



The New Frontiers Report for CDR

An assessment of innovation
breakthroughs in carbon removal

October 2026

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Declaration of AI use

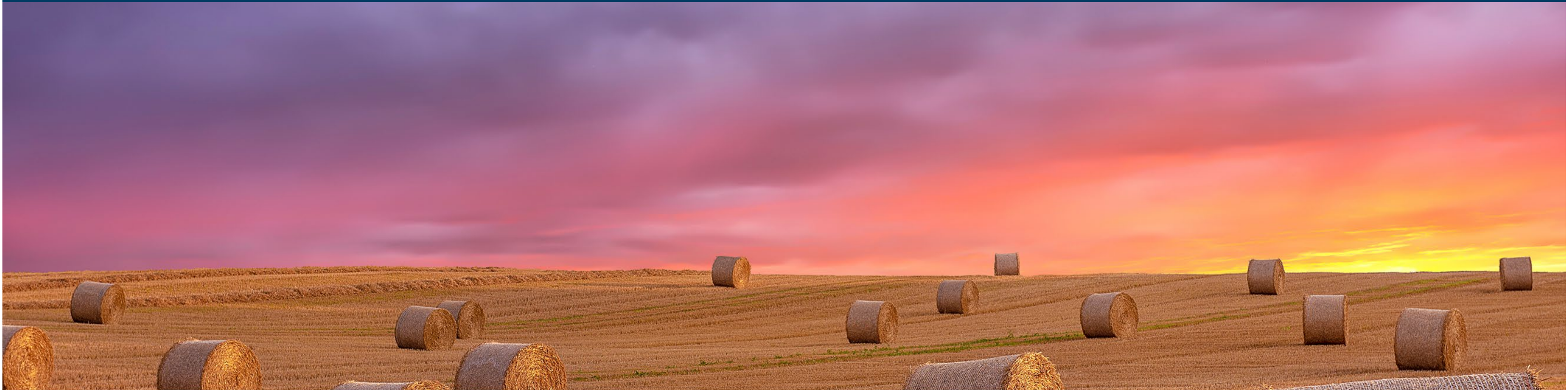
To develop overall current and future cost stacks, representative cost ranges across eight contributing components for each CDR approach were created using generative AI through a sequential prompt investigation for each component. This was followed by high-level sense-check of total costs and relative sizes of contributing factors, with manual editing to impose consistency across CDR approaches and manual modeling of select capex costs for sCDR technologies. To develop breakthrough innovation ideas, generative AI was used in initial brainstorming phases alongside ideation by RMI CDR experts, but final selection and descriptions of breakthrough was done without AI. To develop discussions of key cost considerations, AI was used for initial topic brainstorming and searching for published sources during the research phase in some cases, but the final considerations were written without AI by RMI CDR experts. Generative AI was not used to create any of the text or visualizations in the report.

The New Frontiers Report for CDR, 2026, RMI <https://rmi.org/resources/the-new-frontiers-report-for-cdr>



Rocky Mountain Institute (RMI) is an independent, nonpartisan nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to secure a prosperous, resilient, clean energy future for all. In collaboration with businesses, policymakers, funders, communities, and other partners, RMI drives investment to scale clean energy solutions, reduce energy waste, and boost access to affordable clean energy in ways that enhance security, strengthen the economy, and improve people’s livelihoods. RMI is active in over 50 countries.





You can help

Reach out to RMI to get involved in catalyzing a coordinated effort to fund CDR RD&D.

To engage, please contact

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Help RMI stay informed

and up to date about new projects, findings, and project outcomes.

Offer constructive feedback

on the New Frontiers Report.

Express interest in collaborating

to advance projects on the roadmap as a researcher, project developer, or funder for specific projects, or by enabling information sharing or coordination across projects.

Glossary and Abbreviations

AIR: The *Applied Innovation Roadmap*; a comprehensive report covering 32 distinct CDR pathways, published by RMI in 2023

ARL: Adoption readiness level; the state of a CDR approach in terms of its readiness to be implemented writ large by the technology’s target sector

BDS: Biomass direct storage

BECCS: Bioenergy with carbon capture and storage

CCS: Carbon capture and storage; CCS typically refers to point-source carbon capture at sites with high levels of biogenic or fossil-derived CO₂ in emission streams

CDR approach: A set of interventions for removing carbon dioxide from the atmosphere that should be viewed together, for evaluation and scoping purposes, because they share similar inputs, impacts, mechanics, and/or risks

CDR: Carbon dioxide removal; CDR includes any activity specifically enacted to remove carbon dioxide from the atmosphere or ocean and store it in Earth’s biosphere or lithosphere

CDR taxonomic category: A grouping of similar CDR approaches; the AIR uses four major taxonomic categories: biogenic CDR, geochemical CDR, synthetic CDR, and storage of carbon dioxide

CEW: Coastal Enhanced Weathering, a geochemical CDR approach

CORC: A CO₂ removal certificate; one carbon credit

DAC+S: Direct air capture with geologic storage

Demonstration facility: An industrial system used to validate a CDR approach for commercialization. It is larger than a pilot plant, and is the final stage in the research, development, and demonstration of a new CDR approach

DOE: The U.S. Department of Energy; responsible for much of the public funding for CDR to date.

EPA: The U.S. Environmental Protection Agency; responsible for protecting people and the environment from significant health risks

EOA: Electrochemical ocean approaches; CDR methodologies that leverage electrochemical processes to extract CO₂ from the ocean

EW or ERW: Enhanced weathering or enhanced rock weathering

FOAK: First of a kind; FOAK facilities are built to test whether an approach can work at a commercial scale

GHG: Greenhouse gas

Gt: Gigaton, one billion metric tons

KPI: Key Performance Indicator

kt: Kiloton, one thousand metric tons

LCA: Life-cycle assessment; these analyses are required to determine the net carbon dioxide removal of an approach across all its component activities

Low-carbon energy: Any form of electricity generation that does not produce significant carbon dioxide emissions

MAE: Mineral alkalinity enhancement

mCDR: Marine carbon dioxide removal

MCFS: Microalgae carbon fixation and sinking

MRV: Measurement, reporting, and verification, sometimes measurement, monitoring, reporting, and verification (MMRV); these are necessary steps in validating that carbon dioxide has been removed from the atmosphere and durably stored

Mt: Megaton, one million metric tons

NBS: Nature-based solution, CDR pathways that leverages living organisms or their byproducts

NFR: This document: *The New Frontiers Report for CDR*

NOAK: Nth of a kind; NOAK facilities or deployments are made after a successful first demonstration and are important for testing approaches under different geographies and varied conditions

OIF: Ocean iron fertilization, a proposed mCDR pathway for stimulating microalgae growth via the addition of iron, which is a constraining nutrient/mineral for growth

Pilot plants: A pre-commercial production system that employs new production technology and/or produces small volumes of new technology-based products, mainly for the purpose of learning about the new technology

RD&D: Research, development, and demonstration; the activities necessary to take an approach from its current technical state to demonstration at commercial scale

SM: Surficial mineralization

TEA: Technoeconomic assessment; a method for evaluating the economic performance of a technology

TEW: Terrestrial enhanced weathering, used to distinguish enhanced rock weathering on land from coastal enhanced weathering

TRL: Technical readiness level; the TRL is used to consistently and empirically assess the technical maturity of an approach. TRLs can be useful to inform what funding an approach should receive next and how close it is to widescale deployment

WHOI: Woods Hole Oceanographic Institution, a leading research group on OIF



Introduction

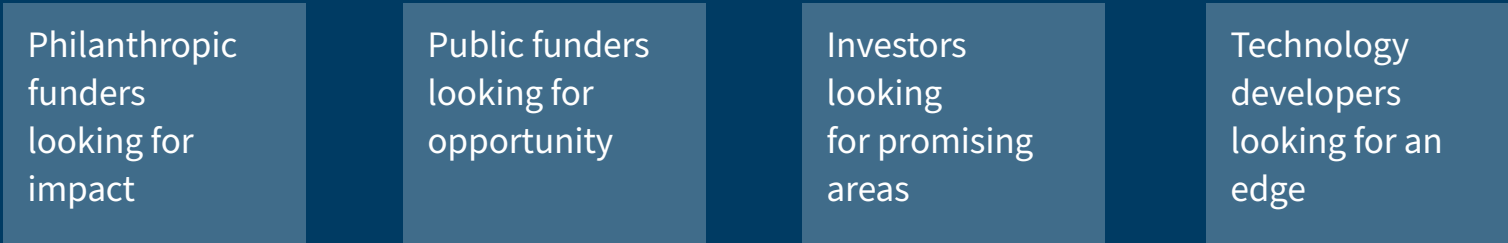
Intended audience and impact of this report

What this report contains

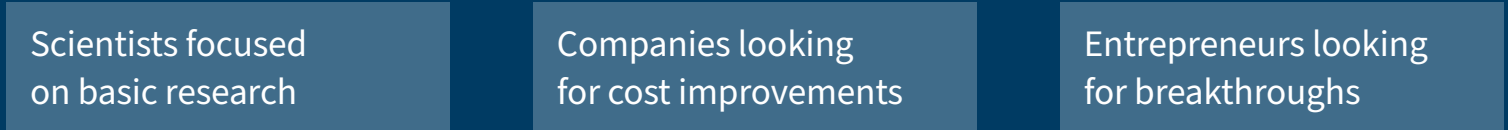
- 1. Review of the **technical history** of carbon dioxide removal (CDR)
- 2. Potential areas for **cost reductions** in existing CDR approaches
- 3. Opportunities for **breakthrough innovation** in new and existing approaches*

Audience

Funders



Researchers and implementers



Intended impact of this report

- 1. Highlight the **progress** that has been made in carbon removal in the last 10 years
- 2. Direct funders and researchers toward the **most promising activities** for the next 10 years

*Note that the scope of this report is focused on technological and process innovations. Governance, public engagement, financing mechanisms, demand, and supply chain planning are all critical to the growth of CDR approaches, and innovations in these spaces continue to be critical for building the field as a whole, but incremental costs associated with these areas are not included in the cost stacks and breakthroughs of this report.

RMI’s taxonomy of carbon removal

CDR term	 Biogenic CDR	 Geochemical CDR	 Synthetic CDR
Definition	Biogenic CDR (bCDR) approaches rely on the use of biomass. Foundationally, these approaches begin by utilizing naturally occurring biogenic carbon fixation mechanisms to capture CO ₂ from the atmosphere. The most important of these mechanisms is photosynthesis. Approaches in this category then utilize that biomass for conservation and carbon sink development, long-term burial, pyrolysis, or combustion to produce electricity.	Geochemical CDR (gCDR) approaches rely on naturally occurring reactions between acidic forms of carbon and alkaline minerals to convert CO ₂ from the atmosphere into durable carbon removal. gCDR approaches depend on the long-term storage of these minerals, either permanently as solid carbonate minerals in terrestrial environments, or in the form of dissolved bicarbonates that encourage CO ₂ drawdown.	Synthetic CDR (sCDR) approaches use engineered systems powered by low-carbon energy to directly remove CO ₂ from the air or from bodies of water. sCDR approaches are some of the most durable long term, storing captured CO ₂ in geologic formations or utilizing it to alter water chemistry and encourage CO ₂ drawdown. Aquatic sCDR approaches rely on separating acidic and basic components in water, and terrestrial sCDR uses sorbents that react with ambient air.
Key input	Sustainable biomass	Alkaline materials	Low-carbon energy
Implications for scaling	<ul style="list-style-type: none">•The potential scale of bCDR will be bounded by the availability of sustainable biomass feedstocks.•The most competitive bCDR solutions, long run, will be those that source and transform available biomass inputs into durable CDR most efficiently.	<ul style="list-style-type: none">•The potential scale of gCDR will be bounded by the availability of alkaline mineral feedstocks needed for neutralization reactions with carbon.•The most competitive gCDR solutions, in the long run, will be those that can source, process, transport, and dispose of alkaline minerals for CDR most efficiently.	<ul style="list-style-type: none">•The potential scale of sCDR will be bounded by the availability of low-carbon energy.•The most competitive sCDR solutions, long run, will be those that can transform low-carbon energy into CDR most efficiently.
Approaches	Living biomass, biomass direct storage, biochar, bio-oil, microalgae in open water, macroalgae in open water, microalgae in ponds, bioenergy with carbon capture and storage (BECCS) to electricity, BECCS to fuels	Enhanced rock weathering (EW), surficial mineralization (SM), mineral alkalinity enhancement (MAE)	Direct air capture (DAC), electrochemical ocean approaches (EOA)

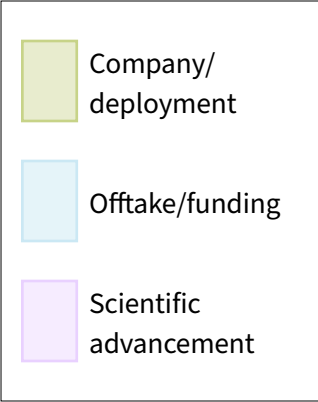
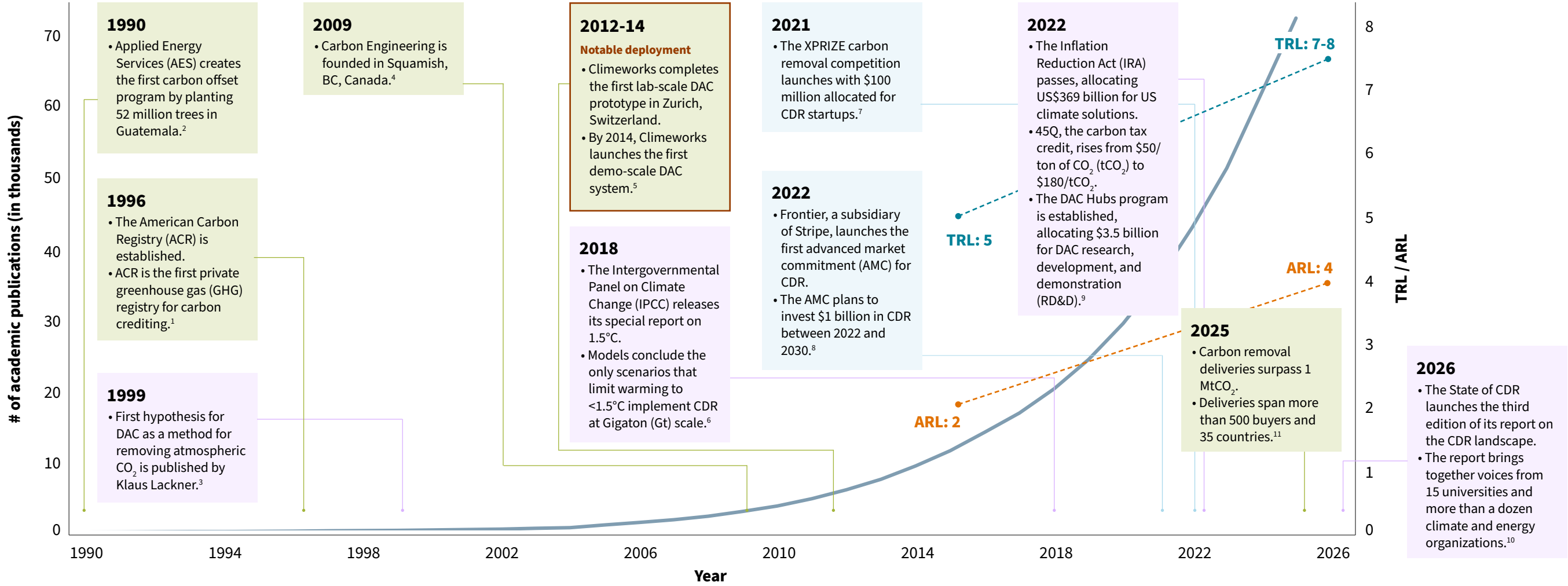
This table reflects an updated taxonomy as first described on page 11 of the [Applied Innovation Roadmap \(AIR\) for CDR](#), RMI, 2023. Definitions have been adjusted and the relevant approaches added since the original AIR publication.



The Story So Far

CDR has progressed significantly over the past three decades, growing exponentially in the past 10 years

Technology readiness level (TRL) and adoption readiness level (ARL) plotted lines reflect the average of the TRL and ARL ratings for each of the 14 approaches covered in this deck.



1. Building confidence in carbon markets, About Us, ACR. 2. Our history, AES. 3. "Carbon Dioxide Extraction from Air: Is It An Option?," DOE Los Alamos National Laboratory, 1999. 4. "Carbon Engineering Fast Facts," Occidental, 2025. 5. Creating climate value, globally, Climeworks. 6. "Summary for Policymakers — Global Warming of 1.5 °C," IPCC, International Governmental Panel on Climate Change, 2022. 7. "XPRIZE and Musk Foundation Announce Guidelines and Open Registration for \$100M XPRIZE Carbon Removal," Businesswire, 2021. 8. "An advance market commitment to buy \$1.8B of permanent carbon removal by 2040," Frontier. 9. "The Inflation Reduction Act (IRA) gives carbon removal a big boost," Atlantic Council, 2022. 10. "The State of Carbon Dioxide Removal Report - 3rd Edition," The State of CDR, 2026. 11. "CDR.fyi: Durable Carbon Removal Marks Milestone 1 Million Deliveries," Carbon Herald, 2025.

Biogenic (bCDR)

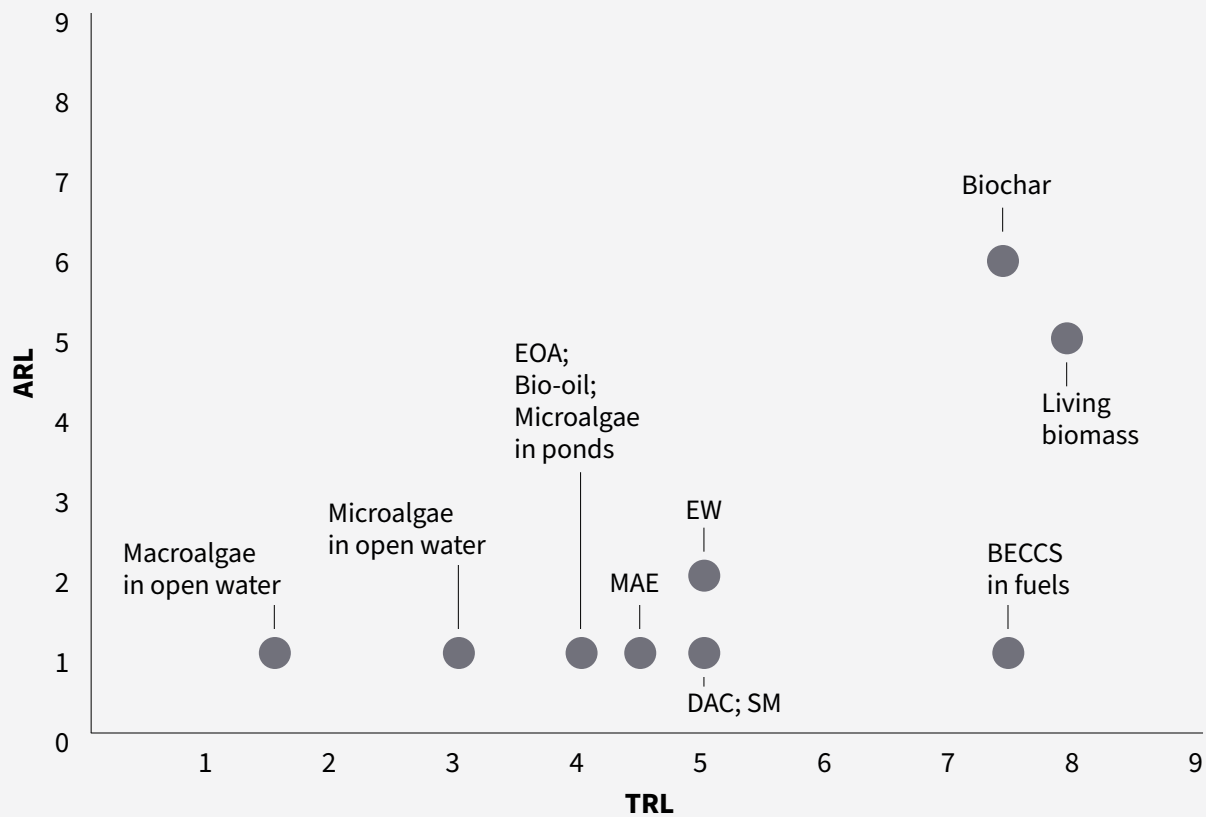


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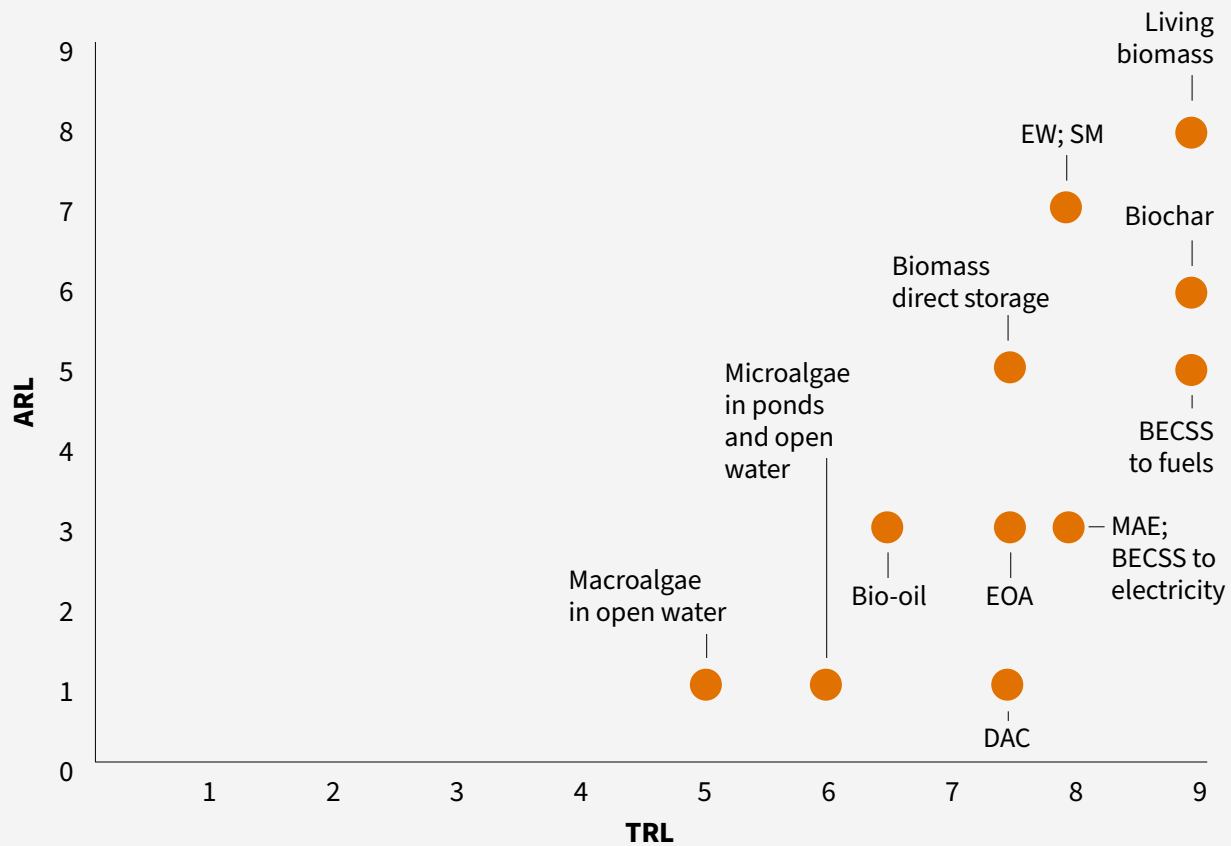
Almost every pathway has advanced its readiness for commercial development in the past 10 years

Sentiment remains high among CDR experts in academia, industry, and civil society that the most impactful solutions already exist in the current CDR portfolio.

Assessed ARL and TRL in 2015¹

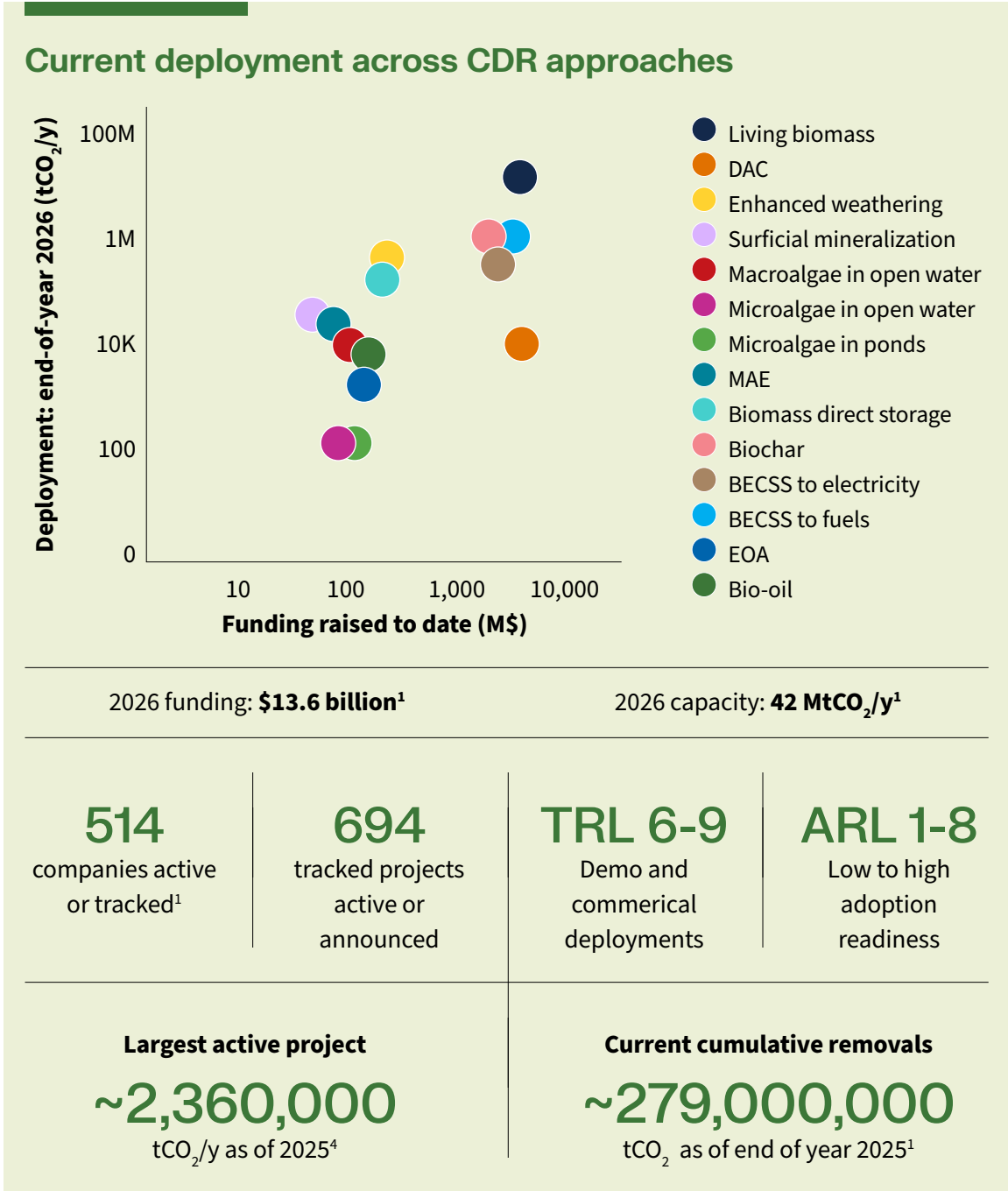
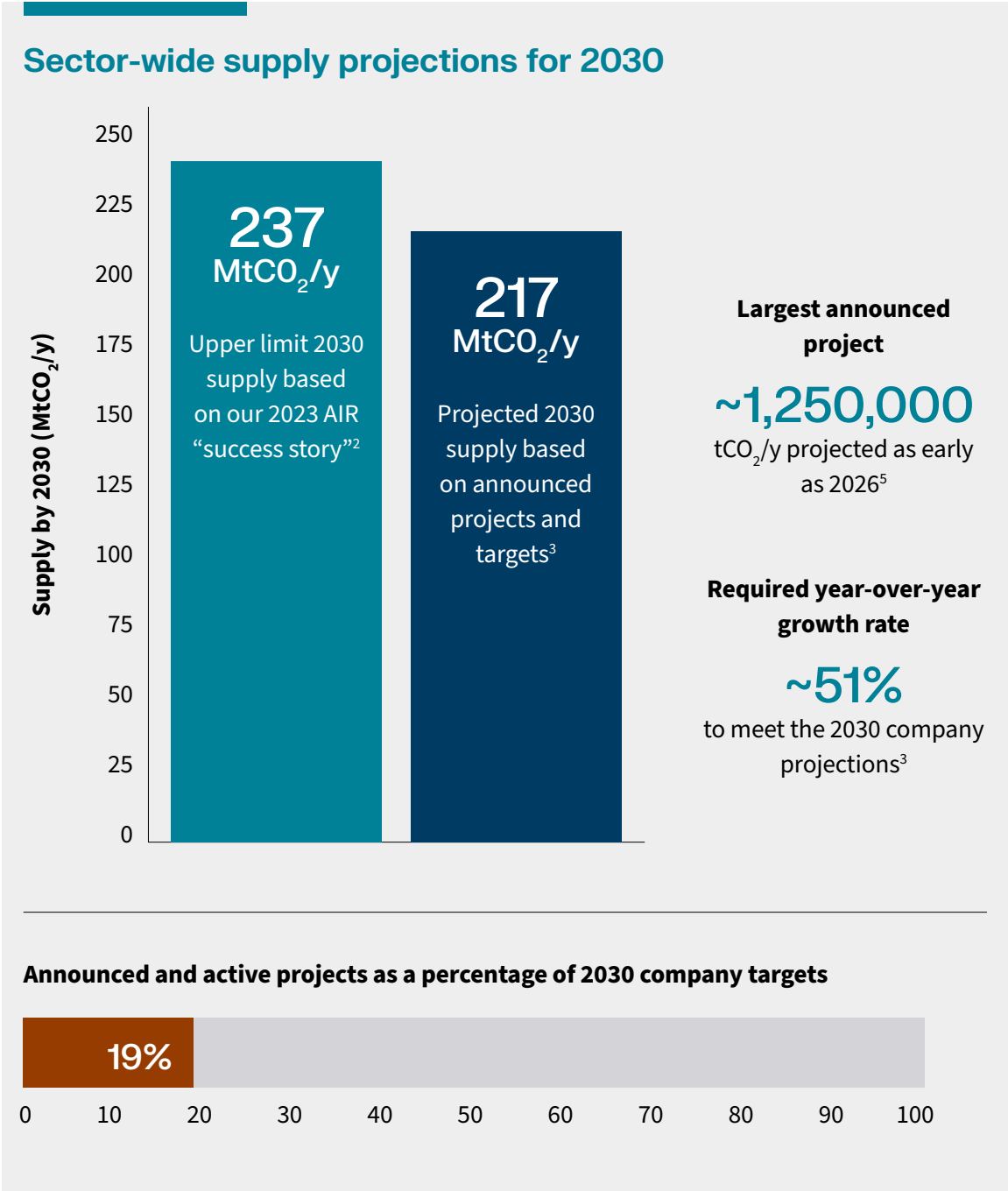


Assessed ARL and TRL in 2026



1. Assessments based on RMI analysis utilizing Department of Energy (DOE) frameworks for evaluating both TRL and ARL levels.

Current deployments and projections of CDR capacity indicate a growing industry, though company targets remain ambitious compared to announced and active projects



1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies, and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within each CDR approach, based on confirmed funding found through public project announcements, offtake agreements, and public deal information available via Pitchbook. 2. Reference capacity of 237 MtCO₂/y is sourced collectively from the approach “success story” section presented for every approach in [The Applied Innovation Roadmap for CDR](#), RMI, 2023. 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. [Delta Blue Carbon - 1: The Indus Delta Mangrove Restoration Project Phase 1](#), Verra. 5. [“Living Carbon secures \\$500m deal with Octopus Energy Generation to restore degraded land and remove CO₂”](#) TMCnet News, 2026.

Shared learnings of the past decade could enable accelerated scale-up and technological advancement through 2030

	Event	Learning
	Running Tide, a macroalgae company based in Maine, US, grew rapidly and then abruptly shut down in June 2024. ¹	Rapid scaling without regulatory clarity and financial backing can rapidly put a company in an untenable financial position. Prematurely accepting offtake agreements that cannot be delivered on could jeopardize company health as well as overall trust in the approach if credit deliveries are not extended. Lack of process clarity and unsustainable growth can sink CDR startups.
	In 2012, former Planktos CEO Russ George led an unpermitted 120 tCO ₂ field trial of ocean iron fertilization off the coast of Canada, creating massive public backlash. ²	Consultation and collaboration with community and local officials are paramount when it comes to successfully deploying first-of-a-kind (FOAK), untested, or unknown technologies. Failing to navigate the proper bureaucratic channels or engage early with community representatives can cause long-term harm to the reputation of whole approaches, making future deployments far more difficult.
	In 2020, Microsoft announced its intention to become carbon negative by 2030. ³	Long-term emissions commitments force corporations to think critically about how to reach net zero and beyond. After eliminating high-emissions processes and fully categorizing Scope 1, 2, and 3 emissions, purchasing carbon credits is the final tool for corporate decarbonization. Commitments like Microsoft's force companies to consider CDR for hard-to-abate operations, which ultimately drives investment. In 2025 alone, Microsoft purchased more than 50 MtCO ₂ in carbon removal. ⁴
	The XPRIZE Carbon Removal program was established in 2021. ⁵	Large incentives, especially prize-based strategies that attract a diverse range of technological approaches, can spur competition and collective advancement of the field. While they lack the certainty that credit purchases provide, the promise of significant, one-time awards can work in a similar manner to tiered or performance-based offtake agreements.
	Climeworks deployed both their Orca (4,000 tCO ₂ /y) and Mammoth (36,000 tCO ₂ /y) DAC plants in Iceland in 2021 and 2024, respectively. ⁶	Rather than going straight to commercial scale, capital expenditure-intensive processes are best scaled incrementally. This process allows companies to rectify process flaws and learn more completely from early-stage deployments, conserving time and resources before diving into commercial-scale planning. Early Climeworks projects have had issues with delivering on nameplate capacity, something they will have the opportunity to address ahead of a 100 ktCO ₂ /y facility scale-up.

 Green represents an event that went as planned or had a positive outcome

 Red represents an event that did not go as planned or had a negative outcome

 Yellow represents an event affiliated with scientific advancement

 Blue represents an event affiliated with funding or offtake

 Melon represents an event affiliated with company or project deployment

1. [Under the sea: Running Tide's ill-fated adventure in ocean carbon removal](#), Canary Media, 2024. 2. ["Full Press Coverage of 2012 Ocean Fertilization Scheme Near Haida Gwaii,"](#) ETC Group, 2012. 3. ["Microsoft will be carbon negative by 2030,"](#) The Official Microsoft Blog, 2020. 4. ["Microsoft Hits Pause on All Carbon Removal Purchases: A Major Shift in Corporate Climate Strategy,"](#) Carbon Credits, 2026. 5. ["XPRIZE and Musk Foundation Announce Guidelines and Open Registration for \\$100M XPRIZE Carbon Removal,"](#) Business Wire, 2021. 6. [DAC Projects](#), Climeworks.



Shared learnings of the past decade could enable accelerated scale-up

(continued from previous page)

	Event	Learning
	Charm Industrial and NULIFE GreenTech, companies that use fast pyrolysis to create bio-oil and then inject it underground, have catalyzed the bio-oil CDR sector. ^{7,8}	Some of the most successful CDR companies may be those that find potential in technologies that are overlooked. Bio-oil injection via fast pyrolysis did not have a single company before 2016; in 2026, it has only two active organizations. Nonetheless, both Charm Industrial and NULIFE GreenTech have secured major offtake agreements and delivered meaningful removals when compared with other more established approaches.
	In 2023, forest-based carbon credits registered with Verra came under scrutiny, with ~90% of rainforest offsets deemed to be “phantom credits.” ⁹	As has become a common phrase in the CDR dialogue, “Durability is the product.” When it comes to scaling carbon removal, trust in the quality and efficacy of a carbon credit is one of the most important barriers discouraging institutional investment. Clear measurement, reporting, and verification (MRV) and third-party validation of registry methodologies are required for sector-wide scaling.
	In 2022, the 45Q tax credit received an upgrade to \$180/tCO ₂ , spurring a new wave of CDR companies. ¹⁰	Tax incentives are one of the most powerful tools currently available to carbon removal advocates and CDR companies when it comes to enabling the industry to reach commercial scale. The use of carbon tax credits, like 45Q, alongside carbon taxes in compliance frameworks that mandate decarbonization, create crucial early market demand for CDR.

- Green represents an event that went as planned or had a positive outcome
- Red represents an event that did not go as planned or had a negative outcome
- Yellow represents an event affiliated with scientific advancement
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7. [Permanent Carbon Removal From Biomass](#), NULIFE GreenTech. 8. [Carbon removal technology](#), Charm Industrial. 9. [“More than 90% of rainforest carbon offsets by biggest certifier are worthless, analysis shows,”](#) *The Guardian*, 2023. 10. [New beginnings for carbon capture with Section 45Q tax credits in the United States](#), IEAGHG, 2022.

Target innovations for each approach involve trade-offs on cost and project configuration at scale

See the “Key cost considerations for scaled deployment” page in each section for detail on three topics related to costs and/or viability of scaled deployment of each approach. The topics selected for discussion often, but not always, overlap with the largest cost categories within each approach’s cost stack. The selected topics were chosen with a focus on technical and process innovations within the scope of this report. Other considerations on topics such as supply chain development, governance, financing, and public acceptance continue to be additional critical elements of CDR development and deployment.

	Approach	Assumed configuration(s) at scale	Where to start
1	Living Biomass: Management, Conservation, Restoration	Management, conservation, and restoration projects with contracted durability	Technological and governance solutions for long-term risk management
2	Biomass Direct Storage	Decentralized burial or sinking projects; injection or dry burial hubs	Hub-style sites colocated with sources of sustainable biomass
3	Biochar	Distributed or hub-style models producing biochar as a product	Integration into waste biomass collection and processing workflows
4	Bio-oil	Distributed or hub-style models with bio-oil transportation to injection wells	Feasibility studies for regional biomass handling and processing hubs
5	Microalgae in Ponds	Scaled deployment in land-constrained regions with abundant energy	Pilot projects to inform techno-economic assessments (TEAs) based on biomass storage or conversion modality
6	Microalgae Open Water	Open-water deployments with public acceptance and responsible governance	Ocean systems science and governance models to determine the possibility of scaled deployment
7	Macroalgae Open Water	Coastal or open-water deployments with public acceptance and responsible governance	Expanded measurement and modeling of long-term carbon fates and ecosystem impacts
8	BECCS to Electricity	Standardized integration with grid-scale bioenergy supply	Identifying geographies with needs for seasonal power or waste heat colocated with biomass supply
9	BECCS to Fuels	Standardized integration into biofuel production	Identifying revenue streams from growing fuel markets
10	Surficial Mineralization (SM)	Integration across mine life cycle and process steps	Integration into existing mine sites with range of tailings management processes
11	Enhanced Rock Weathering (EW)	Standardized integration into activities such as agriculture and coastal infrastructure improvements	Watershed-scale measurement and monitoring of carbon fates
12	Mineral Alkalinity Enhancement (MAE)	Coastal or open-water deployments with public acceptance and responsible governance	Deployment integrated into water outflows; local and regional ocean impact modeling improvements
13	Electrochemical Ocean Approaches (EOA)	Integration into desalination infrastructure, or stand-alone plants with long-term financing	Modular designs integrated into existing water processing infrastructure
14	Direct Air Capture (DAC)	Large-scale plants directly connected to CO ₂ transportation infrastructure or colocated with storage	Nth of a kind (NOAK) project deployments with repeatable engineering, contracting, and financing solutions

 bCDR  gCDR  sCDR

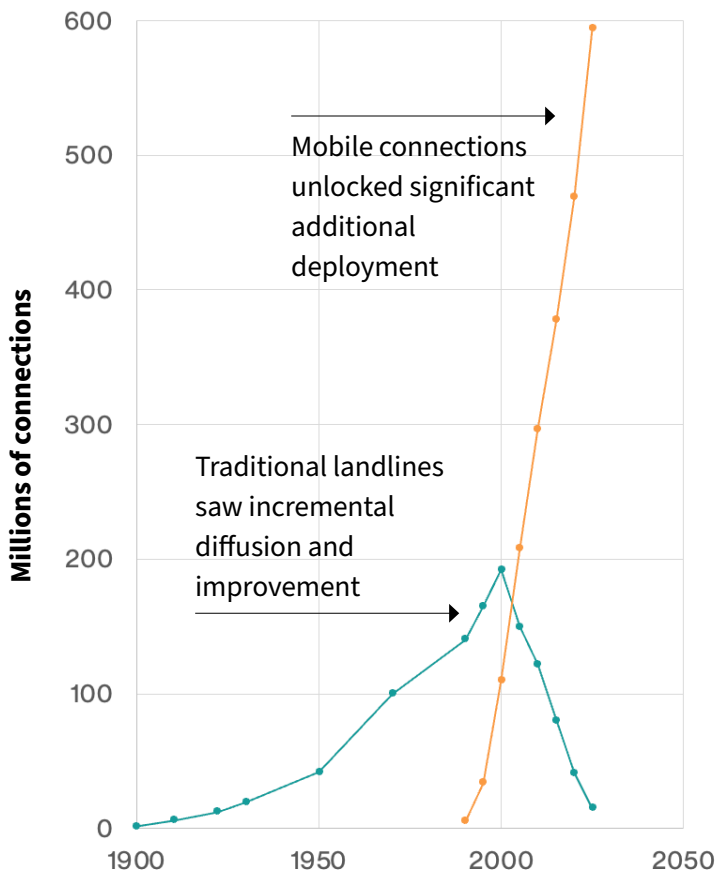


Innovation Breakthroughs

Innovative breakthroughs have driven cumulative gains in efficiency, cost, and scale across many fields

Technology area	Breakthrough year(s)	Breakthrough description	Quantified cumulative gain
Lighting	1960s (fluorescent bulbs) 2000s (LEDs)	Halogen bulbs to modern LEDs	Energy efficiency per lumen increased by 10x ²
Desalination	1970s (multistage flash) 1990s (reverse osmosis)	Shift from thermal separation to reverse osmosis, pressure-based approaches	Energy efficiency per unit of water increased by 10x ³
Steelmaking	1950s (basic oxy furnace [BOF]) 2000s (electric arc furnaces [EAFs])	Shift from open hearth to basic O ₂ , followed by electrification	Energy efficiency improved by ~60% ^{4,13}
Aluminum smelting	1886 (Hall-Héroult smelting) ⁵	Inert anodes, better electrolytes, larger cells	Energy efficiency was increased by 4x ⁶
Telecom (bandwidth)	1980s–1990s (fiber optics)	Copper wire use transitioned to fiber optics, which continue to improve	Information transfer speed was increased by 10 ⁴ ⁷
Computing	1970s–2010s	Specialized chips enabled accelerated computing power	Energy (kilowatt-hours [kWh]) per computation was reduced by 10 ⁷ ⁸
Transportation (aviation)	1960s (turbofan jet engines)	Reengineer the jet engine with high-bypass turbofan	Fuel burn was reduced 80% ⁹
Cement	2000s–present (clinker substitution, alternative fuels)	Clinker factor reduction, waste energy recovery, and transition to a dry kiln process	~5.5 GJ/t → ~3.3 GJ/t (~40% emissions reduction per ton cement) ¹⁰
Data transmission	1990s–2000s (packet switching, digital compression)	Analog voice circuits transitioned to digital compression & VoIP	~27x lower cost per minute ¹¹
Renewables (solar photovoltaics)	2000s–2020s	Thin-film, PERC, passivated contacts, and tandem cells all evolved solar efficiency	Solar PV efficiency in a lab setting increased from a maximum of 6% in 1954 to ~48% in 2020 ¹²

US phone and cellular connections¹

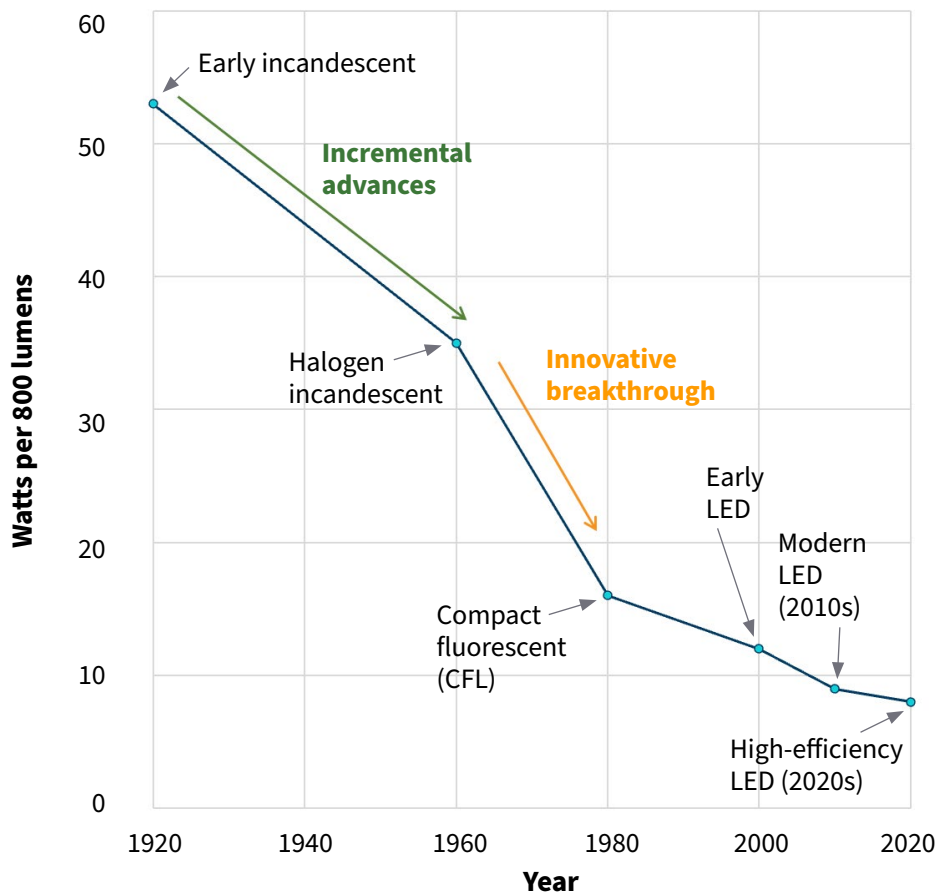


1. Data compiled from World Bank / FRED series Mobile cellular subscriptions from 1990–2000 and CTIA annual survey estimated total subscriber connections from 2000–2025. 2. [The next wave of LED lighting: Smarter, circular and more efficient](#), IEA, 2026. 3. M. Antonyan, [“Energy Footprint of Water Desalination.”](#) University of Twente, 2019. 4. [Energy use in the steel industry](#), worldsteel. 5. [Hall-Héroult Process Evolution: From 1886 to Hydrogen-Powered Smelters](#), Elka Mehr. 6. C. Tan, [“Different technology packages for aluminium smelters worldwide to deliver the 1.5°C target,”](#) Nature Climate Change, 2025. 7. [“Fiber vs. Copper Bandwidth Capacity and Transmission Speed,”](#) Atlantech Online, 2024. 8. Loomey et al., [“Computations per kilowatt-hour over time,”](#) IEEE Annals of the History of Computing, 2011. 9. [Fuel efficiency through the jet age](#), Boeing Cascade. 10. [Specific Heat Consumption Reduction Cement Kiln](#), Oxmaint, 2026. 11. [Changing Landscape of Calling Costs Over the Years](#), Calilio, 2025. 12. [Solar Cell Efficiency Records 2026](#), SurgePV, 2026. 13. D. Stewart, [“Pyrometallurgical removal of zinc from basic oxygen steelmaking dust,”](#) Resources, Conservation and Recycling, 2020.

Innovative breakthroughs often lead to step changes in key metrics of a technology area

Lighting^{1,2}

The evolution of energy requirement

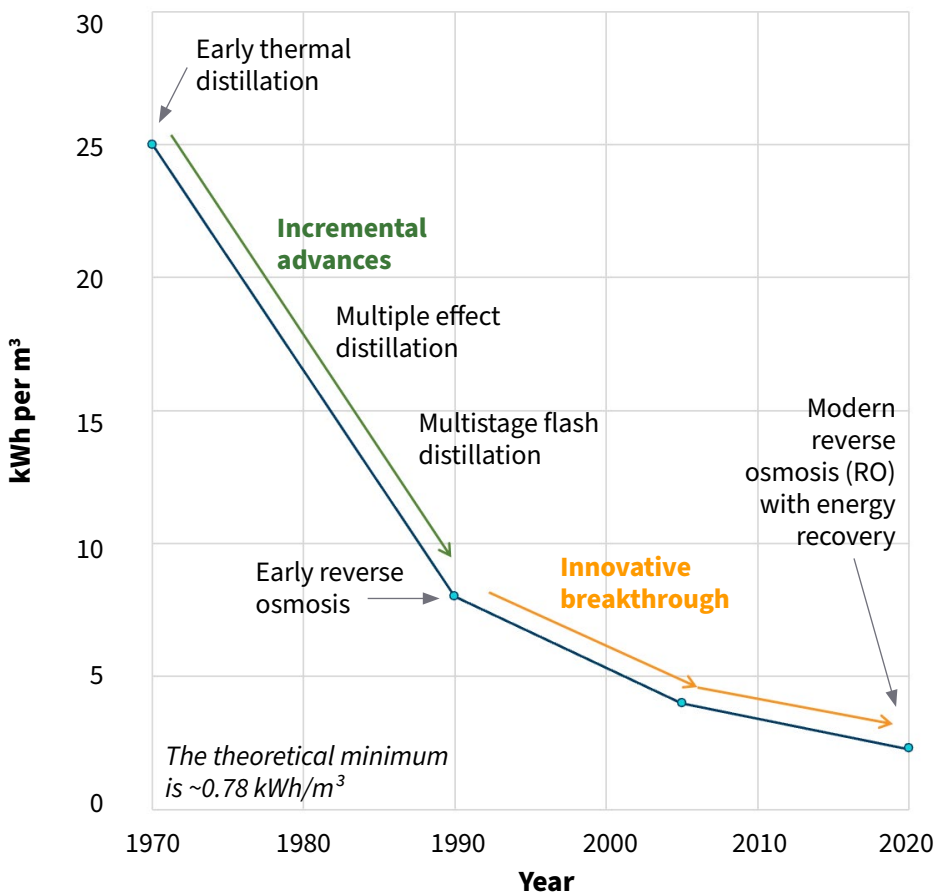


Incremental advances seek better materials, heat recovery, larger scale, automation.

Innovative breakthroughs find entirely new mechanisms (e.g., membrane RO vs. distillation; LED vs. incandescent filament).

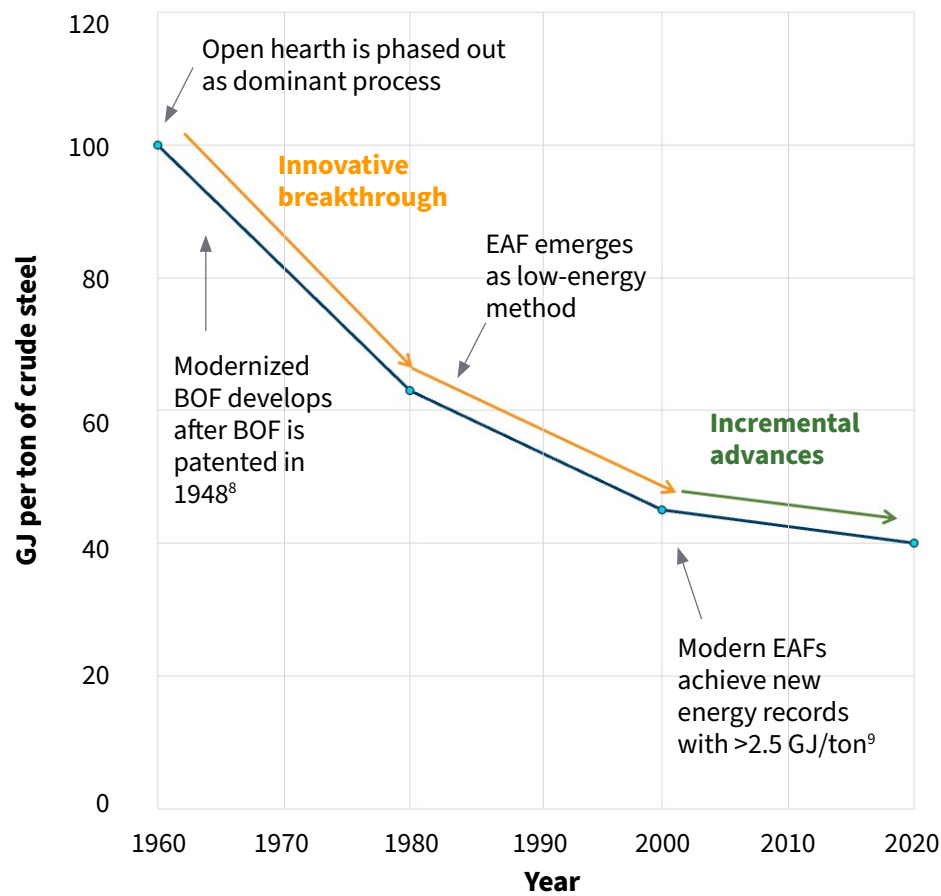
Desalination^{3, 4, 5, 6}

Energy to desalinate 1 cubic meter of water



Steelmaking⁷

Global average energy intensity of steel production over time



1. Lumens, Watts, and LED Conversion Charts, Disabled World, 2023. 2. Energy Efficiency: Light Sources in the 20th Century, National Museum of American History. 3. Jones et al., “The state of desalination and brine production: A global outlook,” Science of the Total Environment, 2019. 4. K. Ng, “A thermodynamic platform for evaluating the energy efficiency of combined power generation and desalination plants,” npj Clean Water, 2021. 5. Reducing the Greenhouse Gas Emissions of Water and Sanitation Services, IWA, 2022. 6. Danfoss helps set new Guinness World Records title in SWRO energy efficiency, Danfoss, 2024. 7. Energy use in the steel industry, worldsteel. 8. L. Hillyard, “Metallurgy: Oxygen Furnace – Metallurgy,” MHCC Library Press Open Educational Resources. 9. World Best Practice Energy Intensity Values for Selected Industrial Sectors, Lawrence Berkley National Laboratory, 2008.

What drives innovative breakthroughs?

Support and investment



Public investment in basic science

The biggest breakthroughs often originate from knowledge creation rather than product development.



Commercial investment

Innovation is driven when the private sector is eager to take risks on commercializing new technologies.



Incubation time

Technology development needs patient capital and stable research funding without obvious commercial returns.

People and networks



Open transformation of knowledge

Most breakthrough ecosystems have unusually rapid knowledge sharing. Innovation slows when information becomes excessively siloed.



Dense networks of talent

Innovation is social. Ideas recombine faster when experts can easily find one another.



Cross-disciplinary mixing of knowledge

Environments that maximize interaction across disciplines generate disproportionately more breakthroughs.

Hardware and tools



Platforms that lower experimentation costs

The most important innovations often are not end products but platforms that make future innovation easier, e.g., the internet or 5G.



Emergence of enabling technologies

Breakthroughs often depend on infrastructure that was built for other reasons.



Convergence of new technologies

Many breakthroughs appear suddenly because several supporting technologies have quietly matured.

Selection pressure



Mission-driven demand

Technology accelerates when someone desperately wants it.



Urgent problems

Innovation tends to be driven when it is in service of a clear external threat rather than a yet-to-be materialized opportunity.



Competitive collaboration

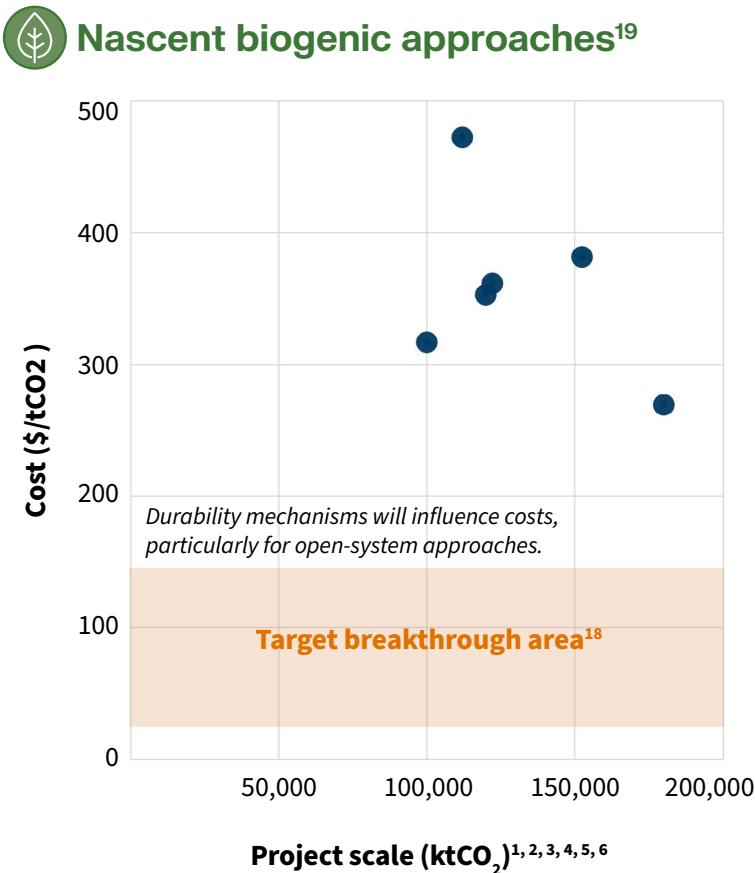
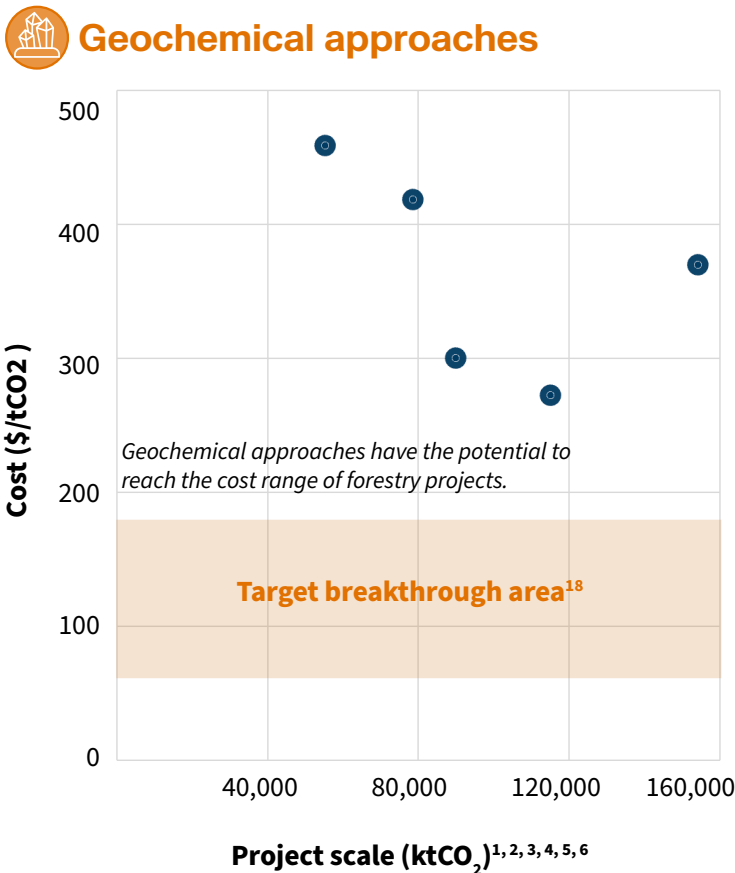
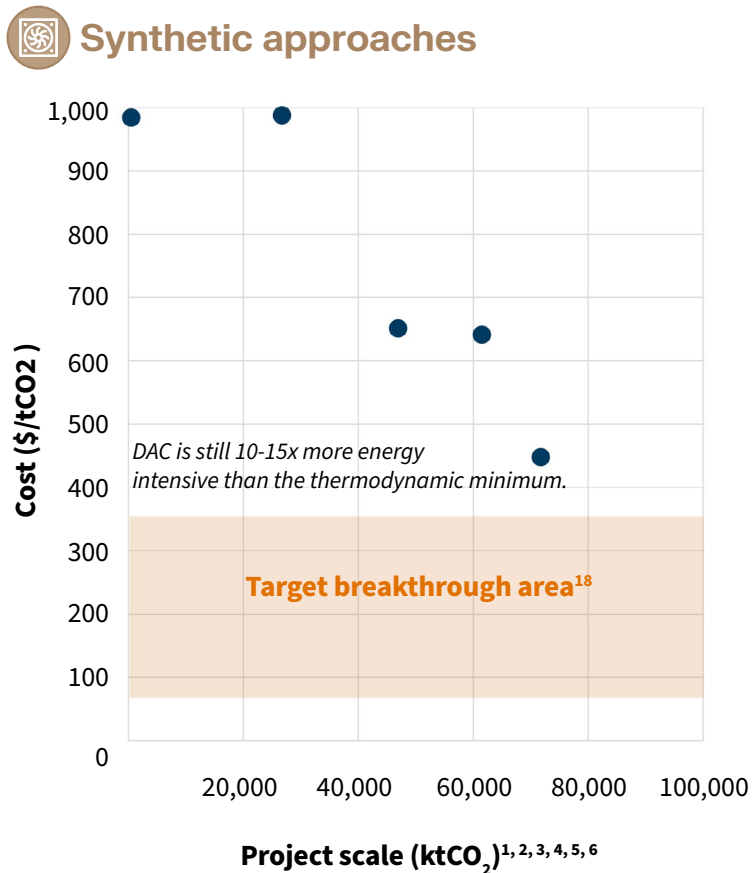
The most productive environments tend to have multiple teams pursuing different approaches on shared scientific foundations

Brian Arthur, “The Nature of Technology: What It Is and How It Evolves,” Free Press, 2011; William Bonvillian, et al., [“The DARPA Model for Transformative Technologies: Perspectives on the U.S. Defense Advanced Research Projects Agency,”](#) Open Book Publishers, 2020.

There is still significant potential for innovative breakthroughs to drive down costs in CDR

The projects shown are selected from real projects with reported offtake, and although they do not demonstrate base cost of CDR, they do represent the price markets are willing to pay for removals across each approach.

Target breakthrough areas: The “target breakthrough areas” for each approach reflect a future where advancements in technology and efficiency, as well as unlocking economies of scale, allow for costs to be driven down to areas at or near best-case scenario deployment.



1. [Frontier buyers sign \\$58.3M in offtake agreements with Vaulted Deep](#), Frontier, 2024. 2. [Frontier & Stockholm Exergi Offtake Agreement](#), Frontier, 2024. 3. [Frontier & Hafslund Celsio Offtake Agreement](#), Frontier, 2025. 4. [Frontier & Arbor Offtake Agreement](#), Frontier, 2025. 5. [Frontier & NULIFE GreenTech Offtake Agreement](#), Frontier 2026. 6. [“Frontier Fund Closes \\$53M Carbon Removal Deal With Charm,”](#) Carbon Credits, 2023. 7. [Frontier buyers sign world’s first enhanced weathering offtake agreements with Lithos Carbon](#), Frontier, 2023. 8. [Frontier & CarbonRun Offtake Agreement](#), Frontier, 2024. 9. [Frontier & Terradot Offtake Agreement](#), Frontier, 2024. 10. [Frontier & Eion Offtake Agreement](#), Frontier, 2025. 11. [Frontier & Planetary Offtake Agreement](#), Frontier, 2025. 12. [Frontier & 280Earth Offtake Agreement](#), Frontier, 2024. 13. [Frontier & Heirloom Offtake Agreement](#), Frontier, 2024. 14. [Frontier & CREW Carbon Offtake Agreement](#), Frontier, 2024. 15. [Frontier & Captura Prepurchase Agreement](#), Frontier, 2022. 16. [Captura](#). 17. [Frontier & Phlair Offtake Agreement](#), Frontier, 2024. 18. These target breakthrough areas are based on RMI’s assessment of what is possible based on fundamentals of each core category of CDR. 19. Nascent biogenic approaches include BECCS to electricity / fuels and bio-oil injection removal methodologies.

 Opportunities for breakthroughs in Biogenic CDR (bCDR)

Note: These breakthroughs are referenced in greater detail in the Advancements and Breakthrough Areas section of each of the core approaches later in this report.

	Breakthrough approach	Why now?	Goals	Technical difficulty	Social difficulty	Modes of action
B1	Enhanced cultivars for high-carbon-storage applications: Modified plants to have characteristics that enable faster, more durable carbon removal and storage	<ul style="list-style-type: none">• Emergence of genetic modification technologies• Development of new monitoring technologies and gene regulation tools	<ul style="list-style-type: none">• Fast biomass growth• High lignin content• Increased environmental stability (e.g., drought resistance)• Nondegradable plant structures	Medium: Developing enhanced cultivars is a known and established practice	High: Modifying cultivars for potential open system requires significant safety considerations. There is preexisting pushback to genetically modified crops.	<ul style="list-style-type: none">• CRISPR modification• Cross breeding• Other genetic modifications• Nutrient signaling• Greenhouse systems
B2	On-site microreactors: Convert biomass, including waste biomass, into stable forms such as biochar or bio-oil on site without central infrastructure	<ul style="list-style-type: none">• Emergence of enabling technologies in new materials and modular systems	<ul style="list-style-type: none">• Small kilns <1 ton/day• Low cost <\$1,000/unit• Enhanced methods with heat and microbes	Medium: Biochar reactors are a known and simple technology, but small units are more complex to operate and maintain without skilled personnel	Medium: Getting people to use biochar reactors in a distributed way requires behavior shifts and education	<ul style="list-style-type: none">• City-, municipality-, and county-level engagement at landfills and municipal waste facilities
B3	Autonomous algae growing and sinking systems: Autonomous operation for cultivation and sinking	<ul style="list-style-type: none">• Convergence of autonomous AI-powered aquatic drones, sensors, remote monitoring systems, and solar-powered systems	<ul style="list-style-type: none">• Free-drifting, GPS and AI-driven platforms	Medium: Drones and their enabling technologies are developing quickly	High: Ensuring safe operating conditions for humans and ocean life	<ul style="list-style-type: none">• Semiautonomous, open-ocean operations in large fleets• Can also include cultivation via seeding
B4	Autonomous precision growing and MRV: Reduce costs for growing and monitoring open system CDR	<ul style="list-style-type: none">• Digital MRV, spaceborne LIDAR, multimodal satellites, AI ecosystem models, distributed ledgers	<ul style="list-style-type: none">• Solar powered; battery operated• Robotic aerial seeding• Drone imaging for MRV crediting	Medium: Drones and their enabling technologies are developing quickly	Low: Transparent, high-quality MRV and data sharing can help mitigate social concerns	<ul style="list-style-type: none">• Data fusion services combined with advanced UAVs
B5	Synthetic biology for non-photosynthetic CO₂ capture and use: Modified microbes or enzymes that can directly fix CO ₂ from the environment	<ul style="list-style-type: none">• Emergence of new genetic modification techniques• Social acceptance of new methods for extracting CO₂ and growing materials	<ul style="list-style-type: none">• Durable carbon molecules• Precursors to other durable carbon molecules such as graphene or carbon fiber• Produce animal feed	High: Developing highly productive microbes has proven difficult over many decades	Medium: There may be social concerns on both the operational approach and to production	<ul style="list-style-type: none">• Advances could be used in closed- or open-system environments
B6	Biogenic co-benefits: Plant species and management practices that can deliver non-CDR primary benefits with CDR attributes	<ul style="list-style-type: none">• Convergence of high-impact cultivars with enabling social and technical environment	<ul style="list-style-type: none">• Plants that can remove critical minerals from the environment• Plants that can provide toxin removal	Low: Most enabling technologies exist but must be validated	Medium: Successful operations will deliver both technical and social benefits	<ul style="list-style-type: none">• Engagement with distributed enablers such as wastewater treatment systems



Opportunities for breakthroughs in Geochemical CDR (gCDR)

Note: These breakthroughs are referenced in greater detail in the Advancements and Breakthrough Areas section of each of the core approaches later in this report

	Breakthrough approach	Why now?	Goals	Technical difficulty	Social difficulty	Modes of action
G1	Biogenically enhanced reactions: Processes that modify microbes to dramatically increase mineralization rates in open environments	<ul style="list-style-type: none"> Identification of existing microbial communities influencing weathering rates Emergence of genetic modification technologies 	<ul style="list-style-type: none"> Development of new biological systems that enhance the rate of natural weathering The ability to tune and control open-system interventions 	Medium: Developing enhanced strains of microbes and bacteria is a known and established practice	Medium: Modifying strains for potential open system requires significant safety considerations. Regulatory hurdles for GMOs remain vague and challenging.	<ul style="list-style-type: none"> Synthetic lichens Engineered fungal networks Biofilms tailored for specific rock types Identification/selection of existing beneficial biologies without modification
G2	Industrial integration: Processes that can incorporate geochemical CDR into existing industry	<ul style="list-style-type: none"> Sophistication of environmental monitoring through sensors and remote systems Acceptance of CDR interventions 	<ul style="list-style-type: none"> Distributed network of interventions Delivery of co-benefits to justify costs Preoperational safety validation 	Low: Most enabling technologies exist but must be validated	Medium: There may be social concerns on the operational approach	<ul style="list-style-type: none"> Engagement with desalination, wastewater stormwater, and hydrothermal power systems at regional levels
G3	Autonomous deployment: Drones that can source, grind, and distribute alkaline materials and measure impacts	<ul style="list-style-type: none"> Emergence of small, inexpensive sensors, drones, and hardware Emergence of AI and autonomous operating systems 	<ul style="list-style-type: none"> Fully autonomous drones Integrated monitoring and MRV Solar powered and battery operated 	High: Development of drones that can operate cost-effectively and safely	Medium: There may be social concerns on the operational approach	<ul style="list-style-type: none"> Fully autonomous drones that can mine, deposit, and monitor the introduction of environmental alkalinity
G4	On-site mineralization: Rather than moving alkaline minerals, produce acidity on site	<ul style="list-style-type: none"> So far, gCDR has focused on moving minerals to where they can be deployed. A more mature industry may deposit acidity onto existing mineral sites. 	<ul style="list-style-type: none"> Minimize transport costs Minimize environmental impact Concentrate weathering process on a limited site 	Low: Using existing electrochemical alkalinity systems	Medium: There may be social concerns on the operational approach	<ul style="list-style-type: none"> Operation of electrochemical process on site to neutralize acids and then deposition of alkalinity into the environment
G5	Geothermal carbonation systems: Injection and reaction of CO ₂ into underground alkaline systems	<ul style="list-style-type: none"> There is currently massive new investment into geothermal technologies and subsurface mining Convergence of sensors and technical subsurface equipment 	<ul style="list-style-type: none"> Rapid silicate dissolution Circulation of transport fluids Coproduction of minerals or thermal energy for electricity production 	High: High engineering requirements to co-engineer subsurface injection with CO ₂ capture and chemistry	High: There may be social concerns on the operational approach, including pushback on CO ₂ infrastructure and injection	<ul style="list-style-type: none"> Injecting CO₂-rich fluids Rapid underground mineralization Using geothermal circulation
G6	Scaled supply chains for naturally suited microbes: Production and sourcing of naturally occurring microbes and bacteria with high weathering rates	<ul style="list-style-type: none"> Pre-existing microbial knowledge has advanced, enabling screening of naturally occurring species that accelerate weathering The use of non-GMO microbes dramatically reduces the regulatory barrier 	<ul style="list-style-type: none"> Improve weathering rates Reduce regulatory burden Reduce risk of unintended environmental impacts 	Medium: Creating a sustainable supply chain for these microbes requires capital and a larger existing market	Medium: Deployment of specialized, potentially non-native microbes could require environmental impact assessments or permitting	<ul style="list-style-type: none"> Engagement with pharmaceutical industry Collaboration with geochemical researchers at leading institutions



Opportunities for breakthroughs in Synthetic CDR (sCDR)

Note: These breakthroughs are referenced in greater detail in the Advancements and Breakthrough Areas section of each of the core approaches later in this report

	Breakthrough approach	Why now?	Goals	Technical difficulty	Social difficulty	Modes of action
S1	Capture by reaction: Processes that directly react CO ₂ out of the atmosphere	<ul style="list-style-type: none">Advances in electrochemistry, catalysis, and surface science combined with advances in microfluidics, microsensors, and surface chemistry	<ul style="list-style-type: none">Create a commercial output such as fuels, carbonate products, polymers, synthetic aggregates, or carbon composites	High: Reacting CO ₂ out of the air or water is difficult because of low concentrations, thermodynamic reduction requirements, and transport, surface, and chemistry challenges	Low: Technical development should proceed in closed systems	<ul style="list-style-type: none">Combine the separation step with a conversion step to decrease combined costs
S2	Passive-flow DAC: Systems that remove CO ₂ from the atmosphere without active industrial activity and monitoring	<ul style="list-style-type: none">New technologies in flow systems, monitoring, and AI and autonomous operations	<ul style="list-style-type: none">Non-temperature-based CO₂ separationPassive air flow via low-pressure-drop systems through tall towers, skyscrapers, or cave systems	High: Thermodynamic challenges of low ambient concentrations, rate of removal, and methods for concentration of captured CO ₂	Medium: There may be social concerns pertaining to open-system deployment	<ul style="list-style-type: none">Atmospheric heat pumps based on natural temperature or pressure gradients
S3	Electro-swing DAC: The use of electricity to adsorb and desorb CO ₂	<ul style="list-style-type: none">The convergence of new advances in electrochemical systems, nanoporous structures, surface science, and precision monitoring	<ul style="list-style-type: none">Eliminate sorbents, solvents, and temperatureUse electrostatic fields, plasma effects, and phase changes	High: Transport, surface, and chemistry challenges; materials development and engineering operation challenges	Low: Technical development should proceed in closed systems	<ul style="list-style-type: none">The use of electricity to adsorb and desorb CO₂ from a surface
S4	Pressure-based or biomimicry DAC: Using membranes or systems mimicking plants for gas-phase CO ₂ separation	<ul style="list-style-type: none">New breakthroughs in membrane science, interfacial chemistry, nanotechnology, and microfluidics	<ul style="list-style-type: none">Non-temperature CO₂ separationMicrofluidicsSynthetic modules that continuously separate CO₂ from air at ambient conditions	High: Development of sufficient membranes that can cost-effectively separate CO ₂ from air based on pressure gradient	Low: Technical development should proceed in closed systems	<ul style="list-style-type: none">The use of pressure to separate CO₂ from airSynthetic microfluidic systems that separate CO₂ from air akin to mechanisms in plants
S5	Small DAC modules: Portable DAC modules that can be stacked	<ul style="list-style-type: none">Technologies for separating CO₂ from air are becoming more common and knownSocial acceptance and interest in DAC is growing	<ul style="list-style-type: none">Development of appliance-sized DAC systemsDevelopment of on-site CO₂ conversion approaches to avoid distributed collection	High: Developing small DAC systems will require overcoming significant engineering and chemistry challenges	Medium: There may be social concerns pertaining to open-system deployment	<ul style="list-style-type: none">Integration with residential and commercial HVAC systemsDeployment by individuals
S6	Offshore electrochemical facilities: Large offshore facilities that generate alkalinity or directly desorb CO ₂ from seawater	<ul style="list-style-type: none">New breakthroughs in membrane resilience and monitoring technologies allowing remote operationEmergence of low-cost solar and battery-powered, autonomous systems that can be operated by AI	<ul style="list-style-type: none">Expand beyond coastal deployment of electrochemical approachesDevelop distribution systems to collect and store or neutralize generated CO₂ or acid streamsUse solar and wave powerOperate in open ocean with remote monitoring	High: Operational costs of electrochemical alkalinity systems combined with autonomous operations, cost of distributed material delivery and collection for purified CO ₂ (for CO ₂ stripping approaches), acid, or alkaline feedstock (for alkalinity generation)	Medium: There may be social concerns on the operational approach	<ul style="list-style-type: none">Autonomous, solar-powered systems operating in open water

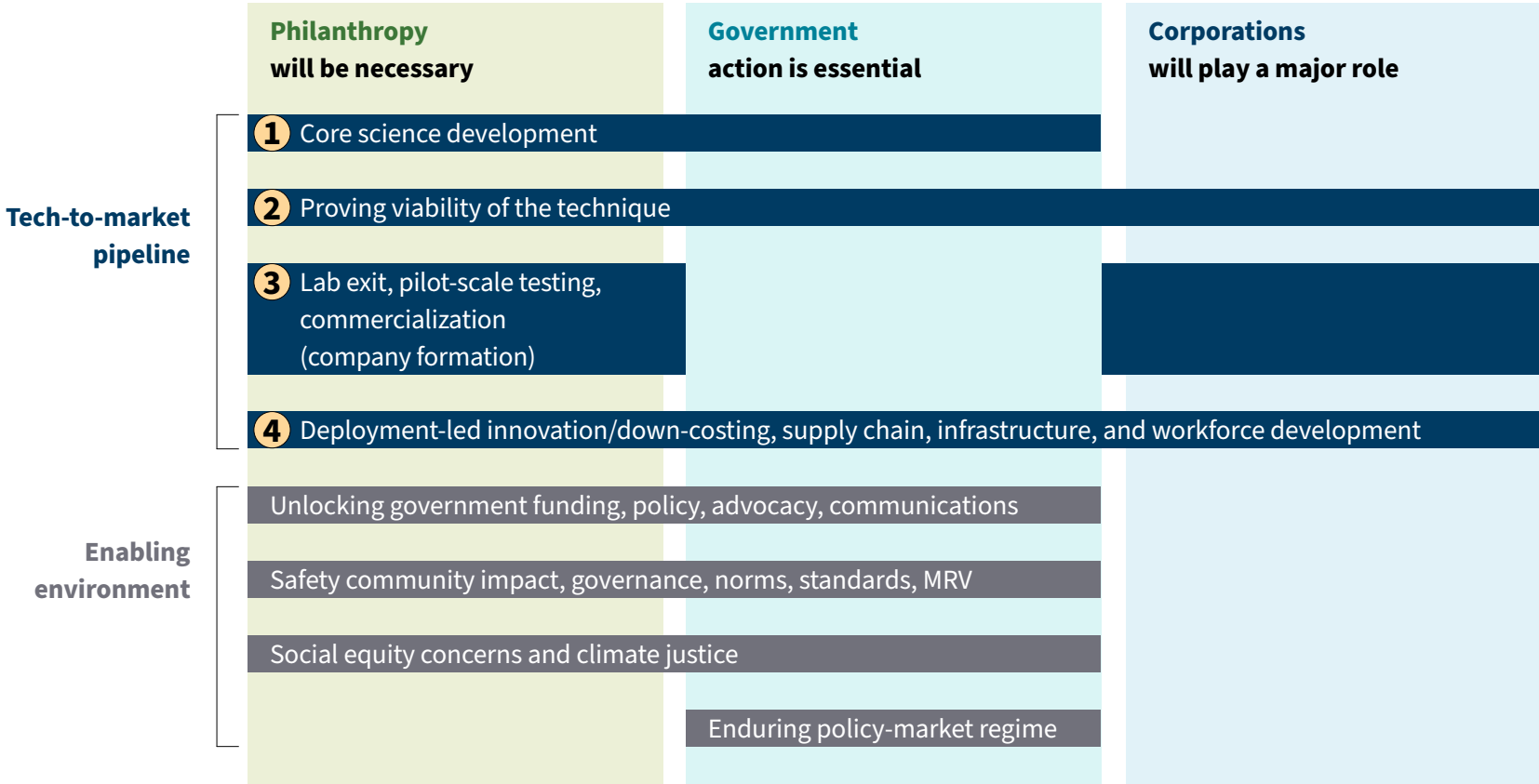
Three leading areas we think have outsized potential

	<div><div>Biogenic CDR Specialty engineered biomaterials</div></div>	<div><div>Geochemical CDR Microbially mediated mineralization</div></div>	<div><div>Synthetic CDR Reactive capture of carbon dioxide</div></div>
Technical challenges	<ul style="list-style-type: none">• Enhancing or engineering cultivars to meet breakthrough specifications such as being nonbiodegradable• Identifying acceptable growing conditions (location, safety requirements, etc.) needed to pursue this approach• Matching cultivars with use cases to meet safety and performance metrics	<ul style="list-style-type: none">• Microbes are not currently optimized for achieving high environmental mineralization reactivity• Safety and environmental considerations are not sufficiently understood	<ul style="list-style-type: none">• Current processes for reactive capture of CO₂ have low selectivity to desired products, low utilization of available CO₂, and require too much energy input
Social acceptance challenges	<ul style="list-style-type: none">• Addressing real and perceived risks of enhanced or engineered cultivars	<ul style="list-style-type: none">• Real and perceived risks of open-system micro-organism release• Real and perceived risks of open-system alkaline mineral weathering	<ul style="list-style-type: none">• Expected to be low
Commercial constraints	<ul style="list-style-type: none">• Commercial cultivation and deployment may require controlled processes and environments, e.g., greenhouses, and special safety protocols	<ul style="list-style-type: none">• Locations of available alkaline mineral deposits are mismatched with storage locations• Controlled environments may be required	<ul style="list-style-type: none">• Current reactive capture processes are not commercially viable. They are too fragile to scale (e.g., low-durability electrochemical membranes with short lifetimes) or require materials that are too expensive to scale (special metals, membranes, and hardware)
Potential interventions	<ul style="list-style-type: none">• Identify optimal cultivars to satisfy ultimate use cases• Achieve 30%+ of photosynthate stored in stable long-term pools• Achieve 85% stability of carbon over 100 years	<ul style="list-style-type: none">• Identify suitable microbial strains for mineralization• Identify suitable and effective modifications for microbial strains• Achieve mineral dissolution rates at least 10x beyond natural abiotic rates• Increase the fraction of stable cations to >50%	<ul style="list-style-type: none">• Achieve >85% of captured carbon in the final product (rather than vented or lost)• Achieve energy intensity of < 400 kJ/mol °C• Achieve costs at <\$3/gal liquid fuel• Produce C4+ oxygenates or C3+ alkanes
Relevant contributors	<ul style="list-style-type: none">• Biological studies experts (e.g., academics and institutes)• Experts in commercial activation of biomass processes (e.g., vertical farming)• Bio-ethicists	<ul style="list-style-type: none">• Experts in mineralization and biomineralization (e.g., academics and institutes)• Commercial experts (e.g., agricultural companies)• Environmental ethicists	<ul style="list-style-type: none">• Experts in surface science and catalysis (e.g., academics and institutes)• Commercial breakthrough experts (e.g., automotive and space companies)

RMI plans to design rapid development plans (RDPs) to bring promising breakthroughs from inception to reality

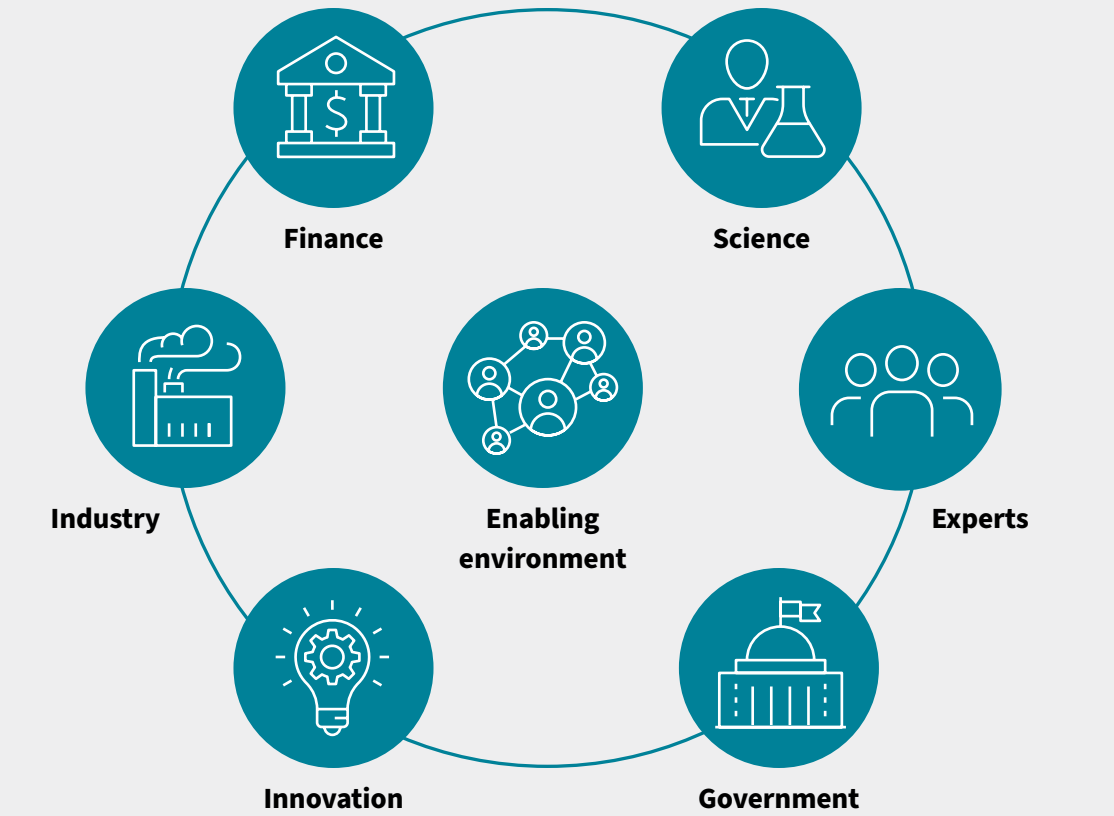
Stylized tech-to-market process for new climate technologies

Bringing new technologies to market requires multiple steps, each of which can become a bottleneck. RMI has demonstrated success at identifying and resolving these blockers for many new climate and energy technologies.



Rapid development plans (RDPs)

Our RDPs are our methodology for creating a sequenced plan for responsibly testing and advancing a new technological area toward technical, social, and commercial viability as rapidly as possible.



Even with breakthroughs in technology, the CDR industry will need support from the public, markets, and government in order to scale

Note that the scope of this report is focused on technological and process innovations. Governance, public engagement, financing mechanisms, demand, and supply chain planning are all critical to the growth of CDR approaches, and innovations in these spaces continue to be critical for building the field as a whole, but incremental costs associated with these areas are not included in the cost stacks and breakthroughs of this report.

Public engagement

Critical area of focus	Rationale
 Safe and equitable deployment	Developers across many CDR approaches still struggle to communicate to host communities that their operations are safe for humans and the environment. Ongoing transparency is paramount.
 Community support	For CDR projects to be successful, communities must believe they deliver measurable value in economic and environmental contexts.
 Community co-development	Successful CDR deployments are characterized by early and continued engagement with community leaders and representatives.

Finance and markets

Critical area of focus	Rationale
 Capital investment	Many CDR projects require scaled capital expenditure for deployment, which can be difficult for unproven or FOAK projects.
 Demand	A big question facing CDR is a stable source of demand. Markets can and must create favorable signals to developers to ensure supply is ready to meet demand.
 MRV and standard setting	Successful CDR projects require robust validation and ongoing monitoring to ensure removals are durable. The guarantee of durability is the pivotal quality that often dictates investment.

Government and policy

Critical area of focus	Rationale
 Compliance systems and demand policy	Instituting policies that drive decarbonization and mandate emissions reduction can create demand for CDR in hard-to-abate sectors, in turn creating market stability.
 Permitting	Successful CDR deployments require permitting clarity. This is to ensure safety and integrity, but also to enable CDR projects to reach deployment on reasonable timescales.
 Experimental funding	The CDR ecosystem still needs additional funding support to achieve the scientific progress and breakthroughs required to make approaches commercially viable.

1. [Scaling Technological Greenhouse Gas Removal: A Global Roadmap to 2050](#), Bezos Earth Fund and RMI, 2024. 2. [The Potential for Marine Carbon Dioxide Removal in Canada](#), RMI and Canada’s Ocean Supercluster, 2025. 3. [How Can We Ensure That CDR Technologies Are Deployed Equitably?](#), Sustainability Directory, 2025.



New Frontiers Assessments



Living biomass

Conservation, management and restoration

* Relevant approaches from RMI’s 2023 *Applied Innovation Roadmap for CDR*:

- 1.1–1.3: Living Biomass Approaches

DEFINITION

(1) The management of terrestrial and marine ecosystems to improve CO₂ storage capacity, (2) the conservation of existing ecosystems that store carbon, and (3) the restoration and creation of carbon sinks in areas that have suffered degradation or land use change.

APPROACH OVERVIEW

Despite controversies around additionality and permanence, living biomass approaches continue to act as the foundation of the modern CDR market. Anchored by meaningful co-benefits, CDR activities like mangrove restoration and grassland conservation bolster our natural carbon storage capacity. This report covers only removals from living biomass projects and omits avoidance and reduction.

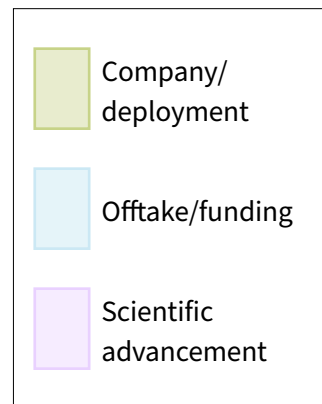
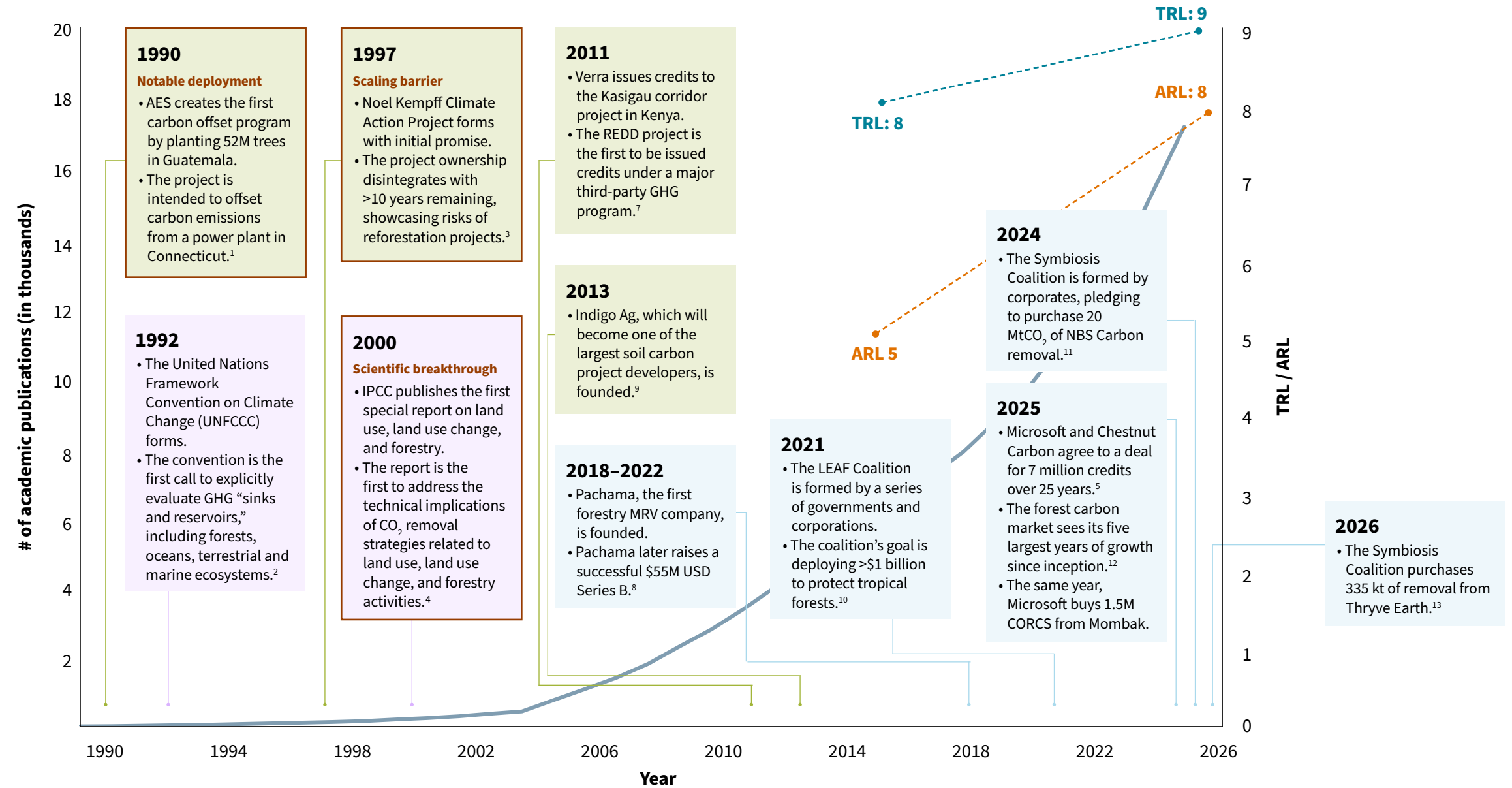


How we got here

Status: Expected progress toward sector-wide scale up

Approach trend: Positive

Milestones selected for the graph were chosen based on their impact on and significance to the living biomass sector.



1. [Clean Energy Leadership for a Net Zero Future](#), AES. 2. [About the secretariat](#), UNFCCC. 3. [“Noel Kempff Mercado Climate Action Project: The Promise and Peril of High-Potential Environmental Partnerships.”](#) Belfer Center for Science and International Affairs (Harvard), 2023. 4. [Summary for Policymakers - Land Use, Land-Use Change, and Forestry](#), UNEP, 2000. 5. [“Chestnut Carbon Inks Deal with Microsoft for Groundbreaking New Carbon Removal Project.”](#) Chestnut Carbon, 2025. 6. [“Microsoft Goes Big In Brazil’s Voluntary Carbon Market With Amazon Project.”](#) Bloomberg, 2023. 7. [“Kenya project issues first REDD credits under VCS.”](#) Verra, 2011. 8. [“Forest Carbon Monitoring Platform Pachama Raises \\$55M In Series B Round.”](#) Carbon Herald, 2022. 9. [Where Ag Meets Innovation and Impact](#), Indigo Ag. 10. [“New Public-Private Coalition Launched To Mobilize More Than \\$1 Billion to Protect Tropical Forests and Enhance Global Climate Action.”](#) Leaf Coalition, 2021. 11. [“Google, Meta, Microsoft, And Salesforce Establish World’s Largest Advance Market Commitment For Nature-Based Projects.”](#) Carbon Herald, 2024. 12. [“Resilient growth in US forest carbon markets.”](#) Fastmarkets, 2025. 13. [“Symbiosis Announces New Carbon Offtake Agreements with Thryve.Earth.”](#) Symbiosis, 2026.

Current and projected state of deployment

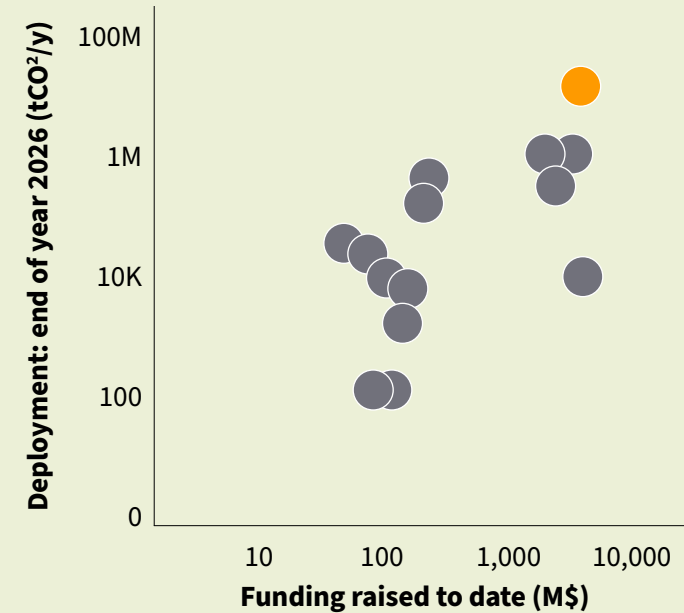
Past 5 years

After serious questions around quality, registries and sector leaders reevaluated credit issuance

Next 5 years

Project developers aim to reach 100 MtCO₂/y before 2030 while improving removal standards

Current deployment



Database includes 12 companies founded within the past five years.¹

Recent funding successes include Living Carbon's \$13 million deal with Octopus Energy Generation in April of 2026.⁵

2026 funding: **\$3.14 billion**

2026 capacity: **36 MtCO₂/y¹**

- Living biomass approaches

- Other CDR approaches

93

companies
tracked¹

1,567

projects
active/announced

TRL 9

established
commercial
market⁶

ARL 8

high
readiness⁶

Current cumulative removals

~242,000,000

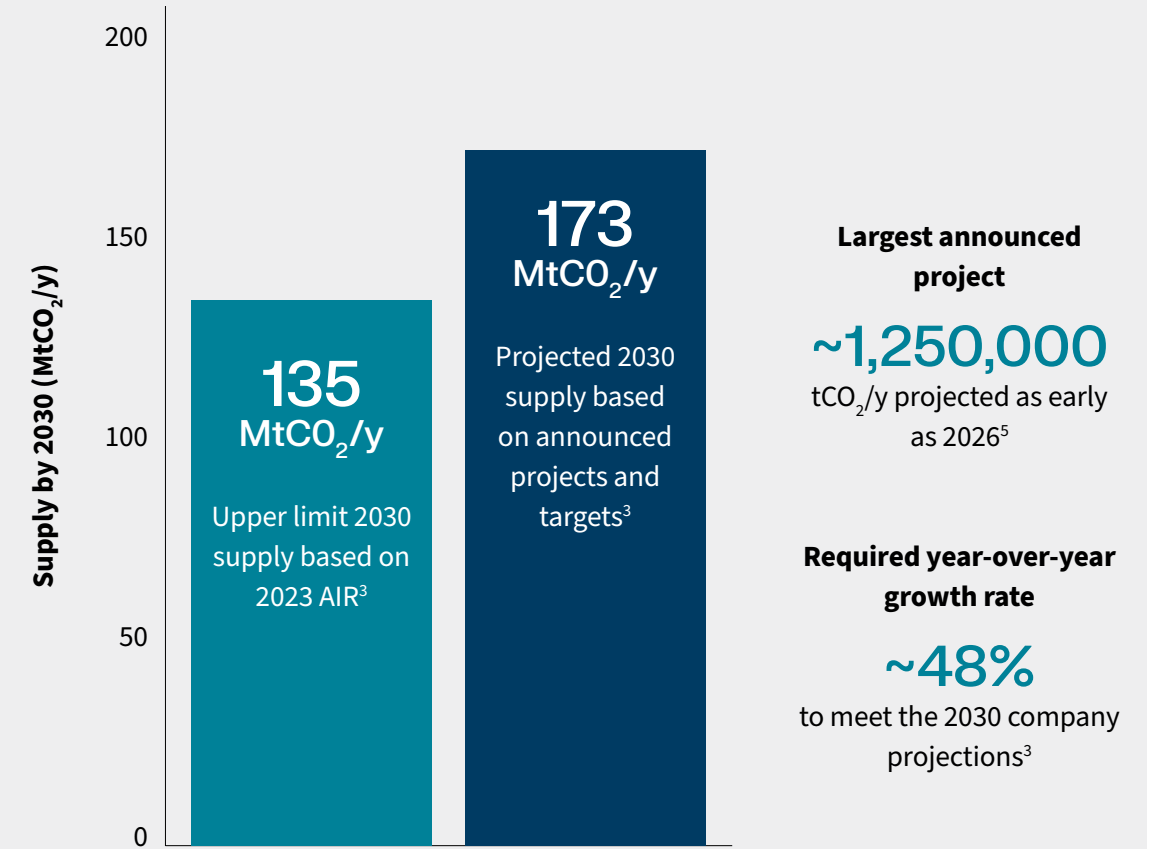
tCO₂ as of end-of-year 2025¹

Largest active project

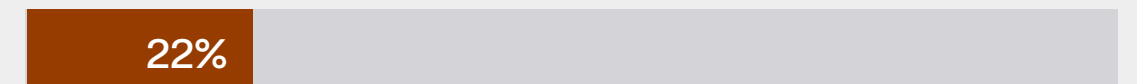
~2,360,000

tCO₂ /year 2026⁴

Supply projections for 2030



Announced and active projects as a percentage of 2030 company targets



1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies, and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference capacity goal of 135 MtCO₂/y is aligned near-term growth in Living Biomass “success story” in [The Applied Innovation Roadmap for CDR](#), RMI, 2023 (p. 38). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. [Delta Blue Carbon - 1: The Indus Delta Mangrove Restoration Project Phase 1](#), Verra. 5. [“Living Carbon secures \\$500m deal with Octopus Energy Generation to restore degraded land and remove CO₂.”](#) Living Carbon, 2026. 6. ARL and TRL ratings reflect high readiness approaches in the Living Biomass category, such as afforestation, reforestation, integrated forest management (IFM), and soil carbon. This rating acknowledges there are improvements that can still be made in additionality, MRV, and living biomass project standards.



Key cost drivers

Major cost drivers
Labor, site monitoring, and permanence risk

Improvement areas
Remote monitoring and sensing, durability mechanisms

Today: \$25–\$110/tCO₂
Future: \$25–\$110/tCO₂
Limited cost reduction likely as projects are already operating at scale; permanence risk considerations for durable projects will change in future.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

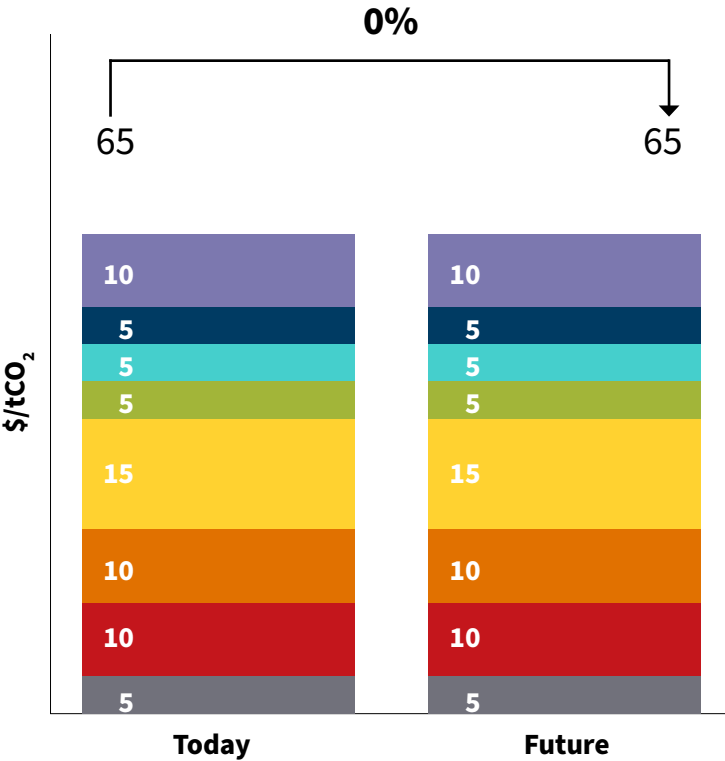
2. Some reviewers suggested that \$66/tCO₂ was higher than expected for a representative midpoint for Living Biomass approaches; though most agree with the value stated.

Today's cost range (0-40, \$/tCO₂)
Future cost range (0-40, \$/tCO₂)

Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex • •	Tools, equipment, nurseries, irrigation systems, land acquisition and leasing	Standardized operations, nursery scaling
Energy • •	Fuel or electricity for cultivation or management	Efficient electrified operation, reduced need for manual sampling
Feedstock • •	Seeds/seedlings, soil amendments	Nursery scaling, advanced cultivars
Transport • •	Transportations of seedlings, staff/equipment to deployment sites	Regional nursery networks, drone logistics, remote monitoring
O&M • •	Watering, weeding, thinning, other land management	Automation, drone logistics
Storage • •	Prevention of hazards such as fires and pests, buffer pool contributions	Diversified project portfolios to minimize permanence risk
MRV • •	Biomass surveys, site monitoring	Remote monitoring and modeling of carbon stocks and ecosystem status
Embodied Emissions • •	Fuel, fertilizer, equipment manufacturing	Electrification, low-carbon materials

Note about cost stacks¹
X Not actual project costs ✓ Qualitative cost ranges
See [page 121](#) for more detail on this analysis



Cost stack considerations

- This broad approach category captures a wide range of restoration and management activities of both terrestrial and coastal ecosystems. Total costs and distributions between cost categories will vary widely based on project type.
- Future market demands on verified durability on timescales beyond several decades will impact project viability and risks.



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Management, conservation, and restoration projects with contracted durability

Where to start: Technological and governance solutions for long-term risk management



Reversal risk management

Living Biomass approaches are often the cheapest option per ton of carbon dioxide removed compared with the technological approaches discussed later in this report. Ensuring durable storage becomes a key risk and cost driver, especially when **relying on actions taken several decades in the future**. Reversal risks include environmental hazards such as storms, wildfires, pests, and droughts; uncertainties such as changes in carbon sequestration rate as ecosystems develop under future conditions; and risks related to future governance and land use change, particularly when project durations exceed human lifespans while requiring continuous stewardship.

Contracted durability mechanisms, such as horizontal stacking or a permanence trust, can help by ensuring **ongoing liability for addressing reversals** and by providing ways to **compensate for reversals** that ensure the credited level of removal is achieved long term. Developing robust reversal risk assessment methods and the institutional design needed to manage risk over timescales that exceed the lifespan of most organizations will be important for contracted durability implementation. Recent work by RMI and collaborators discusses frameworks for contracted durability in greater detail.¹

Example KPIs:

- 100% of projects utilize some mechanism for long-term contracted durability, such as planned horizontal stacking or a permanence trust, when used in a compensation claim



Co-benefits and shared land use

Living biomass approaches require access to substantial areas of land over long project durations. This is both a key cost driver and a key limiting factor for maximum deployment scales in the face of competing land uses such as agriculture, timber harvesting, and urban development. Though **restoration of native ecosystems can provide significant benefits beyond carbon removal**, ranging from biodiversity conservation to erosion and drought control, deploying such projects in areas with high-value productive agricultural land is economically challenging in the absence of alternative project revenue streams.

The **monetization of co-benefits** such as erosion control, water supply and water quality, and biodiversity recovery can make projects cost-competitive and increase long-term project stability and community support.² **Integration of carbon removal projects into productive land uses** can provide co-benefits while also directly sharing land use costs. Examples include agroforestry, mangrove restoration improving fishery stocks, and riparian restoration as part of water quality improvement or flood prevention projects. Projects prioritizing ecosystem services without competition with food production are more likely to be viable.²

Example KPIs:

- Identify projects fully viable from co-benefits alone
- >50% blended finance for restoration projects Identify mechanisms to monetize ecosystem services



Remote sensing and MRV

Verified durability of Living Biomass projects requires **continuous monitoring of large-scale project sites** over long timescales. The use of remote sensing and modeling technologies such as satellites and LIDAR and the use of targeted field plots as proxies for larger-scale systems enable the monitoring of biomass growth and disturbance at lower costs than regular manual sampling.³ This can significantly reduce long-term carbon accounting costs.⁴

The monitoring and verification of forest management projects, for example, involves heterogeneous data on tree size and density as well as relevant risk parameters such as wildfire risks and soil health. A hierarchical approach combining remote sensing data with inventory data specific to the local ecology can produce and update estimates of carbon stocks over large areas.⁵

Within the context of contracted durability and other mechanisms for Living Biomass projects to provide long-term carbon sequestration, remote sensing supports disturbance detection to monitor reversal risks and events such as fires, illegal clearing, or storm damage. This can provide clear **thresholds for identifying and responding to reversals**.

Example KPIs:

- Scaled MRV costs <\$10/tCO₂ maintaining sufficient certainty
- Carbon stock estimation uncertainty <10%
- <1 week time span before disturbances are identified

1. [Contracted Durability: A Framework for Performance-Based Carbon Removal](#), RMI, 2026. **2.** [How Blue Carbon Can Tackle the Climate, Biodiversity and Development Crises](#), WRI, 2023. **3.** [Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive](#), ETC, 2022. **4.** For a more detailed accessible overview of the applications and limitations of remote sensing technologies in nature-based climate solutions, see [Nature-Based Credit Science Decoder Series: Remote Sensing](#), The Nature Conservancy, 2025. **5.** This includes projects informed by the [NASA Carbon Monitoring System](#). **6.** S. Illarionova et al., “[Advancing forest carbon stocks’ mapping using a hierarchical approach with machine learning and satellite imagery](#),” *Nature Scientific Reports*, 2024.



Advancement and breakthrough areas

Key research areas
Automated monitoring, improved environmental resilience, biogenic co-benefits

1. See [page 21](#) for more detail on crosscutting opportunities for breakthroughs in biogenic CDR, including assessments of the technical and social difficulty of implementation. 2. Reviewers highlight that, alongside resistance to acute weather events, improved salinity tolerance will enable plants to withstand rising sea levels in vulnerable coastal areas and reduce habitat loss. Reviewers also highlight the tension between risks of introduced ecological risks or sensitivities with new modified cultivars, especially if deployed as monocultures.

Crosscutting bCDR breakthrough themes¹

B1: Enhanced cultivars for high-carbon-storage applications

Modified plant types showing increased resistance to adverse environmental conditions (e.g., droughts), rapid growth, low resource needs, or high lignin content.

B3/B4: Autonomous growing and MRV

Autonomous monitoring and cultivation for the restoration and conservation of both marine and terrestrial living biomass assisted by remote monitoring systems and/or drones.

B6: Biogenic co-benefits

Non-CDR primary benefits with CDR attributes can be provided by many conservation, restoration, and management projects through ecosystem services (e.g., erosion control, biodiversity).

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Improved satellite monitoring capacity and capability of living biomass projects	Increased mapping of projects and remote monitoring efforts to confirm practices and analyze stock for disease, wildfire, and land use changes improves project durability and verifiability and informs reversal risk	\$\$ Improved O&M, improved MRV quality, reduced need for manual surveying	All projects, particularly larger projects in remote land tracts	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Sorbent/membrane/solvent/ cryogenic separation experts, industrial emitters, government researchers, RD&D funders
2	Bio-engineered plants to withstand more extreme fires, drought, flooding, or other local adverse conditions	Amid a changing climate with more extreme weather events, ² advancements in plant genetics increase the ability of reforested regions to resist natural disasters	\$\$ Reduced capex, reduced O&M, improved storage, improved MRV	All new projects focused on reforestation degraded areas	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Industrial emitters, syngas and gasification experts, CCS supply chains
3	Creation of artificial land formations and greening of dryland / deserts	Constructing hills to modify rainfall patterns to maximize precipitation via orographic weather patterns, or half-moon pits to catch runoff for desert greening, has the potential to improve growth and minimize drought risk	\$ Improved storage, improved weather resistance	Projects in remote regions with large capex	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Plant biologists, botanists, genetics experts, energy and waste-to-heat experts
4	Colocate living biomass projects with important community and environmental services	Siting forestry projects and other Living Biomass projects to support native ecosystems or offer co-benefits such as water filtration, slowing flow rate in rivers, or erosion and flood control offers support beyond CDR credits	\$\$ Reduced cost of co-benefit services, reduced cost of environmental damages	All projects, especially those near population centers	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Energy analysts and grid specialists, bioenergy reactor experts and researchers, local and state regulators
5	Tools to coordinate project integration with other CDR approaches	Formal tools to document project sites and identify opportunities for cross-approach CDR opportunities , such as EW combined with reforestation, or forestry projects collaborating with biochar companies	\$\$ Reduced capex, feedstock, MRV and O&M costs for joint projects	All projects	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Farming communities, logging communities, bioenergy reactor researchers, local regulators

\$ \$1–\$30/tCO₂ **\$\$** \$20–\$50/tCO₂ **\$\$\$** \$40–\$100/tCO₂ **\$\$\$\$** \$75–\$300/tCO₂



Biomass direct storage

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 2.1: Biomass Direct Storage

DEFINITION

Storing terrestrial biomass in land or aquatic settings, specifically under conditions designed to prevent significant decomposition.

APPROACH OVERVIEW

First proposed as a removal pathway in the mid-2000s, Biomass Direct Storage is a growing pathway with newly approved crediting methodologies. Validation of critical science in 2021 clarified removal durability and catalyzed the sector, and the field grew to more than a dozen companies. As of 2026, Biomass Direct Storage pilot and demonstration projects are active across multiple geographies, with many set to deliver removals at multi-kiloton scale before 2030.

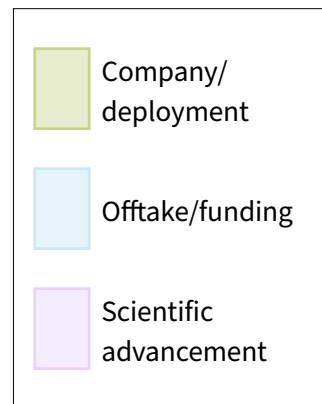
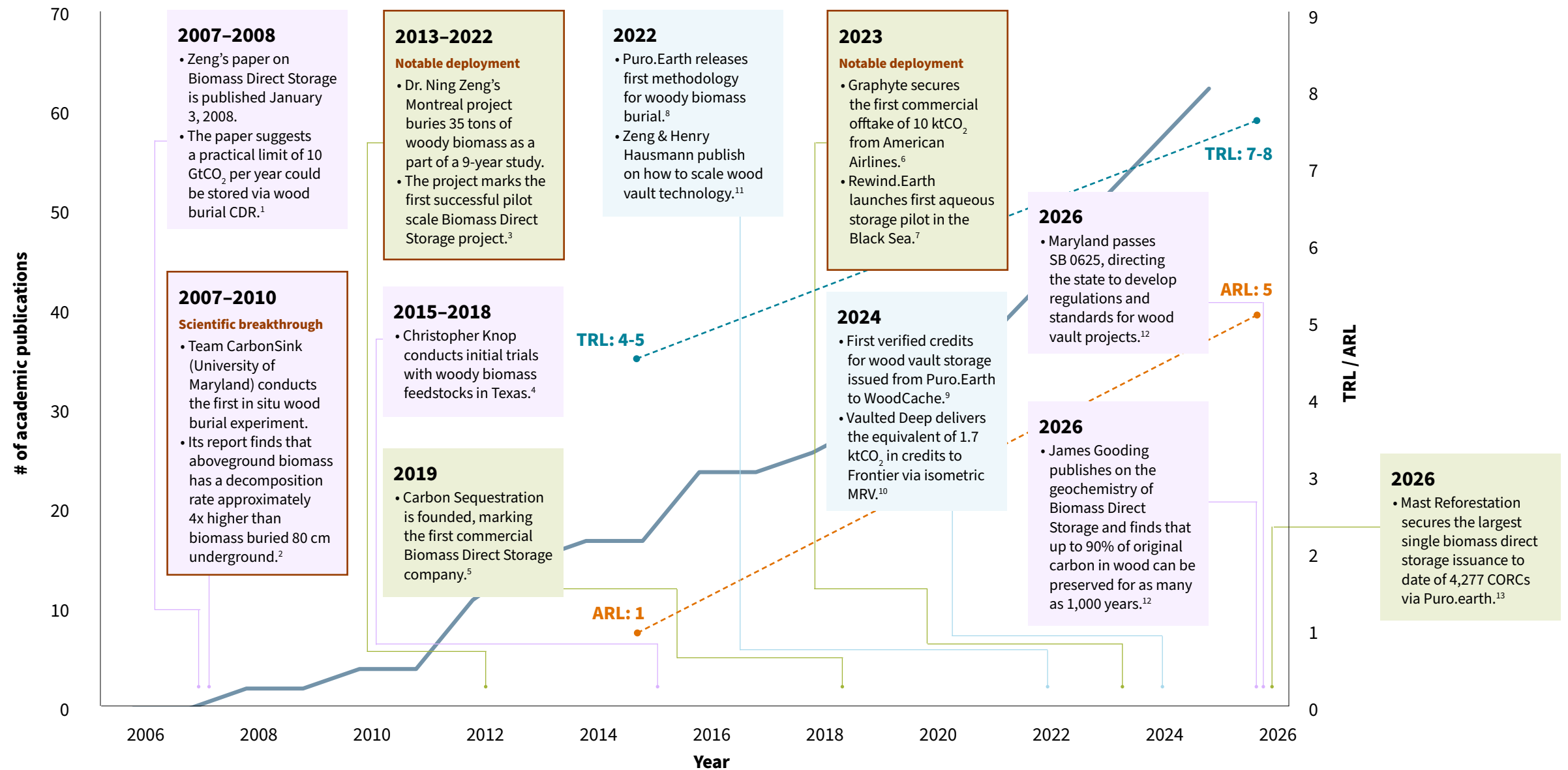


How we got here

Status: Significant progress toward commercial-scale deployment

Approach trend: Positive

Milestones selected for the graph were chosen based on their impact on and significance to the biomass direct storage sectors.



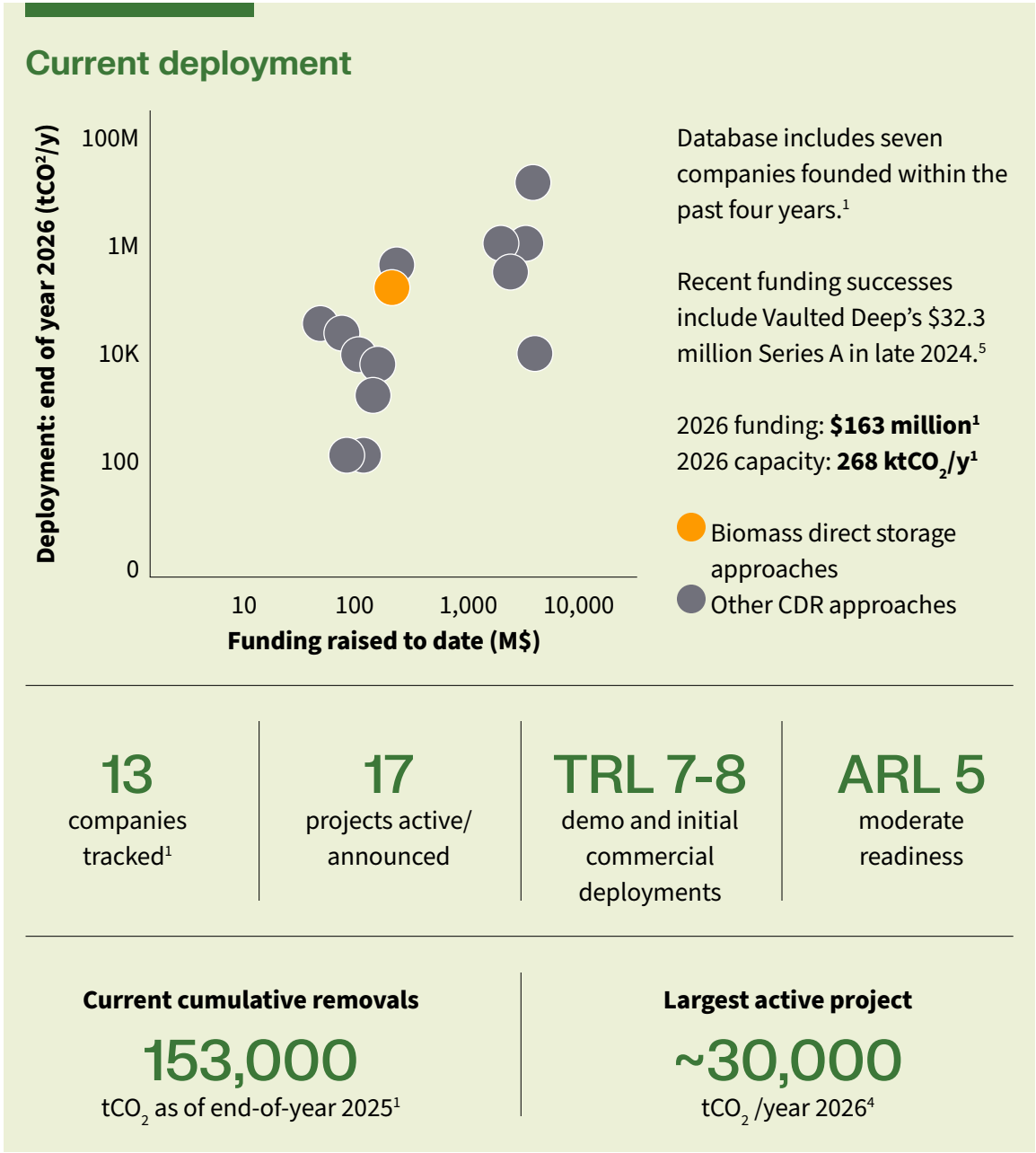
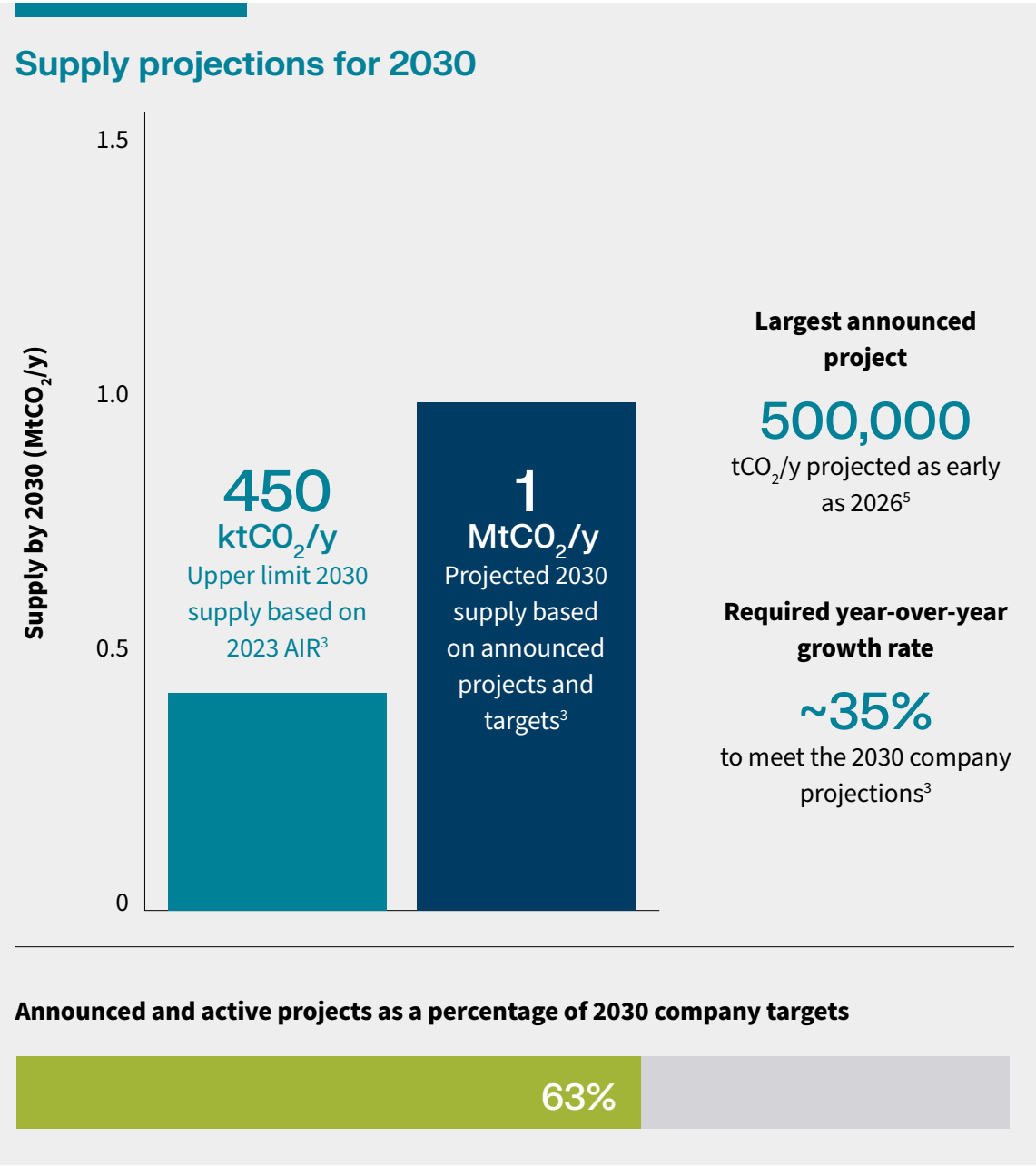
1. N. Zeng, “Carbon Sequestration via Wood Burial,” *Carbon Balance and Management*, 2008 2. N. Zeng et al., “The Effect of Wood Burial and Submersion on Decomposition: Implications for Reducing Carbon Emissions,” University of Maryland DRUM, 2010. 3. *The Montreal Project*, Carbon Lockdown. 4. *About Us - Sustainable Carbon Farming & Removal*, Carbon Sequestration Inc. 5. *About*, Carbon Lockdown. 6. “Graphyte signs first carbon removal purchase agreement with American Airlines 10,000 tons of carbon dioxide removal will be delivered using new Carbon Casting technology,” *PR Newswire*, 2023. 7. *Project MACS Romania*, Rewind. 8. “Woody Biomass Burial Methodology Webinar,” Puro.Earth, 2022. 9. “2024 Annual Recap,” Puro.Earth, 2024. 10. “Vaulted Deep’s Rapid Deployment of CDR Reaches 2000 Tonnes with Frontier Delivery, Supplies First-of-their-Kind Isometric Issued High-Quality Carbon Credits,” *PR Newswire*, 2024. 11. “Wood Vault: remove atmospheric CO₂ with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future,” *Carbon Balance and Management*, 2022. 12. *Maryland State Legislation - SB0625 - Wood Vault Technology Standards*, Maryland General Assembly. 13. “Mast Reforestation Issues First Biomass Burial Carbon Credits, Funding Post-Wildfire Restoration in Montana,” *ESG News*, 2026. 14. J. Gooding, “Geochemistry of carbon sequestration through woody biomass burial,” *AIMS Geosciences*, 2025.



Current and projected state of deployment

Past 5 years
Supported by initial offtake, FOAK demonstration projects proved approach efficacy at scale

Next 5 years
Advancing new deployments, developers aim to meet megaton-scale capacity by 2030



1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies, and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference capacity goal of 450 ktCO₂/y is aligned near-term growth in Biomass Direct Storage “success story” in [The Applied Innovation Roadmap for CDR](#), RMI, 2023 (p. 53). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. [“Vaulted Deep Great Plains Facility Organic Waste Sequestration: Isometric PDD,”](#) Vaulted Deep, 2023. 5. N. Louise, [“Climate tech startup Vaulted Deep raises \\$32M to inject carbon-containing waste deep underground and combat carbon emissions,”](#) Tech Startups, 2024. 6. [For Investors](#), InterEarth.



Key cost drivers

Major cost drivers

Feedstock transport and long-term storage

Improvement areas

Scaled deployment with optimized logistics

Today: \$95–\$170/tCO₂

Future: \$55–\$110/tCO₂

40%–50% cost reduction possible via scale, automation, logistics, and MRV efficiencies.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

2. Available costs for biomass burial CDR vary dramatically with a high level of uncertainty for future reduction. Current estimates for cost per ton are as little as \$10/tCO₂ to as high as \$200/tCO₂.

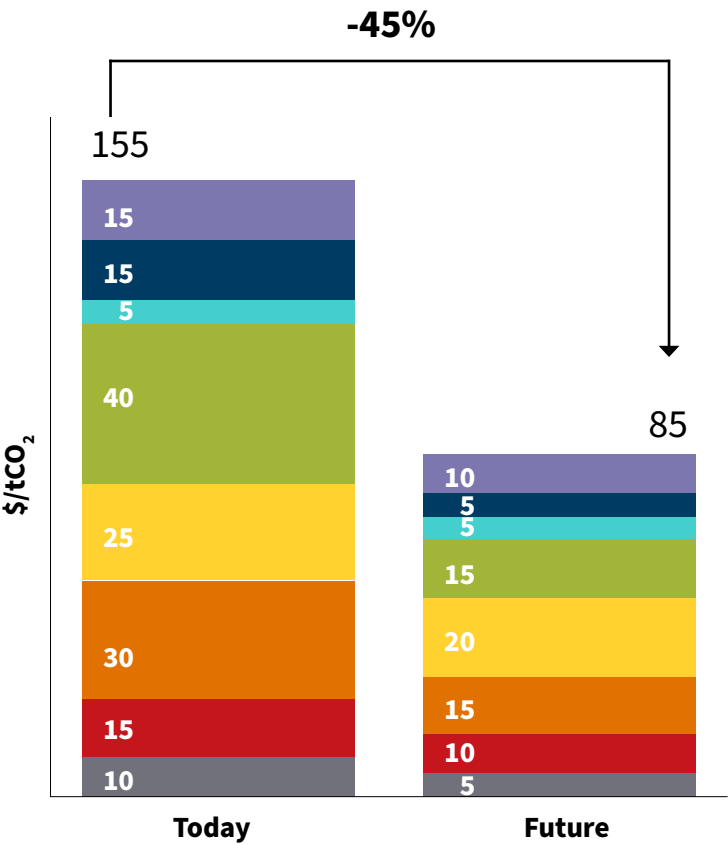
Today's cost range (0-40, \$/tCO₂) Future cost range (0-40, \$/tCO₂) Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex • •	Equipment and contractors for biomass processing, site prep, project finance	Standardization and modularization of burial or sinking systems
Energy • •	Fuel or electricity for harvesting and handling (e.g. , chipping, drying, sinking)	Electrification, siting strategies to reduce drying needs
Feedstock • •	Biomass; often free at FOAK scale if sourcing residues/wastes	Long-term contracts, aggregation efficiency
Transport • •	Trucking of biomass to storage site	Optimized project siting, logistics optimization, densification, electrification
O&M • •	Labor, land lease, repairs, insurance	Automation of processing and storage, shared service models
Storage • •	Excavation and liners for burial, or coastal infrastructure and materials for sinking	Standardized trenching and sealing, hub models
MRV • •	Sensors, sample extraction, third-party verification, registry fees	Sensor automation, standardized protocols
Embodied Emissions • •	Transportation, embodied emissions in materials used for storage	Low-carbon material inputs, electrification

Note about cost stacks

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations¹

- Waste feedstock is cheap or free; dedicated growth need may increase costs at large scales.
- Aqueous deployments avoid energy and O&M costs from burial, but have additional processing and capital expenditure needs, with higher overall costs today.



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Decentralized burial or sinking projects; injection or dry burial hubs

Where to start: Hub-style sites colocated with sources of sustainable biomass



Supply of sustainable biomass

Scaled Biomass Direct Storage deployment will require **low-cost, sustainable sourcing** that doesn't negatively influence food supply or soil health. Projected scales of 1.4–4.5 MtCO₂/y by 2030 will require the permanent sequestration of 1–3 Mt/y of dry biomass globally. For context, this represents 2%–7% of all logging residues produced in the United States today, of which half are not collected.¹ Optimal biomass types for dry vaulting include bulky residues that need minimal processing. Other categories of biomass, such as municipal solid waste, biosolids from wastewater, or bio-oil (see [Section 4](#)) have different storage characteristics and face distinct risks from the burial of dry, woody biomass.

At larger deployment scales, careful guardrails on land use allocation and carbon accounting frameworks will be needed to balance possible removals against impacts on food systems, ecosystems, and the climate. Estimates of the **global sustainable supply of all biomass** range from 4 to 12 Gt/y, equivalent to 6 to 17 GtCO₂/y.^{2,3} Other CDR approaches, material demands, and energy uses will compete for this resource.⁴ Further study is needed to identify the optimal use case of different types of biomass among different CDR approaches or other uses.

Example KPIs:

- Feedstock cost <\$10/tCO₂
- >80% waste-/residue-sourced biomass
- 100% sustainably sourced purpose-grown biomass



Biomass transport

Project deployment **colocated with biomass sources** reduces the cost and embodied emissions associated with transportation to the storage site. This needs to be **balanced against cost savings from land use and process efficiency** from large, centralized storage projects drawing biomass from several sources. Flexible, decentralized deployment may be particularly beneficial in regions with biomass residues generated through forestry thinning and storm blowdown, where rapid collection of biomass for direct storage or other bCDR approaches discussed in this report can become a part of fire risk reduction strategies.

Some projects today use cheap or free feedstock that would otherwise have been treated as waste from industries such as forestry, paper and pulp, and agriculture. Sources used include sawmill offcuts, forest thinnings, agricultural waste, paper sludge, and invasive plant species removed from conservation areas. Mapping local niches where biomass sources are available near suitable storage sites, such as arid ground for burial, wells suitable for injection, or anoxic basins suitable for sinking, will enable scaled project planning optimizing available resources.

Example KPIs:

- Average haul distance <100 km
- 50% electric or low-carbon transport modes
- <\$15/tCO₂ transportation costs



Long-term biomass storage

Long-term storage of biomass is a key cost driver for stabilized biomass approaches, requiring suppression of microbial decomposition for long periods after project deployment and crediting. Each storage modality — **vaulting, injection, dry burial, or sinking in anoxic basins** — carries different risks and associated MRV needs. Trade-offs include complexity in up-front project design, such as the construction of closed-system storage infrastructure, against long-term open-system monitoring, such as the identification and measurement of direct and indirect variables confirming biomass stability over time. Contracting and project designs need to incorporate long-term management and monitoring to ensure durability.⁵

Storage costs will vary geographically on local and global scales based on the availability of suitable geological and ecological conditions, unused land, and permitting landscapes. Aquatic deployments typically show low storage costs but rely on the identification of stable anoxic zones and the establishment of favorable international governance frameworks. Land-based storage projects, particularly open-system modalities such as arid land burials, also need to navigate land use and waste classification regulations, impacting siting decisions and realistic long-term costs.

Example KPIs:

- <0.5% annual loss rate confirmed with direct measurements
- >50-year guarantee of biomass monitoring and management
- <2-year permitting timeline with reusable projects

1. 19 and 23 Mt of collected and unharvested logging residues, respectively ([2023 Billion-Ton Report](#), DOE), converted using a factor of 1.4 tCO₂/t dry biomass. **2.** Estimates of the prudent and maximum supply of sustainable biomass include 40–60 or 120 EJ, respectively ([Bioresources within a Net-Zero Emissions Economy](#), ETC, 2021). One-third to half of this supply is represented by agricultural residues and woody biomass from forestry not used as building materials. **3.** Each Mt of dry biomass is equivalent to 15–19 GJ of primary energy ([Roads to Removal](#), DOE, 2023). **4.** The majority of biomass will be used in other industries, including for other decarbonization efforts. A WRI model of US non-food biomass use for a decarbonized economy by 2050 suggests a maximum allocation of 25% of waste and energy crops, or 110 Mt/y, by 2050 ([Biomass and land use in a decarbonizing U.S. economy](#), WRI, 2025). **5.** For sample guidance on ensuring site-specific durability in wood vaulting, see N. Zeng et al., [“Implementation Guidance for Wood Harvesting and Storage,”](#) arXiv, 2023.



Advancement and breakthrough areas

Key research areas
Enhanced cultivar, standardized preprocessing and storage, waste biomass supply chain

1. See [page 21](#) for more detail on crosscutting opportunities for breakthroughs in biogenic CDR, including assessments of the technical and social difficulty of implementation.
2. Siting and biomass supply chain optimization is critical for all biomass-based CDR approaches, including biochar, bio-oil, and BECCS.

Crosscutting bCDR breakthrough themes¹

B1: Enhanced cultivars for high-carbon-storage applications
Modified plant types with high lignin content, increasing the amount of carbon sequestered per unit volume, or resistance to degradation, increasing durability.

B2: On-site microreactors
Preprocessing of biomass for storage, such as chipping, drying, and compressing, could be performed on site to aid in collection and transportation from distributed sources.

B5: Synthetic biology for non-photosynthetic CO₂ capture
Microbes fixing CO₂ from the atmosphere may produce materials compatible with storage (avoiding the need for separate cultivating and harvesting steps) or durable products.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Prefabricated modular vault and liner systems	Standardized, factory-made vault cell components reduce need for customized engineering and permitting and design-specific contingencies	\$\$ Shorter build times, fewer design-specific contingencies, simplified permitting	Land burial, carbon casting storage	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Civil engineering firms, geomembrane manufacturers, prefab construction companies, EPC contractors
2	Ultra-low-cost, durable sensors and digital MRV networks	Continuous low-power, long-life sensors or remote monitoring such as satellite monitoring of methane emissions enable both cheaper and higher-confidence MRV , including over long timescales to verify durability	\$\$ Reducing MRV and verification labor, cutting uncertainty buffers, lowering insurance costs	All, though distinct needs in aquatic deployments	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Sensor manufacturers, MRV platform developers, standards bodies, data analytics experts
3	Carbon casting to create compressed biomass blocks	Converting loose biomass into dense, dry, sealed blocks for long-term storage greatly reduces decomposition risk and space requirements	\$\$ Smaller storage footprint, reduced handling and capping costs, at cost of increased capex	Land burial, carbon casting storage	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Engineering startups, construction materials firms, process engineers, researchers
4	Automated residue collection and preprocessing	Automating residue gathering, sorting, and densification in fields or forests lowers labor intensity and helps utilize waste biomass	\$\$ Lower labor and equipment hours, improved yield per crew, reduced transport idle time	All projects relying on residues as feedstock	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Agricultural machinery manufacturers (e.g., John Deere, Komatsu Forestry), forestry service contractors, bioeconomy programs
5	Siting and supply-chain optimization ²	Mapping residue sources, transport links, use cases for waste material, and environmental constraints minimizes haul distance and embodied emissions	\$ Reducing average haul distance, improving backhaul utilization	All	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Data scientists, satellite imagery providers, regional planning agencies, project developers
			\$ \$1–\$30/tCO ₂	\$\$ \$20–\$50/tCO ₂	\$\$\$ \$40–\$100/tCO ₂	\$\$\$\$ \$75–\$300/tCO ₂



Biochar

* Relevant approaches from RMI’s 2023 *Applied Innovation Roadmap for CDR*:

- 2.4: Pyrolysis (Biochar) and Storage

DEFINITION

Thermal conversion of biomass while excluding oxygen, optimized to produce solid char for storage in open or controlled environments, removing biomass carbon from the fast carbon cycle.

APPROACH OVERVIEW

Biochar has emerged as a leader in the CDR industry, providing reliable, durable removals for the voluntary carbon market. In the past 10 years, biochar has grown significantly; in response, new crediting methodologies aimed at addressing initial durability concerns have been adopted by leading registries. As of 2026, biochar continues to see meaningful offtake from leading CDR investors.

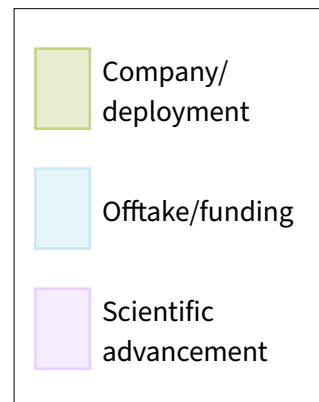
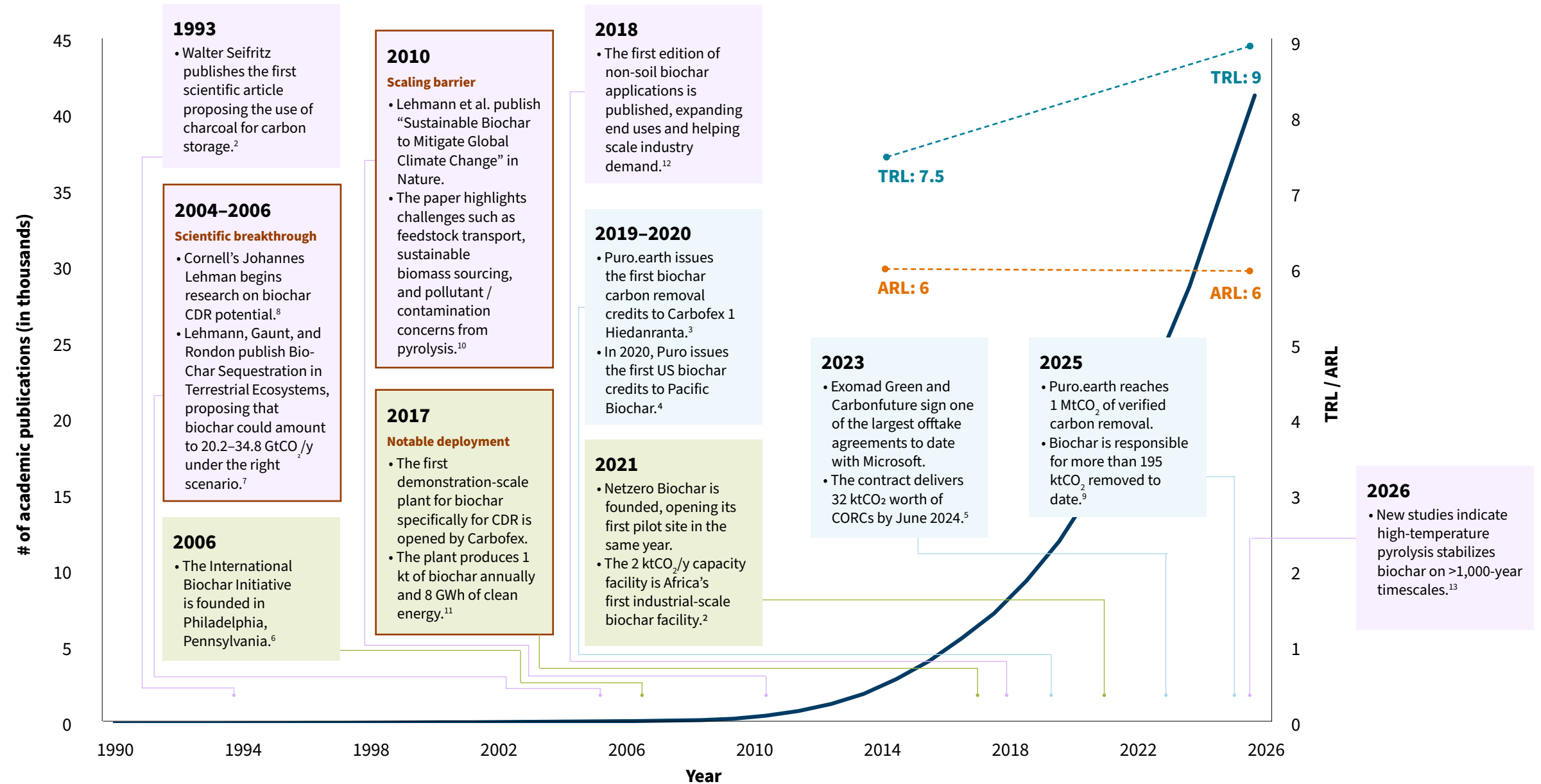


How we got here

Status: Significant progress toward sector-wide scale-up

Approach trend: Positive

Milestones selected for the graph were chosen based on their impact on and significance to the biochar and pyrolysis sectors.



1. [Our production sites](#), NetZero. 2. W. Seifritz, “Should we store carbon in charcoal?,” *International Journal of Hydrogen Energy*, 1993. 3. [Carbofex 1 Hiedanranta](#), Puro.Earth. 4. [“Pacific Biochar Secures First U.S. Biochar Carbon Credits,”](#) Humboldt Sawmill Company, 2020. 5. [“Carbonfuture Announces Innovative Offtake Collaboration with Exomad Green and Microsoft for Large-Scale Biochar Carbon Removal,”](#) Carbon Future, 2023. 6. [About IBI, International Biochar Initiative](#). 7. J. Lehmann et al., “Bio-Char Sequestration In Terrestrial Ecosystems–A Review,” *Mitigation and Adaptation Strategies for Global Change*, 2006. 8. [Biochar - Lehmann Lab: Cornell School of Integrative Plant Science](#). 9. [“Puro.earth Hits 1M Tonnes of Verified Carbon Removal – Exclusive Interview with President Jan-Willem Bode,”](#) Carbon Credits, 2025. 10. D. Wolff et al., “Sustainable biochar to mitigate global climate change,” *Nature Communications*, 2010. 11. [Homepage – Carbofex](#). 12. D. Kalderis et al., “Non-Soil Biochar Applications,” *Nova Science*, 2018. 13. [“Understanding Biochar: Carbon Storage vs Soil Benefits,”](#) *Biochar Today*, 2026.



Current and projected state of deployment

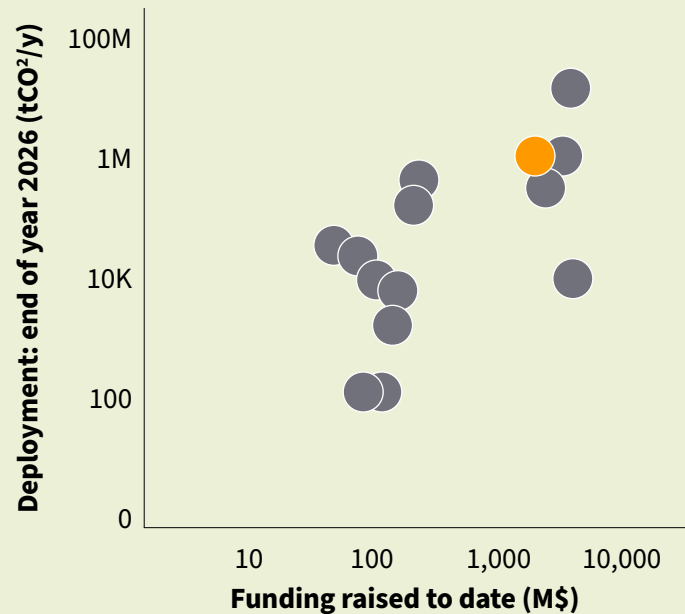
Past 5 years

Commercial deployment grew rapidly, with dozens of projects reaching multi-kiloton scale

Next 5 years

With FOAK commercial facilities online, replication and scale-up remain the focus through 2030

Current deployment



119

companies tracked¹

169

projects active/announced¹

TRL 9

demo and initial commercial deployments

ARL 6

moderate readiness⁷

Current cumulative removals

~3,220,000

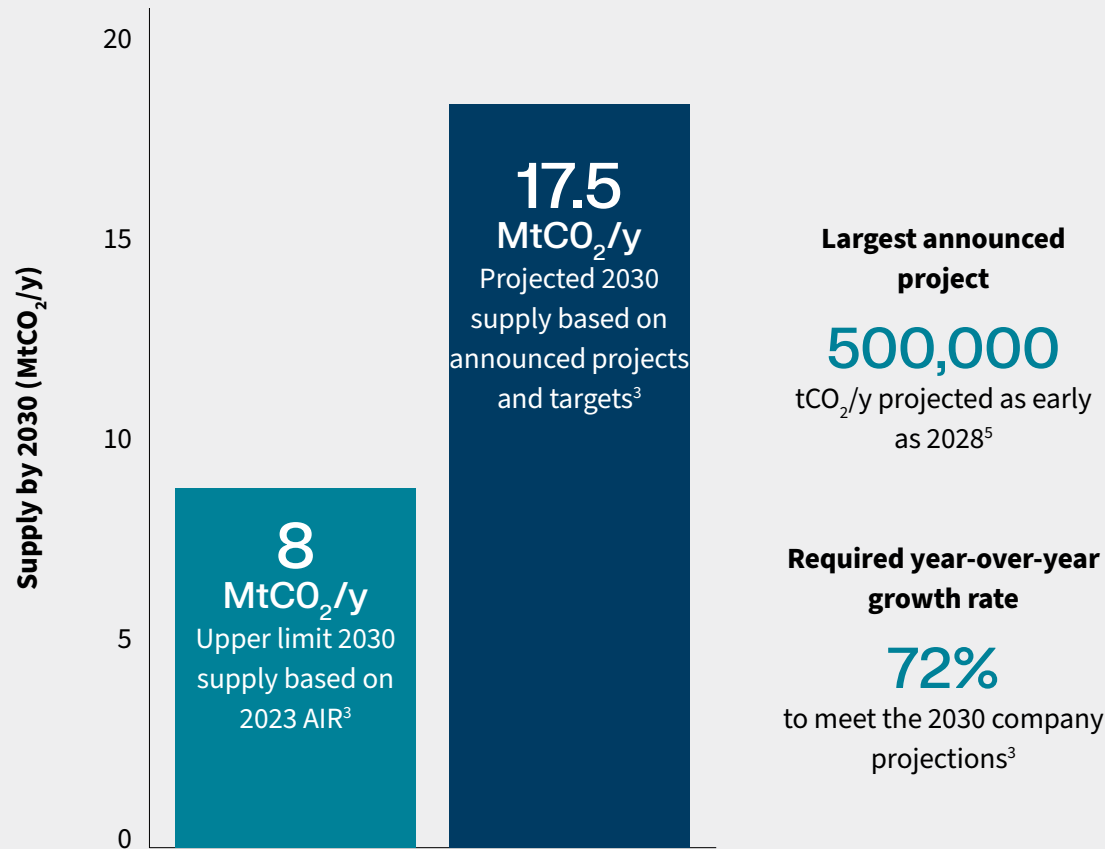
tCO₂ as of end-of-year 2025¹

Largest active project

140,000

tCO₂/year 2026⁴

Supply projections for 2030



Announced and active projects as a percentage of 2030 company targets

15%

1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. **2.** Reference capacity of 8 MtCO₂/y in 2030 is aligned with near-term growth in the EOA “success story” in [The Applied Innovation Roadmap for CDR](#), RMI, 2023 (p. 80). **3.** Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. **4.** “[Turning Invasive Plants Into Climate Action: Carbonfuture MRV+ to Track Australia’s Landmark Biochar Carbon Removal Project at Half a Million Tonnes Annually](#),” Carbonfuture, 2025. **5.** [High Quality Carbon Credits, Delivered at Scale](#), Exomad Green. **6.** “[Google to Purchase Carbon Removal Credits Generated by AMP’s AI-Powered Organic Waste Processing](#),” Amp Sortation, 2026. **7.** A select number of reviewers indicated that risks exist for biochar across project financing and distribution of biochar end products, lack of inclusion in compliance legislation and funding opportunities, and issues with price competition with BECCS. If the DOE CARAT tool was adjusted to reflect these risks, the ARL of biochar could be lower than moderate readiness. Some reviewers also suggested ARL could be as high as 8 (high readiness).



Section 3: Biochar

BIOGENIC

Key cost drivers

- Major cost drivers
- Facility capex, feedstock sourcing and processing
- Improvement areas
- Continuous, large-scale operations

Today: \$80–\$225/tCO₂
Future: \$40–\$12/tCO₂

40%–60% cost reduction possible⁴ via scaled continuous operations, hubs, and standardized integration into soil or product applications.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs. 2. Additional benefits are seen over long timescales from continuous application. See, e.g., [Intergenerational Value of Farmland Applied Biochar](#), Pacific Biochar, 2026. 3. Experts agree that cost reductions may come from blending pyrolysis/biochar with other CDR technologies, such as bio-oil/pyrolysis, carbon capture/pyrolysis, or BECCS/biochar production. 4. Reviewers noted scenarios where increasing biochar supply, phase-out of biomass power subsidies, and inflation/labor costs drive prices such that cost reduction is unlikely.

Today's cost range (0-75, \$/tCO₂)
Future cost range (0-75, \$/tCO₂)

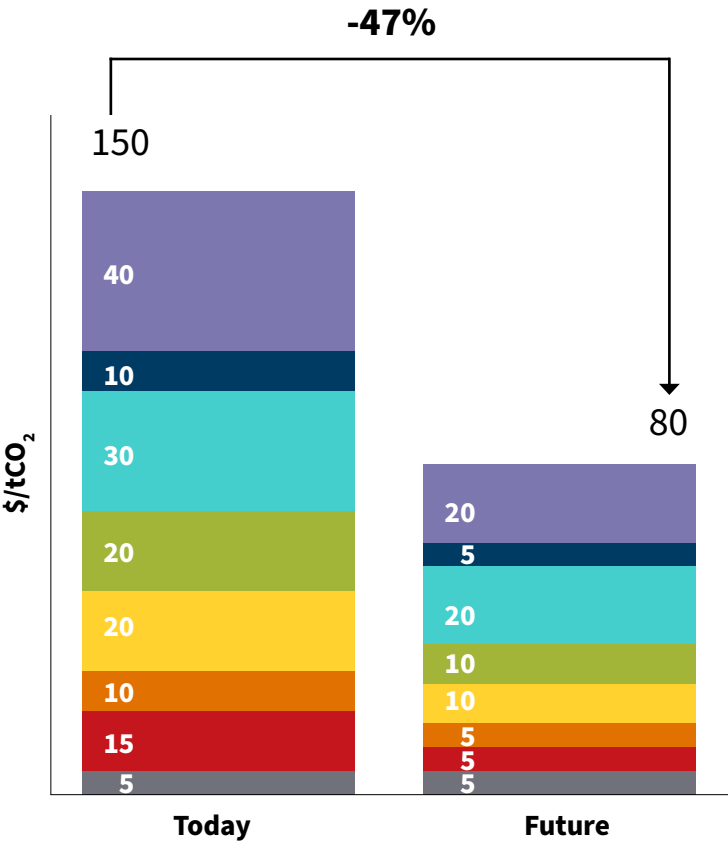
Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex	Pyrolysis reactors, biomass preprocessing equipment (chippers, dryers), facility construction	Mass-produced, modular equipment, optimized feedstock specifications, economies of scale
Energy	Biomass drying, chipping/shredding, reactor start-up, ancillary equipment	Continuous operation, optimized feedstock specifications, passive drying or waste heat integration
Feedstock	Biomass sourcing, preprocessing at source	Established (waste) biomass supply chains, optimized hub-style deployment
Transport	Biomass transportation to reactor, biochar transportation to destination	Optimized hub-and-spoke style siting to cross-optimized local and regional biomass transport
O&M	Labor, equipment maintenance, reactor consumables, environmental compliance	Larger-scale deployments, predictive operations and maintenance from repeat facility designs
Storage	Biochar storage, soil application, or blending into durable products, durability assurance	Standardized integration into farm operations and other supply chains
MRV	Biochar property and stability testing, process monitoring, soil sampling, third-party verification	Standardized biochar testing and certification, automated process monitoring integrated into digital MRV
Embodied Emissions	Plant construction materials, machinery fuel use, biomass and biochar transportation emissions	Green materials, electrified operations and transport, optimized siting and supply chain efficiency

Note about cost stacks¹

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



- Cost stack considerations
- Centralized hub-style deployments provide improved capital expenditure and energy efficiency at the cost of increased feedstock sourcing and transportation costs compared with mobile deployments.
 - Co-benefits such as soil health improvements generate additional revenue streams^{2,3}



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Decentralized burial or sinking projects; injection or dry burial hubs
Where to start: Integration into waste biomass collection and processing workflows



Supply of sustainable biomass

Scaled biomass direct storage deployment will require **low-cost, sustainable sourcing** that doesn't negatively influence food supply or soil health. Projected scales of 8–18 MtCO₂/y **by 2030** will require the permanent sequestration of **10–35 Mt/y of dry biomass** globally. For context, this represents 25%–80% of all logging residues produced in the United States today, of which half are not collected.¹ Both biochar and bio-oil production benefit from lignin-heavy dry biomass that is easy to process into chips or other pieces amenable to continuous processing, including grasses and agricultural residues. The ability to process problematic feedstocks, such as sewage sludge with higher moisture content, can incentivize deployment as a waste management solution.

At larger deployment scales, careful guardrails on land use allocation and carbon accounting frameworks will be needed to balance possible removals against impacts on food systems, ecosystems, and the climate. Estimates of the **global sustainable supply of all biomass** range from 4 to 12 Gt/y, equivalent to 6 to 17 GtCO₂/y.² Other CDR approaches, material demands, and energy uses will compete for this resource.³ Further study is needed to identify the optimal use case of different types of biomass among different uses.

Example KPIs:

- Feedstock cost <\$30/tCO₂
- >80% waste/residue sourced biomass
- 100% sustainably sourced purpose-grown biomass



Siting pyrolysis reactors

Project deployment **colocated with biomass sources** reduces the cost and embodied emissions associated with transportation to the storage site, which are large, especially for biomass with significant moisture content. This savings is balanced **against cost savings from land use and process efficiency** from large, centralized pyrolyzers drawing biomass from several sources in order to run continuously.

Mobile, modular pyrolysis systems reduce haul distance and can be deployed flexibly as part of on-site clean up processes targeting forestry thinnings, agricultural residues, or invasive species removal. They can be designed to process diverse residues at the point of generation, and the produced char may be able to be used on site as a soil amendment.⁴

Hub-style deployment enables the establishment of efficient supply chains for waste and dedicated biomass supplying more efficient, continuously operating pyrolyzers.⁵ At large CDR deployment scales, such hubs could contain pyrolyzers alongside biomass direct storage and BECCS projects, flexibly adjusting the fate of incoming biomass in response to fluctuations in biomass quality and demand for coproducts such as electricity or biofuels.

Example KPIs:

- >75% of recoverable residues utilized in deployment region
- <100 km transport distance for regional hubs
- Capacity factor >80% for centralized deployment



Biochar end uses

The products of biochar projects not only durably sequester carbon but are also valuable in a range of applications. Project economics are more favorable if biochar is utilized rather than simply stored.

The most established utilization option for biochar is application to soils, including agricultural soils. Biochar application has been shown to **improve water and nutrient retention of soils**. Properties of biochar influenced by parameters such as feedstock type, pyrolysis temperature, and residence time influence its impact on soils as well as the efficiency and durability of carbon sequestered within the biochar, meaning projects may trade off the extent of optimization for carbon removal and soil health impacts.

Alternative end uses include the **addition of biochar to concrete or asphalt**. At small substitution rates, addition of biochar to these materials has been shown to result in durable carbon storage while possibly improving material properties such as weather resistance. Further long-term studies will inform durability assessments. Another promising end use is the addition of biochar to ammonia-based fertilizers, producing a **slow-release fertilizer** formulation.⁵

Example KPIs:

- >20% of cost per tCO₂ recovered from utilization of biochar in agriculture or other end uses
- 90% stable carbon verified in biochar product

1. 19Mt and 23Mt of collected and unharvested logging residues, respectively ([2023 Billion-Ton Report](#), US DOE), converted using a factor of 1.4tCO₂/t dry biomass. **2.** The ETC has estimated the prudent and maximum supply of sustainable biomass to be 40-60 or 120 EJ, respectively ([Bioresources within a Net-Zero Emissions Economy](#), ETC, 2021). One-third to half of this supply is represented by agricultural residues and woody biomass from forestry not used as building materials. **3.** The majority of biomass will be used in other industries, including for other decarbonization efforts. A WRI model of US non-food biomass use for a decarbonized economy by 2050 suggests a maximum allocation of 25% of waste and energy crops, or 110 Mt/y, by 2050 ([Biomass and land use in a decarbonizing U.S. economy](#), WRI, 2025). **4.** C. Nobre et al., “[Mobile Pyrolysis Systems for Decentralized Biomass Valorization: Technologies, Products, and Applications](#),” *Recycling*, 2026. **5.** C. Wang et al., “[Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review](#),” *Environmental Science and Ecotechnology*, 2022.



Advancement and breakthrough areas

Key research areas
Durable end uses, increased efficiency in pyrolysis energy usage and biomass conversion

1. See [page 21](#) for more detail on crosscutting opportunities for breakthroughs in biogenic CDR, including assessments of the technical and social difficulty of implementation.

2. Reviewers highlight that other coproduct valorization would additionally help with scaling and project economics by generating revenue streams from collected bio-oil, CO₂, or wood vinegar.



Crosscutting bCDR breakthrough themes¹

B1: Enhanced cultivars for high-carbon-storage applications

Growing crops with genetically enhanced characteristics that improve photosynthetic rates or increase carbon content would maximize the carbon % in biochar derived from those sources.

B2: On-site microreactors

On-site microreactors reduce cost and emissions associated with transportation and increase carbon removal benefits while ensuring the biochar’s positive effects on soil remain localized.

B6: Biogenic co-benefits

Biochar offers co-benefits like drought resistance, nutrient storage, erosion prevention, and improved crop yields, which provide tangible benefits in the context of farming applications.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Scaled, continuous-operation pyrolysis	Continuous operation through engineering improvements preventing build-up of tar or other residues would reduce startup energy costs, simplify maintenance, and maximize throughput	\$\$ Improved uptime and simplified maintenance, reduced energy cost from reactor startup	Large/hub-style projects	<div>CapexEnergyFeedstockTransportO&MStorageMRVEmbodied</div>	Facility operators, pyrolysis system developers, process engineers
2	Biochar-integrated concrete mixes ²	Adding biochar to concrete or ex situ carbon mineralization projects increases removals durability while producing valuable coproduct	\$ Use in building materials opens new markets, increases demand, and reduces durability concerns	Projects in need of a diversified char end use	<div>CapexEnergyFeedstockTransportO&MStorageMRVEmbodied</div>	Industrial construction operations, offtakers / credit buyers, registries, MRV bodies
3	Autonomous solar-powered pyrolysis	Pyrolysis systems operating autonomously would reduce labor needs , particularly in contexts of flexible deployment for site cleanup	\$\$\$ Reduced labor, increased credit generation due to reduced emissions from fuel	Modular, small-scale projects	<div>CapexEnergyFeedstockTransportO&MStorageMRVEmbodied</div>	Solar developers, AI and autonomous technology specialists, manufacturing supply chains
4	Use of low-value feedstocks	Processing feedstocks such as sewage sludge, biosolids, invasive plants, or other materials with no economical uses would increase feedstock supply while reducing existing waste treatment costs	\$\$ Reduced feedstock cost, increased deployment scale as targeted waste remediation solution	Biochar facilities and large infrastructure projects	<div>CapexEnergyFeedstockTransportO&MStorageMRVEmbodied</div>	CDR project developers, waste management utilities, permitting agencies, environmental scientists
5	Retrofitted carbon capture on pyrolysis systems	Point-source capture on pyrolysis technology makes the combustion process nearly zero emissions , meaning units can capture all carbon present in feedstocks	\$ Increased credit generation due to reduced emissions, less feedstock selectivity	Pyrolysis reactors powered by gas, diesel, or syngas	<div>CapexEnergyFeedstockTransportO&MStorageMRVEmbodied</div>	CCS developers, existing biochar facility owners, future project developers

\$ \$1–\$30/tCO₂ **\$\$** \$20–\$50/tCO₂ **\$\$\$** \$40–\$100/tCO₂ **\$\$\$\$** \$75–\$300/tCO₂



Bio-oil

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 2.5: Pyrolysis (Bioliquid) and Storage

DEFINITION

Thermal conversion of biomass via either fast pyrolysis or hydrothermal liquefaction, optimized to produce crude bioliquid that can be stored underground, geologically, or in other environments.

APPROACH OVERVIEW

The production of bio-oil for storage and carbon removal is a relatively novel approach: The first commercial entity launched in 2016. In the decade since, a small number of companies have advanced bio-oil injection operations to commercial scale, removing thousands of tons of CO₂ to date and securing meaningful investment from large offtakers in the process. By 2030, bio-oil companies are set to remove over 100 ktCO₂.



Section 4: Bio-oil

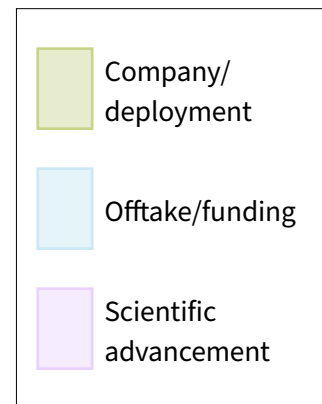
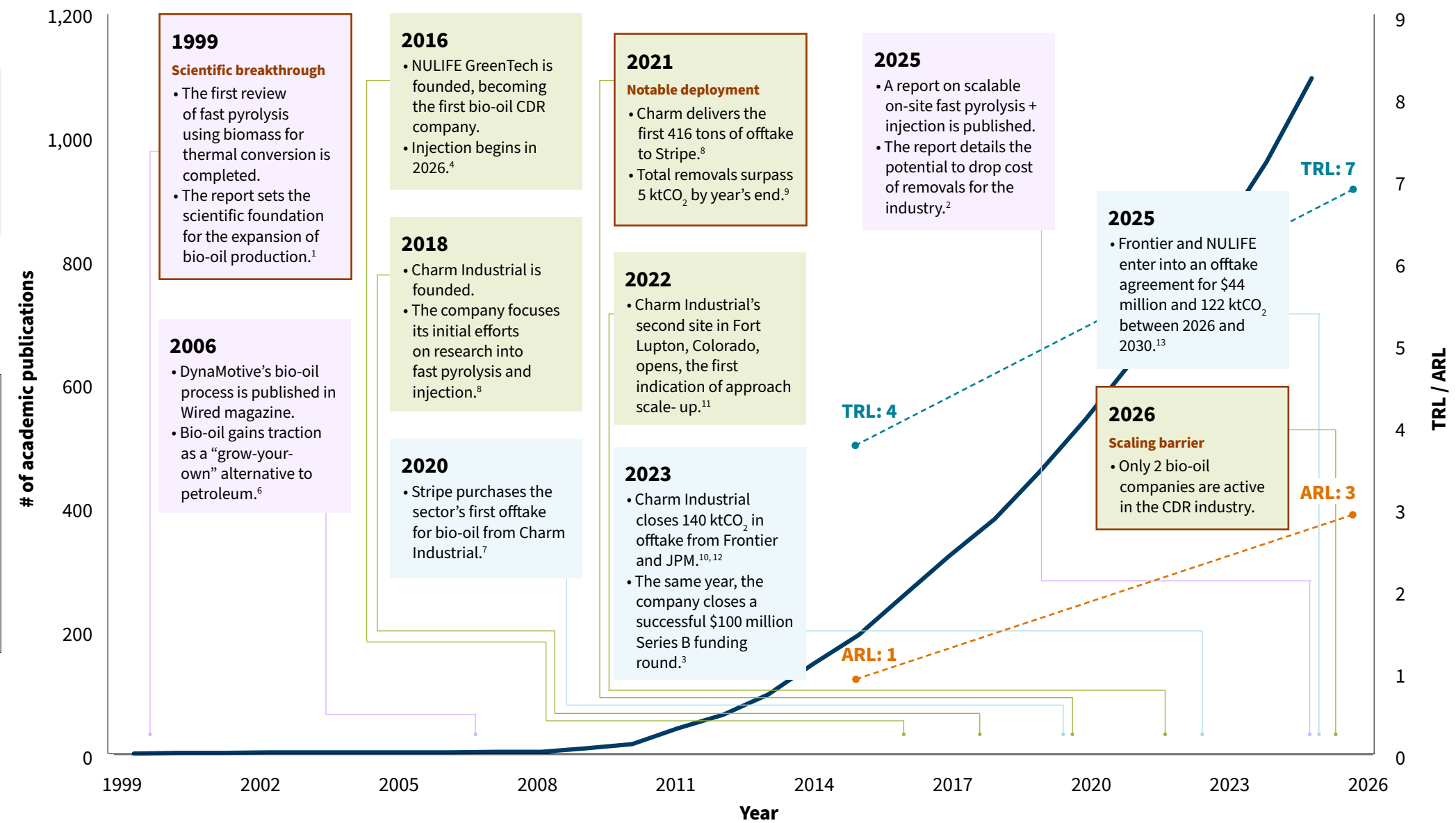
BIOGENIC

How we got here

Status: Expected progress toward commercial scale deployment

Approach trend: Positive

Milestones selected for the graph were chosen based on their impact on and significance to the bio-oil sector.



1. A.V Bridgwater et al., "An overview of fast pyrolysis of biomass," *Organic Geochemistry*, 1999. 2. P. Dubey et al., "Enhancing carbon removal via scalable on-site pyrolysis and well-plugging systems," *Energy Conversion and Management*, 2025. 3. "Accelerating Carbon Removal with our \$100m Series B," Charm Industrial, 2023. 4. About NULIFE | Scalable Permanent Carbon Removal Platform. 5. "Charm Industrial - Putting Scalability Into Practice," C Carbon, 2022. 6. "Grow Your Own Oil, U.S.," *Wired*, 2006. 7. "A New Negative Emissions Method and Our First Customer," Charm Industrial, 2020. 8. "Charm Delivers Stripe's Carbon Removal Purchase Ahead-of-Schedule," Charm Industrial, 2021. 9. "Charm Marks A Carbon Removal Milestone - 5,000 Tons Of CO₂ Equivalent Delivered," *Carbon Herald*, 2021. 10. "Frontier buyers sign first \$53M in offtake agreements with Charm Industrial," Frontier, 2023. 11. "Opening our Colorado Miniforge Site," Charm Industrial, 2022. 12. "JPMorgan Chase is paying \$200 million to permanently remove greenhouse gases from the atmosphere," *Footprint Coalition*, 2023. 13. "Frontier and NULIFE scale new biowaste carbon removal approach," Frontier, 2025.



Current and projected state of deployment

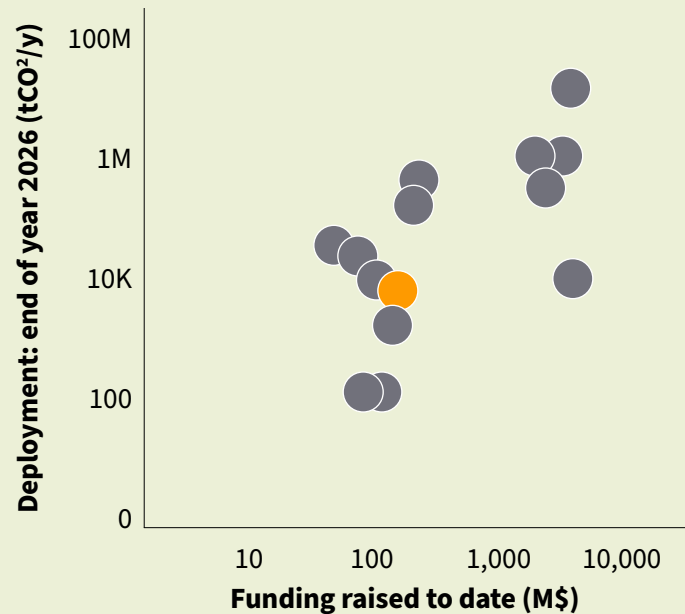
Past 5 years

Bio-oil companies scaled operations, winning major offtake and mainstream investor support

Next 5 years

With technology at commercial scale, a lack of company diversity may hinder approach removals

Current deployment



3

companies tracked¹

2

projects active/
announced¹

TRL 6-7

FOAK commercial
deployments

ARL 3

low readiness

Current cumulative removals

~14,000

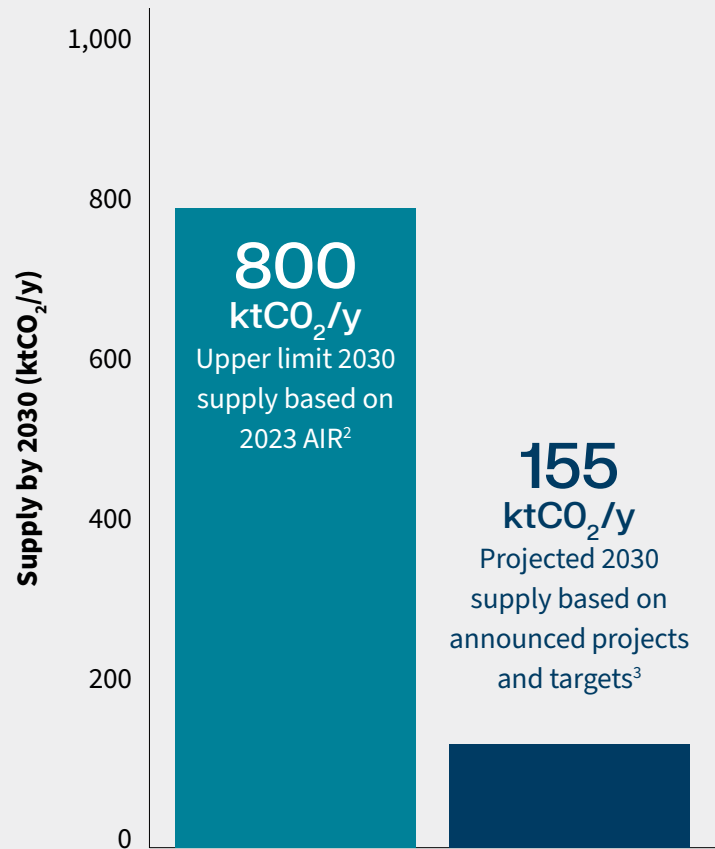
tCO₂ as of end-of-year 2025¹

Largest active project

~5,000

tCO₂/year 2026⁶

Supply projections for 2030



Largest announced project

25,000

tCO₂/y projected as early as 2026⁴

Required year-over-year growth rate

~113%

to meet the 2030 company projections

Announced and active projects as a percentage of 2030 company targets

42%

1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. **2.** Reference capacity of 800 ktCO₂/y in 2030 is aligned with near-term growth in the Bio-oil “success story” in *The Applied Innovation Roadmap* for CDR, RMI, 2023 (p. 89). **3.** Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. **4.** [Kansas Biooil Charm Industrial Project Description & Deployment Estimates](#), Charm Industrial. (This Project Design Document initially forecasted 25 ktCO₂/y capacity by 2025. This remains the target removal of the project, but it is uncertain at what point the project will reach that scale.) **5.** [“Charm Industrial Secures 61,500-Ton Carbon Removal Purchase and \\$20 Million Debt Financing to Catalyze Growth.”](#) Charm Industrial, 2026. **6.** [Commercial HTL Facilities for Carbon Removal](#), NULIFE GreenTech.



Section 4: Bio-oil

BIOGENIC

Key cost drivers

Major cost drivers: Pyrolysis and pre-processing equipment, biomass transport

Improvement areas: Continuous large-scale operation, supply chains and hubs

Today: \$350–\$620/tCO₂
Future: \$60–\$160/tCO₂

60%–85% cost reduction possible via scaled operations and optimized injection well siting and operations.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

Today's cost range (0-300, \$/tCO₂)
Future cost range (0-300, \$/tCO₂)

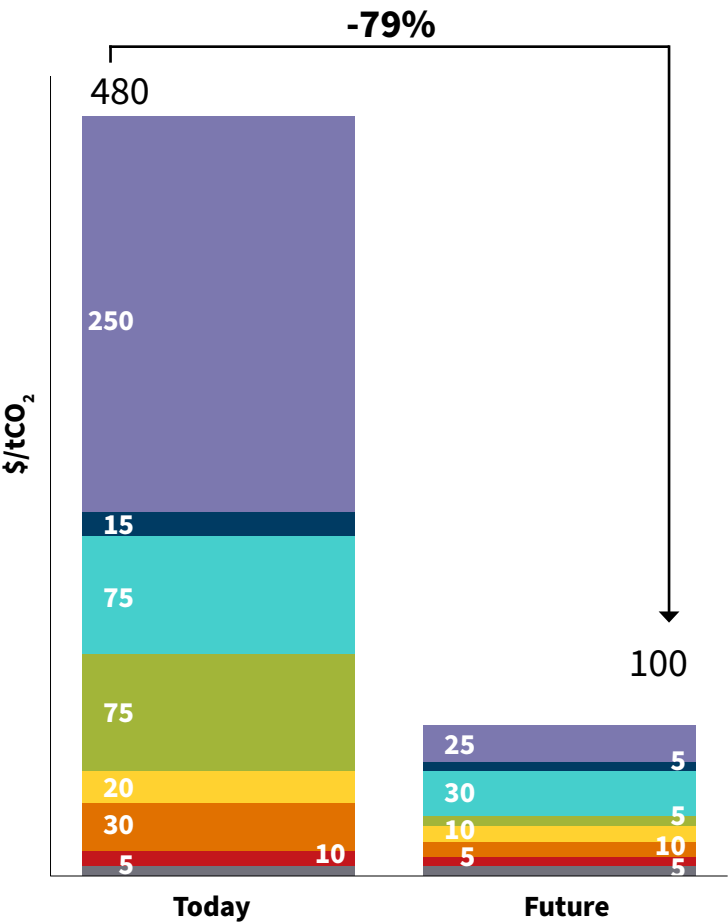
Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex	Pyrolysis reactors, preprocessing equipment, bio-oil storage tanks, injection systems	Modularization and deployment of decentralized bio-oil facilities, economies of scale, developed well infrastructure
Energy	Biomass drying, grinding, or chipping; reactor startup; ancillary equipment; bio-oil pumping	Heat recovery or passive drying, continuous large-scale operation
Feedstock	Biomass cost and collection, on-site preprocessing for transport	Established waste biomass supply chains, optimized siting or biomass aggregation hubs, sustainable biomass protocols
Transport	Biomass transport, bio-oil transport to injection site, logistics management	Improved siting, injection hubs
O&M	Labor (especially for mobile units), pyrolyzer and injection unit maintenance, reactor downtime	Scaled operation, predictive maintenance in NOAK projects
Storage	Baseline site characterization, injection well access, pumping into well, downhole pressure control	Dedicated injection wells, engineering solutions for viscous oil pumping
MRV	Pyrolysis mass balance monitoring, bio-oil carbon content measurement, flow metering, third-party verification	Real-time monitoring during pyrolyzer continuous operation, standardized injection monitoring
Embodied Emissions	Facility construction materials, equipment emissions, biomass supply chain and transport emissions	Green materials, optimized supply chains

Note about cost stacks¹

X Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- Future costs will be heavily influenced by engineering and permitting pathways for efficient transportation and injection of bio-oil into subsurface storage
- Conversion of bio-oil into usable products such as biofuel would impact net carbon impacts and project economics
- Capital expenditure costs are significantly influenced by project scale



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Distributed or hub-style models with bio-oil transportation to injection wells

Where to start: Feasibility studies for regional biomass handling and processing hubs



Supply of sustainable biomass

Scaled biomass direct storage deployment will require **low-cost, sustainable sourcing** that doesn't negatively influence food supply or soil health. Projected scales below 1 MtCO₂/y **by 2030** will require the permanent sequestration of **less than 2 Mt/y of dry biomass** globally. For context, this represents <5% of all logging residues produced in the United States today, of which half are not collected.¹ Both biochar and bio-oil production benefit from lignin-heavy dry biomass that is easy to process into chips or other pieces amenable to continuous processing, including agricultural residues. Biomass direct storage may be better suited for bulky residues that need minimal processing.

At larger deployment scales, careful guardrails on land use allocation and carbon accounting frameworks will be needed to balance possible removals against impacts on food systems, ecosystems, and the climate. Estimates of the **global sustainable supply of all biomass** range from 4 to 12 Gt/y, equivalent to **6 to 17 GtCO₂/y**.² Other CDR approaches, material demands, and energy uses will compete for this resource.³ Further study is needed to identify the optimal use case of different types of biomass among different CDR approaches or other uses.

Example KPIs:

- Feedstock cost <\$30/tCO₂
- >80% waste/residue sourced biomass
- 100% sustainably sourced purpose-grown biomass



Reactor and well siting

Bio-oil projects face siting considerations not just for biomass processing but also for the transportation and storage of bio-oil, which can be injected into subsurface wells for durable sequestration. The decision of centralized or distributed deployment is based on trade-offs between **efficient transportation through colocation with biomass sources** balanced against **cost savings from process efficiency** from large, centralized pyrolyzers drawing biomass from several sources in order to run continuously.

Bio-oil is highly viscous and can polymerize or phase separate during storage, presenting engineering challenges for pumping and injection systems. Solutions under development include heated pipeline and standardized specifications for bio-oil material properties, facilitating standardized handling in scaled hubs. Alternative methods such as rail and trucking favor distributed-deployment bio-oil projects.⁴

At large CDR deployment scales, bCDR hubs could contain pyrolyzers and storage wells alongside biomass direct storage and BECCS projects, flexibly adjusting the fate of incoming biomass in response to fluctuations in biomass quality and demand for coproducts such as electricity or biofuels.

Example KPIs:

- >75% of recoverable residues utilized in deployment region
- Storage hub scale >0.5 MtCO₂/y
- Capacity factor >80% for centralized deployment



Dual biochar and bio-oil generation

Bio-oil and biochar are shared outputs of the biomass pyrolysis process, alongside potentially combustible gases such as syngas. Although pyrolysis conditions can be tailored to favor one output, there are also current projects **cross-optimizing for dual biochar and bio-oil generation**. The ability to flexibly adjust outputs may help carbon removal projects save net costs by responding to fluctuating seasonal biochar demand or access to bio-oil transportation. In some cases, the conversion of bio-oil into usable fuels such as sustainable aviation fuel (SAF) or biodiesel may provide alternative product markets in the future.

Flexible dual generation may be particularly valuable in the context of centralized biomass hubs, adjusting production depending on biomass characteristics and biochar or bio-oil offtake markets. This helps capital-intensive biomass conversion units operate economically. However, flexible generation increased engineering complexity, as variations in feedstock and pyrolysis rates can temporarily disrupt pyrolyzer functionality.

Example KPIs:

- >50% capacity flexible between outputs
- <24 hours to transition between production modes
- >20% of costs per tCO₂ from coproducts

1. 19 Mt and 23 Mt of collected and unharvested logging residues, respectively ([2023 Billion-Ton Report](#), DOE), converted using a factor of 1.4 tCO₂/t dry biomass. **2.** The ETC has estimated the prudent and maximum supply of sustainable biomass to be 40–60 or 120 EJ, respectively ([Bioresources within a Net-Zero Emissions Economy](#), ETC, 2021). One-third to half of this supply is represented by agricultural residues and woody biomass from forestry not used as building materials. **3.** The majority of biomass will be used in other industries, including for other decarbonization efforts. A WRI model of US non-food biomass use for a decarbonized economy by 2050 suggests a maximum allocation of 25% of waste and energy crops, or 110Mt/y, by 2050 ([Biomass and land use in a decarbonizing U.S. economy](#), WRI, 2025). **4.** P. Dubey et al., [Enhancing carbon removal via scalable on-site pyrolysis and well-plugging systems](#), *Energy Conversion and Management*, 2025.



Advancement and breakthrough areas

Key research areas

Advancements in bio-oil infrastructure and instrumentation, bio-oil pipeline feasibility

Crosscutting bCDR breakthrough themes¹

B1: Enhanced cultivars for high-carbon-storage applications

Development of genetically modified cultivars could improve the logistics of waste biomass procurement, reduce transport costs and emissions, and increase carbon storage potential.

B2: On-site microreactors

On-site pyrolyzers would enable localized production at the site of waste biomass, concentrating feedstocks and improving transport to injection sites and reducing embodied emissions.

B4: Autonomous precision growing and MRV

Autonomously growing specialized feedstocks that are well-suited for the process of fast pyrolysis could reduce maintenance on equipment, lower transport costs, and improve labor costs.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Use municipal waste as biomass input	Using landfill waste and other low-value waste as feedstock would significantly reduce feedstock costs and provide an alternative waste management stream	\$ Cost savings from feedstock procurement, reduced feedstock transport, revenue from waste disposal	All future projects for colocation, all projects generally		Local and state regulators, waste management companies, methane experts, community representatives
2	Heated bio-oil injection wells and pipes	Heated pipes and injection infrastructure accelerate injection rates and reduce maintenance needs caused by clogging of viscous low-temperature bio-oil	\$\$ Reduced maintenance and repairs, increased rate of injection, at cost of increased energy use	All future projects for adoption, all current projects for retrofitting		Piping and instrumentation specialists, geothermal experts
3	Repurposed orphaned wells used for bio-oil injection ²	Infrastructure for large-scale injection, combined with municipal waste feedstocks, provides storage opportunities with eased well permitting and removes the need for new wells	\$\$ Reduced capital expenditures for well siting, permitting, reduced time to injection, reduced monitoring	All projects performing geologic injection		Oil and gas engineers, local and state regulators, community representatives
4	Fully optimized process for dual biochar/bio-oil synthesis	Pyrolyzer technology optimized to maximize reactor production of valuable material allows for shifting product outputs between biochar and bio-oil based on shifts in offtake market or feedstock input	\$\$ Reduced waste disposal, increased/additional revenue stream, increased efficiency/reduced cost per ton	All future projects for integration, current projections for retrofitting		Pyrolyzer engineers and developers, biochar offtakers, RD&D investors
5	Public infrastructure for bio-oil synthesis & disposal	Modular community pyrolyzers converting locally collected household waste into bio-oil provides a waste management alternative to landfilling or municipal composting	\$ Reduced infrastructure burden, transport, feedstock procurement	Individual user-level adoption		Community representatives, local and state commissions, WM companies, pipeline experts

\$ \$1–\$30/tCO₂

\$\$ \$20–\$50/tCO₂

\$\$\$ \$40–\$100/tCO₂

\$\$\$\$ \$75–\$300/tCO₂

1. See [page 21](#) for more detail on crosscutting opportunities for breakthroughs in biogenic CDR, including assessments of the technical and social difficulty of implementation.

2. Projects utilizing orphaned wells to inject bio-oil are being deployed by [Charm Industrial](#).



Microalgae in Ponds

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 2.6: Pyrolysis (Bioliquid) and Storage

DEFINITION

Cultivation, harvest, and storage of microalgae biomass grown in raceway ponds and other land-based systems.

APPROACH OVERVIEW

Microalgae cultivation in ponds has experienced headwinds since the first company was founded in 2013. Many of the early companies have had to diversify their model away from CDR, using algal biomass to create and sell algae-derived products, such as faux leather. However, although progress has been slow to this point, a select number of companies have lofty goals of reaching scaled removals before 2030.

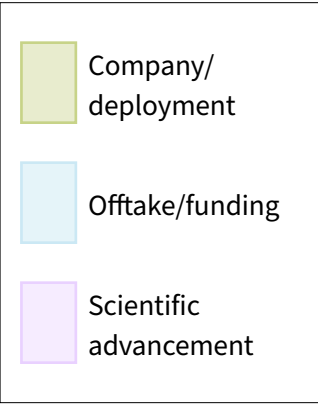
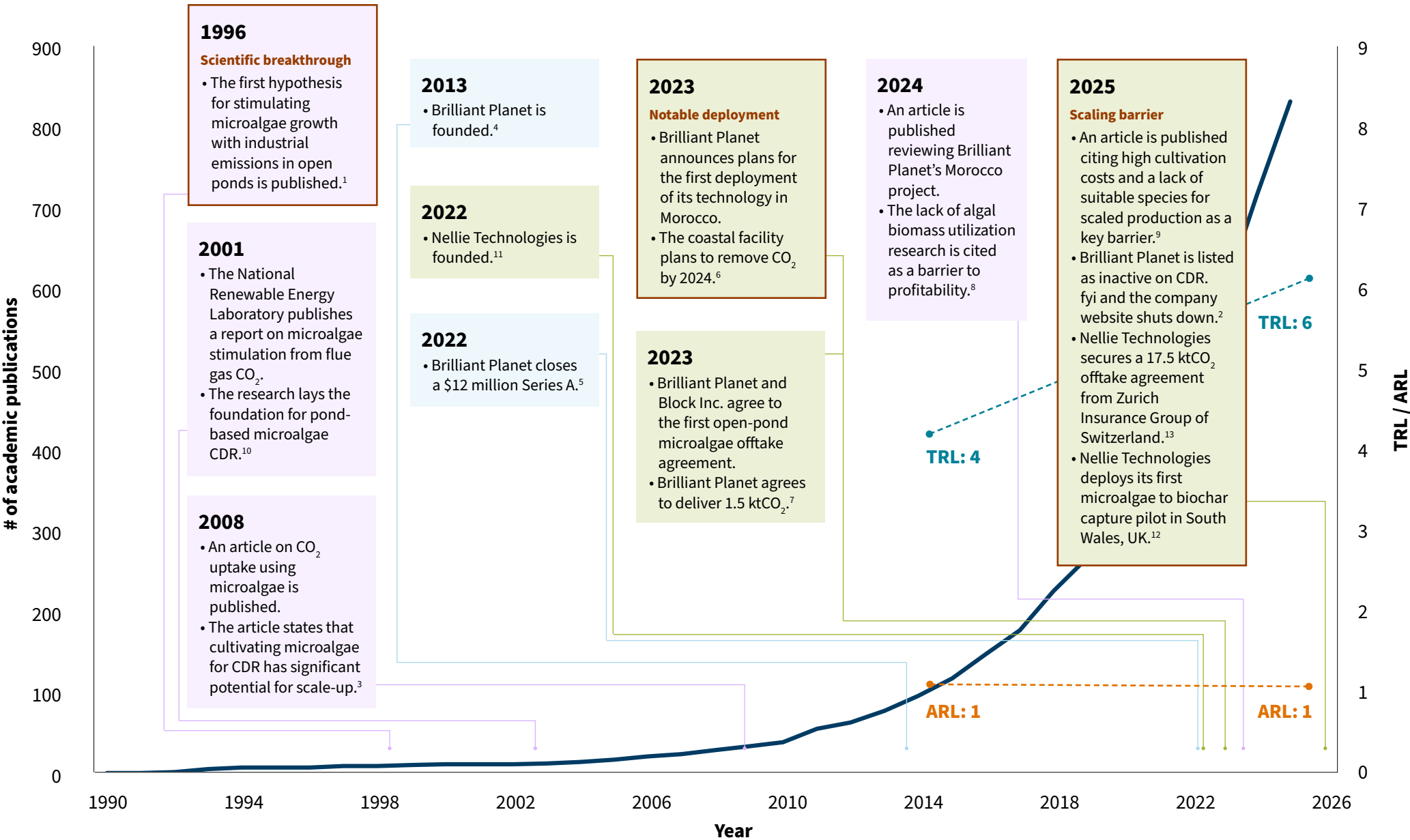


How we got here

Status: Minimal progress toward demonstration-scale deployment

Approach trend: Challenging

Milestones selected for the above graph were chosen based on their impact on and significance to the microalgae cultivation in terrestrial settings sector.



1. J. Benemann, "CO₂ mitigation with microalgae systems," *Energy Conversion and Management*, 1997. 2. [Brilliant Planet | Inactive — Carbon Removal Supplier Profile & Sales Data, CDR.fyi](#). 3. Wang et al., "CO₂ bio-mitigation using microalgae," *Applied Microbiology and Biotechnology*, 2008. 4. [Brilliant Planet Company Overview, Climate Tech List](#). 5. "Brilliant Planet Limited announces the closing of its \$12 million Series A funding co-led by Union Square Ventures and Toyota Ventures," *PR Newswire*, 2022. 6. "Brilliant Planet to Work with Mott MacDonald on Algae Carbon Removal Facility in Morocco," *Carbon Herald*, 2023. 7. "Brilliant Planet Announces First Large-Scale Carbon Removal Purchase, Made by Block, Inc. through the Watershed Marketplace," *PR Newswire*, 2023. 8. A. Chaudhary, "Start-Ups Are Supercharging Algae to Clean Up the Environment," *ACS Central Science*, 2024. 9. S. Nayak et al., "Harnessing the potential of microalgae for carbon sequestration to achieve net-zero emissions," *Mitigation and Adaptation Strategies for Global Change*, 2025. 10. [Microalgae Production from Power Plant Flue Gas: Environmental Implications on a Life Cycle Basis](#), National Renewable Energy Laboratory, 2001. 11. [Explore Climate Solutions Today, Nellie](#). 12. "Nellie Mwyndy Cross Project Registration," *Puro.Earth*, 2022. 13. "Zurich Signs 17,500 Ton Carbon Removal Deal with Climate Solutions Provider Nellie Technologies," *ESG Today*, 2025.



Current and projected state of deployment

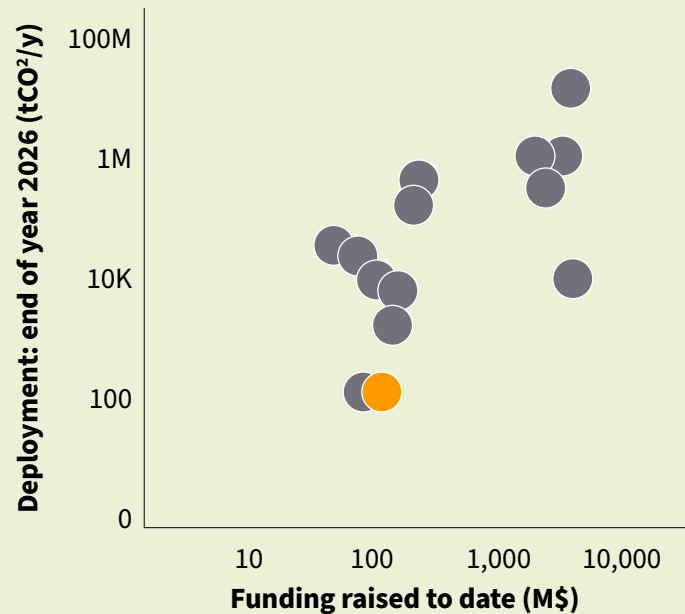
Past 5 years

A decade that began with momentum saw company closures and slowed deployments

Next 5 years

Remaining companies have secured offtake, but FOAK projects likely will not reach 2030 targets

Current deployment



9

companies tracked¹

4

projects active/
announced¹

TRL 6

Pilot and demonstration deployments

ARL 1

low readiness

Current cumulative removals

~120

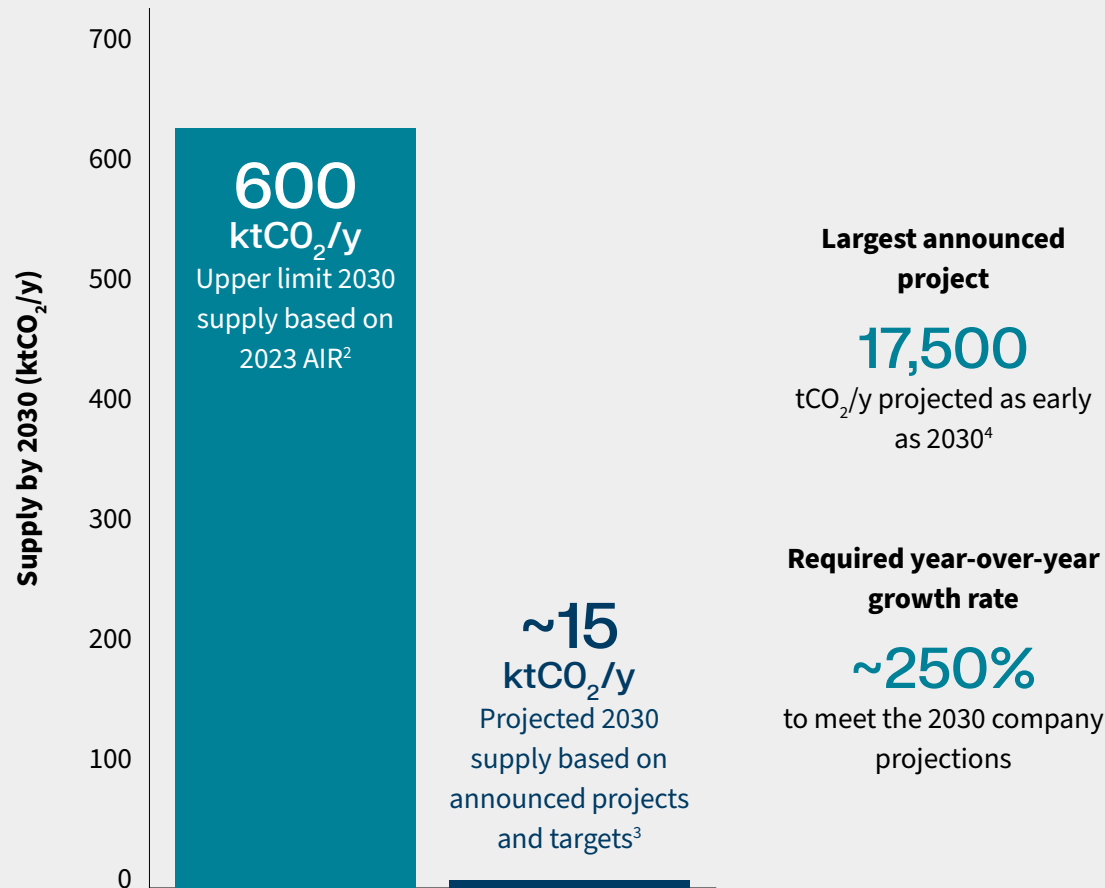
tCO₂ as of end-of-year 2025¹

Largest active project

~100

tCO₂/year 2026¹

Supply projections for 2030



Announced and active projects as a percentage of 2030 company targets

<1%

1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference capacity of 600 ktCO₂/y in 2030 is aligned with near-term growth in the microalgae in ponds “success story” in *The Applied Innovation Roadmap for CDR*, RMI, 2023 (p. 99). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. “Zurich Signs 17,500 Ton Carbon Removal Deal with Climate Solutions Provider Nellie Technologies,” *ESG Today*, 2025. 5. “\$4m secured for CyanoCapture-led Horizon Europe Project in Portugal 2024 – 2027,” CyanoCapture, 2024.



Key cost drivers

Major cost drivers

Pond construction, water handling systems, biomass drying

Improvement areas

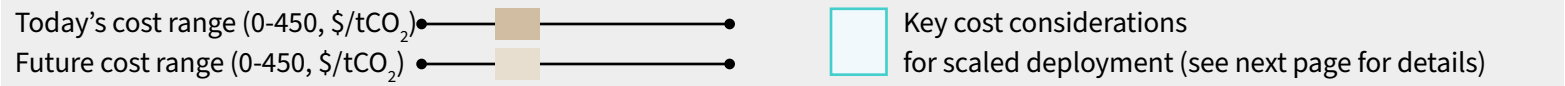
Passive drying, conversion of wet biomass

Today: \$600–\$1,100/tCO₂

Future: \$60–\$170/tCO₂

70%–90% cost reduction possible via established modular designs, circular nutrient and material flows, passive drying, and siting optimization.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

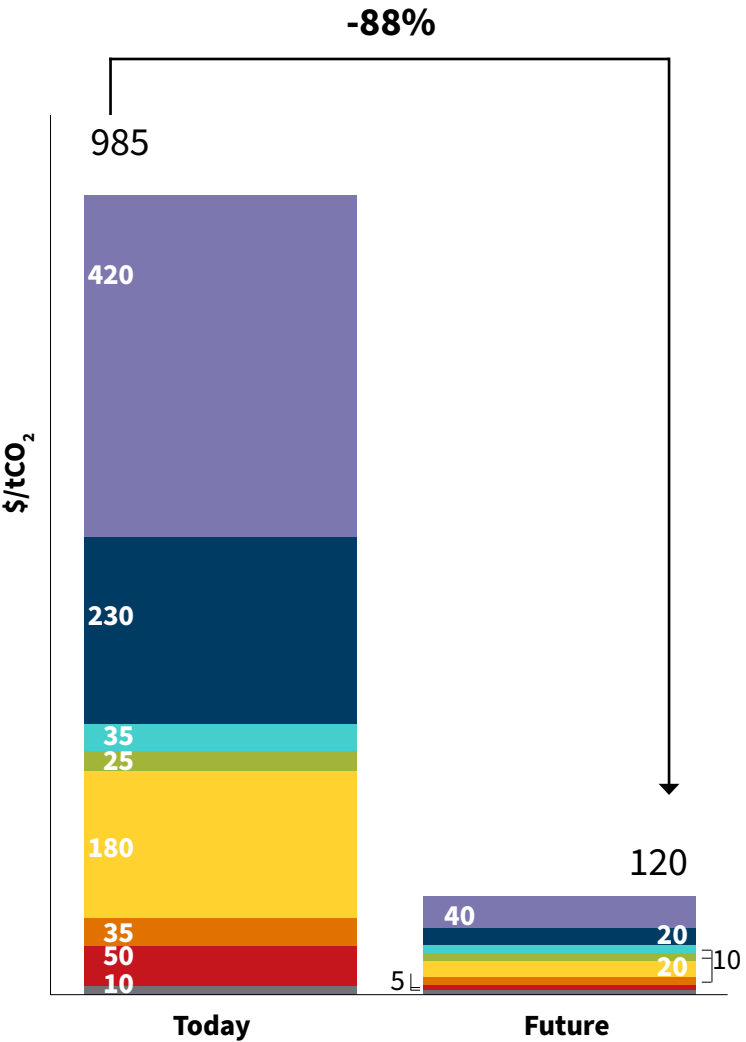


Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex	Pond construction, pumping and water treatment systems, drying and storage infrastructure	Modular designs, bulk manufacturing
Energy	Water pumping, mixing, and aeration; biomass harvesting and drying	Efficiency improvements from scaled designs, solar drying
Feedstock	Nutrient inputs (N, P, and trace nutrients), pH control	Biological nitrogen management, improved nutrient recycling
Transport	Material delivery (dominated by construction), biomass transport to storage or conversion sites	Optimized colocation with nutrient sources and storage/conversion sites
O&M	Labor, pond equipment maintenance, water management and quality control	Predictive maintenance from modular designs, automated sensors
Storage	Excavation and liners, drying and compaction of biomass, long-term site management and monitoring	Standardized trenching and sealing, hub models, colocation with conversion
MRV	Biomass and carbon content metering, storage site monitoring, third-party verification	Automated continuous monitoring
Embodied Emissions	Pond construction and liner materials, biomass transport emissions, nutrient production	Circular materials, efficiency gains, electrification, circular nutrient flows in closed system ponds

Note about cost stacks¹

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- More pilot-scale deployments are needed to demonstrate realistic costs at scale.
- Biomass can be dried and stored or converted into durable forms of carbon such as biochar or bio-oil, which carry a higher up-front cost but potentially easier monitoring of long-term stability.



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Scaled deployment in land-constrained regions with abundant energy

Where to start: Pilot projects to inform TEAs based on biomass storage or conversion modality



Biomass drying and conversion

A key difference between sourcing biomass from land-based plants and using microalgae grown in closed systems is the **energy cost of algae collection and drying**. Studies exploring the use of algae as a biomass input for biofuel production have shown that over half of the production cost can stem from drying.¹ This poses a key **trade-off of energy versus land use intensity**. Project economics can improve by either reducing the cost of drying collected microalgae or identifying durable storage or conversion mechanisms that can tolerate high water contents.

Passive drying methods, including solar drying beds or greenhouse drying, reduce energy demand at the cost of slow processing times and increased labor costs. Low-carbon thermal energy sources such as industrial waste heat could reduce costs and embodied emissions at scale.

Novel technologies such as hydrothermal liquefaction into a bio-oil that can be utilized or stored,² or direct surface injection of algal slurries require further study and are more capital expenditure-extensive but would provide promising opportunities to utilize microalgae.

Example KPIs:

- Drying energy <200 kWh/t biomass through passive drying
- Ability to convert biomass with <25% solid content without further drying



Microalgae for biomass hubs

Dried microalgae provides an alternative biomass input to conversion and storage approaches discussed elsewhere in this report, including biomass direct storage, conversion into biochar or bio-oil, and utilization for BECCS projects producing electricity or fuel. Though raceway ponds likely have higher up-front costs and energy needs than waste biomass collection, they **do not require productive, arable land** and have a smaller footprint than dedicated biomass growth. This creates new options for bCDR deployment in regions with limited available agricultural land or forestry activities.

Colocating microalgae production with suitable conversion or storage projects reduces the cost and embodied emissions associated with transportation to the storage site. Microalgae grown in ponds represent a reliable, continuous source of biomass, less affected by seasonal fluctuations in agricultural output and forestry waste production. Mapping local niches with **sufficient energy and water** for microalgae growth, collection, and drying near suitable conversion or storage sites will enable scaled project planning optimizing available resources. Suitable sites may include arid regions for burial or regions with seasonal energy needs that can be supplied with BECCS.

Example KPIs:

- Biomass conversion hub with >50% of annual production supplied from baseload supply of algal biomass
- <5 km transport distance from colocation with raceway ponds



Biomass storage or conversion

Long-term storage of biomass is a key cost driver for stabilized biomass approaches, requiring suppression of microbial decomposition for long periods after project deployment and crediting. Each storage modality — vaulting, injection, dry burial, or conversion into biochar or bio-oil — carries different risks and associated MRV needs. Trade-offs include **complexity in up-front project design**, such as the construction of closed-system storage infrastructure, against **long-term open system monitoring**, such as the identification and measurement of variables confirming biomass stability over time. Contracting and project designs need to incorporate long-term management and monitoring.

Storage costs will vary geographically on local and global scales based on the availability of suitable geological and ecological conditions, unused land, and permitting landscapes. Land-based storage projects, particularly open-system modalities such as arid land burials, also need to navigate **land use and waste classification regulations**, affecting siting decisions and realistic long-term costs. The conversion of algal biomass into products such as biochar or bio-oil, or combustion in a BECCS project, may prove economical depending on achievable biomass quality.

Example KPIs:

- <0.5% annual loss rate confirmed with direct measurements
- >50-year guarantee of biomass monitoring and management
- <2-year permitting timeline with reusable project structure

1. [Economic, Greenhouse Gas, and Resource Assessment for Fuel and Protein Production from Microalgae](#), DOE, 2024. 2. Hydrothermal [Liquefaction: Turning domestic waste and biomass into drop-in fuels, chemical products, and more](#), PNNL.



Advancement and breakthrough areas

Key research areas
Bioengineered microalgae species, modular lower-energy drying technology

Crosscutting bCDR breakthrough themes¹

B2: On-site microreactors

On-site microreactors on boats and algae-processing facilities could turn fast-decaying feedstocks into long-term, durable carbon removal with reduced logistics costs.

B4: Autonomous precision MRV

Automated MRV for microalgae approaches could increase certainty and optimize nutrient dosages during continuous growth and harvesting processes.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Solar-powered drying system to remove water from biomass	Solar drying reduces cost and embodied emissions of energy-intensive biomass drying step before storage or conversion	\$\$ Cost savings from reduced energy usage	Larger existing facilities for retrofitting, future projects		Solar PV engineers / developers, large-scale supply chains for reactor and/or kiln technologies
2	Hub-style deployment colocating ponds with heat sources or biofuel production	Targeting of deployment regions with demand for algae product, industrial waste heat sources, or significant land constraints aiding competition over other biomass approaches improves project LCAs	\$\$\$ Reduced cost from transport proximity, increased revenue from utilization	All future projects		State and local regulators, heavy industry, fuel and material production supply chains
3	Optimized algae species in closed-system cultivation setting	Algal communities selected or modified to improve carbon fixation rates or resistance to pathogens or decomposition can improve efficiency with reduced risks compared with open-system approaches	\$\$ Reduced risk of biofouling, increased capture rates, increased credit generation	All project, existing and future		Marine biologists, botanists, plant disease experts, horticulture supply chains
4	Modular, at-home microalgae pond kits for distributed deployment	At-home microalgae kits integrated into municipal waste systems targeting carbon removals could increase total sustainable biomass supply and divert waste	\$\$\$ Cost savings from reduced infrastructure burden and transport consolidation	Future, single-home deployments		Horticulture supply chains and manufacturers, WM companies, local regulators
5	Microalgae species with harvestable component	Cultivable species modified and selected to produce carbon-dense biomass structures outside the living cells could ease growth and harvesting and reduce nutrient needs	\$\$ Reduced cost from efficiency of feedstock and reduced harvest	All future projects, adoption into existing operations		Marine biologists, botanists, horticulture supply chains

\$ \$1–\$30/tCO₂

\$\$ \$20–\$50/tCO₂

\$\$\$ \$40–\$100/tCO₂

\$\$\$\$ \$75–\$300/tCO₂

1. See [page 21](#) for more detail on crosscutting opportunities for breakthroughs in biogenic CDR, including assessments of the technical and social difficulty of implementation.



Microalgae in Open Water

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 2.7: Microalgae cultivated in open water and sunk

DEFINITION

The process of sinking phytoplankton in open water environments by leveraging either the natural processes of oceanic circulation or via bioengineered components that expedite microalgae export to deep ocean environments for long-term storage.

APPROACH OVERVIEW

The concept of leveraging fast-growing microalgae species for deep ocean carbon storage was born from the process of ocean iron fertilization, which was first proposed in the 1980s and involves adding iron-rich compounds to ocean water to spur phytoplankton growth. After 40 years of research and experimentation, new ventures are now exploring how to control the environmental impacts of traditional ocean iron fertilization (OIF) by eliminating direct addition of iron in favor of engineered carbon capsules that improve long-term storage in deep water environments. However, major questions remain around removal durability, social acceptance, and ecological / biological impact, making the future of the approach, and its deployment capacity, uncertain.

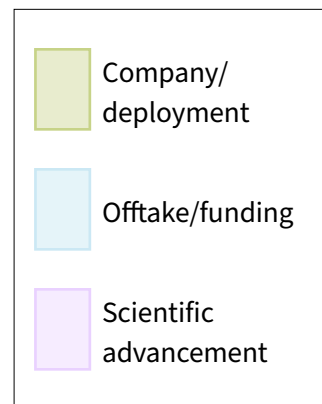
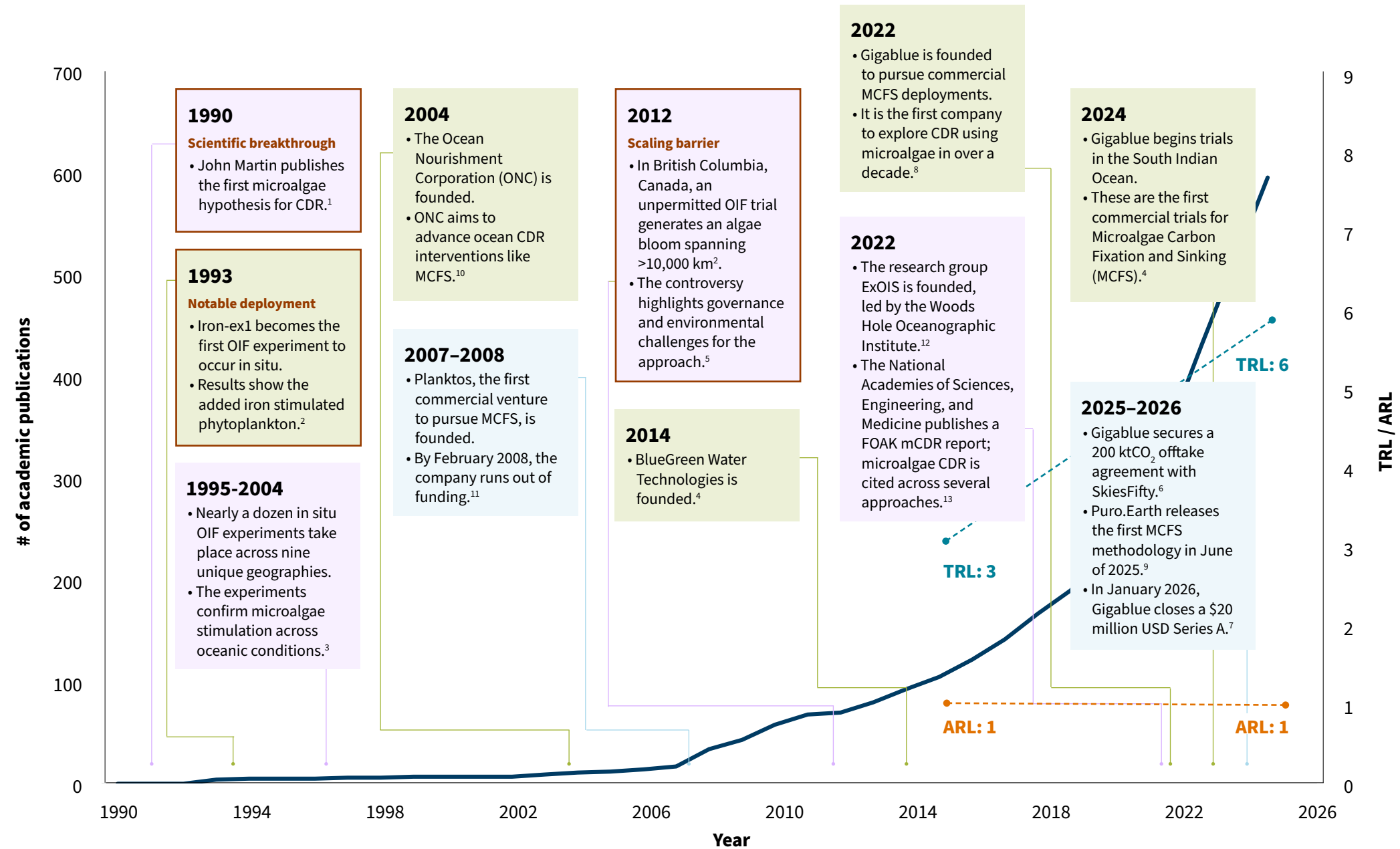


How we got here

Status: Expected progress toward initial field trials

Approach trend: Challenging

Milestones selected for the graph were chosen based on their impact on and significance to the MCFS and OIF sectors.



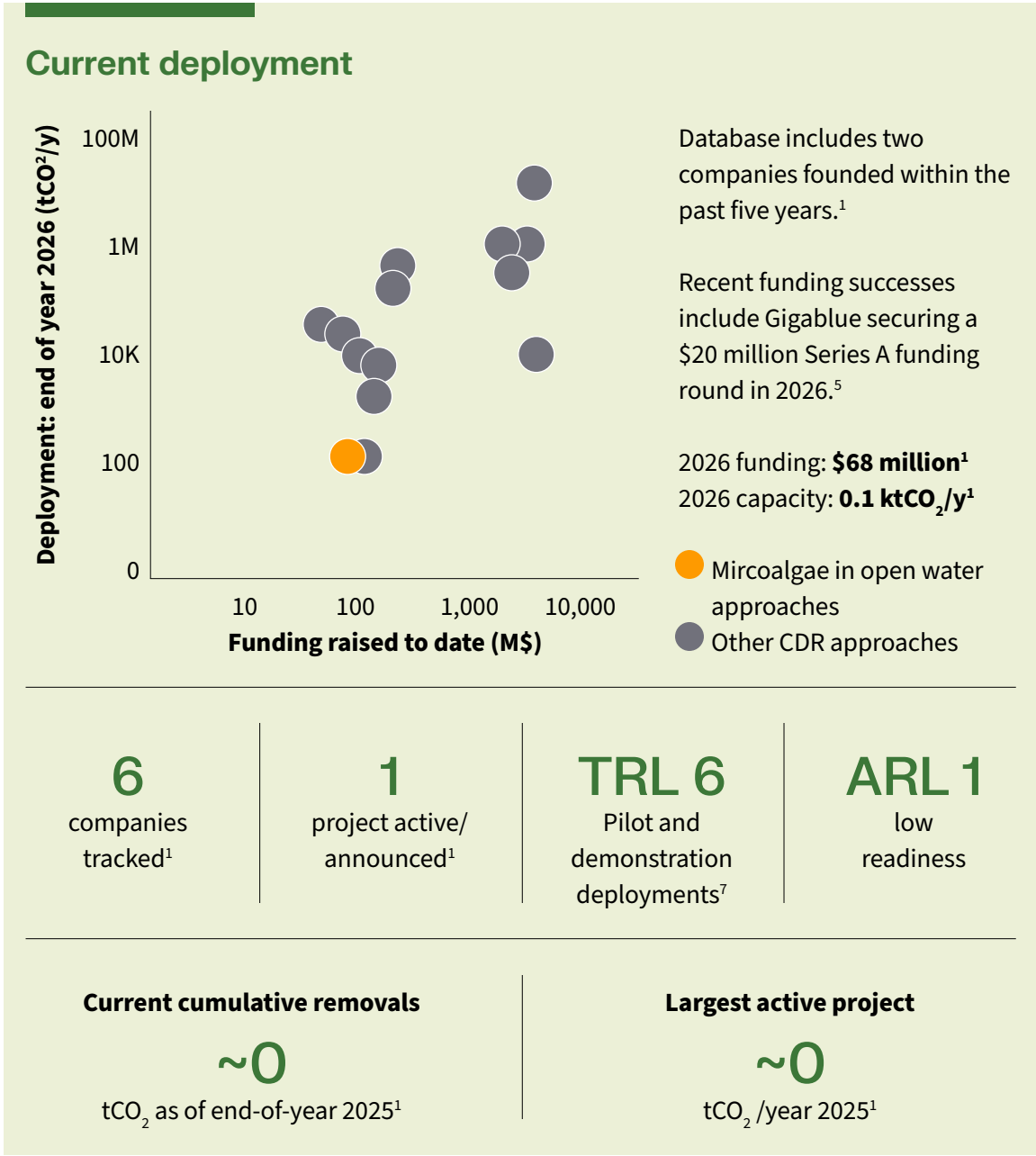
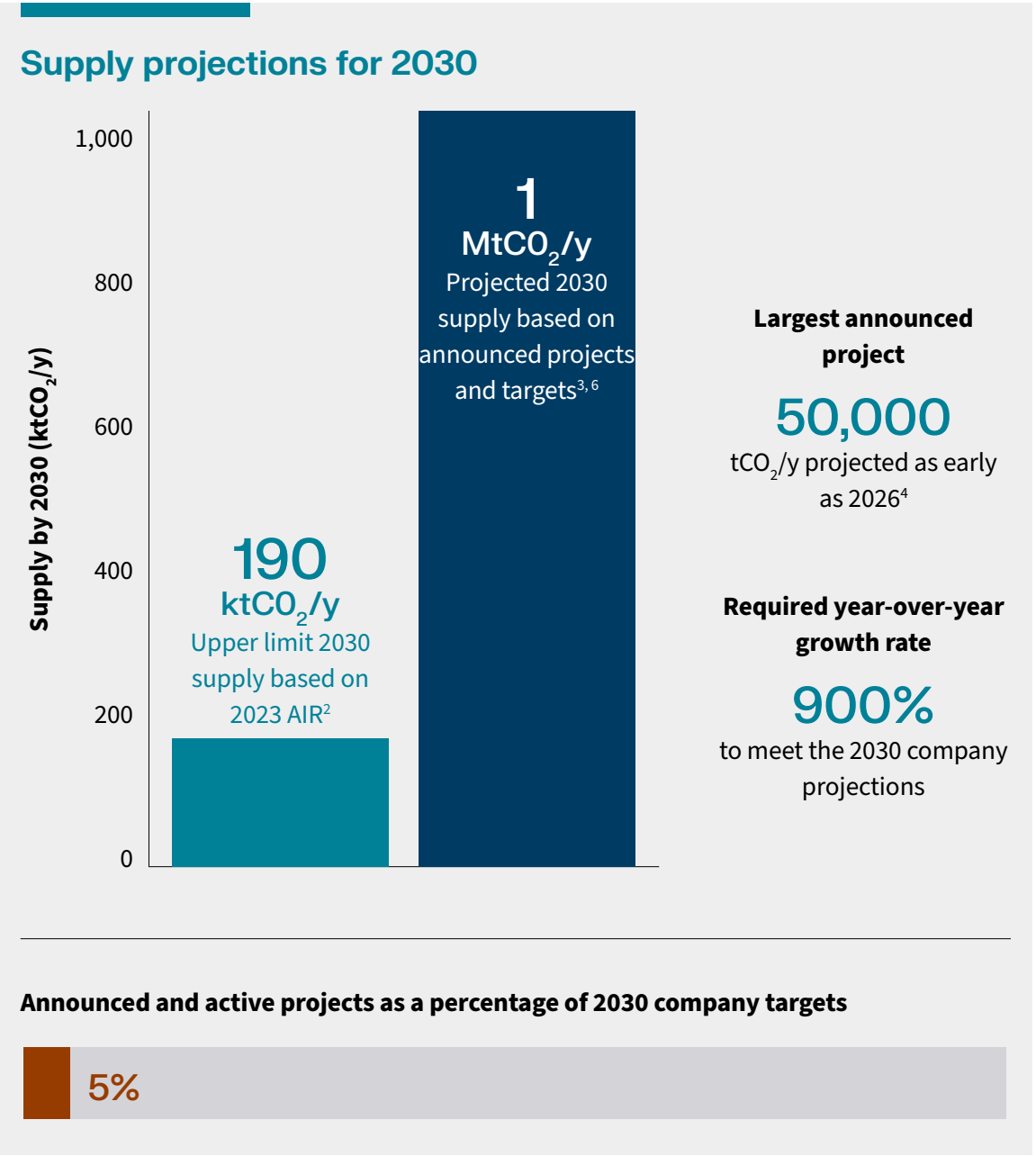
1. J.H. Martin, "Glacial - Interglacial CO₂ change: The iron hypothesis," *Paleoceanography*, 1990. 2. K. Coale et al., "IronEx-I, an in situ iron-enrichment experiment: Experimental design, implementation and results," *Deep Sea Research Part II: Topical Studies in Oceanography*, 1998. 3. H. de Baar et al., "Synthesis of iron fertilization experiments: From the Iron Age in the Age of Enlightenment," *Journal of Geophysical Research*, 2005. 4. [BlueGreen Water Technologies: Company Profile, LinkedIn](#). 5. J. Tollefson, "Ocean-fertilization project off Canada sparks furor," *Nature*, 2012. 6. "Gigablue Signs The Largest mCDR Deal To Date With SkiesFifty," *Carbon Herald*, 2025. 7. "Gigablue Announces \$20 Million Series A First Close at Davos 2026," Gigablue, 2026. 8. [Gigablue - 2026 Company Profile, Team, Funding & Competitors](#), Tracxn. 9. "Microalgae Carbon Fixation and Sinking methodology Public consultation draft v.0.1," Puro.Earth, 2025. 10. [About Ocean Nourishment | Mission, History & Leadership](#). 11. R. Courtland, "Planktos dead in the water," *Nature*, 2008. 12. [Our Work - Exploring Ocean Iron Solutions](#), ExOIS. 13. "A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration," *National Academies of Sciences, Engineering, and Medicine*, 2022.



Current and projected state of deployment

Past 5 years
Initial field trials and early deployments have shown promise, but scientific questions remain

Next 5 years
With the first methodology approved, focus shifts to trials, FOAK deployments, and regulations



1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference capacity of 190 ktCO₂/y in 2030 is aligned with near-term growth in the EOA “success story” in [The Applied Innovation Roadmap for CDR](#), RMI, 2023 (p. 108). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. “New ocean carbon capture projects aim to remove thousands of tons of CO₂,” *Tech Brew*, 2025. 5. “Gigablue Signs The Largest mCDR Deal To Date With SkiesFifty,” *Carbon Herald*, 2025. 6. Gigablue has indicated it expects to reach 1 MtCO₂/y in removals by 2028, with a pathway to 500 MtCO₂ in cumulative removals by 2035, with major scale-up through the end of this decade. This justifies the massive increase in deployment, given no major projects are currently online. Gigablue is a leader in microalgae sinking in open ocean, responsible for the first puro methodology for MCFS and pioneering a unique carbon capsule approach that expedites phytoplankton export to deep-ocean environments. 7. This TRL is reflective of discrepancies between ocean iron approaches and more engineered deployments like Gigablue’s MCFS methodology. MCFS is likely higher than TRL 6, while OIF is likely lower.



Key cost drivers

Major cost drivers

Capex and energy costs for marine deployments

Improvement areas

Demonstrated efficacy, integration into existing industries

Today: 290–\$780/tCO₂

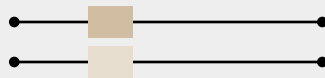
Future: \$90–\$170/tCO₂

60%–80% cost reduction possible via integration, automation, and improved deployment efficiency.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

2. Due to lack of existing or scaled deployments, current prices for microalgae in open water removal approaches vary dramatically, with estimates exceeding \$1,000/tCO₂.

Today's cost range (0-200, \$/tCO₂)
Future cost range (0-200, \$/tCO₂)



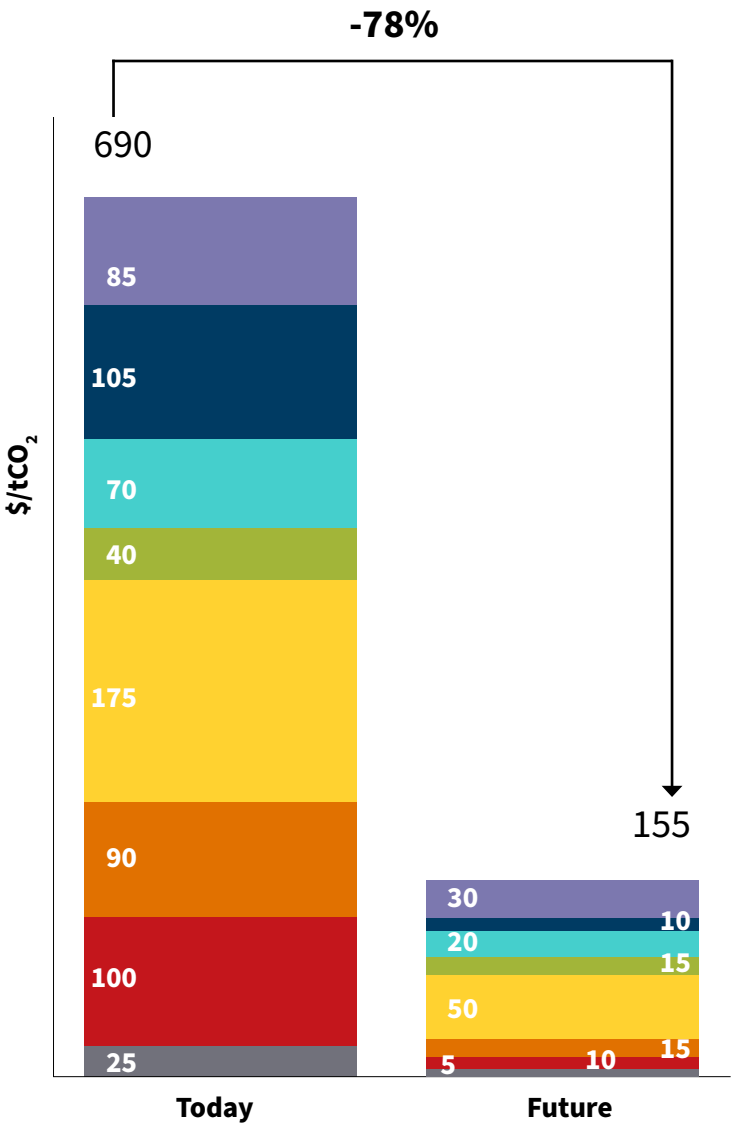
Key cost considerations
for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex • [range] • • [range] •	Marine infrastructure, nutrient dispersal systems, sensor arrays, permitting	Integration into existing infrastructure (e.g., shipping), economies of scale
Energy • [range] • • [range] •	Vessel fuel for dispersal and monitoring, pumping energy (for upwelling approaches)	Electrification, integration into existing processes (e.g., shipping)
Feedstock • [range] • • [range] •	Fertilizer compounds, flocculants/ballast	Improved efficiency of dispersal and uptake
Transport • [range] • • [range] •	Feedstock transport to deployment site, marine logistics	Improved efficiency through hub-style deployment or integration into existing processes
O&M • [range] • • [range] •	Ship crew and operations, maintenance, feedstock handling, sampling, ongoing regulatory compliance	Improved efficiency, centralized operations, modular dispersal infrastructure, automation
Storage • [range] • • [range] •	Sequestration durability, risk buffers	Reduced uncertainty from fate modeling as basic science and knowledge from initial tests advance
MRV • [range] • • [range] •	Ship-based sampling, lab analysis, deep-sea verification, satellite data collection	Automated sampling and remote monitoring, improved ocean system modeling
Embodied Emissions • [range] • • [range] •	Ship fuel combustion, production of fertilizer compounds, equipment manufacturing	Electrification, increased project lifetime

Note about cost stacks¹

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- Advancements in the basic science of microalgae fertilization, including the fate of carbon and understanding of ecosystem impacts, alongside data from small-scale tests are needed to inform achievable per-ton costs at scale.



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Open-water deployments with public acceptance and responsible governance

Where to start: Ocean systems science and governance models to determine the possibility of scaled deployment



Governance considerations

Microalgae cultivation through nutrient dispersal in the open ocean remains a largely theoretical approach to carbon removal,¹ with only a **small number of field trials** performed and no significant verification of carbon impacts. More indirect approaches, such as artificial upwelling and downwelling induced by pumps redistributing ocean nutrients, are at an even lower level of scientific and technological readiness.²

Ocean-based activities have the potential to affect ecosystems in international waters or have downstream **impacts on communities across borders**, making their governance a key factor in innovation. International advisory groups currently recommend against commercial deployment of microalgae in open water. Governance frameworks guided by core principles of precaution, prevention, due diligence, and careful environmental impact assessments are needed to direct and enable even small-scale field testing.^{3,4}

Deployment and testing by rogue actors in the absence of clear governance frameworks and buy-in from local and impacted communities will not lay the groundwork for responsible deployment and instead has resulted in major global pushback against further study.

Example KPIs:

- Clarified international governance and project-specific permitting pathways in place before testing/deployment
- 100+ year durability for converted macroalgae biomass



Automation and modularization

If large-scale microalgae sinking proves to be a viable approach for responsible scaled CDR deployment, automation and modularization would significantly reduce costs. Advances from related industries such as **shipping, aquaculture, offshore energy projects, and maritime robotics** can provide efficiency improvements and inform optimization of deployment logistics.

Standardized, modular cultivation systems and integration into existing shipping activities rather than deployment of dedicated vessels would significantly reduce costs. Automation of processes such as monitoring of deployment rates, ocean systems, and local environmental factors such as nutrient levels would pose up-front costs but provide valuable data for MRV and safety monitoring. It would also inform target deployment regions based on locally specific factors affecting viability and cost.

However, these advancements first **require foundational scientific advancement on approach viability and safety** and are unlikely to pose key bottlenecks to deployment in the next five years.

Example KPIs:

- <72-hour data updates on monitoring of biomass growth, ocean conditions, and infrastructure integrity
- Small-scale projects demonstrating engineering validity



Ocean models

Robust ocean modeling remains a foundational scientific pillar for the potential of deploying microalgae-based carbon removal. This especially applies to approaches sequestering carbon within ocean systems, such as by microalgae cultivation and sinking or artificial upwelling, to understand the long-term fate of carbon in sunk biomass, interactions with ocean currents and siting decisions, and impacts on local ecosystems from nutrient withdrawal. However, approaches based on cultivating and harvesting macroalgae also require understanding of downstream ecological impacts of nutrients removed from ocean ecosystems from cultivation.

Key modeling needs include tracking vertical carbon transport, remineralization rates, and upwelling potentials for carbon having reached the deep ocean. Ecosystem impact modeling considering nutrient cycles, light availability, and marine food webs is needed to ensure safe, responsible deployment and inform unresolved questions on regulations and international governance concerns related to open ocean deployments.³ For projects ranging from small field trials to scaled deployment, measurement-informed modeling approaches will be key to monitor climate benefits as well as ecological safety.

Example KPIs:

- <20% uncertainty in net CO₂ removed on 100+ year timescale
- <20% nutrient drawdown relative to baseline seasonal levels to ensure ecological safety

1. Though this report focuses on technological and process innovations, it is important to note that public acceptance and successful governance remain key for responsible CDR deployment, particularly open-system approaches such as MAE. For some additional discussion of this topic, see Section 6: Microalgae in Open Water. **2.** For more detail on proposed global research efforts on the feasibility, suitability, and risks of macroalgae sinking see [Macroalgae Cultivation & Sinking for Carbon Sequestration](#), Ocean Visions, 2022. **3.** F. Idoko et al., “[Exploring the role of IoT, AI, and remote sensing in precision aquaculture: Monitoring, automation, and data-driven decision-making](#),” Magna Scientia Advanced Biology and Pharmacy, 2025. **4.** The Sabin Center for Climate Change Law is building expertise on governance concerns related to CDR deployment in the ocean. Recent publications include S. Vican et al., [The Role of Marine CO₂ Removal in Combating Climate Change](#), Columbia Law School Scholarship Archive, 2025.



Advancement and breakthrough areas

Key research areas

Ecosystem impacts to OIF, automated dosing, microalgae carbon cycle duration/removal durability

1. See page 21 for more detail on crosscutting opportunities for breakthroughs in biogenic CDR, including assessments of the technical and social difficulty of implementation.

2. This and other research priorities for microalgae carbon removal processes are described in further detail in [Microalgae Roadmap](#), Ocean Visions, 2024.

Crosscutting bCDR breakthrough themes¹

B1: Enhanced cultivars for high-carbon-storage applications

Genetically enhanced microalgae, such as a species capable of autonomous sinking triggered by size / maturity, could improve operational logistics and reduce labor and transport.

B4: Autonomous precision MRV

Autonomous sampling for microalgae approaches would lower labor costs and improve clarity around long-term storage by tracking microalgae blooms and dispersal.

B5: Synthetic biology for non-photosynthetic CO2 capture

Accompanying fertilization solutions that are used to stimulate natural growth, the incorporation of microbes that increase carbon fixation ability.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Established models of long-term impacts on GHGs and local ecosystems	Establish consensus of complex ocean models needed to predict long-term carbon fates and counterfactual baselines , including fraction of sunk microalgae that settles into ocean sediment	\$\$ Reduced MRV costs, informed siting and timing for responsible deployment, increased creditability	All projects		Academics including ocean biogeochemical scientists, ecologists, MRV platform developers, carbon registries and standards bodies, regulators, impacted communities
2	Integration into shipping vessels or other existing marine activities	Save capital expenditure and operational costs by fitting deployment equipment onto vessels already traveling across suitable sites	\$\$\$ Reduced capital expenditures, vessel, and labor costs, reduction in dedicated fuel usage from optimized integration	Seeding		Shipping industry stakeholders, project developers, engineering firms, ocean biogeochemical scientists, regulators
3	Improved design of deployment and monitoring processes ²	Based on basic science advancements, develop efficient, scalable fertilizer dispersal or pumping systems proven via field tests, as well as increasingly automated sensing equipment	\$\$ Increased efficiency, lower project risk	All (dispersal for seeding, pumps for upwelling)		Project developers, engineers, ocean biogeochemical scientists, carbon registries and standard bodies, regulators
4	Remote sensor and monitoring systems	Combine satellite data, real-time remote water sensing, and understanding of ocean system models to track carbon and other ecosystem impacts to improve safety, MRV efficiency, and certainty of removals	\$\$ Reduced need for ship-based sampling, improved certainty and understanding of impacts and safety	All projects		Project developers, sensor manufacturers, remote sensing companies, carbon registries and standard bodies, regulators
5	Microalgae-mineral co-flocculation treatments for efficient sinking	Development of environmentally safe treatments, potentially mineral-based, that encourage aggregation of microalgae for more efficient sinking and improved storage	\$\$ Improved sinking and storage, accelerated operations	All projects		Marine biologists, phytoplankton ecologists, mineral suppliers, environmental toxicologists, fisheries managers, ocean regulators, coastal and Indigenous communities

\$ \$1–\$30/tCO₂ \$\$ \$20–\$50/tCO₂ \$\$\$ \$40–\$100/tCO₂ \$\$\$\$ \$75–\$300/tCO₂



Macroalgae in Open Water

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 2.8: Macroalgae cultivated in open water and sunk

DEFINITION

Enhancing macroalgae growth either in cultivated algae farms or in the open ocean, followed by sinking the biomass in the open ocean in benthic environments where decomposition dramatically slows.

APPROACH OVERVIEW

Macroalgae sinking emerged in the late 2010s with significant momentum. The first commercial enterprise was founded in 2017; by 2023, initial FOAK projects had been deployed. However, as of 2024, the sector saw its largest company close operations, leaving remaining ventures to grapple with questions around permanence and environmental impact. Despite these challenges, a suite of macroalgae companies is beginning initial deployments and working to clarify uncertainties, with the goal of storing macroalgae in deep-sea environments and long-lived products (e.g., biochar and building products).

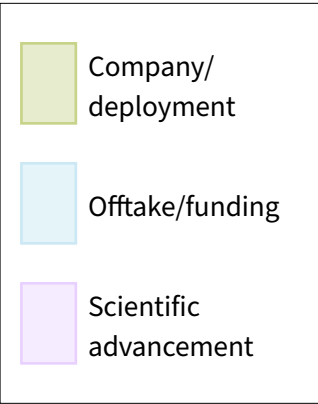
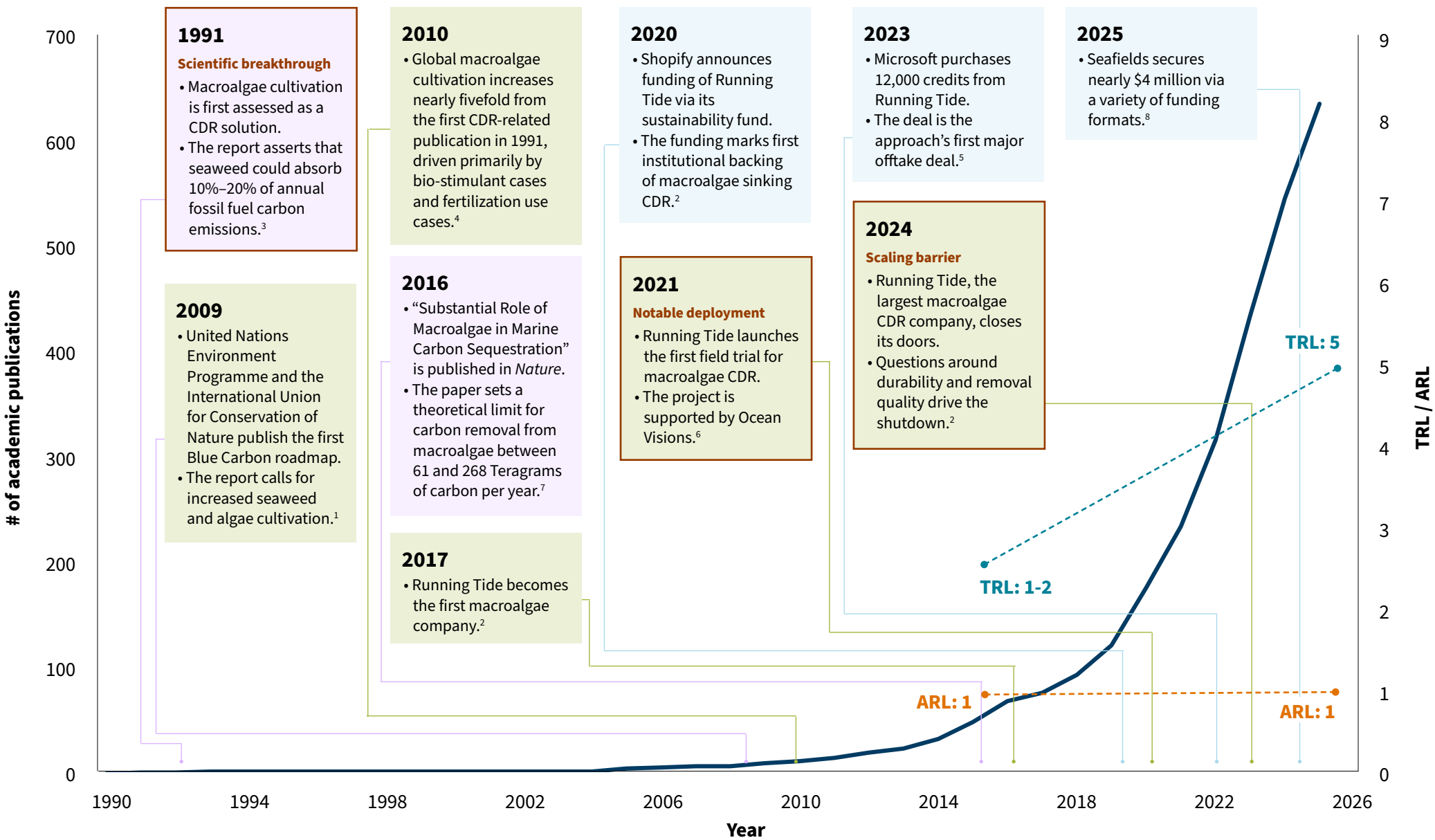


How we got here

Status: Recent setbacks during pilot-scale deployment

Approach trend: Challenging

Milestones selected for the graph were chosen based on their impact on and significance to the macroalgae cultivation and sinking sectors.



1. “Blue Carbon Report - The Role of Healthy Oceans in Binding Carbon,” United Nations Environment Programme, 2009. 2. “Under the sea: Running Tide’s ill-fated adventure in ocean carbon removal,” Canary Media, 2024. 3. E.P. Glenn et al., “Seaweeds and halophytes to remove carbon from the atmosphere,” Electric Power Research Institute, 1991. 4. “Fishery and Aquaculture Statistics,” Food and Agriculture Organization of the UN, 2010. 5. “Running Tide Becomes Microsoft’s First Open Ocean-Based Carbon Removal Supplier,” PR Newswire, 2023. 6. “Running Tide Technologies Overview,” Ocean Visions, 2021. 7. D. Krause Jensen et al., “Substantial role of macroalgae in marine carbon sequestration,” *Nature Geoscience*, 2016. 8. “Seafields Is Gathering Funds To Turn Coastal Seaweed Crisis Into A CDR Solution,” *Carbon Herald*, 2025.



Current and projected state of deployment

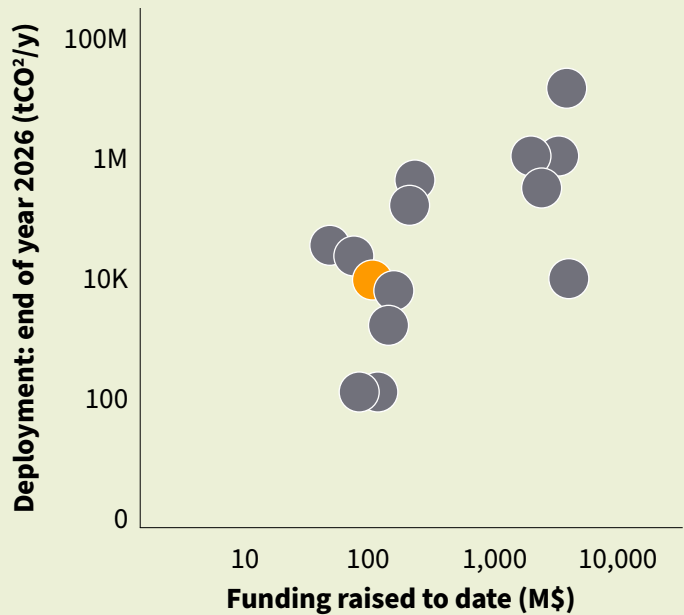
Past 5 years

After winning initial offtake and investment, macroalgae sinking faced significant setbacks

Next 5 years

Remaining companies are cautiously preparing to scale to FOAK demonstration projects

Current deployment



14

companies tracked¹

7

projects active/
announced¹

TRL 5

Initial field
trials and pilot
deployments

ARL 1

low readiness

Current cumulative removals

42,500

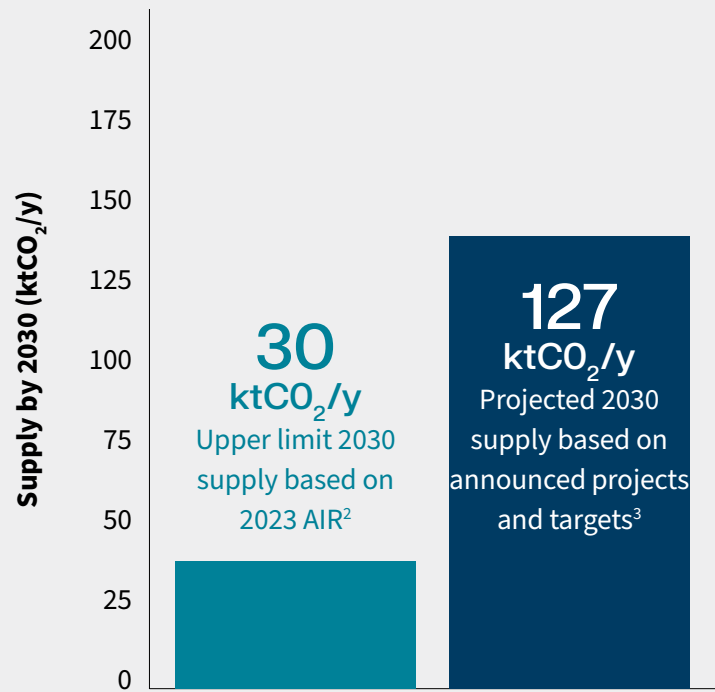
tCO₂ as of end-of-year 2025¹

Largest active project

~5,000

tCO₂ /year 2024–25⁵

Supply projections for 2030



Largest announced project

7,500

tCO₂/y projected as early as 2026⁴

Required year-over-year growth rate

~78%

to meet the 2030 company projections

Announced and active projects as a percentage of 2030 company targets

10%

1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference capacity of 30 ktCO₂/y in 2030 is aligned with near-term growth in the EOA “success story” in *The Applied Innovation Roadmap for CDR*, RMI, 2023 (p. 118). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years 4. “Seafields is gathering funds to turn coastal seaweed crisis into a CDR solution,” *Carbon Herald*, 2025. 5. “Pilot project sends kelp—and carbon—to the seafloor,” *IEEE Spectrum*, 2023. 6. *Newsletter #18, Climate Foundation*, 2025.



Key cost drivers

Major cost drivers
Labor intensity, manual sampling and verification

Improvement areas
Ecosystem and carbon impact modeling, modularization

Today: \$710–\$1,300/tCO₂
Future: \$190–\$400/tCO₂

50%–75% cost reduction possible via improved understanding of impacts and durability from ocean modeling, modularization, and automation.

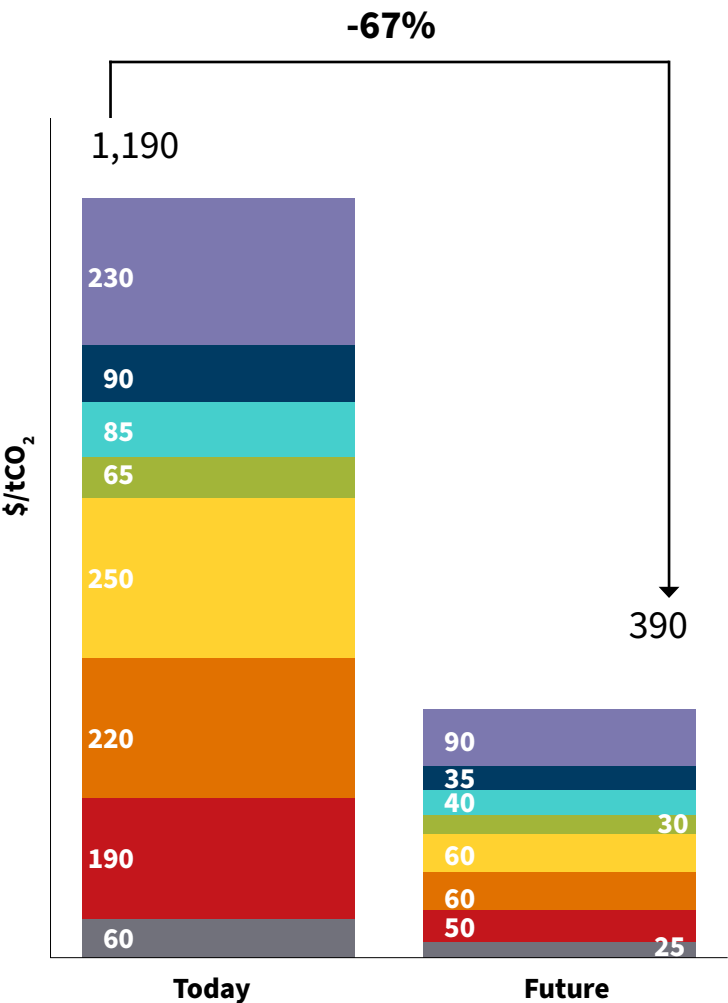
1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

Today's cost range (0-275, \$/tCO ₂) Future cost range (0-275, \$/tCO ₂)			Key cost considerations for scaled deployment (see next page for details)		
Cost (\$/tCO ₂)	Contributors		Improvement potentials		
Capex	Offshore infrastructure and equipment including moorings, floating cultivation structures, vessels, staging facilities		Modular designs, autonomous deployment platforms with integrated sensors, shared shore hubs		
Energy	Vessel fuel, platform power, handling and sinking equipment energy		Electrified autonomous equipment, direct solar power supply for platforms, passive sinking methods		
Feedstock	Frequently replaced materials on cultivation platforms, ballast, possibly nutrient supplements		Durable cultivation materials designed for reuse, optimized ballast strategies		
Transport	Transport of materials to and from ports, crew logistics, seasonal equipment repositioning		Centralized hubs, optimized and localized material supply chains		
O&M	Labor costs for offshore deployment, maintenance, repairs, and monitoring		Remote monitoring, predictive maintenance for modular systems		
Storage	Sinking operations, contribution to permanence buffer pool, regulatory and permitting compliance		Passive engineered sinking designs, improved understanding of long-term fate of carbon from ocean modeling		
MRV	Manual sampling of biomass, deep-ocean storage verification		Continuous on-platform sensing, integration of satellite modeling data, reduced verification frequency at scale		
Embodied Emissions	Platform materials and manufacturing, vessel fuel emissions		Lightweight materials, electrification, durable components designed for reuse		

Note about cost stacks¹

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- Efficient, scaled deployment of sinking- or harvesting-based approaches requires demonstration of long-term carbon sequestration without negative impacts on benthic ecosystems related to nutrient cycling or anoxic conditions.
- Projects based on active management of living biomass avoid storage/harvesting costs but require careful consideration of counterfactual baseline scenarios.



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Open-water deployments with public acceptance and responsible governance¹

Where to start: Ocean systems science and governance models to determine the possibility of scaled deployment



Governance considerations

Carbon removals can be deployed by **managing living macroalgae blooms that would otherwise decompose**. This can be done either by harvesting macroalgae and converting the carbon into durable products or sinking macroalgae into deep ocean environments, preventing decomposition. Each pathway presents trade-offs in cost, durability, MRV complexity, and possible co-benefits.

Ongoing management in surface waters has the lowest immediate costs but requires careful consideration of counterfactual baselines and durability. **Harvesting and conversion into biochar** or other long-lived materials offer simplified MRV and certainty of durable sequestration at the cost of increased processing and infrastructure needs. **Deep ocean sinking** offers a low-cost durable storage modality at scale, but uncertainties around long-term carbon fate and ecological impacts require further study.² Clarified permitting pathways will be needed to enable deployment of sinking methods at scale, particularly in the open ocean.

Early projects benefit from hybrid models where CDR is deployed alongside the sale of algae-based products to support up-front costs.

Example KPIs:

- 50% of biomass allocated dynamically across CDR and product sales based on changing market conditions
- 100+ year durability for converted macroalgae biomass



Automation and modularization

If large-scale sinking proves to be a viable approach for responsible, scaled CDR deployment, **automation and modularization would significantly reduce costs**. Advances from related industries such as aquaculture, offshore energy projects, and maritime robotics can provide efficiency improvements and cost savings for labor-intensive macroalgae farming practices.

Standardized, modular cultivation systems, such as longlines or floating platforms, could be mass produced and deployed across a variety of project sites, enabling rapid scale-up and shared learnings across projects, alongside simplified permitting, construction, and maintenance.³

Automation of processes such as ballast attachment, towing, and monitoring of cultivation progress could significantly lower project costs at scale, especially for projects deployed far from shorelines. Safe and effective automation will require **remote sensing and monitoring of key environmental and operational factors** such as growth rates, system integrity, oxygen levels, and any changes in nutrient availability. Up-front costs of complex monitoring systems offer trade-offs against reduced O&M and MRV costs.

Example KPIs:

- <72-hour data updates on monitoring of biomass growth, ocean conditions, and infrastructure integrity
- Small-scale projects demonstrating engineering validity



Ocean models

Robust ocean modeling remains a foundational scientific pillar for the potential of scaling macroalgae-based carbon removal. This especially applies to approaches sequestering carbon within ocean systems, such as by macroalgae sinking, which require an in-depth understanding of the long-term fate of carbon in sunk biomass, interactions with ocean currents and siting decisions, and impacts on local ecosystems from nutrient withdrawal. However, approaches based on cultivating and harvesting algae also require understanding of complex ocean systems to understand downstream climate and the ecological impacts of nutrients removed from ocean ecosystems.

Key modeling needs include tracking vertical carbon transport, remineralization rates, and upwelling potentials for carbon having reached the deep ocean. Additionally, ecosystem impact modeling considering nutrient cycles, light availability, and marine food webs is needed to ensure safe, responsible deployment and inform unresolved questions on regulations and international governance concerns related to open ocean deployments.⁴ For projects ranging from small field trials to scaled deployment, **measurement-informed modeling approaches** will be key to monitor climate benefits as well as ecological safety.

Example KPIs:

- <20% uncertainty in net CO₂ removed on 100+ year timescale
- <20% nutrient drawdown relative to baseline seasonal levels to ensure ecological safety

¹. There is geological evidence for large microalgae sinking events, such as the Azolla events 49 million years ago, having caused significant global cooling. Events of such significant scale caused major disruptions to Earth systems. The science of how to reliably implement carbon sequestration through microalgae-based mechanisms in the open ocean, and what the marginal impact of a given deployment scale on the climate is, requires further research. ². For an accessible overview of microalgae-based CDR approaches, see [Microalgae Cultivation and Artificial Upwelling and Downwelling](#), Ocean Visions, 2023. ³. K. Silverman-Roati and R. Webb, “[International Legal Guidelines for Marine Carbon Dioxide Removal Governance under the London Convention and London Protocol](#),” Sabin Center for Climate Change Law, 2025. ⁴. For a more detailed exploration of outstanding needs for the exploration of microalgae-based CDR approaches, including social and governance considerations, see [Microalgae Roadmap](#), Ocean Visions, 2024.



Advancement and breakthrough areas

Key research areas
Automated sinking, harvesting, and monitoring technology, genetically modified algal strains

1. For R&D strategies addressing algae strain development, molecular biology toolkits, and ecosystem dynamics, see [Mapping the Path Forward to Next Generation Algal Technologies](#), U.S. DOE Office of Scientific and Technical Information, 2020.

2. See [page 21](#) for more detail on crosscutting opportunities for breakthroughs in biogenic CDR, including assessments of the technical and social difficulty of implementation.

Crosscutting bCDR breakthrough themes¹

B1: Enhanced cultivars for high-carbon-storage applications

Genetically enhanced microalgae species that have elevated photosynthetic rates would improve baseline capture efficiency and reduce land use for similar removal capacity.

B2: On-site microreactors

On-site pyrolysis at cultivation facilities would improve the transport costs and emissions for the operation while also improving durability and quality of the associated removals.

B4: Autonomous precision MRV

Automation of microalgae cultivation in ponds could reduce labor costs and operational overhead, creating more feedstock for biochar or utilization in microalgae-based products.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Modular platforms for seaweed cultivation	Standardized offshore components would reduce capex and maintenance costs through simplified project planning and maintenance . Bio-based cultivation materials could be sunk alongside cultivated algae.	\$\$ Reduced capex and maintenance, predictive repair schedules, lower project risk from proven designs	All projects (sinking, harvesting, and management)		Offshore project and aquaculture engineering firms, project developers, marine construction contractors, marine certification bodies
2	Established models of long-term impacts on GHGs and local ecosystems	Established consensus of complex ocean models is needed to predict long-term carbon fates and counterfactual baselines , including avoided methane emissions and any competition for nutrients	\$\$\$ Lower MRV costs, impact and safety data reduce need for additional long-term field campaigns	All, particularly sinking and management		Academics including ocean biogeochemical scientists, ecologists, MRV platform developers, carbon registries and standards bodies, regulators, impacted communities
3	Automated equipment for cultivation, harvesting, sinking, and monitoring	Significant reduction in labor costs for deployment and/or measurement and verification at scale, reduced frequency of required trips to project site	\$\$\$\$ Reduction in labor and vessel costs, reduced number of trips, increased project uptime	All projects (sinking, harvesting, and management)		Marine robotics and remote vessel developers, aquaculture engineering firms, sensor manufacturers, remote sensing companies
4	Identification of regionally optimized strains of macroalgae ¹	Efficiency improvements achieved by selecting macroalgae species ideal for project's local environmental conditions (e.g., habitat co-benefits, improved growth rates) could reduce costs and increase possible deployment range	\$ Improvement in carbon removal efficiency, global capacity increase from increased deployment range	All projects (sinking, harvesting, and management)		Marine biologists, genomics and synthetic biology scientists, aquaculture companies, marine conservation scientists
5	Genetic modification of specific algal strains for ideal CDR properties	Research and advancements create specialized algae species that are without buoyancy or natural decomposition properties	\$\$ Cost savings from sinking process components and increased durability of removals	All projects (sinking, harvesting, and management)		Marine biologists, genomics and synthetic biology scientists, seed developers and OEMs, RD&D funders, government research labs

\$ \$1–\$30/tCO₂ \$\$ \$20–\$50/tCO₂ \$\$\$ \$40–\$100/tCO₂ \$\$\$\$ \$75–\$300/tCO₂



BECCS to Electricity

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 3.1: BECCS to Electricity

DEFINITION

Thermal conversion of biomass (either dedicated feedstock or waste) to generate electricity and produce CO₂, which is then captured with CCS technology.

APPROACH OVERVIEW

Built on the foundation of incumbent technologies, namely, waste-to-energy powerplants, biomass power plants that sell electricity to the grid, and those that produce on-site electricity at pulp and paper mills, BECCS to Electricity operations emerged as the adoption of CCS technologies became more widespread. Many of the companies delivering kiloton-scale removals in 2026 were founded in the past 15 years. The sector continues to see steady growth, particularly for alternative power generation at community scale across Europe, with strong support from European governments. By 2030, the sector could remove as much as 10 MtCO₂ per year.

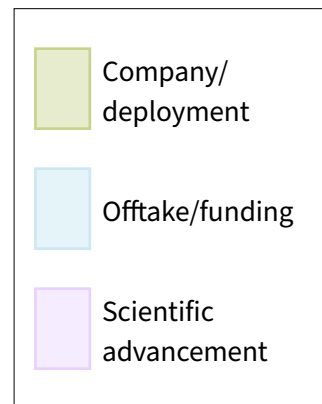
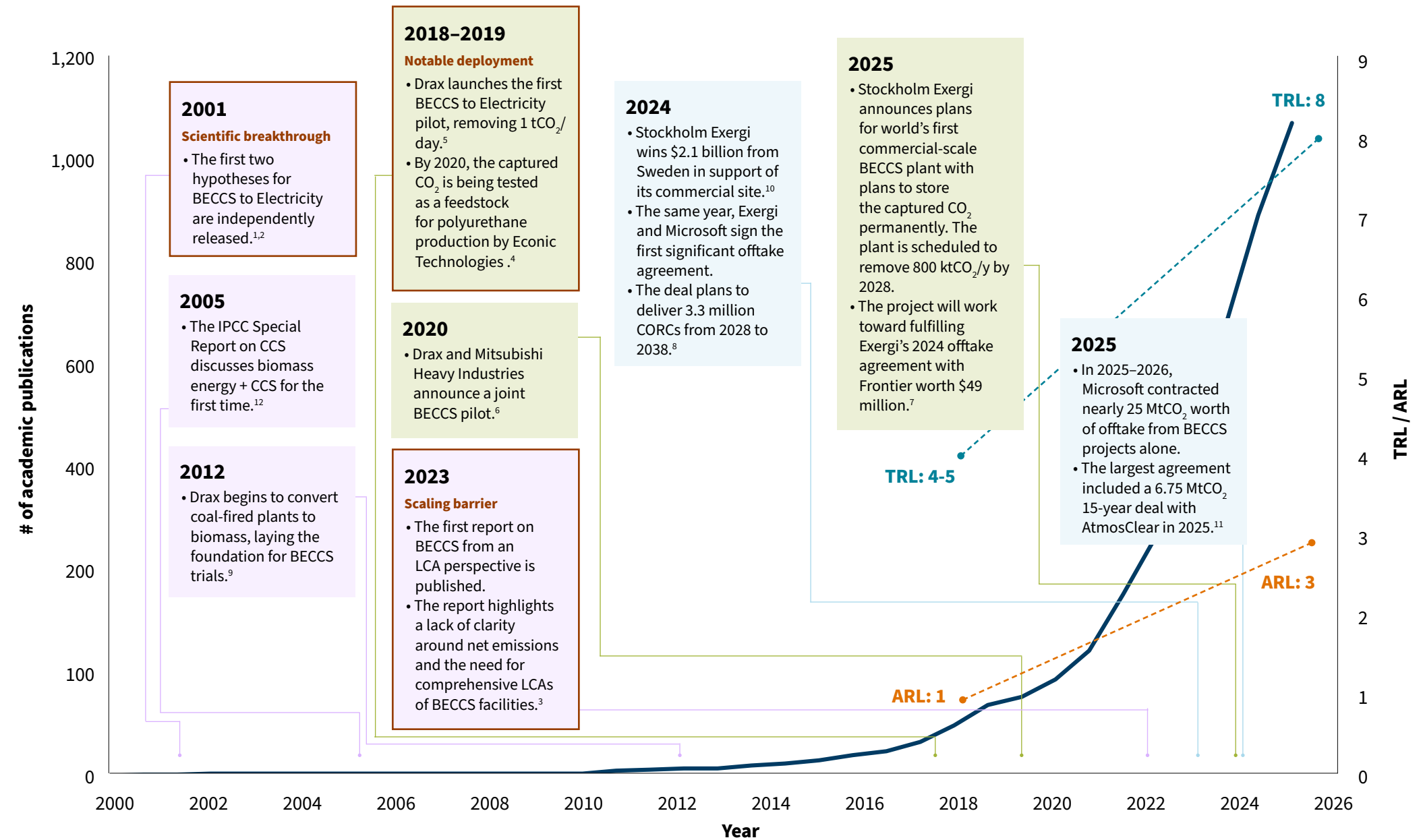


How we got here

Status: Expected progress toward commercial-scale deployment

Approach trend: Positive

Milestones selected for the graph were chosen based on their impact on and significance to the MCFS and OIF sectors.



1. D. Keith, "Sinks, Energy Crops and Land Use: Coherent Climate Policy Demands an Integrated Analysis of Biomass," *Climatic Change*, 2001. 2. M. Obersteiner et al., "Managing climate risk," *Science*, 2001. 3. Wang et al., "Can bioenergy with carbon capture and storage deliver negative emissions? A critical review of life cycle assessment," *Journal of Cleaner Production*, 2024. 4. "Negative emissions pioneer Drax announces new CCUS projects during Energy Minister's visit," Drax Global, 2020. 5. "Europe's first bioenergy carbon capture and storage pilot now underway," Drax Global, 2018. 6. "Negative emissions pioneer Drax and leading global carbon capture company - Mitsubishi Heavy Industries Group - announce new BECCS pilot," Drax Global, 2020. 7. "Final Investment Decision - Stockholm Exergi moves ahead with world's first large-scale BECCS using Capsol's carbon capture technology," Capsol Technologies, 2025. 8. "Stockholm Exergi and Microsoft sign the world's largest agreement to date for permanent negative emissions," Stockholm Exergi, 2024. 9. "Coal to Bioenergy with Carbon Capture and Storage, Drax Power Station," World Economic Forum, 2023. 10. "SEK 20 billion to capture and store over 11 million tons of biogenic carbon dioxide," Swedish Energy Agency, 2024. 11. "Fidelis' AtmosClear signs agreement with Microsoft for high-quality carbon removal from project in Louisiana," *PR Newswire*, 2025. 12. "Carbon Dioxide Capture and Storage (SRCCS)," IPCC, 2005.



Current and projected state of deployment

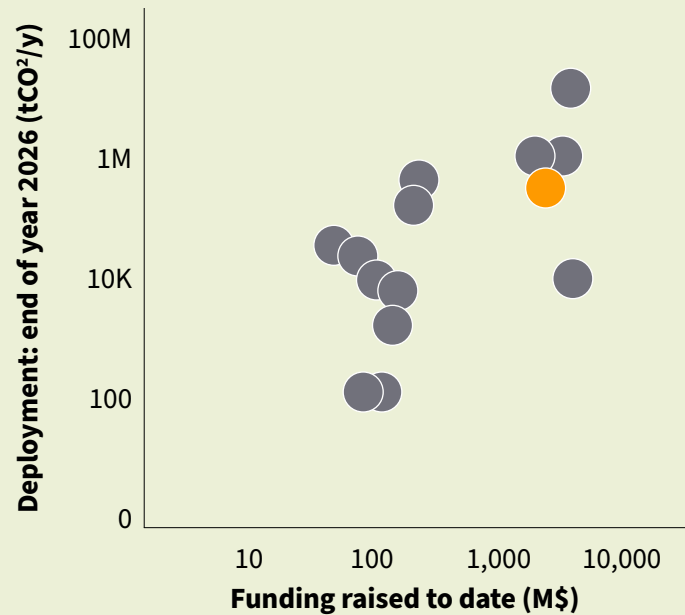
Past 5 years

Offtake and BECCS adoption grew, but no geologic injection performed with captured CO₂

Next 5 years

The sector plans to begin injection and storage at scale, with meaningful annual removals by 2030

Current deployment



16

companies tracked¹

31

projects active/
announced¹

TRL 8

Scaling
commercial
deployments

ARL 3

low readiness

Current cumulative removals

~0

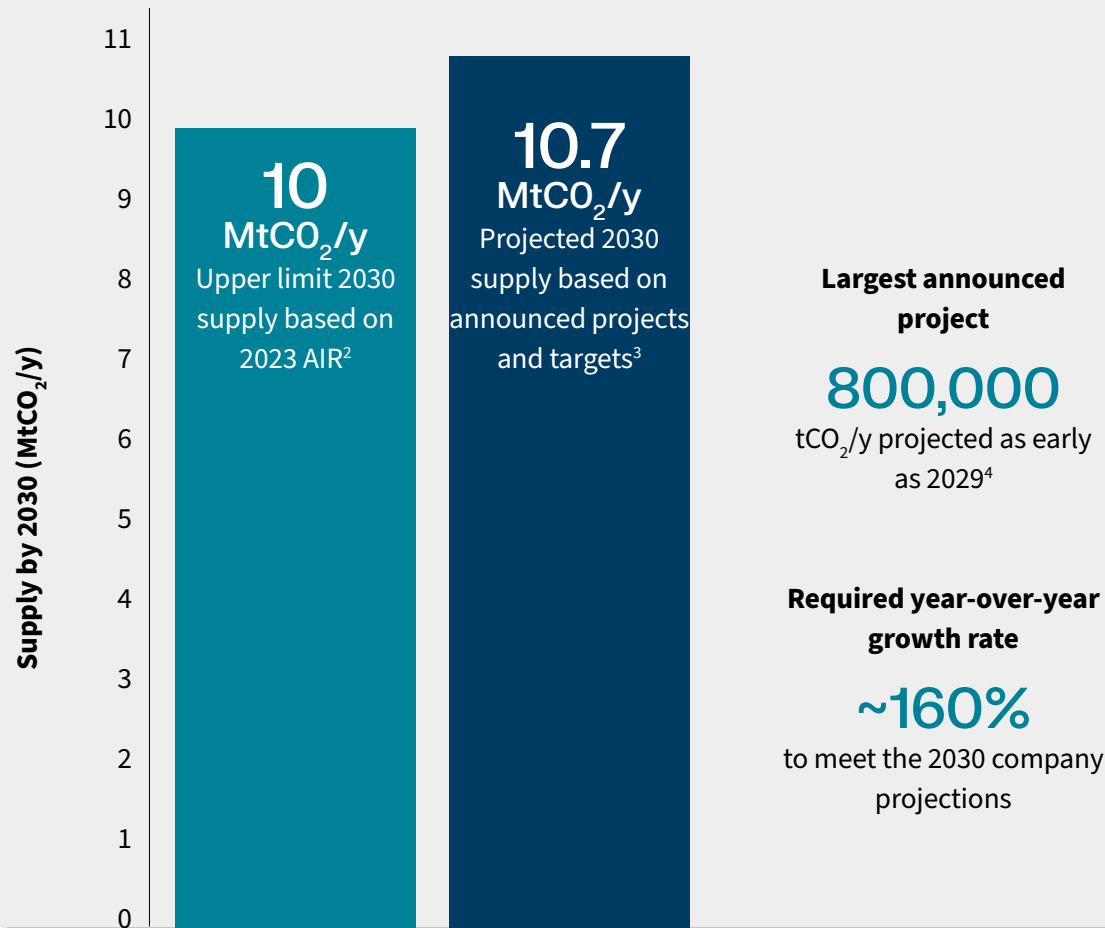
tCO₂ as of end-of-year 2025¹

Largest active project

~0

tCO₂/year as of December 2025

Supply projections for 2030



Announced and active projects as a percentage of 2030 company targets

57%

1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies, and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference capacity of 10 MtCO₂/y is sourced directly from the DAC “success story” for BECCS to fuels in [The Applied Innovation Roadmap for CDR](#), RMI, 2023 (p. 139). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. [“CO280 Awards Pre-FEED Contracts for an 800,000 Tonnes per Year Carbon Removal Project at a Pulp and Paper Mill in Canada.”](#) CO₂80, 2025. 5. [“Stockholm Exergi sells permanent negative emissions for SEK 500 million.”](#) Stockholm Exergi, 2024.



Key cost drivers

Major cost drivers

Major cost drivers: Capex, feedstock procurement, CO₂ transportation and storage

Improvement areas

Design standardization, capture efficiency, biomass supply

Today: \$260–\$500/tCO₂

Future: \$145–\$260/tCO₂

40%–60% cost reduction possible via standardization, supply chain build-out, and shared CO₂ transportation and storage infrastructure.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

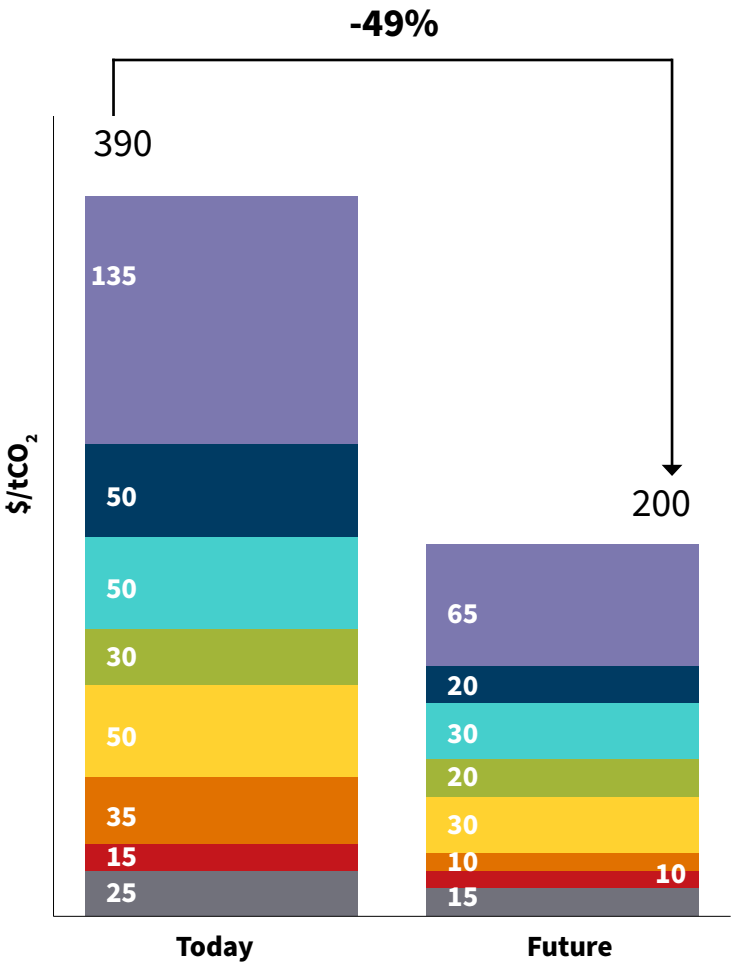
Today's cost range (0-200, \$/tCO₂) Future cost range (0-200, \$/tCO₂) Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex • ————— • • ————— •	Biomass conversion equipment, CO ₂ capture system, connection to power transmission and CO ₂ infrastructure	Standardized, modular designs; integrated CO ₂ compression; grid-ready siting; capture efficiency
Energy • ————— • • ————— •	Energy penalty from CO ₂ capture, biomass preprocessing, auxiliary loads	Improved capture technologies, waste heat recovery
Feedstock • ————— • • ————— •	Biomass feedstock procurement, storage losses	Use of dedicated crops or established waste biomass supply chains, regional biomass processing hubs
Transport • ————— • • ————— •	Biomass transportation	Optimized hub-style deployment with local sourcing, densified biomass
O&M • ————— • • ————— •	Plant labor and logistics, maintenance, including facility outages	Automation, predictive maintenance from standardized plant designs, improved CO ₂ solvent/sorbent lifetimes
Storage • ————— • • ————— •	CO ₂ transportation and storage, long-term liability	Shared storage hubs, standardized project design, permitting, MRV
MRV • ————— • • ————— •	Stack monitoring, biomass-embedded carbon accounting, third-party verification	Digital MRV, standardized project design and MRV
Embodied Emissions • ————— • • ————— •	Emissions from biomass supply chain, construction, CO ₂ solvent/sorbent supply chain	Electrification, low-carbon materials, improvements in capture efficiency

Note about cost stacks¹

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- Deployment is likely most cost efficient in regions with established bioenergy infrastructure and onshore, rather than offshore, storage and transport.
- Seasonal deployment would trade off increased capital expenditure investment per tCO₂ captured against increased offtake price of generated electricity or reduced feedstock costs.



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Standardized integration with grid-scale bioenergy supply

Where to start: Identify geographies with needs for seasonal power or waste heat colocated with biomass supply



Supply of sustainable biomass

Scaled BECCS to Electricity deployment will require **low-cost, sustainable sourcing** that doesn't negatively influence food supply or soil health. Projected scales of 10–13 MtCO₂/y **by 2030** will require the combustion of **7–13 Mt/y of dry biomass globally**.¹ For context, this represents 15%–30% of all logging residues produced in the United States today, of which half are not collected.² The majority of this biomass will need to be sourced locally, and deployment will likely be most significant in geographies with significant existing bioenergy infrastructure, such as Europe, Canada, and Japan.

At larger deployment scales, careful guardrails on land use allocation and carbon accounting frameworks will be needed to balance possible removals against impacts on food systems, ecosystems, and the climate. Estimates of the **global sustainable supply of all biomass** range from 4 to 12 Gt/y, equivalent to **6 to 17 GtCO₂/y**. Other CDR approaches, material demands, and energy uses will compete for this resource.³ Further study is needed to identify the optimal use case of different types of biomass among different CDR approaches or other uses.

Example KPIs:

- Feedstock cost <\$20/tCO₂
- >80% waste/residue sourced biomass
- 100% sustainably sourced purpose-grown biomass



Seasonal power generation

At larger scales, **total sustainable biomass supply constraints** will require prioritization of biomass toward use cases without scalable non-biomass alternatives. This typically means material uses of biomass, which gain advantages from the specific physical or chemical characteristics of biomass rather than the carbon or energy content alone, are prioritized at scale. However, analyses of possible allocations in a net-zero economy indicate that seasonal power generation may prove to be a valuable second priority of biomass, providing **load flexibility at the local or grid scale** when alternatives such as solar or wind power generation are insufficient to meet demand.⁴

Seasonal deployment will significantly impact the cost of BECCS projects. The proportional cost of capital, including the infrastructure needed for CO₂ transportation and storage, is increased if plant uptime is limited. Economic viability will rely on fluctuating fuel costs and increased grid prices during periods of limited alternative supply options.⁵ **Hybrid operations sharing heat, fuel, and CO₂ infrastructure** with other nearby users, including industrial facilities, will support BECCS as a low-carbon load balancing resource.

Example KPIs:

- Economical operation at capacity factor <50% with high-value seasonal generation
- >80% of biomass consumed when renewable generation is low



Infrastructure

BECCS to Electricity projects require complex infrastructure beyond biomass supply chains. These include integration into electrical grids as baseload or seasonal power sources, and integration into CO₂ transportation and storage networks. Deployments may include **retrofits of CCS units onto existing bioenergy power plants** or new builds in regions with significant waste biomass supply or demand for load balancing that can be supplied with bioenergy. Access to infrastructure significantly reduces the cost of deployment, even at commercial deployment scales. Planning and establishing efficient networks of biomass supply, grid loads, and CO₂ infrastructure will unlock key synergies of BECCS to Electricity deployment beyond the cost considerations of a stand-alone project.

Another key opportunity for integration into existing infrastructure is the **provision of waste heat to residential or industrial systems**, reducing the need for fossil fuel heat generation, including in areas with cold weather where direct electrification of heating technologies is challenging. Using waste heat from power plants reduces the energy penalty and provides an alternative to oil-based heating.⁵

Example KPIs:

- >75% shared infrastructure for CO₂ transportation/storage
- Storage and transportation costs <\$10/tCO₂
- >50% of economically recoverable waste heat utilized

1. BECCS to Electricity projects sequester 1–1.5 tCO₂ per ton of biomass utilized. See, e.g., G. Weimann et al., “[Potential for carbon dioxide removal of carbon capture and storage on biomass-fired combined heat and power production](#),” *Global Change Biology Bioenergy*, 2024. **2.** 19 Mt and 23 Mt of collected and unharvested logging residues, respectively ([2023 Billion-Ton Report](#), DOE), converted using a factor of 1.4 tCO₂/t dry biomass. **3.** Estimates of the prudent and maximum supply of sustainable biomass include 40–60 or 120 EJ, respectively ([Bioresources within a Net-Zero Emissions Economy](#), ETC, 2021). One-third to half of this supply is represented by agricultural residues and woody biomass from forestry not used as building materials. **4.** [Bioresources within a Net-Zero Emissions Economy](#), ETC, 2021. **5.** [Bioenergy with carbon capture and storage – basics and opportunities](#), Bioenergy Europe, 2025.



Advancement and breakthrough areas

Key research areas
Specialized feedstocks, scaled syngas technology, improved CCS efficiency at scale

1. See [page 21](#) for more detail on crosscutting opportunities for breakthroughs in biogenic CDR, including assessments of the technical and social difficulty of implementation.

2. Reviewers note that this and other breakthroughs based on genetic modification of crops, whether grown in agricultural fields or managed timber lands, may face social pushback and safety concerns. Additionally, use of this biomass will compete with other use cases, as indicated in the Key Cost Considerations on the previous page.

Crosscutting bCDR breakthrough themes¹

B1: Enhanced cultivars for high-carbon-storage applications

High-carbon, specialized crops grown for the BECCS process would ensure sustainable operations and electricity generation, while improving the efficiency of carbon storage.

B2: On-site microreactors

Modular BECCS to Electricity reactors could allow off-grid, decentralized electricity production at waste biomass sources, reducing transport and offering resilient energy generation.

B6: Biogenic co-benefits

Species utilized for BECCS are chosen based on their environmental co-benefits, such as heavy metal uptake and environmental toxin remediation.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Improved capture efficiency demonstrated in commercial CCS	Improvement in commercial-scale point-source capture efficiency to reach lab-scale performance of 90%–99% would reduce capex intensity and energy of capture	\$\$ Cost savings from increased capture efficiency and reduced material requirements	All future and existing projects		Sorbent/membrane/solvent/cryogenic separation experts, industrial emitters, government researchers, RD&D funders
2	Commercial-scale biomass gasification with CCS	Advancements in thermochemical gasification technology for syngas synthesis to replace natural gas, alongside a durable biochar coproduct, would produce a valuable fuel coproduct	\$\$\$ Cost savings from process simplification and efficiency of biomass conversion	All future projects, potentially existing projects for retrofit		Industrial emitters, syngas and gasification experts, CCS supply chains
3	Genetically modified cultivars optimized for BECCS combustion ²	Cultivars mimicking the high productivity found in poplar or willows and high energy-by-volume hardwoods ideal for long-term turbine power are bred or modified for efficient scaled deployment	\$\$ Cost savings from improved resource use on feedstocks and improved power generation	All future and existing projects		Plant biologists, botanists, genetics experts, energy and waste-to-heat experts
4	BECCS technologies achieve fast ramping for load balancing on grid demand	BECCS facilities that are powering grid capacity are able to increase or decrease power output quickly, increasing the technology's flexibility and applications	\$\$ Reduced embodied carbon by precise operation capacity and cost savings from ideal feedstock usage	All projects that are connected to the grid for delivery		Energy analysts and grid specialists, bioenergy reactor experts and researchers, local and state regulators
5	Modular BECCS technologies developed and deployed near ideal feedstocks	Small-scale BECCS developed for on-site implementation with alternative solvent/sorbent systems and CO ₂ conversion technologies that are cost-effective at small scale would decrease biomass handling and transportation costs	\$ Reduced transportation cost for feedstocks, reduced energy cost due to lower grid demand	Future, small-scale, potentially off-grid projects		Farming communities, logging communities, bioenergy reactor researchers, local regulators
<div><div>\$ \$1–\$30/tCO₂</div><div>\$\$ \$20–\$50/tCO₂</div><div>\$\$\$ \$40–\$100/tCO₂</div><div>\$\$\$\$ \$75–\$300/tCO₂</div></div>						



BECCS to Fuels

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 3.2: BECCS to Fuels

DEFINITION

Thermal or biochemical conversion of biomass (either dedicated feedstock or waste) to generate fuels and produce CO₂ that is captured with CCS technology.

APPROACH OVERVIEW

BECCS to Fuels projects first began deploying in the early 2010s following breakthroughs in geologic CO₂ storage for carbon removal purposes in the mid 2000s. Primarily focused on industrial-scale ethanol production, companies employing BECCS to Fuels approaches in 2026 still number less than a dozen. Despite the small number of active facilities, cumulative capacity from existing BECCS to Fuels operations already surpasses 1 MtCO₂/y and could reach 3 MtCO₂/y by 2030.

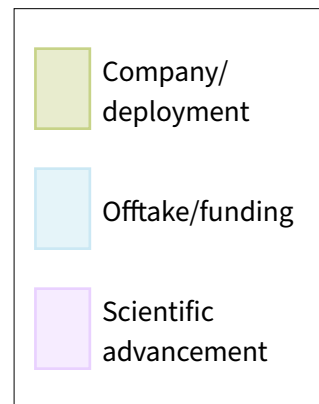
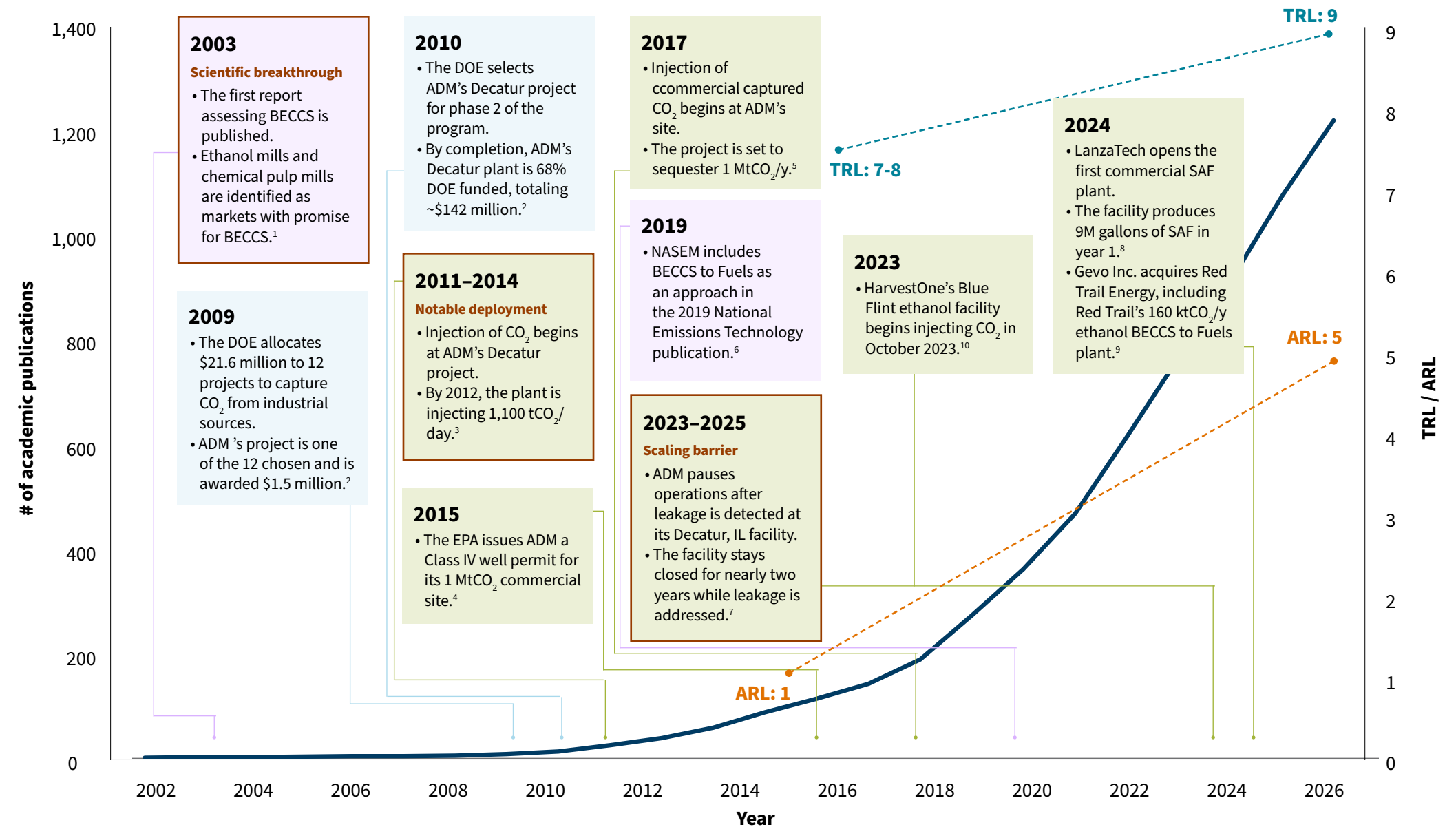


How we got here

Status: Recent setbacks in progress toward commercial-scale deployment

Approach trend: Neutral

Milestones selected for the graph were chosen based on their impact on and significance to the BECCS to Fuels sector.



1. K. Möllersten et. al., "Potential market niches for biomass energy with CO₂ capture and storage—Opportunities for energy supply with negative CO₂ emissions," *Biomass and Bioenergy*, 2003. 2. *Archer Daniels Midland Company*, Department of Energy, 2017. 3. "Decatur Fact Sheet: Carbon Dioxide Capture and Storage Project," Carbon Capture & Sequestration Technologies at MIT, 2016. 4. "Illinois Industrial Carbon Capture and Storage (IL-CCS) Fact Sheet: Carbon Dioxide Capture and Storage Project," Carbon Capture & Sequestration Technologies at MIT, 2016. 5. "ADM starts commercial-scale CCS at Decatur ethanol plant," *Bioenergy International*, 2017. 6. "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda," National Academies of Sciences, Engineering, and Medicine, 2019. 7. "ADM Nears Restart Of Carbon Storage Site After Leak Paused Operations," *Carbon Herald*, 2025. 8. "World's First Ethanol-To-Jet Fuel Plant Paves the Way for Commercial Production of SAF," Department of Energy, 2024. 9. Wang et al., "Can bioenergy with carbon capture and storage deliver negative emissions? A critical review of life cycle assessment," *Journal of Cleaner Production*, 2024. 10. *FACILITIES - Blue Flint, Harvestone Low Carbon Partners*.



Current and projected state of deployment

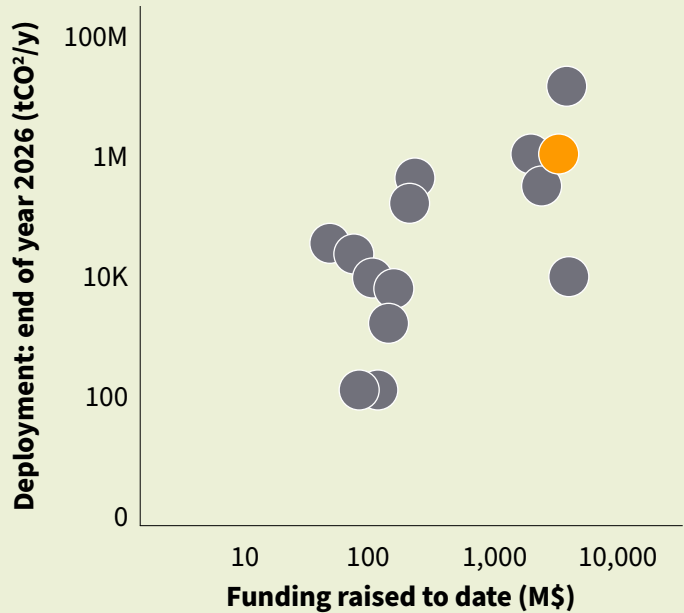
Past 5 years

Major commercial deployment and government support accelerated industry investment

Next 5 years

Companies are evaluating existing projects and recalibrating to ensure strategic deployment

Current deployment



Database includes three companies founded within the past 10 years.

Recent funding successes include Mote Hydrogen securing \$7 million in 2025 as part of a successful Series A.⁵

2026 funding: **\$2.7 billion¹**

2026 capacity: **2 MtCO₂/y¹**

● BECCS to fuels approaches
● Other CDR approaches

15

companies tracked¹

13

projects active/
announced

TRL 9

NOAK commercial
deployments

ARL 5

Moderate
readiness

Current cumulative removals

~6,300,000

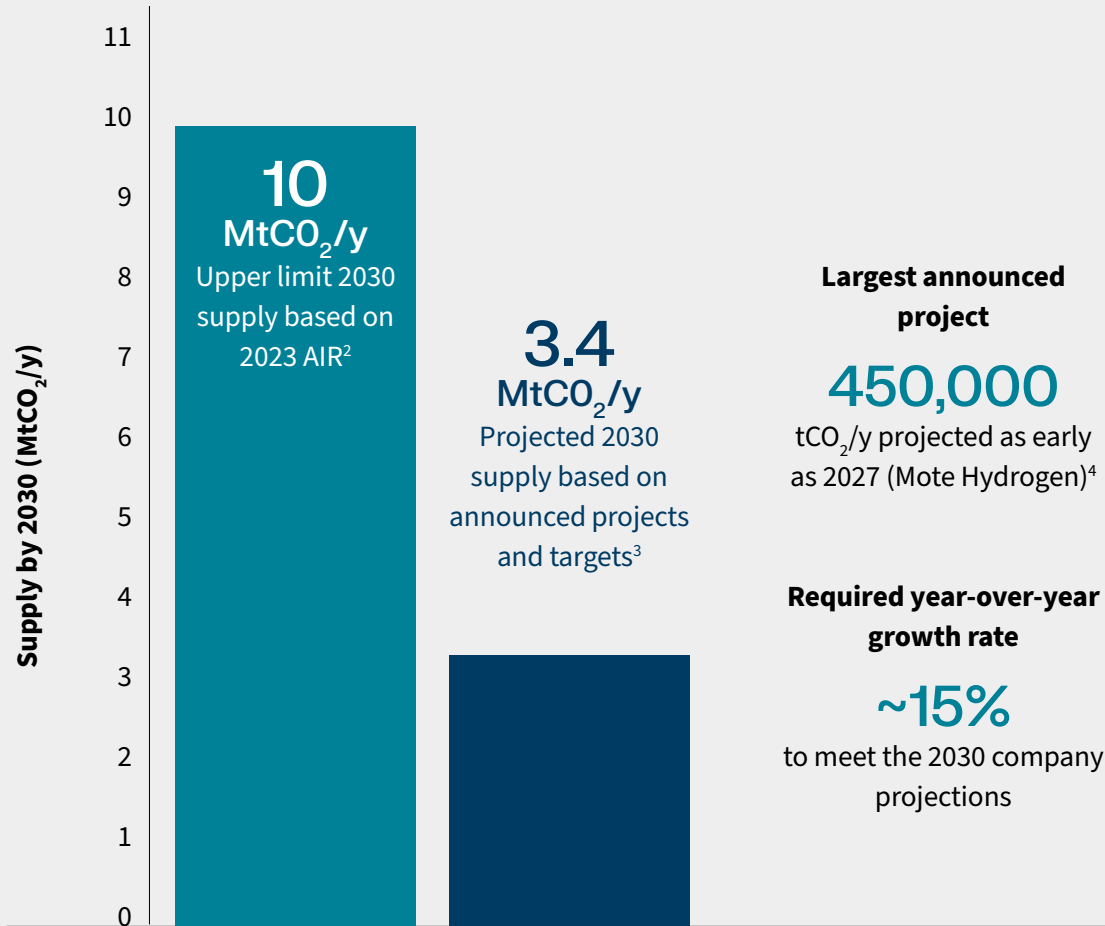
tCO₂ as of end-of-year 2025¹

Largest active project

~500,000

tCO₂/year as of December 2025⁶

Supply projections for 2030



Announced and active projects as a percentage of 2030 company targets



1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies, and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference capacity of 10 MtCO₂/y is sourced directly from the DAC “success story” for BECCS to fuels in [The Applied Innovation Roadmap for CDR](#), RMI, 2023 (p. 139). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. “[Mote Kicks Off Second Biomass to Hydrogen Project in Northern California](#),” Mote, 2023. 5. “[Mote Secures \\$7 Million Funding in First Close of Series A Round to Advance Company’s Carbon-Negative Biomass-to-Energy Technology](#),” Businesswire, 2025. 6. “[ADM Announces Successful Completion of One Million Metric Ton Carbon Capture and Storage Project](#),” ADM, 2021. *ADM’s Decatur project was originally slated to have 1 MtCO₂/y in removal capacity, though ADM and DOE reviewers have noted that current capacity is closer to .5 MtCO₂/y.



Key cost drivers

Major cost drivers

Feedstock procurement and transportation, plant capex

Improvement areas

Feedstock and fuel market diversification, CCS efficiency

Today: \$225–\$500/tCO₂
Future: \$120–\$300/tCO₂

30%–50% cost reduction possible via CCS capture efficiency improvements and standardization of plant design / retrofitting.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

Today's cost range (0-200, \$/tCO₂)
Future cost range (0-200, \$/tCO₂)

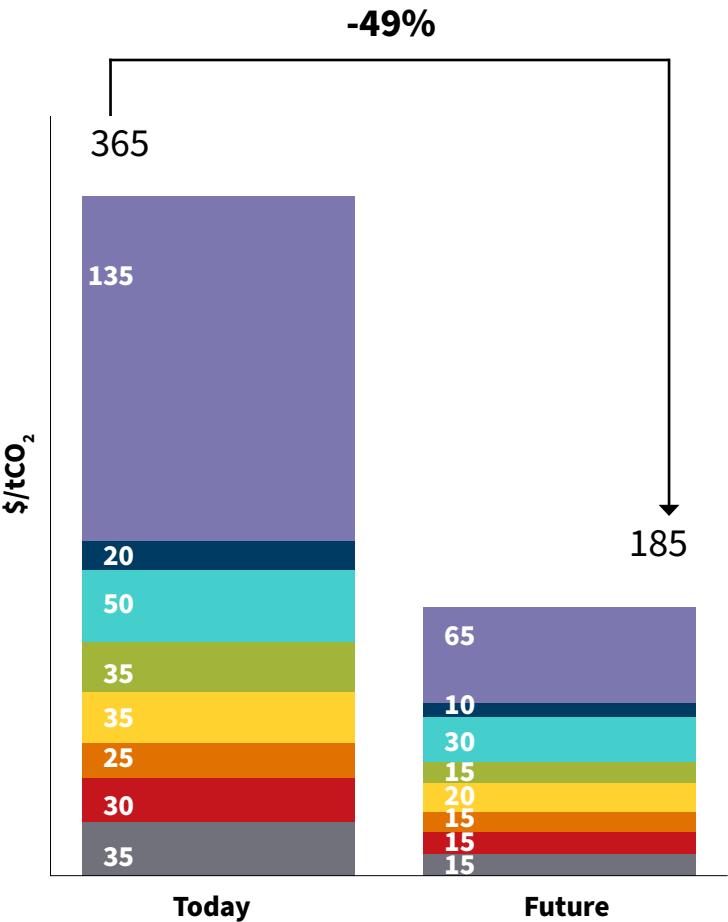
Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex	Fuel production plant, CO ₂ capture and compression equipment, integration and retrofits	Standardization, modularization, improved heat integration, optimized CCS units in new-build plants
Energy	Energy penalty from CO ₂ capture, biomass preprocessing, auxiliary loads	Improved capture technologies, waste heat integration
Feedstock	Biomass feedstock procurement and preprocessing, storage losses	Use of waste biomass rather than food crops, regional biomass processing hubs
Transport	Biomass transportation, fuel transportation	Optimized hub-style deployment with local sourcing, densified biomass
O&M	Plant labor and logistics, maintenance including maintenance outages	Automation, predictive maintenance from standardized plant designs, improved CO ₂ solvent/sorbent lifetimes
Storage	CO ₂ transportation and storage, long-term liability	Shared storage hubs; standardized project design, permitting, and MRV
MRV	CO ₂ flow monitoring, biomass embedded carbon accounting, third-party verification	Digital MRV, standardized project design and MRV
Embodied Emissions	Emissions from biomass supply chain, construction, and CO ₂ solvent/sorbent supply chain	Electrification, low-carbon materials, improvements in capture efficiency

Note about cost stacks¹

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- Diversification of fuel production beyond bioethanol will significantly affect the cost structure and long-term viability of BECCS to Fuels projects
- Siting and deployment will depend on fuel offtake markets, as well as policies that impact industry such as aviation and shipping
- As biomass continues to be allocated to a variety of end uses, feedstock prices could increase



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Standardized integration into biofuel production

Where to start: Identify revenue streams from growing fuel markets



Supply of sustainable biomass

Scaled BECCS to Fuels deployment will require **low-cost, sustainable sourcing of biomass** that doesn't negatively influence food supply or soil health. Projected scales of 3–10 MtCO₂/y by 2030 will require the combustion of **5–17 Mt/y of dry biomass** globally.¹ For context, this represents 15%–50% of all logging residues produced in the United States today, of which half are not collected.² The majority of this biomass will need to be sourced locally, and deployment will depend on the establishment or continuation of sustainable biofuels production.

At larger deployment scales, careful guardrails on land use allocation and carbon accounting frameworks will be needed to balance possible removals against impacts on food systems, ecosystems, and the climate. Estimates of the **global sustainable supply of all biomass** range from 4 to 12 Gt/y, equivalent to **6 to 17 GtCO₂/y**. Other CDR approaches, material demands, and energy uses will compete for this resource.³ Further study is needed to identify the optimal use case of different types of biomass among different CDR approaches or other uses.

Example KPIs:

- Feedstock cost <\$20/tCO₂
- >80% waste/residue sourced biomass
- 100% sustainably sourced, purpose-grown biomass



Fuel markets

The viability of scaled BECCS to Fuels deployment hinges on the evolution of **markets for low-carbon fuels**. Today, the main biofuel market amenable to CCS integration is corn ethanol, which produces a high-purity CO₂ stream.⁴ In the long term, demand for corn ethanol is uncertain because alternatives to fuel mixing for decarbonized light-duty transport, such as battery-powered electric vehicles, are increasing in popularity. Current demand relies heavily on policy support mandating fuel mixing, with significant implications on agricultural land use and allocation of resources including water and fertilizer for non-food crops.

SAF and marine fuels are two alternative markets with significant demand for energy-dense liquid fuels, identified as high-priority applications for future sustainable biomass allocation with limited alternatives. Another promising but less mature opportunity is the direct gasification of biomass into syngas.⁵ Flexibility to produce a range of biofuels as demands shift may make the BECCS to Fuels approach a cost-effective technology in different future niches. Direct enforcement of green fuel use or indirect policies such as carbon pricing could provide consistent demand for the fuel coproduct.

Example KPIs:

- >50% of revenue per net tCO₂ from fuel product
- >50% of existing biofuels plants retrofitted with BECCS
- Pilot projects producing 100% SAF, marine fuel, or biodiesel



Hub-based deployment

Project deployment colocated with biomass sources reduces the cost and embodied emissions associated with transportation to the storage site. This needs to be balanced against cost savings from land use and process efficiency from large, centralized storage projects drawing biomass from several sources. In particular, BECCS to Fuels deployment could ramp production up or down in response to fluctuating fuel prices impacting the expected fuel product revenue.

Though corn ethanol production requires scaled production of a dedicated food-grade feedstock, some **alternative projects in SAF production use waste biomass**. Centralized collection, processing, and distribution of waste biomass with predictable material properties would enable allocation to uses ranging from BECCS to Fuels, electricity generation, direct storage, or conversion to biochar or bio-oil. Mapping local niches where biomass sources are available near suitable storage sites or industrial demands will enable scaled project planning optimizing available resources. Hub-based deployment would also enable scaled planning of infrastructure development including connection to fuel offtakers and CO₂ storage and transportation infrastructure.

Example KPIs:

- >80% of biomass processed through regional hubs
- >50% of biomass processing flexible between outputs based on variations in economics and feedstock quality

1. BECCS to Fuels projects often capture 0.6 tCO₂ or less per ton of biomass processed, though gasification may enable more efficient carbon removals than fermentation. See M. Hayat et al., “Which bioenergy with carbon capture and storage (BECCS) pathways can provide net-negative emissions?,” *International Journal of Greenhouse Gas Control*, 2024. **2.** 19 and 23 Mt of collected and unharvested logging residues, respectively ([2023 Billion-Ton Report](#), DOE), converted using a factor of 1.4 tCO₂/t dry biomass. **3.** Estimates for prudent and maximum supply of sustainable biomass include 40–60 or 120 EJ, respectively ([Bioresources within a Net-Zero Emissions Economy](#), ETC, 2021). One-third to half of this supply is represented by agricultural residues and woody biomass from forestry not used as building materials. **4.** [U.S. Corn Production and Portion used for Fuel Ethanol](#), DOE, 2024. **5.** [Challenges for Biomass Gasification to Fuels and Chemicals](#), GTI Energy, 2022.



Advancement and breakthrough areas

Key research areas

Genetic modification of purpose-grown feedstocks, catalysts, and process microbes for fuel conversion

1. See [page 21](#) for more detail on crosscutting opportunities for breakthroughs in biogenic CDR, including assessments of the technical and social difficulty of implementation.

Crosscutting bCDR breakthrough themes¹

B1: Enhanced cultivars for high carbon storage applications

The utilization of specialized feedstocks that have increased growth rates and break down more efficiently in fermentation processes could improve throughput and capture rates.

B2: On-site microreactors

Small, modular BECCS to Fuels reactors could reduce the cost of feedstock transport to central facilities while creating sustainable CO₂ streams in remote areas lacking built-in infrastructure.

B5: Synthetic biology for non-photosynthetic CO₂ capture

The incorporation of microbes and enzymes in the BECCS process that can increase fermentation rates or uptake additional carbon could improve efficiency, CO₂ capture, and fuel production.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Genetically modified purpose-grown feedstock with high hydrocarbon potential	Genetically modified algae species that naturally synthesize hydrocarbons in their cell chains can increase fuel output , with remaining biomass converted to biochar	\$\$ Cost savings from harvest-like fuel process, revenue generation from biochar production	All future and existing projects		Plant biologists, botanists, large-scale agriculture supply chains, seed developers, synthetic biology firms, forestry genetics groups, universities, USDA/DOE labs
2	Improved microbial treatments and inoculations	Advancements in microbes and microbial pre- and post-treatments improve the reaction rate and quality of fuel produced from biomass fermentation	\$ Reduced cost from decrease in biofouling and improved fermentation rates	Existing and future fermentation fuel production facilities		Microbiologists, RD&D funders in food science and pharmaceuticals, agricultural / seed supply chains, agronomists
3	Advancements in catalyst science to improve fuel quality	Catalyst improvements including resilience to contamination, reduced H ₂ usage, and compatibility with intermittent operations increase efficiency particularly when optimizing for SAF production	\$\$\$ Cost savings in conversion efficiency and SAF production capacity	All projects aimed at creating potent bio-derived fuels		Chemicals companies, refining technology specialists, national labs / universities, fuel developers, oil and gas refiners, OEM equipment providers
4	Feedstock analysis and blending for improved batching	Eliminates variation in size, moisture, and density to create uniform feedstock batches for improved reactor performance and reduced preprocessing requirements	\$ Reduced planning for feedstock sizes and cost savings from clean operations that reduce maintenance	All projects that require feedstock uniformity and preprocessing		AI/software companies, sensor companies, biomass depots, biofuel plant operators, labs for feedstock characterization
5	Regional BECCS + H₂ hubs dedicated to fuels production	Shared infrastructure investment co-deploying H ₂ and CO ₂ transportation and storage infrastructure alongside BECCS plants for more efficient supply chains	\$\$\$ Reduced cost from shared infrastructure and transportation of materials / feedstocks	All future projects with focus on transport, capex cost sharing		Hydrogen producers, CO ₂ transport and storage developers, pipeline companies, utilities, ports/rail/logistics firms, state energy offices, DOE, EPA, local and state regulators

\$ \$1–\$30/tCO₂ **\$\$** \$20–\$50/tCO₂ **\$\$\$** \$40–\$100/tCO₂ **\$\$\$\$** \$75–\$300/tCO₂



Surficial Mineralization

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 4.1: Surficial Mineralization

DEFINITION

Enhancing the natural capacity of excavated or processed alkaline feedstock to passively react with atmospheric CO₂ — through crushing, grinding, spreading, heating, or other physical or chemical means — in order to form carbonate minerals.

APPROACH OVERVIEW

Surficial mineralization (SM) is a novel approach that emerged in the early 2020s. The first pilot to deploy on an active mine site occurred in 2023. Since then, SM has gained attention from buyers and mining companies alike; investors have made 300+ ktCO₂ commitments for offtake, and mining companies have opened talks around hosting SM projects. By 2030, the approach's cumulative removals could reach 250 ktCO₂.

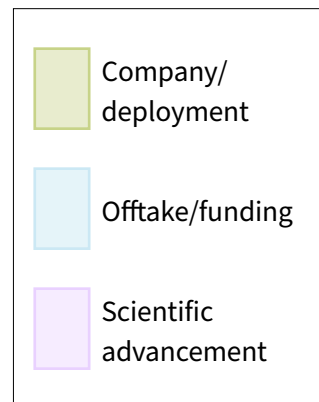
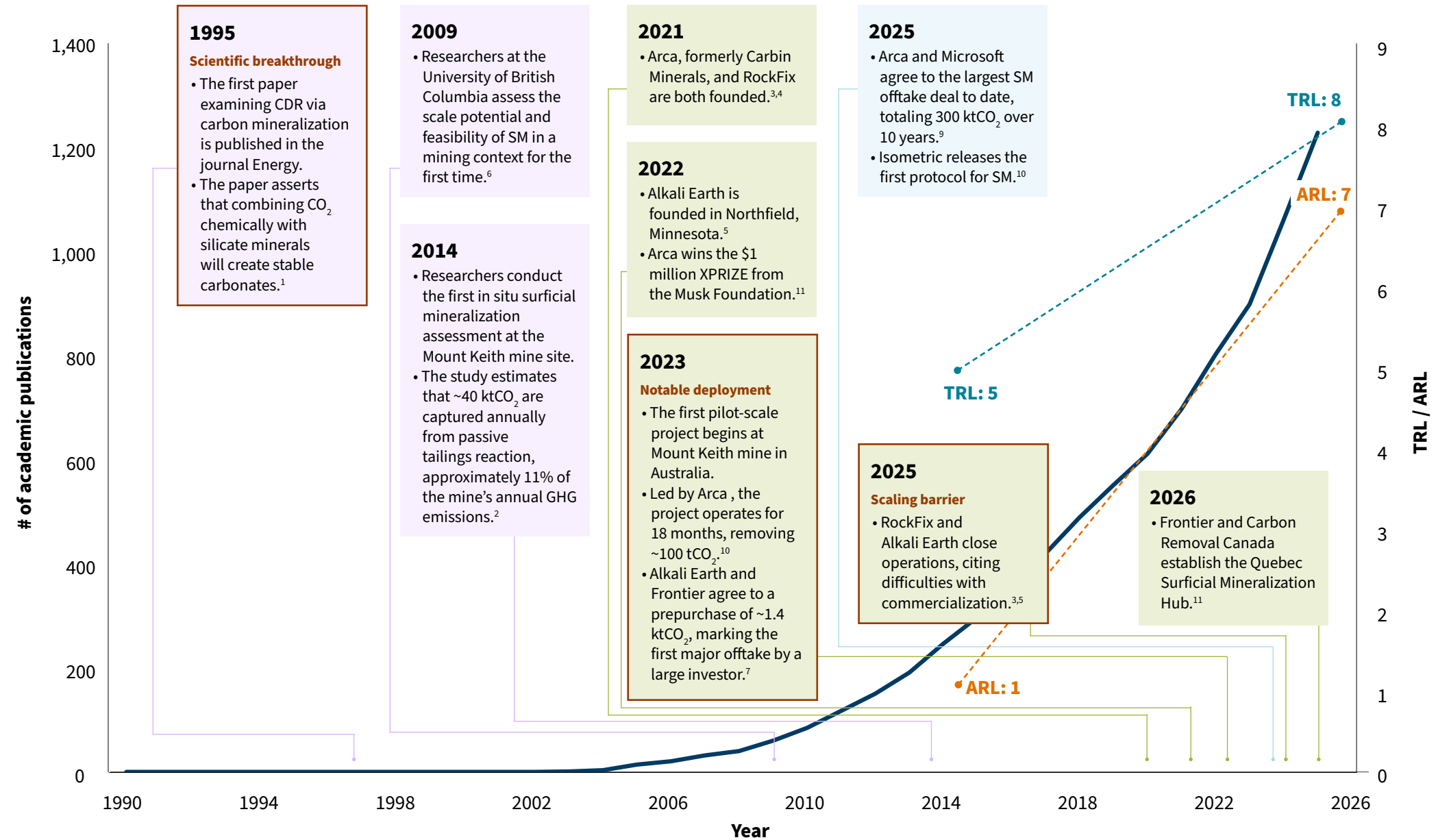


How we got here

Status: Significant progress toward commercial-scale deployment

Approach trend: Positive

Milestones selected for the graph were chosen based on their impact on and significance to the surficial mineralization sector.



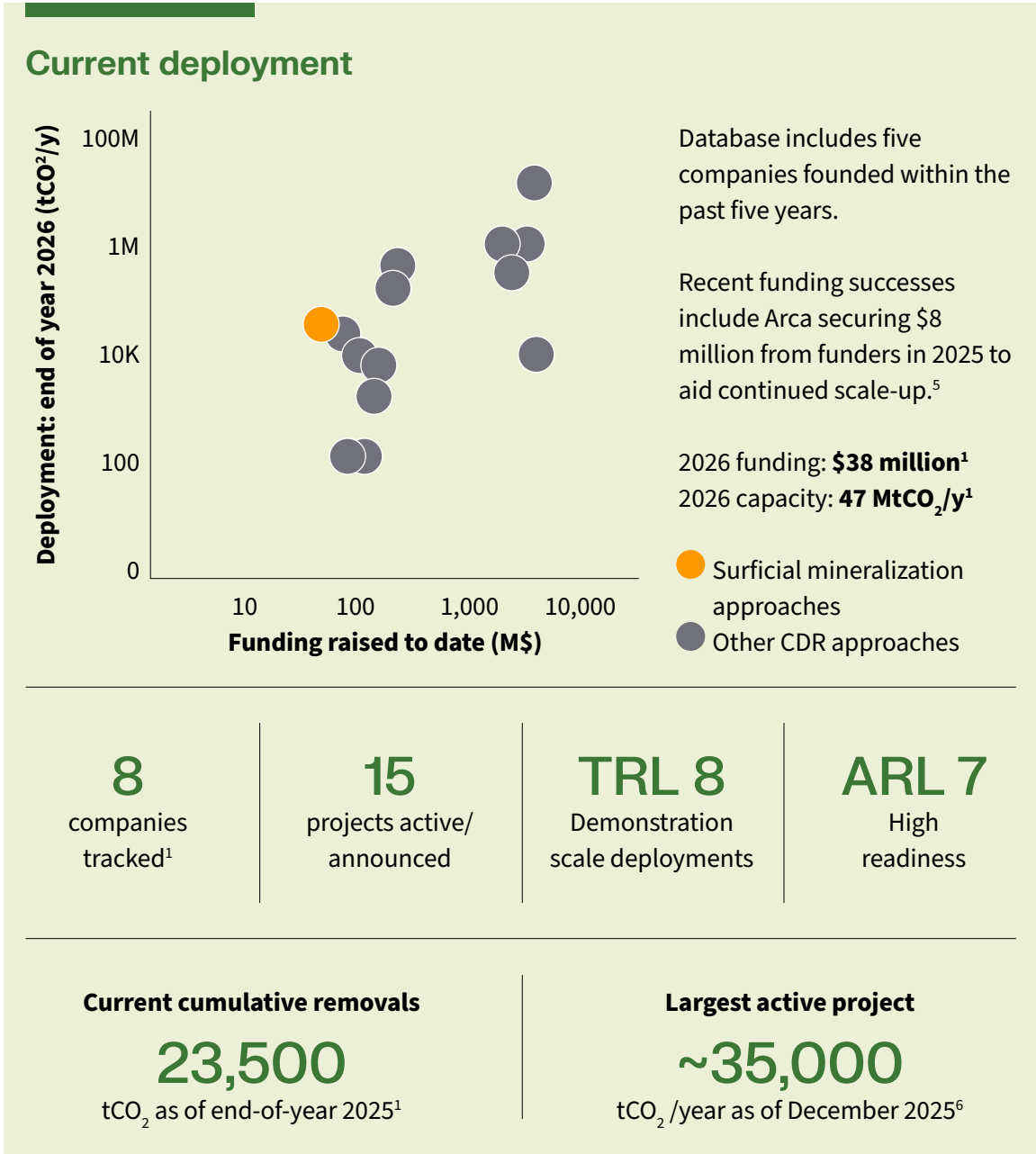
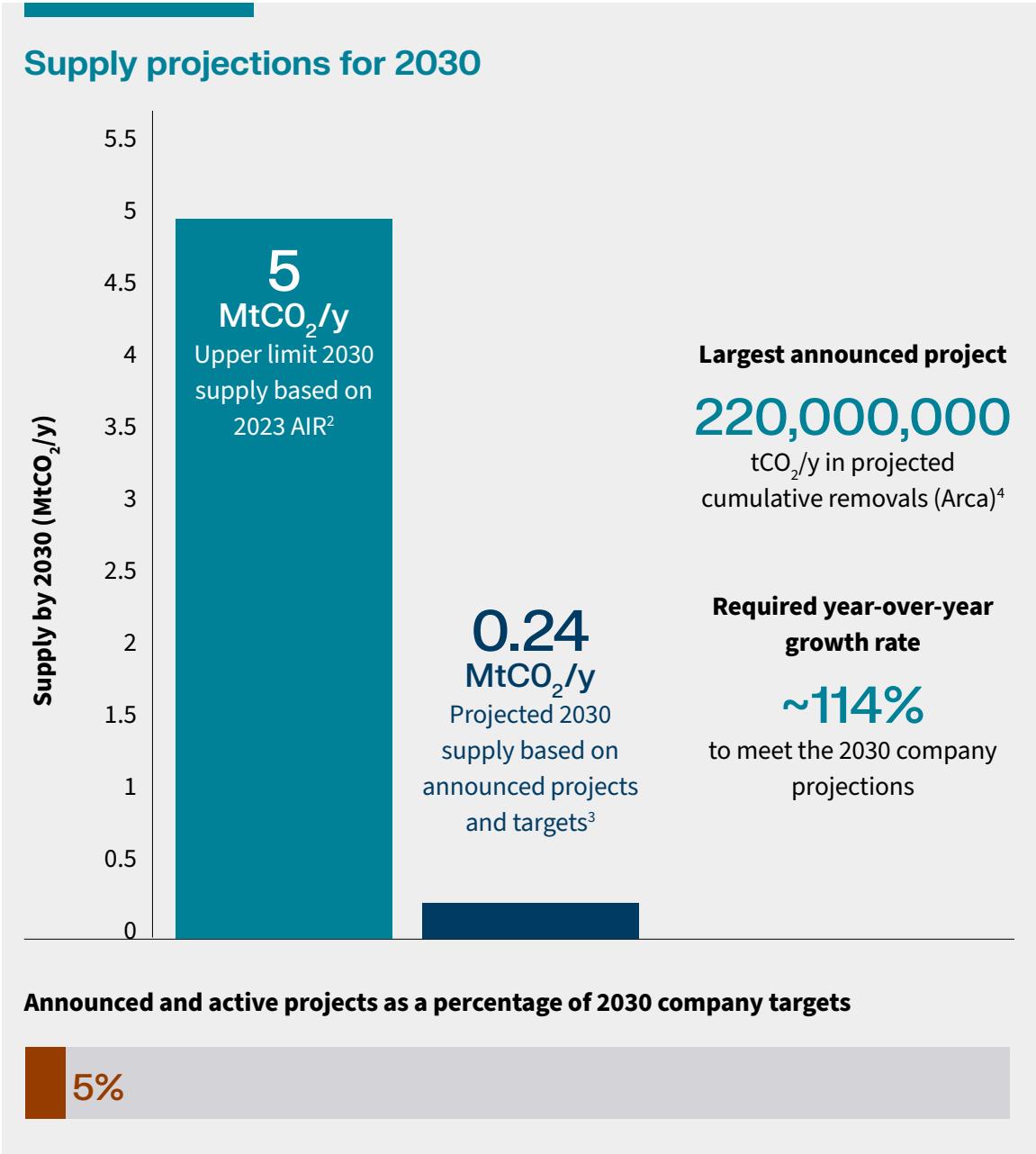
1. K. Lackner et al., "Carbon dioxide disposal in carbonate minerals," *Energy*, 1995. 2. S. Wilson et al., "Offsetting of CO₂ emissions by air capture in mine tailings at the Mount Keith Nickel Mine, Western Australia: Rates, controls and prospects for carbon neutral mining," *International Journal of Greenhouse Gas Control*, 2014. 3. [RockFix Company Profile, LinkedIn](#). 4. [Arca Climate Company Profile, LinkedIn](#). 5. [Alkali Earth Company Profile, LinkedIn](#). 6. S. Wilson et al., "Carbon Dioxide Fixation within Mine Wastes of Ultramafic-Hosted Ore Deposits: Examples from the Clinton Creek and Cassiar Chrysotile Deposits, Canada," *Economic Geology*, 2009. 7. "Frontier facilitates third round of carbon removal purchases," *Frontier*, 2023. 8. "Arca Announces Agreement with Microsoft for Nearly 300,000 tonnes of Durable Carbon Removal," *Arca*, 2025. 9. "Isometric Issues First Protocol For CDR In The Mining Industry," *Carbon Herald*, 2025. 10. "The Current Status of Mineral Carbonation Technology," *Murdoch University*, 2025.



Current and projected state of deployment

Past 5 years
Commercial ventures emerged, deploying pilots and finalizing FOAK crediting methodologies

Next 5 years
Companies look to leverage integration with heavy industry to reach scaled deployment



1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies, and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference capacity of 5 MtCO₂/y is sourced directly from the DAC “success story” for surficial mineralization in [The Applied Innovation Roadmap for CDR](#), RMI, 2023 (p. 157). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. [“Arca and Giga Metals sign exclusive agreement to explore carbon removal at B.C. nickel project with potential to remove 220 million tonnes of atmospheric carbon dioxide.”](#) Arca, 2026. 5. [“Arca October Funding Update and Press Release.”](#) Arca, 2025. 6. [Algoma CDR \(Karbonetiq\), Carbon Console](#), Carbon Removal Canada, 2025.



Key cost drivers

Major cost drivers

Mineral processing and conveying, manual sampling

Improvement areas

Standardized industrial integration, digital MRV

Today: \$350–\$360/tCO₂

Future: \$80–\$170/tCO₂

50%–85% cost reduction possible via standardization and integration into ongoing mine operations.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

Today's cost range (0-200, \$/tCO₂)
Future cost range (0-200, \$/tCO₂)

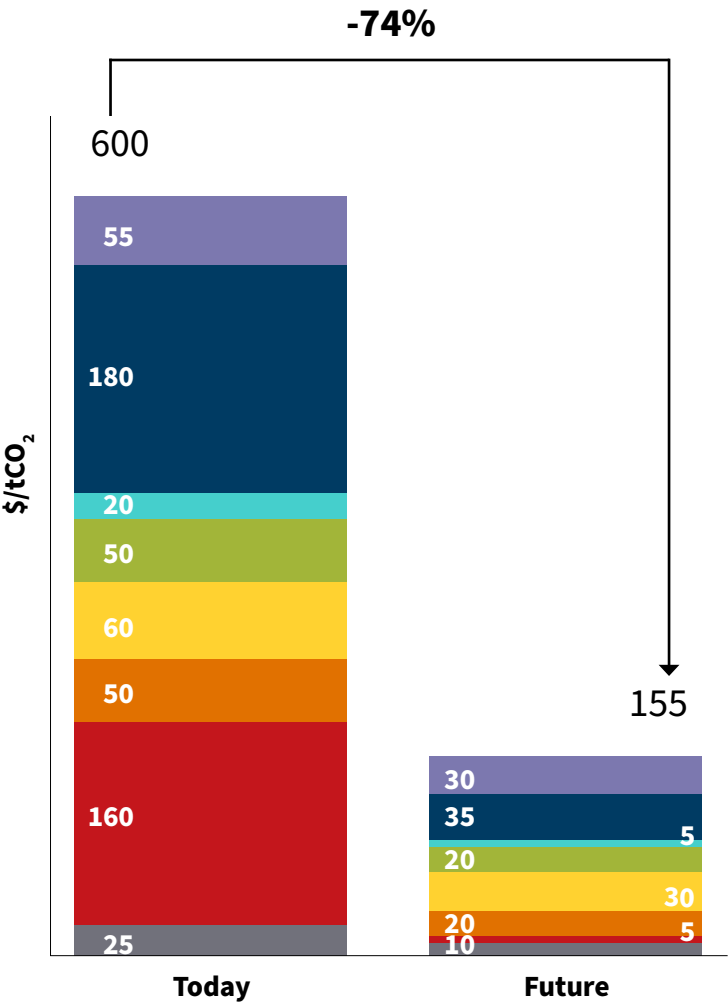
Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex	Equipment for crushing, grinding, and transporting minerals; site preparation; monitoring hardware	Process embedded in mine operations to share equipment cost, improve passive exposure, and create standardization
Energy	Electricity or fuel for crushing, grinding, and conveying equipment	Optimized material processing workflows, electrification with on-site renewables
Feedstock	Material procurement and characterization, losses during preprocessing	Integration into tailings processing
Transport	Mineral feedstock transportation, on-site redistribution, logistics	Integration into tailings processing on site, efficient electrified hauling
O&M	Labor for equipment operation and maintenance, management of dust and runoff	Automatic operation and monitoring, predictive maintenance for standardized processes, standardized permitting
Storage	Carbonation measurement and modeling, assurance buffers and liability	Scaled standardized operations reducing per-project risks
MRV	Mineral sampling, lab analysis, modeling and verification	Standardized protocols, remote sensing proxies, automated reporting through digital MRV
Embodied Emissions	Equipment and transportation emissions, equipment manufacturing	Electrification and direct integration into mine operations

Note about cost stacks¹

X Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- Direct integration into mine operations or mine site remediation procedures will provide case-by-case opportunities for equipment cost sharing and monetization of co-benefits such as impacts on dust and water management
- Passive vs. active tailings management trades energy and labor costs for carbon impact per ton of feedstock



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Integration across mine life cycle and process steps

Where to start: Integration into existing mine sites with range of tailings management processes



Integration into tailings management

Mines today already process, transport, and store significant quantities of alkaline minerals in the form of mine tailings. **Changing the mining industry standard** to integrate carbon removal into the way these tailings are managed could significantly accelerate the scale-up of mineralization-based CDR. **Existing mine tailings worldwide could remove over 0.5 GtCO₂/y** through mineralization. RMI's recently published Mining and Carbon Dioxide Removal roadmap describes the opportunities for integration of various CDR technologies into the mining industry in detail.¹

Current tailings management practices are optimized to minimize cost, dust, water loss, or operational complexity. Altering these practices or adding new process steps at the end of the mining workflow will require the identification of cost-effective technologies that can be implemented without major disruption to mining activities.² Beyond opportunities for cost sharing from capital expenditures, energy, and labor, research programs are exploring how carbon removal activities can be incorporated into mine practices and tailings storage facilities to improve safety, water management, and closure outcomes.³ Appropriate regulations and research support safe and effective implementation.⁴

Example KPIs:

- <\$5/ton of tailings managed in added incremental capital expenditures cost of project integrated into mine site
- 50% of mine site tailings processed for carbon removal



Dedicated feedstock

The viability of scaled BECCS to Fuels deployment hinges on the evolution of **markets for low-carbon fuels**. Today, the main biofuel market amenable to CCS integration is corn ethanol, which produces a high-purity CO₂ stream.⁴ In the long term, demand for corn ethanol is uncertain because alternatives to fuel mixing for decarbonized light-duty transport, such as battery-powered electric vehicles, are increasing in popularity. Current demand relies heavily on policy support mandating fuel mixing, with significant implications on agricultural land use and allocation of resources including water and fertilizer for non-food crops.

SAF and marine fuels are two alternative markets with significant demand for energy-dense liquid fuels, identified as high-priority applications for future sustainable biomass allocation with limited alternatives. Another promising but less mature opportunity is the direct gasification of biomass into syngas.⁵ Flexibility to produce a range of biofuels as demands shift may make the BECCS to Fuels approach a cost-effective technology in different future niches. Direct enforcement of green fuel use or indirect policies such as carbon pricing could provide consistent demand for the fuel coproduct.

Example KPIs:

- \$200/tCO₂ cost of carbon removal through dedicated quarrying, trading off extraction costs with site optimization
- 90% of feedstocks processed and stored on site



Accelerated mineralization

Surficial mineralization for carbon removal relies on increasing the rate or capacity of naturally occurring carbonation reactions. Some project implementations rely on turning mine tailings piles to expose more surface area to the atmosphere, while other technologies under consideration use increasingly engineered pretreatment and processing steps to enhance reactivity.

There are **economic trade-offs** between low-cost passive approaches and high-cost active processes. Parameters such as rock type, particle size, pile structure, aeration, water management, and preconditioning of feedstock all influence mineralization rates and capacities.

Additionally, some **baseline mineralization** occurs in the absence of human intervention. Correctly establishing this counterfactual rate is an essential component of measuring and accounting a mineralization-based carbon removal project.⁵

Example KPIs:

- >0.1 tCO₂/t tailings/year accelerated mineralization rate through engineered acceleration
- >200 tCO₂/hectare/year passive mineralization above baseline

1. [Mining and Carbon Dioxide Removal: A responsible path forward for mine operators, policymakers, and other key stakeholders](#), RMI, 2026. **2.** [Mineral Carbonation using Mine Tailings – A Strategic Overview of Potential and Opportunities](#), IEAGHG, 2022. **3.** See, for example, the [SCO₂UT](#) project hosted by the University of British Columbia. **4.** For a detailed discussion of policy and regulatory support for gCDR technologies, including in mine and industrial waste sites, see [Carbon Mineralization Needs Greater Policy Support to Reach Carbon Removal Potential](#), WRI, 2023. **5.** See, for example, the Isometric protocol for [Open System Ex-situ Mineralization](#).



Advancement and breakthrough areas

Key research areas
Automated feedstock processing, weathering accelerants, and regional feedstock mapping tools

Crosscutting gCDR breakthrough themes¹

G1: Biogenically enhanced reactions

The incorporation of microbial treatments for feedstocks chosen for surficial mineralization could improve baseline reactivity rates and potentially reduce needs for extensive preprocessing.

G3: Autonomous deployment

By utilizing drones and electrifying autonomous components for processing, grinding, and spreading SM feedstocks, operations could reduce their embodied carbon and labor costs.

G4: On-site mineralization

Focusing surficial mineralization projects at sites where large feedstock deposits are present, such as mine sites, reduces emissions and costs from transport.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Autonomous, solar-powered vehicles for feedstock manipulation	Rovers and terrestrial vehicles that can operate autonomously and continuously to reduce labor intensity and minimize impacts on mining operations	\$\$ Reduced O&M cost from labor reduction, cost savings from fuel switch	New and existing mine sites		Mining companies, robotics companies, autonomous equipment OEMs, solar developers, battery/storage providers, geotechnical engineers, mine safety regulators
2	Optimized tailings storage design at CDR mine sites	Tailings storage at mine sites is designed with CDR in mind, with processes such as crushing, circulation, and addition of any accelerant agents co-optimized for mineralization prior to spreading	\$\$\$ Cost savings from transport and process simplification compared to retrofits	New mine sites		Tailings engineers, geotechnical consultants, mine closure/remediation firms, geochemists, hydrologists, environmental regulators, local communities, CDR developers
3	Low-cost, environmentally safe accelerant sprays for increased carbonation rates	Development of accelerant treatments that accelerate feedstock reactions to reduce time to delivery and increase feedstock turnover	\$\$ Cost savings from increasing reaction rates and ability to carbonate larger volumes of feedstock per unit time	All future and existing projects		Chemicals companies, geochemists, environmental toxicologists, water-quality experts, agricultural/industrial sprayer OEMs, regulators, community groups
4	Automated MRV in deployment sites	Remote sensing to reduce the need for manual sampling on site and validate models	\$\$\$ Reduced labor intensity of sample collection and analysis; increased sampling rates	Future regional project efforts		Sensor developers, engineers, CDR providers, MRV platform developers, registries, third-party verification bodies
5	Robust bioengineered microbes that accelerate reaction rates	Development of bioengineered microbial treatments that are effective in extreme pH and contaminated solutions to increase conversion efficiency in mine tailings ponds	\$\$ Reduced energy usage for feedstock manipulation and increased weathering rates lead to higher removals efficiencies	Mine tailings ponds projects		Synthetic biology companies, microbial biotech firms, universities, national labs, soil microbiologists, geochemists

1. See [page 22](#) for more detail on crosscutting opportunities for breakthroughs in geochemical CDR, including assessments of the technical and social difficulty of implementation.



Enhanced Rock Weathering

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 5.1: Terrestrial Enhanced Weathering
- 5.2: Coastal Enhanced Weathering

DEFINITION

Enhancing the natural capacity of alkaline feedstocks to passively react with atmospheric CO₂ and water — through a combination of crushing, grinding, spreading, heating, or other physical or chemical means — to produce dissolved inorganic carbon that is eventually stored in lakes, rivers, and oceans.

APPROACH OVERVIEW

Though alkaline minerals have been applied to farmlands to improve crop yields and manage soil pH for decades, EW for CDR first emerged as a concept in the 1990s when research suggested that silicate minerals could be leveraged for controlling atmospheric CO₂ levels. Since then, EW has become a leader in the geochemical CDR sector. As of 2026, EW companies have garnered some of the largest offtake commitments from CDR investors, with recent agreements surpassing 150 ktCO₂. If sector growth continues, EW could see cumulative capacity near 6 MtCO₂/y by 2030.

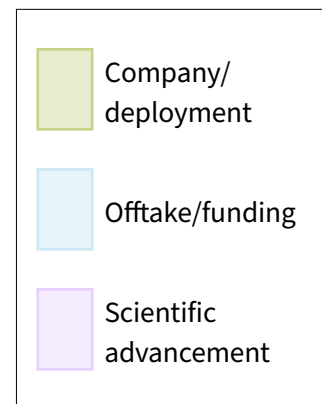
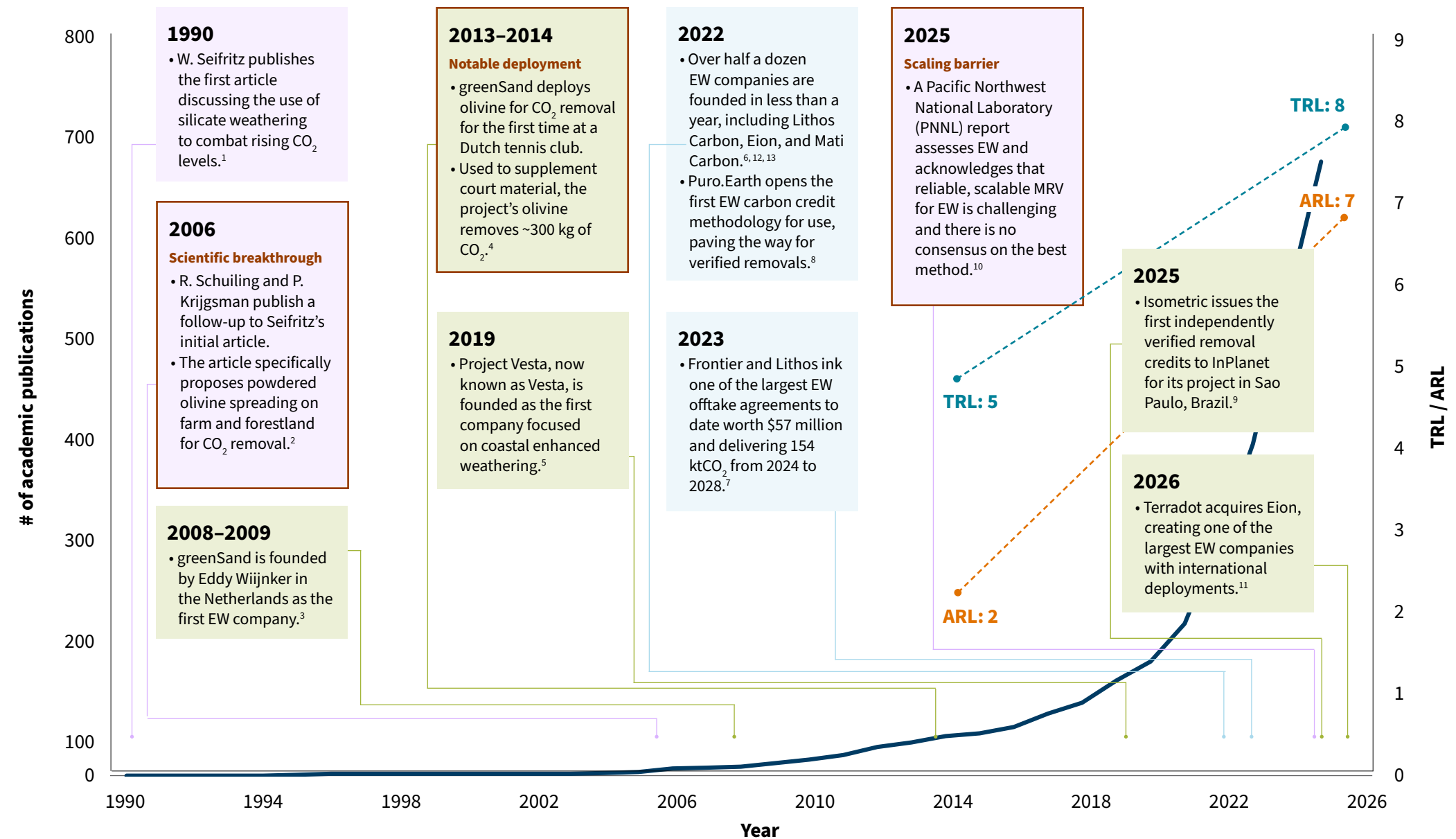


How we got here

Status: Significant progress toward commercial-scale deployment

Approach trend: Positive

Milestones selected for the graph were chosen based on their impact on and significance to enhanced rock weathering sectors.



1. W. Seifritz, "CO₂ disposal by means of silicates," *Nature*, 1990. 2. R.D. Schuiling and P. Krijgsman, "Enhanced Weathering: An Effective and Cheap Tool to Sequester CO₂," *Climatic Change*, 2006. 3. [Our Story - Greensand](#) - greensand. 4. "Tennis club TC de Kijkers: cleans up 300 kg of CO₂," greensand, 2013. 5. [Vesta - Crunchbase Company Profile & Funding](#). 6. [Lithos Carbon - 2026 Company Profile, Team, Funding & Competitors](#), Tracxn. 7. "Frontier buyers sign world's first enhanced weathering offtake agreements with Lithos Carbon," Frontier, 2023. 8. "Puro.earth Enhanced Rock Weathering Methodology Approved," UNDO, 2022. 9. "World's first independently verified Enhanced Weathering credits," Isometric, 2025. 10. H.T. Schaef and M. Villante, "Voucher Opportunity 5-15: Independent Assessment of Monitoring, Reporting, and Verification (MRV) Technologies and Practices for Enhanced Rock Weathering (CRADA 718) Abstract," Pacific Northwest National Laboratory, 2025. 11. "Terradot Acquires Eion to Form Leading Global Enhanced Rock Weathering Carbon Removal Platform," *Businesswire*, 2026. 12. [Mati - 2026 Company Profile, Team, Funding & Competitors](#), Tracxn. 13. [Eion - 2026 Company Profile, Funding & Competitors](#), Tracxn.



Current and projected state of deployment

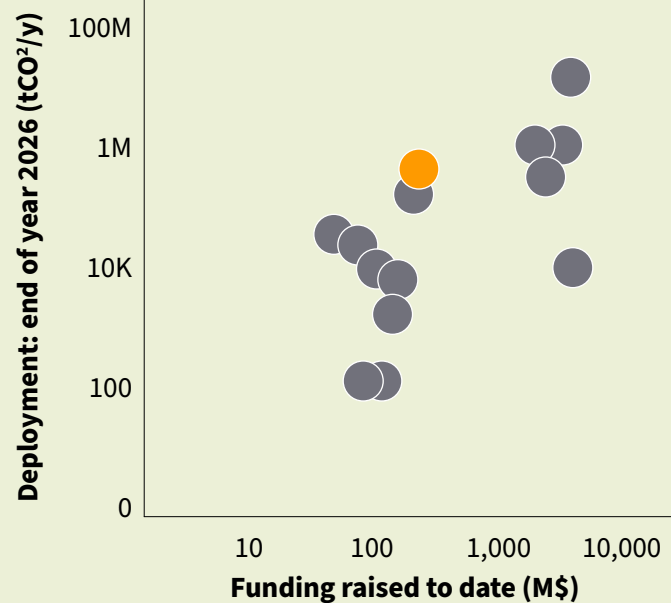
Past 5 years

Commercial ventures emerged, deploying pilots and finalizing FOAK crediting methodologies

Next 5 years

Companies look to leverage integration with heavy industry to reach scaled deployment

Current deployment



24

companies tracked¹

26

projects active/announced

TRL 8

Expanding commercial deployments

ARL 7

High readiness

Current cumulative removals

~165,000

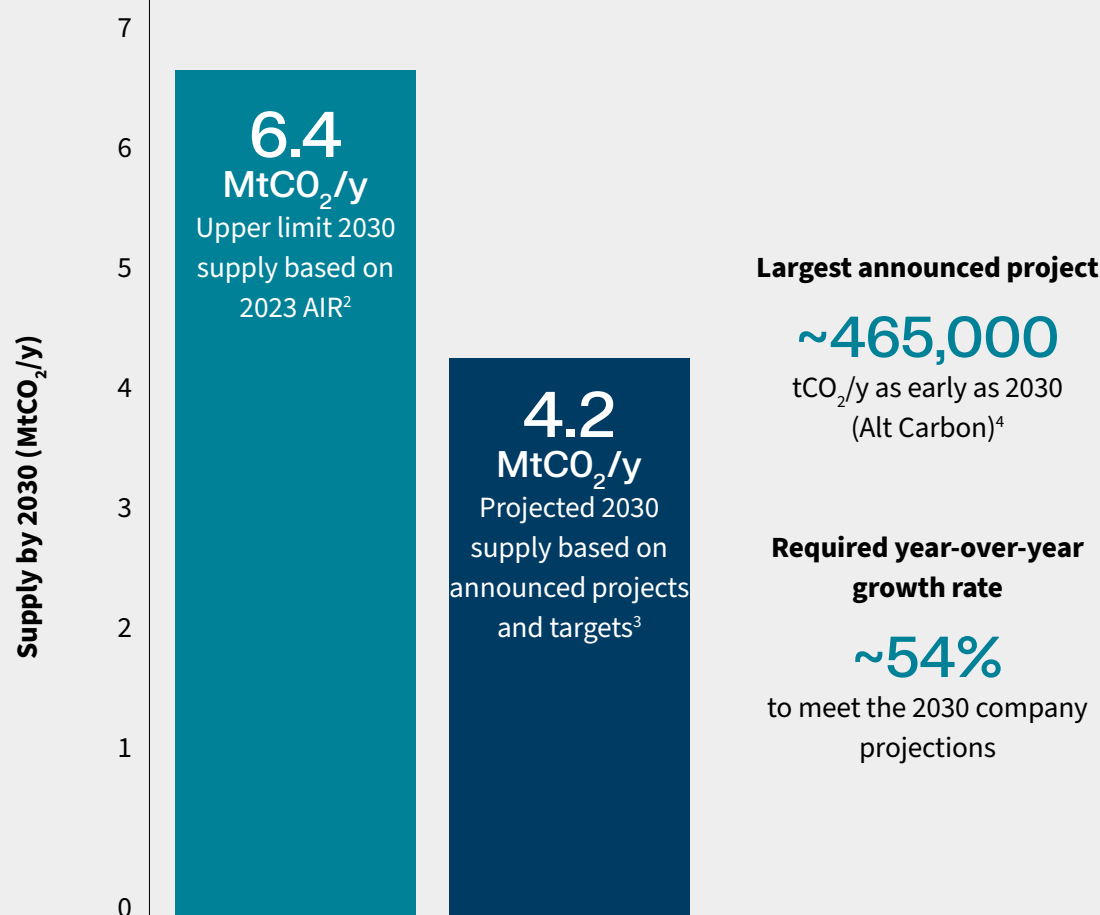
tCO₂ as of end-of-year 2025¹

Largest active project

~20,000

tCO₂/year as of 2025⁶

Supply projections for 2030



Announced and active projects as a percentage of 2030 company targets

17%

1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies, and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference capacity of 6.4 MtCO₂/y is sourced directly from the DAC “success story” for both TEW and CEW in [The Applied Innovation Roadmap for CDR](#), RMI, 2023 (p. 168 and 178). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. [“Restoring darjeeling’s soils through carbon removal,”](#) Alt Carbon, 2024. 5. [“Mati Carbon Is The Grand Prize Winner Of The Xprize Carbon Removal Competition,”](#) Mati Carbon, 2025. 6. [“Flux in Cameroon: lowering fertilizer costs for a huge agricultural project,”](#) Flux Carbon, 2025.



Key cost drivers

Major cost drivers

MRV, equipment energy use, feedstock transport

Improvement areas

MRV standardization, process automation

Today: \$220–\$520/tCO₂

Future: \$90–\$180/tCO₂

50%–70% cost reduction possible via improved and standardized MRV, scaled and optimized feedstock supply chains, and process automation.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

Today's cost range (0-120, \$/tCO₂)
Future cost range (0-120, \$/tCO₂)

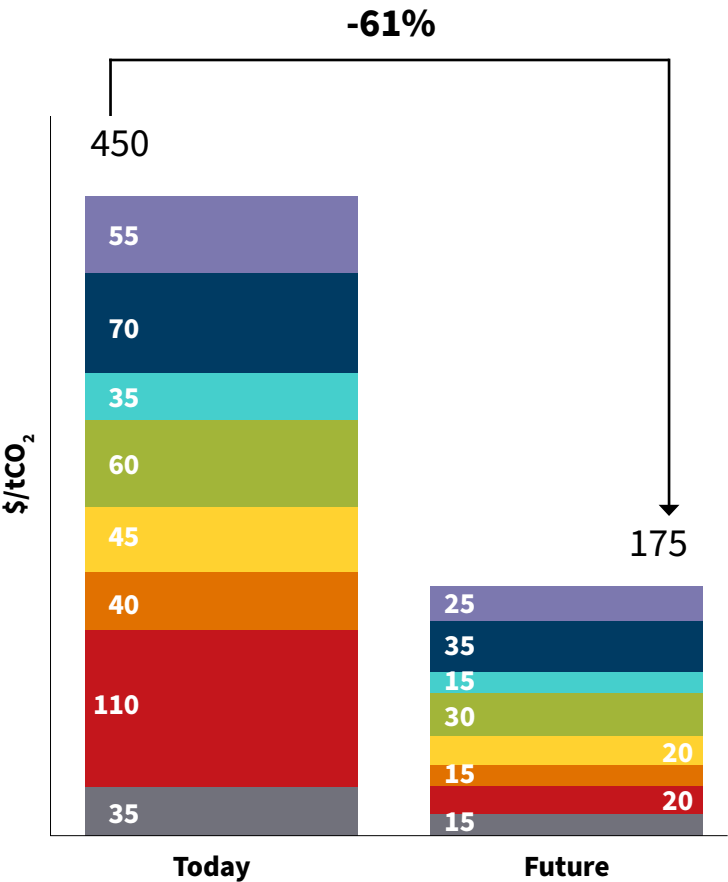
Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex	Equipment for crushing/grinding feedstock, mobile spreading equipment, sensors, cost of financing	Use of more reactive feedstocks (e.g., carbonates), equipment sharing
Energy	Crushing/grinding of rocks, fuel for spreading on agricultural land or coastlines	Use of more reactive feedstocks at larger particle sizes, more efficient electrified vehicles
Feedstock	Alkaline mineral feedstocks (rocks) from dedicated quarrying or suitable tailings, preprocessing at extraction site	Colocation with sources of reactive minerals or suitable waste materials, use of cheaper feedstocks (e.g., carbonates)
Transport	Transportation (truck, rail, or barge) of rocks to deployment site, spreading	Optimized project and feedstock source colocation, scaled feedstock supply chain and transportation infrastructure
O&M	Labor, equipment maintenance	Automated equipment, scaled operations within agricultural processes
Storage	Risk buffering, weathering rate modeling, long-term durability assurance, permitting costs	Reduced uncertainty from improved knowledge of long-term fate of carbon
MRV	Sample collection and analysis, modeling of long-range and long-term impacts, third-party verification	Automated and improved field sensors for alkalinity and ion measurements, standardized protocols, aggregated monitoring
Embodied Emissions	Diesel emissions from transportation and grinding processes, equipment manufacturing	Electrified logistics

Note about cost stacks¹

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- Both coastal and terrestrial projects require scaled and optimized reactive feedstock supply chains colocated with projects
- Established long-term and long-range modeling and monitoring to track the fate of carbon is needed to unlock cheaper and more reliable MRV
- The use of recycled or integrated feedstocks, such as tailings waste, likely introduces governance and permitting complexities



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Standardized integration into activities such as agriculture and coastal infrastructure improvements

Where to start: Watershed-scale measurement and monitoring of carbon fates



MRV advancements

The heterogeneous spatial and temporal scales of monitoring and measurement related to EW deployment make MRV a key cost driver for project development. This includes sampling soil or water at deployment sites, as well as monitoring or modeling the path of downstream carbon in ocean systems. Current MRV frameworks stress the importance of measurement of weathering and bicarbonate formation in the absence of sufficiently reliable models.¹

Advances in **process-based modeling accounting for the relationship between near-term alkalinity changes and net carbon sequestration** are a key for lowering costs. Appropriate densities and frequencies of field data would allow interpolation across sites and over time, reducing MRV costs as uncertainties decrease. Costs at scale would decrease if dense soil sampling can be replaced with interpolation and remote sensing, though verification through some measurements will continue to be required.

Standardized **quantification and data sharing across projects** will increase trust and enable shared learning for efficient and sustainable deployments.² This is particularly key as the approach scales to more regions and industries.

Example KPIs:

- <20% uncertainty of carbon removals
- Watershed-scale mass balance within 30%
- MRV costs <\$15/tCO₂



Dedicated feedstock

Feedstock extraction and transportation are key cost drivers of enhanced weathering projects, with several tons of feedstock needing to be deployed for every ton of CO₂ removed. Local sourcing reduces transportation costs and embodied emissions associated with transportation. This requires the creation of **regional supply chains of minerals** that can be locally sourced and processed into a form proven to undergo efficient reactions on deployment sites.

Small-scale CDR projects sourcing feedstock through individual purchase agreements with quarries pay a premium because their demand volumes are small compared with competing industries. This also makes it difficult to negotiate feedstock parameters such as small grain sizes or testing for specific contaminants. Feedstock costs decrease with larger demand as the supply chain becomes more optimized through regional mineral happing and processing hubs.

Scaled deployment also enables dedicated quarrying of optimal feedstocks. Feedstock selection will hinge on trade-offs between reactivity, environmental performance, ease of processing and transportation, local availability, and public support for increased quarrying activity.

Example KPIs:

- Average transport distance to deployment <100 km
- Feedstock costs <\$20/tCO₂
- Removal efficiency >0.5tCO₂/t of feedstock



Integration into agriculture

Integration into **land management practices already operating at global scales**, such as agriculture or coastal activities including beach nourishment, is a key lever to deployment. This offers both capacity increases through access to large land areas and cost decreases through shared labor costs because EW is an operating expenditures-dominated approach. In an agricultural context, terrestrial EW is equivalent to established liming practices,³ allowing deployment to leverage existing infrastructure, local expertise, and operational practices. Co-benefits can incentivize deployment and decrease costs, including through improvements to soil health, soil pH management, and improved nutrient use efficiency reducing fertilizer demand and the environmental aggregation associated with fertilizer runoff.⁴

Pilot projects are already applying EW feedstocks using conventional spreaders.⁵ Ongoing RD&D will explore and address constraints such as differences in optimal particle sizes and the potential for precision spreading through integration with existing digital farm management systems. So-called **precision agriculture solutions** enable deployment sensitive to in-field heterogeneity of soil quality, improving both carbon removal rates and soil health impacts.

Example KPIs:

- <20% increase in operation time/cost over baseline liming
- <5% yield penalty based on seasonality of deployment balancing growth period impacts against soil health gains

1. [Enhanced Weathering at Isometric](#), Isometric, 2025. **2.** [Foundations for Carbon Dioxide Removal Quantification in EW Deployments](#), Cascade Climate, 2024. **3.** For a more detailed exploration of implementing EW as a substitute for existing liming practices, see Scaling enhanced weathering in limed fields, Carbon Plan, 2025. **4.** Some reviewers believe that co-benefits may outpace carbon credits as income sources for EW projects, whereas others believe that co-benefits, even when accurately monetized, will not be sufficient to fund scaled deployment. **5.** Examples include projects deployed by [UNDO Carbon](#) and [Eion](#).



Advancement and breakthrough areas

Key research areas
Microbes to improve reactivity and weathering rates, automated MRV

1. See [page 22](#) for more detail on crosscutting opportunities for breakthroughs in geochemical CDR, including assessments of the technical and social difficulty of implementation. 2. Ecosystem benefits include impacts on coastal and riparian ecosystems from reduced runoff, improved soil health, and reduced acidification. Agricultural benefits include increased crop yield, improved soil health, and reduced fertilizer use. For an exploration of opportunities to integrate carbon removal into agricultural subsidy programs, see [Enhanced Weathering and Working Lands](#), Carbon Removal Standards Institute, 2026. 3. Reviewers note that this includes impacts on GHG other than CO₂, including reduced methane and nitrous oxide emissions from treated land. 4. Identifying biologicals that increase weathering rates requires screening libraries of microorganisms for relevant modes of action and/or modifying their genome to enhance their functionality before trialing field deployment scenarios with specific crop types and soil conditions.

Crosscutting gCDR breakthrough themes¹

G1: Biogenically enhanced reactions

The use of microbes to inoculate feedstocks for EW could improve baseline reactivity rates and can be used to weather pre-existing silicates in alkaline soils, increasing deployment ranges.

G2: Industrial integration

Integrating EW into existing, large-scale operations, such as industrial agriculture, could improve removal efficiency, increase throughput, and lower capex and opex barriers to scale.

G3: Autonomous deployment

Utilizing drones and electrifying transport for processing, grinding, and spreading EW feedstocks on coasts, farm fields, or in forests could reduce process emissions and labor costs.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Characterization and monetization of agricultural and ecosystem co-benefits ^{2,3}	Improved understanding of how impacts vary by crop and soil type as well as timing of feedstock application helps target deployments for climate benefit and establish revenue streams beyond carbon credits	\$\$ Cost share with farmers or agricultural subsidies for improvements to soil health	Terrestrial projects		Farmers and other land managers, soil scientists, agronomy experts, policymakers, regulators
2	Low-cost MRV solutions with sufficient data density for removals verification	MRV improvements including large-scale automated MRV sharing costs across many projects with central long-range (e.g., satellite) monitoring or remote sensor networks	\$\$\$ Reduced cost and improved certainty from MRV systems	All projects (terrestrial and coastal)		Sensor manufacturers, project developers, geospatial analytics firms, carbon removal registries and standards bodies, regulators
3	Biologically accelerated weathering ⁴	Co-deploying microbes enhancing rock dissolution rates can improve deployment efficiency and save energy from particle grinding	\$\$ Improved deployment efficiency, including through informed siting and seasonality decisions	Terrestrial projects		Academic researchers including ecologists and soil microbiome experts, project developers
4	Improvements in feedstock reactivity	Regionally optimized choices in composition, particle size, and possible pretreatment of feedstock can increase carbon drawdown per ton deployed and increase weathering rates	\$\$ Improved deployment efficiency	All projects		Geochemists, soil scientists, project developers, engineers
5	Comprehensive process electrification	Electrified and partially automated machinery reduces embodied emissions and improves project uptimes	\$ Reduced embodied emissions from fuel	All, particularly terrestrial projects		Agricultural equipment and heavy machinery manufacturers, electric vehicle companies, renewable energy generation and storage developers, farmers and other land managers

\$ \$1–\$30/tCO₂ **\$\$** \$20–\$50/tCO₂ **\$\$\$** \$40–\$100/tCO₂ **\$\$\$\$** \$75–\$300/tCO₂



Mineral Alkalinity Enhancement

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 5.3: Mineral Alkalinity Enhancement

DEFINITION

Direct addition of alkaline minerals or solutions to lakes, oceans, rivers, wastewaters, or other bodies of water to increase the alkalinity of the water and its capacity to absorb CO₂.

APPROACH OVERVIEW

Despite MAE first being proposed over 30 years ago (Khesghi 1995), RD&D was slow to emerge and it is still a relatively nascent technology. The first company in the field, Planetary Technologies, was founded in 2019. By 2023, the first successful in situ MAE trial took place in Halifax, Nova Scotia, Canada. As of 2026, more than half a dozen MAE companies have been founded, with removal projections indicating that annual capacity could feasibly reach more than 150 ktCO₂/y by 2030.

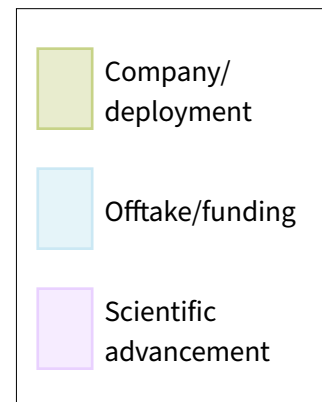
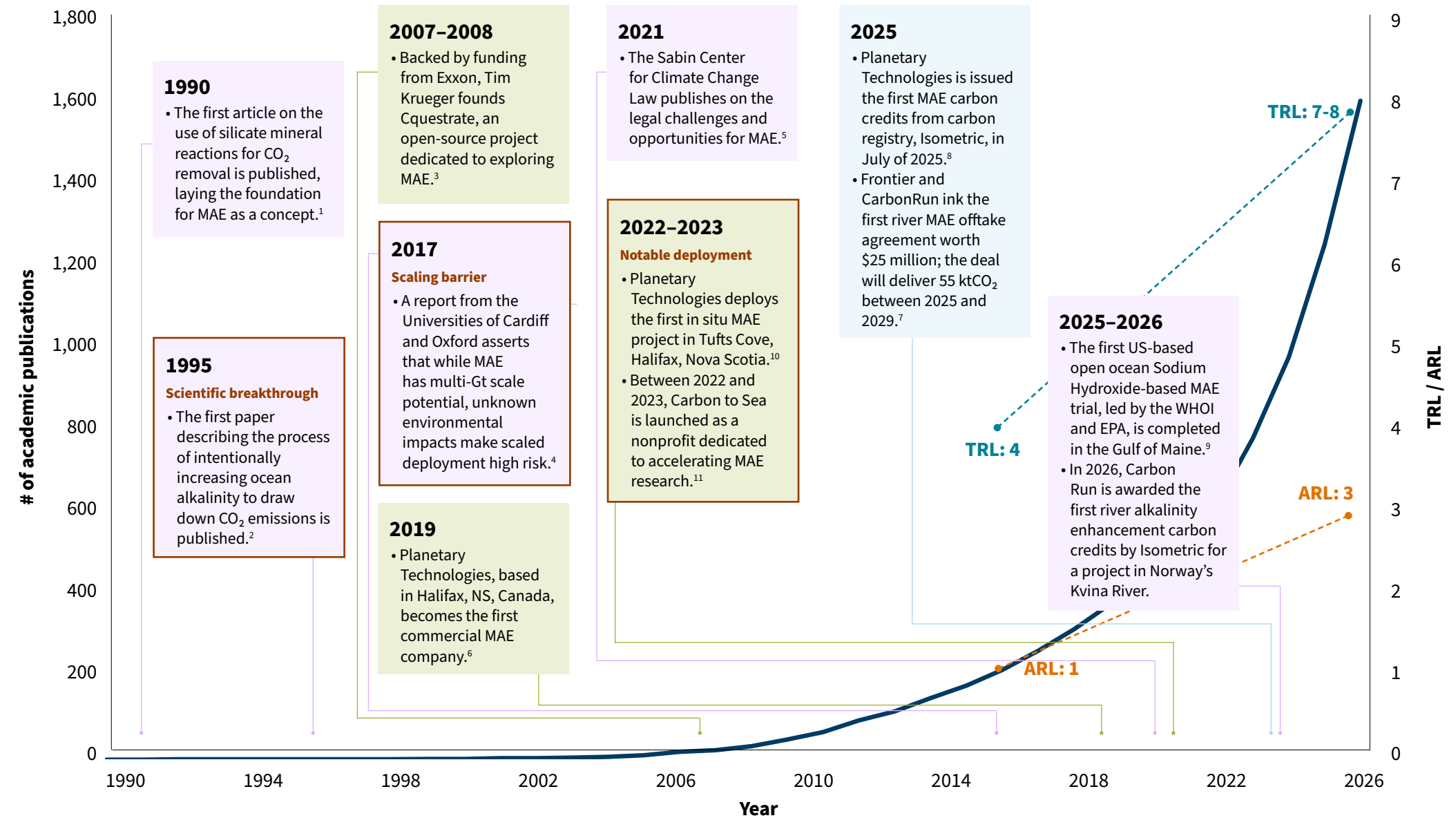


How we got here

Status: Expected progress toward demonstration-scale deployment

Approach trend: Neutral

Milestones selected for the graph were chosen based on their impact on and significance to Mineral Alkalinity Enhancement sectors.



1. W. Seifritz, "CO₂ disposal by means of silicates," *Nature*, 1990. 2. H. Kheshgi, "Sequestering atmospheric carbon dioxide by increasing ocean alkalinity," *Energy*, 1995. 3. "New Geoengineering Scheme Tackles Ocean Acidification, Too," *Wired*, 2008. 4. P. Renforth et al., "Assessing ocean alkalinity for carbon sequestration," *Reviews of Geophysics*, 2017. 5. R. Webb et al., "Removing Carbon Dioxide Through Ocean Alkalinity Enhancement: Legal Challenges and Opportunities," *CDR Law*, 2021. 6. *About, Planetary Technologies*. 7. "Frontier buyers sign world's first river liming carbon removal deal with CarbonRun," *Frontier*, 2024. 8. "How the world's first Ocean Alkalinity Enhancement credits were quantified," *Isometric*, 2025. 9. "Preliminary results from the first EPA-permitted ocean alkalinity enhancement (OAE) field trial," *Woods Hole Oceanographic Institute*, 2026. 10. *Tufts Cove | Projects | Planetary Technologies*. 11. "\$50+ Million 'Carbon to Sea Initiative' Will Accelerate Research into Ocean Alkalinity Enhancement, a Promising Carbon Dioxide Removal Approach to Combat Climate Change," *Carbon to Sea Initiative*, 2023. 12. "CarbonRun Generates World's First River Alkalinity Enhancement Credits," *Carbon Herald*, 2026.



Current and projected state of deployment

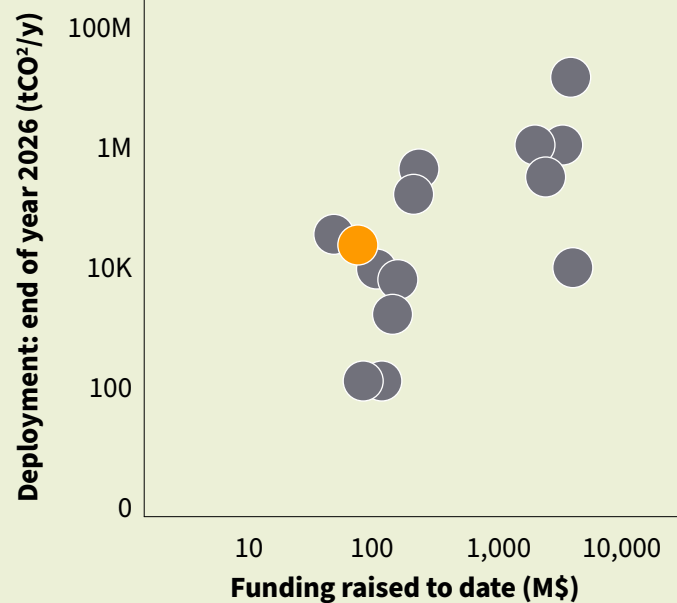
Past 5 years

MAE developers founded companies, moved trials out of the lab, and began FOAK deployments

Next 5 years

Success of early FOAK projects have led companies to set ambitious targets for 2030

Current deployment



Database includes six companies founded within the past five years.

Recent funding successes include CREW Carbon's \$32 million offtake deal with Frontier in December 2024 for 78 ktCO₂.⁵

2026 funding: **\$56 million¹**
2026 capacity: **33 ktCO₂/y¹**

● MAE approaches
● Other CDR approaches

8
companies tracked¹

16
projects active/
announced

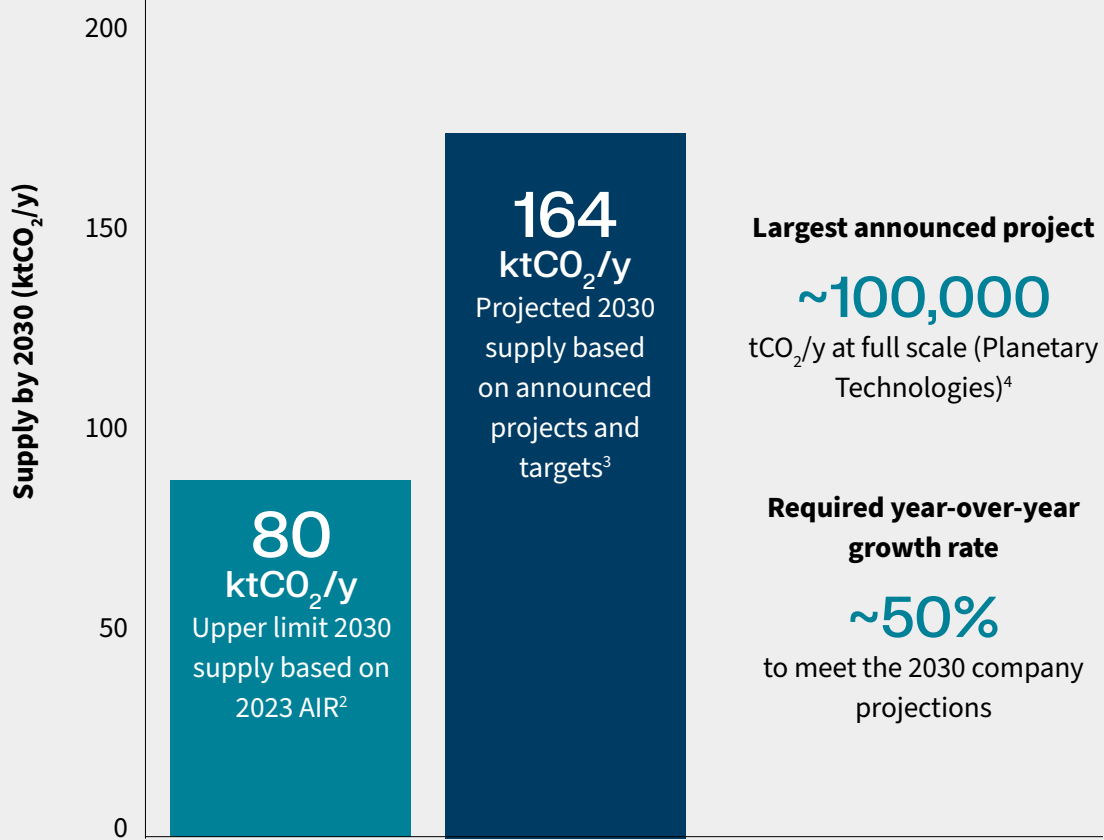
TRL 7-8
Demo- and
commercial-scale
deployments

ARL 3
Low
readiness

Current cumulative removals
~53,000
tCO₂ as of end-of-year 2025¹

Largest active project
~25,000
tCO₂/year as of 2025⁶

Supply projections for 2030



Announced and active projects as a percentage of 2030 company targets



1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies, and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. **2.** Reference removal capacity of 80 ktCO₂/y is directly sourced from the MAE “success story” in [The Applied Innovation Roadmap for CDR](#), RMI, 2023 (p. 189). **3.** Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. **4.** [Tufts Cove | Projects | Planetary Technologies](#). **5.** [“CREW Delivers First Verified WAE Carbon Credits to Frontier Buyers,”](#) CREW Carbon, 2025. **6.** [Projects, CREW Carbon](#).



Key cost drivers

Major cost drivers

Feedstock production, processing, and distribution; MRV

Improvement areas

Scaled optimized supply chains, remote sensing, ocean models

Today: \$200–\$300/tCO₂

Future: \$60–\$130/tCO₂

50%–70% cost reduction possible via establishment of scaled, optimized feedstock supply chains and improved ocean models for MRV.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

Today's cost range (0-100, \$/tCO₂)
Future cost range (0-100, \$/tCO₂)

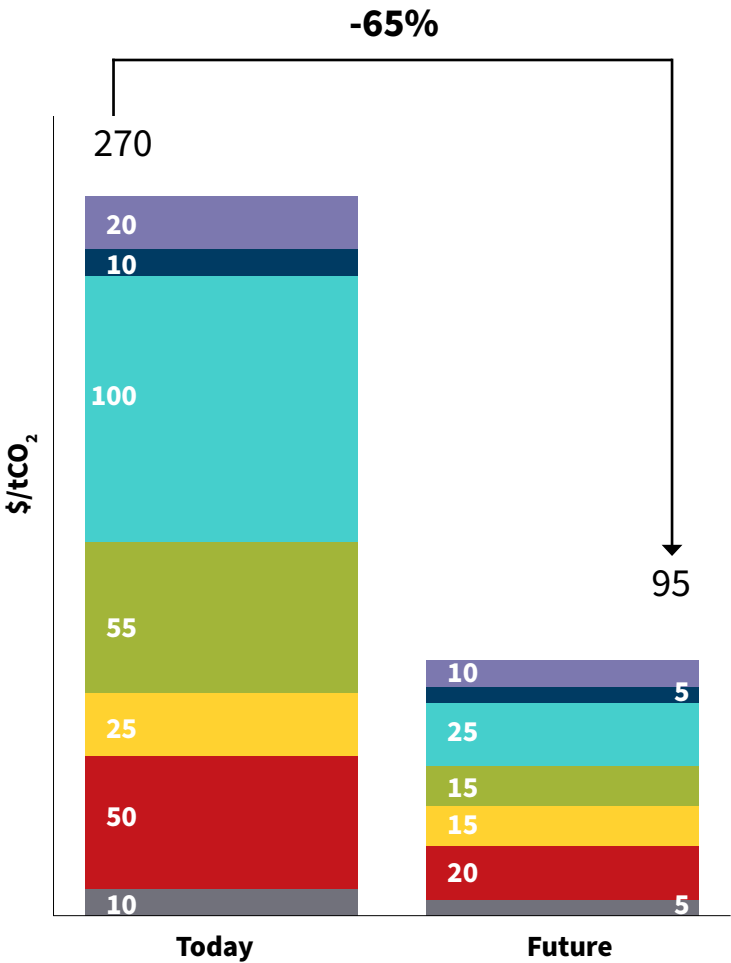
Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex	Alkalinity and mineral handling / dosing equipment, coastal infrastructure	Modular, mass-manufactured systems, multiuser hubs
Energy	Alkalinity and mineral processing, pumping, slurry transport	Optimized material selection, scaled operation
Feedstock	Alkalinity and mineral procurement, pretreatment, conditioning	Optimized conditioning, use of industrial by-products
Transport	Mineral transport, port handling and storage	Efficient local supply chains, scaled operation
O&M	Labor, maintenance, environmental compliance, permitting compliance	Automation, repeatable project and permitting structures
Storage	Possible storage cost from buffer pools and other insurance mechanisms	Possible storage cost from buffer pools and other insurance mechanisms
MRV	Water chemistry monitoring, tracer studies, modeling and third-party verification of ocean impacts	Improved ocean modeling reducing per-project measurement intensity, remote sensing
Embodied Emissions	Mineral and alkalinity processing and transportation emissions	Decarbonized excavation equipment and transportation

Note about cost stacks¹

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- MRV at scale requires suitable combination of measurement and ocean system modeling
- Dedicated quarrying near project sites is only feasible at large scales but would significantly decrease costs
- River deployment carries additional local co-benefits through habitat remediation and localized reversal of river acidification



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Coastal or open-water deployments with public acceptance and responsible governance¹

Where to start: Deployment integrated into water outflows; local and regional ocean impact modeling improvements



Coastal feedstock supply

Feedstock extraction and transportation are key cost drivers of MAE, with several tons of feedstock needing to be deployed for every ton of CO₂ removed. Scaled deployment will be most cost-effective if ideal feedstock types can be sourced near ports or barge access sites, which also reduces the embodied emissions associated with transportation. This requires **regional supply chains** of minerals processed into a form proven to undergo efficient dissolution into usable alkalinity in the conditions set by local ocean systems.

Feedstock costs will decrease with scaled deployment as supply chains become more standardized and optimized through regional mineral processing hubs.² Safe industrial waste products would reduce the need for new quarrying.

Feedstock selection will hinge on trade-offs between reactivity, environmental performance, ease of processing and transportation, and local availability. Smaller particle sizes typically increase dissolution rates, but they may prove challenging to produce and transport and may pose health risks that require management. Similarly, preprocessing steps such as thermal activation or hydration can increase reactivity but carry additional labor and energy costs.

Example KPIs:

- Average transport distance to deployment <100 km
- Feedstock costs <\$30/tCO₂
- One-year removal efficiency >0.5 tCO₂/t of feedstock



Marine infrastructure integration

Another key cost driver of MAE projects is the **high cost of marine equipment and logistics**. Using existing infrastructure, as well as integrating into industries such as water treatment, shipping, and coastal cooling water systems could provide significant cost sharing.

For coastal or inland deployments, **dosing alkalinity into existing water outflows**, such as treated municipal or industrial wastewater, can take advantage of existing pumping, mixing, and water monitoring processes, providing energy and capex savings.³ These facilities are already permitted to release water after restoring it to a state safe for release, which may improve project timelines in regions where water release is strictly regulated compared with establishing permitting pipelines for new stand-alone projects.

For open water deployments, integration may mean dosing alkalinity from ships moving along existing shipping lanes by reserving a fraction of cargo volumes for MAE feedstock and equipment. Using existing ships and logistics networks eases project startup and maintenance. Workforces in seasonal industries, such as fishing, may provide a pool of skilled laborers in the off-season.

Example KPIs:

- Capex <\$30/tCO₂ through cost sharing with existing infrastructure
- >25% of deployments integrated into existing industries



River and ocean models

Robust ocean modeling remains a foundational scientific pillar for the deployment of open-system marine CDR approaches.⁴ Key modeling needs include tracking dissolution rates as a function of regionally varied ocean geochemistry, ocean currents impacting whether alkalinity remains in surface water, vertical carbon transport, and long-term fates of formed bicarbonates. Additionally, **ecosystem impact** modeling that considers nutrient cycles and benefits of local ocean acidification reversal is needed to ensure safe, responsible deployment, as well as to inform unresolved questions on regulations and international governance related to open ocean deployments. Deployment in rivers and closed systems may ease project monitoring.

For early deployments, measurement-informed modeling approaches will be important to monitor climate benefits as well as ecological safety. At larger scales, validated **regional and basin-scale models** tied to ground-truth data can significantly reduce MRV costs while increasing our understanding of how multiple projects deployed within a given region interact.⁵ Autonomous alkalinity measurements captured during a variety of MAE field trials should be used to inform and calibrate higher-resolution models.

Example KPIs:

- <5% uncertainty in net CO₂ removed on 100+ year timescale
- <\$10/tCO₂ MRV cost through combination of measurements and regional high-resolution models

1. Though this report focuses on technological and process innovations, it is important to note that public acceptance and successful governance remain key for responsible CDR deployment, particularly open-system approaches such as MAE. For some additional discussion of this topic, see Section 6: Microalgae in Open Water. **2.** Some reviewers note that use of those feedstocks already mined at scale today will have flat or negative economies of scale. Others note that per-project feedstock costs are high even for established materials as suppliers are used to larger-scale buyers. **3.** For a more detailed discussion on the opportunities and synergies available, see Harnessing Carbon Removal Opportunities in Wastewater Treatment, RMI, 2026. **4.** Coarse-resolution models of MAE impacts are available (see, for example, Mapping the efficiency of ocean alkalinity enhancement, Carbon Plan, 2024), with future work intending to improve resolution to regional and basin-scale domains. Such models should be combined with data from real-world projects in several geographies to verify and build on project MRV practices. **5.** P. Halloran et al., “Seawater carbonate chemistry based carbon dioxide removal: towards commonly agreed principles for carbon monitoring, reporting, and verification,” *Frontiers in Climate*, 2025.



Advancement and breakthrough areas

Key research areas
Autonomous dosing and pH-sensing technology, engineered feedstocks

1. See [page 22](#) for more detail on crosscutting opportunities for breakthroughs in geochemical CDR, including assessments of the technical and social difficulty of implementation.

2. Though breakthroughs discussed in this report generally focus exclusively on technological and process innovations, reviewers note that all innovation related to alkalinity release in the open ocean face significant permitting and legal considerations, affecting viability and cost, meaning developments in governance structures are also critical to scaled deployment and any process improvements resulting in per-ton cost savings.

Crosscutting gCDR breakthrough themes¹

G2: Industrial integration

Integrating MAE into large-scale infrastructure, such as wastewater treatment plants, could increase removal capacity and lower capex and opex barriers to scale.

G3: Autonomous deployment

Utilizing drones for depositing MAE feedstocks in ideal offshore locations, particularly those most prone to acidification, could reduce process emissions and increase rate of removal.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Offshore dosing systems integrated into international shipping corridors ²	Dosing systems integrated into shipping enabling distributed capex and labor costs and allow dosing across wide areas, reducing saturation limitations	\$\$ Shared infrastructure and transport, increased deployment range	Distributed projects integrated into shipping		Shipping companies, port authorities, maritime regulators, shipbuilders and marine engineers, oceanographers, national governments
2	Mineral dissolution and precipitation models informing impact of alkalinity dosing	Validated models incorporating ocean biogeochemistry, currents, and air-sea gas exchange, integrated into regional ocean models, allow for targeted deployments ensuring dissolution of feedstock rather than sinking	\$\$ Reduced removals uncertainty and improved efficiency of feedstock deployment	All projects		Ocean scientists, ocean model developers, ecologists, MRV platform developers
3	Advanced dosing system and outfall mechanism designs	Mass-produced, modular dosing systems and mechanisms for dispersed outfalls of alkalinity can reduce project capex, maintenance, and labor costs , including in projects integrated into infrastructure such as power plants or wastewater treatment	\$\$\$ Shared infrastructure and transport of water	Projects integrated into water processing infrastructure		Wastewater utilities, desalination plants, industrial water users, ports, chemicals/ process equipment companies, EPC firms, water-treatment companies, state water regulators
4	Improved remote sensor technology with robust distance, pH, temperature, and pressure capabilities	Low-cost, durable remote sensors resilient to marine environments can verify ocean models with continuous data, including critical data close to deployment sites, and diffuse long-range impacts	\$\$ Improved process accuracy due to reduced manual sampling and higher-resolution monitoring	All projects		Carbonate chemists, ocean sensor companies, universities, national labs, satellite / remote-sensing firms
5	Engineered pH-controlled pelletized feedstocks for tactical dosing	Pellets or coated alkaline particles delivering slow-release mineral doses avoid local hotspot and ecological stress while still delivering alkalinity efficiently in coastal weathering, closed-system projects, or regions with very slow sinking rates	\$ Cost savings related to improved durability and feasible rate of deployment	Localized, continuous (likely closed-system) projects		Materials-science companies, mineral and chemical companies, mining / quarry operators, toxicologists, marine ecologists, dissolution-modeling experts, national regulators

\$ \$1–\$30/tCO₂ **\$\$** \$20–\$50/tCO₂ **\$\$\$** \$40–\$100/tCO₂ **\$\$\$\$** \$75–\$300/tCO₂



Electrochemical Ocean Approaches

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 6.1: CO₂ Stripping
- 6.2: Electrochemical alkalinity production

DEFINITION

Approaches that utilize electrochemical processes to enhance the baseline alkalinity of oceans, lakes, or other bodies of water.

APPROACH OVERVIEW

Since 2020, EOAs have made tremendous progress, prioritizing technological development and FOAK projects. A new wave of EOA pilots has been successfully deployed, and multiple companies across the sector have announced plans for larger facilities that indicate the field could see rapid commercial scale-up. Compared with 2026, and based on announced projects alone, EOA could see cumulative removal capacity reach >300ktCO₂/y by 2030.

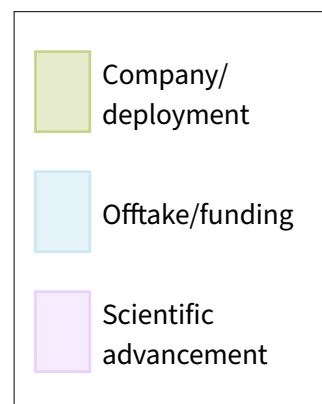
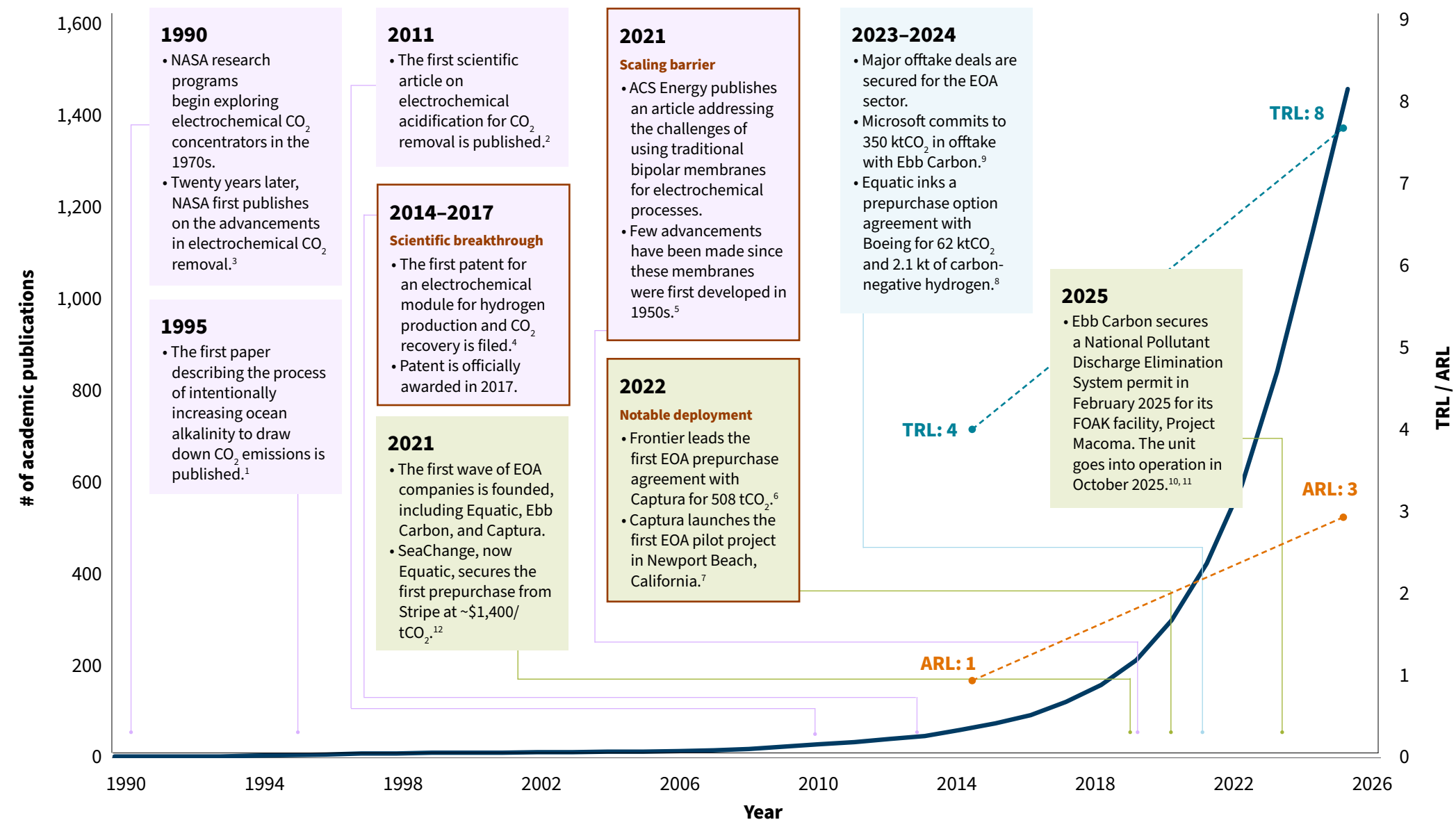


How we got here

Status: Significant progress toward demonstration-scale deployment

Approach trend: Positive

Milestones selected for the graph were chosen based on their impact on and significance to the CO₂ stripping and electrochemical alkalinity production sectors.



1. H. Kheshgi, “Sequestering atmospheric carbon dioxide by increasing ocean alkalinity,” *Energy*, 1995. 2. H. Willauer et al., “Development of an Electrochemical Acidification Cell for the Recovery of CO₂ and H₂ from Seawater,” *Applied Chemistry*, 2011. 3. A.F. Behrend, “Technology for Space Station Evolution. Volume 2: Data Management System (Environmental Control and Life Support Systems),” NASA, 1990. 4. “Electrochemical module configuration for the continuous acidification of alkaline water sources and recovery of CO₂, with continuous hydrogen gas production,” U.S. Patent and Trademark Office, 2017. 5. M. Blommaert et al., “Insights and Challenges for Applying Bipolar Membranes in Advanced Electrochemical Energy Systems,” *ACS Energy Letters*, 2021. 6. “Frontier facilitates second round of carbon removal purchases,” Frontier, 2022. 7. “Captura’s first direct ocean capture pilot begins ocean trials,” Captura, 2022. 8. “CO₂ removal startup lands Boeing deal,” Axios, 2023. 9. “Ebb Carbon and Microsoft: A landmark carbon dioxide removal agreement,” Ebb Carbon, 2025. 10. “Ebb Carbon’s Project Macoma secures first-of-a-kind permit,” Ebb Carbon, 2025. 11. “Project Macoma begins operations in Port Angeles, WA,” Ebb Carbon, 2025. 12. “Stripe commits \$8M to six new carbon removal companies,” Stripe, 2021.



Current and projected state of deployment

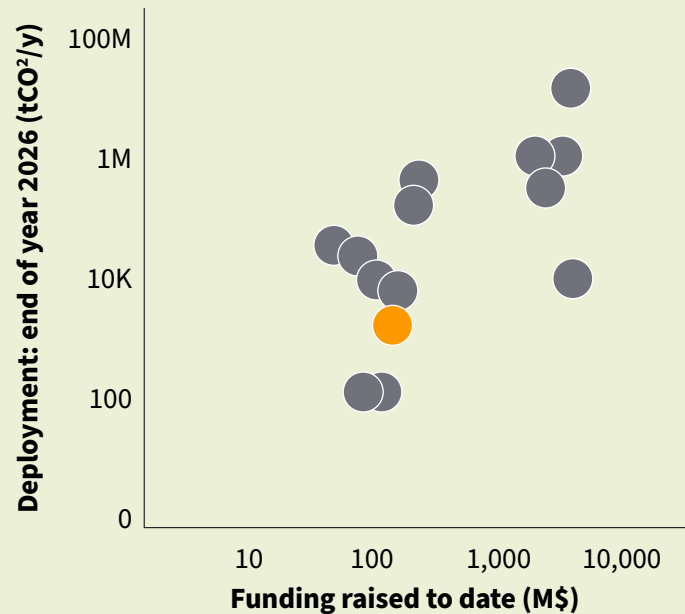
Past 5 years

Substantial progress in permitting and technological advancements enabled FOAK deployments

Next 5 years

Integration with existing coastal infrastructure has potential to achieve rapid scale-up

Current deployment



13

companies tracked¹

17

projects active/
announced

TRL 7-8

Demo initial
commercial
deployments

ARL 3

Low
readiness

Current cumulative removals

~2,300

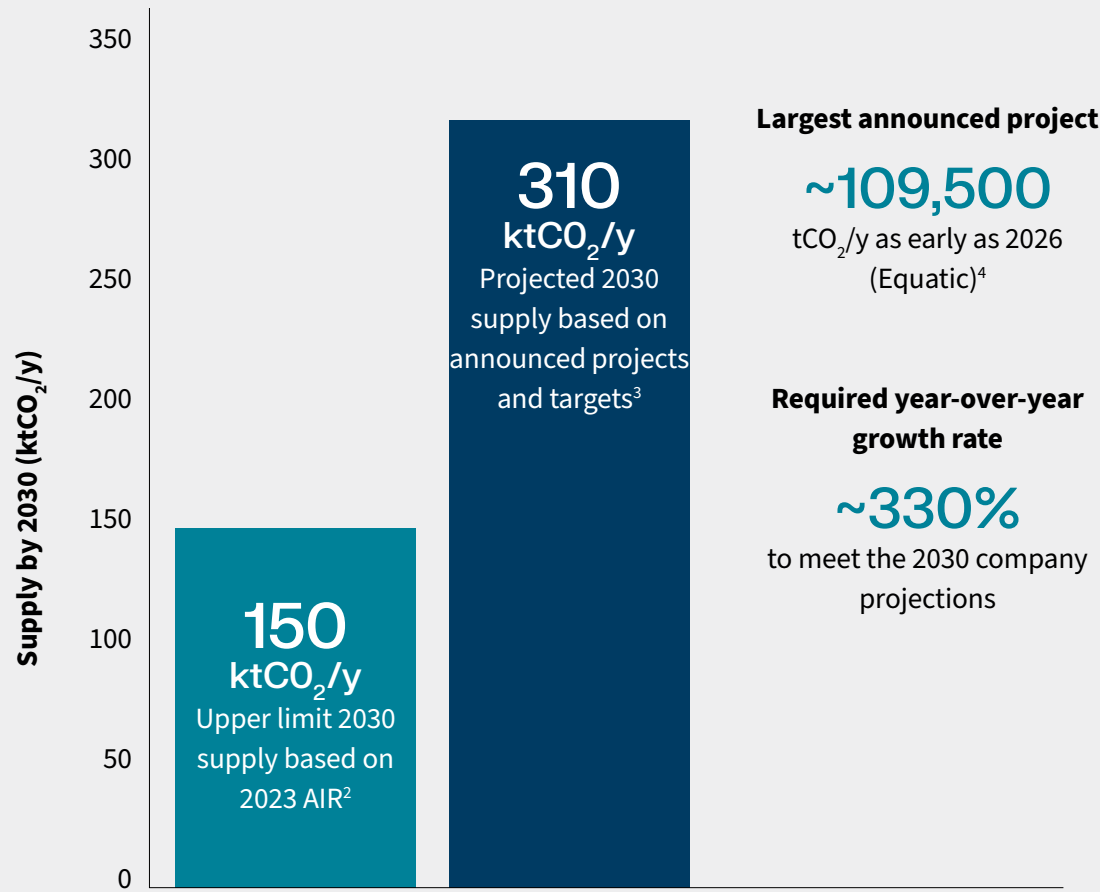
tCO₂ as of end-of-year 2025¹

Largest active project

~1,000

tCO₂/year as of 2025⁶

Supply projections for 2030



Announced and active projects as a percentage of 2030 company targets

38%

1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies, and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference growth rate of 207% aligned near-term growth in the EOA “success story” in *The Applied Innovation Roadmap for CDR*, RMI, 2023 (p. 209). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. “Equatic to build North America’s first commercial-scale ocean-based carbon removal facility,” *Global Newswire*, 2024. 5. “Vycarb secures \$5M to commercialize its water-based, affordable CO₂ capture and storage tech,” *Carbon Herald*, 2025. 6. *Technology & Deployment plans*, Captura, 2026.



Key cost drivers

Major cost drivers

Facility capex and energy costs

Improvement areas

Modular facilities, energy efficiency, industrial integration

Today: \$470–\$1,300/tCO₂

Future: \$130–\$380/tCO₂

60%–80% cost reduction possible via efficiency gains, modular deployments, and integration into water treatment plants.

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs.

2. Reviewers indicate that valorization and sale of by-products, such as fresh water, hydrogen, brine management, acid, acid neutralization by-products, and others, has the potential to reduce the price to below \$100/tCO₂.

Today's cost range (0-600, \$/tCO₂)
Future cost range (0-600, \$/tCO₂)

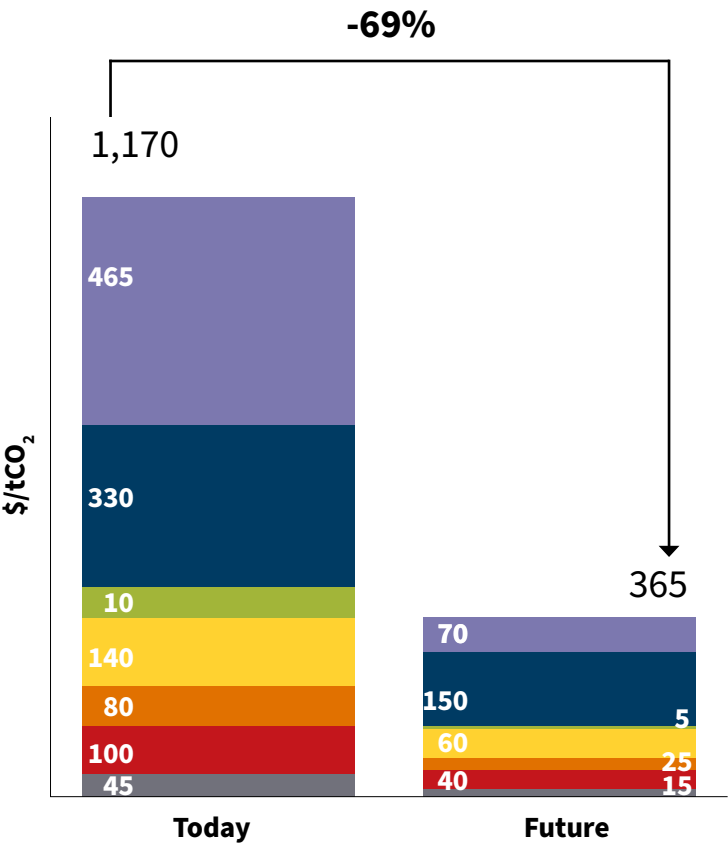
Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex 	Facility construction, balance of plant, equipment (electrochemical stacks and pump systems)	Standardized factory-produced electrochemical stacks, cost sharing through integration into water processing
Energy 	Electrochemical reactions, seawater pumping	Improved process efficiency, integration with water processing facilities
Feedstock (\$0 tCO₂) 	Possible feedstock cost from acid neutralization in some approaches	Possible feedstock cost from acid neutralization in some approaches
Transport 	Transportation of replacement membranes and any consumables/waste	Minor cost driver; slight improvements from improved supply chain integration
O&M 	Labor, including stack maintenance and replacement, treatment of membrane and pumping systems, insurance	Extended stack lifetimes, automation, predictive maintenance
Storage 	Regulatory costs — permitting of operations for alkalinity deposition, storage of CO ₂ or acid, and water intake	Established permitting workflows, integration into hub systems or established CO ₂ transport infrastructure
MRV 	Water chemistry metering, measurement and modeling to determine atmospheric drawdown impacts, risk buffers	Automated sampling and monitoring, more established earth systems models to determine impacts
Embodied Emissions 	Energy supply if nonrenewable, construction of plant, membrane stack manufacturing	Efficiency improvements in larger plants with longer project lifetimes, cleaner material and energy supply chains

Note about cost stacks¹

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- CO₂ stripping versus alkalinity production approaches trade off costs from energy efficiency and subsurface storage versus gaining regulatory approval for alkalinity release
- Integration into existing facilities treating seawater may reduce capex and energy costs
- MRV at scale requires suitable combination of measurement and ocean system modeling
- These costs do not factor in sales from by-products²



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Integration into desalination infrastructure, or stand-alone plants with long-term financing

Where to start: Modular designs integrated into existing water processing infrastructure



Modular design

EOA projects are capex-intensive and, at current pilot-scale deployment levels, are typically designed as bespoke systems for each project. As the approach develops, increased **standardization and modularization will reduce engineering and construction costs**, with additional downstream cost savings from more predictive maintenance and repairs.

Modular designs can also be deployed with incrementally increasing capacities at the same site, adding additional units to rightsize projects as demand grows and positive local environmental impacts are demonstrated.

Modular designs can also be integrated into existing infrastructure that pumps and treats seawater, such as in desalination plants. Utilizing existing pumping and pretreatment infrastructure can present energy savings of up to 30% compared to stand-alone EOA projects.¹ Electrochemical CDR projects integrated into desalinations can provide additional freshwater and/or reduce the salinity of plant outflows.²

Example KPIs:

- Capex <\$400/tCO₂ nameplate capacity
- >80% of system assembled as factory-built modules, with identical electrochemical stacks across five-plus projects



Energy intensity

As a synthetic CDR approach, EOA deployment is driven by energy as a key input. With current technologies, driving the electrochemical process and pumping sufficient water can require up to **2–3 MWh of electricity per tCO₂**.¹ Because the systems require pure electrical (rather than potentially cheaper thermal) energy to operate, energy efficiency improvements alongside deployment in regions with low costs per MWh are key to achieve cost improvements and unlock this approach's ability to scale.

Project planning, especially for large-scale projects, should take both the carbon intensity and capacity of existing electricity grids into account when choosing deployment sites. Behind-the-meter power through direct renewable generation infrastructure may be feasible, but to maintain high plant uptimes, this will require additional costs for battery storage if intermittent renewables are chosen and impact the embodied emissions of energy utilized. Efforts to drive down capex costs through modular deployments that integrate into existing infrastructure may enable the trade-off of reducing system uptime to operate only during times of excess renewables supply, lowering energy cost at the cost of increasing per-ton capex.

Example KPIs:

- Total energy intensity below 1.5 MWh/tCO₂
- Total energy cost <\$150/tCO₂
- System ramp up/down within 15 minutes for intermittent use



Repair and maintenance

Systems that process seawater come with expected maintenance costs from corrosion and biofouling as well as degradation of electrodes and membranes from physical and chemical stress. Many recent process improvements in membrane-based desalination processes that have developed more efficient long-term operations could carry over to EOAs.

Early-stage EOA startups typically design and develop bespoke electrochemical membrane stacks to fit their needs during the R&D process. At scale, **modular, repeatable systems with factory-produced components** will result in cost savings for membranes, which need to be replaced every few years. Repeated designs will enable more predictive maintenance schedules and a reduced need for specialty workforce training to address novel repair needs.

Integration into existing seawater treatment infrastructure may additionally reduce repair and maintenance cost by utilizing **water influx into the EOA system, which has already been pretreated** to reduce the fouling impact on membranes. This may come at a cost of CDR efficiency as many desalination plants are currently constructed in regions with warm water rich in dissolved inorganic carbon.

Example KPIs:

- 100% of intake/outfall systems shared with host facility
- Membrane replacement on >5 year interval
- Electrochemical stack produced in factory (not project-specific)

1. Based on RMI interviews with CDR companies. To learn more about the potential to integrate electrochemical CDR approaches into the desalination industry, see [Harnessing Carbon Removal Opportunities in Desalination](#), RMI, 2025. 2. [SWA Partnership: building the model for scalable carbon removal](#), Ebb Carbon, 2025.



Advancement and breakthrough areas

Key unlock
Standardized production of membranes, improved modeling methodology for open-system diffusion

1. This and other research priorities for electrochemical carbon removal processes are described in further detail in “[Electrochemical CDR Roadmap](#),” Ocean Visions, 2024. See page 23 for more detail on crosscutting opportunities for breakthroughs in synthetic CDR, including assessments of the technical and social difficulty of implementation.

2. Reviewers note that acid neutralization may itself provide a revenue stream if the type and concentration of acid extracted enables profitable extraction of critical minerals from alkaline feedstock.

Crosscutting sCDR breakthrough themes¹

G2: Industrial integration

Integrating electrochemical approaches into coastal facilities processing significant amounts of water, such as desalination plants, would reduce energy, capex, and maintenance costs.

S6: Offshore electrochemical facilities

Offshore facilities would reduce land use and coastal habitat degradation while increasing processing ability and potentially improving targeted dosing of alkaline solutions.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Optimized membrane materials	New membranes designed to lower costs through improved energy efficiency of electrochemical processes and/or increased fouling resistance	\$\$ Reduced energy needs, maintenance frequency and complexity (e.g., self-cleaning membranes)	All projects	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Materials scientists, electrochemists, CDR project developers, membrane manufacturers, desalination companies and other users of water treatment membranes
2	Modular integration into seawater treatment infrastructure	Cost savings from shared water pumping and pretreatment . Reduced capex intensity may enable reduced plant uptime, using curtailed renewable sources for intermittent operation	\$\$ Reduced pumping equipment and energy needs, pretreated inflow reduces maintenance needs	All, particularly CO ₂ stripping (larger treatment volumes)	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Desalination plant operators and planners, water utilities, EPC firms, renewable energy developers, permitting agencies
3	Standardized, factory-produced membrane stacks	Standardized components reduce capex costs that come from designing bespoke equipment, while enabling predictive maintenance with reduced complexity	\$\$ Simplified maintenance and repairs, cheaper material purchases, reduced engineering labor demand	All projects	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Electrochemists, CDR project developers, membrane and industrial equipment manufacturers
4	Reliable modeling for MRV based on full ocean systems impacts ²	Improved understanding of chemistry and mixing downstream of release to allow determination of atmospheric drawdown and ecosystem impacts with less extensive measurements	\$\$ Improved certainty on sequestration durability, smaller number of targeted sensors needed	All, particularly alkalinity release	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Ocean and earth system scientists, biogeochemists, ocean systems data platforms, MRV platform developers, registries and standards bodies
5	Coproduct valorization of acid stream or recovered materials	Creating clear offtake for acid (to uses that do not result in acid re-release into water systems after use) and other coproducts improves project economics and reduces storage burden	\$\$\$ Reduced waste disposal cost, reduced cost from acid neutralization, ² improved project economics	All projects that generate a separate acid stream	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Chemical companies, construction and industrial-waste companies, wastewater operators, fertilizer producers, regulators and permitting agencies, environmental health and toxicology experts

\$ \$1–\$30/tCO₂ **\$\$** \$20–\$50/tCO₂ **\$\$\$** \$40–\$100/tCO₂ **\$\$\$\$** \$75–\$300/tCO₂



Direct Air Capture

* Relevant approaches from RMI's 2023 *Applied Innovation Roadmap for CDR*:

- 7.1: Absorption and High-Grade Heat Regeneration
- 7.2: Absorption and Low-Grade Heat Regeneration
- 7.3: Absorption and Electrochemical Regeneration
- 7.4: Adsorption and High-Grade Heat Regeneration
- 7.5: Adsorption and Low-Grade Heat Regeneration
- 7.6: Adsorption and Electrochemical Regeneration
- 7.7: Adsorption and Humidity/Water Regeneration
- 7.8: Membrane Pressure Gradient Separation
- 7.9: Membrane Electrochemical Separation
- 7.10: Cryogenic Phase Separation (Vapor-Solid)

DEFINITION

The process of removing CO₂ directly from ambient air using engineered systems that separate CO₂ from other gases to produce a concentrated CO₂ stream.

APPROACH OVERVIEW

Despite ongoing challenges, DAC is driving the momentum behind the synthetic carbon removal sector. Almost three decades since it was first proposed as a climate solution, DAC has emerged as a leader in durable carbon removal, amassing billions of dollars in funding in the early 2020s that supported a surge of FOAK projects. Although political headwinds have reduced governmental support as of 2026, the DAC sector still has a credible path to scale annual capacity 100x by 2030.

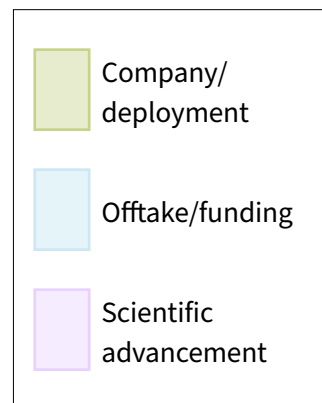
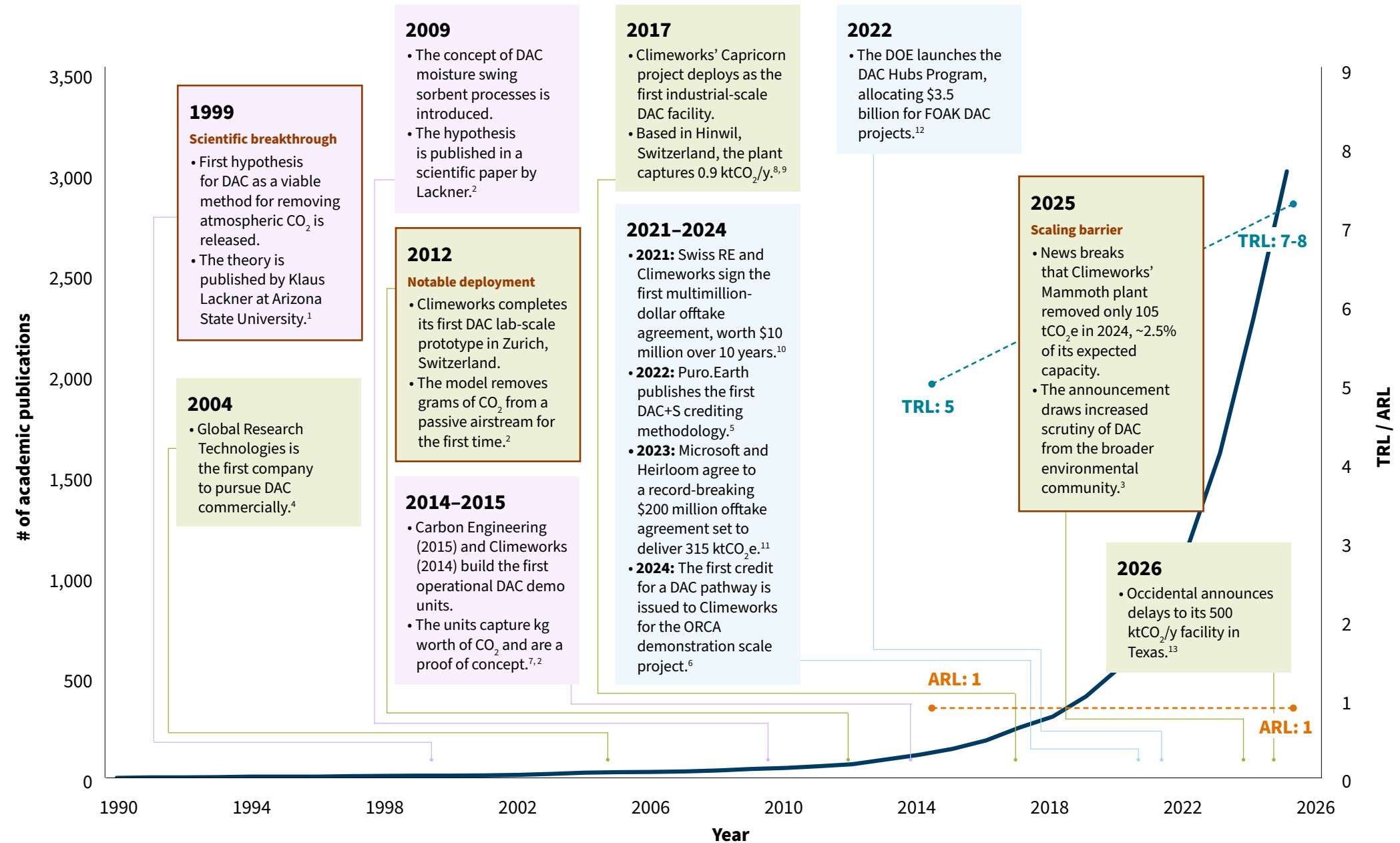


How we got here

Status: Recent setbacks toward commercial-scale deployment

Approach trend: Challenging¹⁴

Milestones selected for the graph were chosen based on their impact on and significance to DAC sectors.



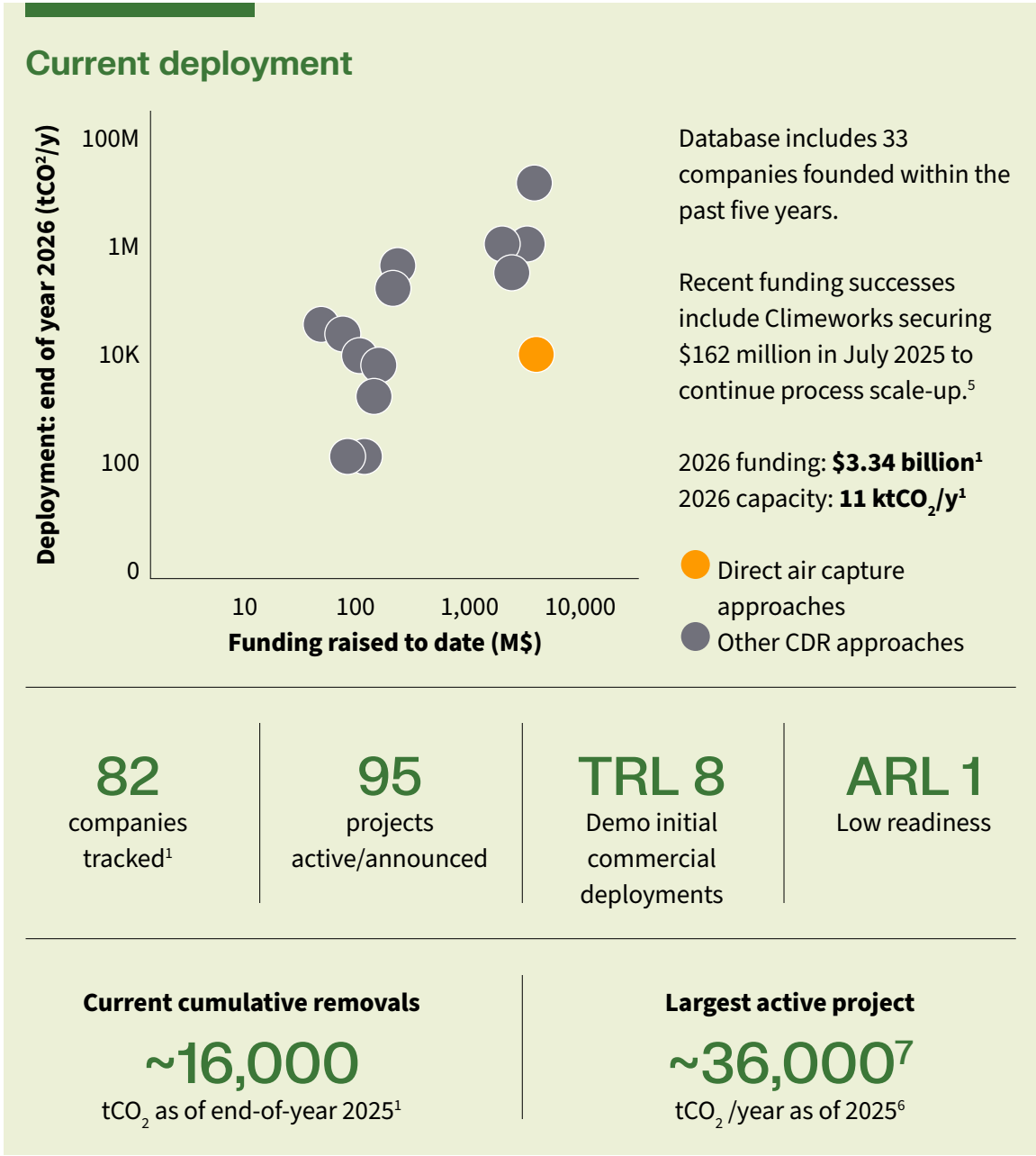
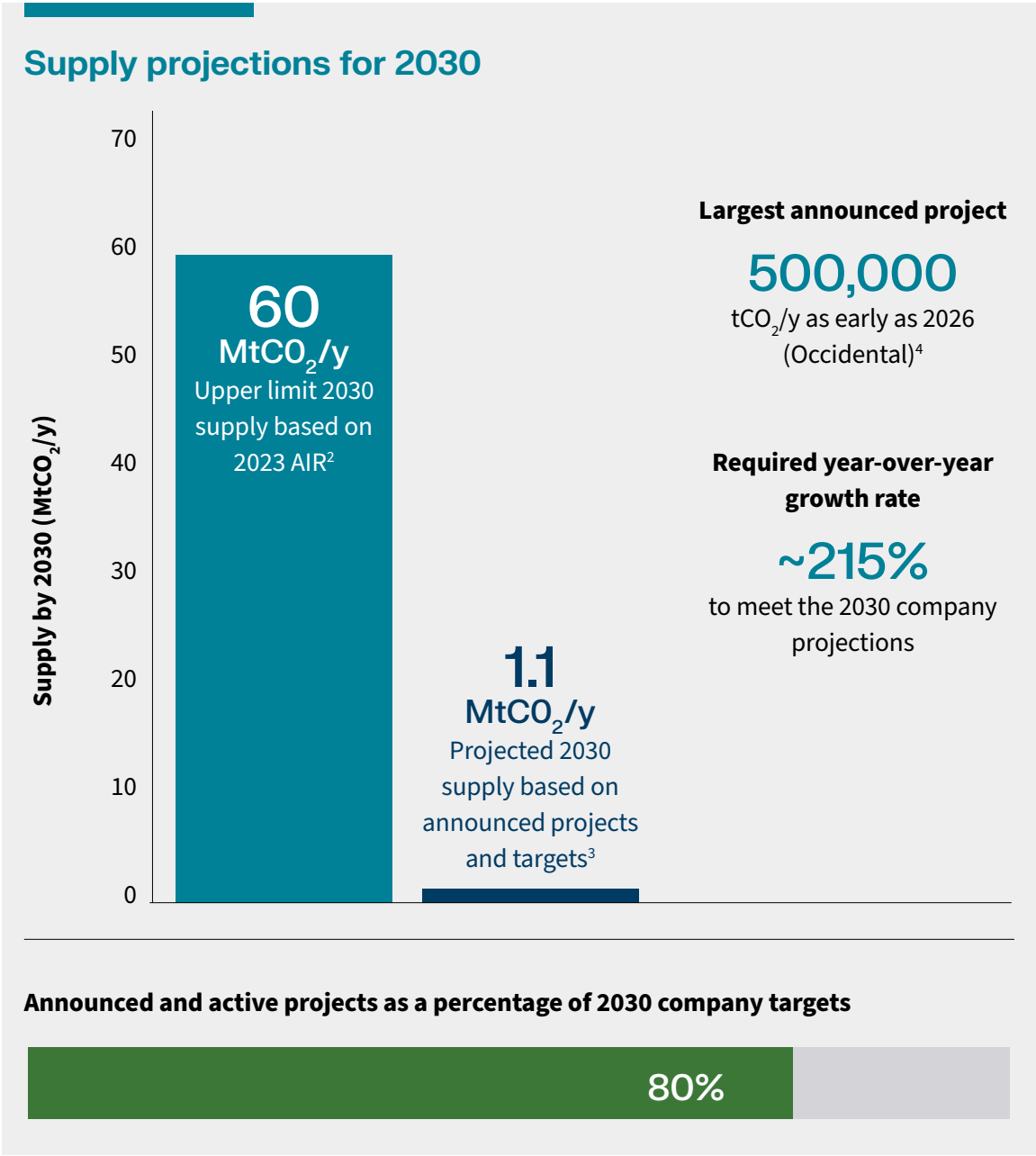
1. "Carbon Dioxide Extraction from Air: Is It An Option?," DOE Los Alamos National Laboratory, 1999. 2. [Projects & Timeline](#), Climeworks. 3. "The Mammoth Failure of Direct Air Capture," Medium, 2025. 4. "Saving the Forest by the Trees," Columbia Magazine, 2006. 5. "DAC+S methodology validated by DNV - developed and implemented by Climeworks and Carbfix as partners for permanent carbon removal," Climeworks. 6. "Puro.earth 2024 Annual Report," Puro.earth, 2024. 7. "Carbon Engineering to expand capacity of Direct Air Capture plant," betakit, 2019. 8. [Climeworks direct air capture plant Capricorn](#), Climeworks. 9. "Climeworks makes history with world's first commercial direct air capture plant," Climeworks. 10. "Swiss Re and Climeworks launch partnership by signing world's first ten-year carbon removal purchase agreement," Swiss Re, 2021. 11. "Microsoft's \$200M Carbon Removal Deal Advances Heirloom's DAC Solution," Carbon Credits, 2023. 12. [DAC Hub Funding Opportunity Notice of Intent 2022 Announcement](#), Department of Energy. 13. "Occidental's Stratos DAC Facility Delayed By Unexpected Component Issue," Carbon Herald, 2026. 14. DAC receives a "Challenging" evaluation for the approach trend. This is largely driven by the difference in nameplate capacity and actual removals that active projects have been producing, coupled with the effective "cancellation" of the DAC Hubs program and supportive US policy for the sector. Unlike other "Challenging" status trends, DAC has the benefit of significant capital investment to date and the backing of large companies that have made significant commitments to deploying the tech (e.g., Oxy by acquiring Carbon Engineering). An argument could be made for a "Neutral" approach trend status; however, news for the industry between January 2025 and June 2026 has been challenging.



Current and projected state of deployment

Past 5 years
A new wave of DAC companies and US government funding created a surge of FOAK projects

Next 5 years
Despite a challenging investment landscape, developers continue to pursue scaled deployments



1. Company data sourced using a combination of public online resources, information directly procured from surveys/conversations with CDR companies, and estimates created using best judgment from comparing similar projects of size and scale. The funding amount listed is an aggregated total from all companies classified within this CDR approach, based on confirmed funding found through public project announcements and public deal information available via Pitchbook. 2. Reference capacity of 60 MtCO₂/y is sourced directly from the DAC “success story” in *The Applied Innovation Roadmap for CDR*, RMI, 2023 (p. 231). 3. Based on company’s own declared scale targets either directly announced for 2030 or interpolated from other target years. 4. “Occidental’s Stratos DAC Facility Delayed By Unexpected Component Issue,” *Carbon Herald*, 2026. 5. “Climeworks raises USD 162M to scale up technology,” Climeworks. 6. “Mammoth: our newest direct air capture and storage facility,” Climeworks. 7. This removal capacity reflects nameplate capacity, removals have been minimal to date, causing 2026 end-of-year capacity to be lower than the largest active project capacity.



Key cost drivers

Major cost drivers

Facility capex and energy costs

Improvement areas

Modular system designs, efficiency improvements

Today: \$440–\$870/tCO₂

Future: \$185–\$340/tCO₂

50%–70% cost reduction possible via established system designs, efficiency improvements, modular deployability, and economies of scale.³

1. The cost stack shown here is intended as an illustrative example showing reasonable current and future cost ranges for a sample project within this approach. No single project will report precisely these costs, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns. This example is intended to highlight common cost barriers and opportunities within the approach based on RMI analysis and conversations with field experts. The figure shown on the right represents a weighted midpoint of the cost ranges outlined in the table on the left based on expert assessment of likely cost reductions over time. The cost stack considerations highlight some dependencies or trade-offs that will significantly affect project-level costs. **2.** As economies of scale develop for DAC, chemical inputs (captured in the feedstock category) should decrease significantly with specific solvent and sorbent supply chains for DAC deployment. **3.** Reviewers note that many of the cost categories for DAC are tightly coupled. Technology choice, siting, process integration, and operating strategy all significantly influence the cost breakdown across other cost-driving categories, making some of these categories less independent, and more connected, as levers for cost reduction in DAC.

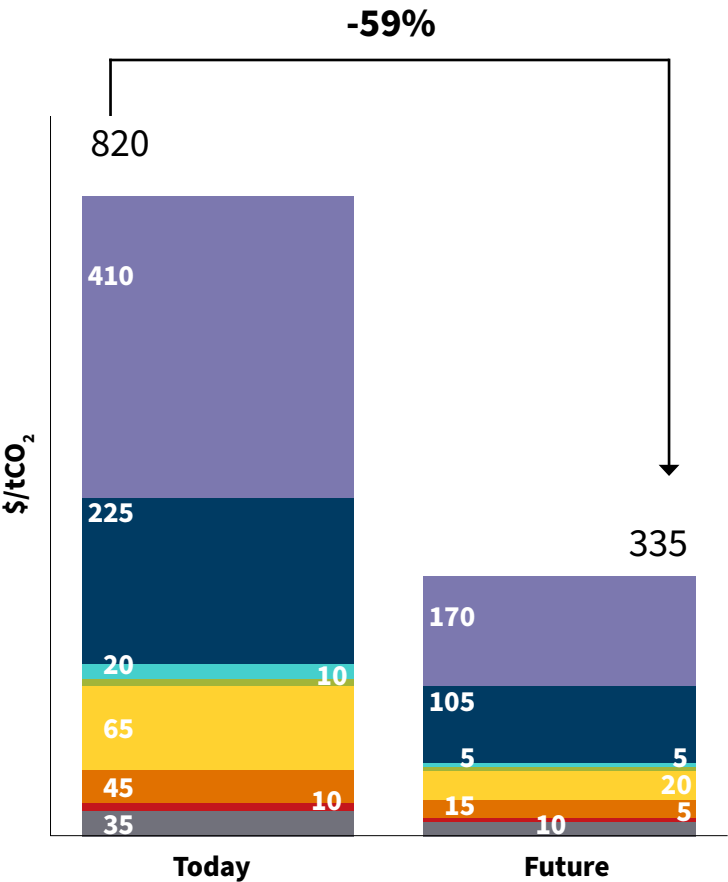
Today's cost range (0-500, \$/tCO₂) Future cost range (0-500, \$/tCO₂) Key cost considerations for scaled deployment (see next page for details)

Cost (\$/tCO ₂)	Contributors	Improvement potentials
Capex ● ————— ● ● ————— ●	Facility construction, balance of plant, and equipment such as air contactors, regeneration system, and compressors	Economies of scale, modular systems, reduced EPC premiums for established technology, improved capture technology
Energy ● ————— ● ● ————— ●	Combination of electrical and thermal energy for air contacting, regeneration, and CO ₂ compression	Improved efficiency in air contactors and solvent/sorbent regeneration, utilization of geothermal or waste heat
Feedstock ● ————— ● ● ————— ●	Solvents or sorbents for CO ₂ capture	Increased lifetime or capacity, cheaper manufacturing
Transport ● ————— ● ● ————— ●	Transportation of sorbent materials and any other consumables/waste	Minor cost driver; slight improvements from improved supply chain integration
O&M ● ————— ● ● ————— ●	Labor, maintenance, insurance, geography	Standardization and modularization reduce novel training and repair costs, enable increased automation
Storage ● ————— ● ● ————— ●	CO ₂ compression, dehydration, and transportation (trucking or pipelines), injection and monitoring at storage site	Hub colocation with storage sites, standardized CO ₂ transportation pathways
MRV ● ————— ● ● ————— ●	CO ₂ metering, long-term storage verification, third-party auditing	Minor cost driver; improvements from automated data logging, shared digital infrastructure, standardized MRV
Embodied Emissions ● ————— ● ● ————— ●	Energy supply (if nonrenewable), construction of plant and transportation infrastructure, sorbent manufacture	Efficiency improvements in larger plants with longer project lifetimes, cleaner material and energy supply chains

Note about cost stacks¹

✗ Not actual project costs ✓ Qualitative cost ranges

See [page 121](#) for more detail on this analysis



Cost stack considerations

- Choice of energy sources affects costs and embodied emissions. Sorbent system affects fraction of thermal versus electrical energy.
- Need consistent energy supply; capex-intensive projects unlikely to be cost effective if uptime reduced by intermittent energy
- Cost savings from integration into already energy-intensive systems (e.g., data center HVAC) will require local energy capacity



Key cost considerations for scaled deployment

Assumed configuration(s) at scale: Large-scale plants directly connected to CO₂ transportation infrastructure or colocated with storage

Where to start: NOAK project deployments with repeatable engineering, contracting, and financing solutions



Facility construction

Even at larger scales, DAC projects remain capex-intensive. The first plants with nameplate capacities exceeding 500 kt/y show project costs of more than \$1 billion.¹ FOAK projects carry additional costs for the design and implementation of novel components and integrated removal solutions. To decrease capex costs in the future, **a larger number of NOAK project deployments is needed to de-risk projects**, along with system designs co-optimizing process engineering with materials design to consider total energy, material, and construction cost impacts.²

Plant uptime and lifetime are key factors when considering per-ton cost impacts of capex investment. Seasonal or daily downtimes significantly increase the effective cost, making it challenging to finance projects operated with an intermittent electricity supply. Timelines of interconnected systems such as grid supply, transformer supply chains, CO₂ transportation infrastructure, and CO₂ storage will all impact deployment rates.

Amortization
per tCO₂
\$1B Capex
500 kt/y, 20-year
lifetime

\$270

9 months/year
12 hours/day
38% uptime

\$110

12 months/year
22 hours/day
92% uptime

Example KPIs:

- Capex <\$200 per tCO₂ capacity including cost of capital
- Annual plant uptime > 90%
- Modularization: >70% of plant constructed off-site³



Energy intensity

While the theoretical minimum energy cost of DAC is around 0.15 MWh,⁴ published estimates of actual energy requirements range from 1 to 3 MWh per ton of CO₂ removed.⁵ Though industrial electricity rates vary by region, even rates of \$0.08/kWh would lead to costs of \$80–\$240/tCO₂ from the cost of electricity alone, and the availability of abundant **low-cost, low-carbon energy will constrain deployment**.

Energy savings through material and process engineering, coupled with demonstration of system integration utilizing waste or geothermal heat or integrating into existing air handling systems, are key avenues to address the energy challenge. Electrochemical processes trade improved total energy intensities against the inability to utilize potential heat sources. It is likely that a range of different technologies with different trade-offs of electricity vs. heat use and capex vs. energy intensity will prove optimal in different contexts.

Energy efficiency breakthroughs will be critical to scale.⁶ Powering 1 Gt of DAC at an energy intensity of 1 MWh/tCO₂ would require 1,000 TWh of energy, equivalent to over 3% of total global electricity generation.

Example KPIs:

- Total energy intensity below 1.5 MWh/tCO₂ including storage
- Total energy cost <\$100/tCO₂
- 90% of thermal energy from low-carbon sources



Financing

Capex-intensive DAC projects carry significant up-front costs. Financing considerations, such as the expected weighted average cost of capital, become direct drivers of per-ton carbon costs throughout several years of the project's lifetime. **De-risking investment** with mechanisms such as loan guarantees, public financing, repeatable insurance products, and establishing a playbook for routine project design and deployment are critical efforts for cost savings as DAC moves from pilot proof-of-concept demonstrations toward commercial NOAK plants.

Clear forward demand signals, such as 10-year or longer advance market commitments, allow rightsizing of deployment and de-risk investment in new projects. Established, modularized project design will improve predictability and reduce time between project development and first removals to meet this demand.

Standardized, simple contracting will ease financing through improved timelines and decreased risk. Additional efforts to de-risk financing, such as the creation of blended portfolios with projects carrying different risk profiles, will be beneficial to lower financing risks and costs at scale.

Example KPIs:

- Weighted average cost of capital <12%
- >80% of capacity contracted under 10+ year offtake supporting project lifetimes of 20+ years

1. [“BlackRock to invest \\$550 mln in Occidental’s carbon capture project,” Reuters](#), 2023. **2.** C. Charalambous, [“A holistic platform for accelerating sorbent-based carbon capture,” Nature](#), 2024. **3.** Reviewers note that gains from modularization and the optimal degree of modularization are technology-dependent. **4.** J. Soeherman et al., [“Overcoming the Entropy Penalty of Direct Air Capture for Efficient Gigatonne Removal of Carbon Dioxide,” ACS Engineering Au](#), 2023. **5.** L. Desport et al., [“Deploying direct air capture at scale: How close to reality?” Energy Economics](#), 2024. **6.** As electricity demand grows across sectors, including from electrification projects targeting emissions reductions, power grid development will be crucial to prevent constraints to deployment. Although the deployment scales anticipated by 2030 (less than 10 MtCO₂/y) will not yet present significant total energy demand constraint, electricity demand is a localized concern, and deployment needs to occur in regions with sufficient supply. Forward-thinking design targeting large-scale deployment needs to prioritize reduced energy consumption through engineering design, utilization of waste or geothermal heat, and integration into industrial air handling processes needs to be paired with regional and national grid planning to facilitate scaled deployment.



Advancement and breakthrough areas

Key research areas

Material science research for sorbent material, passive air contacting systems, modular DAC systems

1. M. Ozkan et al., “Advancements in cost-effective direct air capture technology,” Chem, 2024.

2. See page 23 for more detail on crosscutting opportunities for breakthroughs in synthetic CDR, including assessments of the technical and social difficulty of implementation.

Crosscutting sCDR breakthrough themes¹

S1: Capture by reaction

Advances in chemistry that can overcome low CO₂ ppm in ambient air would allow DAC operators to combine the capture and conversion step, reducing cost and operating expenditures.

S3: Electro-swing DAC

Through advancements in electrochemical systems, DAC processes could eliminate sorbents, solvents, and temperature swing, reducing energy usage and overall opex costs.

S5: Biomimicry DAC

With advancements in membranes and nanotechnology, engineered DAC systems that mimic plants in efficiency and scalability would improve removal rates and reduce energy costs.

	Breakthrough	Benefit	Cost savings	Projects	Cost stack	Key parties
1	Novel sorbent or solvent materials with improved capacity or recovery efficiency	Improved capacity, and more efficient regeneration, would reduce energy intensity and increase system uptime	\$\$\$\$ Energy efficiency savings within regional context of electrical vs. thermal energy availability	All projects	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Materials scientists, systems engineers, CDR startups developing DAC systems, chemicals manufacturers
2	Passive mechanisms for air contactors	Passive designs, or integration into existing air handling systems (e.g., HVAC), would save on air contactor energy costs , which represent up to half of total energy needed ²	\$\$ Electrical energy cost savings from air contactors, with possible trade-off against capex intensity	All projects	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Scientists, structural engineers, CDR startups developing DAC systems, HVAC companies, infrastructure owners open to project integration
3	Efficient thermal-free sorbent regeneration mechanisms	Electrically powered mechanisms reduce inefficiencies from heat transfer and enable use of 100% renewable energy sources in the absence of geothermal heat supply	\$\$\$ Energy cost savings if renewable electricity sources are abundantly available	All projects	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	Electrochemists, systems and process engineers, CDR startups developing DAC systems, grid operators ensuring sufficient local supply
4	Modular facility designs with balance-of-plant optimization	Modular designs could significantly reduce balance-of-plant costs for NOAK projects and ease financing and regulatory approval processes	\$\$ Reduced financing, regulatory, and balance of plant capex costs from repeated project designs	All projects	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	CDR startups developing DAC systems, EPC firms, construction companies, financiers and insurers, regulators
5	Waste-heat power-compatible DAC paired with industrial heat or biochar/BECCS	Heat integration systems approach utilizing waste heat from other CDR projects or industrial heat sources , reducing energy costs and improving project financing	\$\$ Cost savings from waste heat usage, shared infrastructure, and dual business proposition	Projects colocated with waste heat sources	<div><div>Capex</div><div>Energy</div><div>Feedstock</div><div>Transport</div><div>O&M</div><div>Storage</div><div>MRV</div><div>Embodied</div></div>	DAC technology developers, industrial facilities with waste heat, waste heat recovery technology providers, utilities and clean power providers, BECCS and biochar developers

\$ \$1–\$30/tCO₂

\$\$ \$20–\$50/tCO₂

\$\$\$ \$40–\$100/tCO₂

\$\$\$\$ \$75–\$300/tCO₂

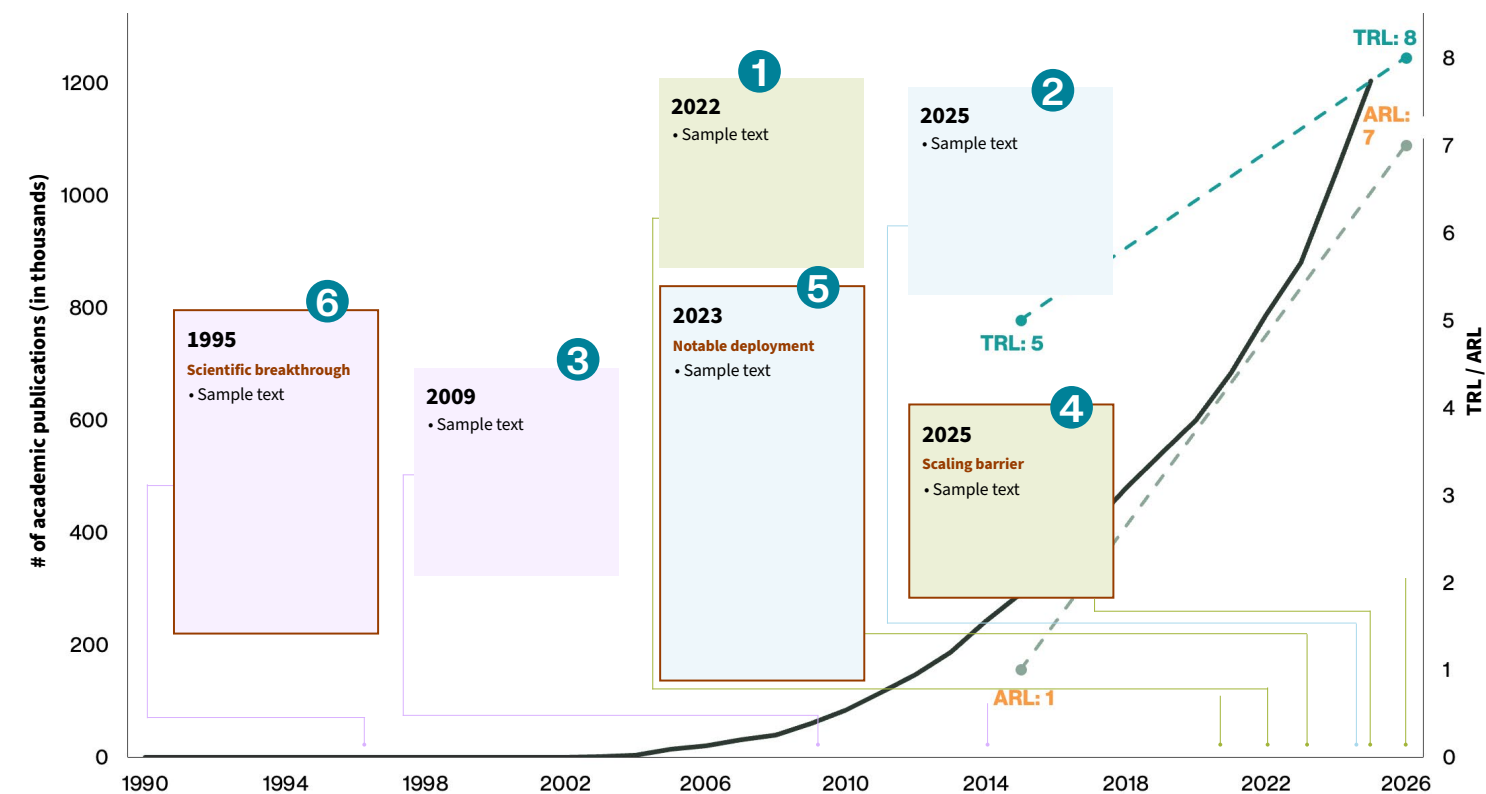


Appendix

Timeline design approach

The following criteria were used to craft a unique, narrative timeline that illustrates important scientific discoveries, notable project deployments, and key funding awards since each approach’s inception.

Selection Process: Events listed on the timeline were selected using desktop research and company interviews. From these resources, events were selected for inclusion on the timeline based on their overall impact on a given approach, positive or negative. While the 8–10 selected events were chosen in an attempt to best represent the evolution of each approach, there may be notable achievements, events, and deployments not listed on a given approach’s timeline. ARL/TRL assignments reflect the approach in 2015 and 2026 based on the methodology captured on pages 118 and 119.



- 1 Green boxes** on the timeline represent significant company milestones or deployments in an approach’s narrative. These events include occurrences such as company founding or FOAK deployments.
- 2 Blue boxes** on the timeline represent significant funding awards or offtake agreements in an approach’s narrative. These events include occurrences such as FOAK investments and prepurchase of credits.
- 3 Purple boxes** on the timeline represent significant scientific advancements or breakthroughs that notably affected the trajectory of an approach’s narrative. This includes events like major publications or lab discoveries²
- 4 Boxes marked “Scaling Barrier”** represent notable challenges to an approach’s success. For each timeline, a single “Scaling Barrier” was selected; in most cases, the event is indicative of a larger problem that persists for the approach in 2026.
- 5 Boxes marked “Notable Deployment”** represent meaningful, often FOAK, deployments for a given approach. For each narrative timeline, a single “Notable Deployment” was highlighted, though additional deployments may be listed across the timeline.
- 6 Boxes marked “Scientific Breakthrough”** on the timeline represent an event that established the fundamental science behind an approach’s current technology. Each approach has a single breakthrough to represent the most impactful event to date.

1. The left-hand y-axis represents the number of academic publications relevant to a given approach. It is intended to demonstrate an approach’s growth based on its prevalence of research and scientific literature that pertain to the approach. Publications were determined based on distinct key terms that are indicative of each approach (e.g., biochar included “pyrolysis” as a key term), and the overarching dataset was drawn from the State of CDR’s 2nd and 3rd edition landscape reports.

Timeline status approach

The following criteria were used to assess recent developments in each approach to create a rating that indicates both near-term progress and anticipated level of deployment.

Example: Recent setbacks toward commercial scale deployment

Status	Criteria	Example
Recent setbacks	Since the publication of the Applied Innovation Roadmap for CDR in 2023, the approach has declined in favorability. This may relate to public acceptance or technical feasibility, and includes concerns around MRV, removal efficacy, or cost. It also may be tied to a failed deployment.	In 2024, Running Tide, a macroalgae CDR company, closed after failure to deliver credits and questions around credit efficacy surfaced. This caused issues for macroalgae CDR, and affected the industry as a whole.
Minimal progress	While no negative or detrimental setbacks have occurred within the approach, negligible progress has been made since 2023. No advancements in TRL, ARL, or deployment levels have been made, and none of the major barriers to the approach have been addressed.	Microalgae in Ponds was listed as “minimal progress,” having seen only one deployment since 2023, which has since closed. There has been no impact on the CDR industry or public opinion, but the approach has not grown.
Expected progress	Expected progress is characterized by approaches making solid, measured advancements in science, deployment, and MRV since 2023. These approaches are metaphorically “on track” for scale-up but have not experienced a breakthrough or major catalyst.	Mineral alkalinity enhancement has advanced at a favorable rate, but not beyond what can be expected for a successful, nascent technology. It has experienced success in early field trials and pilots with no major setbacks since 2023.
Significant progress	Approaches denoted as having made “Significant Progress” have made major advancements in ARL, TRL, deployment levels, or secured funding since 2023. These approaches often exceeded the estimated 2025 removal success stories outlined in the AIR.	Enhanced Rock Weathering shows “Significant Progress”; in 2023, the first major companies were a year old and the first offtake agreement was signed. By 2025, the first credits were delivered, and the largest active project is 200 ktCO ₂ /year.



Status	Criteria	Example
Initial field trials	The next step in approach scale-up involves in situ trials in environments that reflect the real-world conditions under which the approach will be deployed as scale-up continues. These trials generate removals, but they are not intended to be verified for credit sales, but rather serve scientific purposes alone.	MAE field trial in the Gulf of Maine: field trial to determine measurable CDR and environmental effects of adding sodium hydroxide to the ocean.
Pilot-scale deployment	The approach has at least one company that has deployed a pilot-scale project. Pilots are characterized as one of a company’s first projects in the field that is demonstrating that a technology works in real-life conditions. These projects are showing removals but not necessarily at scale.	Carbon Engineering’s initial pilot project, established in Squamish, BC, Canada, in 2015, was the first time its technology removed CO ₂ from the air.
Demonstration-scale deployment	The approach is first demonstrated to be capable of functioning at commercial scale while utilizing feedstock, energy, and labor that a commercial operation would need. These projects are the final confirmation of technology ahead of preparations for commercial deployment.	Many Biomass Direct Storage companies are operating at demonstration scale. For example, WoodCache PBC has launched a FOAK wood vault.
Commercial-scale deployment	At commercial scale, the technology is functional and delivering removals at scale to offtakers or buyers, but only by a small number of companies. The approach is incorporated into supply chains and workforces.	DAC, with commercial operations in Texas and Louisiana, is an example of an approach reaching commercial-scale deployment.
Sector-wide scale-up	The approach has multiple companies that have achieved at least one project at commercial-scale deployment. The approach has established supply chains or integrated into existing supply chains. In some cases, the sector has a profitable dual value proposition.	Biochar, with several large companies established, multiple large offtake agreements secured, and credits being delivered at scale, is achieving sector-wide scale-up.

Trends approach

The following criteria were used to assess the state of each approach and assign a rating that communicates the approach’s overall trend based on a variety of market, deployment, and R&D factors.

Criteria	Positive	Neutral	Challenging
Overall approach trend	The approach is at or on track to reach commercial scale. Deployments are occurring with improvements in cost efficiency and scale. Barriers or challenges that exist do not jeopardize approach scale-up.	The approach is progressing at an expected rate. Barriers and challenges that exist can likely be addressed, though resolution remains unclear. The approach is still capable of reaching commercial scale.	The approach has encountered significant roadblocks or barriers that will slow scale-up or deployment in both the near and long term. Factors could be severe enough to prevent the approach from reaching commercialization.
Market factors	<ul style="list-style-type: none">• The approach has secured several major offtake agreements or investments from CDR buyers• Demand for the approach’s removal credits is growing or consistent• The approach has identified and validated sectors for potential integration or dual value propositions	<ul style="list-style-type: none">• The approach has secured at least one major offtake agreement or investment from CDR buyers• Demand for the approach’s removal credits exists but is unreliable or inconsistent• Opportunities may exist for approach integration or dual value propositions but have yet to be clarified	<ul style="list-style-type: none">• The approach has not yet secured major funding or offtake commitments from the suite of CDR buyers• Demand for removal credits generated by this approach is waning or nonexistent• The approach’s sole source of revenue is CDR. Deployment is CDR specific; no integration opportunities exist
Deployment progress	<ul style="list-style-type: none">• Deployments are occurring at higher-than-forecasted rates in comparison with RMI’s 2023 AIR roadmap• The approach has reached its first commercial deployment or a path to commercial scale is clear and without significant challenges• No setbacks have occurred in existing deployments or setbacks that have occurred have already been addressed	<ul style="list-style-type: none">• Deployments are occurring at expected or average rates when compared with similar, nascent technologies• The approach has identified a potential path to commercial scale, though challenges and obstacles to scaled deployments exist• No major setbacks have occurred in existing deployments, and setbacks that have occurred can be rectified	<ul style="list-style-type: none">• Deployments are occurring much less or more slowly when compared to other CDR approaches or similar, nascent technologies• The approach has reached its first commercial deployment or a path to commercial scale is clear and without significant challenges• The approach’s existing deployments have encountered major setbacks that could prevent commercialization or scale-up
RD&D/Foundational science	<ul style="list-style-type: none">• Minimal concerns exist around risk of reversal, durability, and efficacy of removal• Technology and infrastructure relevant to the approach are available and have an established supply chain• Systems required for removals are effective, reliable, and efficient at scale and have addressed any concerns with deployment at scale	<ul style="list-style-type: none">• Some concerns exist around permanence, durability, and efficacy of removal, but they can likely be addressed via further R&D or are not detrimental to deployment• Technology and infrastructure relevant to the approach are available, but a commercial supply chain is not yet established• Systems required for removals are effective at current deployment level, though concerns may exist around efficiency at scale	<ul style="list-style-type: none">• Several concerns exist around permanence, durability, and efficacy of removal, and path to resolution is unclear• Technology and infrastructure relevant to the approach are not widely available and/or must be specially manufactured for bespoke deployments• Systems required for removals are not yet effective at scale and/or have notable efficiency concerns, including MRV

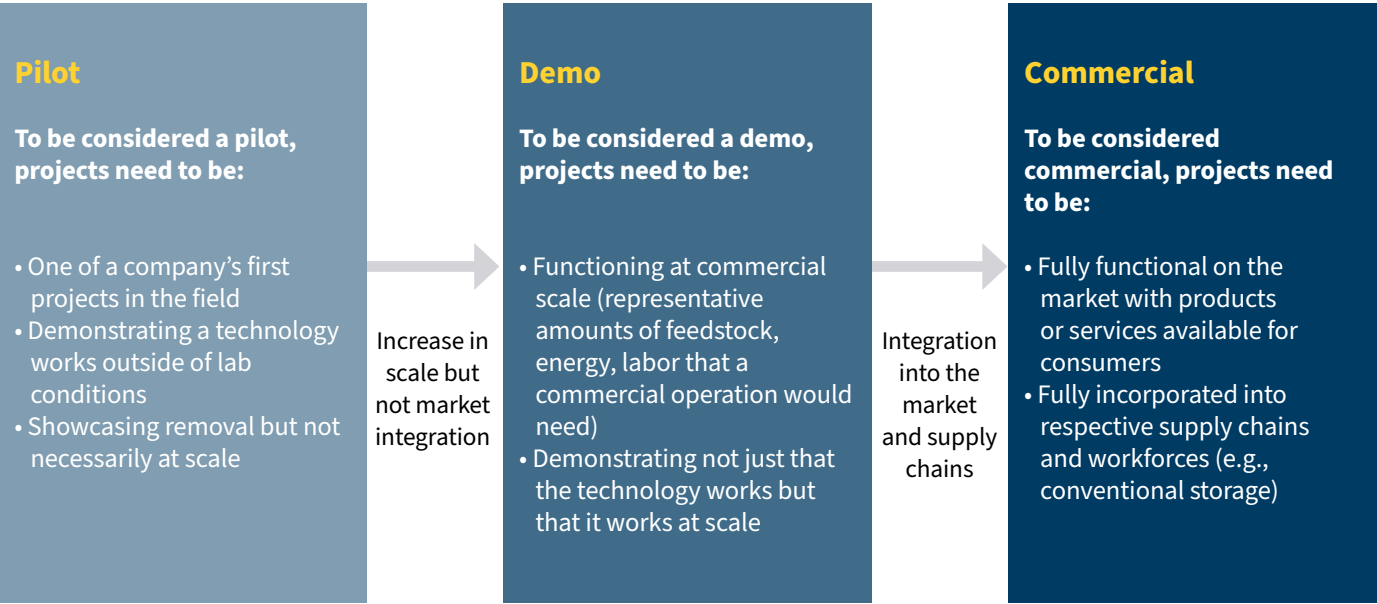
Evaluating Technology Readiness Levels

The following criteria were used to determine each approach’s Technology Readiness Level (TRL) based on the current state of development and deployment. This metric indicates only the technical readiness of a new technology.

TRL criteria

Category	TRL	Definition ¹	Deployment level achieved
First deployment	9	Project is fully operational under real conditions and first commercial activities occur ³	Commercial
Technology demonstration	8	Commercial-scale project undergoes final stages of testing and evaluation	Demo ²
	7	FOAK project occurs at commercial scale and under relevant environmental conditions	Demo
Pilot validation	6	Project occurs at pilot scale and under relevant environmental conditions; FOAK commercial-scale facility not completed	Pilot ²
Technology development	5	Project occurs at lab scale and under relevant environmental conditions	Lab
	4	Components of a project are integrated and tested at lab scale	Lab
Basic research	3	Experimentation occurs to test proof of concept	Concept
	2	Conceptual research applied to practical applications	Concept
	1	Basic principles and concepts of a project researched	Concept

Defining deployment levels



1. TRLs were determined utilizing a well-established scale. The DOE’s Technology Readiness Level Scale ranges from 1 to 9, with 1 representing basic conceptual development and 9 indicating full-scale commercial activities. The scale shown above was used to broadly assess all 14 of the CDR approaches mentioned in this report. For TRL scales pertaining to a specific technology, experts in the field may argue these definitions should shift slightly, but the TRLs for each approach were meant to act as a broad assessments of the overall approach and may differ for individual company’s technology (for example, Enhanced Weathering includes Enhanced Rock Weathering and Coastal Enhanced Weathering, which are at different TRLs but utilize the same process, science, and many of the same components). 2. As defined above, the main distinction between demo and pilot deployment is that the former occurs at commercial (or full) scale whereas the latter occurs at much smaller scale. The main distinction between demo and commercial deployment is that the former has not yet participated in commercial activities whereas the latter is commercially operating. 3. Commercial activities can be defined as selling either a product (e.g., biochar) or carbon removal credits, not including prepurchases.

Evaluating Adoption Readiness Levels

The following criteria, developed by the Department of Energy’s Office of Technology Commercialization, were used to determine each approach’s Adoption Readiness Level (ARL) by assessing existing risks to a given CDR technology.

ARL ranges

Adoption Readiness Levels (ARLs) are separated into three distinct categories that indicate the capability of a given technology to successfully achieve widespread adoption in its intended use case and industry. See below for the categories and their definitions.

Value	ARL	Definition
7-9	High readiness	Adoption risks have largely been addressed. The technology has demonstrated commercial viability and is capable of broad market deployment with established commercial and institutional support.
4-6	Moderate readiness	Key adoption risks exist but are fewer in number or are being reduced through early commercialization activities. Financing, supply chains, regulatory pathways, and public acceptance have improved, but are not yet fully established or clarified.
1-3	Low readiness	Significant adoption risks remain. Market needs, supply chain, financing, regulatory environment, and other commercialization factors are still being assessed or navigated.

ARLs are evaluated using 17 individual criteria that assess a spectrum of risks related to markets, public acceptance, and technological function.

- Delivered cost
 - Functional performance
 - Ease of use/complexity
 - Demand maturity/market acceptance
- Market size
 - Downstream value chain
 - Capital flow
 - Project development, integration, and management
- Infrastructure
 - Manufacturing and supply chain
 - Materials sourcing
 - Workforce
 - Regulatory environment
- Policy environment
 - Permitting and siting
 - Environmental and safety factors
 - Community perception

ARL criteria

Each of the 17 criteria used to evaluate a technology’s ARL was applied to each of the 14 unique CDR approaches in this report. These 17 criteria are intended to assess and scrutinize one of four unique core risk areas for nascent and developing technologies. These risk areas capture the major barriers that developing CDR approaches encounter during scale-up and commercialization.

Categories for core risk areas:

- Value Proposition**
 - Can a technology meet expectations for operation at or below the market price point for similar CDR technologies?
- Market Acceptance**
 - Can the technology thrive in the current marketplace given competition and customer base?
- Resource Maturity**
 - Are the materials, inputs, and supply chains necessary for technology scale-up available and established?
- License to Operate**
 - Do existing policy, regulations, and public opinion create an environment favorable for the technology to deploy?

After each of the 17 criteria has been evaluated as a low, moderate, or high risk, the outcomes across the 17 criteria are summed. A technology begins with an ARL assessment of 9, subsequently losing points for the number of moderate- or high-risk criteria the technology has. Below is the DOE official matrix used for scoring evaluation. Only scores with < 3 high risks or < 5 medium risks qualify for “High Readiness”.

		Number of high-risk criteria								
Number of moderate-risk criteria		0	1	2	3	4	5	6	7	8+
	0	9	8	7	5	3	1	1	1	1
	1	8	7	6	4	2	1	1	1	1
	2	8	7	6	4	2	1	1	1	1
	3	7	6	5	3	1	1	1	1	1
	4	7	6	5	3	1	1	1	1	1
	5	6	5	4	2	1	1	1	1	1
	6	5	4	3	1	1	1	1	1	1
	7	3	2	1	1	1	1	1	1	1
	8+	1	1	1	1	1	1	1	1	1

1. ARL assessments for each of the 14 approaches in this report were created using the Department of Energy’s Office of Technology Commercialization framework, published in April 2025 by the OTC for use by commercial entities in order to establish a common language for benchmarking commercial readiness of new technologies. That evaluation framework, along with the associated criteria used in assessing each approach, can be found at [Department of Energy April 2025 Adoption Readiness Assessment Framework](#). The ARL framework supplanted the MRL framework used in earlier reports by RMI.

Company database – company aggregation

The following methodology was utilized to create a comprehensive, though nonexhaustive, list of CDR companies across the 14 approaches examined in this report.

Applied Innovation Roadmap for CDR

Initial data collection for the company database began with RMI’s Applied Innovation Roadmap for CDR (2023):

- The Applied Innovation Roadmap for CDR was RMI’s first effort at assessing the entire CDR field. The AIR taxonomy included 32 distinct taxonomic categories.
- The AIR aggregated over 420 CDR companies in 2023. Companies in the AIR list were then divided by the taxonomy utilized in this report. Timelines of interconnected systems such as grid supply, transformer supply chains, CO₂ transportation infrastructure, and CO₂ storage will all impact deployment rates.

CDR.fyi Supplier Database

To improve the database, RMI assessed the publicly available version of the CDR.fyi supplier database:

- CDR.fyi documents over 600 organizations across CDR suppliers, marketplaces, and measurement services.
- After assessing the CDR.fyi company list, over 90 additional CDR companies were added to the company database for inclusion in this report.

Open-source online resources

To supplement the database, additional companies were included across a variety of online resources:

- This included press releases regarding newly founded companies and individual resources crafted by leaders in the CDR field.
- Companies were added to the database during the project as new announcements were made. The database does not have information released after April 1, 2026.

Inclusion in database:

RMI decided to omit a variety of CDR approaches due to removal uncertainty and to avoid double counting (e.g., conventional storage “removing” CO₂ captured from a DAC plant)

Omitted approaches included:

- *Ex situ* mineralization
- *In situ* mineralization
- Conventional CO₂ storage
- Biomass building materials
- Timber building materials

All companies were initially evaluated for:

- Funding received to date
- Prior work conducted with RMI
- Current scale of deployment
- Company founding date
- Type of CDR (sCDR, bCDR, gCDR)

The final database included:

- 513 individual companies evaluated across the CDR field
- 690+ distinct projects or project groups (e.g., one EW project might include dozens of “sub-projects”)

Company database – project documentation

The following format was utilized to document and assess active and announced CDR projects, which were used to extrapolate both the scale of a company’s annual removal capacity and cumulative removals.

#	Company	Project	Successes	Failures	Active date	End date	Cumulative removals over project lifespan (tCO ₂)	Cumulative removals for project (tCO ₂) to date	Removal capacity per year of project (tCO ₂ /y)	Notes	Sources
1	Company 1	DAC FOAK commercial	Largest plant for company to date	2Questions around removal durability	2028	TBD	Unknown duration	40	500	6Noted as approximately 5x the scale of pilot plant in press release for the project	Project website
2	Company 1	DAC pilot plant	1First deployment	CO2 leakage	2018	2028	31000	200	5100	Used to estimate commercial plant	Academic paper with relevant removal rate

1 Project successes characterize significant achievements of each project. This information was sourced from available online resources (see Sources column) and was used to document notable milestones for each company/approach.

3 Cumulative removals over project lifespan are relevant to projects with known end dates. This metric is (1) sourced directly from company resources or (2) extrapolated using project lifespan and announced annual capacity.

5 Removal capacity per year of project represents annual capacity at the time of report publication. This metric is (1) sourced directly from company resources or (2) derived by comparing key metrics (e.g., scale – pilot / demo / commercial, approach) to other active projects in the field.

2 Project failures are outcomes of a project that are indicative of overall challenges an approach or technology is facing. This information was sourced from available online resources (see callout box 5) and used to inform recommended KPIs.

4 Cumulative removals for project to date represents total CDR generation of the project as of the publication of this report. This metric is either (1) sourced directly from company resources or (2) extrapolated by multiplying the project’s operating years with announced annual capacity.

6 The notes column represents the key assumptions and comparisons utilized in calculating the metrics in callout boxes 3, 4, and 5. In some cases, where project comparisons were not possible, removal rates were sourced from academic papers; in those cases, rates and sources are noted here.

Company database – deployment forecasting

The following methodology was utilized to create projections for company removal capacity and cumulative removals in 2030. In cases where this information was made publicly available by a company in the form of expected goals or removal targets, that information was substituted as a replacement for this process.

Example company projection

Sourced directly from an organization in the RMI company database. Identifying information has been removed. All project numbers remain accurate and are intended to demonstrate the calculation process.*

1	Cumulative removals through 2025 end of year	100
2	2026 annual capacity	100
3	Cumulative removals in 2030	1,418.75
	Current removals	100
	Current capacity	100
	Growth factor	1.5
	Years of growth	5
4	2030 annual capacity	506.25

*Each company within a given approach was evaluated following the above categories

After each company in a given approach was evaluated, these totals were then summed across all companies in that approach, creating totals for capacity (2030 and 2026) and cumulative removals (2030 and 2026) for the approach overall.

Explanation of methodology

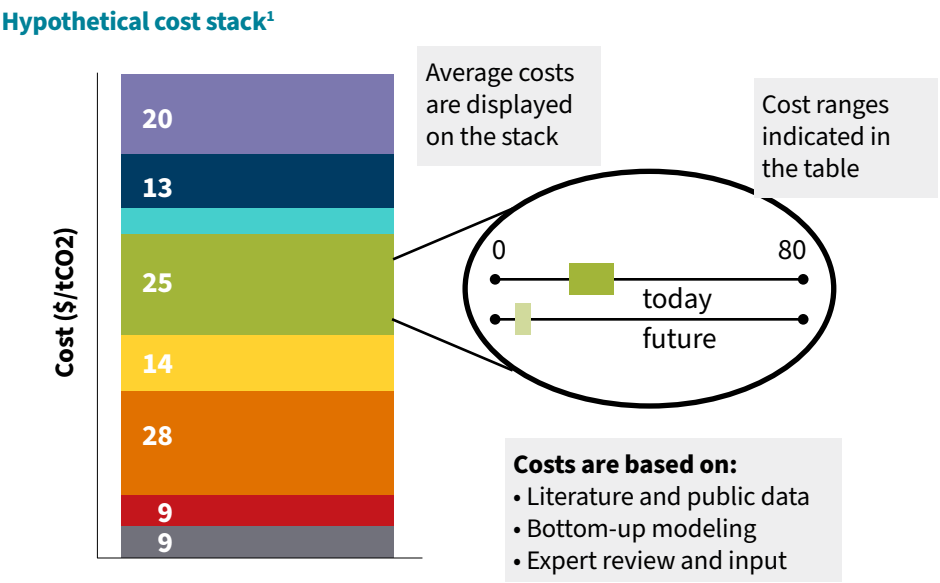
- 1
- In the absence of direct company information, online databases (such as CDR.fyi), or other online resources (e.g., press releases) that could inform the report, cumulative removal estimates for a company were created to reflect the removals that have occurred as of December 31, 2025. These totals were determined by summing the cumulative removals to date (**box 4 on page 118**) for all projects attributed to a company. The outcome represents an approximation of the company’s total removals based on available project information and conservative estimates informed by similar projects / companies within the same approach.
- 2
- Annual capacity estimates were created to reflect a company’s annual removal rate as of December 31, 2026, anticipating announced projects and removals through 2026. These estimates were derived by summing the annual capacity of all active projects that were evaluated for a given company (**box 5 on page 118**). If a company was operating projects that had completed by the time of this report and were no longer delivering removals, these projects were excluded from this metric. The 2026 annual capacity does not incorporate any announced or planned projects.
- 3
- Where company projections were not available, cumulative removals in 2030 were determined using a simplified finite geometric series. The growth factor in this calculation remained constant across approaches to reflect a 50% year-over-year growth rate, ambitious yet feasible for a nascent industry such as CDR. For one approach (Living Biomass) this growth factor was adjusted to 10%–15% on a project-by-project basis to better align with the realistic growth potential compared to current scales. In cases where a company explicitly noted its 2030 removal target or had noted that active and announced projects constituted 100% of the growth planned through end-of-decade, the available data was substituted in place of this process. Where targets were present for 2035 or beyond, the data was used to approximate the 2030 removal capacity by calculating the growth rate needed to reach the target based on current capacity.
- 4
- 2030 annual capacity was determined using a simple exponential growth function, where the initial value is equal to current capacity (**box 5 on page 118**), growth factor is approach dependent (50% vs. 15% annual GR), and the time sequence is (X-1), where X is the number of year to 2030, including 2026. In cases where a company explicitly noted its 2030 capacity target or had noted that capacity from active and announced projects constituted 100% of the planned 2030 capacity, the available data was substituted in place of this process.

Note: The graphic on the deployment forecasting page depicting “Announced and active projects as a % of 2030 company targets” is indicative of the current amount of active or planned capacity as a % of where companies expect to be by 2030. The larger the %, the smaller the gap between company targets and real projects that have been planned, built, or remain under construction.

We use eight cost stack categories across all CDR approaches to allow for comparison and optimization

Eight cost components used across all CDR approaches

	Category	Broad definition (cross-CDR)
1	Capex/conversion	The one-time cost of building and installing the physical infrastructure required to capture or prepare CO ₂ for removal, including specialized equipment, construction, and site development.
2	Energy/grinding	The cost of the power or fuel required to operate the process, whether for moving air/water, regenerating sorbents, grinding or drying feedstocks, or otherwise supplying energy to the capture and handling system.
3	Feedstock/rock sourcing	The cost of acquiring or preparing the material inputs required for the process, such as biomass residues, alkaline rock, minerals, or sorbents; includes collection, extraction, or production of these inputs.
4	Transport and spreading/ feedstock transport	The cost of moving raw inputs (like biomass, minerals, or sorbents) to the capture site or spreading location, including trucking, shipping, or pipeline costs before storage.
5	O&M/operations	The ongoing annual costs to run the facility or process, including staffing, equipment maintenance, land leases, insurance, consumables, and routine operations not directly tied to energy or feedstock.
6	Compression, transport and storage (CSS)	The cost of preparing captured CO ₂ for long-term storage (compression, drying), transporting it (via pipeline, truck, or ship), and securely storing it (e.g., in geological formations, burial sites, ocean depths), including site preparation and monitoring.
7	MRV and monitoring	The cost of measuring, reporting, and verifying that CO ₂ was captured and stored in a durable way, including baseline site surveys, sensors, sampling, third-party verification, and reporting infrastructure.
8	Embodied emissions adjustment/other	The adjustment for indirect life-cycle emissions from building, maintaining, and supplying the system (steel, cement, machinery, fuel supply chains), as well as other miscellaneous factors that reduce net CO ₂ removed.



- What are the cost stacks?
- ✓ Illustrative examples of reasonable costs of an approach

✗ Precise estimates of a specific company or project
- ✓ Generally representative of the costs of the approach

✗ Specific to a particular approach implementation
- ✓ Intended to highlight potential cost reduction areas

✗ Intended to be definitive costs of a particular implementation

1. The cost stacks in this report are intended as illustrative examples that show reasonable current and future cost ranges for a sample project within this approach. No single project will precisely match these costs or these categories, as local factors, variations in approach implementation, economies of scale, and business decisions and trade-offs made by individual CDR companies in response to complex market factors will result in varied cost breakdowns.

Cost savings through breakthrough innovations

Breakthrough innovations were assigned possible cost savings based on impacts across cost categories, including trade-offs between categories.

Category	Range of potential cost savings (\$tCO ₂)	CDR examples	Examples of approaches from this book
\$	\$1–\$30/tCO ₂	Optimization in sourcing of inputs, secondary revenue generation from dual business proposition	bCDR: Siting and supply chain optimization for forest residues, including mapping sources and establishing low-carbon transport links to minimize hauling distance and reduce embodied emissions. gCDR: Comprehensive switch to an electrified process for all machinery and components, including the preprocessing required for maximum reactivity, additional treatments to encourage weathering, and spreading. sCDR: Improved understanding of chemistry and alkaline diffusion in open-system environments that better allow for prediction of most impactful deployment sites and reduced ecosystem impacts.
\$\$	\$20–\$50/tCO ₂	Automation of material handling and processing steps, efficiency and precision improvements in MRV, scaled critical supply chain	bCDR: Ultra-low-cost, durable sensors and digital MRV networks for Living Biomass projects like reforestation plots, reducing labor and sensor maintenance / replacement cost. gCDR: Autonomous feedstock pre- and post-processing that includes the grinding, crushing, and churning of mineral aggregates reduces costs by increasing reactivity per ton of feedstock and reduces labor needs. sCDR: Development of specialized, factory-standard membranes designed for EOA approaches, reducing costs in bespoke component procurement and increasing predictability and removal efficacy.
\$\$\$	\$40–\$100/tCO ₂	Increases in equipment uptime or project lifetime, unlock in integration opportunities to embed in other established industries	bCDR: Autonomous, solar-powered pyrolysis systems operated via drone technology that can reach remote feedstocks, eliminating transport while reducing downtime and labor for biochar operations. gCDR: Optimized tailings storage facilities designed and implemented at mine sites reduce cost by eliminating transport, reducing labor costs, and dramatically reducing feedstock costs. sCDR: Passive mechanisms for air contactors that reduce high energy cost associated with transport of large volumes of ambient air needed for direct air capture approaches.
\$\$\$\$	\$75–\$300/tCO ₂	Breakthroughs in energy efficiency, discovery of a novel technique or unlock of a scientific process	bCDR: Biomass gasification at scale that enables highly efficient syngas synthesis that can replace natural gas, decreasing costs by generating improved output with greater applicability and revenue potential. gCDR: Modular, adaptable dosing systems for industrial integration opportunities that includes automated dosing systems that detect ideal pH and alkalinity, thereby reducing capex and monitoring and labor costs. sCDR: Novel sorbent materials with improved capacity or recovery efficiency that enable more efficient regeneration, reduce energy costs, and increase the ability of the DAC system to operate without downtime / on reduced maintenance.

Development of cost stacks

The following methodology was utilized to create a comprehensive, though nonexhaustive, list of CDR companies across the 14 approaches examined in this report.

1

AI-enabled, subcomponent-level cost generation¹

Prompt overview:

- Sequential prompt investigation for each of the eight components of the cost stack (see previous page)
- Generation of five-plus subcomponents for each of the eight cost stack components (see subsequent page)
- Unique sequence of investigation for current and future cost stacks
- Unique sequence of investigation for each of the 14 approaches

The model was instructed to draw on two bodies of knowledge:

- All publicly disclosed costs of the approach
- Similar costs in adjacent industries, e.g., EPC cost equivalents for capex facilities of similar size and characteristics

2

RMI validation of component-level costs

RMI assessments:

- Sense-checking of individual cost stack components and subcomponents based on expert knowledge
- Crosschecking of subcomponent costs across the eight components of a given stack
- Crosschecking of components of a cost stack between different approaches
- Generation of additional modeling analysis where necessary, e.g., capex costs across different facility sizes
- Generation of sensitivity analyses for some total capex costs, including around major component lifetimes, cost of capital, and expected innovation

3

External review and calibration of component-level costs

External validation of cost stacks and components:

- As part of the external review process, each cost stack was evaluated by one to five experts across commercial and noncommercial fields to ensure balanced review
- Reviewer input on costs was assessed against the model data and known public cost data
- Follow-up interviews and outreach was conducted, where necessary, to verify and refine areas of disagreement

¹. Initial, component-level costs were generated using an RMI-licensed version of ChatGPT 5.2.



The New Frontiers Report for CDR, 2026, RMI

<https://rmi.org/resources/the-new-frontiers-report-for-cdr>

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