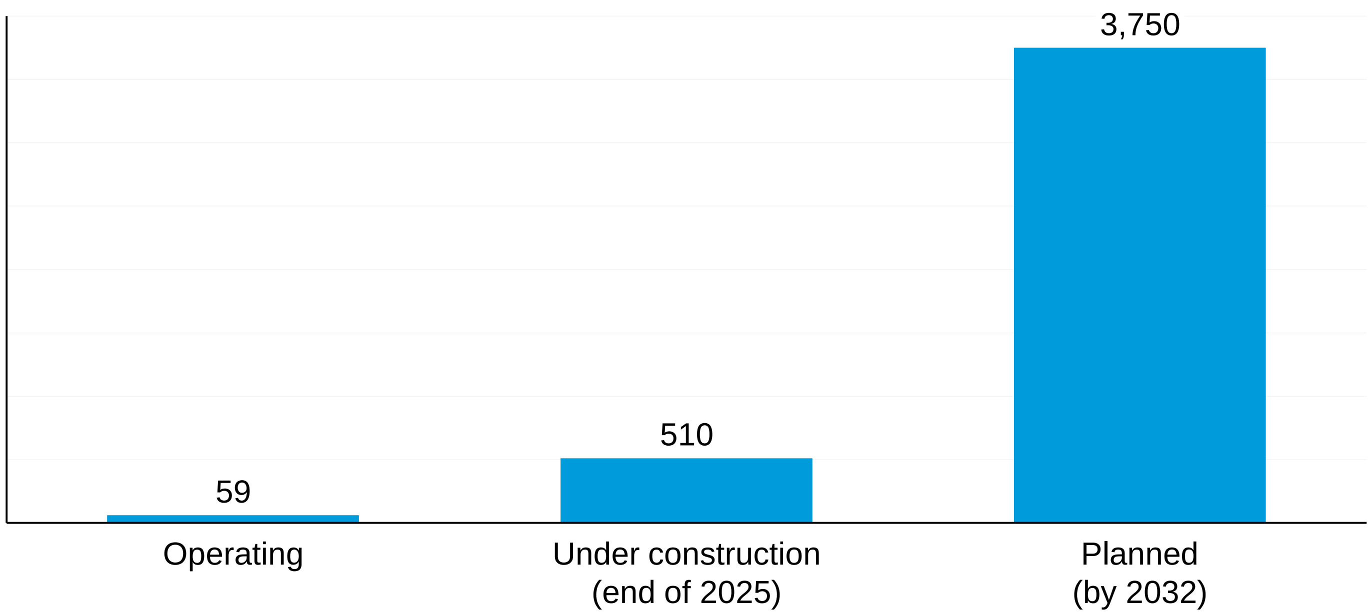
Sources: NETL, Solvent-Based Direct Air Capture Systems for the Removal of Atmospheric (2021); WRI, Direct Air Capture (2021); DOE, Direct Air Capture (2022); IEA, Direct Air Capture (2021); Google Patents, Solvents and methods for gas separation from gas streams (2017); Yale Environment 360, As Carbon Air Capture Ramps Up, Major Hurdles Remain (2023); Naan Group, What Is Direct Air Capture (DAC) Technology and Its Advantages? (2023).

Credit: Christian Sandjaja, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Despite the potential for negative carbon emission, technology not yet proven at commercial scale

Capture facility available today

Estimated CCUS capture capacity
in 2025, in ktCO_2 per year



No. CCUS facilities:	Operating	Under construction (end of 2025)	Planned (by 2032)
	53	**31**	**114**

Considerations

Pros

- **Permanent CO_2 removal:** DAC can permanently remove CO_2, addressing past and current emissions, which is crucial for NZE targets.
- **Location flexibility:** DAC plants can be built anywhere with low-carbon energy and storage, enabling strategic placement.
- **Low land use:** DAC needs far less land than reforestation, using 0.4-66 km² per million tons vs. 862 km² for forests.

Cons

- **High costs:** DAC costs $400-$1,000 per ton, much higher than desired for large-scale adoption.
- **Energy intensive:** High energy needs increase costs and emissions unless powered by clean energy.
- **Limited capacity:** About 30 facilities exist, capturing 540,000 tons/year.

Sources: AZO Cleantech, The Advantages and Disadvantages of Carbon Capture (2022); Center on Global Energy Policy, Low-Carbon Production of Iron and Steel (2021); IEA, Iron and Steel Technology Roadmap (2020); IEA, Is carbon capture too expensive? (2021); Allied Offsets, The Current State of Direct Air Capture (2025).
Credit: Christian Sandjaja, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

Iceland and U.S. are key hubs for DAC, capitalizing on geothermal energy and natural gas reserves

Major CCS facilities are concentrated in Iceland and the United States

	Description	Country	Status	Established	Type of technology	Capture capacity (Mtpa CO2)	Currently captures (Mtpa CO2)
Project Cypress	Large-scale DAC hub in Louisiana, funded by DOE	U.S.	Planned	2024	Solid-DAC	1	N/A
Project Stratos	World's largest DAC facility in Ector County, Texas	U.S.	Commissioning	2025	Liquid-DAC	0.5	N/A
Project Monarch	Large-scale DAC facility in California's Central Valley	U.S.	Demo	2023	Solid-DAC	1	N/A
Project Mammoth	Largest operational DAC plant, powered by geothermal energy	Iceland	Operating	2024	Solid-DAC	0.036	0.036
Project Orca	World's first large-scale DAC and storage plant	Iceland	Operating	2021	Solid-DAC	0.004	0.004

Observations

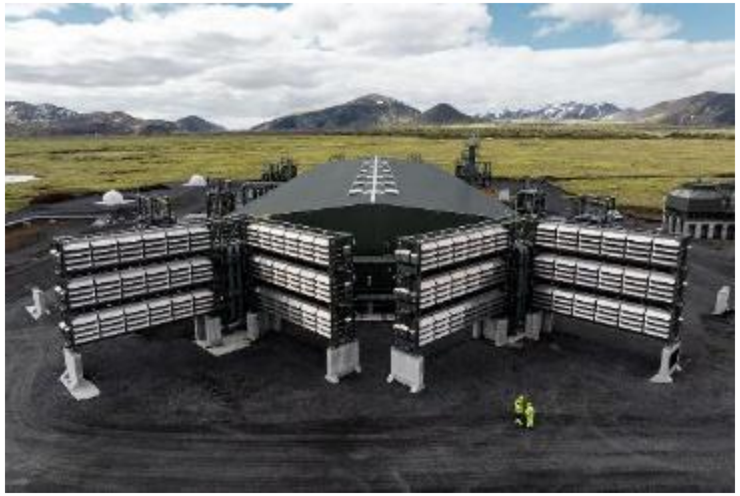
- Project concentration in the U.S. and Iceland is driven by private **funding, geological sites** suitable for permanent CO2 storage, and availability of **renewable energy.**
- Planned megaprojects Cypress and Monarch can achieve higher capacity due to **technology advancement** that combines solid- and liquid-DAC, **intention for scale design, and supportive infrastructure** like pipelines, geological storage, and shared energy sources.

Sources: Carbon Credits, How DAC Works (2023); DOE, Project Cypress Fact Sheet (2024); Climeworks, The Reality of Deploying DAC (2023); Singularity Hub, Project Orca (2022); Batelle, Project Cypress (2023); Climeworks, Project Mammoth (2023); Climeworks, Orca Plant (2023); Capture6, Project Monarch (2023); Capture6, Carbon Removals (2023); OXY, Occidental and 1PointFive Secure Class VI Permits for STRATOS Direct Air Capture Facility (2025).
Credit: Christian Sandjaja, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., “Capturing Carbon” (7 November 2025).

Case study: Project Mammoth paved the way for future DAC cost reduction, 10-20% reduction in CapEx per ton of CO2 capture

Plant overview

- Climeworks' Mammoth is **one of the world's largest DAC and storage plant**, located in Hellisheidi, Iceland.
- It uses **modular technology** to capture CO_2 directly from the air and **permanently stores** it underground by mineralizing it into basaltic rock through a natural process.



CCS implementation and expansion

- Climeworks successfully completed the construction and ramp-up of **Mammoth**; it has been **fully operational since the end of 2024.**
- The plant is powered by **renewable geothermal energy,** ensuring that the carbon removal process remains carbon-negative.
- Mammoth represents a significant scale-up from Climeworks' previous DAC plant, Orca, with a **10x increase in capacity.**
- **Generation 3 technology** will be deployed in future plants, aiming for a **cost reduction of up to 50%.** The goal is to reach a total cost of \$400-\$600 per tonne of CO_2 by 2030, a much larger leap than the 10-20% CapEx reduction achievable from a single project.

Key statistics

Designed to capture…

36,000 tons of CO_2 per year

Secured offtake contract for…

more than **1/3** of running capture capacity

Raised funding for DAC projects of…

\$650M in 2022 equity round

Sources: AWE International, Project Mammoth (2023); Peter Fisk, Project Mammoth (2024); ESG Voices, Climeworks' Plant Starts Mammoth Operations (2023); Climeworks, Mammoth: our newest facility (2023).
Credit: Christian Sandjaja, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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Case study: Project Cypress set a standard for large-scale CCS, tackling the technical, operational challenges of an early adopter

Plant overview

- Project Cypress, set to be the **biggest DAC by capacity,** will be built in Louisiana by Battelle, Climeworks, and Heirloom.
- It will **use renewable energy** to power DAC technology, capturing carbon dioxide for **permanent storage** on privately owned land in Calcasieu Parish.

CCS implementation & expansion

- The project partners with Gulf Coast Sequestration for carbon storage and **prioritizes community engagement** through local outreach and plans for a Community Engagement Council.
- The actual capacity will **depend on various factors,** including technological advancements, operational efficiencies, and successful implementation.

Key statistics

Designed to capture…

1M tons of CO_2 per year

Expected to start operations in...

2026-27

Received public funding by the U.S. DOE for...

$600M

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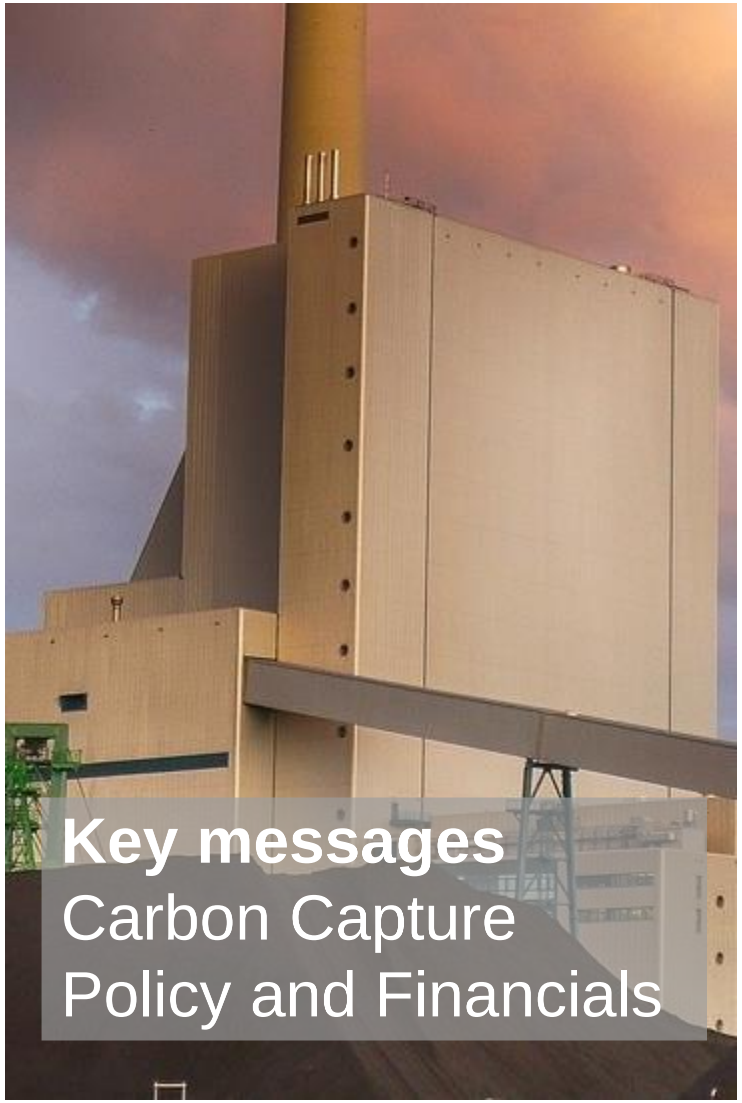
CCUS Policy



Government policies and financial incentives: Governments are intensifying carbon capture deployment through mature policy frameworks.

- The U.S. 45Q tax credits are now the dominant global driver. The key metric is no longer the credit value itself ($85/ton for point-source capture, $180/ton for DAC) but the number of projects that have reached **final investment decision** based on it.
- In Canada and Europe, the focus is on the rising cost of carbon prices and their effectiveness in closing the economic gap for emitters.

Regional hubs and infrastructure efficiency: The UK's HyNet and East Coast Clusters have offtake agreements finalized and are in early construction phases.

- The **Port of Rotterdam's Porthos** in the Netherlands, one of Europe's most advanced carbon capture projects, is operational or nearing completion, serving as a critical proof-of-concept for the hub model.

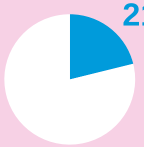
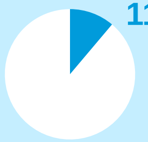
Carbon capture targets and global commitments: The gap between targets and reality is becoming clearer:

- The UK's target of capturing 10 Mtpa by 2030 is under pressure, with current deployment rates lagging. The original U.S. target (50 Mtpa by 2050) is likely a significant underestimate; the DOE's "Liftoff" reports envision a scale of 400-1,800 Mtpa by 2050 to meet climate goals. The key story is the immense acceleration required to meet these more realistic figures.

Deployment challenges: The primary challenges have sharpened:

- **Permitting for Class VI storage wells** in the U.S. remains the single largest bottleneck, with a multiyear backlog at the EPA, though states with primacy like Louisiana are moving faster.
- **Public opposition (NIMBYism)** to CO_2 pipeline construction has intensified, causing delays and route changes for several key projects. Supply chain constraints for specialized components like compressors and absorbers are also beginning to bite as more projects move forward simultaneously.

Diverging policies in the U.S., EU, and UK have shaped distinct CCUS investment climates and emission reduction pathways

	1 United States	2 European Union	3 United Kingdom
Main policies	**Federal:** • **IIJA allocated $2.5 billion for carbon storage validation and testing,** including funding for CarbonSAFE Phase III large-scale storage projects and the development of new regional carbon sequestration hubs • **$3.5 billion designated for direct air capture (DAC) hubs** supports the development of four regional DAC hubs to deploy large-scale carbon removal tech **State:** California's Low Carbon Fuel Standard; Texas's tax exemptions for CCUS infrastructure	• **EU Innovation Fund** setting aside **$1.5B for CCUS R&D and pilot projects** • **Connecting Europe Facility (CEF)** allocating **$0.5B for CO_2 transport and storage infrastructure** • **The Industrial Carbon Management Strategy and the Net-Zero Industry Act target 50 Mt CO_2 storage by 2030,** mandate oil and gas contributions, streamline CCUS permitting, and **mobilize €100B for industrial decarbonization**	• Net-zero strategy • Track-1 clusters (selected in 2021): HyNet and the East Coast Cluster; moving toward final investment decisions • Track-2 clusters (selected in 2023): Acorn project and the Viking project • CCUS Infrastructure Fund: **$1 billion fund** for clusters **contracts for difference** (CfD) for CCUS • Industrial Decarbonization Strategy • **New transport and storage licensing regime**
Subsidies offered	The Inflation Reduction Act's 45Q credits allow for **$85/ton for geological storage and $60/ton for utilization/EOR** (effective only when prevailing wage requirements are met)	**CCUS dedicated funds have been set up by various institutions, e.g., €1.5B** in the latest **Innovation Fund and €0.5B** dedicated to CO_2 transport and storage from **CEF**	**$28.5 billion** in funding: The UK government's stated ambition for the **private investment** it aims to unlock by 2030 through its comprehensive support policies (the CfDs, T&S model)
Emission abatement potential	***Up to 15%*** ***of CO_2 emissions abated in 2050 NZE scenario***	***Up to 30%*** ***of CO_2 emissions abated in 2050 NZE scenario***	***Up to 30%*** ***of CO_2 emissions abated in 2050 NZE scenario***
Carbon capture target	Reduce the cost of industrial CO_2 capture to < **$30/ton** by 2035 and develop regional storage hubs that can store at least **50M tons of CO_2 p.a.** by 2050	**50 million tons of CO_2 by 2030, 280 million by 2040, and 450 million by 2050**	**10 million tons of CO_2 annually by 2030** and up to **50 million tons by 2050**
Share of global CCUS (planned, under construction, and operational)			

Sources: Alberta, CCUS; ANU, ANU sets a new standard for high-quality carbon removal (2022); Australian government, Australian Carbon Credit Unit Scheme, Australia's Energy Commodity Resources; EY, Why carbon just became an economic fastball (2022); Journal of Cleaner Production, The impact of CCUS (2024); Canadian government, Canada's Carbon Management Strategy, 2030 Emissions Reduction Plan; IEA, CCUS Projects Explorer (2024); IEA, NZE (2021); NETL, CarbonSAFE; UK government, The Carbon Capture and Infrastructure Fund (2021); CCSA (2023).

Credit: Grace Frascati, Yosafat Partogi, Anda Wang, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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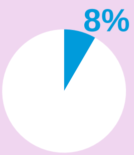
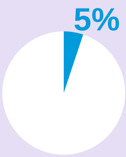
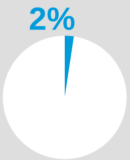
Canada, China, and Australia adopt distinct CCUS policies shaping deployment and abatement potential

	4 Canada	5 China	6 Australia
Main policies	**Federal:** • Specific CCUS investment tax credits • 60% for DAC, 50% for other capture • 37.5% for transportation, storage, and use • Bill C-59 passed in June 2024, establishing the CCUS tax credits **Provincial:** • Alberta's CCUS Incentive Program	• National 1+N policy system for emission peaking and carbon neutrality • National 15th Five-Year Plan (2026-30) • Emission trading system: CCUS included in official implementation plans and the Green Industry Catalogue	**Federal:** • Geoscience Australia's Exploring for the Future program issued AU$225 million over 10 years to map subsurface resources, including for CO_2 geological storage **Regional:** • Western Australia announced $26 million for CCUS projects in November 2024
Subsidies offered	The CCUS Investment Tax Credit is a multibillion-dollar program that provides a direct refund on capital costs (up to 60% for direct air capture and 50% for other capture projects)	**No large-scale, direct national subsidy for commercial CCUS deployment**	**The $50 million CCUS Development Fund** was designed to support pilot, pre-commercial, and research projects (grants have already been awarded to a portfolio of projects)
Emission abatement potential	***Up to 15%*** ***of CO_2 emissions abated in the 2050 NZE scenario***	***Up to 20%*** ***of CO_2 emissions abated in 2050 NZE scenario***	***Up to 25%*** ***of CO_2 emissions abated in 2050 NZE scenario***
Carbon capture target	The 2030 Emissions Reduction Plan includes capturing and storing **15M tons of CO_2 annually by 2030**	To peak CO_2 emissions **before 2030** and achieve carbon neutrality **before 2060; no official, government-mandated targets for carbon capture specifically**	**No formal nationwide target**
Share of global CCUS deployment (planned, under construction, and operational)			

Sources: IEA, CCUS Projects Explorer (2024); NETL, CarbonSAFE; UK government, The Carbon Capture and Storage Infrastructure Fund (2021); CCSA (2023), North Sea Transition Authority, Carbon capture and storage (CCS) is critical to the UK achieving net zero (2024); IEA, CCUS in Clean Energy Transitions; BloombergNEF, Faster Scale-Up of Clean Technologies Could Get China on Track for Net-Zero Emissions by 2050 (2024); Energy, Exploring incentive mechanisms for the CCUS project in China's coal-fired power plants (2024); EC, Climate Action (2025).
Credit: Grace Frascati, Shaurir Ramanujan, Petr Jenicek, Anda Wang, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Capturing Carbon" (7 November 2025).

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Since 2022, U.S. IRA accelerated CC adoption, enabling large-scale emission reduction and positioning the U.S. as a climate tech leader

45Q offers a tax credit for every ton of CO_2 captured and permanently stored in geological formations

Increases tax credit values

Up to **$180** per metric ton of CO_2

for **DAC projects** storing CO_2 geologically (with prevailing wage requirements); **$85/metric ton** for **non-DAC geologic storage**, **$60/metric ton** for **utilization** (e.g., enhanced oil recovery)

- By extending 45Q to $85/ton, the U.S. makes the **tax credit significantly more accessible** to a wide array of investors and developers, **unlocking potential for hard-to-abate sectors.**
- Industrial sectors are now more likely to wield carbon capture tech at more feasible price points.

Extends eligibility

Credit can be realized for **12 years**

after carbon capture equipment is placed **in service;** will be **inflation-adjusted beginning in 2027** and **indexed to 2025 base year**

- **Reduces minimum capture thresholds** for industrial emitters, **from 100,000 tons** of CO_2 emitted per year **to 12,500 tons.**
    - For DAC, capture thresholds decreased **from 100,000 tons to 1,000 tons** per year
- **Extends the deadlines for projects seven years, to January 1, 2033** (projects must begin physical work by then to qualify).
- **Infrastructure Investment and Jobs Act (IIJA):**
    - $3.5 billion for DAC hubs through IIJA
    - $2.5 billion for carbon storage validation and testing (CarbonSAFE)

Encourages investment

Taps **$12 trillion** global market

through direct pay, making the carbon capture market more attractive to a **broader array of investors not operating in the tax equity market**

- **Direct pay** allows developers to receive a **fully refundable tax credit**, **eliminating the need for tax equity partnerships** and **reducing transaction costs.**
- **Transferability** enables **equipment owners to sell tax credits to any tax-paying entity** for a non-taxable cash payment, increasing **financing flexibility.**

Note: Developers must pay workers prevailing wages (Davis-Bacon Act) and meet specific ratios of apprentices to journeymen on projects.
Sources: Clean Air Task Force, CC and the IRA (2022); Clean Air Task Force, The Inflation Reduction Act creates a whole new market for carbon capture (2022); S&P Global, IRA Challenges Persist (2023).
Credit: Grace Frascati, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

One Big Beautiful Bill Act brings both opportunities and challenges for the U.S. carbon capture industry

OBBBA (2025) maintains support for carbon capture while introducing new restrictions and modifications

	Modified project economics via 45Q changes	Foreign entity of concern	Federal support maintained with new constraints
Updates	• OBBBA equalizes rates for sequestration and utilization at a $17/ton base rate and $36/ton for qualified facilities • Parity provision maintains $85/ton for CCS and $180/ton for DAC, whether stored permanently or used in products or enhanced oil recovery (EOR) • EOR now receives the same credit as permanent storage, potentially increasing oil production	• Specified foreign entities become ineligible for credits in tax years after enactment • Foreign-influenced entities lose eligibility two years later • Unlike other credits, FEOC for 45Q applies only to the entity claiming credit, not to supply chain, making compliance easier	• IRA's 45Q credits remain in place with modifications • IIJA funding for **CarbonSAFE** and DAC hubs continues • Projects must move quickly due to new construction deadlines • DOE programs continue but face potential future appropriations risks
Impact	**Positive**: Maintains 45Q credits with potential for increased EOR projects due to parity provision.	**Challenge**: Foreign entity restrictions may limit international partnerships and investment.	**Opportunity**: Simplified FEOC compliance compared to other clean energy credits maintains project viability.

Key takeaway:

- While OBBBA significantly rolled back many clean energy incentives under the IRA, it **preserved and modified the 45Q carbon capture credit** – underscoring how CCUS remains compatible with U.S. fossil fuel and energy security objective and remains bipartisan support.

Sources: Frost Brown Todd, One Big Beautiful Bill Act Cuts the Power (2025); Columbia University Center on Global Energy Policy, Assessing the Energy Impacts of the One Big Beautiful Bill Act (2025); ClimeCo, What the One Big Beautiful Bill Act (OBBB) Means for Your Company: 5 Key Takeaways (2025).
Credit: Maitreyi Menon, Grace Frascati, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

EU dedicating €2B of funding to reach 50 MtCO_2 annual capture and storage by 2030 and 450 million captured p.a. by 2050

EU is ahead on framework development and regulation of CCUS; direct investments and incentives are lagging behind

Goal

450 Mt CO_2/year

expected to be **captured by 2050 through various CCUS projects across the EU,** with anticipated capture of **50 MtCO_2 per year by 2030**

- **Initial deployment is focused on hard-to-abate sectors** like cement and steel production.
- TSOs and other players along the energy value chain are expected to participate in phase 2.
- **The primary focus** is on **development of transport and storage infrastructure** prior to implementation of the CCUS tech.

Regulation

3 existing directives and industry acts

regulating the development and implementation of CCUS and regulating the geological storage of the carbon captured by the CCUS technologies

- **Net-Zero Industry Act:**
  - **Identifies CCUS** as a key technology and mandates EU countries to invest into CCUS technology across hard-to-abate industries
  - Mandates the 50 Mt of annual CO_2 injection capacity target by 2030 and streamlines permitting for strategic projects

Incentives and funding

€2 billion

across various European funds and EU Parliament subsidies

- **The EU Innovation Fund dedicated €1.4 billion** to support **CCUS R&D** efforts in European countries and **development of pilot projects** across the CCUS value chain.
- **Connecting Europe Facility**, an EU Commission fund, **dedicated €0.5B to develop CO_2 transport and storage network and infrastructure** across EU countries.

EU's Carbon Trading Mechanism

- **Creates a direct financial incentive:** By putting a high price on carbon (often over €80/ton), the EU ETS makes it cheaper for industries to pay for capturing and storing their CO_2 rather than buying expensive permits (EU Allowances) to emit it.
- **Protects investment with a carbon border tax (CBAM):** The Carbon Border Adjustment Mechanism ensures that EU companies investing in CCUS are not undercut by foreign competitors that produce goods with higher emissions, as those imports will face an equivalent carbon price at the border.
- **Defines captured CO_2 as *not emitted*:** Under the ETS rules, any CO_2 that is captured and permanently stored does not require a company to surrender a carbon allowance. This is the fundamental rule that makes capturing CO_2 a direct and legally recognized method of compliance.

Sources: IEA, CCUS Projects Explorer (2024); CATF, EU pushes forward climate action in Europe with Industrial Carbon Management Strategy (2024); EC, Industrial Carbon Management (2025).
Credit: Petr Jenicek, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

UK is slowly streamlining government incentives to create the market environment needed to accelerate carbon capture adoption

The UK's incentive system is rather simple, offering support in the form of direct grants and tax breaks

Targeted investment

20-30 $MtCO_2$ per year

expected to be **captured by 2030 in low-carbon industrial clusters,** with anticipated capture of **50 $MtCO_2$ per year by 2035**

- CO_2 to be collected from 14 planned industrial hubs and stored in saline aquifers and the North Sea
- Plans to establish a robust CCUS market by 2035, with a faster and **more competitive allocation process by 2027**

Project finance

$28.5 billion invested

in long-term projects focused on two clusters, **and their associated infrastructure needs**, over 25 years

- **East Coast cluster:**
  - **Hydrogen production facilities and £4 billion net-zero gas-fired power plant built by BP and Equinor**
  - Initial construction on pipeline and onshore facilities commenced in early 2025
- **HyNet cluster:**
  - **Decarbonizing cement plant, equipping** oil refinery with **waste-to-hydrogen tech,** and building **energy-from-waste plant**
  - Expected for a significant portion of the UK's initial low-carbon hydrogen production target
  - Received final government go-ahead for construction in April 2025, with site preparation now underway

Market incentives

$5 billion

in contracts were unlocked when the UK granted **Net Zero North Sea Storage** a **transport and storage license** in December 2024

- The government is expected to provide **tax relief** for oil and gas companies that **decommission assets by transferring them to a CCUS company.**
  - With Track-1 clusters now in early construction, the government is **advancing the Track-2 cluster sequencing process** (e.g., Acorn and Viking projects) to expand the network.
  - **The Energy Profits Levy (EPL)** provides investment allowances for decarbonization projects. EPL, a windfall tax, remains a contentious issue, with the government working with industry to develop a **long-term successor regime to provide certainty beyond its current 2030 sunset date.**

Sources: Clean Air Task Force, UK's £21.7 billion funding for carbon capture and storage projects is a significant step forward (2024); UK government, Relief for Payments Made into a Carbon Capture Usage and Storage Decommissioning Fund (2024); Pinsent Masons, UK Budget: CCUS and tax relief measures may soften oil and gas energy profits levy blow (2024); NSTA Authority NSTA awards Endurance first ever UK carbon storage permit (2024); UK government, Carbon capture, usage and storage (2024).
Credit: Shaurir Ramanujan, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Canada leverages federal and provincial policies for carbon capture, but economic viability remains a key hindrance in

Policy		Description	Key features	Challenges
Federal policy	Investment Credit Tax (ITC) for CCUS	• CCUS refundable tax credit for eligible and qualified CCUS projects • Enacted by Parliament in June 2024 • Considered the cornerstone of Canada's CCUS Policy Framework	• Applies to eligible expenditures incurred from Jan. 1, 2022, to Dec 31, 2040, which can vary from equipment to property • Credit rates (up to 2030): 60% for DAC, 50% for CO_2 capture, 37.5% for carbon transport and storage	• **Economic viability:** High up-front cost, which requires significant capital • Credit rates reduced by half for expenses after 2030-2040 • Rates reduced by 10% if labor requirements not met
	Emission Reduction Target Plan	• Canada pledged to reduce GHGe by 40-45% below 2005 level by 2030 and to net zero by 2050	• Increase national CCS capacity more than 3x and store at least 15 MT of CO_2 per year by 2030 • Energy Innovation Program; budgeted $319M over seven years in CCUS R&D	• **Incomplete policy framework:** – Only 45% of the measures have an implementation deadline – 95% of measures don't have target for emission reduction
	Carbon Pricing	• Maintains a carbon pricing system for large industrial emitters; the federal consumer fuel charge was eliminated	• Applies a carbon price to large industrial facilities through the Output-Based Pricing System (OBPS) and ensures a market for emissions credits	• Complexity in ensuring fairness and international competitiveness for trade-exposed industries under the OBPS
	Clean Fuel Standard	• Designed to reduce GHGe and promote the adoption of cleaner fuels by creating a market-based credit system that incentivizes CC projects	• Takes a lifecycle approach to measuring carbon intensities and extends credit generation time frame for longer period	• **Economic viability:** Gap between price of carbon and the cost of implementing full-scale CC facility • **Policy design:** Often perceived as hypertechnical and difficult to fully understand
Provincial policy	Alberta CC Incentive Program	• The cornerstone of Alberta's CC policy, focused on financial support	• 12% grant for eligible CCUS capital costs • $3.2 billion to $5.3 billion expected between 2024 and 2035 • Preapproval applications open as of 2025, with retroactive eligibility to 2022	• **Economic viability** of CCUS project • **Uncertainty** over long-term revenue potentials from carbon credits

Sources: Canada ITC, ERM Policy Alert (2024); Torys, Cross-country carbon capture and sequestration check-in (2024); OAG Canada, Emission Reduction Plan (2023); Climate Choices, The State of Carbon Pricing in Canada (2021); Global CCS Institute, Global status of CCS 2024 report at a glance (2024); McCarthy Tétrault, Clean Economy Tax Credits: Investment Tax Credit for Carbon Capture, Utilization and Storage (2024).
Credit: Yosafat Partogi, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Alberta Carbon Capture Incentive Program (ACCIP) provides incentive to accelerate CCUS capital development through grants

About ACCIP

- **Provincial initiative designed to accelerate** carbon capture, utilization, and storage projects in Alberta
- Preapproval applications opened in 2024; full program launched in spring 2025 with finalized guidelines
- Key focus is **to reduce emissions in hard-to-abate industries** while supporting economic growth

Key features

- **12% grant** for eligible CCUS capital costs, paid in three annual installments starting one year after project operations begin
- **$3.2B-$5.3B allocated between 2024 and 2035,** with potential to leverage up to $35B in private investments
- **Retroactive eligibility:** Costs incurred as early as January 1, 2022 qualify for support

Eligibility criteria

- Projects **must be in Alberta and focus on capturing, preparing, compressing, transporting, storing or utilizing CO_2**
- **Supported sectors** include oil sands, oil and gas production, power generation, cement manufacturing, petrochemicals, and hydrogen
- **Grants cover capital costs only,** such as equipment installation and retrofitting; **payments are tied to operational milestones** to ensure accountability

Key projects

1. **Shell Canada (Quest Project):**
   - Announced new CCUS expansion at a Scotford refinery with ATCO EnPower, targeting 810,000 tons per year by 2028
   - Project is a prime candidate for ACCIP funding
2. **Entropy Inc.:**
   - Expanded its Glacier Gas Plant CCS project near Grande Prairie (2026 start), leveraging federal and provincial incentives
3. **Wolf Midstream (Alberta Carbon Trunk):**
   - Operational since 2020, storing 4.5M+ tons of CO_2 from fertilizer and refining facilities
4. **Pathways Alliance:**
   - Plans to invest $16.5M in a carbon capture network for oils and emissions, likely using ACCIP alongside federal tax credits

Sources: Alberta, Alberta Carbon Capture Initiative (2024); Invest Alberta, New Investment Incentive (2023).
Credit: Yosafat Partogi, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

China leverages national policies, large-scale demonstration projects, and source-sink matching to achieve carbon neutrality

China's carbon neutrality strategy integrates CCUS as a key technology for achieving the 2030/60 goals

National policy and demonstration projects

70 national-level policies

related to CCUS have been issued; CCUS was included in the 14th Five-Year Plan (2021-2025) and is expected to feature even more prominently in the upcoming 15th Five-Year Plan (2026-2030)

- China's national policy encompasses **R&D and demonstration projects** while placing greater emphasis on **technical standards and investment/financial support.**
- Besides the oil and gas industries, CCUS has been taken into account in the policy guidelines for **more hard-to-abate industries.**
- Over **100 demonstration projects** have been announced or are in development, with a potential total capture capacity exceeding **15 Mt per year.**
- China is home to one of Asia's first and largest full-chain CCS projects in a saline reservoir (Sinopec Qilu-Shengli)**, with several larger scale projects now under construction.**

CCUS potential based on source-sink matching

1.21-4.13 trillion tons (Tt)

theoretical geological storage capacity, mainly including saline aquifers, oil and gas fields, and other geological formations

- **Onshore deep saline aquifers** can reach a large scale and have a storage potential of **2.417 Tt.**
- In the northern part of the country, large basins like the **Songliao Basin and Bohai Bay Basin** have great potential for carbon storage.
- In the southern and coastal areas, **offshore geological storage** is the best solution because basin storage is limited.
- The CO_2 pipeline length will be **capped to 250 km** due to the cost of pipeline and the CO_2 relay compressor station.

CCUS cost assessment

$20-$40 US$/ton

by 2060

for the whole CCUS process

- China is transitioning from demonstration to commercial deployment. With over 100 projects announced or in development and several large-scale facilities already operational, China has moved beyond the early stage of CCUS and is now a world leader in its development.
- The primary cost is the **cost to make** the whole system operate **(input price);** the cost is expected to decrease from 2025 to 2060:
  - Capture (US$/t): $15-$80 to $3-$20
  - Transport (US$/t*km): $0.1-$0.2 to <$0.1
  - Storage (US$/t): $7-$9 to ~$3

Sources: Carbon Management, China's pathways of CO_2 capture, utilization and storage under carbon neutrality vision 2060 (2022); Global CCS Institute, CCS Progress in China – A Status Report (2023; PR Newswire, Sinopec Completes China's First Megaton Scale Carbon Capture Project (2022); USEA, China's Carbon Capture Utilization and Storage (CCUS): Development Status and Prospect (2024).
Credit: Xiaodan Zhu, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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Australia leverages targeted funding, legislative action, and resource mapping to drive carbon capture adoption

Australia's federal budget allocates funding accessible through grants, spurring transboundary CCUS

Federal geoscience storage funding

$345M over 10 years

allocated in the **2024-25 federal budget for geoscience; Australia** to **map subsurface resources**, including CO_2 geological storage potential

- Australia **boasts an estimated 31 Gt of sub-commercial CO_2 storage capacity** and **470 Gt of undiscovered storage resources,** highlighting a vast potential for long-term carbon sequestration.
  - **Significant storage resources are located in offshore basins** such as Gippsland Basin in Victoria.
- The **Oil and Gas Climate Initiative of 2022 utilized a CO_2 storage management system** to catalog Australia's storage resources, emphasizing the country's **readiness to support CCUS as part of decarbonization.**

Formal national strategies around CCUS

Grants of up to **$15M** for pilot or pre-commercial projects

from the Carbon Capture, Use, and Storage Development Fund, underscoring the impact of the Future Gas Strategy (2024)

- **Future Gas Strategy (FGS)** emphasizes CCUS as essential for Australia's transition to net-zero emissions by promoting geological storage of CO_2.
- The **Climate Change Authority** is consulting on sectoral decarbonization strategies, with initial papers for key industries **released for review throughout late 2024 and early 2025.**
- Western Australia, whose gas industry is central to the country, passed the Petroleum Legislation Amendment Act, providing a legislative framework for transport and geological storage of GHG.

Transboundary infrastructure expansion

Western Australia's **$16M** under the CCUS Action Plan helping to fund the CCUS transboundary industry

as part of a general push to energy transition and the state's economic diversification

- Action Item 5 of FGS, which promotes geological storage of CO_2 and supports transition to net zero, establishes the **Transboundary CCS Program,** providing energy security and carbon management solutions for regional partners.
- Vopak and the Northern Territory government **are progressing on a joint development agreement** for a CO_2 terminal, following a 2024 MOU. The project is currently in the pre-FEED stage.

Sources: Ashurst, Transboundary CCUS for AUS (2023); Australian government, CC and Storage (2024), Funding for CC, Future Gas Strategy (2024); Global CCS Institute, Status Report (2024); Reuters, Vopak agreement (2024); S&P Global, Western Australia unveils CCUS action plan with funding boost (2024); WA.gov, CC and Storage Bill Passes (2024).
Credit: Grace Frascati, Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

Scaling CCUS requires coordinated action across technology development, policy support, infrastructure build-out, and market creation

Point-source focus

Focus deployment on ready-to-commercialize sectors with high CO_2 purity streams like cement and ammonia production where capture costs are lowest.

Tax credits and subsidies

Extend and enhance programs like 45Q credits ($85/ton storage, $180/ton DAC) while ensuring policy stability across political transitions.

Regional hubs

Develop shared transport and storage infrastructure through coordinated regional clusters to achieve economies of scale and reduce per-project costs.

Green public procurement

Establish government purchasing programs for low-carbon cement, steel, and fuels to create early demand for CCUS-enabled products.

R&D investment

Accelerate cost reduction in high-potential technologies through targeted research, with DAC costs needing to drop from $600-$1,200 to <$100/ton by 2030.

Carbon pricing

Implement robust carbon pricing mechanisms and border adjustments to create economic incentives for CCUS adoption across industries.

Pipeline networks

Build dedicated CO_2 pipeline infrastructure, leveraging existing oil and gas assets where possible to minimize capital requirements.

Performance standards

Set mandatory emission reduction targets for hard-to-abate sectors, making CCUS economically necessary rather than voluntary.

Sources: IEA, CCUS in Clean Energy Transitions (2020); DOE, Pathways to Commercial Liftoff (2024); McKinsey, Scaling the CCUS industry to achieve net-zero emissions (2022); Global CCS Institute, Global Status Report (2024).

Credit: Maitreyi Menon, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., “Capturing Carbon” (7 November 2025).

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Appendix

Component-level cost modeling enables precise CCUS cost projections by 2035

STEP 1: Decompose total costs into capital and operational components

Capital and operational costs reduce at different rates; separate them to apply targeted reductions
Capital % = Capital Cost ÷ (Capital + O&M + Energy)
Operational % = (O&M + Energy) ÷ (Capital + O&M + Energy)

Technology	Capital %	Operational %	Implication
Ammonia	89%	11%	CapEx reductions drive total cost down
Hydrogen	88%	12%	Energy efficiency gains also matter
Cement	87%	13%	Process optimization more important

Capital costs dominate across all technologies (80-90%)

Why ranges vary: Technologies with higher capital percentages (like ammonia at 89%) see greater cost reductions because CapEx improvements have more impact than OpEx improvements based on CCSA's industry consultation findings.

STEP 2: Apply differentiated cost reductions by component

2030 Cost = (Current Cost × Capital %) × (1 - CapEx Reduction %) + (Current Cost × Operational %) × (1 - OpEx Reduction %)

Cost-reduction drivers:
- **CapEx (15-30%):** Learning curves, collaborative contracting, design optimization
- **OpEx (5-25%):** Process improvements, operational learning, economies of scale

STEP 3: Calculate final cost ranges using conservative and optimistic scenarios

Lower cost scenario: Lower CCSA reduction rates (15% CapEx, 5% OpEx)
Higher cost scenario: Upper CCSA reduction rates (30% CapEx, 25% OpEx)

STEP 4: Final cost ranges

Technology	Current range	2035 projected range
Ammonia	$25-$35	$19-$32
Hydrogen	$50-$80	$38-$72
Cement	$60-$120	$46-$109

Sources: IEA, CCUS in Clean Energy Transitions (2020); IEA, Levelized Cost of CO2 Capture by Sector and Initial CO2 Concentration (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs in the US Context (2022).
Credit: Maitreyi Menon, Michelle Priscilla, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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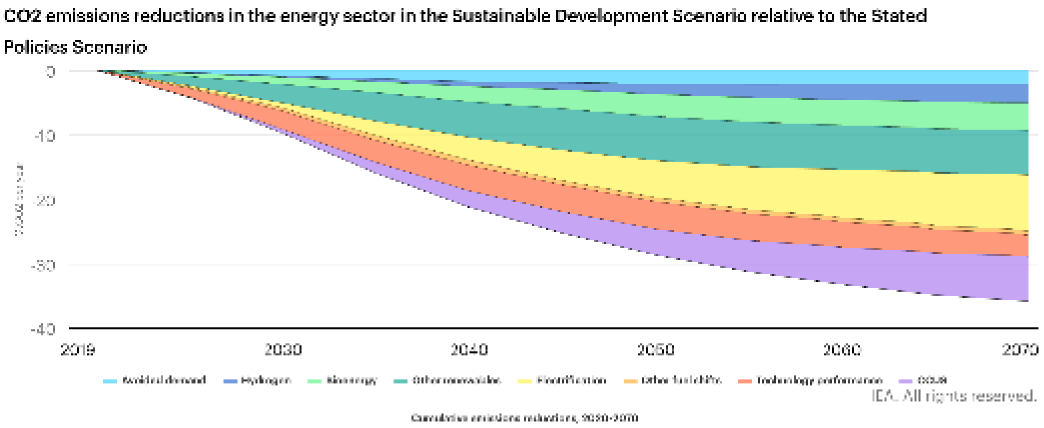
Analyzing technology-specific cost data informs strategic investment for industrial decarbonization

IEA scenario specification



Abatement potential

Technology	Potential %
Fuel transformation	90%
Ammonia	90%
Bioethanol	90%
Cement	61%
Hydrogen	90%
Iron & steel	25%
Natural gas power	15%
Power generation	7%

Abatement potential based on planned facilities, 2030

Technology	Potential % based on planned facilities
Natural gas processing	1.74%
Power & heating	0.59%
Iron & steel	1.7%
Other industries	0.51%
Cement	0.7%

Key global CCUS indicators in Sustainable Development Scenario

CCUS contribution to sector CO_2 reductions	2030	2050	2070	Cumulative
Iron & Steel	4%	25%	31%	25%
Cement	47%	63%	61%	61%
Chemicals	10%	31%	33%	28%
Fuel transformation	86%	86%	92%	90%
Power generation	3%	13%	25%	15%

CapEx and energy cost breakdown

	Ammonia	Ethanol	Natural gas processing (low)	Hydrogen	Cement	Steel & iron	Natural gas processing (high)	Coal power plant	Natural gas power plant	Refinery-FCC	Industrial furnaces
CC capital cost	71	71	80	196	199	275	276	327	354	412	472
Non-energy O&M cost	3.55	4.97	4.8	9.8	13.93	13.75	16.56	13.08	17.7	16.48	18.88
Energy cost	5	6	5	18	17	17	5	17	18	16	17

Sources: IEA, CCUS in Clean Energy Transitions (2020); IEA, Levelized Cost of CO2 Capture by Sector and Initial CO2 Concentration (2019); Harvard Kennedy School Belfer Center, Carbon Capture Utilization and Storage: Technologies and Costs in the US Context (2022).
Credit: Anda Wang, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

CCUS costs span 40x range with capture driving 75% of total system costs while transport offers greatest scale economies

	Technology	Sectors	Cost range (US$/t$CO_2$)	Cost drivers/assumptions
Capture	Chemical absorption	Power generation, fuel transformation, industrial production, natural gas processing	$15-$100+	Grouped diverse chemical solvents (MEA, CANSOLV, advanced amines) under single category
	Physical separation	Natural gas processing, ethanol/methanol production, hydrogen production	$15-$50	Combined pre-combustion and high-purity separation technologies
	Oxyfuel separation	Coal power generation, cement production	$50-$120	Oxygen production costs, equipment integration
	Membrane separation	Natural gas processing, biogas treatment, flue gas	$30-$80	Grouped polymer, ceramic, and mixed-matrix membranes together; membrane material costs, selectivity limitations
	Calcium looping	Coal power, cement production	$40-$90	High-temperature operation, sorbent makeup costs
Transport	Pipeline transport	Onshore CO_2 transport, industrial hubs	$1-$8	Capacity utilization, distance, terrain
	Ship transport	Long distance, offshore storage, cross-border	$10-$50	Distance, cargo size, port infrastructure
Storage & use	Deep saline aquifers	Dedicated geological storage	$5-$35	Site characterization, injection infrastructure
	Depleted oil & gas reservoirs	Storage using existing infrastructure	$3-$25	Well recompletion, existing infrastructure reuse
	Enhanced oil recovery	Oil production with CO_2 storage	-$10-$20	Oil prices, reservoir characteristics, CO_2 purity
	Synthetic fuels	Aviation kerosene, diesel, gasoline	$200-$600/ton fuel	Hydrogen costs, energy intensity, scale
	Chemicals and polymers	Methanol, polymers, primary chemicals	$100-$400/ton product	Hydrogen costs, process complexity, market size
	Building materials	Concrete curing, aggregates, cement additives	$50-$150/ton material	Process integration, material properties, scale
	Food & beverage	Carbonation, food preservation, greenhouses	$100-$300/ton CO_2	Range noted as conservative; actual market prices higher

Sources: IEA, CCUS in Clean Energy Transitions (2020); IEA, Is carbon capture too expensive? (2021); NETL, Cost and Performance Baseline for Fossil Energy Plants (2022); NETL, Cost of Capturing CO_2 from Industrial Sources (2022); NETL, FECM/NETL CO_2 Transport Cost Model (2023); Global CCS Institute, Global Status of CCS Report (2024); McKinsey & Company, Scaling the CCUS industry to achieve net-zero emissions (2021); ScienceDirect, Techno-Economic Analysis of Amine-based CO_2 Capture Technology: Hunter Plant Case Study (2022); ScienceDirect, Calcium looping processes for low CO_2 emission cement plants (2019); Thunder Said Energy, Costs of liquefied CO_2 carriers (2024); IEAGHG, Oxy-combustion Processes for CO_2 Capture from Power Plant (2005); IPCC, Climate Change 2022: Mitigation of Climate Change Report (2022).

Credit: Maitreyi Menon, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., "Capturing Carbon" (7 November 2025).

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CCUS faces a key imbalance, as transport and storage are ready but 70% of capture tech is still in demonstration

CO_2 capture

CO_2 to chemicals
- Ammonia
- Methanol

Cement
- Chemical absorption
- Calcium looping
- Oxyfueling

Iron & steel
- Direct reduced iron
- Blast furnace
- Fuel
- Natural gas processing
- Hydrogen
- Ethanol from sugar
- Hydrogen from coal

Power generation
- Coal
- Natural gas
- Biomass

DAC
- Liquid-DAC
- Solid-DAC

Transport
- Pipeline
- Ship
- Ship (offshore)

Storage
- EOR
- Saline aquifers
- Depleted O&G

Use
- Urea
- Concrete
- Methanol
- Synthetic methane
- Synthetic hydrocarbons

Mature
Early adoption
Demonstration
Large prototype

Source: IEA, CCUS Technology Innovation (2020).
Credit: Maitreyi Menon, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al*., “Capturing Carbon” (7 November 2025).

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Glossary (1/2)

A3C	Advanced cryogenic carbon capture
ACCIP	Alberta Carbon Capture Incentive
ACCU	Program Australian carbon credit unit
ACTL	Alberta Carbon Trunk Line
APAC	Asia Pacific
ARENA	Australian Renewable Energy Agency
AS	Amine scrubbing
ATR	Autothermal reforming
BECCS	Bioenergy with carbon capture storage
BF-BOF	Blast furnace-basic oxygen furnace
BIL	Bipartisan Infrastructure Law
BNEF	Bloomberg New Energy Finance
CAGR	Compound annual growth rate
CapEx	Capital expenditure
CBAM	Carbon border adjustment mechanism
CCS	Carbon capture and storage carbon
CCUS	Capture, utilization, and storage
CEF	Connecting Europe Facility
CEMBUREAU	European Cement Association
CfD	Contracts for difference
CFPP	Carbon Free Power Project
CFS	Clean Fuel Standard
CII	Carbon Intensity Indicator
CPP	Clean Power Plan
DAC	Direct air capture
DOE	Department of Energy
DRI	Direct reduced iron
EAF	Electric arc furnace
EBITDA	Earnings before interest, taxes depreciation, and amortization
EOR	Enhanced oil recovery
EPL	Energy Profit Levy
ERF	Emissions Reduction Fund
ESG	Environmental, social, and governance
ETS	Emissions trading system
EWR	Enhanced water recovery
FCC	Fluid catalytic cracking
FEED	Front-end engineering and design
FGS	Future Gas Strategy
FID	Final investment decision
FYP	Five-Year Plan
GCCA	Global Cement and Concrete Association
GHG	Greenhouse gas
GPP	Green public procurement
Gt	Gigatons
ICM	Industrial carbon management
IEA	International Energy Agency
IMO	International Maritime Organization
IRA	Inflation Reduction Act
IRR	Internal rate of return
ISR	Iron and steel recycling
ITC	Investment Credit Tax
kWh	Kilowatt-hour
L-DAC	Liquid direct air capture
LCFS	Low Carbon Fuel Standard
LCOC	Levelized cost of capture
LNG	Liquefied natural gas

Glossary (2/2)

MEA	Monoethanolamine
MMt	Million metric tons
MOF	Metal-organic frameworks
MOU	Memorandum of understanding
Mt	Million tons
Mtpa	Million tons per annum
MWh	Megawatt-hour
NG	Natural gas
NZIA	Net-Zero Industry Act
NZE	Net-zero emissions
O&M	Operations and maintenance
OAG	Office of the Auditor General
OCCS	Onboard carbon capture and storage
OGCI	Oil & Gas Climate Initiative
OpEx	Operating expenditure
PCA	Portland Cement Association
PSA	Pressure swing adsorption
R&D	Research and development
S-DAC	Solid direct air capture
SMR	Steam methane reforming
SRMS	Storage resource management system
TRL	Technology readiness level
TSO	Transmission system operator
TWh	Terawatt-hour
USD	United States dollar
VCOM	Voluntary carbon offsets market
WtE	Waste to energy