The Applied Innovation Roadmap for CDR

An independent perspective to guide RD&D funding

NOVEMBER 2023

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RMI

Glossary and abbreviations

AIR: This document: The Applied Innovation Roadmap for CDR

BECCS: Bioenergy with carbon capture and sequestration

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 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 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.

Critical path activities: Activities that must be completed to advance a given CDR approach toward technical viability at scale

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.

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

GHG: Greenhouse gas

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

LPO: US Department of Energy's Loan Programs Office

MRL: Market readiness level; the state of market diffusion of a CDR approach after its having achieved technical viability at scale.

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.

NOAK: N^{th} 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.

O&G: Oil and gas

Path-boosting activity: RD&D projects that are not critical path but have the potential to boost progress and outcomes

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.

Roadmaps: A proposed set of prioritized and sequenced RD&D activities for advancing CDR approaches to technical viability at scale

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

Technical projects: RD&D activities that are covered in this AIR

Technical viability at scale: The ability of a CDR approach to successfully remove carbon dioxide from the atmosphere, store it, and measure the process at scale for a competitive cost

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.

Introduction

Who and what this roadmap is for

Purpose of this work To offer a comprehensive, objective, and action-oriented perspective on how to best advance the technical viability at scale of 32 carbon dioxide removal (CDR) approaches this decade

Audience Anyone in a position to help advance the technical readiness of CDR for scaled deployment. This includes:

- Policymakers
- Students, educators, and other learners
- Technology developers and venture capitalists
- Government funding agencies, private donors, and other research funders
- Scientists and researchers focused on basic research
- Anyone else in a position to shape, support, fund, or conduct CDR RD&D

Intended Impact

1. **Greater global visibility** into what CDR RD&D is underway and what is needed
2. Increased, coordinated **funding for RD&D gaps in CDR**, especially critical path projects identified in the AIR

Roadmap scope and reach

This Applied Innovation Roadmap (AIR) describes critical path RD&D activities for 32 CDR approaches. It is not an assessment of which of the 32 should be prioritized.

THIS AIR INCLUDES (for all 32 approaches)	THIS AIR DOES NOT INCLUDE
An assessment of the challenges and risks to achieving technical viability at scale across scalability, secure storage, measurement, and cost	Modeling of current and future costs
An assessment of technical readiness levels, the current state of RD&D, and a roadmap for future technical and RD&D projects	An assessment and roadmap for actions needed to establish a scaled, sustainable CDR industry, that are not technical
A menu of proposed projects, with project scopes, timelines, budgets, and costs	Information on who should fund these projects or optimal funding mechanisms, e.g., grants, prizes, results-based payments, etc.

NON-TECHNICAL NEEDS

Systems integration and infrastructure

Supply chain development

Workforce development

Social license and accountability regimes

Scaled demand

Addressing these omissions would require potential follow-on work, such as roadmaps for non-technical projects.

How to navigate this roadmap

CONTENT

Introduction

Executive summary

Overviews of the four major categories of CDR

After the overviews are deep dives on individual CDR approaches:

10 elements repeated for all 32 approaches

1. **Definition** of the approach
2. **Summary** of the roadmap findings
3. **Risk assessment**: An evaluation of risks to achieving technical viability at scale
4. **Cost improvement** potential: An assessment of two key drivers of learning rates
5. **Current state** of RD&D: A mapping of companies, plus other notable activities
6. **Success story** to 2100: An optimistic scenario for technical viability and deployment
7. **Roadmap**: Timeline, scope, and funding for proposed RD&D activities
8. **Pre-demo projects**: Scoping of pre-demonstration activities on the roadmap
9. **Demonstration projects**: Scoping of demonstration activities on the roadmap
10. **Path-boosting projects**: Scoping of path-boosting activities on the roadmap

Appendix

USER CATEGORY

Policymakers:
- Executive summary and category overviews

Students, educators, and other learners:
- Executive summary and category overviews
- Slides 1, 2, 3 and 6 of each approach

Technology developers and venture capitalists:
- Slides 2-6 of each approach

Government funding agencies and other donors:
- Slides 7-10 with a focus on demonstration

Researchers:
- Slides 7-10 with a focus on R&D gaps

Contributors

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INTERNAL RMI REVIEWERS

- **Expert review**: Aurimas Bukauskas, Chris Magwood, and Emily Rogers

EXTERNAL REVIEWERS

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- **Several others who requested to remain anonymous**

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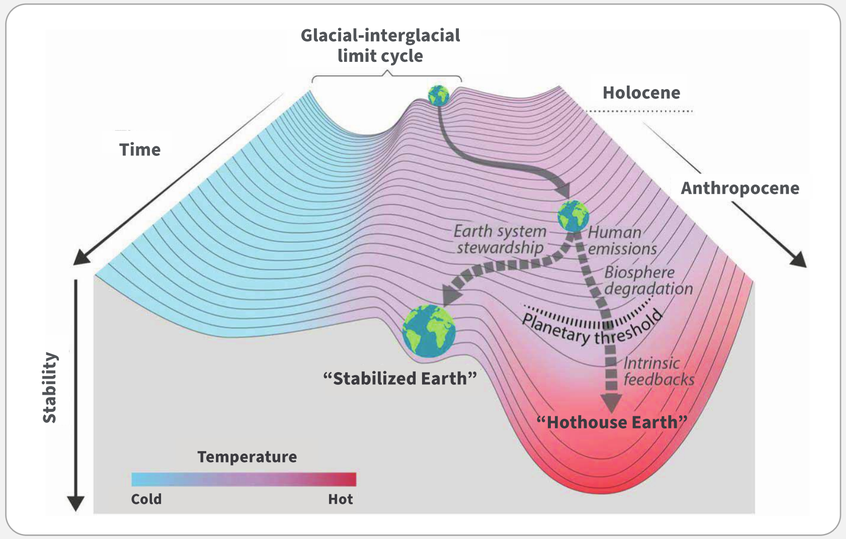
Executive summary

According to the IPCC, CDR is needed at scale, urgently, to limit temperature overshoot, address any overshoot that does occur, and sustain net zero

Limiting temperature rise is important to prevent potentially catastrophic climactic tipping points.[1]



Significant CDR is needed in IPCC scenarios that limit temperature rise to 1.5C. More CDR will be needed if we overshoot.[2]

YEAR	AVERAGE CDR IN IPCC 1.5C SCENARIOS WITH NO OVERSHOOT (C1)[1]	AVERAGE CDR IN IPCC 1.5C SCENARIOS WITH OVERSHOOT (C2)[1]
2030	2.3 $GtCO_2/y$	3.4 $GtCO_2/y$
2040	7.0 $GtCO_2/y$	8.0 $GtCO_2/y$
2050	10.8 $GtCO_2/y$	13.4 $GtCO_2/y$
2100	17.6 $GtCO_2/y$	27.0 $GtCO_2/y$

The IPCC AR6 also states that CDR is unavoidable in order to achieve net zero.[3]

"The deployment of carbon dioxide removals to counterbalance hard-to-abate residual emissions is unavoidable if net zero … emissions are to be achieved."

Notes and sources: [1]This figure was taken from the Steffen (2018) paper, which discusses near-term tipping points. [2]The data shown here is an average of all C1 scenarios (1.5C aligned with "no or limited [temperature] overshoot") in the IPCC AR6 report (2022). The C2 scenarios (those that overshoot and require retroactive removals in the second half of the century) have even greater demand for CDR. The data was obtained from the AR6 Scenario Explorer and Database hosted by IIASA. [3]The IPCC AR6 WGIII report.

Known CDR approaches fall into three groups, based on their key input. Storage of captured CO_2 is a fourth, separate domain.

CDR term:	Biogenic CDR	Geochemical CDR	Synthetic CDR	Storage of CO_2
Definition:	Biogenic CDR (bCDR) approaches use naturally-occurring biogenic carbon fixation mechanisms to capture CO_2 from the atmosphere. The most important of these mechanisms is photosynthesis.	Geochemical CDR (gCDR) approaches use naturally-occurring neutralization reactions between acidic forms of carbon and alkaline minerals to convert CO_2 from the atmosphere into solid carbonate minerals or dissolved bicarbonates.	Synthetic CDR (sCDR) approaches use engineered systems powered by low carbon energy to directly separate CO_2 from the air and capture it or to alter water chemistry to indirectly remove CO_2 from the air.	Storage of CO_2 approaches store captured and concentrated streams of CO_2 through trapping, mineralization, or other physical or chemical processes.
Key input:	**Sustainable biomass**	**Alkaline materials**	**Low-carbon energy**	**Suitable sites for CO_2 storage**
Implications for scaling:	• 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.	• 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, long run, will be those that can source, process, transport, and dispose of alkaline minerals for CDR most efficiently.	• 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.	• The potential scale of these approaches will be determined by access to suitable storage sites. • The most competitive storage solutions, long run, will be those with the lowest cost to establish and operate.

We have developed a taxonomy for all known CDR approaches that allows for the addition of new approaches in the future

BIOGENIC (bCDR)	GEOCHEMICAL (gCDR)	SYNTHETIC (sCDR)	STORAGE
Living biomass **1.1** Improved management **1.2** Conservation/protection **1.3** Restoration/creation	**Solid carbonate minerals** **4.1** Surficial mineralization	**Indirect water capture**[1] **6.1** CO_2 stripping **6.2** Electrochemical alkalinity production	**Storage of CO_2** **8.1** Conventional storage **8.2** In-situ mineralization **8.3** Ex-situ mineralization
Stabilized biomass **2.1** Biomass direct storage **2.2** Timber building products **2.3** Other biomass building products **2.4** Pyrolysis (biochar) and storage **2.5** Pyrolysis (bioliquid) and storage **2.6** Microalgae in ponds **2.7** Microalgae in open water **2.8** Macroalgae in open water	**Dissolved bicarbonate sequestration** **5.1** Terrestrial enhanced weathering[1] **5.2** Coastal enhanced weathering[1] **5.3** Mineral alkalinity enhancement[1]	**Direct air capture**[1] **7.1-7.3** Liquid solvent **7.4-7.7** Solid sorbent **7.8-7.9** Membranes **7.10** Cryogenic	
Sequestration of CO_2 from biomass **3.1** BECCS to electricity **3.2** BECCS to fuels			

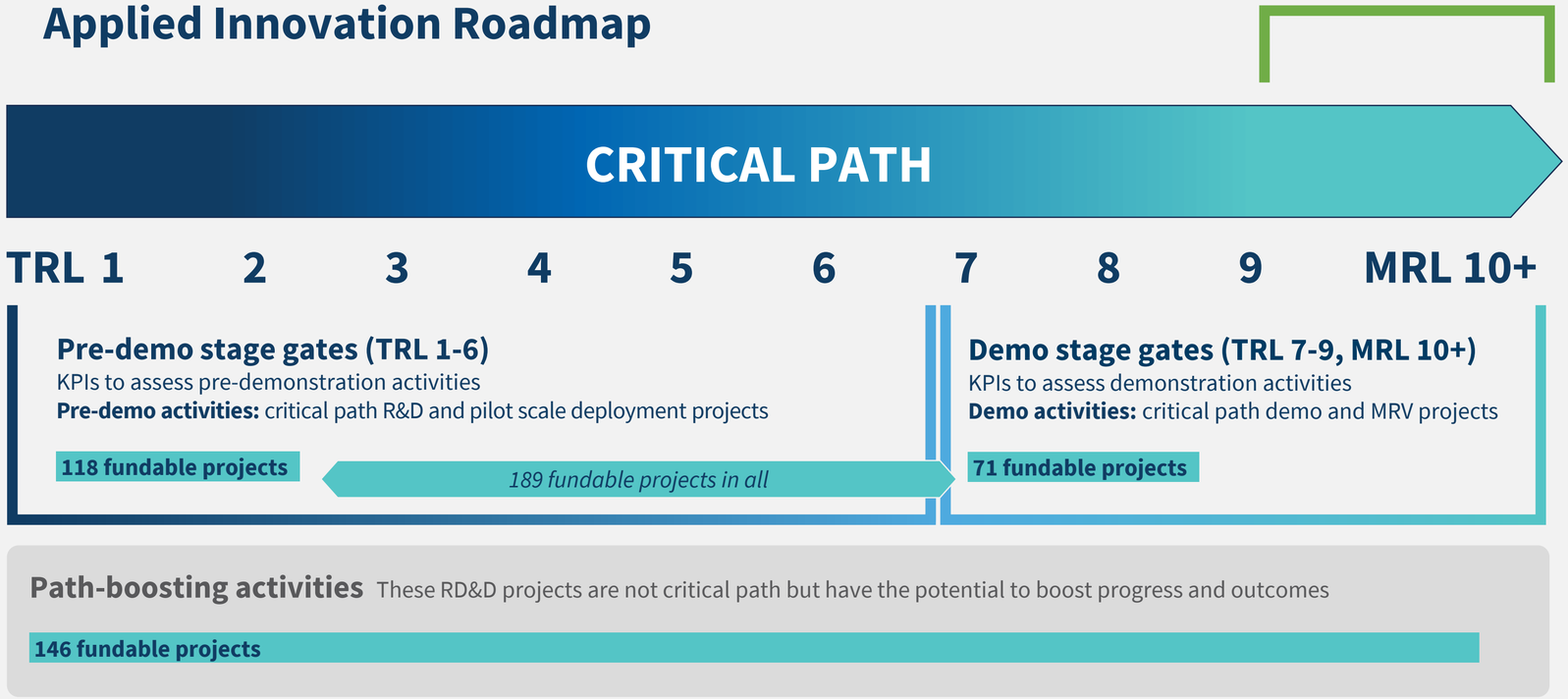
Taxonomy matters; we have worked to be precise in our language to (1) distinguish each approach from others while still (2) being broad enough to allow for new ideas that are newly emerging or haven't yet been identified, e.g., conducting alkalinity enhancement in lakes instead of the ocean.

Some terms will be new and unfamiliar, so we will do our best to illustrate what they look like in practice in the individual roadmaps.

Notes and sources: [1]Throughout the AIR, we use acronyms for several approaches and categories including terrestrial enhanced weathering (TEW), coastal enhanced weathering (CEW), mineral alkalinity enhancement (MAE), indirect water capture (IWC), and direct air capture (DAC)

Our Applied Innovation Roadmap identifies critical path activities for testing which CDR approaches can achieve technical viability at scale

Applied Innovation Roadmap

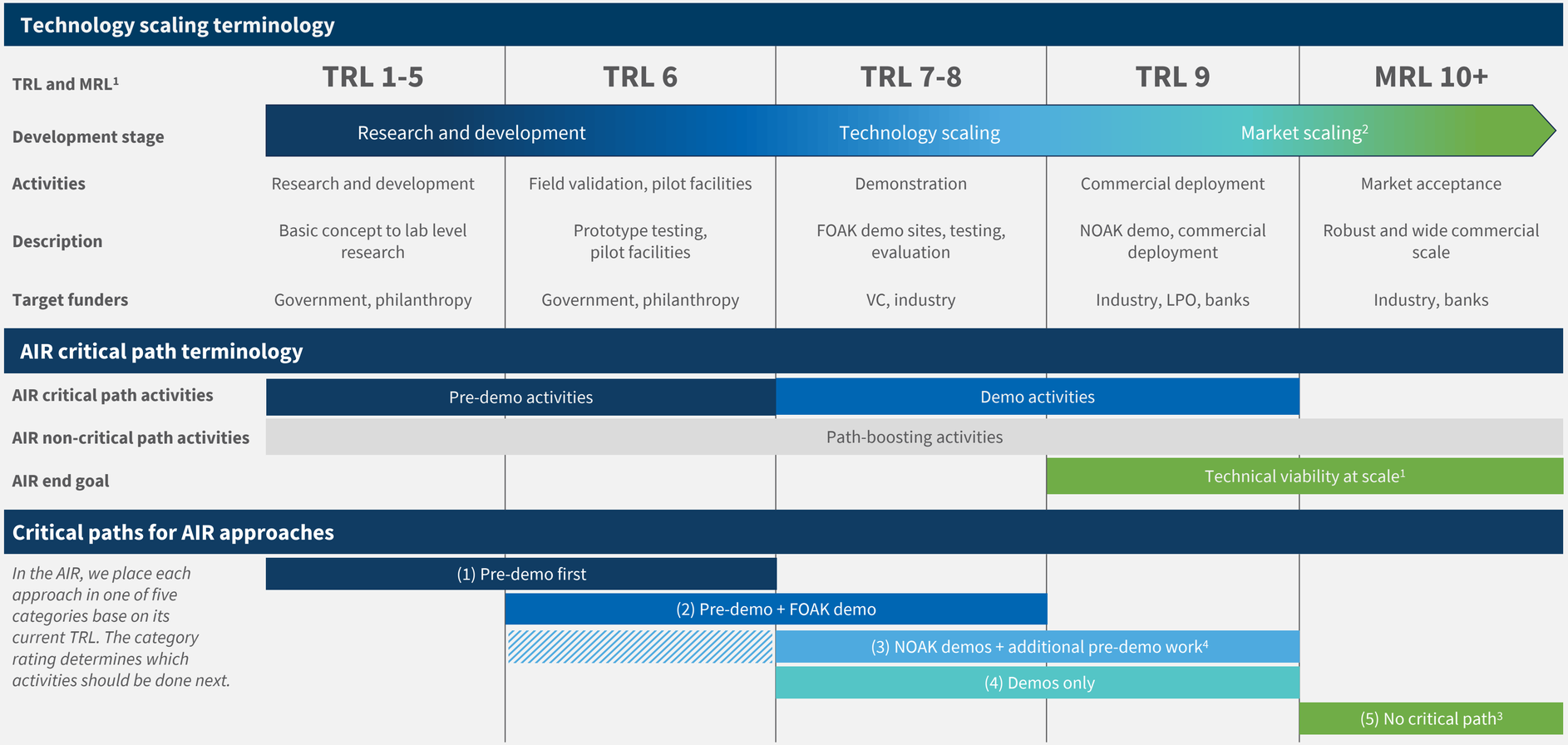


Technical viability at scale (TRL 9, MRL 10+)
We provide indicators that an approach has reached technical viability at scale

Methodology:

1. The critical path to technical viability at scale includes pre-demonstration and demonstration activities.
2. Stage-gates define the KPIs that determine whether pre-demo and demonstration activities have been sufficiently completed.
3. Path-boosting activities are meant to non-exhaustively highlight opportunities to increase the rate of development toward technical viability at scale.
4. Fundable projects include several specifications: scope, budget estimates, timelines, total cost, and areas in which the activity can cross-cut with other approaches.

We determine the critical path of each CDR approach based on its current TRL/MRL

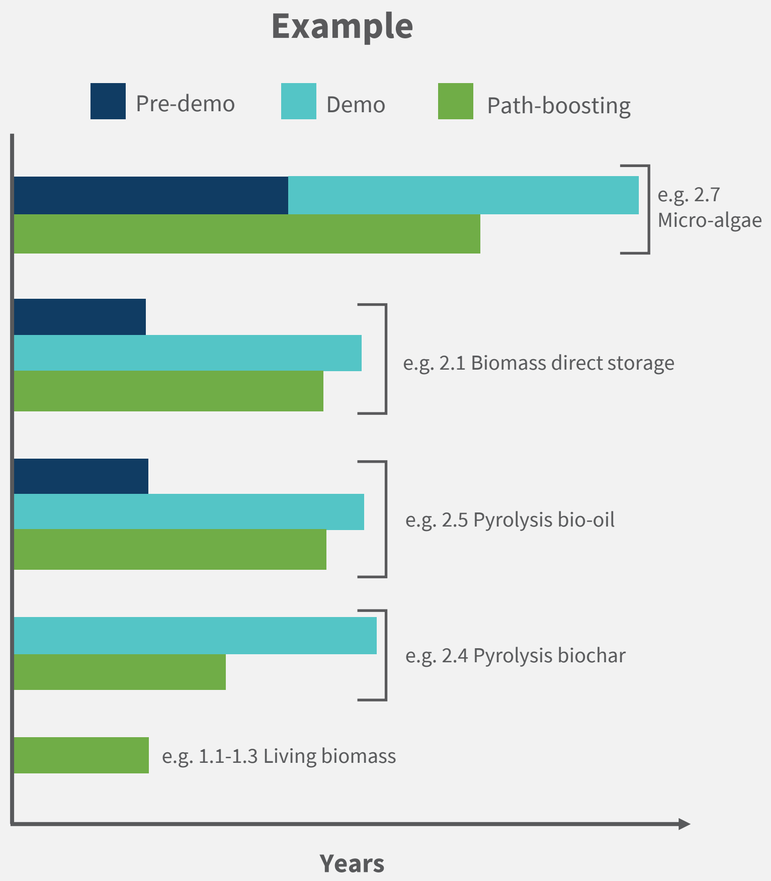


Notes and sources: [1]TRL and MRL stand for Technical Readiness Level and Market Readiness Level. [2]The AIR is scoped to focus only on technical RD&D needs. It does not include other critical non-technical activities, such as projects to advance systems integration and infrastructure, supply chain development, workforce development, social license and accountability regimes, and scaled demand. [3]These approaches have already reached widespread commercial scale, so no critical path activities are needed. Path-boosting activities at any TRL or MRL can be done next. [4]While critical path 3 does have pre-demo work involved, no approach below a TRL 7 is considered critical path 3 because necessary activities involve NOAK demos rather than an FOAK demo. We've added diagonal lines to indicate that critical path 3 overlaps with pre-demo activities although it does not overlap with TRLs below 7.

Our critical path ratings reflect what should be done next for each approach

Critical path rating	Critical path	Description of what should be done next
1	**Pre-demo activities must be done first**	These approaches still need to pass important pre-demo stage gates before demonstration-scale projects are initiated.
2	**Pre-demo and demo can be done simultaneously – demo is FOAK**	These approaches are ready for demonstration scale activities but also require continued pre-demo activities.
3	**Pre-demo and demo can be done simultaneously – demo is new sites/conditions**	These approaches have reached demonstration or early commercial scale but require additional demonstrations in new geographies or with new conditions. They also require additional pre-demo work.
4	**Demonstration activities**	These approaches are ready for demonstration scale activities and do not have pre-demo activities on their critical path.
5	**There are no critical path activities. Path-boosting activities are optional.**	These approaches are already at commercial scale and are widely adopted. Path-boosting activities can increase their rate of adoption.

In critical paths 2 and 3, it is advisable to perform the pre-demo work first, but not required. The tech is available to deploy. In these cases, there may be risks and impacts of a deployment gone wrong, but it may be necessary or desirable to take the risk.



Notes and sources: [1]The AIR methodology for assessing timelines of individual activities, critical path needs, and total incubation timeline for CDR approaches is described in detail in the AIR appendix

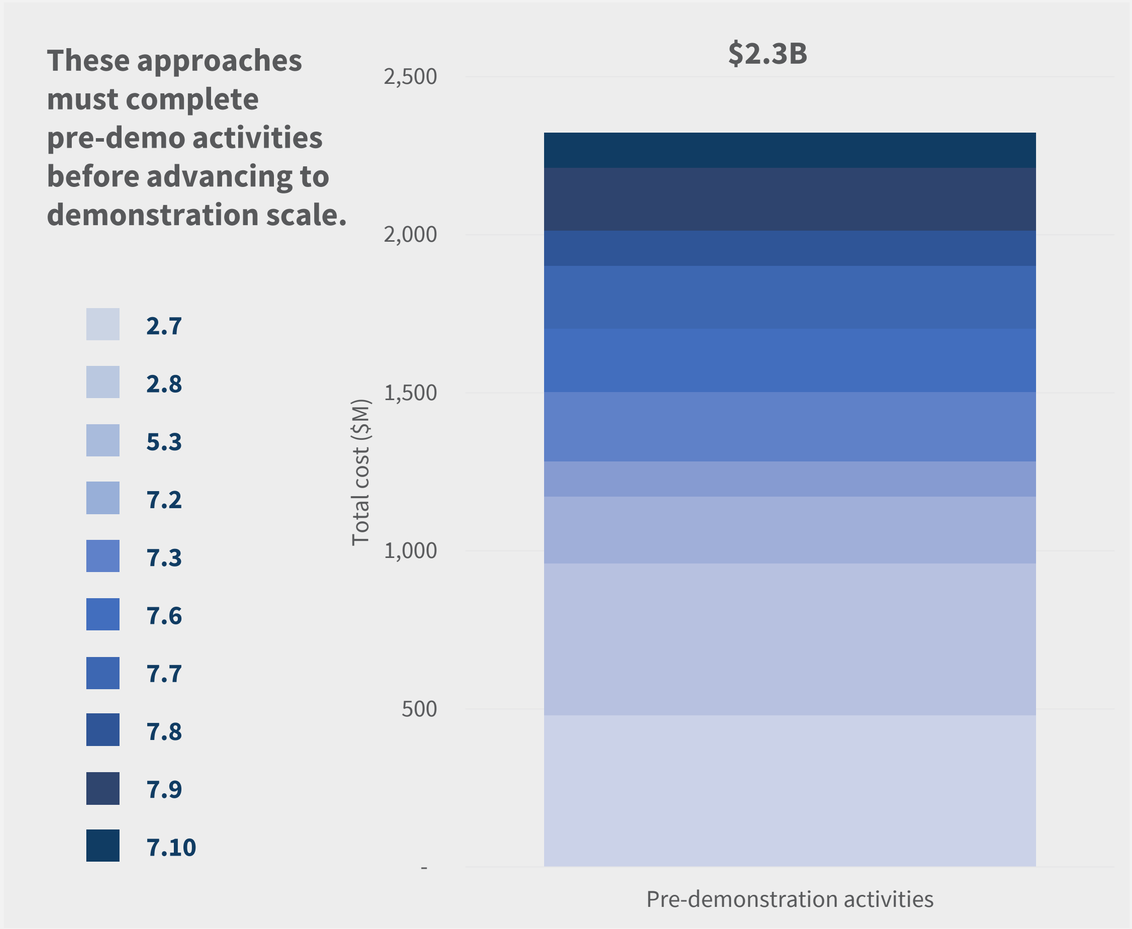
Critical path category 1

These approaches still need to pass important pre-demo stage gates before demonstration-scale projects are initiated.

INDEX	APPROACH	CURRENT TRL/MRL	CRITICAL NEEDS
2.7	Microalgae ocean	TRL 4	Characterization of environmental impacts
2.8	Macroalgae ocean	TRL 6	
5.3	Mineral alkalinity enhancement	TRL 6	
7.2	Absorption and low-grade heat regeneration	TRL 5	Advancements in basic science
7.3	Absorption and electrochemical regeneration[1]	TRL 6	
7.6	Adsorption and electrochemical regeneration	TRL 6	
7.7	Adsorption and humidity / water regeneration	TRL 6	
7.8	Membrane: pressure gradient separation	TRL 2	
7.9	Membrane: electrochemical separation	TRL 3	
7.10	Cryogenic: phase separation	TRL 4	

Critical path 1 needs:
Pre-demonstration funding to either (A) achieve advancements in their basic science or (B) better understand expected environmental impacts before larger amounts of funding are spent on demonstrations.

These approaches must complete pre-demo activities before advancing to demonstration scale, either because the CDR technology is not ready or because there are significant safety concerns facing wider deployment. Note that the roadmaps of these approaches include demonstration scale activities to be completed once pre-demonstration stage gates are validated.



Notes and sources: [1]Approach 7.3 includes several companies, including Capture6 and mission zero, that state they are pursuing pilot or demonstration scale facilities. However, some AIR reviewers think that the technology of this approach has still not been sufficiently proven to warrant demonstration scale funding.

Critical path category 2

These approaches are ready for demonstration scale activities, but also require continued pre-demo activities that can be done in parallel.

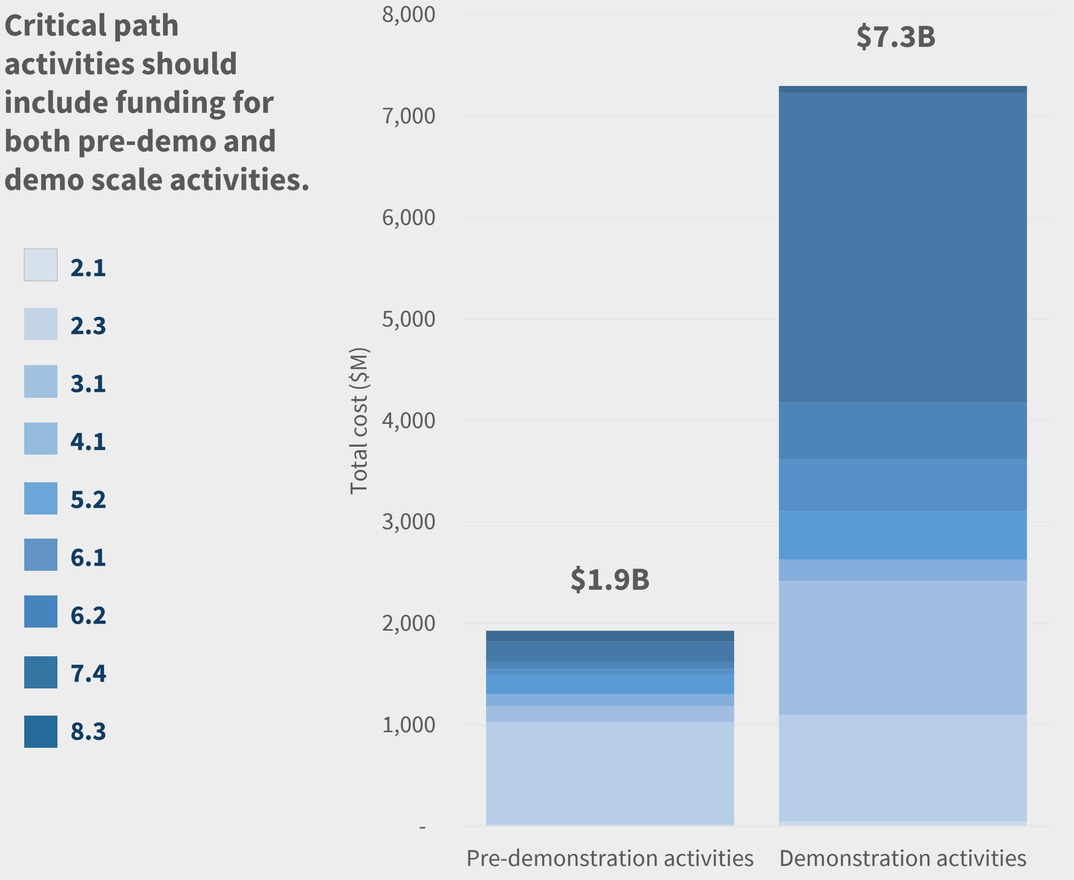
INDEX	APPROACH	CURRENT TRL/MRL
2.1	Biomass direct storage	TRL 6
2.3	Other biomass building products[1]	TRL 9
3.1	BECCS to electricity[4]	TRL 6
4.1	Surficial mineralization	TRL 6
5.2	Coastal enhanced weathering	TRL 6
6.1	CO_2 stripping	TRL 6
6.2	Electrochemical alkalinity production	TRL 6
7.4	Adsorption and high-grade heat regeneration	TRL 6
8.3	Ex-situ mineralization	TRL 6

Critical path 2 needs:

1. Conduct pre-demo work to ensure that these approaches achieve their long-term scaling goals.[2]
2. Deploy FOAK demonstrations to test whether an approach will work at scale.[3]

The critical path demonstration activities in these approaches are focused on FOAK deployment.[3] These approaches also include critical pre-demo activities that must be done either before or in parallel with demonstration activities.

Critical path activities should include funding for both pre-demo and demo scale activities.



Notes and sources: [1]Some sub-approaches are already commercial scale; however, many are still at an early TRL and need additional pre-demo incubation. [2]These approaches are technically ready to be demonstrated. However, pre-demo work is also critical to accomplishing the demonstration scale stage gates and must be funded either before or in parallel with the demonstration activities. [3]The individual AIR roadmaps include scope for both FOAK and NOAK demonstrations. FOAK are used to prove that an approach works, and NOAK demonstrations are used to prove that an approach works under different conditions and geographies. FOAK and NOAK stand for first of a kind and Nth of a kind. [4]See the BECCS to electricity pathway to see the full state of this approach. Some companies such as DRAX, Toshiba, and others are in the process of creating demo-scale facilities, but these have not yet demonstrated functionality. By contrast, BECCS to fuels is much more advanced.

Critical path category 3

NOAK demos are needed. These approaches are already at the demonstration scale but need to be tested in new and diverse conditions to achieve long term scaling goals.

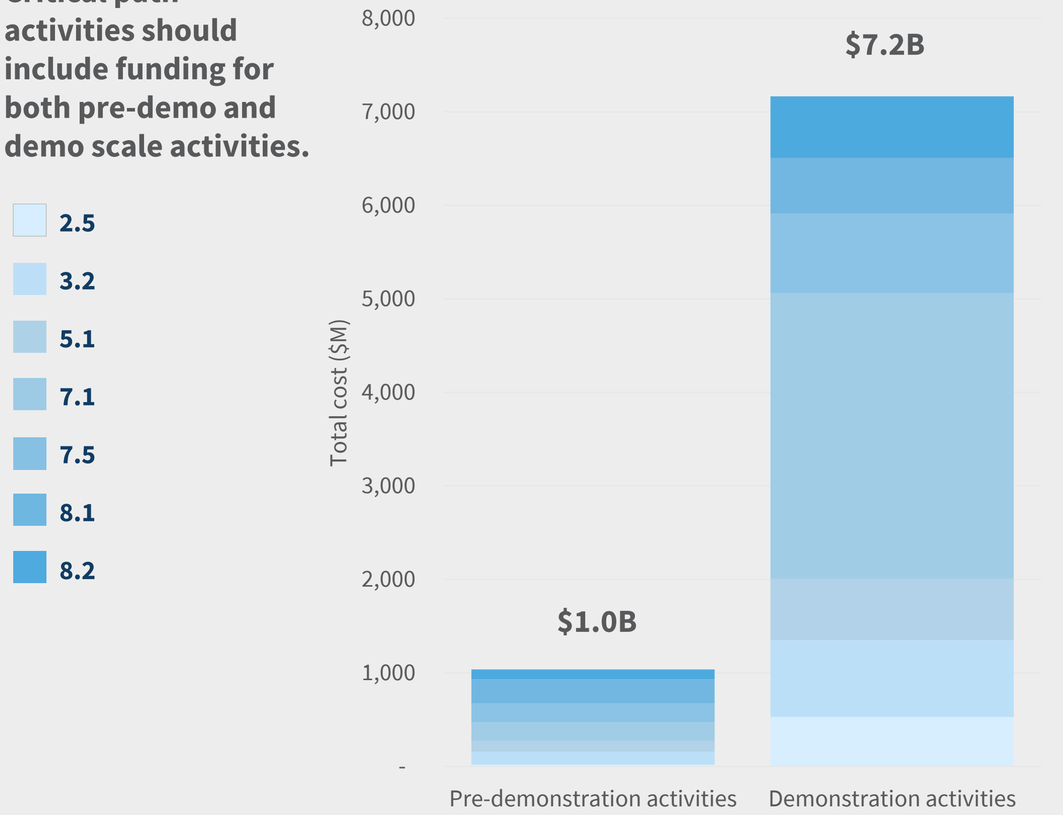
INDEX	APPROACH[1]	CURRENT TRL/MRL
2.5	Pyrolysis (bioliquid)	TRL 7
3.2	BECCS to fuels[1]	MRL 10+
5.1	Terrestrial enhanced weathering	TRL 7
7.1	Absorption and high-grade heat regeneration	TRL 7
7.5	Adsorption and low-grade heat regeneration	TRL 9
8.1	Conventional storage[1]	MRL 10+
8.2	In-situ mineralization	TRL 8

Critical path 3 needs:

1. Deploy additional demonstrations (NOAK) of these approaches in more diverse conditions.[1,2]
2. Simultaneously conduct pre-demo work to ensure that these approaches achieve their long-term scaling goals.[3]

NOAK demonstrations are used to prove that an approach works under different conditions and geographies.[2] The goal of these demonstrations is to advance the TRL of an approach. These approaches also include pre-demo activities that are necessary for achieving long term scaling goals; however, total spending on pre-demo activities is much less than in critical path categories 1 and 2.

Critical path activities should include funding for both pre-demo and demo scale activities.



Notes and sources: [1]These approaches are already at commercial scale; however, BECCS to fuels still needs to develop, deploy, and verify that CCS works on these units at scale and under varying conditions, while conventional storage needs pre-demo and demo work to prove that the approach works safely, at scale, under varying conditions. [2]FOAK and NOAK stand for first of a kind and Nth of a kind. [3]Pre-demo work is critical to accomplishing the demonstration scale stage gates and must be funded either before or in parallel with the demonstration activities.

Critical path category 4

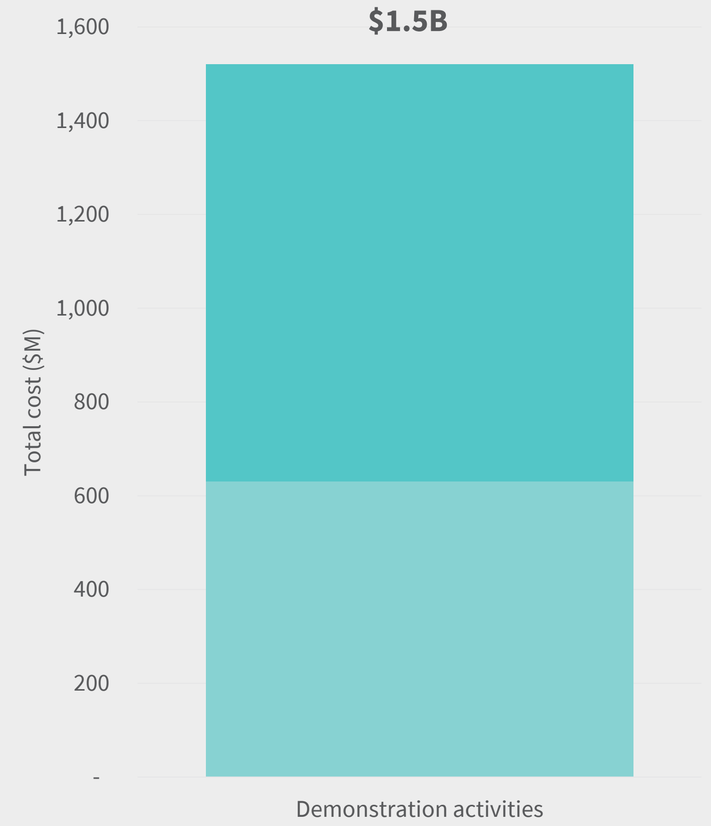
CDR-specific demos are needed. These approaches already have many years of research and deployment but not necessarily for CDR.

INDEX	APPROACH	CURRENT TRL/MRL
2.4	Pyrolysis (biochar)	TRL 9
2.6	Microalgae ponds	TRL 7

Critical path 4 needs:
These approaches should be deployed immediately at the demonstration scale to test how they work in practice for CDR.

This category includes AIR approaches that are well known and have already had many years of research and development. What is now needed is not additional R&D but immediate deployment of demonstration scale facilities with a specific focus on CDR.[1] The goal of these demonstrations is to advance CDR-specific MRL, including advances in technical capabilities and decreases in cost per ton of CO_2 removed. In critical path 4, no pre-demo work is included on the critical path.

Critical path activities should focus on demo scale activities to validate the CDR potential of these approaches with the technology that we have today.



Notes and sources: [1]These approaches already have operations at the demonstration and / or commercial scale. However, these approaches may not have been deployed for CDR purposes. For example, biochar has been used to turn waste into soil amendments and cultivated microalgae has been used to make cosmetics and supplements.

Critical path category 5

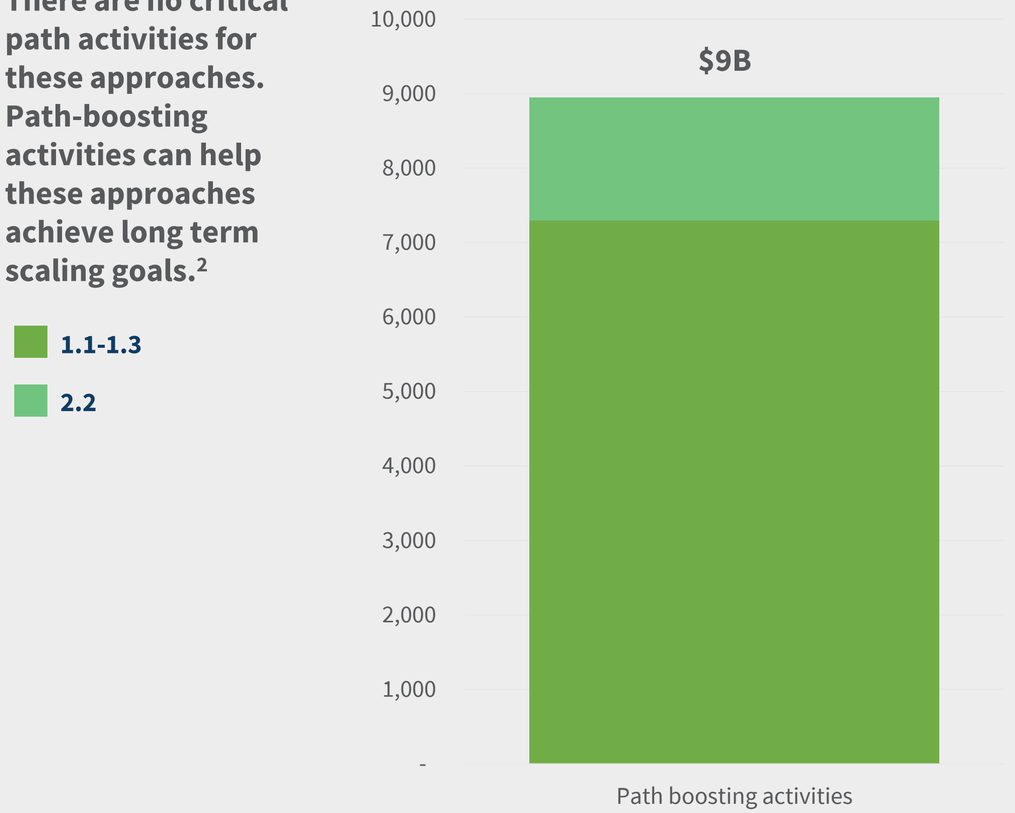
These approaches are already at commercial scale and are widely adopted. Path-boosting activities can increase their rate of adoption, increase their ability to scale, decrease their cost, or otherwise improve their processes.

INDEX	APPROACH	CURRENT TRL/MRL
1.1-1.3	Living biomass	MRL 10+
2.2	Timber building products	MRL 10+

Critical path 5 needs:
This category includes AIR approaches that are already commercial and do not have critical path RD&D activities.[1]

This category includes living biomass approaches and timber building products. Both approaches are currently deployed at a global, commercial scale. However, there is still significant potential for improvements in the technology of these approach areas. Improvements in these areas may come naturally over time, but may be aided by targeted, path-boosting activities.[2]

There are no critical path activities for these approaches. Path-boosting activities can help these approaches achieve long term scaling goals.[2]



Notes and sources: [1]The sections of the AIR for these approaches do not include a critical path roadmap, pre-demo, or demonstration slides. They only include a path-boosting slide. [2]Note that the path-boosting activities across the AIR are not exhaustive of all activities that could be done. Instead, they are meant to illustrate a sample selection of activities with significant potential to advance a CDR approach area.

There are also several cross-cutting activities that can benefit multiple CDR approaches at the same time

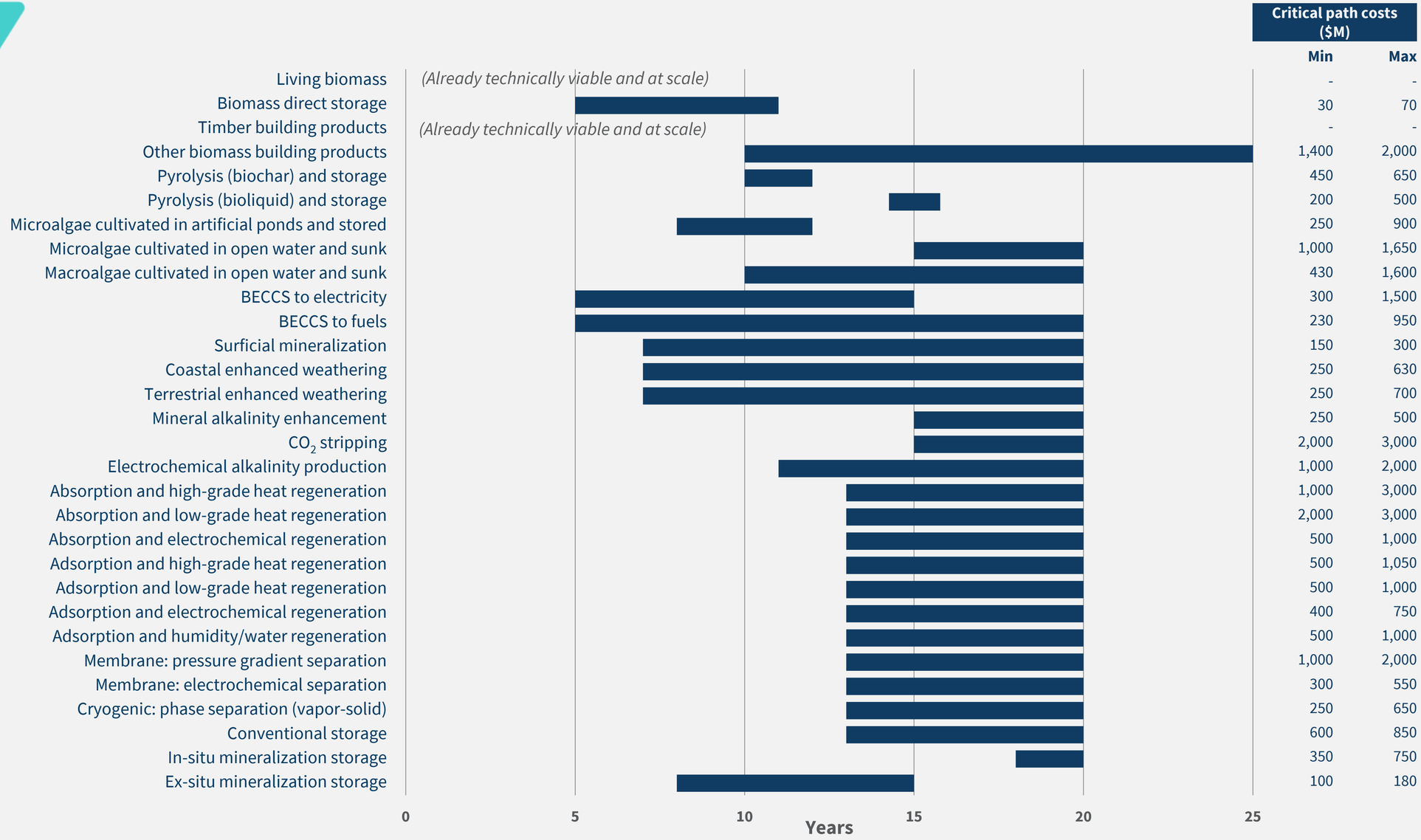
NOT EXHAUSTIVE

ACTIVITY:	Enhanced cultivars for bCDR	Ocean monitoring	RD&D alongside industrial transitions
DEFINITION:	**Research on enhanced cultivars:** Research programs to develop plant-based feedstocks that have enhanced qualities. This could include improved survivability through pest and pathogen resistance and enhanced environmental durability.	**Aggregated ocean monitoring to address ocean MRV and track ecosystem impacts:** Develop an aggregated global ocean monitoring program. The goal is to (1) understand baseline ecosystem health, (2) quantify removals, and (3) establish more robust MRV.	**Assessments, studies, and demos of systems integration opportunities:** Research should seek systems approaches to deploy CDR alongside other major energy transition activities. This could include pairing bCDR approaches with SAF production, deploying gCDR alongside mining, and incorporating sCDR with new industrial corridors and processes.
SPECIFICS:	• Development of gene banks, plant cultivars, and soil microbes to preserve genetic diversity, increase plant carbon uptake and storage, provide biological early warning systems, improve survivability through pest and pathogen resistance, and develop greater environmental durability. • Enhanced cultivars should support diverse ecosystem development for greater resilience. • Enhancements should be aimed at any number of cultivars that could be used for bCDR activities.	• These activities should seek to demonstrate the efficiency of atmospheric CO_2 uptake over realistic timeframes, with uncertainty bounds. • Initial funding should seek to demonstrate this theory in practice with (1) dedicated field testing and (2) dedicated modeling of removals. • Funding should include continual assessment of key marine ecosystem metrics near demonstration sites to ensure regulatory compliance, low impact, and to support transparency / social acceptance.	• Value chain and opportunity assessments, to identify opportunities for CDR technology integration with industrial technology transitions • Feasibility and design studies for regional hubs and clusters than combine industrial technology transitions and CDR RD&D • Demonstration projects on industrial sites, integrated into industrial technology transition projects
APPROACH	1.1-1.3, 2.1-2.8, 3.1-3.2	2.7, 2.8, 5.3, 6.1, 6.2	All
ACTIVITY	Path-boosting	MRV	Path-boosting
COST[1]	$600M – $1B	$100M – $300M	$20M – $40M
TIME	15 years	5-10 years	3-5 years

Notes and sources: [1]Project costs are listed as the total cost of a single project over all project years. For most activities, several projects are recommended

For most approaches, the critical path can be completed within 20 years

Timelines are the overall time range for each individual approach to complete its critical path activities. Timelines are based on (1) pre-demo and demonstration scale critical path activities and (2) the critical path category rating of each approach.[1]



Notes and sources: [1]The methodology for calculating overall approach timelines is presented in the AIR Appendix.

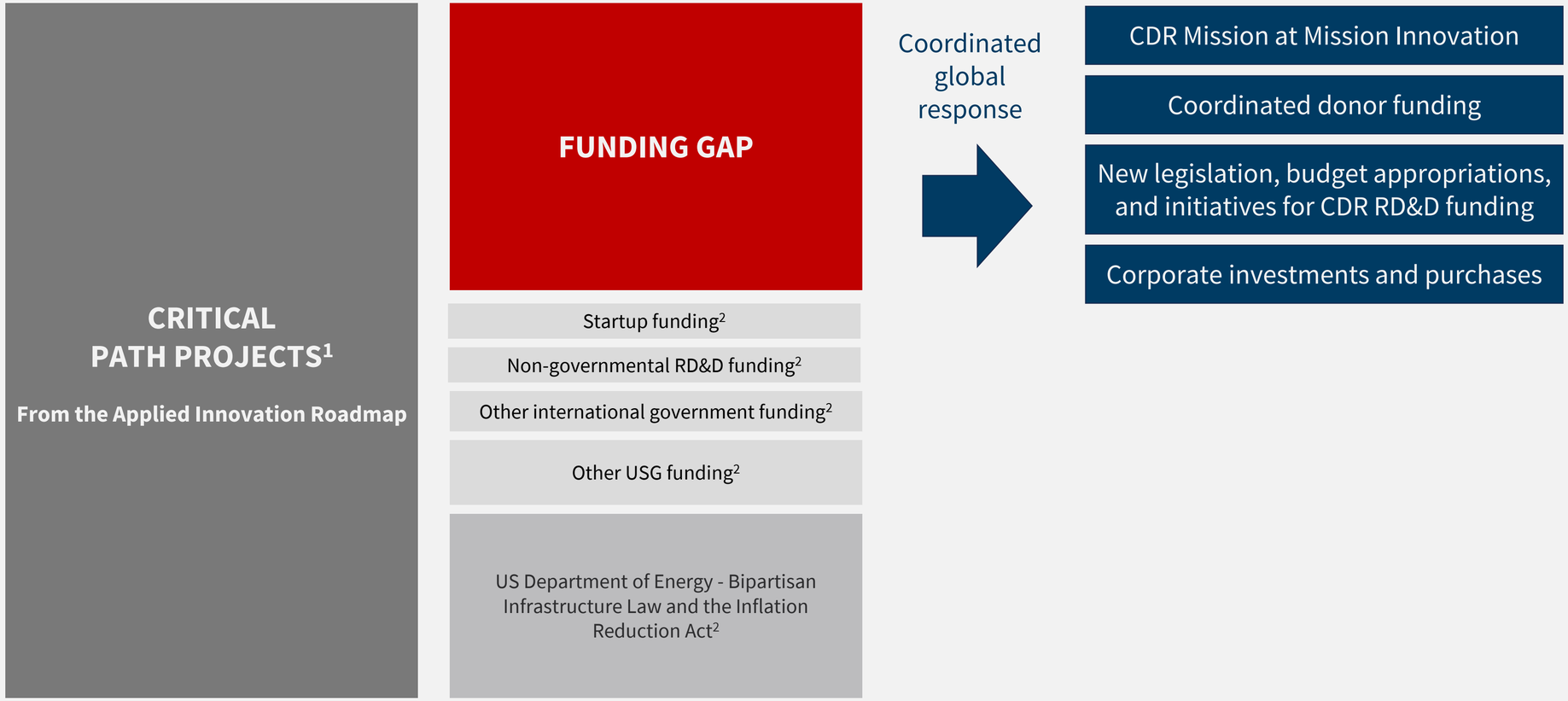
Current and planned funding from the US Department of Energy offers a launchpad for getting critical path CDR RD&D funded, in time

NOT EXHAUSTIVE

PROGRAM[1]	SCOPE	FUNDING (amount and status)	RELEVANT CDR APPROACHES
DAC Hubs[2]	Development of four regional DAC hubs selected based on geography, scalability, jobs, and other considerations	$3.5B expected, $1.2B awarded[3]	• Direct air capture
Carbon Storage Validation and Testing[4]	Advancement of carbon sequestration projects and supporting transport infrastructure through development and validation of technologies	$2.5B expected, $444M awarded[5]	• Storage of CO_2
CDR prizes[6]	Advancement of technologies and incubators for CDR through a suite of prizes	**DAC EPIC:** $3.7M expected, $1.3M awarded[7] **DAC Pre-Commercial Technology:** $3.2M expected[8] **CDR Purchase Pilot:** $35M expected[9] **Commercial DAC Pilot:** $60M expected[10]	• Direct air capture • Long-term biomass technologies • Enhanced weathering and mineralization technologies • Planned and managed carbon sinks
Sensing Exports of Anthropogenic Carbon through Ocean Observation (SEA-CO2)[11]	Advancement CDR approaches in marine pathways including MRV and R&D	$36M awarded	• Marine CDR approaches
National Labs call: Measurement, reporting, and verification (MRV)[12]	Advancement of MRV best practices and capabilities at four National Labs	$15M awarded	• CDR MRV broadly • Mineralization technologies • Cement and concrete technologies • Biomass and storage technologies
Carbon Negative Shot: Pilots[13]	Development and commercialization of a variety of CDR technologies through pilot deployment	TBD, expected in late 2023 – early 2024	• Long-term biomass technologies • Mineralization technologies • Marine CDR approaches • Multi-pathway testbeds
Carbon Negative Shot: MRV[13]	Improvement of MRV through Carbon Negative Shot projects	TBD, expected in 2024	• Terrestrial CDR approaches • Marine CDR approaches
Carbon Negative Shot: Technology development and research[13]	Technology development and research through Carbon Negative Shot projects	TBD, expected in 2024	• Direct air capture • Marine CDR approaches • Possibly other topics

Notes and sources: [1]This table is not exhaustive but shows some of the most relevant funding opportunities to the AIR. For information on other opportunities, see Box 1 in the DOE's Notice of Intent for Carbon Negative Shot Pilots (download the full FOA). [2]DOE DAC Hubs announcement [3]Awardee announcement [4]Carbon Storage and Validation Testing information [5]Awardee announcement [6]DOE CDR prizes [7]EPIC information [8]DAC Pre-Commercial Technology information [9]CDR Pilot information [10]DAC Commercial Prize information [11]CDR Pilot information [11]SEA-CO2 recent announcement [12]National Labs announcement [13]DOE Notice of Intent

RMI hopes the AIR will be used to fill the remaining funding gaps, by entities that can mobilize and coordinate RD&D funding for CDR



Notes and sources: [1]The critical path funding that is outlined in the AIR does not include adjacent funding streams that might also advance CDR. [2]According to WRI, the Bipartisan Infrastructure Law and the Inflation Reduction Act have set aside $14B in funding for CDR. BIL and IRA RD&D activities amount to $3.8B. "Other USG funding" is funding not included in the BIL or IRA that still influences CDR in the US. This includes programs such as ARPA-E, HESTIA, and other DOE programs. "Other international government funding" includes funding set aside by the UK, Australia, the EU, and other governments for CDR research and implementation. "Non-governmental RD&D funding" includes voluntary corporate programs such as Frontier and Microsoft, grants from private donors and donor-funded programs like XPRIZE and Carbon to Sea, and other organizations that provide funding for RD&D for startups. "Startup funding" is a culmination of seed funding, government grants, and other startup funding sources.

RD&D funding gaps must be met this decade, across approaches, for CDR to emerge in time

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

The cumulative CDR described below is the summation of the upper limit of CDR deployment taken from individual CDR success stories in the AIR report.[1] The assumptions for each projection are based on a range of sources described in the individual CDR success stories.

2025

- Global capture from CDR operations reaches **20 $MtCO_2$/y**, primarily through living biomass removals.
- Critical path **RD&D projects are funded** for nearly all CDR approaches.

2035

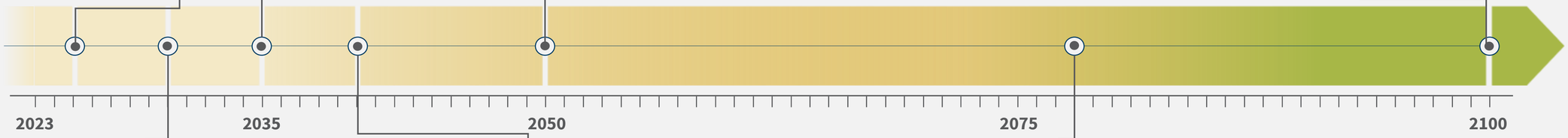
- Global capture from CDR operations reaches **800 $MtCO_2$/y**
- Biogenic CDR provides >50% of removals
- **BECCS** must grow to 74 $MtCO_2$/y in order to be on track
- **Surficial mineralization** must rise quickly to ~160 $MtCO_2$/y

2050

- Global capture from CDR operations reaches **13.7 $GtCO_2$/y.** More than 10 GtCO2/y of these removals come from biogenic CDR
- **DAC** reaches its global target of 1 $GtCO_2$/y
- BECCS surpasses 2 $GtCO_2$/y, largely through reconfiguration of old thermal generators
- Microalgae and macroalgae sinking finally reach 1 $GtCO_2$/y removals and begin to scale quickly

2100

- Global capture from CDR operations reaches **35 $GtCO_2$/y**.[1]
- Biomass feedstock must remain abundant and dedicated for CDR
- Geochemical approaches require deployment of alkaline minerals all around the world
- Synthetic approaches are deployed globally



2030

- Global capture from CDR operations reaches **200 $MtCO_2$/y**.
- Measurement, accounting, and standards for living biomass approaches must be widely established
- DAC must reach 60 $MtCO_2$/y in order to be on track for scaling in the 2030s and 2040s.

2040

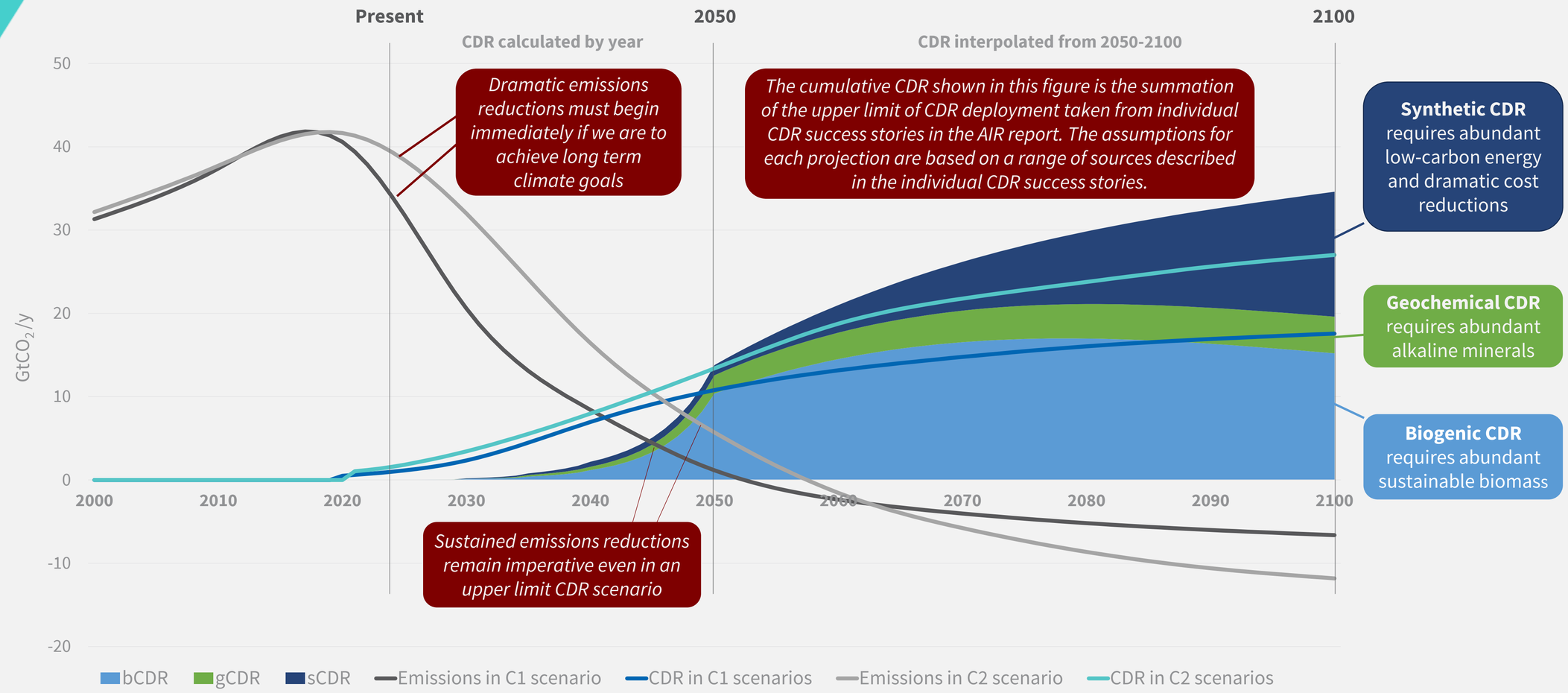
- Global capture from CDR reaches **2.2 $GtCO_2$/y**
- Important breakthroughs are made in the cultivation, sinking, and measurement of ocean algae CDR, allowing for rapid growth in the coming decades
- bCDR and sCDR approaches have demonstrated a **measurable learning curve**, with costs falling as deployment increases.

2050-2100

- bCDR continues to provide significant CDR despite competition for – and climate impacts on – biomass feedstock.
- Microalgae and macroalgae growth and sinking increase significantly with key RD&D and MRV developments.
- Significant growth in gCDR deployment continues in the second half of the century.
- sCDR approaches grow rapidly to 2100 as efforts focus on small set of approaches with the strongest learning curves on efficiency and cost.

Notes and sources: [1]The AIR includes 26 individually assessed CDR roadmaps of 29 CDR approaches plus 3 individually assessed CO_2 storage approaches. The overall AIR CDR success story values shown here are the unconstrained sums of these 29 CDR roadmaps. The values shown here are not an indication of the CDR that will be achieved; they are meant to represent an optimistic, best-case scenario for what is possible. As is discussed in the bCDR, gCDR, and sCDR success stories, all three of these taxonomic areas face potential constraints and scaling challenges that will likely prevent them from reaching the values shown here. Details and growth assumptions for each individual pathway can be found in the individual approach success stories.

The upper bound for CDR in 2100 — in the unlikely scenario that success stories are realized for all CDR approaches — is ~35 Gt CO2 per year



Notes and sources: [1]The IPCC's sixth assessment report includes eight categories of scenarios. Shown here are emissions trajectories and CDR trajectories from both C1 and C2 scenarios. C1 scenarios are those that limit warming to 1.5C by 2100 without overshooting in mid-century. C2 scenarios are those that limit warming to 1.5C by 2100 but "overshoot" in mid century and rely more heavily on CDR in the second half of the century. Data was obtained from the AR6 Scenario Explorer and Database hosted by IIASA.

You can help catalyze a coordinated effort to fund CDR RD&D.

Please reach out to RMI to get involved.

Help RMI stay informed
and up-to-date about new projects, findings, and project outcomes.

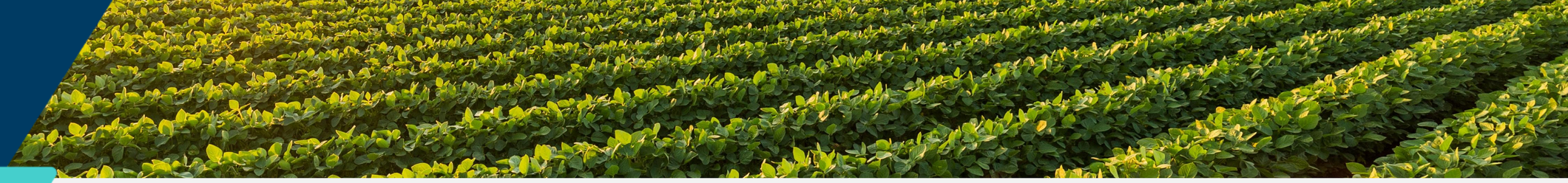
Express interest in collaborating
to advance projects on the roadmap as a researcher, project developer, or funder for specific projects, or by enabling information-sharing or coordination across projects.

Offer constructive feedback
on the Applied Innovation Roadmap itself.

To engage please contact:

Daniel Pike, Project Director: dpike@rmi.org
Rudy Kahsar, Project Manager: rkahsar@rmi.org
Gloria See, Project Lead Analyst: gloria.see@rmi.org

Applied Innovation Roadmaps



Intro to biogenic CDR (bCDR)

DEFINITION: *bCDR includes any CDR approach that uses naturally occurring, biogenic carbon fixation to capture CO_2 from the atmosphere. The most important of these capture mechanisms is photosynthesis.*

We break bCDR into three sub-approaches, based on how the carbon is stored for CDR purposes:

Living biomass

Approaches that maintain or increase living biomass in forests, agriculture, grasslands, and wetlands. This definition is based on the Natural Climate Solutions (NCS) categorization.[1,4]

1.1 1.2 1.3

Stabilized biomass

Approaches that use photosynthesis as the CO_2 capture step, then store the captured CO_2 in a stabilized biomass form.[2,4]

2.1 2.2 2.3 2.4

2.5 2.6 2.7 2.8

Sequestration of CO_2

Approaches that use photosynthesis as the CO_2 capture step but then rely on combustion, fermentation, or gasification to convert that biomass to CO_2 that is then stored.[3]

3.1 3.2

Notes and sources: [1]Natural Climate Solutions are defined in Griscom et al. (2017). This includes enhanced ecosystem techniques such as forestry, afforestation/reforestation, land management, ocean ecosystem restoration, and soil management. Microalgae and macroalgae are included in the stabilized biomass category. [2]This includes actively stabilized forms of biomass, such as biochar, bio-oil, ocean biomass (microalgae and macroalgae) sinking, long duration wood storage, and wood burial. [3]This includes BECCS and other biomass that is converted to CO_2 and stored with CCS, including from waste feedstocks. [4]Because the CO_2 is stored as biomass, not directly as CO_2, the removals are described as tCO_2e, or equivalent tonnes of CO_2.

bCDR definitions and example scenarios

1. Living biomass: Living biomass includes forests, agriculture, grasslands, and wetlands and is based on the Natural Climate Solutions (NCS)[1] categorization

INDEX	APPROACHES	DEFINITION	EXAMPLE SCENARIOS
1.1	Management of lands, forests, and natural carbon stocks	Active management of forests and other biological ecosystems, to enhance atmospheric carbon removal above and below ground	1) Managing tree species, tree ages, pruning and harvesting, fires, and pests in forests so they absorb and store carbon faster; 2) implementing agricultural practices that build up healthy soils rich with life and carbon by adding amendments and reducing tillage; 3) removing invasive sea urchins that consume and damage kelp forests.
1.2	Conservation and protection of carbon sinks	Conserving existing forests and other biological ecosystems that act as carbon sinks in order to maintain the current equilibrium of ecological functions and organic carbon stocks	1) Conserving forests, grasslands, wetlands, coral reefs, etc. so they continue to absorb and store carbon; 2) preventing the conversion of peatlands to other uses to ensure they continue to store and absorb carbon.
1.3	Restoration / creation of sinks	Deliberate manipulation of ecosystems, especially disturbed or degraded areas, to re-establish ecological functions and increase carbon dioxide removal	1) Restoring mangroves along coastlines; 2) reforestation and replanting after forest fires; 3) seeding coral to regrow coral reef ecosystems.

Notes and sources: [1]Natural Climate Solutions (Griscom et al., 2017)

bCDR definitions and example scenarios

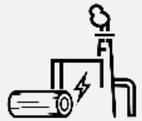
2. Stabilized biomass: Approaches that use photosynthesis as the CO_2 capture step and that store the captured CO_2 in a stabilized biomass form

INDEX	APPROACHES	DEFINITION	EXAMPLE SCENARIOS
2.1	Biomass direct storage	Storing terrestrial biomass in land or aquatic settings, under conditions designed to prevent significant decomposition.	1) Storing biowaste in arctic environments; 2) excavating a hole, filling it with woody biomass, and covering it with clay; 3) sinking agricultural waste, like corn stover, deep in anoxic waters; 4) grinding sawdust and mixing it with water to create a slurry, then injecting it underground; 5) filling temperature- and humidity- controlled warehouses with wood.
2.2	Timber building products	Using timber products to utilize the carbon removal of trees and store it as long-lived building materials, especially structural wood products	1) Building houses or offices out of lumber; 2) building new high-rises out of engineered timber, such as cross laminated timber (CLT) and glue-laminated timber (glulam).
2.3	Other biomass building products	Converting biomass, including purpose grown crops, algal, and fungal matter, agricultural and forestry waste, and synthetic biomaterial, into construction products and component materials other than timber, such as polymers, fibers, framing, and paneling	1) Building paneling out of bamboo; 2) using microorganisms to create carbonate materials that are incorporated into sidewalk pavers; 3) processing agricultural waste into building insulation.
2.4	Pyrolysis (biochar) and storage	Thermal conversion of biomass while excluding oxygen, optimized to produce solid char for storage in open or controlled environments	1) Pyrolyzing corn stover waste into biochar that is then added back to fields as a soil amendment; 2) converting wood waste from hurricane debris into biochar that can be used as an additive to cementitious materials.
2.5	Pyrolysis (bioliquid) and storage	Thermal conversion of biomass while excluding oxygen, optimized to produce crude bioliquid that can be stored underground, geologically, or in other environments	1) Fast pyrolysis of corn stover waste into bio-oil that can be injected into the subsurface of the earth; 2) fast pyrolysis of cultivated grasses or other biomass material into bio-oil that is then stored underground.
2.6	Microalgae cultivated in artificial ponds and stored	Harvest and storage of microalgae biomass grown in land-based systems	1) Growing algae in raceway ponds that are fed with seawater; 2) collecting algal biomass from blooms in lakes resulting from fertilizer runoff; 3) growing algae in bioreactor bags either in warehouses or floating on open water -- then, in all scenarios, drying and burying the biomass.
2.7	Microalgae cultivated in open water and sunk	Sinking microalgae, either cultivated or grown naturally, in open water environments	Sinking the algal biomass created by 1) seeding the open ocean with iron or other trace nutrients to create algae blooms; 2) creating artificial upwelling in the open ocean to induce algae blooms; 3) Seeding lakes or other bodies of water with nutrients to create algae blooms.
2.8	Macroalgae cultivated in open water and sunk	Enhancing macroalgae growth either in cultivated algae farms or in the open ocean, then sinking the biomass in the open ocean	1) Collecting excess sargassum growing in the great sargassum belt using drone submarines that capture the sargassum, taking it to sinking depth, and depositing it on the sea floor; 2) seeding seaweed on purpose-built buoys, which create a platform for algae to grow, and are then deliberately sunk, taking the seaweed with them to the ocean floor.

bCDR definitions and example scenarios

3. Sequestration of CO_2 from biomass: Approaches that use photosynthesis as the CO_2 capture step but then rely on combustion to convert that biomass to CO_2, which is then stored

INDEX	APPROACHES	DEFINITION	EXAMPLE SCENARIOS
3.1	BECCS to electricity	Thermal conversion of biomass (either dedicated feedstock or waste) to generate electricity and produce CO_2 that is captured with CCS technology	1) Combusting pelletized wood from forest thinnings in a thermal power plant to produce electricity and a stream of CO_2 that can be captured and stored; 2) gasification and then combustion of cultivated biomass to produce electricity and a stream of CO_2 that can be captured and stored.
3.2	BECCS to fuels	Thermal or biochemical conversion of biomass (either dedicated feedstock or waste) to generate fuels and produce CO_2 that is captured with CCS technology	1) Fermenting corn into ethanol and capturing the side stream of waste CO_2 to be sequestered; 2) thermally converting waste biomass into liquid fuels with some side production and capture of CO_2 to be sequestered.



Within bCDR, living biomass and BECCS have received the most funding

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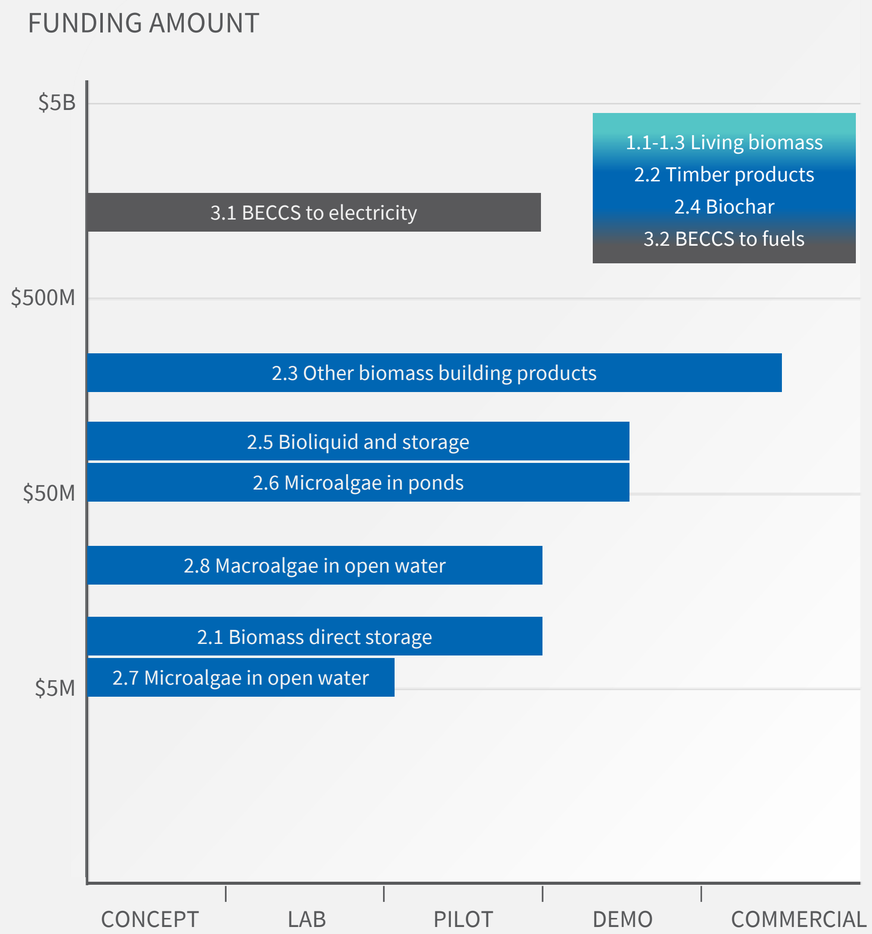
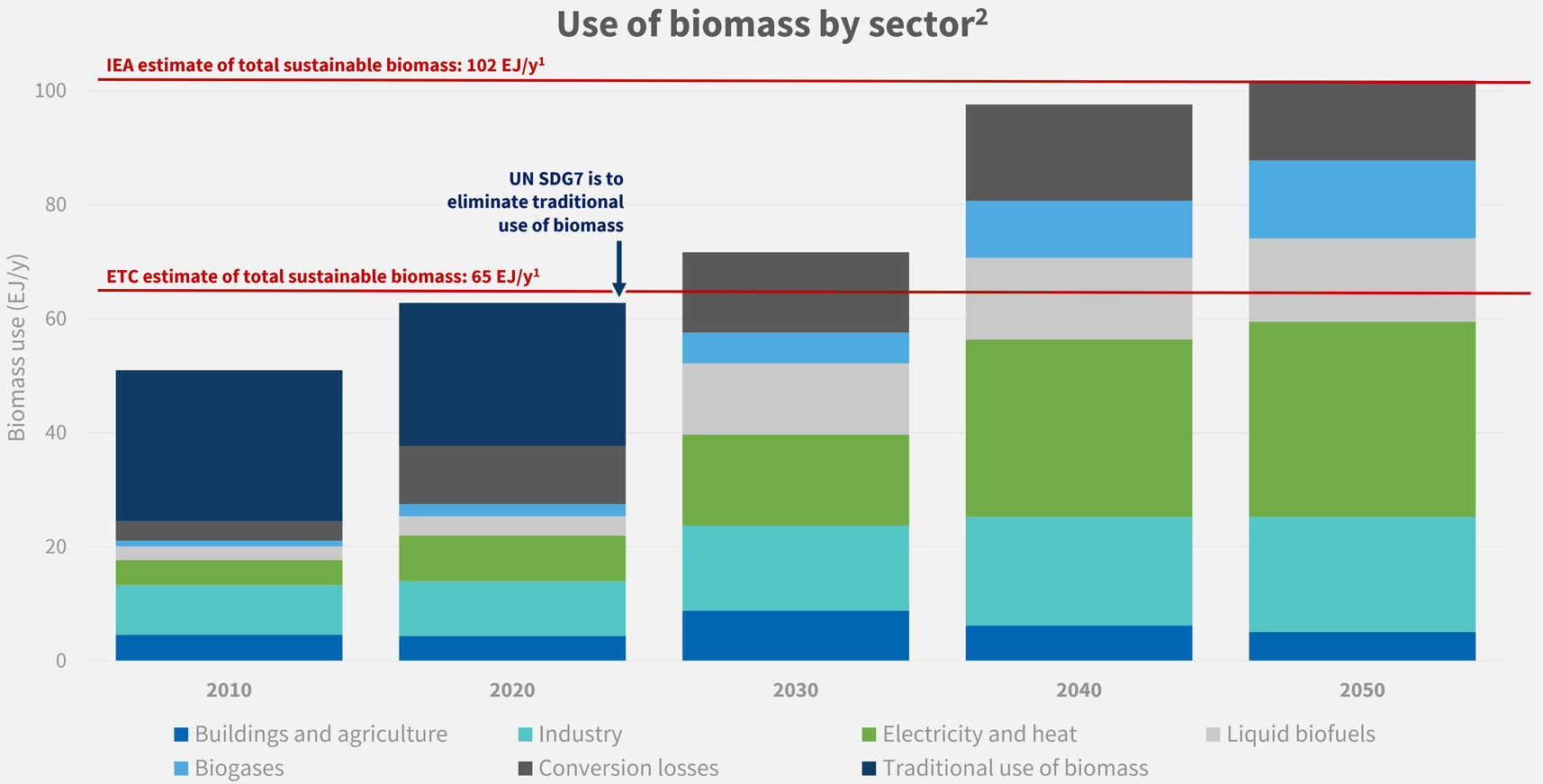


	APPROACH	FUNDS COMMITTED[1]	SIGNIFICANT DEPLOYMENTS
Living biomass	Living biomass (1.1, 1.2, 1.3)	Commercial	**Pachama** has evaluated 150 forestry projects across 14 countries,[9] **Seawater Greenhouse** designed agricultural greenhouse solutions for 5 locations since 1994.[10]
Stabilized biomass	Biomass direct storage (2.1)	>$14M[2]	**Carbon Lockdown** has launched Potomac Project 1 with 5 $ktCO_2$ for pre-purchase.[11]
	Timber building products (2.2)	Commercial	Ascent MKE, the world's tallest timber building, a **New Land Enterprises'** high-rise apartment complex that cost $128M, was built in Wisconsin.[12]
	Other biomass building products (2.3)	>$330M[3]	**Biomason** has created Biocement® to support marine infrastructure and replace traditional cement tiling.[13]
	Pyrolysis (biochar) and storage (2.4)	Commercial	**Carbo Culture** has launched R3 pilot plant with a capacity of 3 $ktCO_2$/y removal near Helsinki.[14]
	Pyrolysis (bioliquid) and storage (2.5)	>$103M[4]	**Charm Industrial** has removed >6 $ktCO_2e$ to date[15] and has sold $53M in credits to remove 112 $ktCO_2e$ between 2024-2030.[16]
	Microalgae in ponds and stored (2.6)	>$100M[5]	**Brilliant Planet** has ongoing trials in Morocco, South Africa, and Oman as well as a 30-hectare facility in progress in Morocco.[17]
	Microalgae in open water and stored (2.7)	>$8.5[6]	**Ocean Nourishment Corporation's Whalex** was in top 60 for XPRIZE in 2022 and is now focused on MRV for ocean carbon.[18]
	Macroalgae in open water and sunk (2.8)	>$37M[7]	**Running Tide** has delivered 100 tCO_2 to Shopify by sinking wooden buoys in the open ocean.[19]
Sequester from biomass	BECCS to electricity (3.1)	>$2,400M[8]	**DRAX**, along with **C-Capture**, opened a pilot in 2019 and is targeting a first commercial plant in 2027.[20]
	BECCS to liquid fuels (3.2)	Commercial	**Archer-Daniels Midland (ADM)**'s commercial facility began operation in 2017 with 1 $MtCO_2$/y removal capacity.[21]

Notes and sources: [1]Total funding includes seed funding, grants, and investments in CDR-relevant projects that have been disclosed by companies included in the AIR. It does not include government funding towards research institutions. As companies reach later stages of development, they disclose less financial information, so the actual funds committed to each of these approaches is likely higher than shown. For commercial approaches, we included a range to indicate potential funds on the graph. [2]$14M sum based on 3 companies. [3]$330M sum based on 7 companies. [4]$103M sum based on 3 companies. [5]$100M sum based on 4 companies. [6]$8.5M sum based on 3 companies. [7]$37M sum based on 6 companies. [8]$2400M sum based on 6 companies. [9]Pachama website [10]Seawater Greenhouse website [11]Carbon Lockdown pilot project [12]Ascent MKE building [13]Biomason materials [14]Carbo Culture pilot [15]Charm Industrial registry [16]Credit sales [17]Brilliant Planet pilot trials [18]Ocean Nourishment Corporation website [19]Running Tide blog [20]DRAX and C-Capture [21]Global CCS Institute

Biomass is the key input for bCDR

Biomass use is 60-80 exajoules per year today, with a total sustainable cap of ~65-102 EJ/year



Notes and context

- IEA projections do not include usage of biomass for CDR.
- Global biomass demand for use across the energy transition grew at a 2% CAGR from 2010 to 2020.[2]
- The IEA bioenergy TCP report and the IEA biofuel feedstock analysis indicate that many analyses may be overestimating additional biomass supply by including new land, more biowaste, or higher land productivity than is likely to occur.[3]

Notes and sources: [1]The IEA Net Zero in 2050 Report commentary on bioenergy and land use requires 102 EJ of sustainable bioenergy in 2050. The report notes that the average IPCC scenario requires around 200 EJ/y. By contrast, the ETC Bioresources within a Net-Zero Emissions Economy (2021) report estimates global sustainable biomass supply at only ~65 EJ/y. [2]Data taken from the IEA Net Zero in 2050 Report (2021). [3]IEA Bioenergy TCP report (2023) and the IEA Biofuel feedstock analysis (2022).

Even if biomass supply increased were increased to its estimated sustainable limit and 100% allocated to CDR, it might only generate ~10 Gt CO2e/y of CDR

Current supply

Current global biomass supply is just over 60 EJ/y which has a CDR potential of around 6 $GtCO_2$/y (4.3 Gt/y dry biomass), if 100% were to be utilized for CDR.[1] All of this biomass is currently used for non-CDR activities.[5]

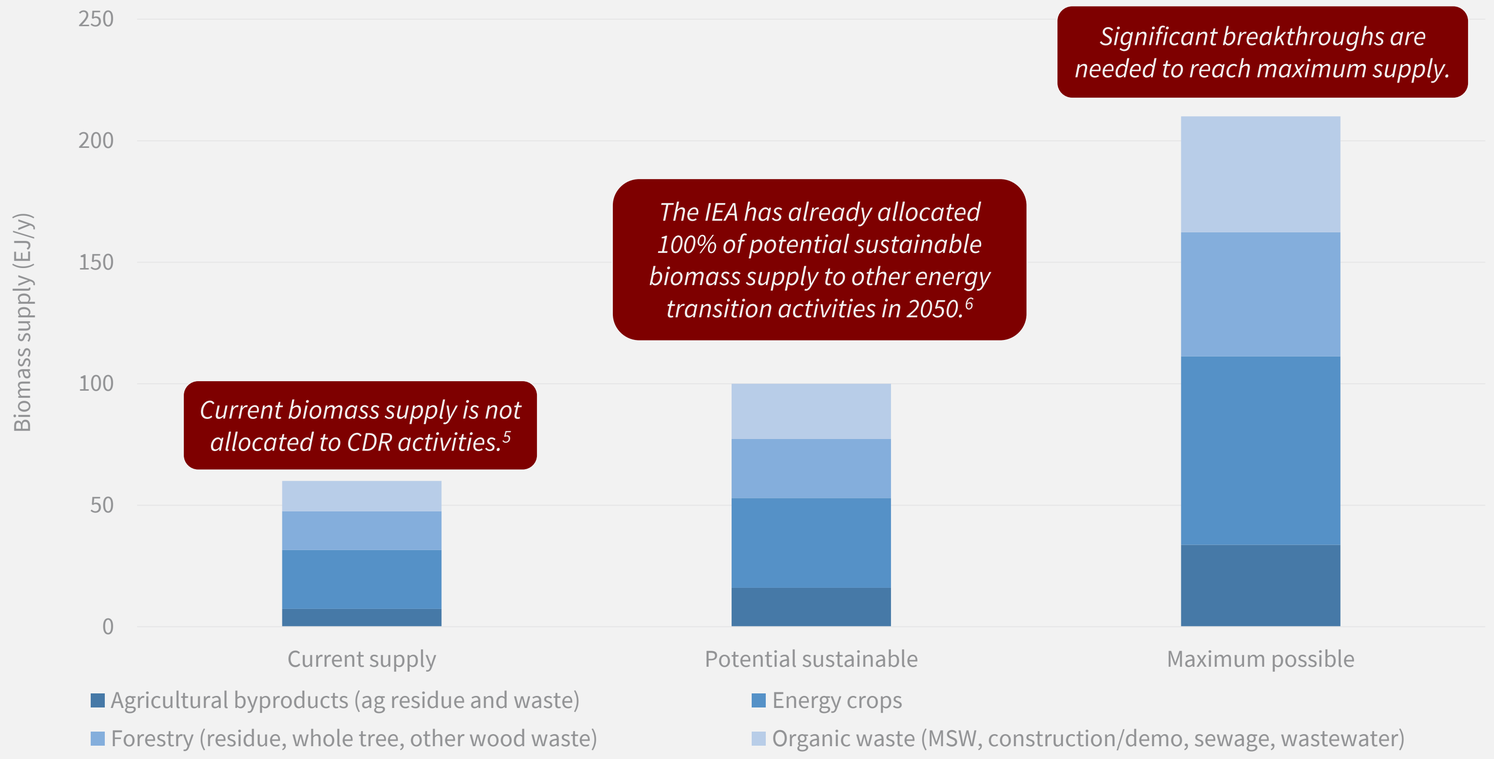
Potential sustainable supply

Total sustainable biomass supply is estimated to be up to 100 EJ/y.2 This represents a CDR potential of up to 10 $GtCO_2$/y (~7.1 Gt/y dry biomass).[5]

Maximum biomass supply

If breakthroughs are achieved, it may be possible to achieve up to 210 EJ/y of biomass supply which would have a total CDR potential of 21 $GtCO_2$/y and would require 15 Gt/y of dry biomass.[1,5]

Estimated global annual biomass supply[1,2,3,4,5]



Notes and sources: [1]This figure is based primarily on the ETC (2021) Bioresources within a Net-Zero Emissions Economy report. The sustainable scenario estimates 40-60 EJ/y of biomass availability, including woody biomass for products. This is also in the range of the current global supply. The maximum biomass supply is taken from the report's analysis of upper limit scenarios which indicate that 200 EJ/y or more may be possible. The report also shows that 1 Gt of biomass contains approximately 14 EJ of primary energy potential and 1.4 $GtCO_2$. This was used to convert between energy, dry tons, and $GtCO_2e$. [2]The IEA Net Zero in 2050 Report commentary on bioenergy and land use requires 102 EJ of sustainable bioenergy in 2050. We use this as our potential sustainable supply. [3]There are dozens of reports and analyses attempting to estimate the upper limits of global or regional biomass supply. The DOE's Billion Ton Report (2016) estimates that the U.S. could sustainably produce 991–1,147 MDT/y (millions of dry tons per year) by 2030, representing a carbon removal potential of ~1.4 $GtCO_2$/y. The World Bank (2018) "What a Waste 2.0" report estimates current biowaste streams rising from about 1 Gt/y to ~2 Gt/yr. [4]Allocation across organic waste, forestry, energy crops, and agricultural byproducts in this figure is based on the Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Table 4.5. Current supply allocation is based on the 2017 technical potential allocation and the potential sustainable and maximum possible scenarios are based on percent allocations of the 2040 technical potential scenario. [5]Currently, almost none of this biomass is used for CDR. In the future, biomass will also likely be used for many other purposes besides CDR. [6]The IEA Net Zero in 2050 Report commentary on bioenergy and land use requires 102 EJ of sustainable bioenergy in 2050.

There are plausible reasons that biomass supply could increase or decrease

Why it could increase

- **Optimized practices:** Precision agriculture, tailored land management, optimized harvesting, water management, and other adjustments for local conditions can improve production with available resources.[5]
- **Expanded agricultural area:** Deployment of dryland farming techniques in arid regions, production in vacant urban and underutilized areas (including vertical or indoor farming),[5,8] and reduced meat consumption enabling land conversion from livestock grazing and feed production can all increase available land for biomass production.
- **Improved productivity:** Cultivar improvement through selection and synthetic biology can increase yields, resilience, nutritional value, pest resistance, carbon uptake, etc.[5,6,7,10]
- **Soil management:** Remediating and improving soil quality, nutrient content, and biome diversity may provide substantial benefits such as increased plant growth, productivity, quality, and pest resistance.[5,7]
- **Diversified land use solutions:** Techniques such as intercropping, agroforestry, and agrivoltaics can increase outputs from the same land area.[5,9]

Why it could decrease

- **Limited or counterproductive social systems change:** Hypothetical "freed up" land assumes radical changes such as no animal product consumption.[2] If instead meat consumption increases, land use for agriculture could also increase, and biomass supply for CDR would decrease.
- **Overestimation of marginal or additional land:** Analyses often assume that large swathes of additional land will become available for cultivating biomass. These analyses often fail to consider land ownership, socioeconomic values of land, or environmental conditions necessary to allow cost effective cultivation of biomass.[3]
- **Impacts of climate change:** Future biomass supply estimates tend to assume predictable historic climate conditions for biomass production.
- **Reduced supplies from biowaste:** Global modernization and intensification of agriculture systems may lead to reduction in biowaste products.[2]
- **Increased focus on conservation:** Land management focused on conservation outcomes could conflict with biomass harvest rates.

Notes and sources: [1]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) p140. [2]ETC (2021) Bioresources notes some global scenarios estimate future potential of ~1300 Mha "freed up" land for biomass production thanks to radical global system improvements. [3]A Carbon180 newsletter (March 2023) summarized this over estimation challenge. [4]Popular science (2022) summary article. [5]The Challenge of Feeding the World Sustainably (NAS, 2021) [6]Transgenic Plants and World Agriculture (NAS, 2000) [7]USA Regenerative Agricultural Alliance, Inc. [8]Dryland Farming: Crops and Techniques for Arid Regions (Creswell & Martin 1998) [9]Rwanda Institute for Conservation Agriculture [10]Living Carbon Photosynthesis Enhanced Trees Grow Faster and Capture More Carbon

bCDR approaches face different risks, largely based on differing feedstock sourcing and storage requirements

Index	Approach	Secure storage for 100+ years	Path to measurement at scale	Path to full costs <$100/t	Land	Water	Energy	Fertilizer	Environmental impacts	Other
1.1-1.3	Living biomass									Labor
2.1	Biomass direct storage									N/A
2.2	Timber building products									Additionality
2.3	Other biomass building materials									N/A
2.4	Pyrolysis (biochar) and storage									Carbon conversion efficiency
2.5	Pyrolysis (bioliquid) and storage									Carbon conversion efficiency
2.6	Microalgae cultivated in artificial ponds and stored									N/A
2.7	Microalgae cultivated in open water and sunk									Capture potential
2.8	Macroalgae cultivated in open water and sunk									Dedicated area
3.1	BECCS to electricity									CCS technology
3.2	BECCS to fuels									CCS technology

Risk Rating
Low
Medium
High

Biomass direct storage approaches have the lowest risk assessment of any land-based bCDR.

The biggest challenge for **living biomass** approaches is the durability of their removals.

Open water algae approaches face the biggest challenges in achieving measurability and durable storage.

Microalgae has been cultivated in ponds for decades and still remains very expensive. New approaches are emerging but are unproven at scale.

BECCS approaches face several challenges to achieving gigaton scale. Cultivated biogenic inputs may require significant land and water.

Pyrolysis approaches today rely largely on biowaste. At gigaton scale, this waste material will be limited, and these approaches may then require significant land for cultivated crops.

Other biomass building materials look promising in terms of risks, but they are currently at very early TRL.

Timber products are most challenged to prove they are additional.

Pyrolysis pathways have low carbon conversion efficiency, which may affect long term scalability.

Microalgae cultivated in open water should be able to scale.

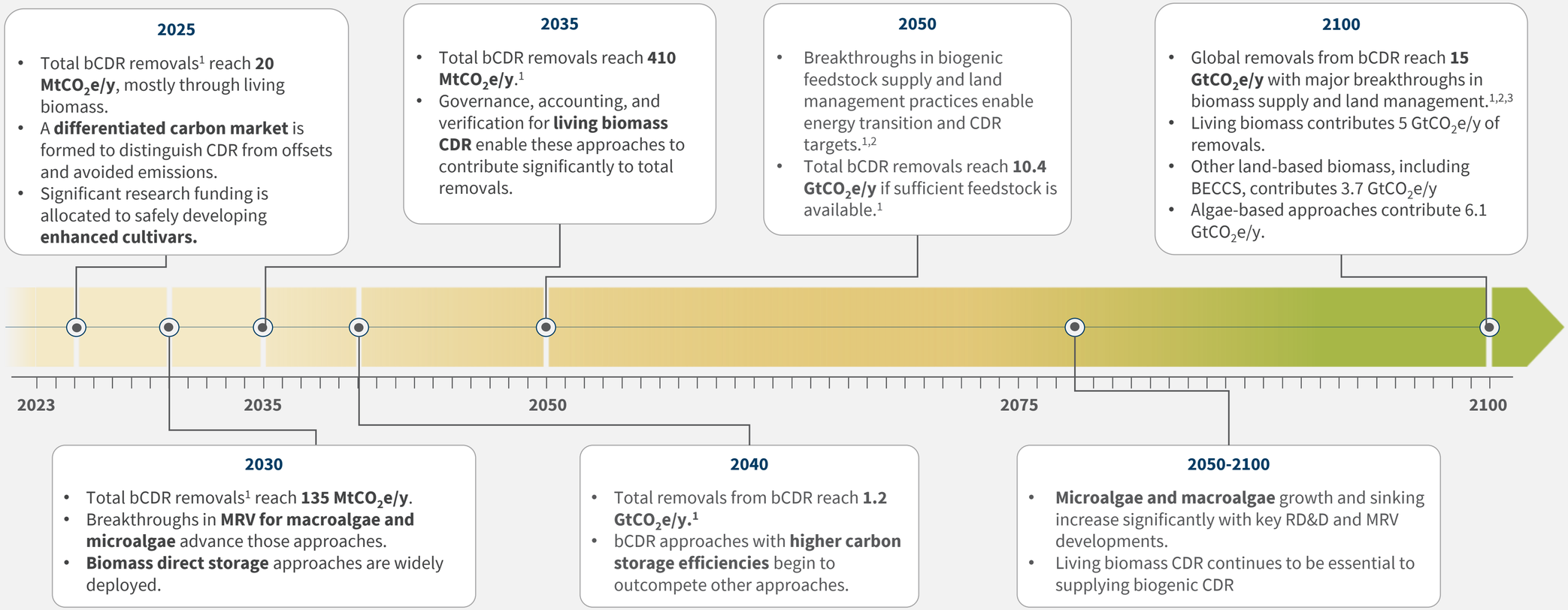
Biogenic CDR success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

The cumulative bCDR described below is the summation of the upper limit of CDR deployment taken from 11 individual CDR success stories from the AIR report.[1] The assumptions for each projection are based on a range of sources described in the individual CDR success stories.



Notes and sources: [1]The bCDR taxonomic area includes 11 roadmaps over 13 total approaches. Each bCDR roadmap success story was assessed independently and added up to give the total value reported here. Details and growth assumptions for each individual pathway can be found in the individual approach success stories. The sum shown here is likely overestimating the total potential of bCDR. Approaches such as living biomass, woody biomass burial, mass timber, biochar, bio-oil, and BECCS will compete for the same land and feedstocks. They will also have to compete against other demand for biomass in the energy transition, including for SAF, fuels, and chemicals. RMI analysis has estimated that total *possible* sustainable cultivated biomass supply in 2050 (the upper limit) will be between 5.1-9.8 dry Gt/y (~9.2-17.6 $GtCO_2e/y$). The ETC estimates that total prudent sustainable biomass is around 40-60 EJ/y with the maximum potential reaching 120 EJ/y. Total ocean bCDR is likely to not be constrained until the second half of the century. [2]Removals from bCDR in the second half of the century depend on a variety of factors, including social and policy considerations for land management, the evolving demand for biomass across the energy transition, and the potential for breakthroughs in enhanced cultivars. [3]The upper limit of bCDR removals is estimated based on maximum estimates for terrestrial biomass as well as maximum major breakthroughs in macro-algae and micro-algae cultivation.

1. Living biomass

Living biomass includes forests, agriculture, grasslands, and wetlands and is based on the Natural Climate Solutions (NCS)[1] categorization

INDEX	APPROACHES	DEFINITION
1.1	Management of land, marine, and coastal ecosystems	Active management of forests and other biological ecosystems, to enhance atmospheric carbon removal above and below ground
1.2	Conservation and protection of carbon sinks	Conserving existing forests and other biological ecosystems that act as carbon sinks in order to maintain the current equilibrium of ecological functions and organic carbon stocks
1.3	Restoration and creation of carbon sinks	Deliberate manipulation of ecosystems, especially disturbed or degraded areas, to re-establish ecological functions and increase carbon dioxide removal

Note: *Companies operating in this space often touch on more than one of these approaches, so we have assessed the current state of living biomass together, rather than as individual approaches.*

RMI classifies living biomass approaches as **biogenic**

Biogenic (bCDR)	Geochemical (gCDR)	Synthetic (sCDR)	Storage
Living biomass **1.1** Improved management **1.2** Conservation / protection **1.3** Restoration / creation **Stabilized biomass** **2.1** Biomass direct storage **2.2** Timber building products **2.3** Other biomass building products **2.4** Pyrolysis (biochar) and storage **2.5** Pyrolysis (bioliquid) and storage **2.6** Microalgae in ponds **2.7** Microalgae in open water **2.8** Macroalgae in open water **Sequestration of CO_2 from biomass** **3.1** BECCS to electricity **3.2** BECCS to fuels	**Solid carbonate minerals** **4.1** Surficial **Dissolved bicarbonate sequestration** **5.1** Terrestrial enhanced weathering **5.2** Coastal enhanced weathering **5.3** Mineral alkalinity enhancement	**Indirect water capture (IWC)** **6.1** CO_2 stripping **6.2** Electrochemical alkalinity production **Direct air capture (DAC)** **7.1-7.3** Liquid solvent **7.4-7.7** Solid sorbent **7.8-7.9** Membranes **7.10** Cryogenic	**Storage of CO_2** **8.1** Conventional CO_2 storage **8.2** In-situ mineralization **8.3** Ex-situ mineralization

Notes and sources: [1]Natural Climate Solutions (Griscom et al., 2017)

SECTION 1.1-1.3

Living biomass

SECTION	1.1-1.3
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Living biomass
APPROACH	Overall

DEFINITION

Living biomass consists of three approaches: (1) management of land, marine, and coastal ecosystems, (2) conservation and protection of carbon sinks, and (3) restoration and creation of carbon sinks.

EXAMPLE SCENARIOS

1) Managing tree species, tree ages, pruning and harvesting, fires, and pests in forests so they absorb and store carbon faster; 2) preventing the conversion of peatlands to other uses to ensure they continue to store and absorb carbon; (3) seeding coral to regrow coral reef ecosystems

RMI

Section 1.1-1.3 overview

Living biomass

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and secure storage** • Key risk areas include land use and labor requirements for planting and maintenance and the security of long-term storage with high risk of reversal
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **NA** • Technology is already well-established
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Commercial** • Many companies at commercial stage
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **4 $GtCO_2$ by 2050** • Success is contingent on careful management practices to generate environmental co-benefits and monitor reversal risks while balancing competition for land
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **NA** • Technology is already well-established

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Land use requirements*	**High risk:** Achieving gigaton scale removals will only be possible with critical implementation breakthroughs.	Some restoration approaches require significant land conversion; reforestation alone could utilize more than 8.1M km^2 (almost 3X the land area of India).[1,2,3,4] Land conversion can be reduced by using marginal lands,[5] and improved land management avoids significant land use changes but is unlikely to provide comparable carbon removals.[1,6]
	Water requirements	**Medium risk:** Water use is likely to increase during early implementation, but living biomass solutions can improve water quality and environmental conditions over time.	Restoration and sink creation efforts are likely to require significant water inputs during early establishment. Species selection for current and anticipated water availability can minimize long-term water risks and provide water quality co-benefits,[7] although rainfall volatility will be increasingly challenging to predict. Active management can also reduce water use through improved irrigation practices where appropriate.[6,8]
	Fertilizer requirements	**Low risk:** Initial fertilizer inputs may be needed, but requirements are expected to decrease over time.	Fertilizer requirements are expected to decrease over time as restoration efforts transition to ongoing management.[7] The development of enhanced plant cultivars and soil microbes,[2,9] combined with implementation of precision agriculture practices, can also minimize ongoing fertilizer inputs.
	Labor requirements	**High risk:** Implementation and maintenance of living biomass systems require ongoing engagement from a trained workforce.	Initial labor requirements for restoration and sink creation are high. Improved management can replace existing practices but will still require ongoing maintenance in agriculture, forestry, and range management.[10] However, some monitoring and verification of biomass stability can be performed remotely to support and optimize ongoing management across living biomass systems.[11]
	Environmental impacts	**Low risk:** Sources indicate low concern for negative environmental impacts.	Improved land management, restoration, and conservation can provide significant ecosystem and social co-benefits when maintained over time,[7] although large scale afforestation efforts should assess potential albedo impacts.[12]
Secure storage for 100+ years		**High risk:** Reversal risk is high without indefinite management.	Maintaining stable storage depends on indefinite management and ongoing monitoring to assess the stability of removals.[13,14] Natural disasters also pose a high risk for large and sudden storage reversals.
Path to measurement at scale		**Medium risk:** Soil and biomass carbon measurement is difficult to scale; remote sensing and modeling will be necessary but also need additional development.[13]	Direct measurement, remote sensing and monitoring, and modeling tools are being actively developed, although technical implementation challenges are significant, especially at scale.[12,13,15]
Pathway to full costs <$100/tCO$_2$		**Low risk:** Significant opportunities already exist.	An estimated 2-11 GtCO$_2$e/y are possible in 2030 at <$100/tCO$_2$[1,13] depending on the management, conservation, or restoration approach.

Notes and sources: [1]Protect, manage and then restore lands for climate mitigation [2]From the Ground Up [3]Clearing the Air [4]The global tree restoration potential [5]Policies for Sustainable Agriculture and Livelihood in Marginal Lands [6]Project Drawdown Food, Agriculture, and Land Use [7]Natural Climate Solutions [8]Greenhouse Gas Removal Report [9]Example efforts include LoamBio and Pivot Bio. [10]Successful Farming [11]Tree Restoration Monitoring Framework [12]Limited climate change mitigation potential through forestation of the vast dryland regions (Rohatyn et al., 2022) [13]ICRLP Soil Carbon Factsheet [14]A reviewer notes that managing for forest resilience is likely a higher priority than optimizing for a specific MRV strategy. The combined co-benefits and reduced risk of reversals from management strategies known to provide net emissions reductions should be considered thoroughly when weighed against MRV uncertainty. [15]Modeling examples include USFS Forest Carbon tools, digital soil mapping; remote monitoring capabilities include SEPAL, Pachama.

CDR potential of living biomass

There is additional CDR capacity beyond the current carbon cycle

SECTION 1.1-1.3

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Living biomass

APPROACH Overall

ACTIONS	CATEGORY	CURRENT NATURAL CARBON CYCLE FLUX (net $GtCO_2$/y)	CARBON SINK POTENTIAL (net tCO_2/ha/y)	ADDITIONAL NET CDR POTENTIAL WORLD (*U.S.*) ($GtCO_2$/y)
The natural carbon cycle both emits and sequesters[2] CO_2. When considering living biomass as a CDR option, we must: ✓ Ensure preservation of existing sinks[8] ✓ Develop and expand new sinks ✓ Optimize management practices to increase carbon storage in existing sinks	*Soil*	3.1[1]	0.2 - 0.5	3 (*0.25*)
	Afforestation / reforestation	7.6[2]	1.5 - 6.4	9 (*0.6*)
	Peatland[3] (terrestrial wetland)	0.37[4]	271.5[5]	1.6[5] (*0.013*)[6]
	Blue carbon[3] (coastal and marine wetlands)	0.84[7]	156.7[5]	1.2[5] (*0.012*)[7]
	Total	**11.9**	**430 – 435**	**14.8 (*0.88*)**

Note: *There is an additional ~15 $GtCO_2$e/y net CDR potential from living biomass.*

Notes and sources: [1]Global Carbon Budget 2022 (Friedlingstein et al., 2022) [2]WRI Global Forest Watch concluded that global annual average living biomass (between 2001-2019) emitted 8.1 $GtCO_2$e/y and sequestered about 15.6 $GtCO_2$e/y, resulting in a net sink of 7.6 $GtCO_2$e/y. [3]The term "blue carbon" has a broad range of definitions, some include all wetland environments while others describe only coastal and marine bCDR pathways and use "peatlands" to describe all terrestrial wetlands. [4]IUCN Issues Brief (2021) Peatlands and Climate Change [5]Natural Climate Solutions (Griscom et al., 2017) [6]Land-based measures to mitigate climate change: potential and feasibility by country (Roe et al., 2021) [7]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [8]Ongoing climate changes will convert some sinks into sources of CO_2.

Current state of RD&D

A mapping of companies, plus other notable activities

NOT EXHAUSTIVE

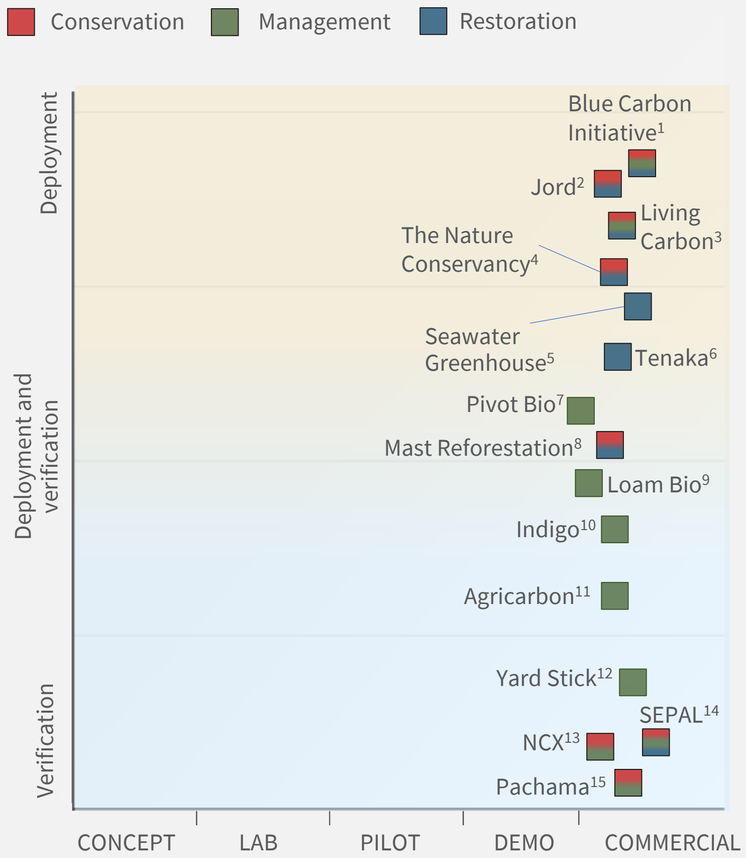
SECTION 1.1-1.3

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Living biomass

APPROACH Overall

FUNDING AMOUNT



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Indigo: Enhancing farmer profitability and sustainability	$1.2B[36]	• Microbes for seed treatment and yield improvement; agriculture carbon credit registry[10]
Pivot Bio: Developing new soil CDR solutions	$619M[31]	• Microbe-based nitrogen production for fertilizer[7]
Loam Bio: Using microbes to transform agriculture CDR	$105M[32]	• Microbial inoculum to enhance soil carbon sequestration[9]
Mast Reforestation: Reforesting burned areas (formerly DroneSeed)	$58.9M[34]	• Expanding seed and seedling supply chain; reforesting using drones for seeding[8]
Pachama: Utilizing satellite and AI to determine forestry project credibility	$79.3M[35]	• Evaluated 150 forestry projects across 14 countries; released updated evaluation criteria in June 2023[15]
Other companies and activities: Ecosia,[16] Open Forest Protocol,[17] Terraformation,[18] Vlinder Climate,[19] Andes,[20] Propogate,[21] Savanna Institute,[22] Working Trees,[23] Mad Agriculture,[24] Savory Institute,[25] Rodale Institute,[26] Regenerative Agriculture Financing Program,[27] Totoka Islands,[28] Delta Ag[29]		
Note: *Living biomass approaches to CDR are the most commercialized of any approach and there are many more companies than are represented here. Here, we included notable companies that:* • *Are pursuing novel technical breakthroughs to advance living biomass CDR* • *Are particularly focused on providing removals, rather than avoidance offsets*		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Forest Inventory Analysis (USFS FIA)[30]	$54.9M (requested for FY24),[33] $32.2M awarded for FY23[37]	• US Forest Service monitors carbon across grasslands and forests[16]

Notes and sources: [1]Blue Carbon [2]Jord [3]Living Carbon [4]The Nature Conservancy [5]Seawater Greenhouse [6]Tenaka [7]Pivot Bio [8]Mast Reforestation [9]Loam Bio [10]Indigo [11]Agricarbon [12]Yard Stick [13]NCX [14]SEPAL [15]Pachama [16]Ecosia [17]Open Forest Protocol [18]Terraformation [19]Vlinder Climate [20]Andes [21]Propogate [22]Savanna Institute [23]Working Trees [24]Mad Agriculture [25]Savory Institute [26]Rodale Institute [27]Regenerative Agriculture Financing Program [28]Totoka Islands [29]Delta Ag [30]USFS Forest Inventory Analysis (FIA) [31]Crunchbase funding estimate for Pivot Bio [32]Loam Bio funding from Lowercarbon Capital (via Agfunder News) [33]National Association of State Foresters request for FY23 [34]Crunchbase funding estimate for Mast Reforestation [35]Crunchbase funding estimate for Pachama [36]Crunchbase funding estimate for Indigo [37]FIA allocated $32.2M for FY23.

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

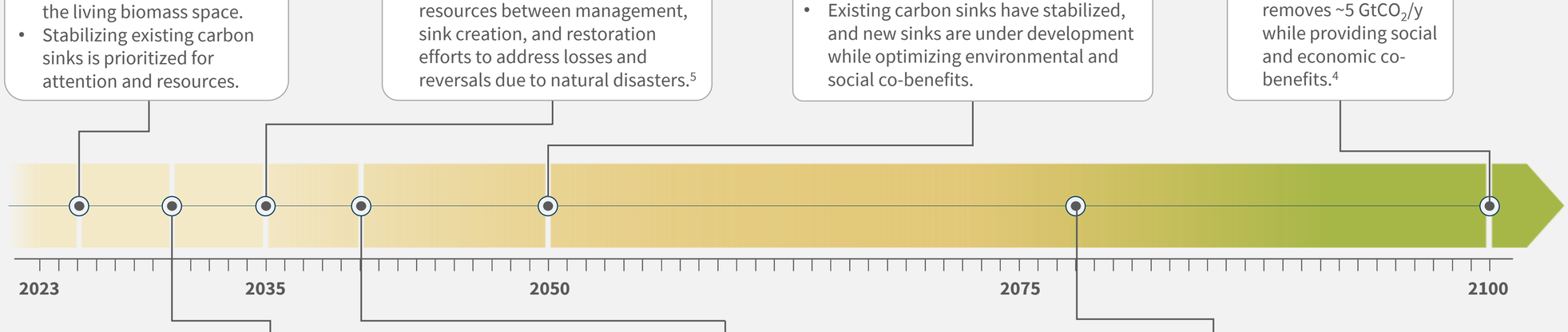
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 1.1-1.3

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Living biomass

APPROACH Overall



2025

- Living biomass removals[1,2] increase to 20 $MtCO_2e/y$.
- A differentiated market is formed to separate removals from mitigated emissions in the living biomass space.
- Stabilizing existing carbon sinks is prioritized for attention and resources.

2030

- Removals[2] reach 50 $MtCO_2e/y$ and constitute >20% of the living biomass carbon credits issued.
- Criteria for removal credits include considerations to avoid single-age stands and monoculture deployments.

2035

- Removals[2] from living biomass reach 150 $MtCO_2/y$.
- Increases in removal volume are driven by improved LCA and MRV.
- Contingency plans optimize resources between management, sink creation, and restoration efforts to address losses and reversals due to natural disasters.[5]

2040

- Removals[2] reach 440 $MtCO_2e/y$.
- Technical breakthroughs in cultivars, environmental remediation, and management practices lead to an increase in living biomass removals and ecosystem stability.
- Land-use conversion for carbon sink creation is balanced with competing needs for available land.

2050

- Removals[3] reach 4 $GtCO_2e/y$.
- Existing carbon sinks have stabilized, and new sinks are under development while optimizing environmental and social co-benefits.

2050-2100

- Policy is focused on (1) maintaining stable ecosystem sinks and (2) optimizing management practices for those sinks.
- Ongoing management and restoration practices optimize the benefits from living biomass to improve ecosystem diversity, food production, and environmental co-benefits.

2100

- Living biomass removes ~5 $GtCO_2/y$ while providing social and economic co-benefits.[4]

Notes and sources: [1]Technical RD&D breakthroughs can accelerate living-biomass based carbon removals, but the success of this approach is heavily dependent on policy and social interventions. [2]Annual removals were estimated based on a starting point of 10 $MtCO_2e/y$ in 2023, growing at 25% y-o-y from 2023 to 2050. Living biomass is already a developed market, and 25% growth y-o-y is on the upper end of what might be expected for a developed industry. This growth is also achieved through anticipated technical breakthroughs in cultivars, environmental remediation, and management practices. Some AIR reviewers thought that these assumptions were too ambitious while others thought that more removals are possible. [3]Assuming a 25% growth rate from previous years would put removals in 2050 at 4.1 $GtCO_2e/y$. [4]It is estimated that additional global CDR potential from living biomass is around 15 $GtCO_2e/y$, but as removals increase, the rate of further deployment will be expected to decrease as the most cost-effective sites and approaches are deployed. We cap removals from living biomass at 5 $GtCO_2e/y$ in 2100, which is about one third of the total estimated potential. [5]Carbon removal reversals due to increasingly frequent natural disasters require correspondingly conservative buffer pools for any living biomass-based carbon credits. Long term resource planning and allocation for afforestation and sink creation should be integrated with the anticipated needs for restoration efforts after natural disasters in order to optimize the long-term carbon flux of living biomass.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Synthetic and enhanced cultivars	Development of gene banks, plant cultivars, and soil microbes to preserve genetic diversity, increase plant carbon uptake and storage,[1,2,3] provide biological early warning systems, and improve survivability through pest and pathogen resistance[4,7] and increased environmental durability.[1,4,5,6] Enhanced cultivars should support diverse ecosystem development for greater resilience.	1-5	$25-50M/y[8]	20 y	$2.5-5B
Improved measurement and monitoring	Expand remote mapping and monitoring[16] tools for soil, aboveground carbon storage, and estimated albedo changes across global conditions. Develop early warning systems for pests, disease, and other environmental risk factors to avoid carbon reversals.[9]	1-5	$2.5M-$5M/y[10]	5-10 y	$60M-$250M
Reverse desertification	Test and deploy strategies for desert greening, such as eco-scaping, environmental remediation, and novel water sourcing or desalination without causing water insecurity.[11]	1	$60M/y[12]	15 y	$900M
Automated planting and management tools	Test deployment of automated tools to increase land management and restoration capacity, such as seeding using drones[13] or mechanical forest thinning.[14]	5	$5M/y[15]	10 y	$250M
Other grand challenge projects to boost carbon removals through living biomass	Other innovations in agroforestry, terraforming, or novel technology development may provide significant opportunities for increased carbon removals in parallel with social and ecological co-benefits.	1	$60M/y[12]	15 y	$900M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include labor, supply chain development, practice changes (such as agroforestry or urban / suburban forestry), policy considerations, and emergency response plans to mitigate the impacts of natural disasters.*[16]

Notes and sources: [1]UN ECLAC Nature-based solutions and carbon dioxide removal [2]Crops for Carbon Farming [3]Current efforts for enhanced cultivars include The Salk Institute's Harnessing Plants Initiative and Living Carbon. [4]National Academy of Sciences Transgenic Plants and World Agriculture [5]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [6]ITIF Gene Editing for the Climate (2020) [7]The Road to Resistance in Forest Trees (Naidoo, 2019) [8]The Salk Institute Harnessing Plants Initiative received $35M in 2019, $45.5M in 2020, and $50M over five years in 2023 (Salk - Audacious project, Hess Press Release, Salk News). NAS 2019 recommends $40-50M/y over 20 years and reports current R&D funding for conventional crop improvements / genetics is $1.5B (public sector) and $1.8B (private sector). The CGIAR Genebanks Initiative budget is $25M/y for three years and the Accelerated Breeding Initiative budget is $33-39M/y for three years. [9]Examples of available tools for modeling: USFS Forest Carbon tools, digital soil mapping, Daily Century Model, COMET-Farm; remote monitoring: SEPAL, FLUXNET; remote risk assessment: Overstory. [10]Cost estimates are based on NAS 2019 recommendations for data platform and monitoring systems. More details can be found in the AIR Appendix. [11]Successful examples include the Kubuqi desertification control in China, the Sahara Forest Project, and Desert Control's demonstration projects in Egypt and the UAE. Water sourcing and farming innovations include Egypt's IBTS Greenhouse and New Delta man-made river. [12]Cost estimates are based on NAS 2019 recommendations for Grand Goal R&D. More details can be found in the AIR Appendix. [13]Drone seeding companies include AirSeed, Flash Forest, and Mast Reforestation. Drones can also be used to support other forestry fieldwork. [14]Kodama Systems Frontier Application, MIT Tech Review [15]Cost estimates are based on NAS 2019 recommendations for engineering design projects. More details can be found in the AIR Appendix. [16]The recent report "Measuring the Carbon (and Other) Benefits of Climate-Smart Forestry Practices" lays out a clear recommendation for what the USDA (which houses the US Forest Service) can do to expand forest-related carbon removals. This includes policy considerations and the deployment of remote sensing and machine learning capabilities to generate evidence-based, verifiable estimates of carbon sequestration in U.S. forests.

2. Stabilized biomass

Approaches that use photosynthesis as the CO_2 capture step and that store the captured CO_2 in a stabilized biomass form

INDEX	APPROACHES	DEFINITION
2.1	Biomass direct storage	Storing terrestrial biomass in land or aquatic settings, under conditions designed to prevent significant decomposition.
2.2	Timber building products	Using timber products to utilize the carbon removal of trees and store it as long-lived building materials, especially structural wood products
2.3	Other biomass building products	Converting biomass, including purpose grown crops, algal, and fungal matter, agricultural and forestry waste, and synthetic biomaterial, into construction products and component materials other than timber, such as polymers, fibers, framing, and paneling
2.4	Pyrolysis (biochar) and storage	Thermal conversion of biomass while excluding oxygen, optimized to produce solid char for storage in open or controlled environments
2.5	Pyrolysis (bioliquid) and storage	Thermal conversion of biomass while excluding oxygen, optimized to produce crude bioliquid that can be stored underground, geologically, or in other environments
2.6	Microalgae cultivated in artificial ponds and stored	Harvest and storage of microalgae biomass grown in land-based systems
2.7	Microalgae cultivated in open water and sunk	Sinking microalgae, either cultivated or grown naturally, in open water environments
2.8	Macroalgae cultivated in open water and sunk	Enhancing macroalgae growth either in cultivated algae farms or in the open ocean, then sinking the biomass in the open ocean

RMI classifies stabilized biomass approaches as **biogenic**

Biogenic (bCDR)	Geochemical (gCDR)	Synthetic (sCDR)	Storage
Living biomass **1.1** Improved management **1.2** Conservation / protection **1.3** Restoration / creation **Stabilized biomass** **2.1** Biomass direct storage **2.2** Timber building products **2.3** Other biomass building products **2.4** Pyrolysis (biochar) and storage **2.5** Pyrolysis (bioliquid) and storage **2.6** Microalgae in ponds **2.7** Microalgae in open water **2.8** Macroalgae in open water **Sequestration of CO_2 from biomass** **3.1** BECCS to electricity **3.2** BECCS to fuels	**Solid carbonate minerals** **4.1** Surficial **Dissolved bicarbonate sequestration** **5.1** Terrestrial enhanced weathering **5.2** Coastal enhanced weathering **5.3** Mineral alkalinity enhancement	**Indirect water capture (IWC)** **6.1** CO_2 stripping **6.2** Electrochemical alkalinity production **Direct air capture (DAC)** **7.1-7.3** Liquid solvent **7.4-7.7** Solid sorbent **7.8-7.9** Membranes **7.10** Cryogenic	**Storage of CO_2** **8.1** Conventional CO_2 storage **8.2** In-situ mineralization **8.3** Ex-situ mineralization

SECTION 2.1

Biomass direct storage

SECTION	2.1
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Stabilized biomass
APPROACH	Biomass direct storage

DEFINITION

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

EXAMPLE SCENARIOS

1) Storing biowaste in arctic environments; 2) excavating a hole, filling it with woody biomass, and covering it with clay; 3) sinking agricultural waste, like corn stover, deep in anoxic waters; 4) grinding sawdust and mixing it with water to create a slurry, then injecting it underground; 5) filling temperature- and humidity- controlled warehouses with wood.

Section 2.1 overview

Biomass direct storage

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability** • Key risks include land use requirements and verification of long-term storage
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **High** • This approach is mass-customized and simple
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot** • ~5 companies at pilot stage, with <$10M in funding each • Other notable activity includes forest thinning projects by the US Forest Service
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **370 $MtCO_2$ by 2050** • Success is contingent on sustainable supply of biomass feedstocks
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$30-70M over 5-11 years** • Key stage gates in siting and sourcing of quality waste biomass or dedicated cultivated crops

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Low risk:** The primary energy requirements for transport and burial of biomass are a small fraction of the overall LCA.[1]	Energy related emissions from collection, transport, shredding, and burial of biomass are typically less than 5% of net CO_2e removals.[1,2,3]
	Water requirements	**Medium risk**: Logging and agricultural waste do not require additional water,[3] but purpose grown crops have substantial water requirements.	Traditional forestry rarely uses irrigation. However, hundreds of gigatons of water could be required if purpose grown crops are necessary at gigaton scale and they should not be grown in locations with risk of water stress. [4,5,6]
	Fertilizer requirements	**Low risk**: Biowaste does not require additional fertilizer and dedicated crops have several options with low or no requirement for fertilizer.[7]	If agricultural residue is used, replenishment fertilizer for high removal rates could be up to 10 Mt/$GtCO_2e$ (5% of 2019 global fertilizer use).[8] Most cultivated woody biomass is not fertilized and, even with gigaton-scale removals, is likely to use less than 1% of 2019 fertilizer consumption.[8,10]
	Land use requirements	**High risk:** At gigaton scale, biowaste alone will not be a sufficient feedstock source, and terrestrial cultivated crops will require significant land use.[3,11]	Gigaton scale removals would require 2-9M km^2 of forest or 1M km^2 of dedicated cropland (the US is about 10M km^2).[12,13,14] Biomass will also have increased competition for use.[15] Additional land will also be required for terrestrial storage locations. If storage prioritizes on-conventional and non-forestry sources, land use risk could decrease.[3]
	Environmental impacts	**Medium risk**: Anaerobic storage is likely low risk;[12] however, poor implementation may result in methane leakage or ecosystem and water quality impacts.	Risks to water, soil, and air quality are low for true anaerobic storage, but poor siting, engineering, or implementation can result in significant negative impacts. Burial at sea (sinking) requires additional study, as it may impact seafloor ecosystem (i.e., Benthic zone), although this is disputed[3,12,16] as most oceans and lakes already sequester large volumes of organic matter each year.[20]
Secure storage for 100+ years		**Medium risk**: Concerns for methanogenesis and decomposition must be assessed to ensure secure storage.	Biomass could decompose if improperly stored. While not expected, methanogenesis and decomposition could be a concern at 100+ year timescales and needs further study.[17]
Path to measurement at scale		**Low risk**: Measurement at the point of sequestration and over time is possible with existing measurement devices or technology currently in development.	Secure burial or sinking for gigaton scale removals will require measurement hardware (particularly methane generation monitoring) and techniques that are within cost requirements and suitable for the relevant environments.[9]
Pathway to full costs <$100/$tCO_2$		**Low risk**: This method is simple in its sourcing and sequestration of biomass.	Pilot costs range from \$50/tCO_2 to \$170/tCO_2 depending on the estimate.[18,19,21,22] Significant cost reduction is expected at larger scales.[12,23]

Notes and sources: [1]RMI verified this information through interviews with 3x biomass direct storage companies. [2]Cost and emissions balances study for biomass transport in Europe. The cost breakeven transport distance is around 145 km. [3]This roadmap pathway only considers terrestrial biomass; marine biomass cultivation is covered in separate pathways on macro- and micro-algae. [4]As a comparison, estimates for BECCS water use are small when waste biomass is used, but can increase dramatically for cultivated crops (EFI – Surveying the BECCS landscape). [5]Royal Society Greenhouse Gas Removal Report [6]Hybrid poplars planted at 900 trees per acre and receiving 10 gallons of water per inch of trunk diameter for 2/3 of the year could require several hundred gigatons of water per $GtCO_2e$ removed. [7]A reviewer notes that this may be medium risk as the measurement of nutrient depletion is challenging to prove at scale. [8]A ton of wheat straw contains about 11, 3, and 20 lbs of nitrogen (N), phosphorus (P), and potassium (K), respectively, and requires ~40 lbs of fertilizer to replace nutrient loss from harvesting a metric ton, or approximately 10 Mt fertilizer per $GtCO_2e$ removed. Global fertilizer consumption in 2019 was 215 Mt. [9]RMI interviews with several startups indicate that most companies expect early MRV to be complex and detailed, while later MRV will be standardized and simple. [10]Woody biomass could be fertilized with up to 200 pounds per acre of nitrogen and 25-50 pounds per acre of elemental phosphorous. Assuming a one-time application of 200 lbs/acre (224 kg/ha) with 10-year harvest rotation producing a biomass yield of 10 t/ha requires 1.2 Mt fertilizer/y per $GtCO_2e$ captured by tree growth (Texas A&M Forest Management). [11]Reviewers consider this to be medium to high risk. [12]Basic assumptions include woody and agricultural biowaste with storage on land, per Zeng and Hausmann (2022), or sinking. [13]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [14]Based on low intensity harvesting rates from [8] of 1.1 tCO_2e/ha/y and reviewer input that thinning treatments in the western US yield 50-100 tCO_2e/ha with thinning occurring about every 20 y for annual removal yields of 2.5-5 tCO_2e/ha/y. [15]The 2016 Billion Ton report estimates there will be sufficient biowaste supply, but biomass will have many competing demands. Further discussion can be found in the bCDR overview. [16]Seaweed Generation [17]Kodama's Frontier application (p2) states that decomposition is expected to be low due to operating conditions. Separately, Kodama estimates that the total degradable carbon stored in wood vaults is ~2% of the total buried carbon. [18]Based on Montreal pilot project (2013). [19]Puro.Earth listed 5,000 credits for pre-purchase at \$173/tCO_2 from Carbon Lockdown pilot - Potomac Project 1. [20]Rewind.earth is examining this question. The Black Sea already stores millions of tons of terrestrial material per year. [21]Kodama's Frontier application estimates removal costs approaching \$60/tCO_2 in the near term, comparable to estimates in Yablonovitch and Deckman (2023). [22]Pilots were small e.g., a 35-t burial in Montreal pilot project, or are not yet validated. [23]Estimates vary by state, but the USFS pays ~\$5-50 per acre to remove slash piles. Each acre of thinnings produces 9-10 tons of biomass.

Potential for cost improvement

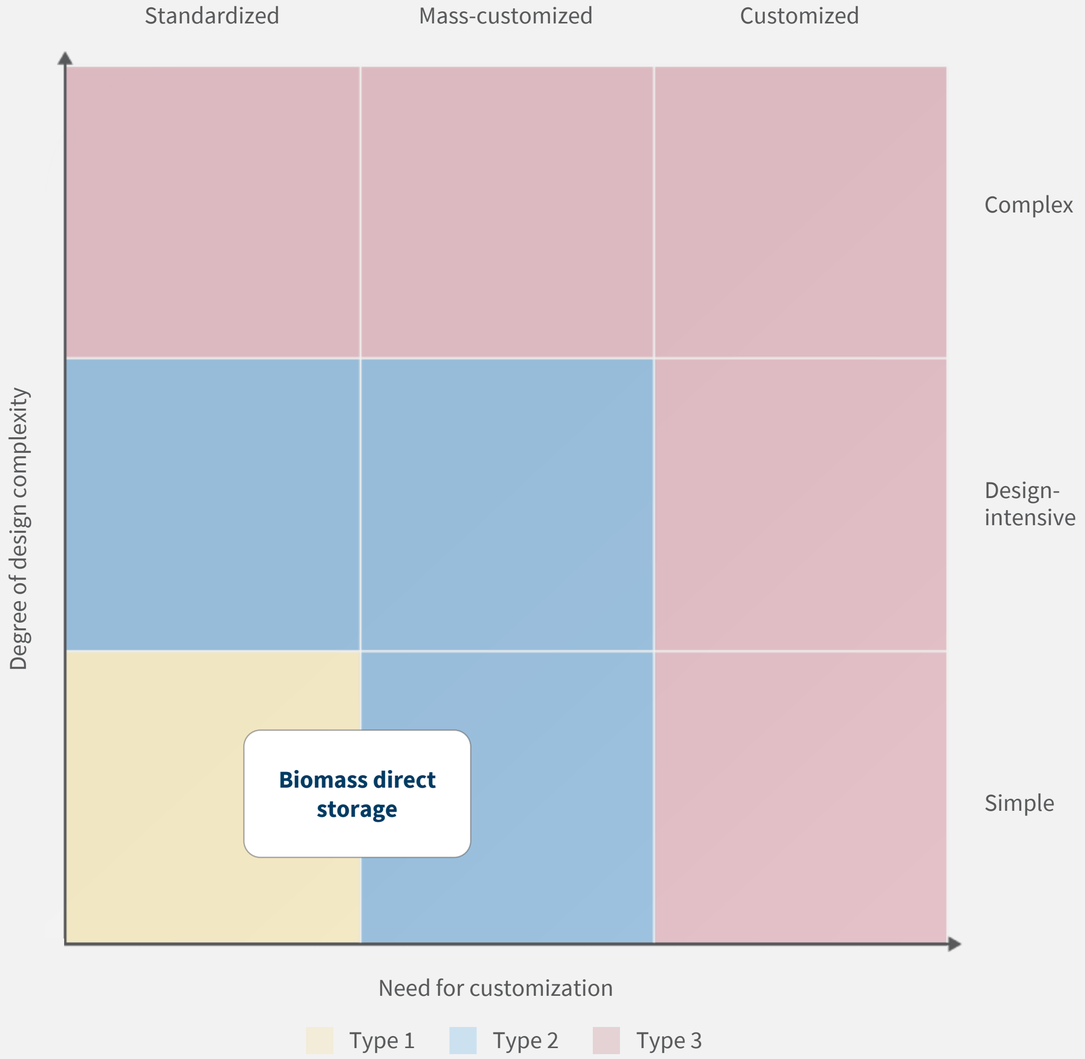
An assessment of two key drivers of learning rates

SECTION 2.1

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Biomass direct storage



OVERALL RATING

Type 1[1]

POTENTIAL LEARNING RATE

Type 1 **High**

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Simple
- **Rationale:** The direct biomass storage process is straightforward and replicable, requiring excavation, deposition, and reburial, or sinking in the ocean, followed by monitoring.

NEED FOR CUSTOMIZATION

- **Rating:** Standardized to mass-customized
- **Rationale:** General storage approaches may be similar between projects, but feedstock characteristics and storage conditions require some degree of customization.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

THE APPLIED INNOVATION ROADMAP FOR CDR

Current state of RD&D

A mapping of companies, plus other notable activities

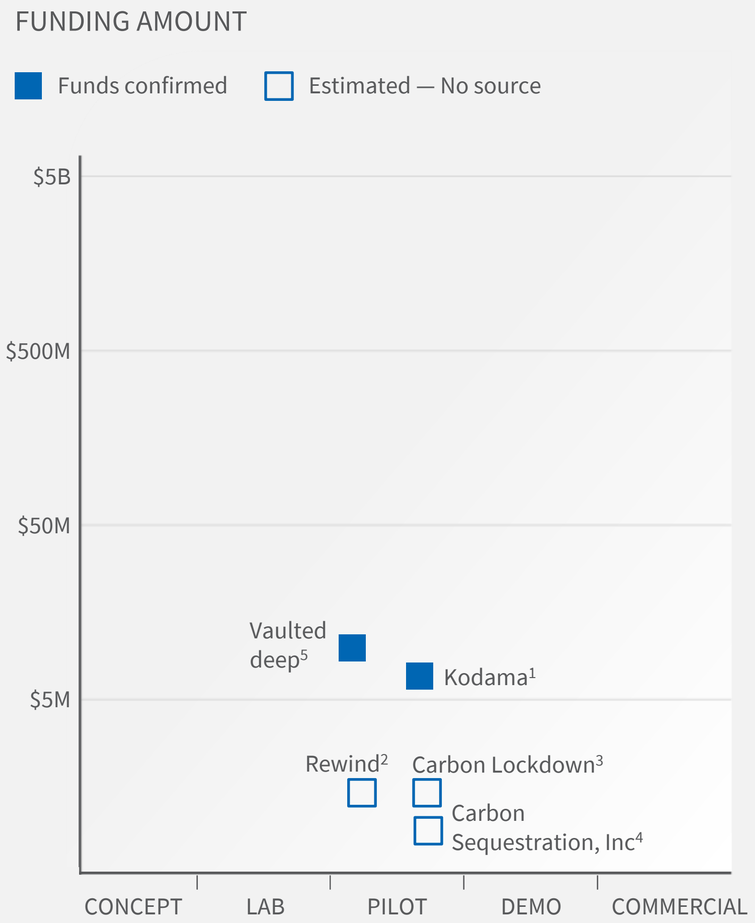
NOT EXHAUSTIVE

SECTION 2.1

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Biomass direct storage



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Kodama: Developing underground vaults to store forest slash[1]	$7.2M (seed round)[6]	• Planning pilot in California desert to bury woody biomass thinned from forests at risk of wildfires
Rewind: Sinking biowaste in anoxic water[2]	Seed funding	• Conducting small scale pilot storage in the black sea and testing measurement technologies and MRV methodologies[2]
Carbon Lockdown: Designing and assessing storage projects[3]	N/A	• Launched *Potomac Project 1* pilot of 5,000 tCO_2 with credits available for pre-purchase[7]
Carbon Sequestration, Inc.: Burying waste wood biomass[4]	N/A	• Began construction of 45-acre biomass burial project in TX • Purchased additional land for a second project
Vaulted deep: Injecting a slurry of organic waste underground[5]	$8M[8]	• Using Advantek (a waste management company) deep well slurry injection technology • Two permitted sites are operational[8]
Other companies and activities: Yale Carbon Containment Lab,[9] Tau Carbon,[10] EnviroNZ,[11] Inter.Earth,[12] Puro.Earth,[13] Carboniferous,[14] Levitree[15]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
US Forest Service: forest thinning projects	$930M[16]	• Thinning forests in western states to produce an estimated 2 Gt of waste wood

Notes and sources: [1]Kodama is using a novel approach to construct underground "vaults" that minimize water, oxygen, and microbial activity that could decompose biomass, while employing numerous surface sensors to detect any decomposition. By determining optimal vault designs, they will be able to minimize CDR costs and maximize storage durability. [2]Rewind website [3]The Carbon Lockdown Project is pursuing several methods of biomass direct storage including in wood vaults, deep ocean environments, and warehouses, using both waste and cultivated materials. [4]Carbon Sequestration, Inc [5]Vaulted deep is exploring injecting a slurry of organic wastes deep underground. [6]Crunchbase funding estimate for Kodama [7]Puro.earth facilitated the pre-purchase of pilot project credits at $173/$tCO_2$. 1,000 credits have been sold as of July 2023. [8]$8M seed investment led by Lowercarbon Capital [9]Yale Carbon Containment Lab is storing slash piles from forest thinning in the American West. [10]Tau Carbon is developing modular biomass storage containers. [11]Waste management utility siphoning woody biowaste from forestry and timber streams into a manmade underground storage units [12]Australian startup working with rural landowners to grow and store woody biomass in degraded saline soils [13]First carbon creditor to establish methodology and begin certifying providers and projects [14]Carboniferous [15]Levitree is exploring injecting deadwood underground to elevate properties against flooding. [16]The USFS allocates $930M for forest thinning in the US west to mitigate fires.

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

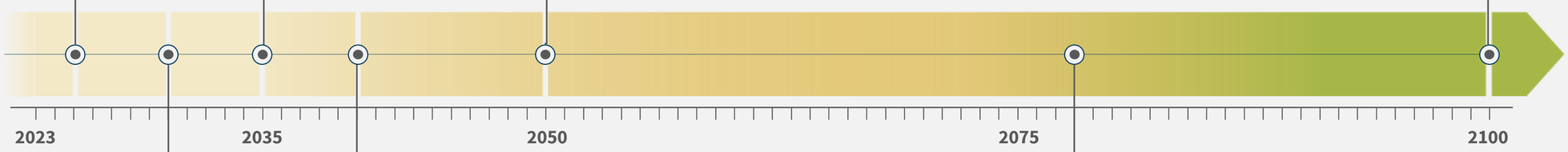
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 2.1

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Biomass direct storage



2025

- Potential biomass direct storage sites are identified around the world.
- Four biomass storage demonstration projects, each at least 5 $ktCO_2e/y$, are funded.[1]
- New funding is allocated for breakthroughs on enhanced cultivars that have the potential to dramatically increase CDR by biomass direct storage techniques.

2030

- LCA, MRV, and cost are validated for demonstration projects.
- Costs are shown to be competitive with other CDR approaches.
- MRV methodologies are established to validate removals.

2035

- Storage[2] of 10 $MtCO_2e/y$ by biomass direct storage techniques
- Activities on 3+ continents include land burial and ocean sinking.
- Breakthroughs in enhanced cultivars enable new opportunities for dedicated biomass direct storage.
- Breakthroughs in automated planting, harvesting, transport, and storage contribute to cost declines and increased market competitiveness.

2040

- Storage[2] by all biomass direct storage techniques reaches 30 $MtCO_2e/y$ of verified removals.
- Biomass direct storage emerges as a bCDR leader due to high carbon conversion efficiency, the diversity of feedstocks that can be used, and feedstock logistics.

2050

- Storage[2] reaches 370 $MtCO_2e/y$ equivalent. This is ~4% of the global sustainable biomass supply.[4]
- Competition for waste biomass has become a critical factor affecting deployment.
- New cultivars are critical to continued growth in removals by direct biomass storage.

2050-2100

- Biomass direct storage is still one of the most competitive bCDR approaches
- Biogenic CDR is potentially displaced by more permanent, less ecosystem-dependent CDR approaches.
- Strong competition for biomass continues to drive allocation considerations across the energy transition.

2100

- Biomass direct storage continues to be used to sequester waste biomass and forest thinnings, reaching a stable and sustainable yearly rate of ~400 $MtCO_2e/y$.[3]
- Biomass direct storage continues to compete for biomass supply with other energy transition activities.
- Breakthroughs in cultivars specifically for biomass direct storage may help carve out dedicated land for this approach and drive higher removals.

Notes and sources: [1]Zeng and Hausmann (2022) suggest pilot size facilities of 100 $ktCO_2e/y$, while other startup reviewers think demonstration sites should be 5 $ktCO_2e/y$ or less. Kodama Systems is pursuing a ~3 $ktCO_2e/y$ pilot in Nevada (Kodama newsletter). The goal of larger demonstration facilities is to test the ability of this CDR approach to scale. [2]Annual storage estimates assume 80% y-o-y growth from 2025 to 2035 based on a starting point of 20 $ktCO_2e/y$ in 2025. From 2036 to 2050 growth of 30% is assumed. [3]By 2100, the use of biomass in other energy transition applications, such as fuels, has competed away about half of the biomass supply from direct storage. [4]2016 Billion-Ton report

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

TRL

CRITICAL PATH ACTIVITIES

$30-70 million | **5-11 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Site selection**: Identify biomass sourcing and storage locations for several deployment options
- **Environmental impact assessment:** Conduct assessments in accordance with local, state, and federal regulations

$5-20 million | **5-7 years**

✓ Identified demonstration sites that are representative of larger, scalable deployment options

✓ Environmental impacts at demonstration sites have been assessed and are manageable.

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Waste biomass sourcing and storage projects**: Demonstrate storage of biomass sourced from (1) forestry residues and (2) from irregular production such as storms
- **Cultivated crop sourcing and storage project**: Demonstrate storage of woody biomass from cultivated crops
- **MRV**: Provide MRV for all demonstrations

$25-50 million | **4 years**

✓ Total costs are market competitive.

✓ Successful measurement of biomass stability and storage permanence

✓ Manageable environmental impacts on air quality, biodiversity, ecology, habitat, and water quality

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

SECTION 2.1

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Biomass direct storage

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$300-550 million | **15 years**

- Continual LCA and TEA refinement
- Development of enhanced cultivars
- Cross-cutting bCDR cost reduction interventions, including sourcing, harvesting, transportation, and storage
- Optimization of storage conditions and environmental monitoring

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Measured carbon removal by demonstration projects
- Verified carbon storage by independent accounting organization
- Manageable impact on sourcing and storage ecosystems

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Site identification	Identify sites that combine access to biomass with access to storage. Site identification should consider:[1] • Sourcing of biomass material[2] • Storage of biomass material[3] • Transportation requirements[4] • Co-siting with existing sourcing or storage sites • Long term stability of site and relevant environmental conditions	✓ Potential to reach gigaton scale with global deployment ✓ Sites identified have a path to market competitive removal costs ✓ Manageable environmental impact at demonstration sites ✓ Risk of spontaneous combustion is addressed and mitigated	1	$1-2M/y	1 y	$1-2M[7]
Field testing	Environmental impact assessment	Characterization of potential environmental impacts of storing biomass in a mound design, underground mining pits / quarries, deep sea sinking, and desert burial.[5]		1	$0.25-1M/y	2 y	$0.5-2M[7]
Field testing	Characterization of heat generation from wood piles	Additional R&D under various operating conditions is needed to determine the risk of spontaneous combustion by self-heating and approaches to mitigate this risk.[6]		1	$0.5-2M/y	1-2 y	$1-4M[7]
Lab / field testing	Biomass slurry injection testing	Assess viability of biomass slurry injection as a direct storage technique, including: • Impact of variation in feedstock and slurry preparation • Decomposition and methanogenesis risk from slurry • Risks of geologic instability at injection site	✓ Biomass slurry has a path to stable long-term removals ✓ Slurry storage sites are geologically stable after injection	1-2	$0.5-1M/y	5-7 y	$3-10M[7]

Notes and sources: [1]Site assessment based on "Wood Vault: remove atmospheric CO_2 with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future" (Zeng & Hausmann, 2022). [2]Sourcing of biomass material should consider currently unexploited urban wood residuals, woody biomass from forest thinning for fire risk reduction, storm-damaged woody biomass due to hurricanes and tornados, agriculture residue, and forestry residue from timber harvest and other operations. Sourcing should ensure sustainably sourced materials and optimize for costs. Cultivated woody biomass may cost $20-200/t. Storm waste may be available for free. Slash waste cost estimates vary by state, but the USFS pays ~$5-50 per acre (each acre of thinnings produces 9-10 t of biomass or ~18 tCO_2e) to remove slash piles via different methods and might pay similarly for CDR. [3]Storage of biomass material should consider burial mound design, underground using mining pits or quarries, deep sea sinking, desert burial. [4]Transportation should be considered as a major driver of cost, not emissions. A single truck that can move 25 metric tons of biomass (20 tCO_2e) costs $150-200/hr to operate. This adds $10/$tCO_2e$ for every hour. [5]This preliminary EIA can be done by an environmental consulting firm or similar external party to characterize environmental concerns at relevant sites before demonstrations are deployed. [6]Zeng and Hausmann have shown in the Montreal pilot project (2013) that spontaneous combustion is not likely under certain conditions. Other burial conditions, site locations, conditions (humidity, permeability, and oxygen content), and burial material (especially the fraction of woodchips and fine material) should be tested to determine the conditions under which spontaneous combustion may become an issue. [7]Estimates based on a combined range of averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for R&D funding. Details of this estimation can be found in the AIR Appendix.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Waste biomass storage:[1] These demonstrations should source their residue biomass from: • Opportunistic waste streams: Forest thinning or storm waste such as hurricane residue OR • Consistent waste streams: Regularly produced municipal and industrial biowaste OR • Fire thinning of forests At least one demonstration should utilize biomass sinking instead of burial and, if viable, one demonstration should utilize biomass slurry injection. Demonstration projects should perform their own measurement, LCA analyses, and environmental monitoring.	20-100 $ktCO_2e/y$ or up to 40,500 cords of dry wood[2]	✓ Full costs, including biomass sourcing, transport, storage, and MRV achieve market competitive costs ✓ Independent measurement and verification of biomass stabilization over 3+ years ✓ Minimal environmental impacts on air quality, biodiversity, ecology, habitat, and water quality	4	$2-5M/y[3,4,5]	1-2 y	$15-35M
Demo	Cultivated biomass storage demonstrations should source their biomass from managed forests.[1] Demonstration projects should perform their own measurement, LCA analyses and environmental monitoring.	5-20 $ktCO_2e/y$ or around 70-280 acres of cultivated forest[6]		1	$2-5M/y[3,4,5]	1-2 y	$5-10M
MRV	Measurement and verification of CO_2 removals performed by a separate entity in addition to the demonstration team. Low-cost sensors should be included in each storage site to monitor the stability of the stored biomass beyond the initial demonstration period.[7]	N/A		1	$1M/y	4 y	$4M

Notes and sources: [1]We propose 4 demonstration projects with specifications as follows. Sourcing of biomass: At least 2 demonstrations with waste biomass and 2 with cultivated biomass. Sequestration: At least 2 facilities should require terrestrial burial, and at least 1 facility should require deep ocean burial. [2]In 2009, the USA consumed 27.4 million cords of wood for heating. This equates to around 37 million metric tons of dry wood or 68 $MtCO_2e$. [3]Costs based on Zeng & Hausmann (2022) at $1.2-1.8M total cost for 100,000tCO_2e for 1 year. (Authors assume a managed forest cost of $5/t of wood or free waste biomass). We have added additional budget to account for administrative costs of a FOAK demonstration project as well as additional cost buffer. [4]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) lists the project cost for demonstration at $500k/y and a duration of 3 years. [5]A reviewer notes that cost estimates may be low given underestimates on early project costs and potential cost improvements at scale. [6]Cultivated forests typically generate ~3-10 metric tons of biomass per hectare per year over a 40-year growth cycle. This is around 80-105 green t/acre or around 40 dry t/acre which equates to around 72 tCO_2e/acre. [7]Specific monitoring for methanogenesis, VOCs, bacterial activity, moisture, and heat are required.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	Breakthroughs on enhanced cultivars	Research and develop plant-based feedstocks that have enhanced growth qualities such as accelerated growth, improved survivability, and / or increased carbon uptake.[1]	1	$40-50M/y[2]	15 y	$600-900M
MRV	Containment and storage monitoring	Develop sensor systems to monitor external conditions around biomass storage spaces to provide advance warning of potential containment breaches.	4	$0.5-1M/y[3]	5-10 y	$10-20M
Desktop research	Continual lifecycle analysis and accounting for emissions and energy[4]	Use demonstration data to continually update lifecycle assessments of energy inputs and outputs to further refine the process and logistics.	1	$1-4M/y	4 y	$5-15M
Desktop research	Continual techno-economic analysis of costs[4]	Use demonstration data to continually update future cost projections to optimize biomass sourcing and storage site selection.	1	$1-4M/y	4 y	$5-15M
Field testing	Cross-biogenic cost reduction interventions[4]	Perform assessments and interventions to optimize biomass type, sourcing, and transport for available storage.	5	$1-4M/y	4 y	$20-80M
Lab / field testing	Automated harvesting	Investigate and test digitization and automation for forestry harvesting practices that can accommodate multi-species, multi-aged stands.	5	$2-4M/y[5]	5-10 y	$50-$150M
Lab / field testing	Feedstock storage optimization	Research and test the interactions between storage conditions, feedstock, and decomposition to optimize storage approaches.	4-6	$2-4M/y[5]	2-5 y	$20-$100M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include updates to tax credits for biomass storage, regulation and permitting for biomass sourcing and storage locations, and improved logistics for transporting biomass.*

Notes and sources: [1]Research could also include the identification of novel cultivars especially suited to carbon cropping. [2]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) recommends $40-50M/y over 20 years for genetic crop improvements and reports current R&D funding for conventional crop improvements / genetics is $1.5B (public sector) and $1.8B (private sector). [3]Estimates based on a combined range of averages from NAS 2019 budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [4]Assessments based on NAS 2019 and Zeng and Hausmann (2022).[5]Estimates based on NAS 2019 budgets for engineering design funding. Details of this estimation can be found in the AIR Appendix.

SECTION 2.2

Timber building products

SECTION	2.2
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Stabilized biomass
APPROACH	Timber building products

DEFINITION

Using timber products to utilize the carbon removal of trees and store it as long-lived building materials, especially structural wood products

EXAMPLE SCENARIOS

1) Building houses or offices out of lumber; 2) building new high-rises out of engineered timber, such as cross laminated timber (CLT) and glue-laminated timber (glulam).

RMI

Section 2.2 overview

Timber building products

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability** • Key risks include additionality of verified removals and land use requirements at scale
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is mass-customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot to commercial** • ~5 companies at pilot through commercial stages • Other notable RD&D activity includes the US Forest Service's World Innovation Grants and the ARPA-E HESTIA program
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **160 $MtCO_2$ by 2050** • Success is contingent on increased use of timber as a building material and verification of CO_2 storage across the timber lifecycle
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **NA** • Technology is already well-established

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Additionality*	**High risk:** Consistent gigaton scale capture is unlikely. Although structural wood products are commercially established, significant challenges must be addressed to ensure verified removals.	0.3-1.09 billion m^3 wood is required to store 1 $GtCO_2$.[1] Global wood production was 1.2 billion m^3 in 2020 and predicted to be 1.3-3.1 billion m^3 by 2050.[1] However, much of that capture is not additional, with significant harvested biomass left as logging residue, and the LCA and MRV of removals is still unproven.[2]
	Energy requirements	**Medium risk:** Harvesting, transporting, and processing structural wood products requires significant energy.	Manufacturing structural wood products requires drying, mechanical processing, assembly, etc,[3] although these energy requirements are often less than the incumbent materials they could replace.[4,5] Transportation energy can be reduced by optimizing the location of manufacturing and production sites relative to sourcing and construction.
	Water requirements	**Medium risk:** Dedicated timber production consumes a small fraction of regional water use in appropriate climates.	Traditional forestry rarely uses irrigation. Cultivation should only occur in locations with low risk of water stress, as even low-water cultivars, such as hybrid poplars, could consume hundreds of gigatons of water per $GtCO_2$.[6] Timber processing also consumes water, but producing engineered timber is more water efficient than many conventional construction materials.
	Fertilizer requirements	**Low risk**: Dedicated forestry requires minimal, infrequent fertilizer application.	If fertilizers are used, an estimated 1.2 Mt fertilizer/$GtCO_2$/y would be applied. This is <1% of the 215 Mt fertilizer demand for 2019.[7]
	Land use requirements	**High risk:** Reaching gigaton scale removals will require significant land use.	A medium harvesting intensity of 4 tCO_2e/ha/y requires 3M km^2 (~30% of US land area) to capture 1 $GtCO_2e$,[8] which is likely to require massive land-use conversion from cropland.
	Environmental impacts	**Medium risk:** Improved forestry provides co-benefits, but production for gigaton scale removals may lead to increased emissions and ecosystem impacts.	Structural wood use could reduce waste wood, improve forest management, and provide many co-benefits,[1,9,10] but increased use (or inadequate LCA) may also lead to increased emissions from production and land-use conversion in addition to the associated ecosystem loss.
Secure storage for 100+ years		**Low risk:** Appropriately designed and monitored buildings can last for >100 years with materials potentially disposed of as CDR assets.	Both construction and demolition of buildings often require permits, providing awareness when storage is ending or disrupted. Long-lived structural wood can last for at least 100 years, especially with end-of-life management to recycle, bury, or pyrolyze wood mass for continued storage.[11,12]
Path to measurement at scale		**Medium risk:** Forestry inclusion in LCAs is limited and cannot currently inform MRV for wood products.	Current LCA for wood products is insufficient as it does not consider forestry management practices and regrowth timelines for MRV.[13,14] Effective LCA also needs to incorporate the additionality of carbon removals and storage for anticipated lumber use.[17]
Pathway to full costs <$100/$tCO_2$		**Medium risk:** Mass timber prices are currently $800-$1000/tCO_2e. A CDR price can help offset the cost of structural wood products for near term CDR development.	One cubic meter of timber stores ~1 tCO_2 and costs about $800-$1k (as mass timber). CDR pricing and improved processing efficiencies are necessary to reach full costs across various structural woods products.[11,15] Ancillary benefits may lower the effective price of timber carbon removals.[11,12,16]

Notes and sources: [1]UN FAO Global forest sector outlook 2050 [2]Wood product yields vary by species, product, and processing. For example, per [13] (Table 1), about 0.32M m^3 of mass timber were used in 2021, only 35-60% of log inputs become mass timber. Climate, Forests and Woodlands eXtension Community of Practice reports that 25-45% of trees' biomass is left as logging residue. Using the most optimistic ranges, only 45% of trees' biomass ends up as mass timber. Without substantial process improvements, 2.2B m^3 of timber must be harvested to produce 1B m^3 of mass timber. [3]Dynamic life cycle carbon and energy analysis for cross-laminated timber in the Southeastern United States (Lan et al., 2020) [4]Carbon Credits for Mass Timber Construction (Taylor et al., 2023) [5]Structural wood production does not require high temperatures and is likely easier to decarbonize than production of concrete and steel. [6]Hybrid poplars planted at 900 trees per acre and receiving 10 gallons of water per inch of trunk diameter for 2/3 of the year could require several hundred gigatons of water per $GtCO_2$ removed. [7]Global fertilizer consumption in 2019 was 215 Mt. Fertilizer requirements vary based on climate, soil condition, species, age and density of planting, co-treatments (e.g., herbicide), etc. Depending on species, harvest takes 15-80 years (Kentucky Energy and Environment Cabinet). Assuming a one-time application of 200 lbs/acre (224 kg/ha) per Texas A&M Forest Management and a 10-year harvest rotation, producing 10 metric tons of biomass/ha requires 1.2 Mt fertilizer/y per $GtCO_2$ captured. This does not account for processing losses during lumber production. [8]Wood Vault: remove atmospheric CO_2 with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future (Zeng and Hausmann, 2022) [9]UN FAO The State of the World's Forests 2022 [10]Protect, manage and then restore lands for climate mitigation [11]Environmental Life-Cycle Assessment and Life-Cycle Cost Analysis of a High-Rise Mass Timber Building: A Case Study in Pacific Northwestern United States (Shaobo Liang et al., 2021) [12]SBCA Life Expectancy of Wood [13]LCA for wood products begins at harvest and / or assumes forestry impact on emissions is neutral 2022 International Mass Timber Report [14]Carbon Leadership Forum LCA of Buildings: Practice Guide [15]Cost from price index in 2022 International Mass Timber Report [16]Wood products can accelerate near term development and deployment, but long-term costs should be for CDR only. [17]MRV methodologies should quantify potential carbon benefits and risks to forest ecologies from harvest, restoration, and regrowth, such as reducing wildfire risk through harvesting thinnings, increased short-term carbon loss from harvesting practices, or long-term stability through effective restoration practices.

Potential for cost improvement

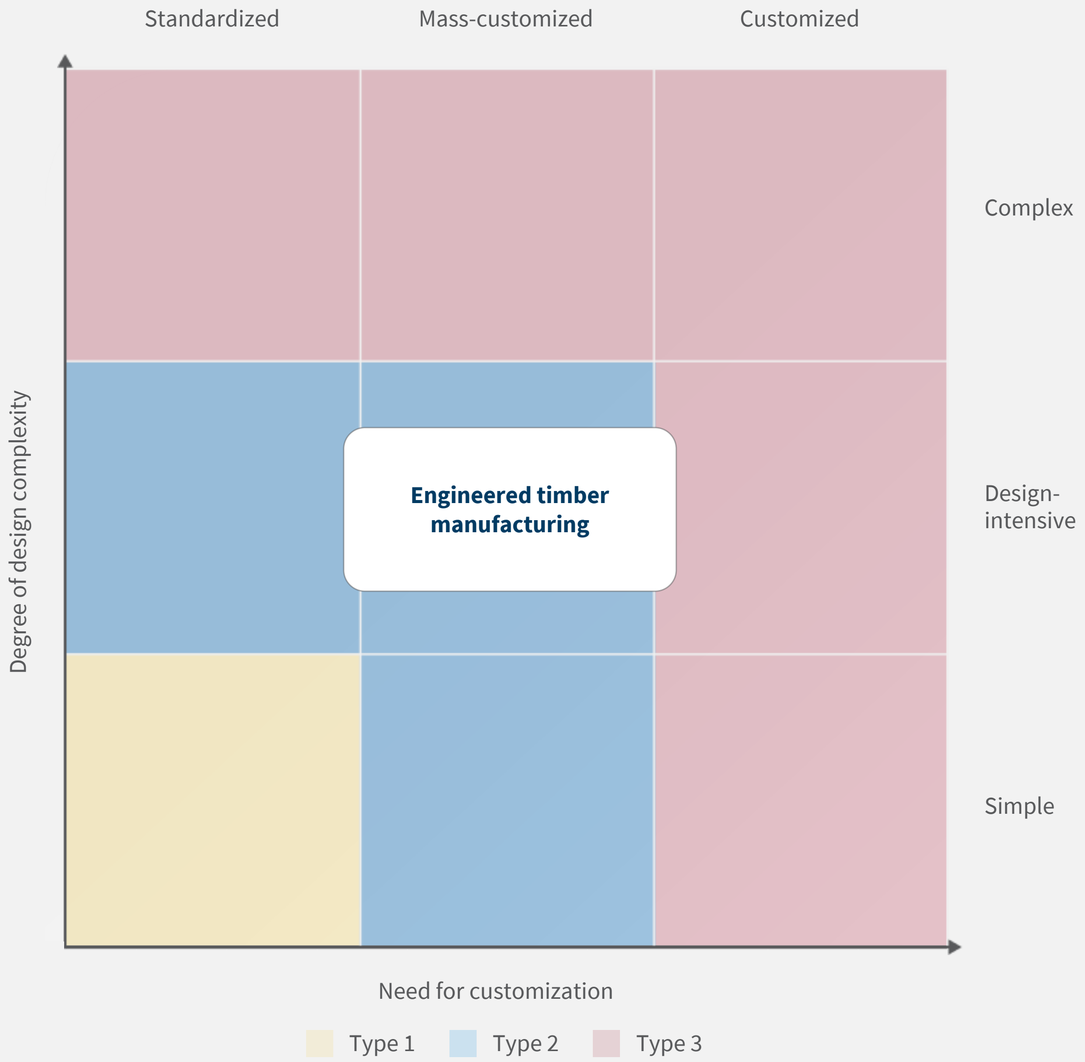
An assessment of two key drivers of learning rates

SECTION 2.2

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Timber building products



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive
- **Rationale:** Structural wood products require a buildup of manufacturing capabilities. High variability in forest diversity and management practice also requires development of novel practice for LCA.

NEED FOR CUSTOMIZATION

- **Rating:** Mass-customized
- **Rationale:** Forest management and harvesting vary, requiring distinct combinations of LCA practice to provide reliable MRV. Factory design must be optimized for each facility.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

Current state of RD&D

A mapping of companies, plus other notable activities

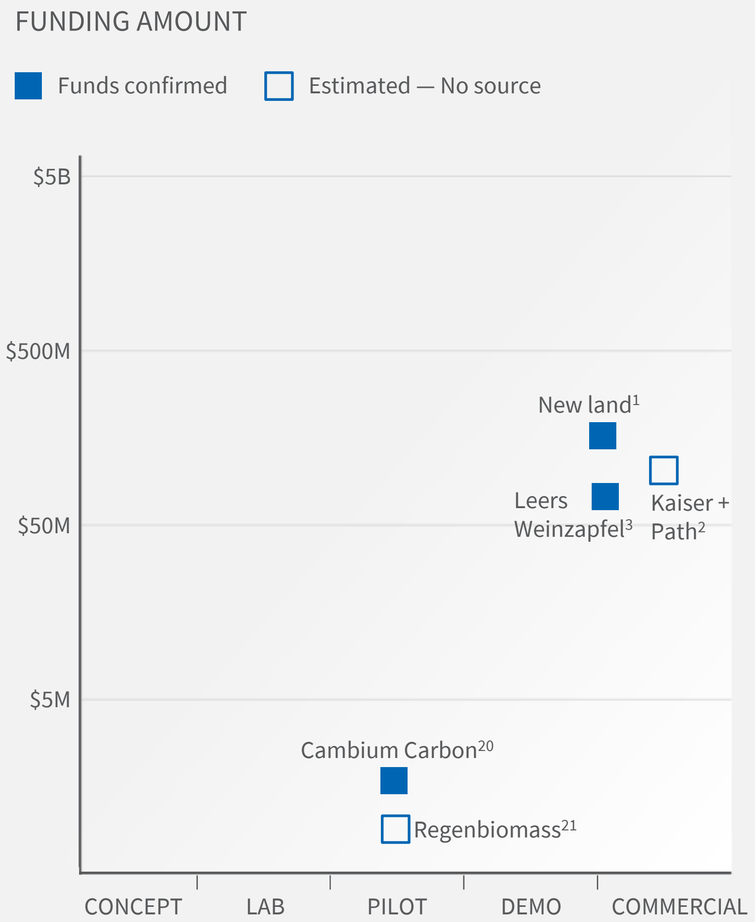
NOT EXHAUSTIVE

SECTION 2.2

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Timber building products



COMPANY TYPE	NOTABLE COMPANIES	SIGNIFICANT DEPLOYMENT
Real estate / architecture firms	**Kaiser+Path[2]**	• Carbon12– condos and commercial, Portland, OR[5]
	New Land Enterprises[1]	• Ascent MKE – 25 story high-rise apartment, $128M[6], WI • World's tallest timber building
	Leers Weinzapfel[3]	• Adohi Hall[9] – Residence Hall, $79.6M, University of Arkansas
	MGA	• T3 Minneapolis Office Building[10]
Builders	**StructureCraft[7]**	• Richmond Olympic Oval, Richmond, BC[8]
	Other builders: Sterling Solutions[11], Element5[17], C.D. Smith[18]	
Manufacturers	DRJ Wood Innovations,[12] SmartLam,[13] USNR,[14] Freres,[16] International Beams,[17] Mercer Mass Timber (formerly StructurLam),[19] Cambium Carbon,[20] Regenbiomass,[21] WholeTree Structures[22]	

Notes: *Engineered lumber and mass timber materials[4] include cross-laminated timber (CLT), glue-laminated timber (glulam), veneer- and strand-based products, and round timber. Most companies in this area are operating commercially.*

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
HESTIA[23]	$39M (2022)[25]	Developing building materials with: • Net carbon storage over building lifetime • Relevant performance testing • Market advantage
Wood Innovation Grants (US Forest Service)[24]	$25M (2022)[26]	• Regularly awards funding for mass timber development projects

Notes and sources: [1]New Land Enterprises [2]Kaiser+Path [3]Leers Weinzapfel [4]Mass timber consists of layered wood products to produce structural building components from timber. The 2021 International Building Code allows cross laminated timber (CLT) and other mass timber buildings up to 18 stories, with additional fire-resistance ratings (Woodworks Summary). The 2022 International Mass Timber Report estimated 1.665M m^3 of mass timber production capacity in North America. Additional companies, such as Katerra, have been substantial contributors but are no longer in operation. [5]Building Carbon12 [6]Urban Milwaukee [7]StructureCraft [8]Richmond Olympic Oval [9]Adohi Hall, University of Arkansas News [10]MG Architecture [11]Sterling Solutions [12]DRJ Wood Innovations [13]SmartLam [14]USNR [15]Freres Wood [16]International Beams [17]Element5 [18]C.D. Smith [19]Mercer Mass Timber [20]Cambium Carbon has raised $3.2M and been a partner in a reforestation hub pilot since 2022. Cambium carbon focuses on salvaging waste wood for timber products. [21]Regenbiomass began a pilot timber and carbon farm in Southern California growing Paulownia trees. [22]WholeTree Structures is a manufacturing company that harvests timber from well-managed forests. [23]HESTIA [24]Wood Innovation Grants 2021, 2022 [25]Award announcement [26]Congressional Research Service Report IF10288, not all of the appropriation is awarded to mass timber related projects

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

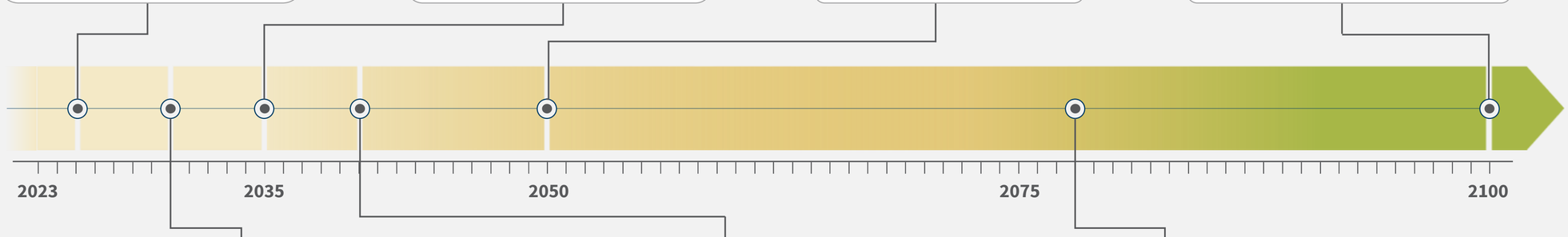
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 2.2

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Timber building products



2025

- Development of comprehensive MRV and LCA that integrates forestry with timber production is ongoing and has broad industry support.[1,2]
- Structural wood production and construction is expanded in timber producing regions.

2030

- Refined LCA for "seed to grave" timber production verifies net carbon removals.[2]
- Timber building codes are standardized, including in the US and EU.[3]
- 500M m^3 of timber are used annually in buildings, 10% of which provides net carbon removals for 50 $MtCO_2e/y$ of verified removals.[4]

2035

- Sustainable timberland reforestation emphasizing resilience and species diversity is standard practice.
- Improved harvest and lumber production, combined with increased use of structural wood products, brings verified removals to 60 $MtCO_2e/y$.[4]

2040

- Timber provides 130 $MtCO_2e/y$ of verified removals.[4]
- The use of engineered timber is incentivized through public policy.[5]

2050

- Global new construction prioritizes structural wood products when appropriate.
- 160 $MtCO_2e/y$ of verified removals.[4]

2050-2100

- Carbon storing building materials are standard practice where appropriate and remove ~200 $MtCO_2e/y$.
- End-of-life for building materials utilizes reuse, burial or other disposal approaches to extend storage lifetimes.

2100

- Structural wood products are utilized for building efficiency and aesthetic considerations and continue to achieve ~200 $MtCO_2e/y$ of verified removals.

Notes and sources: [1]This roadmap is intended to assess carbon removal; however, it is essential to note the potential for avoided emissions through mass timber construction. Replacing traditionally produced steel and concrete with mass timber could provide 25-50% reduction in embodied carbon emissions with potential for gigaton scale avoided emissions by 2050. A reviewer also notes that structural wood manufacturing is likely easier to decarbonize than many other construction materials. [2]LCA accounting for forestry management, logging residue, and full product lifecycle is essential to determine whether net carbon removals are occurring through timber products. [3]Existing mass timber safety standards and building codes currently exist at municipal through international levels, such as the Oregon CLT and Washington Amended Building Codes. [4]Removals were calculated using a starting point of 473M m^3 of wood in 2023, based on data from FAO. Sawn wood production was assumed to increase at 2% y-o-y growth from 2023-2050, based on the annual growth of global softwood consumption. A second key assumption is the percent of building timber that will achieve verified CDR. From 2030-2040, it was estimated that 10% of timber produced would achieve verified removals. It was assumed that the effective removal rate would increase to 20% from 2040-2050, and 30% from 2050 on. The increased removal rates are due to projected improvements in forestry, production practices, etc. [5]See the 2022 French implementation of 50% natural materials in public buildings as an example.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	Develop LCA framework	Studies are needed to ensure that the full lifecycle of structural wood products used in the built environment is sufficiently carbon negative[1,2] with a focus on forestry practices, harvesting, and processing.	1-2	$2-3M/y[3]	10 y	$20-50M
Lab / MRV	MRV methodology development	Demonstration of (1) measurement and monitoring for carbon storing in wood products and (2) third party public accounting to ensure that the sequestration of carbon dioxide can be verified over the full product lifecycle from growth, production, utilization, and end of life. MRV should consider the potential benefits and risks to forest ecologies from harvest (such as decreased carbon uptake or reduced wildfire risk).	3-5	$2-4M/y[4]	10 y	$50-200M
Lab	Breakthroughs on enhanced cultivars	Research and develop plant-based feedstocks that have enhanced growth qualities such as accelerated growth, improved survivability, and / or increased carbon uptake.[5,8]	1	$40-50M/y[6]	15 y	$600-900M
Lab / field testing	Testing and production improvements	Investigate improvements in structural wood products focusing on reducing energy, resource use, and waste in the production process to make building materials that minimize CO_2 emissions and cost, while maximizing the net carbon removals.	5	$5M/y	10 y	$250M[7]
Lab / field testing	Sustainable feedstock and product development	Perform additional research focused on efficient utilization of diverse timber species and underutilized forms of woody biomass inputs (e.g., slash and small-diameter logs) for structural wood products. Research should prioritize sustainable sourcing and harvesting practices.	5	$2-4M/y[7]	5-10 y	$50-$100M
MRV	Industry certification programs	Develop EnergyStar ratings for building materials as well as standards and specs for new carbon negative materials.[10]	1-5	$1-2M/y[9]	5-10 y	$5-50M
Lab / field testing	Automated harvesting	Investigate and test digitization and automation for forestry harvesting practices that can accommodate multi-species, multi-aged stands.	5	$2-4M/y[8]	5-10 y	$50-$100M

Note: *There are non-RD&D gaps that are critical to the success of this approach, such as workforce development, automation, permitting, social license, and policy considerations.*[10]

Notes and sources: [1]Mass timber and wood building products such as cross laminated timber (CLT) and glued laminated timber (Glulam) are already being deployed at demonstration scale. Studies are needed to verify that the use of these materials is sufficiently carbon negative. [2]A 2017 LCA assessment estimates that 0.95-1.05 tCO_2e are stored per cubic meter of lumber produced for the duration of useful life. [3]Cost range is based on an average of LCA tools funded through HESTIA. [4]Estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for lab R&D projects. Details of these estimations can be found in the AIR Appendix. [5]Living Carbon seedlings grow faster with a corresponding increase in CO_2 uptake. [6]NAS 2019 recommends $40-50M/y over 20 years for genetic crop improvements and reports current R&D funding for conventional crop improvements / genetics is $1.5B (public sector) and $1.8B (private sector). [7]Estimates based on NAS 2019 budgets for engineering design funding. Details of this estimation can be found in the AIR Appendix. [8]Use of enhanced cultivars should not incentivize monoculture and single-aged stands, as this leads to less resilient stands and resulting MRV penalties. [9]Estimates based on NAS 2019 budgets for desktop R&D funding. Details of this estimation can be found in the AIR Appendix. [10]Policy incentives can also increase the use of engineered timber construction. Development of industry and government partnerships and certifications should support construction and consumer incentives, accelerating updates to municipal building code, and government procurement priorities.

SECTION 2.3

Other biomass building products

SECTION	2.3
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Stabilized biomass
APPROACH	Other biomass building products

DEFINITION

Converting biomass, including purpose grown crops, algal and fungal matter, agricultural and forestry waste, and synthetic biomaterial, into construction products and component materials other than timber, such as polymers, fibers, framing, and paneling

EXAMPLE SCENARIOS

1) Building paneling out of bamboo; 2) using microorganisms to create carbonate materials that are incorporated into sidewalk pavers; 3) processing agricultural waste into building insulation.

Section 2.3 overview

Other biomass building products

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **None** • Key medium level risks include scalability, storage, path to measurement at scale, and pathway to full costs <$100/t$CO_2$
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • Depending on materials chosen, this approach is simple to design-intensive and standardized to customized
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab to commercial scale** • >10 companies at lab to commercial stages, with <$150M in funding each • Other notable RD&D activity includes projects in the ARPA-E HESTIA program and the DOE Technology Commercialization Fund
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **600 MtCO_2 by 2050** • Success is contingent on breakthroughs and adoption of new materials
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$1.4-2B over 10-25 years** • Key stage gates in material safety standards, cost reduction, and MRV

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Medium risk:** Growing, transporting, and processing materials all require inputs, and those requirements vary by feedstock.	Energy for producing and processing biomass materials varies significantly by type and source. Lab grown materials may require higher energy inputs for growth (for example photobioreactors for algae[1]), while agriculture residue and cultivated crops[2] will need more energy for transport and production.[3] The energy requirements are often much lower than the incumbent building materials being replaced.
	Water requirements	**Medium risk:** Water requirements vary widely by biomass source, but the implications for water-stressed areas can be significant.	Waste stream biomass requires no additional water. Some dedicated crops, such as miscanthus, can be grown with little added water.[4] Purpose grown and lab materials with high water requirements, such as algae, should be grown only in locations with low water stress.
	Fertilizer requirements	**Low risk:** Waste biomass and purpose grown crops that require little to no additional fertilizer are available; however, nutrients lost from harvesting should be replaced for land maintenance.	Some purpose grown crops, such as hemp and bamboo, can be grown with little fertilizer required. Biomass residues, such as lignin[5] and straw,[6] require no additional fertilizer for production but result in nutrient loss when harvested.[7] Replenishment fertilizer for high biomass removal rates could be up to 10 Mt fertilizer per $GtCO_2e$, or about 5% of 2019 global fertilizer use.[7] Lab grown materials require specific feedstocks, including fertilizer, and should be de-prioritized if fertilizer inputs indicate no pathway to competitive costs for carbon removals.
	Land use requirements	**Medium risk:** Agricultural waste does not require additional land, and purpose or lab grown crops utilize less area that forestry to produce comparable biomass.	Wheat straw and other biomass residues require no additional land use. Purpose grown crops can be selected for rapid growth and carbon storage capacity to increase yields. As an example, Plantd panels require 9x less land[3] for woody grass with multiple harvests a year; however, gigaton scale removals may still require millions of km^2 of cultivated land. Biomass will also face increased competition for use.[8]
	Environmental impacts	**Low risk:** Use of agricultural residue reduces logging and pollution from disposal. Some purpose grown crops may be used to restore degraded land.	Use of waste materials reduces pressure to log old growth forests and reduces air pollution from burning waste.[6] Some cultivated crops can offer co-benefits by remediating degraded land. Lab grown materials should be contained during growth to avoid any unintentional introduction to the environment.
Secure storage for 100+ years		**Medium risk:** Many biomaterials are long-lasting, but novel materials require testing to assess their durability.	Storage requires stability during the material and building lifespan. With appropriate construction and maintenance, straw buildings[6] and hempcrete[10] can last centuries; however, bamboo storage is on the order of decades. Novel material lifespans are unknown and require lifecycle testing to assess their durability.
Path to measurement at scale		**Medium risk:** Lifetime material monitoring will likely require new capabilities, including modeling.	Measurement and modeling will be required to assess storage durability over the material and building lifetimes. Existing LCA tools for agricultural processes, such as COMET-Farm and shorter harvesting timeframes (1-10 y) facilitate GHG tracking during biomass production.[3,11,12] Lab grown materials can utilize the same LCA practices as manufacturing processes. In addition, both construction and demolition of buildings often require permits, enabling better tracking when storage is ending or disrupted. Overall, MRV for biomass material utilization requires additional development.
Pathway to full costs <$100/$tCO_2$		**Medium risk:** Costs are variable by material and may include construction costs.	Lab grown materials are likely to be high-cost in the near term, but waste stream materials are inexpensive.[13] Ancillary benefits may reduce the effective costs to enable short-term development until removals are cost competitive.

Notes and sources: [1]Prometheus Materials [2]Input emissions for agriculture production are attributed to the harvested outputs, often divided based on value, so only a small percentage of energy inputs are attributed to agricultural residues. [3]Plantd [4]Miscanthus: A fast-growing crop for environmental remediation and biofuel production (Wang et al. 2020) [5]The Reuse of Biomass and Industrial Waste in Biocomposite Construction Materials for Decreasing Natural Resource Use and Mitigating the Environmental Impact of the Construction Industry: A Review (Rylko-Polak, et al. 2022) [6]Carbon Smart Materials Palette Wheat Straw-Bale [7]A ton of wheat straw contains about 11, 3, and 20 lbs of NPK, respectively, and ~1.5 tCO_2e; requiring ~35 lbs of fertilizer to replace nutrient loss from harvesting. This equates to approximately 10 Mt fertilizer/$GtCO_2e$ removed. Global fertilizer consumption in 2019 was 215 Mt. [8]The 2016 Billion Ton report estimates there will be sufficient biowaste supply, but biomass will have many competing demands. Further discussion can be found in the bCDR overview. [10]Carbon Smart Materials Palette Hempcrete [11]COMET-Farm is a whole farm and ranch carbon and GHG accounting system. [12]Carbon Smart Materials Palette Bamboo [13]A jumbo wheat straw bale weighs about 450 kg (from Folio3 AgTech) and is ~40% carbon by weight, per [12], which is ~0.6tCO_2e and costs ~$30/bale (Straw Bale Construction), or $50/$tCO_2e$, without construction costs.

Potential for cost improvement

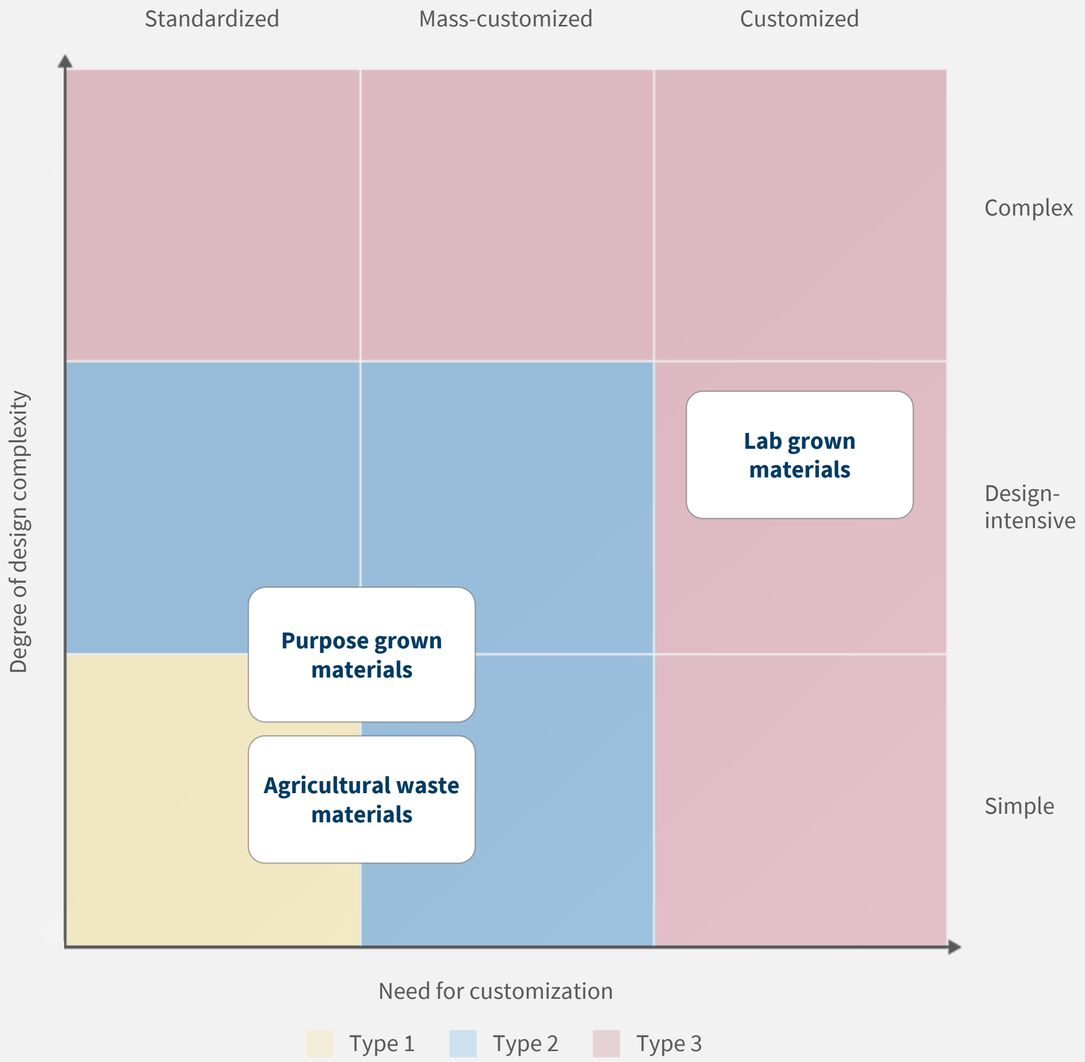
An assessment of two key drivers of learning rates

SECTION 2.3

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Other biomass building products



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Simple to design-intensive
- **Rationale:** (1) Purpose grown materials and agricultural waste utilize established crops. Purpose grown materials require additional planning and supply chain development. (2) Lab grown materials often use known materials with changes made for production and implementation.

NEED FOR CUSTOMIZATION

- **Rating:** Standardized to customized
- **Rationale:** (1) Use of lab grown materials provides an opportunity for customization to specific use cases and requires distinct approaches for different materials and sources. (2) Purpose grown materials and agricultural waste may have unique design considerations for use in construction.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

Current state of RD&D

A mapping of companies, plus other notable activities

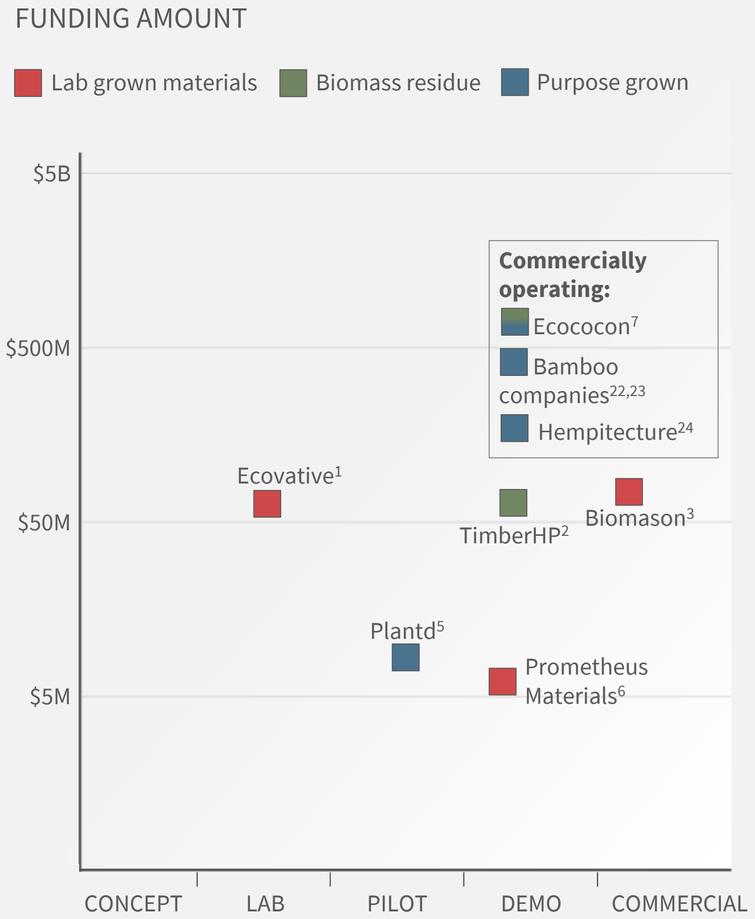
NOT EXHAUSTIVE

SECTION 2.3

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Other biomass building products



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Prometheus Materials	$8M[9]	• Biomineralizing cyanobacteria to produce constituent materials for cement; ASTM standards were passed in February 2023[6]
Biomason	$95M[10]	• Using a wild-type bacteria strain to rapidly produce biocement[3]
Ecovative	$121M[11]	• Developing insulation from mycelium-base with crop waste materials[12]
TimberHP	$85M[13]	• Producing housing insulation from timber waste[2]
Ecococon	Commercial	• Offering commercial sales of straw and wood fiber wall panels[7]
Plantd	$10M[14]	• Developing structural building panels made from perennial grasses[5]
Bamboo[22,23]	Commercial	• Moso Bamboo[15], Rizome Bamboo[16], Bamboo Living[17] BamCore[18], Plyboo[19], C-Squared[20], Komaza[21]

Other companies and activities: Made of Air,[4] Greenfiber,[24] Hempitecture,[25] IND Hemp[26]

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
HESTIA[27]	$39M (2022)[28]	• Developing building materials with carbon storage over full material lifetime, relevant performance testing, and market advantage
DOE Technology Commercialization Fund	Portion of $15M[29]	• Assessing durability of bio-derived products and best practices to evaluate technologies

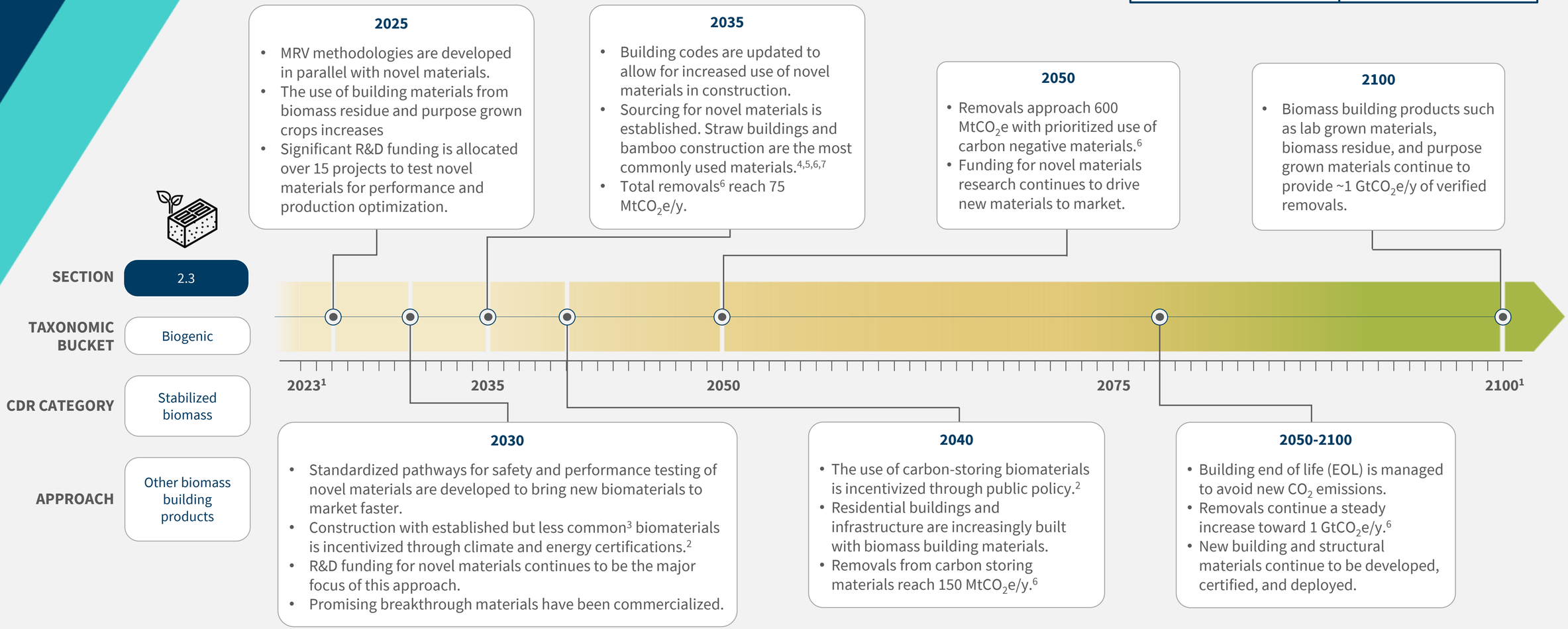
Notes and sources: [1]While Ecovative has commercial products, those related to building materials are in lab stages. [2]TimberHP [3]Biomason [4]Made of Air has raised $5.8M. [5]Plantd [6]Prometheus Materials [7]Ecococon [8]Some lab grown materials companies are not included because the lifecycle of their products (e.g., compostable fungi-based packaging) is too short to be considered carbon storing. [9]Series A, via Dealroom [10]Crunchbase funding estimate for Biomason [11]Crunchbase funding estimate for Ecovative [12]Mycocomposite, Hy-Fy Building [13]Financed by bond sales, TimberHP Press Release [14]Series A, 2023 via Crunchbase [15]MOSO Bamboo Products [16]Rizome Bamboo [17]Bamboo Living [18]BamCore [19]Plyboo products [20]C-Squared [21]Komaza website [22]Bamboo products are being commercially used for beam lumber, paneling, plywood, flooring, and prefabricated housing. [23]Project Drawdown [24]Greenfiber creates cellulose insultation from biomass residue. [25]Hempitecture, purpose grown hemp insulation and concrete, has raised almost $5M. [26]IND Hemp creates purpose grown insulation. [27]HESTIA [28]Award announcement [29]DOE Funding Announcement

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR



Notes and sources: [1]This roadmap is intended to assess carbon removal; however, it is essential to note the potential for avoided emissions by using biomaterials through both material substitution (such as replacing cement aggregate with hemp or forestry / agricultural waste) or process improvements (e.g., avoided use of high heat or fossil fuels such as Biomason Biocement). Cement improvements alone have the potential for 7-15 $GtCO_2e$ reduction / sequestration from 2020-2050. [2]See 2022 French implementation of 50% natural materials in public buildings as an example. [3]Strawbale construction International Residential Code [4]Drawdown estimates 7-19 Gt of CO_2e could be avoided or sequestered through bamboo biomass and long-lived products (2.03 tCO_2e/ha/y over 70-174 Mha) between 2020-2050. [5]If 25% of the 200 Mt of straw burned each year were instead used for buildings, assuming 40% carbon content, 75 $MtCO_2e$ would be stored instead of emitted. [6]Deployment assumes a starting point of 75 $MtCO_2$/y removals in 2035 with 15% y-o-y growth until 2050. Achieving these deployment targets requires establishing accepted LCA and MRV for biomass building products. [7]An inventory of other building materials and net carbon values are available at 2050 Materials.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL[1]
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[2]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 2.3

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Other biomass building products

TRL

CRITICAL PATH ACTIVITIES

$1.4-2 billion | **10-25 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Materials development and testing:** Assess materials against relevant safety and performance standards.
- **LCA framework:** Perform necessary analysis to assess cradle to grave LCA of building materials
- **MRV development:** Identify pathways to MRV methodologies for biomass building materials.

$800M-$1B | **10 years**

- ✓ Meets relevant material safety standards
- ✓ Pathway to MRV methodologies
- ✓ Pathway to market competitive carbon removal costs

STAGE GATES[2]

TRL 7-9

DEMONSTRATION PROJECTS

- **Urban biomaterials demonstration:** Construct operational residential and commercial buildings with ongoing monitoring to confirm removals.

$600M-$1B | **10-15 years**

- ✓ Meets relevant building code and safety standards
- ✓ MRV and LCA confirm removals
- ✓ Pathway to market competitive costs for removals

STAGE GATES[2]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[3]

$75-200 million | **5-10 years**

- Develop consistent and accessible testing to accelerate timelines for labs and small companies to bring new materials to market.
- Perform ongoing research to identify and validate novel materials.
- Establish EnergyStar and relevant industry certifications for biomaterials to incentivize their integration into conventional construction.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[3]

- Demonstrated market competitive carbon removal costs
- Measured carbon removal in demonstration projects
- Carbon removals are confirmed by third party accounting
- Industry and consumer acceptance
- Long term safety record

Notes and sources: [1]Although this approach has a TRL of 9 because some sub-approaches are already commercial scale, many are still at an early TRL stage and need additional pre-demo incubation. [2]Stage gates and critical path ratings are explained in the AIR Appendix. [3]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION[1]	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	Develop LCA framework	Develop LCAs for novel material types that can address multiple approaches (e.g., biocement from different microorganisms) to ensure that the lifecycle of production and built environment is sufficiently carbon negative.	✓ LCA framework confirms that building materials will be carbon negative ✓ Pathway to MRV methodologies to confirm removals	3-6	$2-3M/y[2]	2 y	$10-15M
Lab / MRV	MRV methodology development	Demonstration of (1) measurement and monitoring technology and (2) third party public accounting to ensure that the sequestration of carbon dioxide can be reliably confirmed over the life of the demonstration.		1-2	$2-5M/y	10 y	$30-50M[3]
Lab	Material development	Mature and pilot test novel materials to verify performance and optimize production.		15[4]	$4-6M/y[5]	10 y	$600-800M
Lab	Materials testing	Perform testing for relevant materials to assess safety and performance, such as structural stability, fire resistance,[6] water resistance, etc.	✓ Material safety and performance standards can be met	10-20	$1-2M/y[6,7]	10 y	$150M

Notes and sources: [1]Materials such as bamboo and straw bales are already in use commercially and advancing those approaches should focus on consumer and commercial acceptance rather than demonstrations. Other biomaterials (e.g., biocement and fiber insulation) have much lower TRLs and need additional time and funding in the pre-demonstration phase. [2]Cost range based on average of LCA tools funded through HESTIA. [3]Estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for data platform projects. For additional details, see the AIR Appendix. [4]The number of projects is based on currently funding HESTIA projects.[5]Estimates based on averages from NAS 2019 budgets for pilot R&D funding. Details of this estimation can be found in the AIR Appendix. [6]Estimates based on averages from NAS 2019 budgets for lab R&D funding. Details of this estimation can be found in the AIR Appendix. [7]Materials are not likely to go through testing multiple years in a row, but new materials will be tested as they reach maturity.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION[1]	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Distributed construction of buildings and infrastructure utilizing durable biomaterials throughout a region or municipality. Construction should incorporate MRV with lifetime performance of each relevant material throughout the cradle to grave period of the demonstration site. The design should also consider opportunities to incorporate new materials as they mature to demonstration stage. The demonstration(s) should include: • Residential and commercial use • City infrastructure (where viable) • Distinct geographic sites Potential demonstration sites include new “live-work-play” communities[4] or universities.	100 $ktCO_2e/y$ over many different buildings and infrastructure[2]	✓ Meets relevant industry and municipal safety standards ✓ Demonstrations achieve market competitive costs ✓ Demand for materials is shown to be sustainable ✓ Long term MRV includes performance and stability of materials ✓ Demonstrated designer, builder, and manufacture interest beyond demonstration sites	1-2	$60M/y[3]	10-15 y	$600M - 1B
Demo	Construction of individual buildings or infrastructure elements in dispersed geographies. Projects should integrate appropriate practices to accommodate local climate, land, and resources.	Refer to above		8-10	$1M/y[5]	5-7 y	$30-50M

Notes and sources: [1]Materials such as bamboo and straw bales are already in use commercially and advancing those approaches should focus on consumer and commercial acceptance through integration in the demonstration buildings. [2]The built environment should include infrastructure like sidewalks, roads, etc., where possible. [3]Estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for Grand Goal R&D funding. Details of this estimation can be found in the AIR Appendix. [4]A program through USDA RD's Mutual Self-Help Program includes Strawburb using strawbale construction for homes. [5]Estimates based on averages from NAS 2019 budgets for field R&D funding. Details of this estimation can be found in the AIR Appendix.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab / desktop research	Identifying and developing new building and structural materials	Additional lab and desktop R&D to identify, develop, and improve building materials, either from micro-organisms, waste biomass, or purpose grown crops	1-10	$1-3M/y[1]	5-10 y	$25-100M
Lab / desktop research	Pathway to testing	Develop shared protocols and access to accelerate material testing for analogous conventional materials (e.g., established and available testing facilities for all biocements to assess materials at relevant development stages and facilitate testing to meet relevant safety and performance standards).	4-6	$1-2M/y[2]	5-10 y	$20-50M
MRV	Industry certification programs	Create EnergyStar ratings for building materials as well as standards and specs for new carbon negative materials.[3]	2-4	$3M/y[4]	5 y	$30-50M

Note: *There are non-RD&D gaps that are critical to the success of this approach such as optimization of logistics for processing and transportation, permitting, social license, and policy considerations.*

Notes and sources: [1]Estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for desktop assessment and lab R&D funding. [2]Estimates based on NAS 2019 budgets for desktop assessment. [3]Development of industry and government standards and certifications should encourage construction incentives, accelerating updates to municipal building code, and government procurement priorities. [4]Estimates based on NAS 2019 budgets for social science R&D as a proxy for standard development in parallel with technical testing and implementation.

SECTION 2.4

Pyrolysis (biochar) and storage

SECTION	2.4
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Stabilized biomass
APPROACH	Pyrolysis (biochar) and storage

DEFINITION

Thermal conversion of biomass while excluding oxygen, optimized to produce solid char for storage in open or controlled environments

EXAMPLE SCENARIOS

1) Pyrolyzing corn stover waste into biochar that is then added back to fields as a soil amendment; 2) converting wood waste from hurricane debris into biochar that can be used as an additive to cementitious materials.

Section 2.4 overview

Pyrolysis (biochar) and storage

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability** • Key risks include carbon conversion efficiency of biochar formation, land use, and water requirements from scale up beyond waste biomass supply
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is standardized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot to commercial** • 6 companies with <$15M in funding each • Other notable RD&D activity includes the DOE BETO program
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **1.6 $GtCO_2$ by 2050** • Success is contingent on improvements in carbon efficiency of biochar formation and supply of sustainable biomass feedstock
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$450-650M over 10-12 years** • Key stage gates in securing a sustainable feedstock supply and developing more efficient biochar formation and transportation processes

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Medium risk:** Pyrolysis is the most energy intensive part of the biochar production process.	Collection and transportation energy requirements are expected to be small, while pyrolysis consumes the most energy. This should be verified by LCA for each biochar deployment.[1]
	Water requirements	**High risk:** Biowaste does not require additional water; however, biochar at gigaton scale is likely to require dedicated forestry or crops with significant water consumption.	Dedicated forestry for gigaton scale removals should not be grown in locations with risk of water stress.[2] Traditional forestry rarely uses irrigation, but even efficient wood species, such as eucalyptus, require as much as 6 gigatons of water per $GtCO_2e$ removed.[3,4]
	Fertilizer requirements	**Low risk:** Biowaste does not require fertilizer and dedicated crops that require little fertilizer are currently available.	Fertilizer for wood or eucalyptus plantations is less than 12 Mt or 10 Mt, respectively, per $GtCO_2e$, which is ~5% of global fertilizer use in 2019.[5]
	Land use requirements	**High risk:** Biowaste will not provide sufficient feedstock at gigaton scale, and cultivated crops will require significant land use.	Purpose grown crops require millions of $km^2/GtCO_2e$,[6] and biochar in soil amendments or durable products does not require additional land for storage.[7] Competition for biomass will also increase.[8]
	Environmental impacts	**Low risk:** Biochar does not pose significant, unmitigable risks and has potential co-benefits for pollution remediation.	Particulates may be generated during the pyrolysis process, but the potential harms and mitigation strategies of biochar are well established and understood.[9]
	Carbon conversion efficiency	**High risk:** Pyrolysis processes risk being out-competed by alternative biogenic pathways with higher sequestration rates.	Current commercial pyrolysis reactor technology retains 5%-50%[10, 11] of the organic carbon in the final biochar.[12] Wood burial retains >90% of the feedstock's carbon. Producing biochar from end-of-life bio-based building materials can extend storage lifetimes of those materials.
Secure storage for 100+ years		**Medium risk**: A substantial fraction of biochar stored in both controlled and open environments can be stable for hundreds of years.[16]	Biochar decays 10-100x more slowly than the original biomass,[13] and scientific consensus[11, 14] is that a substantial fraction of biochar is stable in soil for at least a century.[15] Incorporation in durable products should prioritize longevity of the product and potential reuse for soil amendments at end of life.[14]
Path to measurement at scale		**Medium risk:** Measurement capabilities exist, but long-term monitoring in open environments (such as soil) needs further development.[16]	Removals range from 0.4-1.2 tCO_2e/t of dry biomass,[10] but it is challenging to assess the fraction of stable removals over time through soil monitoring. The diversity of biochar applications also affects LCA.
Pathway to full costs <$100/$tCO_2$		**Medium risk:** Feedstock sourcing, cost volatility, and transport distance all affect prices on a regional scale.	Biochar products can reduce removals costs in the short term, but it is still considered a niche market, and CDR credits can vary dramatically between <$10-600/$tCO_2e$.[17, 18]

Notes and sources: [1]Interviews conducted by RMI's third derivative startup incubator, as well as most studies, indicate that the biggest draw for energy is in the processing step. [2]Royal Society Greenhouse Gas Removal Report [3]Estimate of eucalyptus water consumption from 785 L/kg of biomass is 2.9 Gt water/$GtCO_2e$ in the biomass. Per [10, 11], only 5-50% of feedstock carbon is retained, indicating at least 6 gigatons (6 trillion liters) of water is needed per $GtCO_2e$ removed. For reference, New York City consumes ~3.7B liters or 0.004 gigatons of water per day. [4]EFI – Surveying the BECCS landscape. As a comparison, estimates for water use for BECCS are small when waste biomass is used. However, water use can increase dramatically when cultivated crops are used. The same would be true for biochar production using cultivated crops at scale. [5]Global fertilizer consumption in 2019 was 215 Mt. Wood plantation fertilizer could be up to 200 lbs/acre (224 kg/ha), or 12 Mt/$GtCO_2e$. Eucalyptus requires ~133 kg/ha, or 10 Mt/$GtCO_2e$. [6]Given 5-50% carbon retained and 0.74 M $km^2/GtCO_2e$ land required for eucalyptus, at least 1.5M $km^2/GtCO_2e$ is required. [7]Biochar is unlikely to be directly stored, but rather be incorporated into durable products, such as concrete, and soil amendments. The goal of this pathway is to achieve scale and costs that are profitable though CDR value alone without depending on co-benefits. [8]The 2016 Billion Ton report estimates there will be sufficient biowaste supply, but biomass will have many competing demands. Further discussion can be found in the bCDR overview. [9]Ling Xiang et al., (2021) provide a comprehensive review of biochar's known potential environmental impacts and mitigation approaches. [10]The Biomass to Biochar (2021) report is an in-depth analysis of current trends and potentials for sustainable growth of the biochar industry in the Pacific Northwest US. [11]International Biochar Institute (IBI) Biochar Carbon Stability Test Method [12]Slow pyrolysis is significantly more efficient at producing biochar and retaining carbon inputs than fast pyrolysis. [13]Greenhouse Gas Inventory Model for Biochar Additions to Soil [14]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) incorporates the prevailing scientific conclusion about biochar stability in a variety of environmental conditions. [15]Per [13], biochar permanence varies with process temperature, feedstock, and soil temperature. With soil temperature of 25°C, biochar permanence is at least 50% for 100 years, and greater with cooler soil temperatures. [16]Some reviewers considered this criteria to be high risk. [17]The CDR.fyi 2022 end of year report analyzed trends in the CDR credit market. [18]Biochar co-products can accelerate short term development and deployment, but long-term costs should be CDR only.

Potential for cost improvement

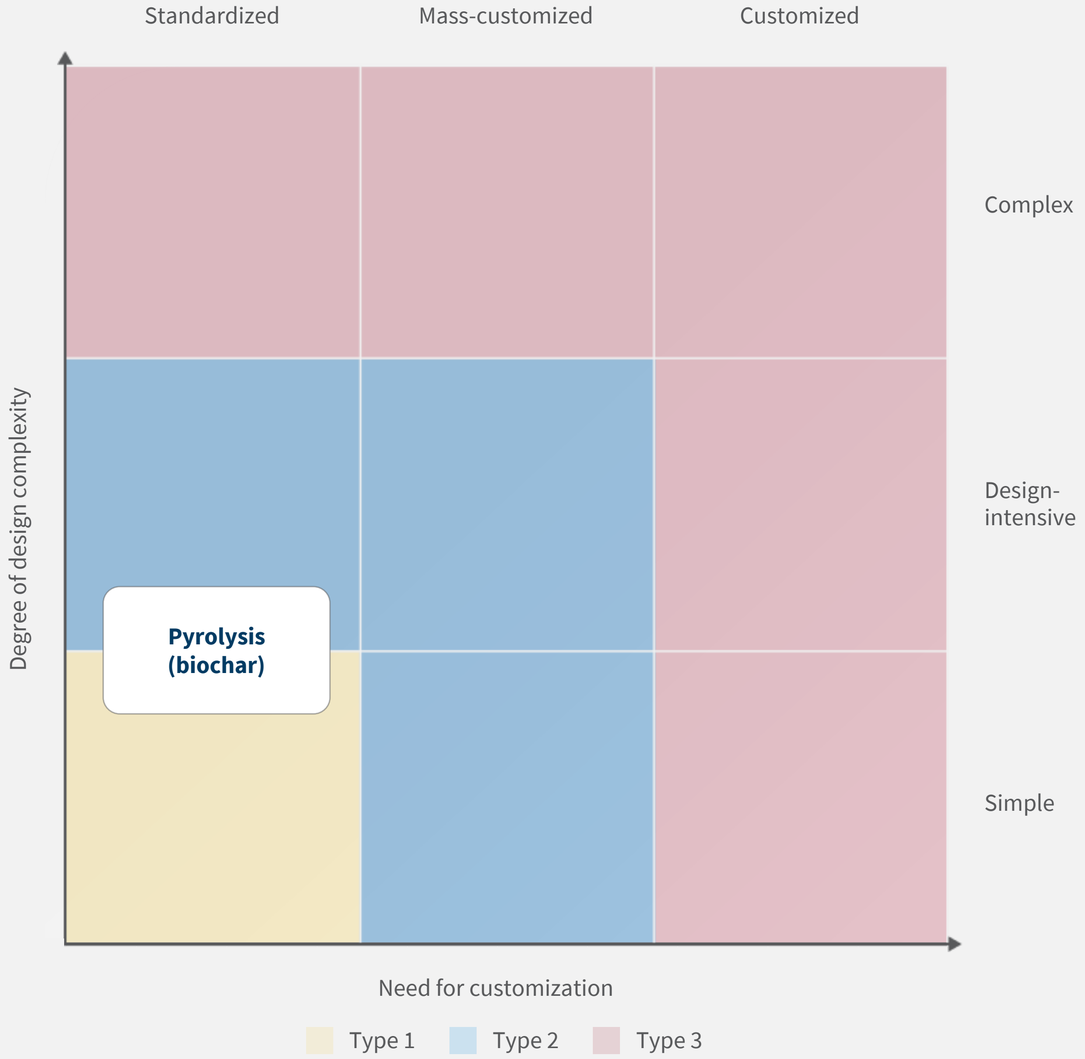
An assessment of two key drivers of learning rates

SECTION 2.4

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Pyrolysis (biochar) and storage



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Simple to design-intensive
- **Rationale:** Traditional biochar pyrolysis systems are simple, but novel systems tend to be design-intensive for optimal operation and production efficiency, such as switching from batch to continuous operation systems.

NEED FOR CUSTOMIZATION

- **Rating:** Standardized
- **Rationale:** Mature pyrolysis reactors and ancillary process equipment are standardized and mass-produced. Similarly, novel systems can be mass-produced once the technology is developed for process and feedstock conditions.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

THE APPLIED INNOVATION ROADMAP FOR CDR

Current state of RD&D

A mapping of companies, plus other notable activities

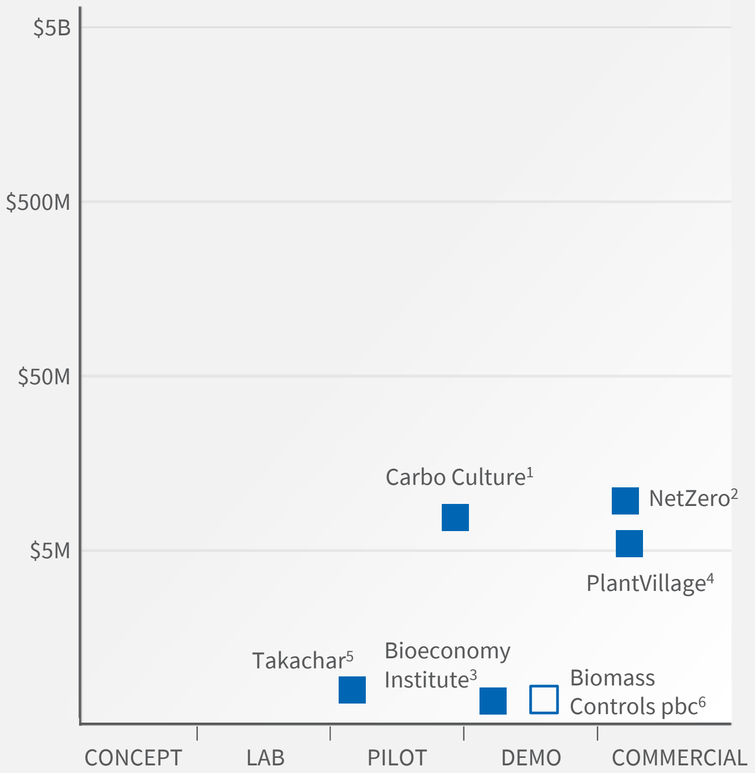
NOT EXHAUSTIVE

SECTION 2.4

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Pyrolysis (biochar) and storage



BIOCHAR APPROACH	NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Small: Mobile field units	**Takachar:** Pyrolyzing ag waste in the field[5]	$1.7M[7]	• Small scale pilots in India
Medium: Industry integrated units	**Bygen**[8]	N/A	• Demonstrations of 0.5-6 t biowaste per hour
	Biomass Controls pbc[6]	N/A	• Pilots in rural Alaska and India
Large: Centralized plants	**Carbo Culture:** Biowaste for soil[1]	$10.1M[9]	• Launched R3, operating at 3000 tCO_2/y in Helsinki[1]
	NetZero: Ag biochar[2]	$12M[11]	• 2 sites • Brazil site produces >4500 t biochar per year

Other companies and activities: Made of Air,[10] Carbon Cycle,[12] Climate Robotics Inc,[13] Echo2,[14] Freres Biochar,[15] Oregon Biochar Solutions,[16] Pacific Biochar,[17] Puro.Earth,[18] Wakefield Biochar,[19] RCMP,[20] Carbofex,[21] ARTi,[22] ClimateAdd,[23] Sonnenerde,[24] Mercurius Rising,[25] Perpetual Next,[26] Biochar Now,[27] Hago Energetics,[28] Myno Carbon,[29] All Power Labs,[30] Mash Makes,[31] Novocarbo,[32] Pyreg,[33] Carba,[34] Graphyte[34]

Note: *There are many commercial biochar providers, including most of the top 10 of the CDR.fyi database. However, for this assessment, we selected notable companies that are advancing the biochar space in new directions or with new technology.*

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
DOE – BETO: Funds R&D projects to boost sustainable biofuels production	$25.5M[35]	• FOA 2910 includes funding for biochar soil amendment as CDR
USDA – ARS & NRCS: Leading research projects biochar incorporation in soils	N/A	• Recently published biochar soil amendment practice standard[36]

Notes and sources: [1]Carbo Culture, R3 launch [2]NetZero [3]Bioeconomy Institute [4]PlantVillage [5]Takachar [6]Biomass controls pbc pyrolizer can take mixed feedstock with high moisture levels (up to 35%), including food and manure solids. [7]Crunchbase funding estimate for Takachar [8]Bygen [9]Raised ~$3M from 4 rounds of private funds and 2 European government grants [10]Made of Air is creating a biochar substitute for plastics. [11]NetZero crunchbase and press release estimates [12]Carbon Cycle [13]Climate Robotics uses AI and robotics to optimize biochar soil amendment. [14]Echo2 [15]Freres Biochar [16]Oregon Biochar Solutions [17]Pacific Biochar [18]Puro.earth is a leading biochar methodology and carbon credits accreditor registry. [19]Wakefield Biochar [20]RCMP [21]Carbofex [22]ARTi [23]CarStonCon Tech [24]Sonnenerde [25]Mercurius Rising [26]Perpetual Next [27]Biochar Now [28]Hago Energetics [29]Myno Carbon [30]All Power Labs [31]Mash Makes [32]Novocarbo [33]Pyreg [34]Carba and Graphyte both use a process called torrefaction to dehydrate biomass rather than using pyrolysis. [35]DOE announced funding for R&D projects enhancing cultivated biomass feedstock production for biofuels production. Subtopic Area 1b focuses on "Biochar Strategies to Increase Soil Carbon Levels and Agronomic Benefits of Crops for Energy Production." [36]USDA Standards

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

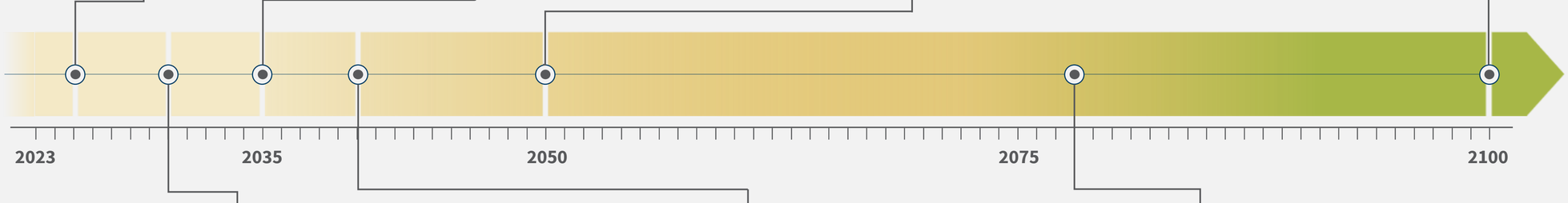
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 2.4

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Pyrolysis (biochar) and storage



2025

- 10 large scale facilities of 10-20 $ktCO_2e/y$ each are funded globally for the primary purpose of CDR.
- 10 demonstration "fleets" of pyrolizers are funded to operate alongside sources of waste biomass such as fields.
- MRV methodologies are established alongside demonstration projects.

2030

- Biochar for CDR reaches 8 $MtCO_2e/y$ globally.[1]
- Commercial CDR biochar facilities for are built on 4+ continents.
- Breakthroughs in R&D for pyrolysis approaches lead to smaller, more carbon efficient pyrolysis units.
- New applications for biochar, such as environmental remediation and elimination of invasive species, lead to new sources of feedstock and increased demand.

2035

- Biochar for CDR reaches 30 $MtCO_2e/y$ of removals globally.[1]
- Biochar is considered "established" for financing purposes.
- Biochar is profitable based on its CDR value. Other beneficial uses are seen as additional rather than necessary.
- Biochar MRV is validated for a wide range of soil conditions.

2040

- Biochar removals reach 120 $MtCO_2e/y$ globally.[1]
- Storage of biochar is established as a soil amendment and in durable products.
- Breakthroughs in enhanced cultivars increase feedstock and geographic conditions for biochar production.

2050

- Commercial biochar hubs are a global practice integrated into most biowaste stream processing facilities in both developed and developing economies.
- Biochar removals reach 1.6 $GtCO_2e/y$ globally.[2]
- Biochar is deployed with other CDR approaches in a synergistic way, e.g., biochar with enhanced weathering

2050-2100

- Biomass feedstock supply may be diverted to other higher priority utilization pathways or bCDR approaches with higher carbon conversion efficiency.[3]
- Basic research leads to ongoing breakthroughs in biochar applications and increased demand for biochar.

2100

- Biochar as a CDR service has decreased slightly from its peak to around 1 $GtCO_2e/y$ removals
- Commercial regional hubs continue to supply biochar as a product to a diverse and mature global market.
- Small, efficient pyrolizers are used globally to stabilize biomass waste.

Notes and sources: [1]Today's (2023) estimated biochar deployment is around 0.5 $MtCO_2e/y$ and was about the same in 2018 (p149). Future estimated global deployment assumes 50% y-o-y growth from 2023-2030. This growth value in the near term is lower than other AIR success stories but higher than biochar market research that estimates the growth of the sector at around 10% y-o-y during this time. However, this market research focuses on biochar as a soil amendment rather than a CDR method. Here we assume that growth after 2030 decreases to 30% y-o-y until 2050. [2]Estimates from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) p107 suggest 3-8 $GtCO_2e/y$ is possible, though these values will run into feedstock competition with other biomass uses including energy and CDR (see the AIR bCDR introduction on total global biomass supply). [3]Improved processes for converting biomass into fuels or chemicals could reduce the available feedstock for biochar. Additionally, lower cost or higher carbon efficiency uses of biomass for CDR, such as burial or sinking, may outcompete biochar.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 2.4

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Pyrolysis (biochar) and storage

TRL

CRITICAL PATH ACTIVITIES

$450-650 million | **10-12 years**

TRL 1–5

PRE-DEMONSTRATION WORK

There are no critical path pre-demonstration activities for this approach.

N/A | **N/A**

This approach has no pre-demonstration stage-gates.

STAGE GATES[1]

TRL 6-MRL 14[2]

DEMONSTRATION PROJECTS

- **Large scale FOAK pyrolysis facilities:** Demonstrate 5-9 biochar facilities that optimize processing and total removals.
- **Distributed "fleets" of small pyrolizers:** Demonstrate modularity and operation of individual units.
- **Biochar application:** Test the impact of biochar deployed over distinct environmental conditions.
- **MRV**: Develop and validate MRV methodologies across demonstrations.

$450-650 million | **10-12 years**

- ✓ Path to market competitive costs for removals, not including ancillary benefits
- ✓ Improved energy consumption with minimal transport and processing
- ✓ Secure and sustainable feedstock supply
- ✓ Validated MRV methodologies

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$250-800 million | **15 years**

- Establish an open-source global biochar database to streamline aggregating and sharing technically validated knowledge
- Pyrolysis R&D for technology optimization and biomass processing
- Mechanistic modeling to improve predictive models for optimizing removal performance of biochar
- Demonstrate biochar incorporation into durable products

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Market competitive costs for biochar-based removals
- Financing costs in line with similar, established capital-intensive industries
- Established and low cost MRV methodologies
- Well-established paths for sustainable sourcing of biochar feedstocks
- Well-established channels for disposal of biochar in sustainable, accepted ways

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Demonstrate large scale FOAK pyrolysis facilities. Siting should consider diversity and optimized logistics of feedstock sourcing and storage options. Demonstrations should include: • Larger scale deployment achieving (1) cost competitiveness and (2) beneficial storage or disposal of biochar • Developing continuous systems and increasing carbon conversion efficiency[1]	10-20 $ktCO_2e/y$[2]	✓ Path to competitive costs for biochar removals and storage (not including ancillary benefits such as sales for soil enhancement or additives to products) ✓ Feedstock sourcing is secure and sustainable ✓ Environmental impacts are manageable	5-9	$20-25M/y	10-12 y	$200-250M
Demo	Distributed "fleets" of small pyrolizers with a focus on: • Achieving modularity and independent operation of individual units • Fleet operation in geographic proximity with shared resources (e.g., maintenance services) but independent operation • Diverse feedstocks from waste and cultivated crops • Access to different biochar storage options, such as soil amendments, burial, or supply lines to durable products[1]	5 $ktCO_2e/y$ (across 10+ smaller units)		5-9	$20-25M/y	10-12 y	$200-250M
Demo	Biochar application on cropland, range, and forest land: • Projects should vary by climate, soil type, and land management practices. • Projects optimized and evaluated based on CDR and environmental benefits.	1-10 $ktCO_2e/y$		2-5[3]	$0.5-3M/y	5-10 y	$30-100M
MRV	Empirical and analytical methods inform the development of MRV methodologies that: • Validate against the heterogeneity of site conditions • Account for variety in feedstock source, type, and quality	N/A	✓ MRV based on empirical data and numerical modeling accuracy is verified and accepted across the field	2-3	$0.5-1M/y	10 y	$10-30M

Notes and sources: [1]The goal of these demonstrations is to achieve scale and costs that are profitable though CDR value alone without depending on products or co-benefits. [2]Based on estimated potential capacity from startups like Carbo Culture that plan to build 10 centralized biochar facilities of 20 $ktCO_2e/y$ by 2026. [3]Budget estimates are based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Research Tasks & Budgets, Table 4.8 and Table 3.11. Both recommend projects lasting 1-5 years with multiple projects per year over the 10-year timeframe. [4]Demonstration estimates are based on NAS 2019 Research Tasks & Budgets, Table 4.8. These are for BECCS demonstrations but include biochar production. Costs are on the lower end of the report estimates to account for the reduced complexity of biochar production without optimizing for energy production.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	Breakthroughs on enhanced cultivars[1]	Research and develop plant-based feedstocks that have enhanced growth qualities such as accelerated growth, improved survivability, and / or increased carbon uptake.	1	$40-50M/y	15 y	$600-900M
Desktop research	Global technical biochar database	Establish and maintain an open-source technical knowledge database to fill knowledge gaps about commercialization of biochar CDR applications, improving MRV methodologies, and improving global knowledge transfer.	1	$0.5-1M/y	5-10 y	$2.5-10M
Lab	R&D pyrolysis technology	Test novel pyrolysis technologies like microwave heating,[2] hydrothermal carbonization (HTC),[3] etc. to improve understanding and optimization of the thermochemical dynamics within the pyrolysis process based on variation in feedstock type, pyrolizer size, and desired biochar output.[4]	2-10	$1-3M/y	3 y	$6 – 90M
Lab	Biomass supply and pre-treatment	Test and model novel approaches to address biomass logistics and optimize processing and pre-treatment.	2-10	$2-5M/y	2 y	$8-100M
Lab	Mechanistic modeling	Utilize data from ongoing projects to establish a mechanistic model to improve predictions and optimization of biochar production and application for CDR purposes.[5,6]	1	$1-2M/y	5 y	$5-10M
Demo	Hybrid biochar and EW application	Test combined biochar and enhanced weathering CDR approaches, as studies suggest certain soil types could benefit and maximize CDR potential.	2	$3-6M/y[7]	3-5 y	$40-120M
Demo	Incorporation into durable products	Demonstrate biochar incorporated into durable products, such as polymer composite products and biochar incorporation with cement products.[2]	1	$5-10M/y[7]	5-10 y	$50-200M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include knowledge transfer, permitting, expanding pyrolizer manufacturing, forestry policy considerations, and scaling operational workforce.*

Notes and sources: [1]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) recommends $40-50M/y over 20 years for genetic crop improvements and reports current R&D funding for conventional crop improvements / genetics is $1.5B (public sector) and $1.8B (private sector). [2]Biochar Production Technologies from Agricultural Waste, Its Utilization in Agriculture and Current Global Biochar Market: A Comprehensive Review (Phadtare & Kalbande, 2022) provide an updated and comprehensive review of the biochar approach, including novel pyrolysis approaches. [3]HTC is an under researched approach to pyrolysis with the advantage of effectively processing minimally or untreated feedstock even with high moisture content. [4]Pyrolysis technologies should be optimized for varied production scales as categorized in the Biomass to Biochar report. [5]Biochar's CDR performance is highly variable and affected by feedstock types, pyrolysis processes, soil types, weather conditions, and application methods. Demonstration project sites must accommodate testing possible variable permutations in parallel. James Amonette et al. (2022) estimates a total budget of $150M for a ten-year research agenda, including about 20 small-scale pilot sites. [6]USDA – ARS & NRCS gather biochar application data to improve understanding. [7]Budget estimates are based on Research Tasks & Budgets Table 4.8 Section 3 Biomass to Fuel with Biochar (NAS 2019, p. 173).

SECTION 2.5

Pyrolysis (bioliquid) and storage

SECTION	2.5
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Stabilized biomass
APPROACH	Pyrolysis (bioliquid) and storage

DEFINITION

Thermal conversion of biomass while excluding oxygen, optimized to produce crude bioliquid that can be stored underground, geologically, or in other environments

EXAMPLE SCENARIOS

1) Fast pyrolysis of corn stover waste into bio-oil that can be injected into the subsurface of the earth; 2) fast pyrolysis of cultivated grasses or other biomass material into bio-oil that is then stored underground.

Section 2.5 overview

Pyrolysis (bioliquid) and storage

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability** • Key risks include carbon conversion efficiency of bioliquid formation, land use, and water requirements from scale up beyond waste biomass supply
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is standardized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab to demo** • ~2 companies at lab to demo stages • Other notable RD&D activity includes the DOE BETO program
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **150 $MtCO_2$ by 2050** • Success is contingent on improvements in carbon efficiency of bioliquid formation and supply of sustainable biomass feedstock
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path funding: **$200-500M over 15 years** • Key stage gates in securing a sustainable feedstock supply, siting, and carbon efficiency improvements

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

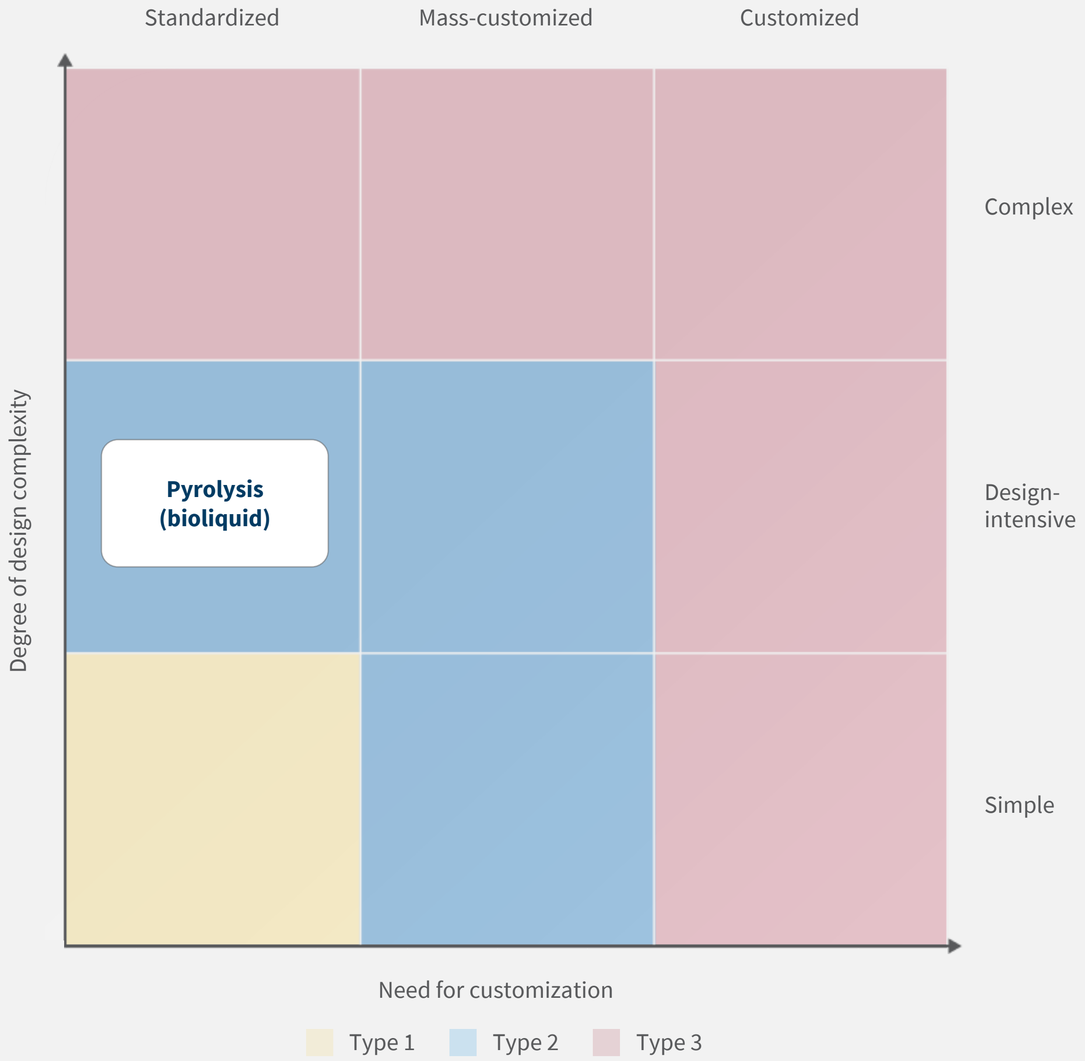
CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Medium risk:** The pyrolysis step of bioliquid[1] production is the most energy intensive.	The pyrolysis process consumes the most significant portion of energy required.[1] Although the recapture of syngas produced during pyrolysis can reduce total energy inputs, the potential impact will vary with different approaches. Operation in proximity to feedstock and storage sites will reduce transportation energy requirements.
	Water requirements	**Medium risk:** Biowaste requires no additional water. Dedicated crops can be produced with low water demand but are likely to consume significant water at gigaton scale.	Bioliquid[2] pyrolysis is currently only considered for cellulosic waste biomass, such as corn stover. The use of forestry products or dedicated crops is unlikely but may be required to reach gigaton scale removals and should only be deployed in areas at low risk of water stress.[3]
	Fertilizer requirements	**Low risk:** Biowaste does not consume additional fertilizer, although nutrients removed by harvesting should be replaced. Dedicated feedstocks are unlikely to be used, but crops with little or no fertilizer requirements are available.	Charm Industrial estimates that 50% of cellulosic ag waste can be safely removed without impacting soil quality.[4] At higher removal rates, without returned biochar,[5] replenishment fertilizer could require 10-25 Mt/GtCO_2e.[6] This is ~10% of 2019 global fertilizer use and 20-50% of the excess fertilizer produced.[7] Dedicated biomass production should prioritize cultivars with minimal fertilizer requirements.
	Land use requirements	**High risk:** Waste biomass will not provide enough feedstock for gigaton scale removals. Cultivated crops will require significant land use.	Agricultural residue and other waste biomass will not produce enough biomass for gigaton scale removals. Purpose grown crops require millions of km^2/GtCO_2e.[8] Competition for biomass will also increase.[9]
	Environmental impacts	**Medium risk:** Utilizing biowaste has net waste mitigation benefits.[10] There may be potential environmental risks with bioliquid handling.	Global biowaste handling may be improved through appropriate utilization.[10] The bioliquid pyrolysis process emits 98% of its total lifecycle emissions in the processing step and mitigation strategies are well understood.[9] Other risks include potential exposure to bioliquids that include volatile components and may need separate regulation for handling and transport.[11]
	Carbon conversion efficiency	**High risk:** Pyrolysis processes risk being out-competed by alternative biogenic pathways with higher sequestration rates.	Charm Industrial's LCA estimates ~50% CO_2 capture efficiency with pyrolysis as the greatest source of process emissions.[1]
Secure storage for 100+ years		**Medium risk**: Bioliquid injection into geological reservoirs has minimal reversal risk.	Dense bioliquids have minimal risk of resurfacing, and microbial decay is negligible.[12] However, potential leakage of water-soluble carbon species in geologic reserves needs additional research.[13]
Path to measurement at scale		**Low risk:** LCA and MRV development is still required but has a clear pathway forward.	Measurement of removals is mass-based and straightforward. Established monitoring standards from biodiesel can be applied to most of the bioliquid pyrolysis CDR approach.[12,14]
Pathway to full costs <$100/t$CO_2$		**Medium risk:** While current prices are ~$550/t$CO_2$,[11] Charm Industrial expects them to drop to under $50/t$CO_2$e.[15,16]	Transport and processing costs can be reduced when operating at feedstock source. Reducing feedstock costs will be an important future cost reduction.[13,16]

Notes and sources: [1]Charm Industrial FAQ about their LCA. [2]The terms "bio-oil" or "pyrolysis oil" are also used along with "bioliquid" in existing literature. [3]For comparison, per EFI – Surveying the BECCS landscape, estimates for water use for BECCS are small when waste biomass is used. When cultivated crops are used, water requirements can increase dramatically. The same would be true for bioliquid that used cultivated crops at scale. [4]Charm Industrial on Open Air Collective This is CDR: Dry biomass contains 1.65 tCO_2e/t; 0.78 tCO_2 is released from processing, 0.017 from production, 0.002 from transport, and 0.002 from injection for net removal of 0.76 tCO_2e/t of biomass. [5]Per reviewer comments, Charm Industrial will return biochar to the field, potentially improving soil nutrient content. [6]An average ton of corn or sorghum residue contains 17, 4, and 34 lbs of NPK, respectively. Per 4, removals of 0.76 tCO_2e/t of biomass would require ~25 Mt of fertilizer per GtCO_2e removed at full replenishment rates. [7]Global fertilizer consumption in 2019 was 215 Mt and 2019 fertilizer supply was projected to be 271 Mt, providing ~50 Mt excess. [8]Per reviewer comments. [9]The 2016 Billion Ton report estimates there will be sufficient biowaste supply, but biomass will have many competing demands. Further discussion can be found in the bCDR overview. [10]World Bank status and outlook report on global waste streams. [11]CDR.fyi spot price tracking and analysis. [12]Charm Industrial's MRV proto-protocol (p6). Additionally, according to Charm Industrial, Class 1 wells can store millions of tons of bioliquid in a single injection well. [13]Bioliquid co-products (e.g., fuels) can accelerate short term development and deployment, but long-term costs should be for CDR only. [14]Full LCA requires consideration of processing / conversion, bioliquid density, carbon and water content with for monitoring of gases, water, and storage stability (e.g. seismicity). [15]Charm Industrial's live registry. [16]Open Air Collective This is CDR at 16:27.

Potential for cost improvement

An assessment of two key drivers of learning rates

SECTION	2.5
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Stabilized biomass
APPROACH	Pyrolysis (bioliquid) and storage



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive
- **Rationale:** Traditional pyrolysis systems are simple, but new versions tend to be design-intensive to optimize processing and production efficiencies.

NEED FOR CUSTOMIZATION

- **Rating:** Standardized
- **Rationale:** Mature pyrolysis reactors and ancillary process equipment are standardized and mass-produced. Similarly, novel systems can be mass-produced once the technology developed.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

Current state of RD&D

A mapping of companies, plus other notable activities

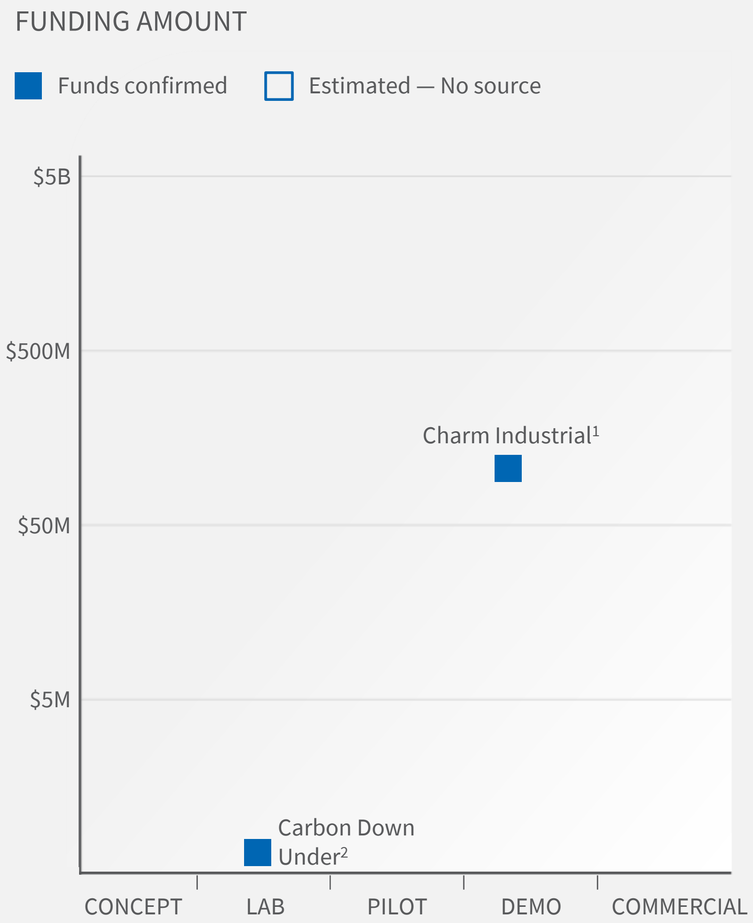
NOT EXHAUSTIVE

SECTION 2.5

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Pyrolysis (bioliquid) and storage



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Charm Industrial: Producing crude bioliquid using modular fast pyrolysis that is injected underground	$3.5M seed funding,[3] $100M Series B[4]	• Charm has injected 6,417 tCO_2e[45] • Established their own MRV[6] • Expanded into new testing and operation location in Colorado[7] • Charm has sold $53M of credits to remove 112,000 tons of CO_2e between 2024 and 2030 (via Frontier).[8]
Carbon Down Under: Developing waste biomass liquification for underground microbe consumption and sequestration	$125k from XPRIZE student team funds[2]	• Project co-sponsored by Thermaquatica • Continuing to experiment through labs at Southern Illinois University (SIU)[2]

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
DOE – BETO: Funding R&D projects to boost sustainable biofuels production	$2M[9]	• The DOE BETO is the lead government R&D funder for pyrolysis technology, and biomass processing.

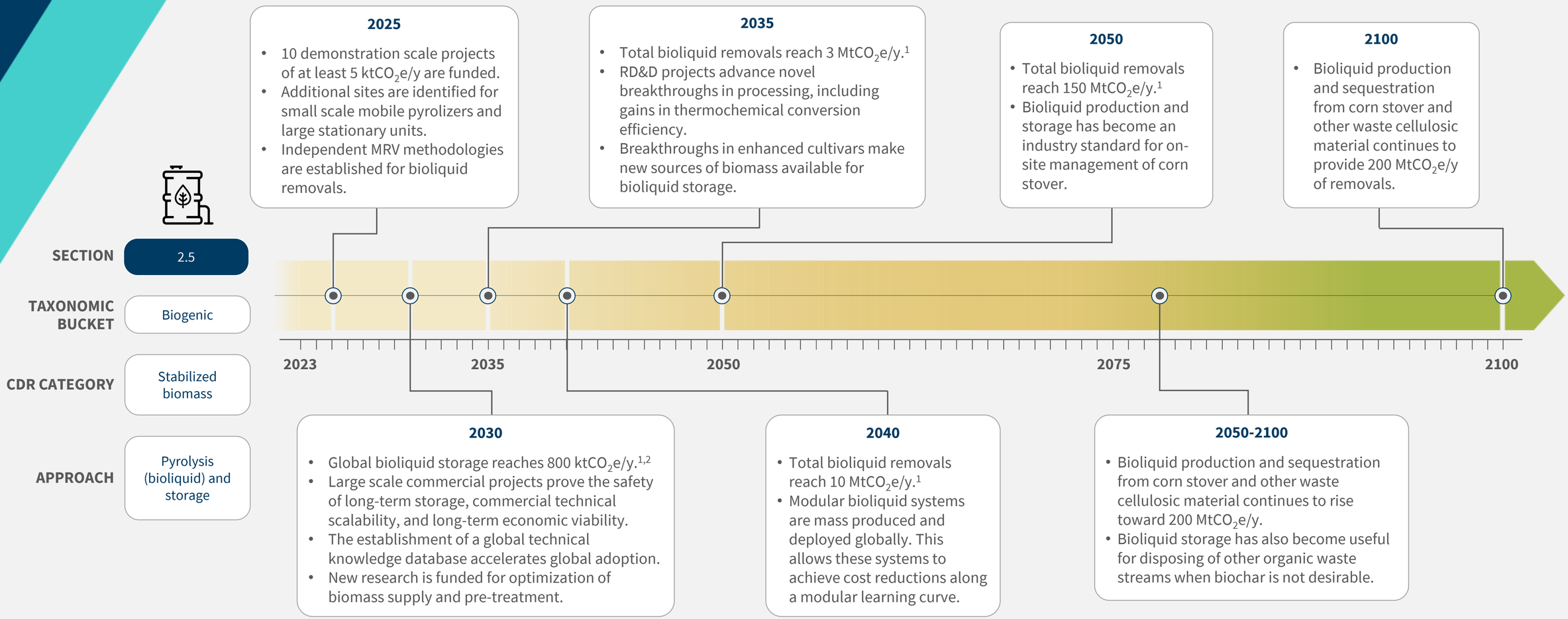
Notes and sources: [1]Charm Industrial [2]Carbon Down Under team [3]Crunchbase Charm Industrial [4]Axios [5]Charm Industrial has its own registry, value as of November 2023. [6]MRV proto-protocol [7]Charm blog - new facility in Fort Lupton, CO dedicated to pyrolysis R&D, ironmaking, and biomass processing [8]Frontier buyers signed first $53M in offtake agreements with Charm Industrial. [9]As part of $118M of funding in 2023 to accelerate domestic biofuel production, $2M was awarded for a Corn Stover Pyrolysis Pathway for Sustainable Aviation Fuel, which is a similar process that could be used for bioliquid CDR.

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR



Notes and sources: [1]The global scaling of bio-oil CDR assumes 100% y-o-y growth from 2023-2030, starting from todays' estimated capacity 6 ktCO2e/y. This growth is representative of what could happen if a concerted deployment strategy were taken over the next 7 years, similar to the rollout for corn ethanol seen in the 2000s. From 2030-2050, growth is assumed at 30% y-o-y, which is aggressive but also feasible given the latent potential of waste cellulosic biomass, specifically corn stover. According to Charm Industrial, the leader in this space, total corn stover waste in the USA alone is 200 MtCO2e/y. The biggest barrier to this deployment is sufficient procurement and sustained policy. [2]In May 2023, the Frontier Fund announced a $53M deal with Charm Industrial to remove 112 ktCO2e total by 2030.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

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CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

TRL

CRITICAL PATH ACTIVITIES

$200-500 million | **15 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Site suitability analysis:** Identify areas best for bioliquid implementation, optimized for different feedstocks, pyrolysis approaches, transport logistics, and optimal injection locations
- **Pyrolizer design:** Develop novel pyrolizers to improve efficiency and expand deployment

$10-20 million | **3-5 years**

- ✓ Suitable demonstration sites identified
- ✓ Sustainable feedstock supply is validated
- ✓ Pathway to achieving market competitive removal costs
- ✓ Manageable environmental impacts

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Demonstration of fast pyrolysis and injection at 5-9 sites:** The demonstration should optimize fast pyrolysis at larger scales utilizing (1) different feedstocks and (2) different conditions at demonstration locations

$200-500 million | **10 years**

- ✓ Clear pathway to market competitive costs
- ✓ Improved carbon conversion efficiency with minimized transport and processing logistics
- ✓ Secure and sustainable feedstock supply
- ✓ Validated MRV methodologies

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$250-600 million | **2-15 years**

- Develop an open-source database for global bioliquid pyrolysis to streamline dissemination of validated technical knowledge
- Optimize pyrolysis technology operation and biomass logistics to improve process efficiencies
- Determine ideal injection and storage dynamics, process, and geological conditions for bioliquid geologic storage

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Market competitive costs
- Financing costs in line with similar, established capital-intensive industries
- Established and low cost MRV methodologies
- Well-established paths for sustainable feedstock sourcing
- Well-established and safe approaches for bioliquid storage

SECTION 2.5

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Pyrolysis (bioliquid) and storage

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Site suitability analysis[1]	Conduct a regional suitability analysis for future demonstration sites that optimizes for the following criteria: • Representation of key feedstock types[2] • Access to different pyrolysis processes and technologies, including mobile solutions • Access to different injection storage sites or storage infrastructure • Optimized transportation distances validated through LCA • Manageable environmental impacts from biomass harvesting, pyrolysis, and storage	✓ Bioliquid fast pyrolysis is determined to have the potential to scale significantly once commercialized. ✓ Identify optimal parameters to improve bioliquid yield[3] ✓ Environmental impacts are manageable	2	$0.5-1M/y[4]	2-5 y [5]	$2-5M
Lab / pilot research	Pyrolizer reactor development	Develop and test novel pyrolizer designs to optimize process performance, operations costs, and enable scale up. Designs should consider heat recovery, carbon efficiency, diversity of feedstocks, etc. and seek to enhance understanding of pyrolysis reaction kinetics.	✓ Improved process efficiency and pathway to market competitive removal costs ✓ Identify the key parameters that dictate pyrolysis efficiency	3-5	$1M/y	3-5 y	$9-15M

Notes and sources: [1]A site suitability analysis is a report-based study of location considerations for siting bioliquid solutions. [2]Charm industrial blog describes the challenges in biomass preparation. [3]The multi-scale challenges of biomass fast pyrolysis and bio-oil upgrading: Review of the state of art and future research directions (Sharifzadeh et al., 2019) [4]Budgets estimates are based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Research Tasks & Budgets Table 4.8 section 2.1 Biomass supply and logistics (p. 171-2), and DOE's fast pyrolysis R&D pilot (RTI 2021). [5]A reviewer notes that Charm Industrial already has operational sites and does not anticipate needing 2-5 years for siting analysis.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Multiple demonstrations of fast pyrolysis bioliquid to geological storage. Projects should assess several conditions, including: • Different feedstocks, especially different forms of agricultural waste, such as corn stover, pistachio shells, and wood trimmings • Different deployment geographies • Different sizes of pyrolysis units, including small scale or modular facilities that can be moved around fields, and large centralized facilities in agricultural areas • Optimal injection parameters and process integration	10-55 $ktCO_2e/y$ [1]	✓ Clear pathway to market competitive costs ✓ Improved energy consumption with optimized transport and processing logistics ✓ Secure and sustainable feedstock supply ✓ Established best practice for bioliquid injection	5-9[2]	$20-50M/y	5-10 y[3]	$200-500M
MRV	Empirical and analytical methods inform the development of MRV methodologies that: • Account for the heterogeneity of site conditions • Include monitoring for volatile organic compounds from the stored bioliquid	N/A	✓ MRV methodologies are developed accepted across the field ✓ Environmental impacts are manageable	2-3	$0.5-1M/y	10 y	$10-30M

Notes and sources: [1]Current pilots by Charm Industrial are less than 10 $ktCO_2e/y$. Biochar pyrolysis plants are targeting 10 $ktCO_2e/y$ as the low end of their demonstration facilities. We based the upper limit on biomass as 100 t/day. This is about 35 kt biomass/y with operation at full capacity. Assuming 70% biomass to crude bioliquid conversion efficiency, this would produce about 25 kt crude bioliquid/y with 60% carbon content for 50-60 $ktCO_2e/y$/project. This volume of biomass should be sourced within a 50-mile radius to minimize transportation distances. Assuming market ready oven-dry biomass of 1.24 t/acre, and 50% farmland per acre, a 50-mile radius could contain 3 Mt of oven dry corn stover per year. Note that the largest pyrolysis plant under construction plans to process 100 kt of waste biomass per year. [2]Budgets estimates are based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Research Tasks & Budgets Table 4.8 (p. 171-2) and DOE's fast pyrolysis R&D pilot grant (RTI 2021). [3]Charm Industrial plans to expand with additional pyrolysis sites in the next 3-10 years, accelerating this timeline for demonstrated technology approaches.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	Breakthroughs on enhanced cultivars[1]	Research and develop plant-based feedstocks that have enhanced growth qualities such as accelerated growth, improved survivability, and / or increased carbon uptake.	1	$40-50M/y	15 y	600-900M
Desktop research	Global technical fast pyrolysis database	Establish and maintain an open-source technical knowledge database to accelerate commercialization of fast pyrolysis CDR applications, improve MRV methodologies, and improve global knowledge transfer.	1	$0.5-1M/y	5-10 y	$2-10M
Lab	Biomass supply and pre-treatment	Test and model novel approaches to address biomass logistics and optimize processing and pre-treatment.	2-10	$2-5M/y	2 y	$8-100M
Lab / MRV	Optimization of geologic storage	Test and model improved geological storage performance of crude bioliquid. Determine ideal injection and storage dynamics for distinct crude bioliquid characteristics (dependent on feedstock and pyrolysis process), geological characteristics, and injection processes.	5	$5-10M/y	3 y	$75-150M
Lab / pilot	Thermochemical conversion efficiency	Perform pyrolysis R&D to maximize bioliquid yield. Identify fast pyrolysis[3] reactor types with bio-liquid yields of >65% per dry feedstock and carbon content >60%.[3]	9	$1-3M/y	3 y	$25-80M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include knowledge transfer, permitting, expanding pyrolizer manufacturing, and scaling operational workforce.*

Notes and sources: [1]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) recommends $40-50M/y over 20 years for genetic crop improvements and reports current R&D funding for conventional crop improvements and genetics is $1.5B (public sector) and $1.8B (private sector). [2]Budget estimates are based on NAS 2019 Research Tasks & Budgets Table 4.8, Section 2.1 Biomass supply and logistics (p. 171-2), and DOE's fast pyrolysis R&D pilot (RTI 2021). [3]Mahdi Sharifzadeh et al (2019) describes nine known fast pyrolysis reactor types.

SECTION 2.6

Microalgae cultivated in artificial ponds and stored

SECTION	2.6
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Stabilized biomass
APPROACH	Microalgae cultivated in artificial ponds and stored

DEFINITION

Harvest and storage of microalgae biomass grown in land-based systems

EXAMPLE SCENARIOS

1) Growing algae in raceway ponds that are fed with seawater; 2) Collecting algal biomass from blooms in lakes resulting from fertilizer runoff; 3) Growing algae in bioreactor bags either in warehouses or floating on open water – then, in all scenarios, drying and burying the biomass.

Section 2.6 overview

Microalgae cultivated in artificial ponds and stored

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Pathway to full costs <$100/tCO$_2$** • The key risk is whether the cost can drop below the $100/tCO$_2$ threshold
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot to commercial** • ~4 companies at pilot to commercial stages, with ~1 focusing on growing algae for CDR specifically • Other notable RD&D activity includes the DOE BETO APEX program
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **120 MtCO$_2$ by 2050** • Success is contingent on breakthroughs in cultivation efficiency and validation of long-term CO_2 storage
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path funding: **$250-900M over 8-12 years** • Key stage gates in competitive and stable costs and manageable environmental impacts

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

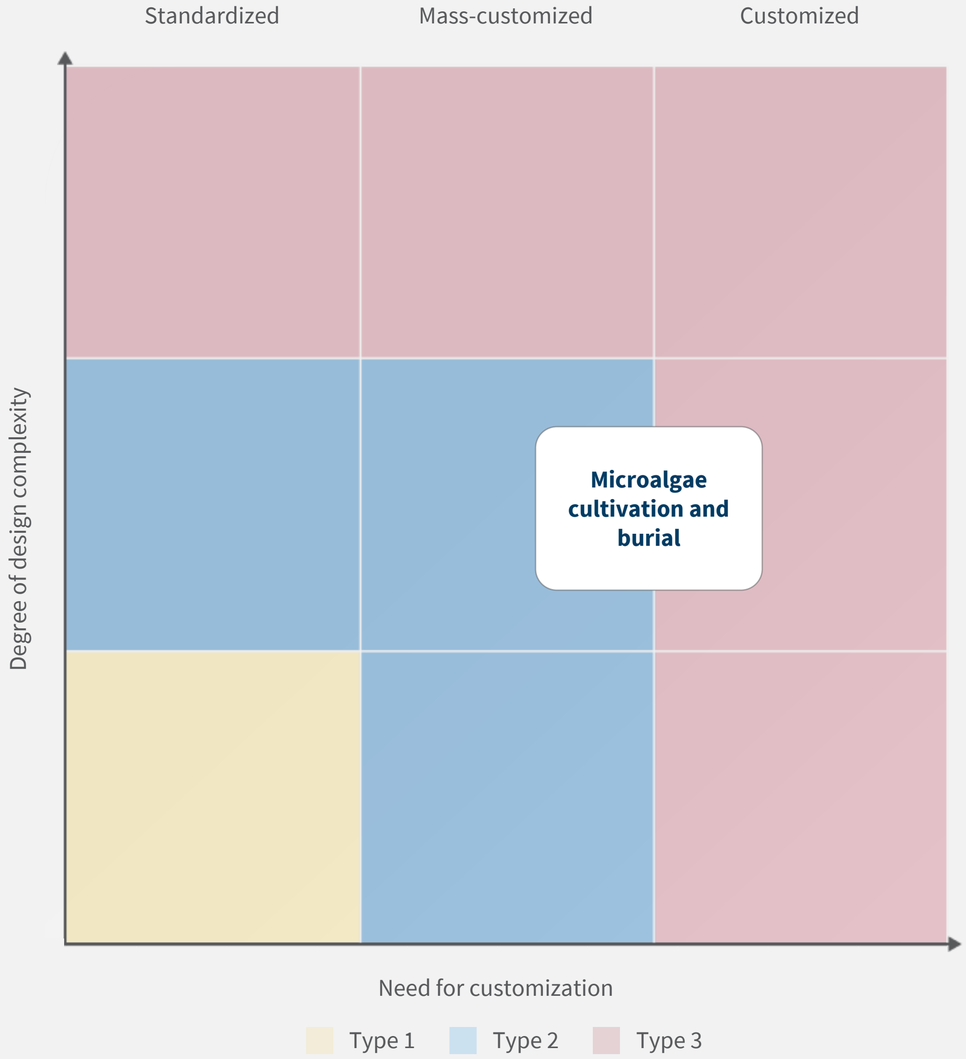
Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Medium risk:** Water pumping is energy intensive and necessary for contained algae cultivation systems.	Based on NREL estimated energy inputs,[1] energy requirements are about 3.6 GJ/tCO_2e.[2,3] This is primarily for water pumping, but drying and storage may also consume significant energy.
	Water requirements	**Medium risk:** Total water consumption varies with the cultivation approach and location (e.g., open ponds in dry locations lose more water).	Estimated water requirements are approximately 60-780 t of saline water per tCO_2e.[4] Using seawater and water recycling reduces water stress but increases energy demand.[1,5]
	Fertilizer requirements	**Medium risk:** Cultivated microalgae requires nutrient inputs to ensure sufficient growth.	Algae projects should minimize use of anthropogenic fertilizer.[1,6] For example, the Brilliant Planet pilot project in Morocco utilizes natural ocean upwelling to significantly reduce fertilizer inputs.[5,7]
	Land use requirements	**Medium risk:** Existing approaches have high yields and can be cultivated on non-arable land; however, land area with optimal conditions is limited.	Current algae cultivation achieves ~60-100 tCO_2e/ha/y.[5,8] Gigaton scale removals require cultivation of 0.1-0.2M km^2 of land in areas with appropriate environmental conditions, plus area for burial.[9]
	Environmental impacts	**Low risk:** Closed system cultivation and burial of algae products pose low environmental risk.	The burial of desiccated biomass in an arid environment is very stable and has low anticipated environmental risks.[5]
Secure storage for 100+ years		**Medium risk:** Optimal storage is expected to be stable; however, recovery and burning of stored biomass or methanogenesis are potential risks.	Monitoring is necessary to ensure storage is not disturbed and that no methanogenesis occurs. Storage in arid environments or with increased salt content can increase storage stability.[5]
Path to measurement at scale		**Low risk:** Cultivation and storage in closed systems allows for straightforward measurement and accounting.	Known sensors and measurement tools are readily available to determine biomass composition,[1,10] although monitoring will likely be necessary for quantifying removals at gigaton scale.
Pathway to full costs <$100/$tCO_2$		**High risk:** Microalgae cultivation in ponds has been researched for many decades and is still far more expensive than $100/$tCO_2$.	NREL cradle to pond gate prices are more than $600/t dry biomass[1] and $333/$tCO_2e$.[2] Brilliant Planet reports $200/$tCO_2e$ at their pilot site.[5]

Notes and sources: [1]NREL Algal Biomass Production via Open Pond Algae Farm Cultivation [2]Assumes 50% carbon content in dry biomass with the conversion of 3.67 tCO_2e/t of carbon. [3]Per [1,2], NREL estimated energy inputs are 486-591 kWh/t of dry biomass. This requires about 1 MWh or 3.6 GJ per tCO_2e removals. [4]Per [1,2], saline water requirements are 8.6k-114k gallons/t dry biomass. This converts to 32-430 kL/t dry biomass, or about 58-780 t water/tCO_2e. [5]This is CDR Ep 57: Brilliant Plant with Dr. Raffael Jovine [6]CO_2 and ammonia are the primary nutrient inputs required to maintain high growth rates and productivity. [7]While Brilliant Planet uses natural ocean upwelling for 7 months of the year, they must close the facility from mid January to mid February due to sandstorms. They also supplement nutrients for the two months prior to and following January due to reduced upwelling. The use of ocean upwelling to surface nutrients also introduces the possibility of surfacing dissolved CO_2 and reducing the net removals of this approach. [8]Per [1], algae cultivation in ponds provides ~24 tCO_2e/acre/y, which is approximately 60 tCO_2e/ha/y. [9]Cultivation locations require appropriate ambient conditions to facilitate algae growth without the addition of heat or light and with minimal evaporative loss. An assessment of available land meeting these conditions would provide increased fidelity in the potential scale of this approach . [10]Brilliant Planet measures the bicarbonate and CO_2 concentration in the incoming and outgoing streams of water and in production ponds. They estimate that about half of their CO_2 comes from the atmosphere contacting their ponds and half comes from the inlet water.

Potential for cost improvement

An assessment of two key drivers of learning rates



SECTION 2.6

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Microalgae cultivated in artificial ponds and stored

OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive
- **Rationale:** Systems integration of cultivation infrastructure, growth, environmental monitoring, and burial are moderately complex. MRV development requires solutions to address longevity in potentially complex environments over time.

NEED FOR CUSTOMIZATION

- **Rating:** Standardized to mass-customized
- **Rationale:** Local environmental and geologic conditions require customized consideration to implement both cultivation and burial. The initial MRV can be standardized and easily be reused for monitoring at future burial / storage sites.[2]

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]Based discussion of sensors from This is CDR Ep 57: Brilliant Plant with Dr. Raffael Jovine

Current state of RD&D

A mapping of companies, plus other notable activities

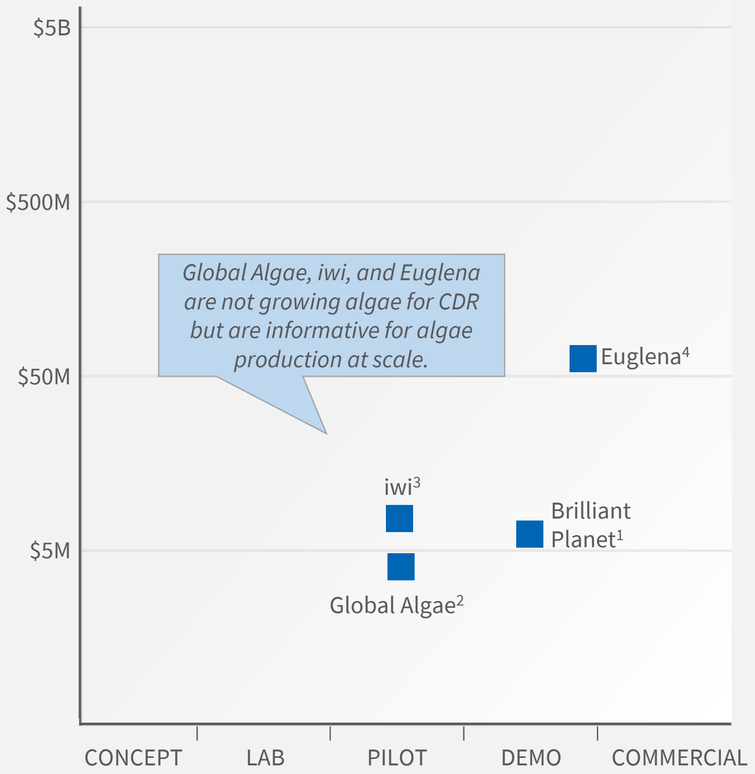
NOT EXHAUSTIVE

SECTION 2.6

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Microalgae cultivated in artificial ponds and stored



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Brilliant Planet[1]	$12M (Series A, 2022); $26.7M (total)[5]	• Field trials in Morocco (4 years, 3 hectares),[6] South Africa, Oman • Coastal Morocco 30-hectare production facility with burial under construction
Global Algae Innovations[2]	$4.6M,[7] including $1M XPRIZE Grant	• 13-hectare open pond algae cultivation[8] • 65-hectare farm planned (pending funding)[8]
iwi (formerly Qualitas Health)[3]	$10M (2021), $8M (2022)[9,10]	• ~40 acres of algae cultivation in Texas and New Mexico (US)
Euglena[4]	¥7.8B[11]	• Completed demonstration plant for production of low-carbon jet and diesel fuel using microalgae in 2018[12]

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Algae Productivity Exceeding Expectations (BETO)[13]	Up to $20M (2021)	• Objective to improve productivity with CO_2 supply from ambient or DAC sources
Carbon Utilization Technology: Improving Efficient Systems for Algae (EERE, FECM)[13]	$16.5M (2022)	• Objective to improve carbon utilization efficiency from biomass- or atmospheric-based sources of CO_2 and algae-based technology to utilize anthropogenic CO_2 from utility and industrial sources

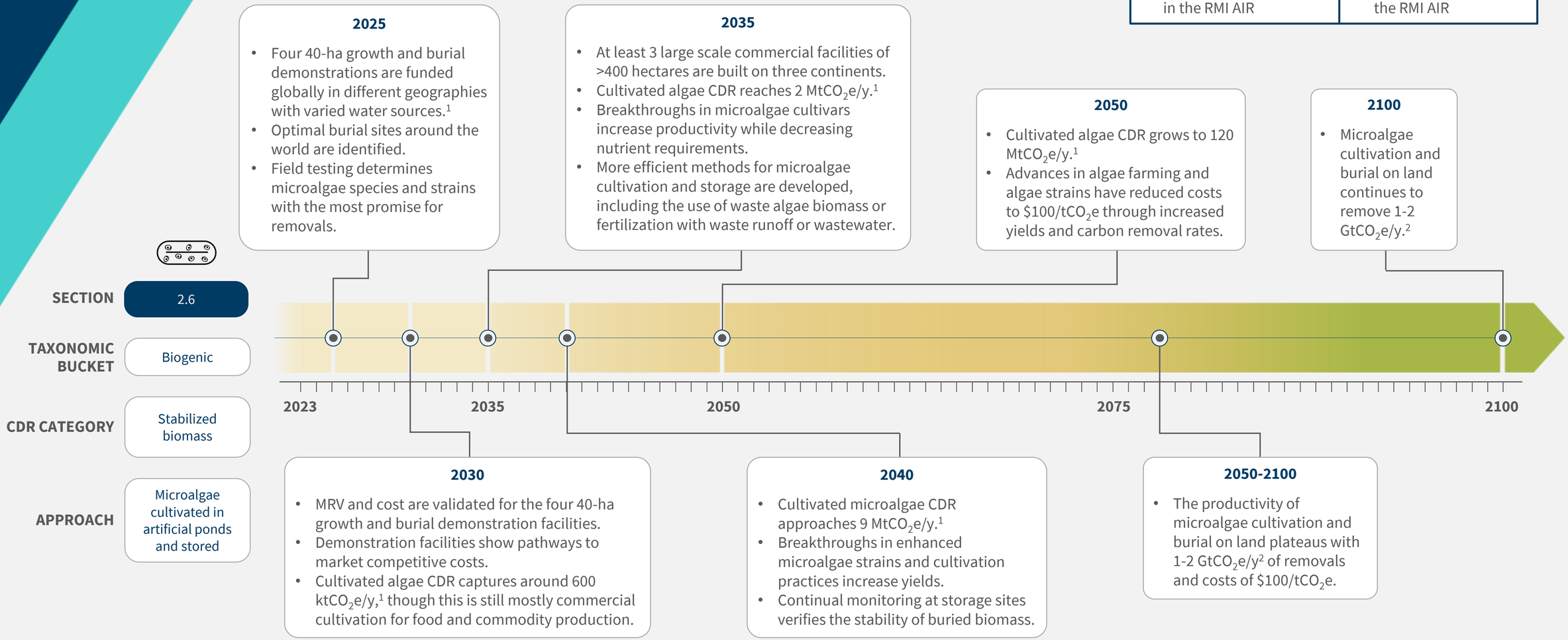
Notes and sources: [1]Brilliant Planet [2]Global Algae [3]iwi [4]Euglena, Co. is a Japanese company growing algae at scale for products including nutritional supplements and biofuels, although not for CDR. [5]Crunchbase estimate for Brilliant Planet [6]TechCrunch article about Brilliant Planet field trials [7]Crunchbase estimate [8]Global Algae About page, 30 Jan 2023. Global Algae is growing large amounts of algal biomass but not for burial. [9]Crunchbase estimate for iwi [10]iwi is growing large amounts of algae for nutritional supplements (IEEE Spectrum) and transitioning into alternate protein production (AgFunder). [11]Funding announcement for Euglena [12]Demonstration plant in Japan [13]BETO Funding Announcement

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR



Notes and sources: [1]As of 2023, Brilliant Planet is building a 30-hectare facility that should be able to capture about 3 ktCO$_2$e/y (using Brilliant Planet's own estimates of 40t CO$_2$e/acre/y). Currently, "one of the largest commercial cultivation of microalgae in natural water is located at Hutt Lagoon, Australia which is capable of producing 6 tons of β-carotene every year from *Dunaliella* using its 700-hectare ponds." We assume that there are 20 kt of annual algae cultivation worldwide in 2023, which would be provide approximately 37 ktCO$_2$e/y of removals by algae. We assume 50% year over year growth from this starting point to 2030 and 30% y-o-y growth after that. [2]Ocean Visions estimates of total potential could be up to 5 GtCO$_2$e/y, but this value is based exclusively on Brilliant Planet's estimates. We estimate a more conservative 1-2 GtCO$_2$e/y potential that is based on limited suitable land area.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost[2]
- Timeline to complete[2]

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 2.6

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Microalgae cultivated in artificial ponds and stored

TRL

CRITICAL PATH ACTIVITIES

$250-900 million | **8-12 years**

TRL 1–6

PRE-DEMONSTRATION WORK

There are no critical path pre-demonstration activities for this approach.

N/A | **N/A**

This approach has no pre-demonstration stage-gates.

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Growth demonstration:** Four 40 ha biomass production site demonstrations
- **Burial demonstration:** 2-4 burial projects with ongoing, long-term monitoring

$250-900 million | **8-12 years**

- ✓ Achieved stable, market competitive costs for CO_2 removal
- ✓ Fertilizer use is sustainable
- ✓ Environmental impacts are manageable

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[3]

$100-250 million | **5-10 years**

- Develop methods for NPK recovery before biomass burial
- Determine methods for using waste streams and remediation pathways as inputs
- Develop new strains of microalgae with improved growth characteristics
- Identify alternate sourcing for waste microalgae biomass to reduce purpose grown microalgae

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[3]

- Verified storage stability
- Market competitive costs are stable over seasonal and multi-year cycles
- Established and low-cost MRV methodologies
- Anthropogenic fertilizer use is minimal and sustainable
- Financing costs are comparable to similar established capital-intensive industries
- Environmental impacts are manageable

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Workstreams and spending assessments are based on the National Academies Ocean CDR Research Strategy (2022). [3]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Growth demonstrations: 4 x 40-ha microalgae pond demonstration facilities. Demonstrations should: • Be varied in geography, environmental conditions, process approach, and microalgae species selection[1] • Identify optimal algae varieties and production conditions to meet required production for CO_2 removals at scale • Achieve commercially viable costs that are stable over 2+ years to account for seasonal variability • Perform ongoing monitoring of environmental conditions and impacts • Seek to store their algae on site or nearby in stable burials[3] (see below) Emissions monitoring should be ongoing, especially to assess any CO_2 produced during cellular respiration at night.	4 $ktCO_2e/y$ per project[2]	✓ Achieved market competitive costs for CO_3 removal ✓ Market costs are stable enough over yearly cycles and multi-year cycles to ensure regular commercial deployment.	4	$10-20M/y[4]	8-12 y	$200-800M
Demo	Burial demonstrations should consist of at least 2 burial projects for the sequestration of algae grown in the above demonstration projects. Demonstrations should: • Perform measurement to inform MRV and ongoing LCA • Perform ongoing monitoring of environmental conditions and impacts	4-8 $ktCO_2e/y$ per burial demonstration site[2]	✓ MRV is validated including LCA of production and burial.	2-4	$2M/y[5]	8-12 y	$20-40M
MRV	Measurement performed with sensors[6] distributed through buried biomass for long term monitoring to inform MRV development	N/A		1-4	$3-5M/y	5-10 y	$15-50M

Notes and sources: [1]Demonstration facilities funded by the USG should include at least one facility each on the west coast and east coast of the USA. Globally, sites should consider conditions similar to Brilliant Planet in Morocco with access to plentiful sunlight, ocean water, inexpensive and suitable oceanfront land, sufficient clean electricity, and nearby burial sites. [2]Assumes total production from 4x 40 ha demonstrations. According to NREL, this much acreage should yield 26-32 tons of ash free dry weight (AFDW)/acre. Assuming 3.67 tCO_2e per tC, and 50% C mass in AFDW, this would yield 3 kt AFDW/y (5.5 $ktCO_2e/y$) per 40 ha facility. According to this is CDR Ep 57: Brilliant Plant with Dr. Raffael Jovine, Brilliant Planet removes ~40 tCO_2e/acre/y or ~62 t dry biomass. Using these values, a 40-ha facility would remove 4 $ktCO_2e/y$. [3]If burial is not used, early phase projects could utilize or sell their algae rather than bury it. [4]Based on Brilliant Planet's $12M fundraising in 2022 to build its next 30-hectare facility. [5]Based on estimates for woody biomass burial from Zeng & Hausmann (2022) at $1.2-1.8M total cost per year. 100 tCO_2e/ha/y is around 40 tCO_2e/acre/y. [6]Monitoring should include sensors to detect methanogenesis.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab / field testing	NPK recapture	Explore pathways to recapture NPKs and mineral content from biomass for fertilizer or soil amendments to minimize nutrient lockup	3-6	$1M/y	5 y	$15-30M[9]
Lab / field testing	Integrate waste stream inputs	Assess wastewater, agricultural runoff, flue gas remediation, and other waste stream outputs for algal growth inputs and nutrient media.[1]	5-12	$1M/y	5 y	$30-60M[8]
Lab	Engineering microalgae or growth conditions	Investigate improvements in algae growth and CO_2 uptake through approaches such as:[2,3,4] • Harnessing natural phenomena to increase microalgae growth • Creating biotechnologically enhanced microalgae with high carbon sequestration potential.[5] • Investigating the incorporation of cyanobacteria with the ability to fix atmospheric nitrogen to increase growth rates of other microorganisms • Decreasing nutrient requirements or expanding tolerable environmental conditions	5-8	$1-3M/y[6]	5-10 y	$25M-100M
MRV	Containment and storage monitoring	Develop sensor systems to monitor external conditions around the biomass storage space that can provide advance warning of potential containment failures.	2-4	$0.5-1M/y[6]	5-10 y	$5-20M
Field testing	Identify other microalgae products for biomass sourcing	Investigate other industries (e.g., biofuel, nutritional supplement, cosmetic production) that utilize microalgae and determine if waste streams could be utilized for burial instead of purpose grown biomass.	3-4	$0.5-2M/y	5 y	$15-20M[7]
Lab / field testing	Novel cultivation practices	Investigate and test cultivation improvements, such as low-energy bioreactors and improvements in harvesting and processing practices.	2-6	$1-2M/y	5 y	$10-50M[9]

Notes and sources: [1]Depending on burial site, dried and buried biomass may not have stringent requirements on contamination, providing easier integration of waste streams for algae cultivation inputs. [2]Bioengineering of Microalgae: Recent Advances, Perspectives, and Regulatory Challenges for Industrial Application (Kumar et al., 2020) [3]NREL Algae Biomass Production via Open Pond Algae Farm Cultivation 2020 Report [4]Ocean Visions roadmap for microalgae cultivation notes this as a first order priority. [5]Cross-cutting research between open ocean and artificial pond cultivation provides closed environments to test enhanced microalgae before any integration into open ecosystems. [6]Estimates based on BETO PEAK Project [7]Estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for resource database development projects [8]Estimates based on NAS 2019 budgets for environmental impact projects [9]Estimates based on NAS 2019 budgets for field R&D projects

SECTION 2.7

Microalgae cultivated in open water and sunk

SECTION	2.7
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Stabilized biomass
APPROACH	Microalgae cultivated in open water and sunk

DEFINITION

Sinking microalgae, either cultivated or grown naturally, in open water environments

EXAMPLE SCENARIOS

Sinking the algal biomass created by 1) seeding the open ocean with iron or other trace nutrients to create algae blooms; 2) creating artificial upwelling in the open ocean to induce algae blooms; 3) seeding lakes or other bodies of water with nutrients to create algae blooms.

Section 2.7 overview

Microalgae cultivated in open water and sunk

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Secure storage and path to measurement at scale** • Key risks include durability of storage and the development of new technologies needed for measurement at scale
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • The sinking approach is standardized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Concept to demo** • ~4 companies at concept to demo stages, with <$10M in funding each • Other notable RD&D activity includes the ONCE working group
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **810 $MtCO_2$ by 2050** • Success is contingent on breakthroughs in process design and verification, especially for validation of long-term CO_2 storage and environmental safety
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$1-1.6B over 15-20 years** • Key stage gates in growth and sinking, measurement hardware, and environmental impact assessment

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

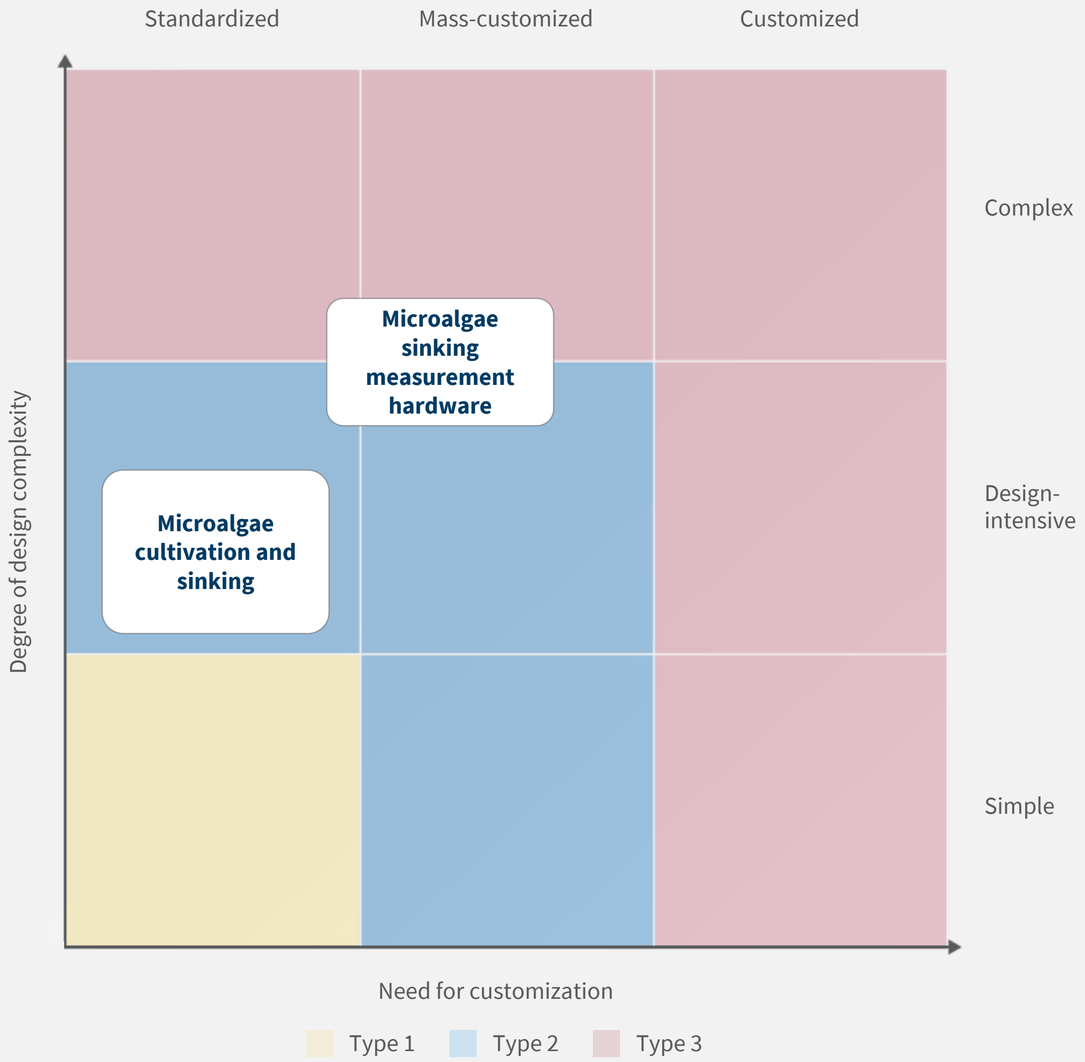
CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Low risk:** The energy costs for sourcing and shipping open ocean fertilizers, such as iron, are low. The energy needed to distribute the iron is also low.	The cost of chartering a fishing boat and deploying 100 tons of iron a few hundred kilometers off the coast was found to be around \$0.50/tCO_2e. The associated energy costs would be a fraction of that.[1] Upwelling can move water passively, avoiding additional energy costs.
	Fertilizer requirements	**Low risk:** Fertilizer requirements are relatively small and inexpensive.	The most significant fertilizers considered for promoting microalgae growth at scale are usually iron filings. These are inexpensive and easily distributed.[1]
	Capture potential	**Low risk:** Photosynthetic uptake of CO_2 is well-established and would be extensive, if applied widely.	Thirteen studies on ocean fertilization were conducted between 1993-2009, resulting in literature indicating significant global growth potential.[2] Algae sinking remains a significant challenge to implementation.
	Environmental impacts	**Medium risk:** Local ecosystems could potentially be disturbed to the point of tipping equilibrium, especially at gigaton scale.	At gigaton scale, microalgae cultivation through fertilization or upwelling would require significant ocean surface area, could affect nutrient balances, water chemistry, biological activity, and mixing of water column zones. Harmful algae blooms could also result.[3,4]
Secure storage for 100+ years		**High risk:** There is low certainty as to whether durable or permanent storage is achievable.	There is low consensus on the sequestration and permanent storage of microalgae.[2] Most captured carbon is re-released in the upper levels of the ocean. There are also questions about the permanence of the algae that does sink which must be addressed for deployment at scale.
Path to measurement at scale		**High risk:** New carbon measurement technologies are needed to determine and monitor carbon removals through sinking, and modeling will likely be required at scale.	Open ocean measurement and monitoring for microalgae sinking is unproven and difficult to measure. Developing robust measurement or modeling for quantifying removals will require breakthroughs in equipment and deployment approaches.[5]
Pathway to full costs <\$100/tCO_2		**Medium risk:** The cost of creating microalgae blooms is assumed to be low. However, adequate MRV would need to be extensive with correspondingly high costs.	There is significant uncertainty in cost due to the extent of the MRV challenge and the lack of a clear path to a solution.[6] There is also insufficient real-world project data from which to estimate the full cost.

Notes and sources: [1]A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) (p92) [2]NAS 2022 (p81) [3]NAS 2022 (p89) [4]Some reviewers consider this a high risk that can only be addressed if essential breakthroughs are made in our understanding of potential impacts given unknown risks to benthic and other marine ecosystems, especially at scale. [5]NAS 2022 report notes that both satellites and Argo profiling float networks can be used to track the surface productivity of biomass growth and that autonomous sensors could cycle through the water column to measure transport. Still, additional modeling will need to be developed to accurately verify and certify CO_2 removals. [6]Reviewers consider the pathway to full costs to be low risk if permanence is not prioritized.

Potential for cost improvement

An assessment of two key drivers of learning rates

SECTION	2.7
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Stabilized biomass
APPROACH	Microalgae cultivated in open water and sunk



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive
- **Rationale:** Microalgae cultivation is simple, requiring only the potential dispersal of fertilizers. MRV will be more complex and may require sensors, drones, and other automated or unmanned systems. It may also be accomplished by sonar systems or satellites.

NEED FOR CUSTOMIZATION

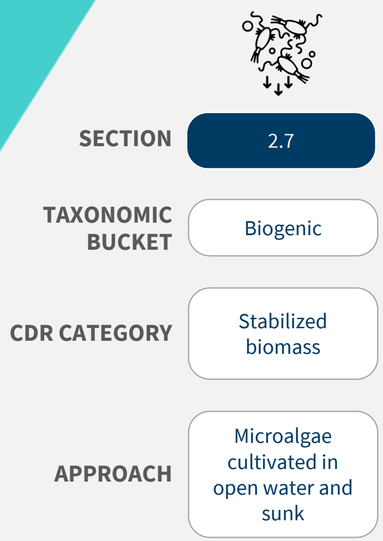
- **Rating:** Mass-customized
- **Rationale:** Microalgae cultivation has the potential to become significantly standardized and will benefit from economies of scale and global deployment.

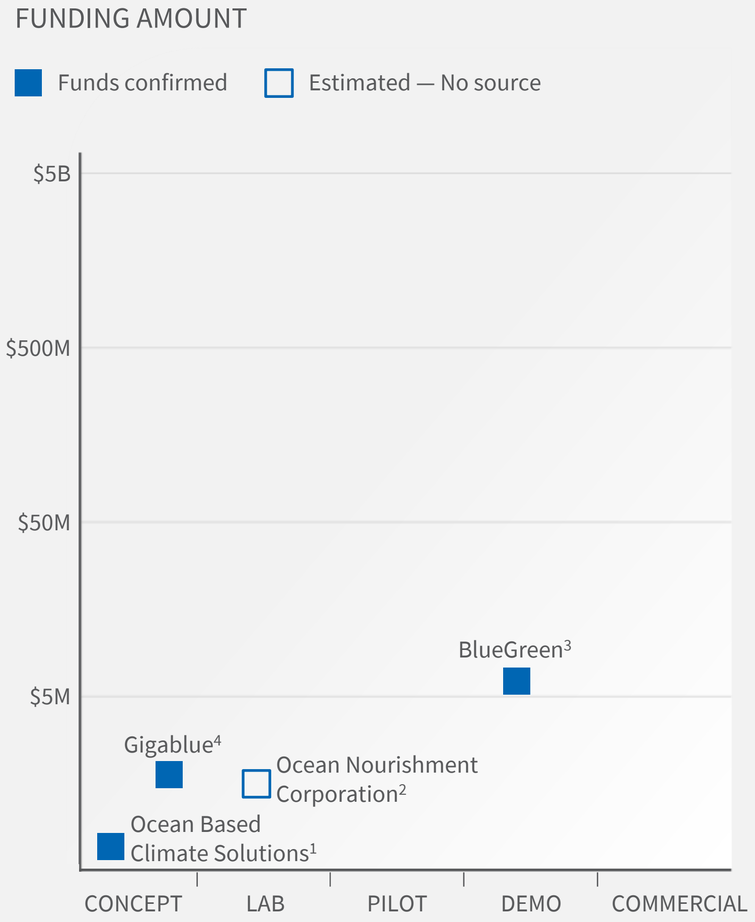
Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

Current state of RD&D

A mapping of companies, plus other notable activities

NOT EXHAUSTIVE





NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Ocean Based Climate Solutions, Inc.: ocean upwelling pumps[1,5]	50k[6]	• Goal of 1 $GtCO_2e$ captured with 5 million pumps • Each pump generates 10 t of marine life and fish annually
Ocean Nourishment Corporation: Dispersing nitrogen and phosphorous into the ocean[2,7]	Seeking $10M (AUD$13M) raise for demo[8]	• Seeking partnerships with the Australian government • 2024 goal to conduct measurement studies in controlled mesocosm with 1 $ktCO_2e$ removal in NW Australia
BlueGreen: Sinking toxic algae blooms[3]	$6M[9]	• States 1.5-3 $MtCO_2e$ removals through treatment of algae blooms[10,11]
Gigablue: Developing geo-optimized particles to stimulate algae growth[4]	$2.5M (seed funding - 2022)[12]	• Seeking to partner with merchant fleets, governments, and corporations to leverage existing infrastructure
Other companies: ExOIS,[13] Two Frontiers Project,[14] Ocean Visions[15,16]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
EXport Processes in the Ocean from Remote Sensing (EXPORTS)[17]	Funding may have lapsed	• Large scale NASA-led field campaign to quantify the export and fate of upper ocean net primary production (NPP)
Controls over Ocean Mesopelagic Interior Carbon Storage (COMICS)[18]	Funding from 2017-2022	• Quantifying the flow of carbon in the ocean between 100 m and 1,000 m
Ocean Negative Carbon Emissions (ONCE)[19]	Currently active	• Working Group 46: Joint PICES / ICES Working Group on Ocean Negative Carbon Emissions

Notes and sources: [1]Ocean Based Climate Solutions, Inc. [2]Ocean Nourishment Corporation [3]BlueGreen Water Technologies is a company focused on algae bloom remediation. They state that they have removed CO_2 through this process as well. However, it is not clear that they have verified any of these removals or sold them on a CDR exchange. [4]Gigablue website [5]Results from the study "Expected Limits on the Potential for Carbon Dioxide Removal From Artificial Upwelling" (Koweek, 2022) indicate that field trials for ocean upwelling are justified. [6]Crunchbase funding estimate for Ocean Based Climate Solutions, Inc. [7]Ocean Nourishment Corporation plans to create Aquafood fertilizer from green ammonia made from offshore wind. Measurement and verification are to be done by satellite data processing with direct measurements using unmanned underwater vehicles. Each site is expected to remove 4-6 $MtCO_2e/y$. [8]Jill Storey Creating Ocean Carbon Credits [9]Pitchbook for BlueGreen [10]Canary Media overview of BlueGreen [11]BlueGreen has developed a methodology with SocialCarbon but does not have any active projects or credits currently registered. [12]Funding for Gigablue [13]ExOIS is designing field trials for ocean iron fertilization. [14]Two Frontiers Project, alongside teams from Cornell and Harvard, are conducting research on a type of cyanobacteria off the island of Vulcano. Early data shows the cyanobacteria converts CO_2 to biomass faster than other cyanobacteria. [15]Ocean Visions is conducting spatial analysis on nutrient fertilization pathways. [16]A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by 2030 (Ocean Visions, 2023) outlines several funding opportunities and programs that are relevant across multiple CDR approaches that occur in the ocean, including MRV research, field trials, and spatial planning. [17]NASA funded EXPORTS [18]UK funded COMICS program [19]Ocean Negative Carbon Emissions

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

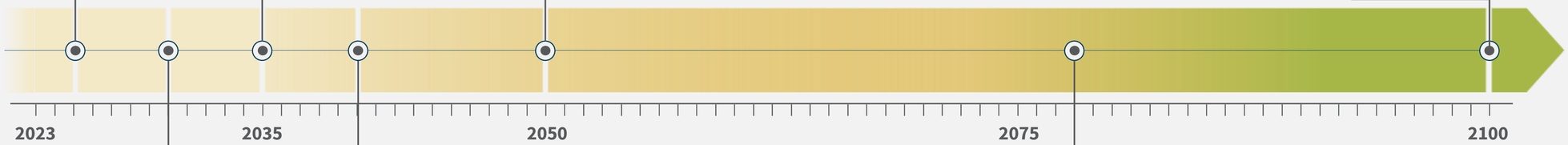
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 2.7

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Microalgae cultivated in open water and sunk



2025

- Funding is allocated for microalgae cultivation with 5-10 field trials of ocean fertilization 3-5 field trials of artificial upwelling.
- Funding for new measurement hardware development to quantify algae growth and sinking
- Open-source, global data tracking system funded and established to inform MRV and verify ecological impacts

2030

- The first independently verified growth and permanent sinking of microalgae is completed
- 5-10 demonstrations of ocean fertilization and upwelling are funded for >1,000 km^2 patch size with comprehensive monitoring.
- Significant increases to funding for ocean monitoring to verify sinking, inform MRV, and track ecological impacts

2035

- MRV has been developed, including shared hardware, processes, and systems of measurement.
- Significant research and funding continues for ocean monitoring and verification software and hardware
- Basic R&D, field testing, and demonstrations have led to improved growing and sinking practices.
- Verified yearly removals reach 250 $ktCO_2e/y$.[1]

2040

- Significant research and funding continues for ocean monitoring and removal validation capabilities
- Breakthroughs in autonomous fertilization, monitoring, sinking, measurement, and verification lead to dramatic improvements in the viability of this approach and a rapid increase of removals.
- Sequestration reaches 60 $MtCO_2e/y$.[1]

2050

- Aggregated ocean monitoring systems, first developed independently for algae, alkalinity enhancement, and electrochemical processes, are consolidated and used across all ocean CDR.
- Continued breakthroughs in growing and sinking of algae drive rapid expansion of this approach.
- Sequestration reaches 810 $MtCO_2e/y$.[1]

2050-2100

- Microalgae sinking continues to grow globally and is integrated with other sustainable ocean practices.[2]
- Long term ecological monitoring confirms that growing and sinking microalgae is safe and sustainable.

2100

- Cultivated microalgae in oceans reaches a steady state of around 4 $GtCO_2e/y$ removals.[2]
- If key breakthroughs are made in fertilization, monitoring, sinking, measurement, and verification, it is possible for this approach to scale further and become one of the greatest contributors to negative emissions.

Notes and sources: [1]The global scaling of cultivated microalgae will be significantly limited until adequate MRV methodologies can be developed. We estimate that it will take until at least 2030 to develop adequate MRV hardware, protocols, and third-party verification to ensure that microalgae cultivation is additional and that the carbon is sunk and sequestered to permanent depth. However, while microalgae is starting from small initial values, significant breakthroughs in sinking and MRV would make a rapid period of growth in the 2030s feasible. As such, we assume that there will be 1 $ktCO_2e/y$ removed in 2030, increasing by 200% each year to 2040, then increasing at 30% y-o-y from 2040-2050. Some of our reviewers think that even greater growth is possible. [2]A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022), p88 indicates that it might be possible to reach 5 GtC/y (18.3 $GtCO_2e/y$) of CDR from microalgae cultivation but that would drop to 2 GtC/y in 10 years and reach a steady state of around 1 GtC/y (3.6 $GtCO_2e/y$) on centennial timescales due to macronutrient depletion.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost[2]
- Timeline to complete[2]

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION: 2.7

TAXONOMIC BUCKET: Biogenic

CDR CATEGORY: Stabilized biomass

APPROACH: Microalgae cultivated in open water and sunk

TRL

CRITICAL PATH ACTIVITIES

$1-1.6 billion | **15-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Field trials:** Perform controlled open ocean trials for both artificial upwelling and fertilization to determine the best cultivation methods and approaches for sinking
- **Environmental impact assessment:** Monitor ocean conditions during field trials to assess environmental impacts
- **Measurement hardware development:** Demonstrate measurement hardware to validate global algae removals and inform MRV

✓ Successful demonstration of microalgae growth, sinking, and sequestration

✓ Successful demonstration and use of measurement hardware

✓ Environmental impacts are determined to be manageable

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Ocean fertilization demonstrations:** 5-10 demonstrations of >100 t Fe and >1,000 km^2 initial patch size
- **Artificial upwelling demonstrations:** 2-3 locations for >1 year covering >1,000 km^2
- **Biomass sinking:** Demonstration of effective sinking
- **MRV:** Demonstration of (1) measurement technology and (2) defensible public accounting

$800M – $1.3B | **10 years**

✓ Successful operation of 10+ microalgae cultivation projects over 10+ years

✓ Development of reliable and accepted MRV, including growth measurement and transfer of that growth to sequestration depth

✓ Market competitive costs

✓ Ecosystem impacts are manageable

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[3]

$300-600 million | **20 years**

- Establish an open-source system for documenting and disseminating information on project data and impact assessments
- Perform ongoing studies of environmental and other impacts as projects are scaled
- Improve yields by engineering microalgae or their growth conditions
- Develop monitoring across all ocean CDR to address ocean MRV and track ecosystem impacts (cross-cutting activity)

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[3]

- Successful growth and sequestration of CO_2 without negative geochemical, physical, and ecological impacts over 10+ project sites over 10+ years
- Globally accepted measurement and MRV methodologies for validating removals and ensuring manageable environmental impacts
- Demonstration of removals through microalgae cultivation and storage at market competitive costs

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Workstreams and spending assessments are based on A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022). [3]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Field testing	Field trials for ocean fertilization[1]	Controlled trials testing open ocean fertilization[2] to determine the best dispersal methods, locations, and timing to increase the bioavailability of iron and other nutrients	✓ Determine best iron dispersal approach(es) ✓ Successful demonstration of increased microalgae growth and biomass sequestration	2-4	$3-5M/y[3]	5 y	$30-50M
Field testing	Field trials for artificial upwelling[1]	Controlled trials to test open ocean artificial upwelling with a specific focus on pump durability in open ocean environment,[2] with laboratory and mesocosm experiments to assess potential biological responses in deep water	✓ Successful demonstration of increased microalgae growth and sequestration ✓ Upwelling pumps withstand durability testing	2-4	$3-5M/y[3]	5 y	$30-50M
Field testing	Field trials for algae sinking	Assess different approaches to sink microalgae biomass as produced during the ocean fertilization and artificial upwelling field tests.	✓ Field experiments successfully demonstrate approaches for permanently sinking microalgae biomass	2-4	$1-5M/y[3]	2-4 y	$20-30M
Field testing	Environmental impact assessment	Measurement and monitoring of critical ocean metrics such as nutrient levels, oxygen content, and carbon content to ensure that all potential impacts are accounted for and assessed	✓ Environmental impacts are determined to be manageable ✓ Monitoring approach can be utilized for demonstrations	5-10	$0.5-1M/y[3]	5-10 y	$20-50M
MRV	Development of MRV methodologies	Development of (1) measurement technology and (2) defensible public accounting for tracking the carbon flux of microalgae to sequestration depth[1] and ensuring that sequestration of carbon dioxide is reliably measured over time	✓ Demonstrated measurement and verified secure storage of CO_2 for 10+ y ✓ Lab modeling supports the field testing results	2-3	$5-15M/y[4]	5-10 y	$50-300M

Note: *Early community engagement will be essential to ensure successful pilots, demonstrations, and commercial CDR activities. New permitting and laws also need to be instituted before large scale projects can or should be conducted.*[5]

Notes and sources: [1]A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) Chapters 3 and 4 [2]Controlled trials are expected to demonstrate durability and operability of microalgae equipment in a field environment. For artificial upwelling, this should include the testing of ~100 pumps in various locations. For both ocean fertilization and artificial upwelling, the field testing should test new measurement techniques including underwater drones. More detail can be found in the NAS 2022 report. [3]Estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) and NAS (2022) budgets for lab R&D funding. Details of this estimation can be found in the AIR Appendix. [4]The NAS 2022 (p124) estimates that $10M/y is needed for 10 years to develop new testing hardware and test it in open ocean environments. This will likely prove too low. [5]In the white paper Depending on the Ocean released in May 2023, Carbon180 calls for more robust policies and legal frameworks. Tagliabue et al. (2023) notes that ocean fertilization impacts could play out over decades with negative impacts on ecosystems.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Field demonstrations of >100 tons Fe and >1,000 km^2 initial patch size followed over annual cycles[1] with ongoing monitoring	10 $ktCO_2e/y$	✓ Successful operation of 10+ microalgae cultivation projects over 10 years ✓ Ongoing ecosystem monitoring with manageable ecological impacts, including benthic (ocean floor) systems ✓ Market competitive removal costs ✓ Reliable measurements of all geochemical, physical, and ecological impacts over the 10+ project locations ✓ Reliable measurement of additional nutrient growth and transfer of that growth to sequestration depth ✓ Demonstrated secure storage for 10+ y	5-10	$5-8M/y	10 y	$500M - $800M[3]
Demo	Implementation of demonstration-scale artificial upwelling and monitoring for more than a year over >1,000 km^2	10 $ktCO_2e/y$		3-5	$5-8M/y	10 y	$200-300M[3]
Demo	Implement permanent sinking of microalgae biomass grown during field trials. Perform ongoing monitoring of sunken biomass to assess storage permanence.	See above		4-6	$2-5M/y	5-10 y	$25-100M[3]
MRV	Ensure that the sequestration of carbon dioxide by carbon transfer to sequestration depth is validated through demonstration of (1) measurement technologies and (2) defensible public accounting.	N/A		1-3	$3-5M/y[2]	5-10 y	$15-50M
MRV	Monitor critical ocean metrics such as nutrient levels, oxygen content, and carbon content to ensure that all impacts are accounted for, including in deep sea environments.[2]	N/A		3-5	$2-5M/y[2]	10 y	$100-300M

Note: *These two cross-cutting methods can be superseded by cross-cutting aggregated ocean monitoring.*[6]

Notes and sources: [1]A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) notes that demonstrations that are both significantly longer and significantly larger than earlier studies are necessary to advance this approach. They note that demonstrations should be up to 100-1,000 tons of iron covering up to 1m km^2 of ocean (p95). Later, they recommend 5-10 sites each for ocean fertilization and artificial upwelling to gain predictive understanding of the impacts and sequestration potential of ocean seeding (p100). [2]NAS 2022 (Table 3.4, p100) notes that carbon fluxes might be tracked with drones or other field experiments for $3M/y for 5 y. However, it is likely that MRV will prove more complicated than described there. [3]This estimate is an amalgam of the NAS 2022 estimate (p124) and our general estimate of RD&D funding, as described in the AIR Appendix.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

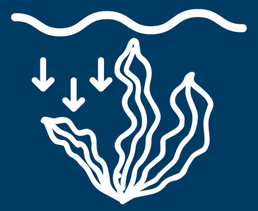
TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Open-source, global documentation system for studies, trials, and results	Creation of an open-source documentation system for recording ongoing projects, data, results, and independent impact assessments.[1] The system would include: • A map of current projects including activities, funders, status • Sharing and review of collected data • Sharing and review of impact assessments, and • Code of conduct for research and deployment of this CDR approach The open-source system can also be used to inform ongoing policy efforts and foster public acceptance.[2]	1	$2-4M/y	15-20 y	$30-80M
Lab / field testing	Additional environmental impact assessments	Additional areas of study should include outgassing of carbon from artificial upwelling, faunal impacts, water column impacts, etc.	3-4	$0.5-1M/y[3]	3-5 y	$5-15M
Lab / field testing	Engineering microalgae or growth conditions	Investigate improvements in algae growth and CO_2 uptake through approaches such as:[4] • Harnessing natural phenomena to increase microalgae growth • Creating biotechnologically enhanced microalgae with high carbon sequestration potential[5] • Investigating the incorporation of cyanobacteria with the ability to fix atmospheric nitrogen to increase growth rates of other microorganisms • Decreasing nutrient requirements or expanding tolerable environmental conditions	5-8	$1-3M/y[3]	5-10 y	$30M-200M
MRV	Aggregated ocean monitoring to address ocean MRV and track ecosystem impacts	Develop an aggregated global ocean monitoring program to assess the current state of the oceans including temperature, nutrient contents, and other relevant qualities. This can be done with a combination of empirical data (satellites, buoys, ships, drones, remote sensors) combined with analytical modeling. The goal is to (1) understand ecosystem health and (2) inform MRV development.[1]	1	$40-60M/y	20 y	$800M - $1.2B

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include new legal frameworks and permitting for ocean activities.*[6]

Notes and sources: [1]Activities that seek to use the oceans for CDR should ideally collaborate globally. Oceans are an interconnected ecosystem in which activities can have wide-ranging effects. These activities will also largely operate in international waters. Data sharing at all levels of projects will be essential to maintaining a healthy global commons. ICEF recommends in their Blue Carbon Roadmap (2022) that low-cost sensors be developed for monitoring, including hyperspectral, multispectral, LIDAR, biologging, and more. [2]Additional social and legal research is out of the scope of this AIR but will be essential to better understand where projects can best be deployed from both a legal governance and a social acceptance perspective. [3]Estimates based on averages from A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) and Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for lab R&D funding. Details of this estimation can be found in the AIR Appendix. [4]Ocean Visions roadmap for microalgae cultivation notes this as a first order priority. [5]Cross-cutting research between open ocean and artificial pond cultivation provides closed environments to test enhanced microalgae before any integration into open ecosystems. [6]In the white paper Depending on the Ocean, released in May 2023, Carbon180 calls for more robust policies and legal frameworks. Tagliabue et al. (2023) notes that ocean fertilization impacts could play out over decades with negative impacts on ecosystems.

SECTION 2.8

Macroalgae cultivated in open water and sunk



SECTION	2.8
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Stabilized biomass
APPROACH	Macroalgae cultivated in open water and sunk

DEFINITION

Enhancing macroalgae growth either in cultivated algae farms or in the open ocean, then sinking the biomass in the open ocean

EXAMPLE SCENARIOS

1) Collecting excess sargassum growing in the great sargassum belt using drone submarines that capture the sargassum, taking it to sinking depth, and depositing it on the sea floor; 2) seeding seaweed on purpose-built buoys, which create a platform for algae to grow, and are then deliberately sunk, taking the seaweed with them to the ocean floor.

RMI

Section 2.8 overview

Macroalgae cultivated in open water and sunk

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability, secure storage, and path to measurability at scale** • Key risks include dedicated area requirements of macroalgae cultivation, measurement at scale, and secure storage for deep water sinking
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • The sinking approach is mass-customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot stage** • ~6 companies at pilot stage, with <$15M in funding each • Other notable RD&D activity includes the ARPA-E MARINER program and basic research through the NASA Earth and Space Science Fellowship
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **300 MtCO$_2$ by 2050** • Success is contingent upon breakthroughs in ocean monitoring for verification and ecological impact assessments
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$425M-$1.6B over 10-20 years** • Key stage gates in cultivation and sinking processes as well as monitoring of CO_2 storage and environmental impacts

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability[2]	*Energy requirements*	**Low risk:** Near shore farming is low energy, but large-scale cultivation is likely to require considerably more energy input.	"Larger power sources" may be needed to operate large scale farms.[1,9] Harvesting and sinking may require additional energy.
	Suitable conditions	**Medium risk:** Gigaton scale CDR will encounter foreseeable constraints related to suitable growth and sinking locations.	There are uncertainties in whether there are sufficient growth environments with suitable nutrient availability and temperate range for macroalgae growth.[2] Similarly, there are uncertainties about the best places for sinking macroalgae.[1] Millions of tons of removals should be possible,[2,3] but gigatons will be difficult.
	Dedicated area requirements	**High risk:** The ocean surface area required for macroalgae cultivation at scale presents massive engineering, logistical, and maritime footprints.[1]	Gigaton scale CDR is only plausible on the high seas. At such scales, other considerations, such as environmental impacts, interference with commerce or shipping, conversion of macroalgae farming, and availability of suitable conditions will be stressed.[1,4] Removals of 100 $MtCO_2e/y$ are estimated to require 7.3 Mha of ocean surface.[1]
	Environmental impacts	**Medium risk:** Potential impacts on both the growth ecosystem and the benthic ecosystem may be significant, especially at scale.	There are large uncertainties as to the impacts from intensive farming on local environment nutrient cycles and ecosystem functions. These may include local ecosystems including deoxygenation, acidification, and eutrophication as well as impact on fauna in both the growth and sinking (benthic) ecosystems. There are also concerns about introducing invasive species.[1,4]
Secure storage for 100+ years		**High risk:** There is low certainty as to the permanence of deep water sinking of biomass that require additional study to be addressed.	Estimates of permanence are as low as 10-100 years,[1] with some estimates up to 1,000 yrs.[4] More study is needed, especially for depths less than 1000 m.
Path to measurement at scale		**High risk:** Reaching gigaton scale CDR will only be possible if essential breakthroughs are met in cultivation, measurement, and validation.	MRV for macroalgae sinking does not yet exist. Measurement and verification are generally understudied. Developing adequate MRV will require a significant effort to develop a combination of ocean monitoring and modeling.[1,8]
Pathway to full costs <$100/$tCO_2$		**Medium risk:** Operational costs are currently high but expected to come down with maturity and scale. MRV and insurance are major hurdles.	The spot price of macro-algae is currently ~$240[5] or around $1,368-2,052/t of dry biomass.[6] ARPA-E's MARINER program[7] has a goal for macroalgae production equivalent to ~$75/$tCO_2e$.

Notes and sources: [1]A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) [2]The NAS 2022 report indicates that total sequestration potential is limited to ~0.6 $GtCO_2e/y$ globally through natural macroalgae systems. "Uncertainties about nutrient availability and durability of sequestration, seasonality will limit sites" (p22). However, artificial or enhanced systems might be able to achieve higher rates of sequestration. [3]The Great Atlantic Sargassum Belt is estimated to contain >20 Mt material that contains between 27.41% - 29.23% carbon when dried. By weight, 6.861 t of wet Sargassum has absorbed 1 tCO_2. [4]Ocean Visions Sinking Macroalgae for Carbon Dioxide Removal (2023) [5]CDR.fyi [6]Offshore macroalgae biomass for bioenergy production: Environmental aspects, technological achievements and challenges (Fernand et al., 2016) [7]ARPA-E MARINER program 2021 annual review [8]One company shared their work building their own robot with cameras and lights to track sargassum on its path to the ocean floor. Their system will include sonar to track sargassum to 3,000 m and turbidity sensors dropped once a month to assess water clarity from upwelling. [9]NAS 2022 (p 137)

Potential for cost improvement

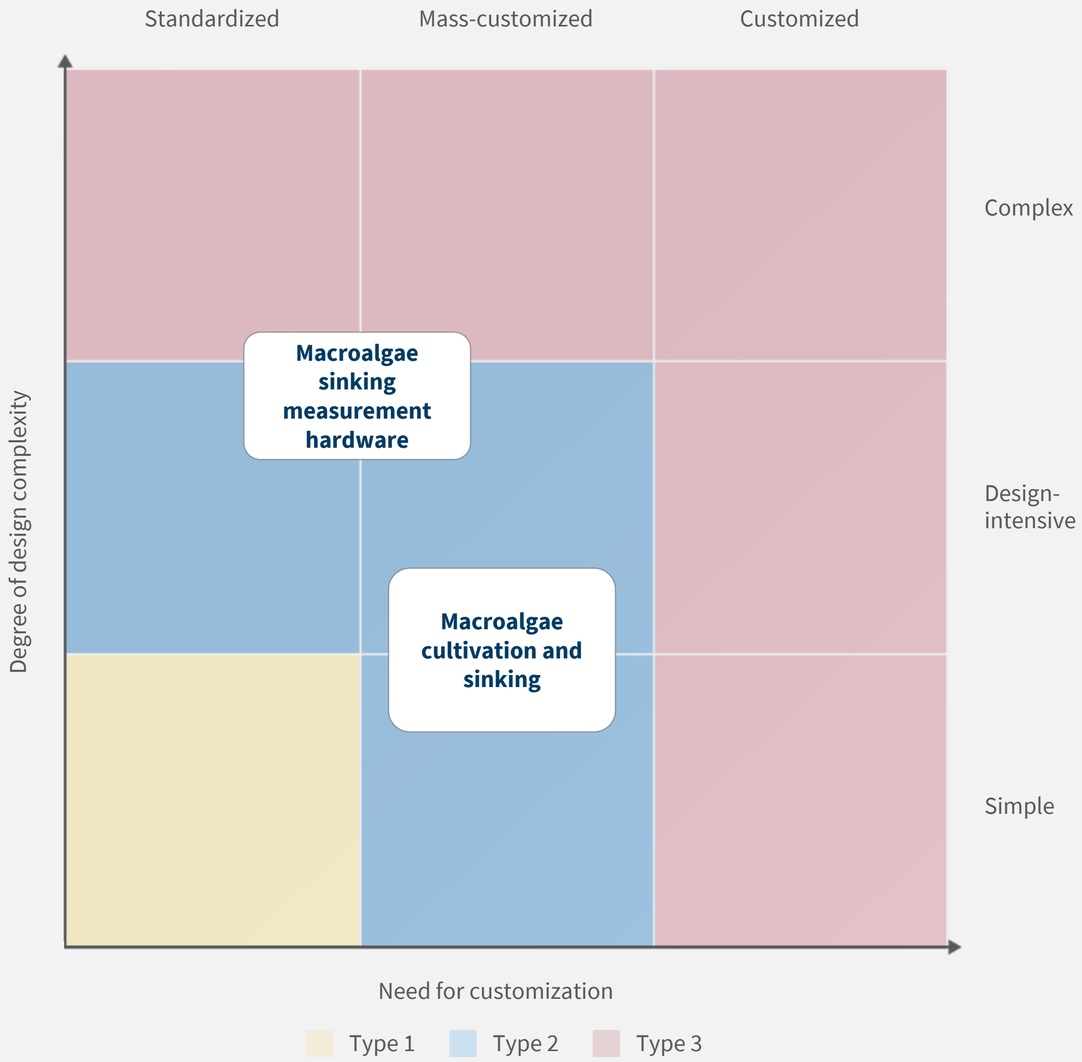
An assessment of two key drivers of learning rates

SECTION 2.8

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Macroalgae cultivated in open water and sunk



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating**: Design-intensive
- **Rationale:** Macroalgae cultivation systems are increasingly moving toward fewer parts. Some companies are pursuing macroalgae sinking with robots and automation reducing overall design complexity while still accounting for the complexity of the ocean environment.

NEED FOR CUSTOMIZATION

- **Rating:** Mass-customized
- **Rationale:** Macroalgae cultivation is a mass producible industry, possibly to the point of standardization. Macroalgae cultivation will benefit from economies of scale and deployment across global conditions.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

Current state of RD&D

A mapping of companies, plus other notable activities

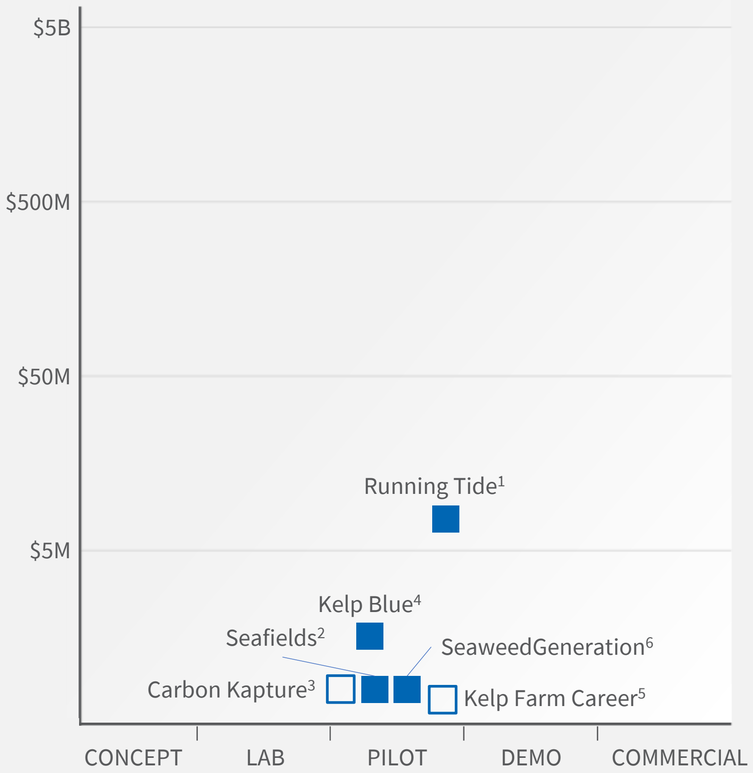
NOT EXHAUSTIVE

SECTION 2.8

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Macroalgae cultivated in open water and sunk



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Running Tide: Macroalgae growth on biodegradable buoys that sink[1]	$15M total[7]	• Delivered 100 t to Shopify for removals by sinking wooden buoys in the open ocean.[8] • Developing suite of in-situ monitoring hardware.[9]
SeaFields: Offshore farms for floating sargassum, followed by baling and sinking[2]	$310k innovation grant[10]	• 2022 — Growth experiments with baling and sinking • 2023 — Deploying prototype in open ocean • 2025 — Scale to 150 km^2 for 1 $MtCO_2e/y$ removals • 2030 — Scale to 65,000 km^2
Carbon Kapture: Macroalgae for biochar[3]	N/A	• Planning 200 farms over the next 10 years, which could capture over 360 $ktCO_2e/y$[11]
Kelp Blue: Growing and managing kelp[4]	$2M[12]	• Pilot operations underway in Namibia • Pilots planned in Alaska and New Zealand[4]
Kelp Farm Career: Large kelp farms in deep water[5]	N/A	• Ongoing research for mooring and anchor tech • Demonstrations at multiple kelp farms in China
Other companies and activities: SeaweedGeneration,[6] CarbonWave / Climate Foundation,[13,14] OceanWise,[15] Phykos,[16] Pull to Refresh Inc.,[17] Seaforestation.co,[18] SOSCarbon,[19] Kee Farms,[20] TROFX,[21] Ocean Visions[22,23]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
ARPA-E MARINER[24]	$60M over 2009-2021	• 18 large scale pilot and research operations on algae for biofuels
NASA Earth and Space Science Fellowship[25]	N/A	• Basic research for ocean carbon sequestration pathways

Notes and sources: [1]Running Tide is mainly focused on macroalgae sinking; however, the company is also working on mineral alkalinity enhancements by coating buoys with alkaline minerals which changes the pH of the ocean, facilitating the conversion of fast cycle aqueous carbon into slow carbon bicarbonate. [2]Seafields [3]Carbon Kapture [4]Kelp Blue [5]Kelp Farm Career [6]Seaweed Generation [7]Running Tide, MIT Technology Review (2022) [8]Running Tide Blog (2023), GreenBiz [9]Running Tide Blog [10]Seafields receives innovation grant. [11]Carbon Kapture plans for scale [12]DeBeers group has invested $2M as part of its carbon neutral goals. [13]CarbonWave utilizes seaweed throughout fertilizer and plant performance boosters. [14]Climate Foundation [15]OceanWise [16]Phykos [17]Pull to refresh Inc [18]Seaforestation.co [19]SOSCarbon [20]Kee Farms [21]TROFX [22]Ocean Visions, along with the Monterey Bay Aquarium Research Institute published Framework to Guide Research on Seaweed Cultivation and Sinking for CDR (2022) [23] A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by 2030 (Ocean Visions, 2023) outlines several funding opportunities and programs that are relevant across multiple CDR approaches that occur in the ocean, including MRV research, field trials, and spatial planning. [24]ARPA-E MARINER program 2021 annual review [25]NASA Fellowship #80NSSC18K1353 has supported basic research including "Quantifying the carbon export and sequestration pathways of the ocean's biological carbon pump" (Nowicki et al., 2022).

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

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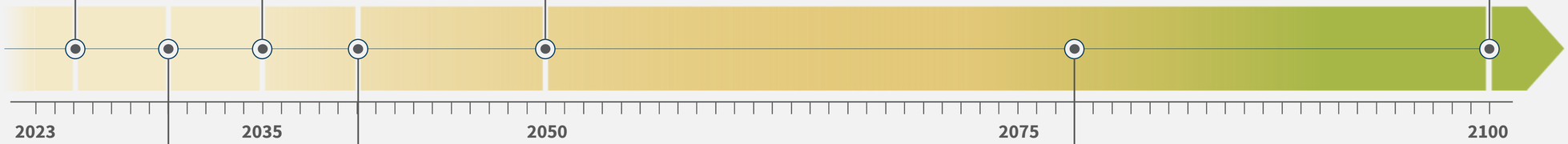


2025

- Four macroalgae farming demonstrations of 100 hectares or larger are funded[1]
- Four demonstrations of autonomous vehicles for macroalgae sinking are funded
- Additional cross-cutting ocean CDR funding is committed for ecological monitoring of ocean systems and verification of removals.
- First 1 $ktCO_2e$ of removals are measured and verified.

2030

- Publicly accepted MRV methodologies are established based on field measurements and modeling.
- Dramatic increases are made to funding ocean monitoring for verification of sinking, MRV, and ecological monitoring
- Field trials, R&D, and demonstrations build consensus in the academic community that macroalgae sinking is safe and effective.
- 30 $ktCO_2e/y$ is sequestered.[3]

2035

- Successful commercialization of macroalgae sinking
- Effective measurement hardware, modeling, and processes are utilized globally to inform MRV
- Significant continued research and funding for software and hardware to provide ocean monitoring
- Rapid expansion of macroalgae sinking deployment in the 2030s
- Removals [3] reach 1 $MtCO_2e/y$.

2040

- Significant research and funding for monitoring and verification software and hardware continues.
- Basic R&D, field testing, and demonstrations have led to improved growing and sinking performance.
- Enhanced macroalgae cultivars are safely deployed to increase growth and removals.
- Removals[3] reach 21 $MtCO_2e/y$.

2050

- Aggregated ocean monitoring systems, first developed independently for algae, alkalinity enhancement, and electrochemical processes, are consolidated and used across all ocean CDR.
- Continued breakthroughs in growing and sinking of macroalgae drive increased deployment of this approach
- Removals[3] of 300 $MtCO_2e/y$ [2]

2050-2100

- Macroalgae sinking continues to expand globally and becomes an established practice along with other sustainable ocean practices.[4]
- Long term ecological monitoring determines that growing and sinking macroalgae is safe and sustainable.

2100

- Macroalgae sinking reaches a steady state of around 600 $MtCO_2e/y$ removals.[4]

Notes and sources: [1]Ocean Visions Sinking Macroalgae for Carbon Dioxide Removal (2022) [2]A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) indicates that 100 $MtCO_2e/y$ would require ~7.3 Mha of ocean surface. [3]We expect the global scaling of macroalgae sinking to be significantly limited until adequate measurement capabilities and MRV can be developed. We estimate that the first thousands of tons will be claimed in the next few years, but that it will take until at least 2030 to develop sufficient measurement hardware, protocols, and third-party verification to ensure that macroalgae CDR is additional and that the carbon is sunk and sequestered to permanent depth. However, similar to microalgae sinking, while macroalgae sinking is starting from a small initial capacity, if significant breakthroughs are made on sinking and measurement, a rapid period of growth in the 2030s is feasible. Based on these assumptions, we assume that there will be 1 $ktCO_2e/y$ removed in 2025 and that this will increase by 100% y-o-y (doubling each year) to 2040 and then grow at 30% until 2050. [4]The NAS (2022) report estimates that it may be possible to reach 600 $MtCO_2e/y$ removals in a sustainable way. Ocean Visions estimates that it may be theoretically possible to reach 10 $GtCO_2e/y$, but that realized CDR may be much lower due to complicating factors.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost[2]
- Timeline to complete[2]

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 2.8

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Stabilized biomass

APPROACH Macroalgae cultivated in open water and sunk

TRL

CRITICAL PATH ACTIVITIES

$425M-$1.6B | **10-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Development of macroalgae harvesting:** Pilot macroalgae harvesting and conveyance to durable ocean storage
- **Environmental monitoring:** Field trials to monitor the long-term fate and environmental impacts of macroalgae following pilot scale sinking
- **Measurement and monitoring:** Verify and track carbon transfer to sequestration depth

$75-300 million | **5-10 years**

- ✓ Manageable ecosystem and environmental impacts at scale
- ✓ Confirm net sequestration rates are positive and significant
- ✓ Confirm operational and economic feasibility of sinking processes
- ✓ Measurable, secure storage of CO_2

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Macroalgae farms:** Demonstrate cultivation, harvesting, and sinking of macroalgae
- **Autonomous vehicle macroalgae sinking:** Demonstrate sinking using unmanned systems to sink existing macroalgae
- **Monitoring and MRV:** Develop (1) measurement technology and (2) defensible public accounting to inform MRV

$350M-$1.3B | **5-10 years**

- ✓ Cultivation at scale with consistent removals
- ✓ Operational and economic feasibility of MRV at scale
- ✓ Demonstrated safety and efficacy of automated sinking systems
- ✓ Manageable ecosystem impacts
- ✓ Demonstration of 100+ y expected permanence

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[3]

$250-550 million | **5-20 years**

- Enhanced modeling to better understand the long-term fate of macroalgae during and after sinking
- Spatial planning for macroalgae sinking in proximity to suitable growth sites
- Genetic engineering and synthetic biology to improve growth and sequestration qualities of macroalgae
- Develop monitoring across all ocean CDR to address ocean MRV and track ecosystem impacts (cross-cutting activity)

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[3]

- Manageable ecosystem impacts
- Scalable for ongoing, impactful amounts of CO_2 removal
- Reliable measurability with verified secure storage of CO_2
- Widely accepted public accounting for macroalgae sinking removals
- Market competitive costs
- Accessible private financing for large scale macroalgae projects

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Workstreams and spending assessments are based on A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022). [3]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Field testing	Development of macroalgae harvesting and sinking machinery	Perform pilot field trials to test various methods for harvesting, transporting, and sinking macroalgae. The purpose is to validate the conveyance of macroalgae to durable ocean storage. This can be done by various approaches, such as: • Drones that capture existing macroalgae, sink it, and release it at depth • Purpose built buoys that cultivate algae pods and sink with their contents	✓ Manageable environmental impacts across ocean systems ✓ Pathway to sufficient scale for ongoing, impactful CO_2 removals ✓ 100+ y expected storage permanence ✓ Path to market competitive costs	2-10	$2M/y[1]	1-3 y[2]	$5-50M
Field testing	Long term tracking and characterization of macroalgae sinking	Determine the viability of long-term storage and associated environmental impacts: • Assess long-term impacts of macroalgae biomass on ecosystems (benthic and other)[3] • Monitor the long-term fate of macroalgae following pilot-scale sinking.[4]		2-4	$4-5M/y[5]	5-10 y	$40-80M
Field testing	Environmental impact assessment	Monitoring of critical ocean metrics such as nutrient levels, oxygen content, and carbon content to ensure that all potential impacts are accounted for	✓ Environmental impacts are manageable ✓ Monitoring approach can be deployed for use in demonstrations	5-10	$0.5-1M/y[3]	5-10 y	$20-50M
MRV	Monitoring of carbon transfer and stability at sequestration depth	Demonstration of (1) measurement technology and (2) defensible public accounting to track the carbon flux of algae to sequestration depth[6] and ensure the sequestration of carbon dioxide is reliably measured over time	✓ Demonstrated, reliable measurability and verified secure storage of CO_2 for 10+ y ✓ Lab modeling supports the field test results	2-3	$5-15M/y[5]	10y	$50-300M

Notes and sources: [1]One startup that provided input believes these costs are closer to $500k whereas other macroalgae experts put costs at $2-4M/y. [2]A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) lists the timeframe as 10 y, but reviewers suggest it may be possible to do these tests over a shorter period. [3]Ocean Visions contributed to an expert advice report for Running Tide that identifies many potential ecosystem impacts at different scales. [4]Controlled trials should monitor for macrofaunal entanglements, introduction of nonnative cultivars, potential biomarkers for tracking and quantification, hazards to navigation, displacement of fishing efforts and other human, economic, and environmental impacts. More detail can be found in the NAS (2022) report. [5]The NAS (2022) report estimates that $4M should be spent for 10 y on ecosystem impacts and $5M for 5 y on biomass sinking. These values may need to be higher to account for the development of new hardware and with testing in open ocean environments. Thematic experts and startup founders that provided input have suggested that costs may need to be even higher and involve cross-cutting, collaborative ocean monitoring. We have kept this line-item cost estimate smaller but included a path-boosting activity for aggregated ocean monitoring. [6]NAS (2022) Chapters 3 and 4

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET[7]	DURATION[7]	TOTAL COST
Demo	Large scale macroalgae farms of at least 100 hectares to demonstrate growth, harvesting, and sinking of macroalgae[1]	1 $ktCO_2e/y$[2] per project	✓ Demonstrated potential scale for impactful, ongoing CO_2 removals ✓ Demonstration of 100+ y expected permanence ✓ Market competitive removal costs	4-6	$10-15M/y	5-10 y	$200-600M
Demo	Large scale demonstration of autonomous vehicles for sinking existing macroalgae[3]	5-10 $ktCO_2e/y$[4]		2-4	$5-10M/y	5-10 y	$50-400M
MRV	Monitoring at demonstration-relevant locations to assess critical ocean metrics such as nutrient levels, oxygen content, and carbon content to ensure that all impacts are accounted for, including on deep sea environments	Demonstrations of 100 hectares or larger[2]	✓ Impacts to growth and benthic (ocean floor) ecosystems are manageable ✓ Reliable measurability and verified secure storage of CO_2 for 10+ y	3-5	$2-5M/y	10 y	$100-300M
MRV	Demonstration of (1) measurement technology and (2) defensible public accounting to ensure that the sequestration of carbon dioxide can be reliably assessed[5]	Demonstrations of 100 hectares or larger[2]		1-3	$3-5M/y[2]	10 y	$15-50M

Note: *These two cross-cutting methods can be superseded by cross-cutting aggregated ocean monitoring.*[6]

Notes and sources: [1]Demonstration scale facilities should consider including at least one coastline-based macroalgae farm and two open ocean farms. At least one farm should be built in the Atlantic and one in the Pacific. One should be considered as part of an offshore wind farm consortium. [2]The demonstration size of 100 hectares is based on the largest size of a demonstration facility cited by Ocean Visions (p29). They estimate that a 1 km^2 growth area would cost $105M for 5 y and sequester 6.6 t/y of macroalgae (wet weight). [3]SeaweedGeneration, for example, is building test robots that can capture sargassum at the surface in less than 1 minute, take that biomass to ~200 m and then release it before cycling back to the surface. Fleets of drones should work in tandem and demonstrate safe operational performance with the environment and maritime activity. [4]By weight, 6.861 t of wet Sargassum has absorbed 1 tCO_2; therefore, ~68 kt sargassum biomass is required to provide 10 $ktCO_2e$ removals. The Great Atlantic Sargassum Belt is estimated to contain >20 Mt material that must be removed each year. [5]A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) Table 5.2 is to validate and monitor the macroalgae cultivation system. This can be reframed as a demonstration of measurement technology accompanied by defensible public accounting to ensure carbon sequestration and inform MRV development. [6]The (NAS 2022) report estimates that $4M should be spent for 10 y on ecosystem impacts and $5M for 5 y on biomass sinking. We have included a similar line item for technical MRV considerations in the pre-demonstration needs. All of these MRV activities may be superseded by a cross-cutting, path-boosting activity that monitors ocean environments and impacts across all ocean CDR approaches. [7]Estimates based on (NAS 2022) and our general estimate of RD&D funding, as described in the AIR Appendix.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTIONS	# OF PROJECTS	PROJECT BUDGET[2]	DURATION[2]	TOTAL COST
Desktop research	Extended modeling to understand the long-term fate of stored macroalgae	Better ocean modeling can improve understanding and deployment of biomass storage at depth for increased fidelity in permanence and spatial stability over time.	2-5	$1M/y	5 y	$10-20M
Desktop research	Document “best practices” and perform geographic deployment planning in tandem with other ocean resources	Macroalgae removals at scale will require significant ocean surface area for cultivation. Ocean space for macroalgae must be sited in relation to suitable growth conditions, as well as competition for space with offshore wind, shipping, fishing, and protected ecosystems.	2-5	$1M/y	5 y	$10-20M
Lab	Enhanced macroalgae cultivars	Research on species and genomics, including synthetic biology and microbiomes, to identify, select, and develop favored strains that can uptake more CO_2, decay more slowly, and thrive in waters that are warmer, more acidic, or less nutrient dense.	5-8	$1-3M/y[3]	5-10 y	$30-100M
MRV	Aggregated global ocean monitoring to address ocean MRV and track ecosystem impacts[1]	Develop an aggregated global ocean monitoring program to assess the current state of the oceans including temperature, nutrient contents, and other relevant qualities, including deep sea environments. This can be done with a combination of empirical data (satellites, buoys, ships, drones, remote sensors) combined with analytical modeling. The goal is to (1) understand ecosystem health and (2) inform MRV development.	1	$40-60M/y	20 y	$800M - $1.2B

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include new legal frameworks and permitting for ocean activities.[4]*

Notes and sources: [1]A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) estimates that $4M should be spent for 10 y on ecosystem impacts and $5M for 5 y on biomass sinking. These values may need to be higher to account for the development of new testing hardware and testing it in open ocean environments. Thematic experts and startup founders that we have talked to think that costs may need to be even higher and involve cross-cutting, collaborative ocean monitoring. This cross-cutting activity would develop a comprehensive global ocean monitoring program to study ocean health and establish accepted MRV. It would apply to macroalgae and microalgae sinking in the open ocean, as well as terrestrial biomass sinking and all forms of ocean-based capture. ICEF recommends in their Blue Carbon Roadmap (2022) that low-cost sensors be developed for monitoring, including hyperspectral, multispectral, LIDAR, biologging, and more. [2]Estimates based on NAS 2022 and on the cost estimation methodology detailed in the AIR Appendix. [3]Estimates based on BETO PEAK Project [4]In the white paper Depending on the Ocean released in May 2023, Carbon180 calls for more robust policies and legal frameworks.

2. Sequestration of CO_2 from biomass

Approaches that use photosynthesis as the CO_2 capture step but then rely on combustion to convert that biomass to CO_2, which is then stored

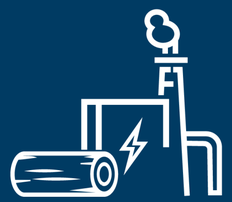
INDEX	APPROACHES	DEFINITION
3.1	BECCS to electricity	Thermal conversion of biomass (either dedicated feedstock or waste) to generate electricity and produce CO_2 that is captured with CCS technology
3.2	BECCS to fuels	Thermal or biochemical conversion of biomass (either dedicated feedstock or waste) to generate fuels and produce CO_2 that is captured with CCS technology

RMI classifies sequestration of CO_2 from biomass approaches as **biogenic**

Biogenic (bCDR)	Geochemical (gCDR)	Synthetic (sCDR)	Storage
Living biomass **1.1** Improved management **1.2** Conservation / protection **1.3** Restoration / creation **Stabilized biomass** **2.1** Biomass direct storage **2.2** Timber building products **2.3** Other biomass building products **2.4** Pyrolysis (biochar) and storage **2.5** Pyrolysis (bioliquid) and storage **2.6** Microalgae in ponds **2.7** Microalgae in open water **2.8** Macroalgae in open water **Sequestration of CO_2 from biomass** **3.1** BECCS to electricity **3.2** BECCS to fuels	**Solid carbonate minerals** **4.1** Surficial **Dissolved bicarbonate sequestration** **5.1** Terrestrial enhanced weathering **5.2** Coastal enhanced weathering **5.3** Mineral alkalinity enhancement	**Indirect water capture (IWC)** **6.1** CO_2 stripping **6.2** Electrochemical alkalinity production **Direct air capture (DAC)** **7.1-7.3** Liquid solvent **7.4-7.7** Solid sorbent **7.8-7.9** Membranes **7.10** Cryogenic	**Storage of CO_2** **8.1** Conventional CO_2 storage **8.2** In-situ mineralization **8.3** Ex-situ mineralization

SECTION 3.1

BECCS to electricity



SECTION	3.1
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Sequestration of CO_2 from biomass
APPROACH	BECCS to electricity

DEFINITION

Thermal conversion of biomass (either dedicated feedstock or waste) to generate electricity and produce CO_2 that is captured with CCS technology

EXAMPLE SCENARIOS

1) Combusting pelletized wood from forest thinnings in a thermal power plant to produce electricity and a stream of CO_2 that can be captured and stored; 2) gasification and then combustion of cultivated biomass to produce electricity and a stream of CO_2 that can be captured and stored.

Section 3.1 overview

BECCS to electricity

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/tCO$_2$** • Key risks include energy requirements across the full life cycle, land use, and water requirements from scale up, limited waste biomass supply, CCS technology challenges, and cost path to <$100/tCO$_2$ threshold
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Low** • This approach is customized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot stage** • ~4 companies at pilot stage • Other notable RD&D activity includes the DOE FECM program
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **1.9 GtCO$_2$ by 2050** • Success is contingent upon breakthroughs in CCS technologies and sufficient supply of sustainable feedstocks
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$300M-$1.5B over 5-15 years** • Key stage gates in feedstock supply, validation of CO_2 capture incorporating net life cycle energy balance, and pathways for retrofits as well as new plants

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

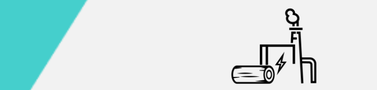
Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**High risk:** The full life cycle net energy balance can result in overall energy loss.	The most significant energy demand is drying and pelletizing feedstock. It can be ~70% of the full life cycle energy consumption for feedstocks with high moisture content in woody biomass.[1,2]
	Water requirements	**High risk:** Biowaste does not require water, but dedicated crops and processing will consume significant amounts of water.	Waste and non-irrigated crops should be prioritized. The use of dedicated crops could require significant water demand,[3] with studies reporting 5-60 gigatons of water may be required per $GtCO_2e$ sequestration. If so, each gigaton of removals would require up to 1.5% of global freshwater withdrawals.[2,4,5]
	Fertilizer requirements	**Medium risk:** Dedicated wood crops require infrequent, minimal application of fertilizers.	Fertilizing commercial wood plantations to produce biomass is rarely practiced. However, some sources indicate up to 200 lbs/acre of nitrogen can be used.[6] This rate of application could require up to 12 Mt/y fertilizer per $GtCO_2e$, or about 5% of 2019 fertilizer consumption.[4,7]
	Land use requirements	**High risk:** Gigaton scale removals will require both cultivated crops and biowaste, with significant associated land requirements.	Gigaton-scale BECCS may need 30-80 Mha of land (for comparison, Texas is about 70 Mha). This would likely require significant land-use conversion in proximity to power generation sites.[2,4,5,8] Biomass will also face increased competition for use.[9]
	Environmental impacts	**Medium risk:** Impacts are likely to include air quality and ecosystem impacts from land-use conversion for dedicated crops.	BECCS has associated combustion emissions but may also improve air quality by moving disposal burning to closed systems.[2,4] Significant land use conversion also impacts local ecosystems.
	CCS technology	**High risk:** Significant challenges in CCS must be addressed for BECCS to achieve affordable, high capture rates.	Current pilots are focused on amine-based post combustion CCS technologies for BECCS plants. Initial results indicate this approach is highly sensitive to the feedstock type and power plant system. It also cannot capture 100% of emissions in an economically feasible way.[4,8,10,12]
Secure storage for 100+ years		**Low risk:** CCS provides secure, durable storage.	CO_2 geological storge is a mature and well-regulated practice; however, proximity to feedstock and conversion affects the availability and cost of storage.
Path to measurement at scale		**Medium risk:** The measurement of sequestered CO_2 is straightforward, but the LCA of BECCS approaches is challenging.	While measurement of sequestration is simple, there is a lack of consensus for BECCS lifecycle accounting, resulting in a wide range of net removal estimates.[1,8] Creation of a Product Category Rule could provide comparable LCAs.[14]
Pathway to full costs <$100/$tCO_2$		**High risk:** Given the current state of technology and operations, there is not yet a clear path to unsubsidized, all-in costs <$100/$tCO_2$.[8]	In most geographies, BECCS systems will require significant subsidies.[8,13] Future cost reduction pathways are limited due to the high complexity and customization of BECCS systems.[11]

Notes and sources: [1]The energy return on investment of BECCS: is BECCS a threat to energy security? (Fajardy & Mac Dowell, 2018) [2]Reviewers note that the use of different feedstocks could bring risks to low or medium due to differences in feedstocks and processing approaches. [3]Hybrid poplars planted at 900 trees per acre and receiving 10 gallons of water per inch of trunk diameter for 2/3 of the year could require several hundred gigatons of water per $GtCO_2e$ removed. [4]Surveying the BECCS Landscape (EFI, 2022) [5]Royal Society Greenhouse Gas Removal 2018 [6]Texas A&M Forest Management [7]Global fertilizer consumption in 2019 was 215 Mt [8]Greenhouse Gas Removal Technology – Chapter 5 (Fajardy, 2022) [9]The 2016 Billion Ton report estimates there will be sufficient biowaste supply, but biomass will have many competing demands. Further discussion can be found in the bCDR introductory material. [10]Impact of BECCS on amine-based CO_2 capture solvents in a pilot-scale combustion environment (Strege et al., 2022) [11]Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020) [12]Toshiba SSE's largest pilot only captures 47% of whole BECCS plant emissions. [13]A reviewer notes that public benefits from reduced wildfire risk through use of forest thinnings may justify subsidies. [14]Product Category Rules

Potential for cost improvement

An assessment of two key drivers of learning rates

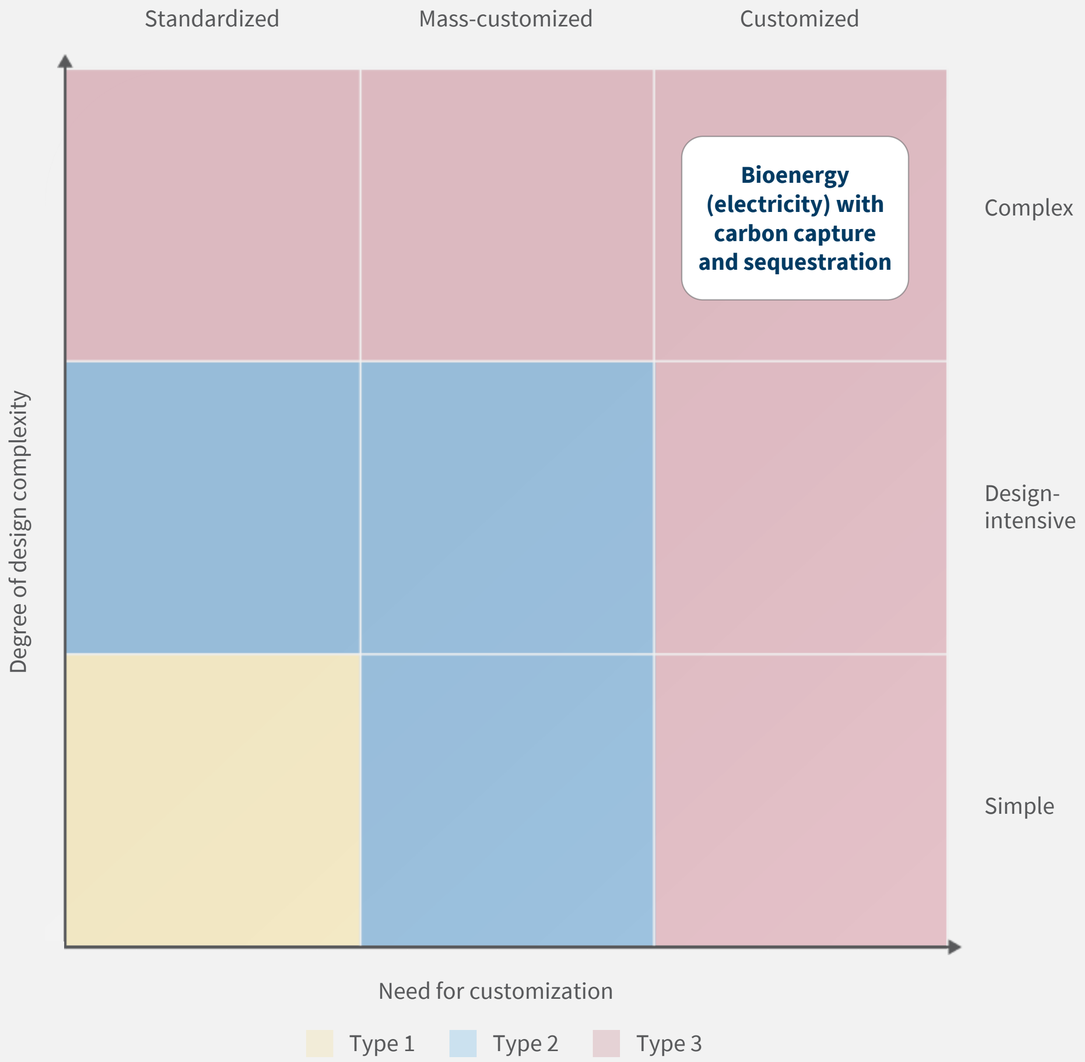


SECTION 3.1

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Sequestration of CO_2 from biomass

APPROACH BECCS to electricity



OVERALL RATING

Type 3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Complex
- **Rationale:** The full lifecycle of BECCS systems include numerous distinct processes, including feedstock growth, harvest, transport, and processing, then a complex thermal recovery system and CCS unit.

NEED FOR CUSTOMIZATION

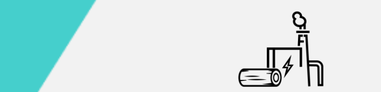
- **Rating:** Customized
- **Rationale:** BECCS plants are highly customized to the specific quality and characteristics of any given feedstock. Even similar feedstock types of different origin could affect BECCS performance.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

Current state of RD&D

A mapping of companies, plus other notable activities

NOT EXHAUSTIVE



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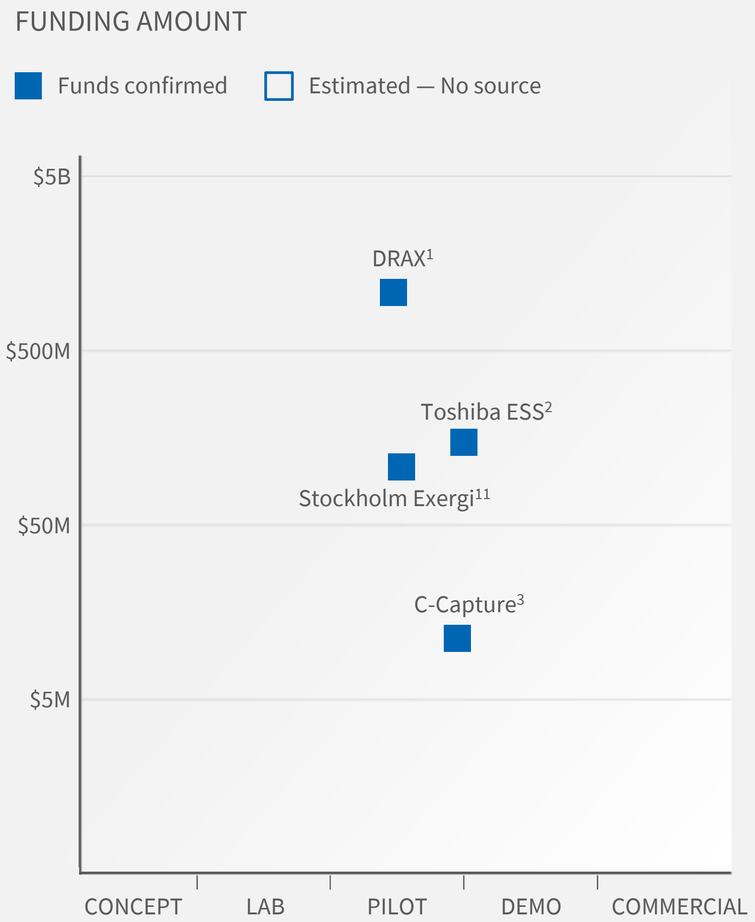


NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
DRAX: British power utility scaling BECCS in the UK and US[1]	$2B company investment over a decade[4]	• DRAX completed ~100% conversion of plant with 2,600 MW capacity from coal to wood pellet feedstock[1] • Targeting first commercially operating BECCS plant in 2027 with CCS capacity of >8 $MtCO_2/y$[4]
Toshiba ESS: Japanese utility investing in CCS technology for BECCS plants	$212 .63M[5]	• 2017 — Completed full conversion of coal plant (50 MW capacity) to 100% palm kernel combustion • Since 2009 — Testing small pilot with post-combustion CCS design (~10 tCO_2/day) • 2020 — Completed large pilot CCS unit with a capacity of 223 $ktCO_2/y$[6]
C-Capture: British company capturing CO_2 using a post-combustion approach	$23.3M[7,8,9]	• BECCS pilot plant operational at DRAX in 2019 • New XLR8 CCS project funded and under development for demonstration
Other companies and activities: Mitsubishi Heavy Industries,[10] Stockholm Exergi,[11] Ince Biomass Plant,[12] Ørsted,[13] Arbor Energy[14]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
DOE – FECM: CCS RD&D[15]	Past: $2.7B Future: $12.1B	• US government funded CCS related research since 1997 • Appropriated budget for FY22-26 include $8.5B (IIJA) and $3.6B (DAC-hubs)

Notes and sources: [1]DRAX [2]Toshiba ESS [3]C-Capture [4]DRAX will invest £2B to build two BECCS units during the 2020s. [5]Reported cost of the entire BECCS project to date, including coal to biomass plant retrofit and CO_2 capture pilot projects, with the storage phase under construction. The funding source is not clear but was assumed to be PPP Japan government backing for Toshiba ESS. [6]Current CCS capacity is only 50% of power plant emissions, which are captured but not stored. [7]Crunchbase funding estimate for C-Capture [8]UK government awarded C-Capture £5M for RD&D of CCS technology at the DRAX plant. [9]£1.7M awarded [10]Mitsubishi Heavy Industries [11]Stockholm Exergi BECCS funding [12]Ince Biomass Plant website and $6.6M funding from UK government and from BEIS [13]Ørsted awarded 20-year contract for plant to begin capturing carbon in 2025. [14]Arbor Energy has raised an estimated $12.5M (Pitchbook). [15]Congressional Research Service Report on CCS (2022)

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

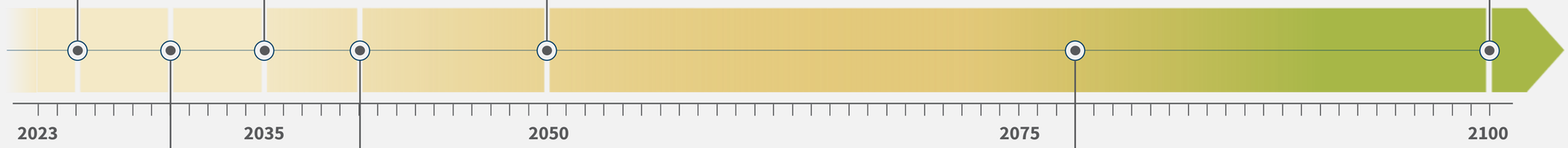
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 3.1

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Sequestration of CO_2 from biomass

APPROACH BECCS to electricity



2025

- In line with IEA projections, 20-25 $MtCO_2/y$ of BECCS facilities are either operational, under construction, or undergoing feasibility assessment.[1]
- Significant R&D funding is dedicated to feedstock pre-treatment, CCS technology, and BECCS systems to achieve high capture rates at low costs.
- Demonstration scale funding is allocated for (1) thermal power generator retrofits and (2) first of a kind BECCS facilities.

2030

- At least 2 new FOAK commercial BECCS plants and at least 2 BECCS thermal generator retrofits are fully operational
- Full LCA data demonstrate significant and externally verified net removals.
- Global BECCS removals reach 10 $MtCO_2/y$.[1]
- Increasing emphasis is placed on developing smaller-scale BECCS systems using gasification, tailored to local conditions and biomass sources, and linked together in regional CCS hubs.

2035

- Thermal generation retrofits have shown significant success in the previous 10 years and now have access to private capital at low-risk rates.
- FOAK BECCS facilities are funded and built in geographies with favorable feedstock options.
- Global BECCS removals reach 40 $MtCO_2/y$.[1]

2040

- Advances in feedstock supply logistics and enhanced cultivars decrease the cost of removals and improve the LCA.
- Sustainable biomass supply is still prioritized and BECCS facilities have a positive, publicly disclosed LCA.
- Global BECCS removals reach 140 $MtCO_2/y$.[1]

2050

- Global BECCS operations have achieved stable, sustainable biomass sourcing.
- Breakthroughs in enhanced cultivars plus improved feedstock supply logistics create specialized geographic pockets where BECCS processes are competitive.
- Broad energy transition funding leads to breakthroughs in CCS technologies that significantly benefit BECCS.
- If all prior activities are achieved, BECCS removals could reach 1.9 $GtCO_2/y$.[1,2]

2050-2100

- BECCS plants continue to operate where economically sensible and environmentally sustainable.
- Total removals reach a steady state of about 1 $GtCO_2/y$ and are capped due to feedstock constraints, sustainability concerns, and lack of cost competitiveness.[1,2]

2100

- BECCS plants continue to operate where economically sensible. This is likely to occur in key geographic areas.
- Total removals remain at about 1 $GtCO_2/y$.

Notes and sources: [1]According to the IEA, there are around 2 Mt of biogenic CO_2 currently captured per year, mainly in bioethanol applications. No new BECCS facilities are expected to be operational by 2025. Drax has noted that it hopes to be removing 8 $MtCO_2/y$ as early as 2027, though these projects may already be at risk. Drax has also announced 2 new facilities with capacity of 6 $MtCO_2/y$ by 2030 in the US. IEA data expects BECCS plants that are either operational, under construction, or in feasibility to reach approximately 40 $MtCO_2/y$ by 2030. By contrast, IEA Net Zero Emissions by 2050 scenario calls for about 250 $MtCO_2/y$ by 2030. The State of CDR report estimates that 10 $MtCO_2/y$ may be possible. Here we have assumed 30% y-o-y growth from 2030-2050 based on a starting point of 10 $MtCO_2/y$ in 2030. [2]Removals continue at 1-2 $GtCO_2/y$. The IPCC AR6 WG3 (p158) expects BECCS to remove 2.75 $GtCO_2/y$ in 2050, but this does not account for other bCDR demand for biomass feedstock. The IEA DACCS report (Apr 2022) expects 1.4 $GtCO_2/y$ from BECCS in 2050.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

TRL

CRITICAL PATH ACTIVITIES

$300M - $1.5B | **5-15 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Feedstock R&D:** Assess novel feedstock cultivation, processing and pretreatment pathways
- **BECCS plant equipment R&D:** Model and test novel designs for process intensification, power generation efficiency, and CCS approaches, materials, and impacts

$60-150 million | **3-5 years**

✓ Sustainable feedstock supply

✓ Demonstrate CO_2 capture rates and energy efficiency at or above industry standard

✓ Pathway to market competitive costs[2]

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Thermal generator to BECCS retrofits:** Test novel BECCS systems as retrofits to retired coal power plants
- **New BECCS plants:** Demonstrate FOAK BECCS systems equipped with Best Available Control Technology (BACT)

$250M - $1.3B | **5-10 years**

✓ Clear pathway for NOAK retrofitted and new plants to reach market competitive CDR costs

✓ Full LCA indicates net removals

✓ Full BECCS system energy balance is net positive

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

SECTION: 3.1

TAXONOMIC BUCKET: Biogenic

CDR CATEGORY: Sequestration of CO_2 from biomass

APPROACH: BECCS to electricity

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[3]

$200-300 million | **15 years**

- Test and model alternative biomass collection and distribution systems / business models to improve supply chain logistics
- Establish a standardized methodology for full life cycle assessment and net energy balance accounting frameworks
- Evaluate solvent degradation and emissions for relevant CCS methods
- Develop enhanced cultivars for biomass production

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[3]

- Demonstrate unsubsidized, market competitive costs
- Demonstrate full LCA net negative emissions via independent review
- Achieve financing costs in line with commercially accepted technologies

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Short-term CDR costs may be subsidized by utilization of fly-ash or other byproducts as a carbon utilization product. [3]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	Equipment optimization R&D	Advances in feedstock pre-treatment: • Model and test alternative biomass pre-processing systems, such as passive designs or electrified units.[1,2,5]	✓ CCS energy demand and capture efficiency in line with or better than current industry average for non-BECCS plants[3,5]	3-5	$0.5-2M/y[8]	1-3 y	$5-20M
		Advances in CCS: • Model and test alternative materials and / or unit designs to improve CO_2 capture rates, gas separation, and compression for storage.[4]		2-4	$1-2M/y[8]	3-5 y	$10-20M
		Advances in power generation efficiency: • Model and test alternative unit designs optimizing for increased power generation capacities and CO_2 capture rates.[5]		2-4	$1-2M/y[8]	3-5 y	$10-20M
Pilot	System optimization R&D	Test alternative system configurations for new feedstocks, process integration and intensification, novel treatment processes, and novel CO_2 capture and separation approaches.	✓ CO_2 capture performance meets or exceeds EPA regulations[7] ✓ Pathway to market competitive removal costs[9]	1-2	$5-10M/y	3-5 y	$20-40M
Pilot	FEED study	Conduct Front End Engineering & Design, feasibility, and siting studies of novel systems for both new BECCS and converted coal plants.	✓ Identify appropriate sites for demonstrations	1-2	$10-20M/y[6]	2-3 y	$20-50M

Notes and sources: [1]This may include innovative approaches to crop intensification like aquaponics systems or other methods investigated by the DOE BETO programs. [2]Pre-treatment is the most energy intensive phase for most BECCS and can account for 50-80% of the full life cycle energy consumed (EFI BECCS). [3]Greenhouse Gas Removal Technology – Chapter 5 (Fajardy, 2022) [4]Impact of BECCS on amine-based CO_2 capture solvents in a pilot-scale combustion environment (Strege et al., 2022) [5]The energy return on investment of BECCS: is BECCS a threat to energy security? (Fajardy & Mac Dowell, 2018) [6]Congressional Research Service CCS report (2022), Table 3 [7]New BECCS facilities should seek Best Available Control Technology (BACT) in line with new facilities in attainment areas and Lowest Achievable Emissions Rate (LAER) in non-attainment areas. [8]Estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for lab R&D funding. Details of this estimation can be found in the AIR Appendix. [9]Short-term costs may be subsidized by utilization of fly-ash or other byproducts as a carbon utilization product.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Thermal power generator retrofit to demonstrate the use of biomass feedstock and CCS units on retrofitted thermal generation facilities: • Retrofit 2-4 thermal generation facilities to BECCS plants that operate with a variety of feedstocks. • CO_2 capture should be aligned with EPA guidelines[1] and 45Q permitting.	>1 $MtCO_2e/y$[2] per project	✓ Pathway for retrofitted and / or first of a kind plants to reach market competitive costs ✓ Demonstrated use of sustainable feedstocks at scale with a business model that provides adequate sustainable biomass in the future ✓ CO_2 capture technologies meet or exceed EPA regulations for modified and new facilities[1]	2-4	$10-15M/y	5-8 y [3,7]	$100-500M
Demo	FOAK BECCS to electricity facilities: • 2-4 BECCS facilities that utilize a variety of feedstocks. • CO_2 capture should be more rigorous than current 45Q permitting and in line with "Best Available Control Technology" (BACT).[1]	>1 $MtCO_2e/y$[2] per project		2-4	$15-20M/y	5-10 y[4,7]	$150-800M[4,6]
MRV	Independent measurement to inform MRV should be performed concurrently with the demonstrations to verify: • Cradle to gate net emissions of BECCS • LCA of the cradle to gate net energy balance of BECCS	N/A	✓ Full LCA is verified as net negative ✓ Full BECCS system net energy balance is positive, i.e., BECCS plant is a net energy producer ✓ Market competitive removal costs	2-4	$1-2M/y[5]	5-10 y	$10-20M

Notes and sources: [1]New BECCS facilities should seek Best Available Control Technology (BACT) in line with new facilities in attainment areas and Lowest Achievable Emissions Rate (LAER) in non-attainment areas. [2]The Toshiba SEE BECCS pilot was used as a reference case. It has a 50 MW generation capacity and a CCS capacity of 300 $ktCO_2/y$ when capturing ~50% of whole plant emissions. Here we assume a power plant capacity of 100 MW and capture rate of 95% of all plant emissions for a total removal potential of >1 $MtCO_2/y$. [3]Based on DRAX and Toshiba's retrofit projects, approximately 3 years are expected to be required to convert coal units to 100% biomass, with an additional 3-5 years to install FOAK CCS pilot units. [4]DRAX's new BECCS plant is expected to take 5-10 years to complete with a greater cost assumed since it is a FOAK plant. [5]Cost estimates are based on an average assessment from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019). More details can be found in the AIR Appendix. [6]Reviewers note that costs could vary considerably depending on the BECCS approach and implementation. [7]A reviewer noted that these timelines may be overly optimistic and demonstration projects may require up to 15 years.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

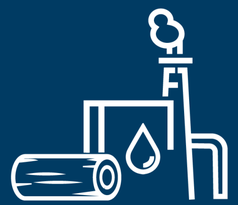
TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	Breakthroughs on enhanced cultivars[1]	Research and develop plant-based feedstocks that have enhanced growth qualities such as accelerated growth, improved survivability, and / or increased carbon uptake, or genetically enhanced crops optimized to minimize water, fertilizers, and land demand for cultivated biomass.[1,2]	1	$40-50M/y	15 y	$600-900M
Desktop research	Advances in supply logistics	Test and model alternative biomass collection and distribution systems or business models. Alternatives will reduce overall logistics costs, especially energy demand for feedstock collection and transport.[3,4,5]	1-2	$0.5-1M/y[6]	2 y	$2-4M
Desktop research	Advances in MRV and LCA	Establish a national standardized methodology for full life cycle assessment and net energy balance accounting framework to inform a holistic public and private decision-making process for investment in BECCS.[3]	2-10	$0.5-1M/y[6]	3-5 y	$10-20M
Lab / field	Advances in CCS	Test and model alternative materials and / or unit designs improving CO_2 capture rates, gas separation, and compression for storage.[8,9,10]	1-3	$1-2M/y[6]	2-3	$2-10M
Lab	Solvent-based CCS assessment	Test effects of flue gas impurities on solvent degradation and emissions utilizing a wide range of feedstocks.	1-3	$1-2M/y[6]	2-3	$2-10M
Lab	Feedstock pretreatment	Test and prototype alternative biomass pre-processing systems to reduce total energy requirements and improve efficiency across diverse feedstocks.[11]	10-12/y[13]	$0.2-1M/y	5 y[13]	$12-35[7]
Pilot	Feedstock pretreatment	Perform feasibility study and pilot-scale prototyping of promising feedstock pre-treatment systems to develop modularized solutions with potential capacity to scale to 100 t/day of dry weight biomass.	3-5/y	$2-3M/y	5 y [13]	$30-60M[7]
Lab / field	Biochar utilization	Investigate the use of biochar co-products in soil amendments and other long-term utilization or storage approaches, along with the relevant impacts on soil, agricultural or utilization practices.	2-3/y[14]	$0.2-1M/y[7]	10 y	$4-30M[7]

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include permitting, CO_2 transportation infrastructure, and social license.*

Notes and sources: [1]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) recommends $40-50M/y over 20 years for genetic crop improvements and reports current R&D funding for conventional crop improvements and genetics is $1.5B (public sector) and $1.8B (private sector). [2]This could include GMO photosynthesis enhanced plants like those produced by Living Carbon. Other examples can be found in EFI – Surveying the BECCS landscape. [3]Based on Fajardy & Mac Dowell (2018) heavy machinery and transport can account for 7-20% of the energy consumption in the full BECCS system [4]EFI – Surveying the BECCS landscape [5]NAS (2019) (p178) [6]Estimates based on averages from NAS (2019) budgets for lab and desktop R&D funding. Details of this estimation can be found in the AIR Appendix. [7]Estimates based on analogous tasks from NAS (2019) Table 4.8 Bioenergy with Carbon Capture Research Agenda, Budget, and Budget Justification [8]Impact of BECCS on amine-based CO_2 capture solvents in a pilot-scale combustion environment (Strege et al., 2022) [9]Greenhouse Gas Removal Technology – Chapter 5 (Fajardy, 2022) [10]Per [8,9] target performance should be CCS energy demand below current industry average of 9% of the full life cycle, and regular CO_2 capture rates above current average rates of 90-95%. [11]This is the most energy intensive phase for most BECCS (EFI BECCS) and improvements may occur throughout densification, pretreatment and formation of different feedstocks (NAS 2019). [13]Per [7], projects are anticipated to last 1-2 years moving from TRL 1-3, and again reaching bench scale prototypes with project costs approximately doubling. [14]Per [7], each project is suggested to last 1-3 years with multiple new projects added over the full workstream duration.

SECTION 3.2

BECCS to fuels



SECTION	3.2
TAXONOMIC BUCKET	Biogenic
CDR CATEGORY	Sequestration of CO_2 from biomass
APPROACH	BECCS to fuels

DEFINITION

Thermal or biochemical conversion of biomass (either dedicated feedstock or waste) to generate fuels and produce CO_2 that is captured with CCS technology

EXAMPLE SCENARIOS

1) Fermenting corn into ethanol and capturing the side stream of waste CO_2 to be sequestered; 2) thermally converting waste biomass into liquid fuels with some side production and capture of CO_2 to be sequestered.

Section 3.2 overview

BECCS to fuels

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/tCO$_2$** • Key risks include energy, water, and land use requirements across life cycle, especially with scale up beyond biowaste supply, plus CCS technology
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Low** • This approach is customized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Commercial** • Several companies at commercial stage • Other notable RD&D activity includes the DOE FECM program
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **200 MtCO$_2$ by 2050** • Success is contingent on breakthroughs in CCS technologies and sustainable biomass feedstock supply
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$225-950M over 5-20 years** • Key stage gates in feedstock, gasification systems, and validation of CO_2 capture in the net life cycle energy balance

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**High risk:** The full life cycle net energy balance can result in overall energy loss.	Non-combustion BECCS can use lower quality biomass, which reduces drying and processing energy needs. However, it still requires in-field operations and processing[1,2,3,4]
	Water requirements	**High risk:** Biowaste does not require additional water to grow, but dedicated crops and processing will consume significant amounts of water.	Waste biomass, non-irrigated, or low water crops[5] should be prioritized,[4] as the use of dedicated crops could require significant water demand. Studies report 5-60 gigatons of water may be required per $GtCO_2$ of sequestration by BECCS (up to 1.5% of global freshwater withdrawals).[3,6,7]
	Fertilizer requirements	**Medium risk:** Biowaste does not require additional fertilizer. Dedicated crops should only be used if they have low fertilizer requirements.	Using appropriate harvesting rates, waste biomass, such as corn stover, does not require additional replenishment fertilizer; however, for high removal rates, replenishment fertilizer needs could be as high as 25 Mt per gigaton of biomass input (about 10% of 2019 global fertilizer use).[8,9]
	Land use requirements	**High risk:** Gigaton scale removals will need both biowaste and cultivated crops, resulting in significant land requirements.	Gigaton-scale BECCS may need 30-80 Mha (0.3M-0.8M km^2) of land for biomass production (for comparison, Texas is about 70 Mha). This would likely require significant land-use conversion, especially near storage sites.[2,3,6,7] In addition, there will be increased competition for available biomass.[10]
	Environmental impact	**Medium risk:** Biofuel processing and combustion may lead to negative air quality impacts. Ecosystem impacts from land-use conversion are likely at gigaton-scale.	BECCS has associated combustion emissions but may also improve air quality by moving disposal burning to closed systems.[6] Biodiversity and other ecosystem losses may result from significant land-use conversion to produce biomass for feedstock.[2,7]
	CCS technology	**High risk:** Significant challenges in CCS must be addressed for BECCS to achieve affordable, high capture rates.	Current post-combustion pilots are focused on amine-based CCS technology for BECCS plants. Initial results indicate this approach is highly sensitive to feedstock type. It also cannot capture 100% of emissions in an economically feasible way.[2,6,11]
Secure storage for 100+ years		**Low risk:** CCS provides secure, durable storage.	CO_2 geological storge is a mature and well-regulated practice; however, proximity to feedstock and conversion affects availability and cost of storage.
Path to measurement at scale		**Medium risk:** The measurement of sequestered CO_2 is straightforward, but the LCA of BECCS approaches is challenging.	The measurement of sequestered CO_2 is simple, but there is a lack of consensus for BECCS lifecycle accounting. resulting in a wide range of net removal estimates.[1,2] Creation of a Product Category Rule could provide comparable LCAs.[12,13]
Pathway to full costs <$100/tCO$_2$		**High risk:** Given the current state of technology and full-system operations, there is not yet a clear path to unsubsidized, all-in costs <$100/$tCO_2$.[2]	In most geographies, BECCS systems will require significant subsidies.[2] Future cost reduction pathways are limited due to the high complexity and customization of BECCS systems,[14] although high value biomass-derived fuels may enable short-term potential for cost reductions.[13]

Notes and sources: [1]The energy return on investment of BECCS: is BECCS a threat to energy security? (Fajardy & Mac Dowell, 2018) [2]Greenhouse Gas Removal Technology – Chapter 5 (Farjady 2022) [3]Reviewers note that the use of different feedstocks could bring risks to low or medium depending on differences in feedstocks and processing approaches. [4]Per [1], wood conversion to biofuels is not widespread. [5]*Miscanthus*: A fast-growing crop for environmental remediation and biofuel production (Wang et al., 2020) [6]EFI – Surveying the BECCS landscape [7]Royal Society Greenhouse Gas Removal [8]Global fertilizer consumption in 2019 was 215 Mt. [9]An average ton of corn or sorghum residue contains 17, 4, and 34 lbs of nitrogen, phosphorus, and potassium, respectively. [10]The 2016 Billion Ton report estimates there will be sufficient biowaste supply, but biomass will have many competing demands. Further discussion can be found in the bCDR overview. [11]Impact of BECCS on amine-based CO_2 capture solvents in a pilot-scale combustion environment (Strege et al., 2022) [12]Product Category Rules [13]As noted by a reviewer. [14]Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020).

Potential for cost improvement

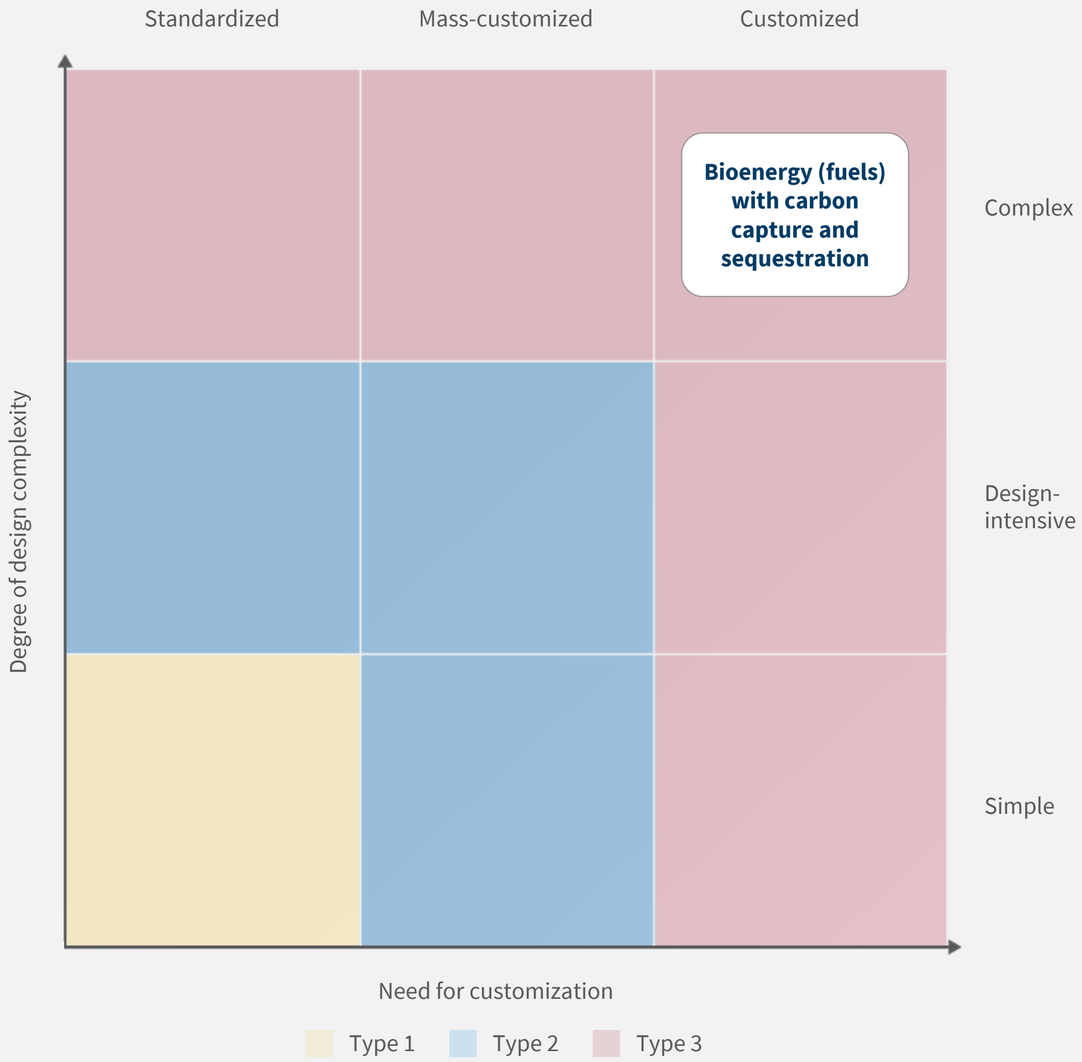
An assessment of two key drivers of learning rates

SECTION 3.2

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Sequestration of CO_2 from biomass

APPROACH BECCS to fuels



OVERALL RATING

Type 3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Complex
- **Rationale:** Full BECCS systems (cradle-grave) include the logistics of feedstock production and handling, plus distinct systems for biochemical processing, gas separation, and CCS integration.

NEED FOR CUSTOMIZATION

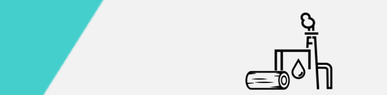
- **Rating:** Customized
- **Rationale:** BECCS plants are highly customized to the specific quality and characteristics of any given feedstock. Even similar feedstock types of different origin could have implications for BECCS performance.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

Current state of RD&D

A mapping of companies, plus other notable activities

NOT EXHAUSTIVE



SECTION 3.2

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Sequestration of CO_2 from biomass

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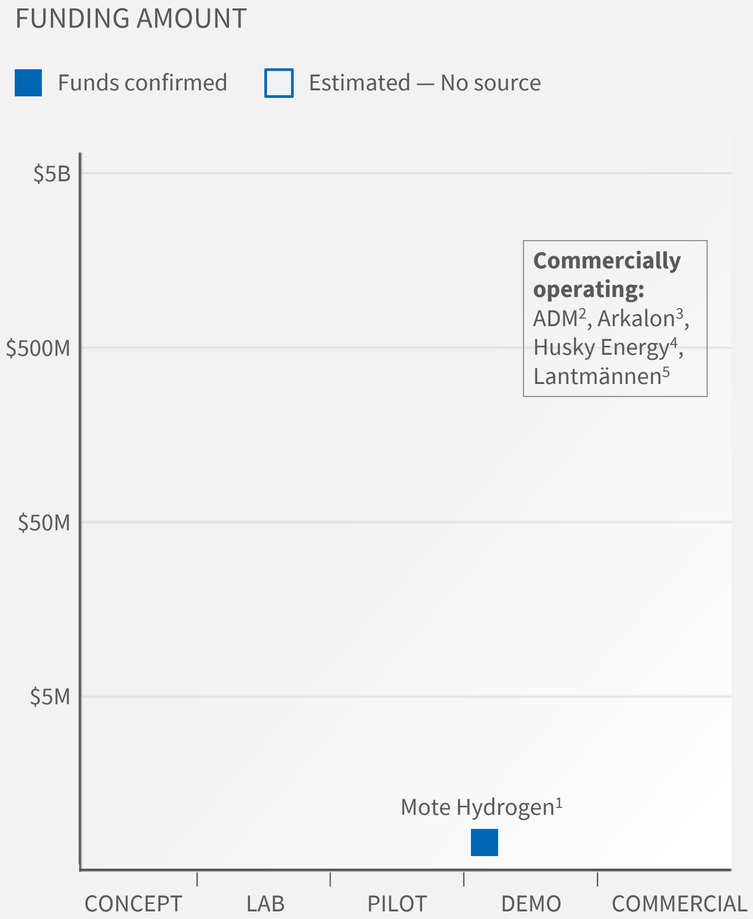


NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Mote: Hydrogen production via thermal conversion of biomass[1]	$1-2M[6]	• First plant planned for 2027 near Bakersfield, CA • Capacity for 900 t/day of woody biomass, 400 $ktCO_2/y$ CDR, and 60 t/day of hydrogen production[1]
Archer Daniels Midland (ADM): Corn-to-ethanol plant, Decatur IL[2]	Not disclosed; received $141.1M from US DOE[7]	• Demonstration and pilot facilities completed from 2011-2014 with capacity for 300 $ktCO_2/y$[8] • Commercial facility began operation in 2017 with 1 $MtCO_2/y$ removal capacity[8]
Arkalon: Energy ethanol plant, Liberal KS[3]	N/A	• Pilot and demonstration facilities in operation since 2009 removing 290 $ktCO_2/y$[8]
Husky Energy Lashburn: Ethanol plant, Saskatchewan, Canada[4]	N/A	• Operational since 2012 • 90 $ktCO_2/y$ max capacity[8]
Lantmännen Agroetanol: Biorefinery in Norrköping, Sweden[5]	N/A	• 200 $ktCO_2/y$ removals[8]
Other notable companies: Occidental Petroleum with White Energy,[8] Bonanza BioEnergy Ethanol,[8] Landwärme and BioCORE,[9] POET,[10] and several others listed in the global CCS institute database.[11] Note that most companies operating in this space are ethanol facilities.		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
DOE – FECM: CCS RD&D[12]	Past: $2.7B Future: $12.1B	• US government funded CCS related research since 1997. • Appropriated budget for FY22-26 include $8.5B (IIJA) and $3.6B (DAC-hubs)

Notes and sources: [1]Mote Hydrogen [2]ADM [3]Conestoga – Arkalon plant [4]Husky Energy [5]Lantmännen Agroetanol [6]Mote pitchbook [7]EESI ADM carbon capture plant, DOE announcement [8]The Global CCS institute 2019 perspective on BECCS [9]Landwärme and bioCORE [10]POET, the world's largest ethanol producer, has joined a $3 billion carbon capture pipeline. [11]Global CCS Institute Database [12]Congressional Research service report on CCS (2022)

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

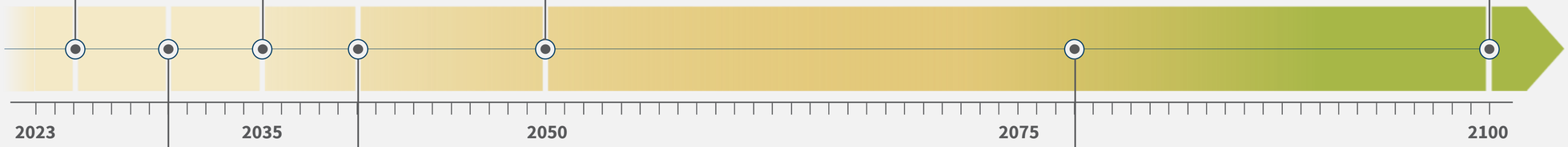
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 3.2

TAXONOMIC BUCKET Biogenic

CDR CATEGORY Sequestration of CO_2 from biomass

APPROACH BECCS to fuels



2025

- More than 5 $MtCO_2/y$ of BECCS to liquid fuel facilities are either operational, under development, or in planning.[1]
- New funding is allocated to develop novel BECCS to fuels pathways, including gasification for carbon negative hydrogen.

2035

- BECCS to fuels pathways remove 50 $MtCO_2/y$ globally.[2]
- US based liquid fuel production must remove 40 $MtCO_2/y$, consistent with the Renewable Fuels Association Pathways to Net Zero report goal.[3]
- Breakthroughs in enhanced cultivars enable new approaches to producing liquid fuels via BECCS processes.

2050

- Globally, BECCS to fuels removals reach 200 $MtCO_2/y$.[2]
- US-based liquid fuel production must reach around 57 $MtCO_2/y$ of removals to achieve Net Zero.[3]

2100

- BECCS for liquid fuels continue to operate largely based on demand for low carbon, sustainable fuels as part of the energy transition.
- BECCS to fuels pathways continue to provide ~300 $MtCO_2/y$ of CDR.

2030

- CO_2 removals from BECCS to fuels pathways reach 10 $MtCO_2/y$,[3] almost entirely through fermentation processes that produce alcohol fuels.
- Substantial global demand for low carbon liquid fuels drives BECCS to liquid fuels production.
- Additional emphasis is placed on developing smaller-scale BECCS systems using gasification, tailored to local conditions and biomass sources, and linked together in regional CCS hubs.

2040

- Global BECCS to fuels removals reach 75 $MtCO_2/y$.[2]
- US based liquid fuel production removes 56 $MtCO_2/y$ according to the RFA Pathways to Net Zero Report.[3]
- Advances in supply logistics and enhanced cultivars decrease the cost of removals and improve the LCA.
- Sustainable biomass supply is still prioritized and BECCS facilities have a positive, publicly disclosed LCA.

2050-2100

- BECCS plants that produce liquid fuels continue to operate where economically and environmentally sensible for producing fuels.[1,3,4]
- Demand for fuels is the primary driver and may be reduced by the energy transition (1) fostering a switch to alternative fuels or (2) decreased demand as more transportation is electrified.

Notes and sources: [1]According to the IEA, there are currently around 2 Mt of biogenic CO_2 captured per year, mainly in bioethanol applications. [2]Here we have assumed 30% y-o-y growth from 2023-2035 and 10% y-o-y growth from 2035-2050 based on a starting capacity of 2 $MtCO_2/y$ in 2023. [3]In the USA, in the Pathways to Net Zero report, the Renewable Fuels Association (RFA) has recommended that 90% of ethanol plants implement CCS on their systems by 2050. The RFA report requires 9.45 $MtCO_2/y$ removals from ethanol fermentation processing in 2025. Additional milestones every 5 years until 2050 build to 56.7 $MtCO_2/y$ of removals, consistent with net zero for the industry. These values are calculated based on an assumption of 126 MJ/gal of ethanol and a constant production of 15B gallons per year of ethanol from today to 2050. [4]Removals continue at 1-2 $GtCO_2/y$. The IPCC AR6 WG3 (p158) expects BECCS to remove 2.75 $GtCO_2/y$ in 2050, but this does not account for other bCDR demand for biomass feedstock.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL[1]
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[2]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION: 3.2

TAXONOMIC BUCKET: Biogenic

CDR CATEGORY: Sequestration of CO_2 from biomass

APPROACH: BECCS to fuels

TRL

CRITICAL PATH ACTIVITIES

$225-950 million | **5-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Feedstock R&D**: Test and model novel feedstock cultivation, processing, and pretreatment pathways
- **Pilot gasification facilities:** Test pilot scale systems for biomass gasification to carbon negative hydrogen
- **Performance and environmental assessments:** Conduct TEA and LCA studies and environmental impact assessments

$75-150 million | **10 years**

✓ Demonstrate gigaton scale sustainable feedstock supply

✓ Achieve CO_2 capture rates at or above current industry standard

✓ Environmental impacts are manageable

STAGE GATES[2]

TRL 7-9

DEMONSTRATION PROJECTS

- **Gasification of biomass for carbon negative hydrogen production:** Demonstrate biomass gasification to produce carbon negative hydrogen
- **Measurement:** Verify LCA and net energy balance of the biomass gasification process to inform MRV

$150-800 million | **5-10 years**

✓ Pathway for gasification facilities to reach market competitive operation for CDR[3] and fuels

✓ Full LCA indicates net removals

✓ Full BECCS system energy balance is net positive

STAGE GATES[2]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[4]

$250-350 million | **15 years**

- Test and model alternative biomass collection and distribution systems / business models to improve supply chain logistics
- Establish a standardized methodology for full life cycle assessment and net energy balance accounting frameworks
- Evaluate solvent degradation and emissions for relevant CCS methods
- Research bioengineering pathways to convert lignin into fuels

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[4]

- Market competitive operational cost, including feedstock and processing costs, as well as final product sales
- Demonstrate net removals via independent review
- Achieve financing costs in line with commercially accepted technologies

Notes and sources: [1]Although the current MRL of this approach is rated at 10+, the approach still needs to develop, deploy, and verify that CCS works on BECCS units at scale and under varying conditions. [2]Stage gates and critical path ratings are explained in the AIR Appendix. [3]Short-term CDR costs may be subsidized by utilization of co- or byproducts as a carbon utilization product. [4]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	LCA, TEA, and IAM evaluations	Conduct TEA and LCA studies to evaluate potential impacts. Use integrated assessment models to improve estimates of critical parameters, including biomass sourcing and land use and conversion. These should be conducted for existing BECCS to fuels pathways, such as ethanol fermentation, and for gasification processes.	✓ Pathway to market competitive costs ✓ Pathway for viable feedstock sourcing	2-3[1]	$0.5-1M/y	10y[1]	$10-20M[2]
Desktop research / field testing	Environmental impact assessment	Assess potential environmental impacts of BECCS to fuels facilities including impacts on air, water, and ecosystems.	✓ Environmental risks are manageable	2-3[1]	$0.5-1M/y	10 y[1]	$10-20M[2]
Pilot	System optimization	Test pilot scale biomass gasification designs of alternative system configurations for new feedstocks, process integration and intensification, novel treatment processes, and novel CO_2 capture and separation approaches.	✓ Pathway to market competitive costs ✓ Significant net negative emissions are achievable	15-25[1]	$1-2M/y[2]	10 y[4]	$30-50 M[2]
Desktop research	FEED study	Conduct Front End Engineering & Design (FEED) and feasibility studies of novel systems for demonstration BECCS fuel production plants.	✓ FEED studies demonstrate ideal sites exist for demonstration scale investment.	1-2	$10-20M/y[3]	2-3	$20-50M

Note: *Fermentation processes, such as those to produce ethanol, are already commercial. As such, this work should focus on alternative pathways that can produce both fuels and negative emissions, such as gasification.*

Notes and sources: [1]Each project is suggested to take 1-3 years with multiple new projects added over the full workstream duration. [2]Estimates based on analogous tasks from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019), Table 4.8 Bioenergy with Carbon Capture Research Agenda, Budget, and Budget Justification. [3]See 3 US GOV congressional research service – CCS report (2022), Table 3. [4]Per [2], projects are anticipated to last 1-2 years moving from TRL 1-3, and again reaching bench scale prototypes with project costs approximately doubling.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Demonstration of gasification of biomass to produce carbon negative hydrogen • Each demonstration facility should utilize different biomass feedstocks • Each demonstration facility should be located in a different geographical area • Capture should be more stringent than current 45Q permitting and in line with "Best Available Control Technology" (BACT)[1]	>500 kCO_2e/y per project[2]	✓ Process shows a clear path to market competitive costs. ✓ TEA shows that the approach will be able to compete with other bCDR pathways on a long-term cost basis.	2-4	$15-20M/y	5-10 y	$150-800M[3,4]
MRV	Measurement with third party validation should be performed during the demonstrations to inform MRV and refine: • LCA of the cradle to gate net emissions of BECCS • LCA of the cradle to gate net energy balance of BECCS	N/A	✓ Full LCA is verified as net negative. ✓ Full BECCS system net energy balance is positive, i.e., BECCS plant is a net energy producer.	2-4	$1-2M/y[3]	5-10 y	$10-20M

Note: *Fermentation processes such as those to produce ethanol are already commercial. As such, this work should focus on alternative pathways that can produce both fuels and negative emissions, such as gasification.*

Notes and sources: [1]New BECCS facilities should seek Best Available Control Technology (BACT) in line with new facilities in attainment areas and Lowest Achievable Emissions Rate (LAER) in non-attainment areas. [2]Mote has planned a 900 t/day woody biomass gasification facility that is expected to achieve 400 $ktCO_2e$/y CDR and 60 t/d hydrogen production. [3]Cost estimates are based on an average assessment from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019). More details can be found in the AIR Appendix. [4]Reviewers note that costs could vary considerably depending on the BECCS approach and implementation.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	Breakthroughs on enhanced cultivars[1]	Research and develop plant-based feedstocks that have enhanced growth qualities such as accelerated growth, improved survivability, and / or increased carbon uptake, or genetically enhanced crops optimized to minimize water, fertilizers, and land demand for cultivated biomass.[2]	1	$40-50M/y	15 y	$600-900M
Desktop research	Advances in supply logistics	Test and model alternative biomass collection and distribution systems / business models. Alternatives should reduce energy demand for collection and transport of feedstock and overall logistics costs.[3,4,5]	1-2	$0.5-1M/y	2 y	$2-4M
Desktop research	Advances in MRV and LCA	Establish a standardized methodology for full life cycle assessment and net energy balance accounting framework to inform a holistic public and private decision-making process for investment in BECCS.[3]	2-10	$0.5-1M/y	3-5 y	$10-20M
Lab / field	Advances in CCS	Test and model alternative materials and / or unit designs improving CO_2 capture rates, gas separation and compression for storage.[6,7,8]	1-3	$1-2M/y [9]	2-3	$2-10M
Lab	Solvent-based CCS assessment	Test effects of flue gas impurities on solvent degradation and emissions utilizing a wide range of feedstocks	1-3	$1-2M/y [9]	2-3	$2-10M
Lab	Feedstock pretreatment	Test and prototype alternative biomass pre-processing systems to reduce total energy requirements and improve efficiency across diverse feedstocks.[10]	10-12/y[11]	$0.2-1M/y	5 y [11]	$12-35 [12]
Pilot	Feedstock pretreatment	Perform feasibility studies and pilot-scale prototypes of promising feedstock pre-treatment systems to develop modularized solutions with potential capacity to scale to 100 t/day of dry weight biomass.	3-5/y	$2-3M/y	5 y [11]	$30-60M [12]
Lab	Biological processing	Research bioengineering pathways to break down lignin and convert it into fuels.	7-10/y [13]	$0.2-1M/y [12]	10 y	$42-60M [12]

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include permitting, CO_2 transportation infrastructure, and social license.*

Notes and sources: [1]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) recommends $40-50M/y over 20 years for genetic crop improvements and reports current R&D funding for conventional crop improvements / genetics is $1.5B (public sector) and $1.8B (private sector). [2]This could include GMO photosynthesis enhanced plants like those produced by Living Carbon. Other examples can be found in EFI – Surveying the BECCS landscape. [3]Based on Fajardy & Mac Dowell (2018) heavy machinery and transport can account for 7-20% of the energy consumption in the full BECCS system. [4]EFI – Surveying the BECCS landscape [5]NAS 2019 (p178) [6]Impact of BECCS on amine-based CO_2 capture solvents in a pilot-scale combustion environment (Strege et al., 2022) [7]Greenhouse Gas Removal Technology – chapter 5 (Farjady 2022) [8]Per [6,7] target performance should be CCS energy demand below current industry average of 9% of the full life cycle and regular CO_2 capture rates above current average rates of 90-95%. [9]Estimates based on averages from NAS 2019 budgets for lab R&D funding. Details of this estimation can be found in the AIR Appendix. [10]This is the most energy intensive phase for most BECCS (EFI BECCS) and improvements may occur throughout densification, pretreatment and formation of different feedstocks (NAS 2019). [11]Per [12], projects are anticipated to last 1-2 years moving from TRL 1-3, and again reaching bench scale prototypes with project costs approximately doubling. [12]Estimates based on analogous tasks from NAS 2019 Table 4.8 Bioenergy with Carbon Capture Research Agenda, Budget, and Budget Justification [13]Each project is suggested to take 1-3 years with multiple new projects added over the full workstream duration.

Intro to geochemical CDR (gCDR)

DEFINITION: *gCDR approaches use naturally-occurring neutralization reactions between acidic forms of carbon and alkaline minerals to convert CO_2 from the atmosphere into solid carbonate minerals or dissolved bicarbonates.*[1]

We break gCDR into two sub-categories, based on how the carbon is stored:

Solid carbonate minerals

Approaches that seek to enhance the formation of carbonate minerals through the acceleration of natural reactions of alkaline materials with CO_2.

4.1

Other emerging approaches include a greenhouse method that reacts alkaline minerals in a sealed chamber.[2]

Dissolved bicarbonate sequestration

Approaches that seek to react alkaline materials with CO_2 to produce dissolved bicarbonates that are ultimately stored in the ocean or other bodies or water.

5.1

5.2

5.3

We define gCDR as those approaches that require alkaline minerals. Approaches that use electrochemistry to produce alkalinity are described in the sCDR section. Approaches that require input CO_2 streams are described in the CO_2 Storage section. Oxide-looping approaches to Direct Air Capture are included in the sCDR section.

Notes and sources: [1] Weathering and mineralization reactions are increased and accelerated, with reaction times ranging from minutes to years, depending on process conditions. [2] See, for example, the work of Corey Meyers.

gCDR definitions and example scenarios

4. Solid Carbonate Materials: Comprises approaches that seek to enhance the formation of carbonate minerals through the acceleration of natural reactions of alkaline materials with CO_2.

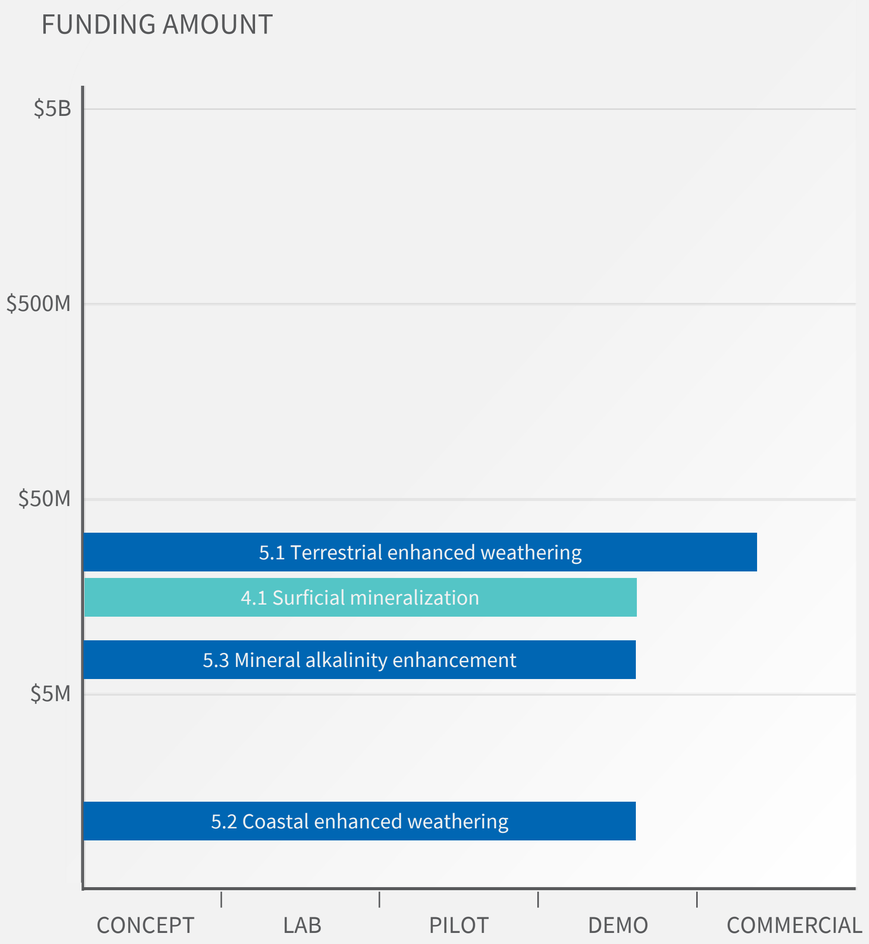
INDEX	APPROACHES	DEFINITION	EXAMPLE SCENARIOS
4.1	Surficial mineralization	Enhancing the natural capacity of excavated or processed alkaline feedstock to passively react with atmospheric CO_2--through crushing, grinding, spreading, heating, or other physical or chemical means--to form carbonate minerals	1) Crushing and spreading alkaline rocks from mine tailings to react with CO_2 and water in the environment to create solid carbonate minerals; 2) excavating alkaline rocks for CDR, then holding them on trays in greenhouse containers where they are passively heated to increase uptake of CO_2.

5. Dissolved bicarbonate sequestration: Comprises approaches that seek to react alkaline materials with CO_2 to produce dissolved bicarbonates that are ultimately stored in the ocean or other bodies or water.

INDEX	APPROACHES	DEFINITION	EXAMPLE SCENARIOS
5.1	Terrestrial enhanced weathering	Acceleration of the natural geologic weathering process through the spreading of finely ground alkaline materials in agricultural, urban, or forest soils, where it reacts with CO_2 and water to produce dissolved inorganic carbon	1) Spreading crushed basalt on farmlands, or 2) adding crushed basalt as a soil treatment during reforestation -- where, in both scenarios, the basalt reacts with carbonic acid produced by soil CO_2 and rain or irrigation water, creating dissolved bicarbonate that eventually flows into riverine systems.
5.2	Coastal enhanced weathering	Distribution of crushed or pulverized alkaline minerals onto beaches and coastal shelves where it reacts under water with CO_2 to produce dissolved inorganic carbon	1) Adding mined and crushed olivine to beach nourishment projects, or 2) adding crushed olivine minerals to coastal shelves -- where, in both scenarios, these minerals can react with dissolved CO_2 in ocean water to create bicarbonate.
5.3	Mineral alkalinity enhancement	Direct addition of alkaline minerals to lakes, oceans, rivers, wastewaters, or other bodies of water to increase the alkalinity of the water and its capacity to absorb CO_2	1) Spreading purified and crushed alkaline mine tailings in the open ocean to reduce acidity and convert dissolved CO_2 into bicarbonates; 2) adding alkaline minerals to water or wastewater treatment processes in order to reduce acidity and take up more CO_2 in the effluent.

NOT EXHAUSTIVE

Geochemical CDR is currently early stage across all approaches



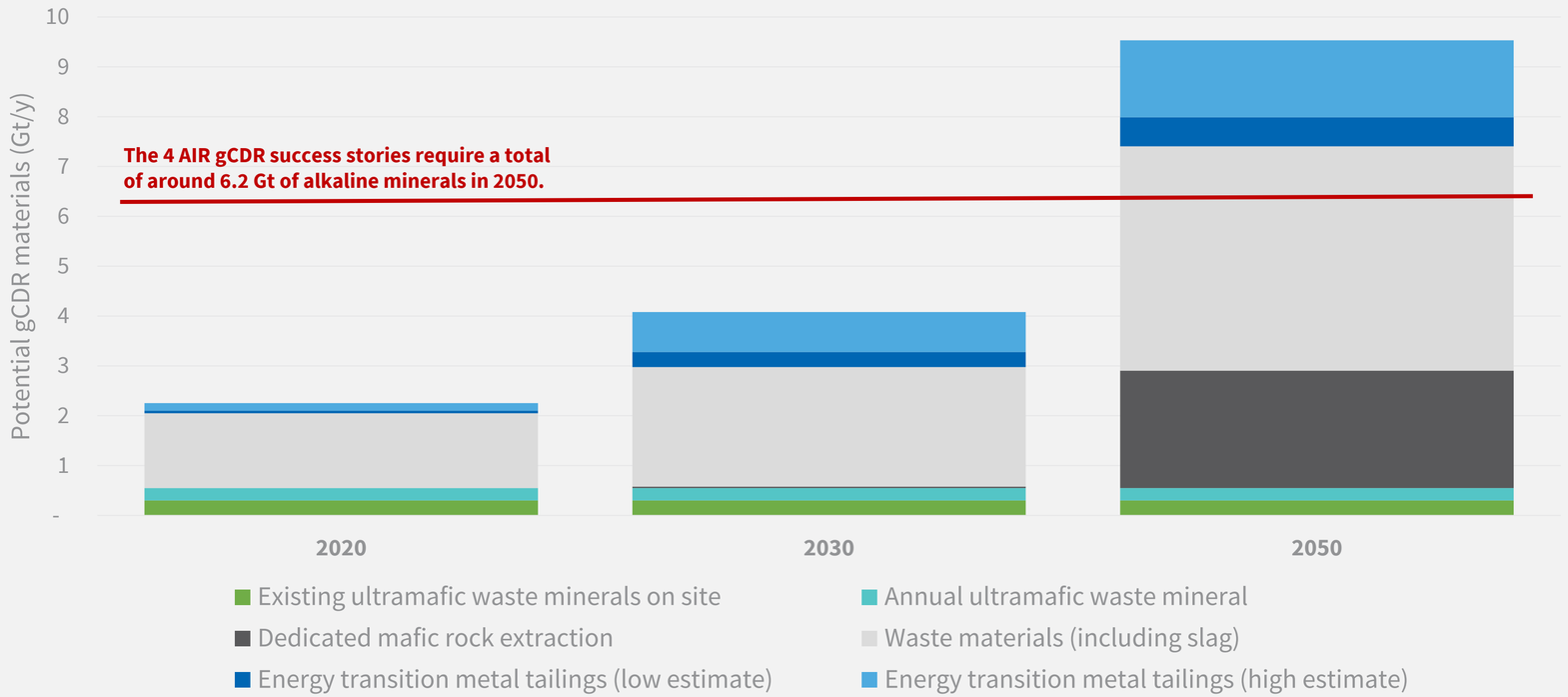
	APPROACH	FUNDS COMMITTED[1]	SIGNIFICANT DEPLOYMENTS
Solid carbonate	Surficial mineralization (4.1)	>$23M[2]	**BHP** has announced plans to conduct field trials at its Nickel West operations in Western Australia.[6]
Dissolved bicarbonate	Terrestrial enhanced weathering (5.1)	>$37M[3]	**UNDO** has deployed 165 kt of basalt at ongoing demonstration projects.[7]
	Coastal enhanced weathering (5.2)	>$1.7M[4]	**Vesta** has deployed 500 yd^3 of olivine sand (5% of total volume placed) in a beach nourishment project in Southampton, NY.[8]
	Mineral alkalinity enhancement (5.3)	>$9M[5]	**Planetary** has a goal of removing 100 tCO_2 by adding alkalinity to existing water flow at a water treatment plant in Cornwall, UK.[9]

Notes and sources: [1]Total funding includes seed funding, grants, and investments in CDR-relevant projects that have been disclosed by companies included in the AIR. It does not include government funding towards research institutions. As companies reach later stages of development, they also disclose less financial information, so the actual funds committed to each of these approaches is likely higher than shown. [2]The $23M sum for surficial mineralization is based on disclosed funding from 4 companies. [3]The $33M sum for terrestrial enhanced weathering is based on 6 companies. [4]The $1.7M sum for coastal enhanced weathering is based on 2 companies. [5]The $9M sum for ocean liming is based on 2 companies. [6]BHP and Nickel West article [7]Personal communication about UNDO's funding and deployment [8]Vesta pilot project [9]Planetary pilot details

Alkaline minerals are the key input for gCDR

Availability of potential suitable materials is ~2 Gt/year today, with the potential to increase by 2050

Estimates of the potential availability of gCDR materials[1,2,3,4]



Notes and context

- The Global Tailings Review estimates that there are around 72 Gt/y of waste rock and 8.9 Gt/y of mine tailings produced by the mining industry.[1,2]
- Most waste rocks and tailings are not reactive, and deployment logistics for those that are may be limiting.[1,2]
- No more than 10 Gt of the most mineralizable alkaline materials exist on mine sites. New extraction is around 200 Mt/y.[3]
- Increased production of metal ores for the energy transition will produce up to an additional 1.5 Gt/y of minerals.[4]
- Our gCDR success stories are based on suitable alkaline mineral deployment and achieve ~2.2 $GtCO_2$/y removals in 2050.

Notes and sources: [1]Estimates are based on data from the Global Tailings Review. Not all of these rocks or mine tailings will be mineralizable. Of the rocks that are, the mineralization rates depend on the type of waste. Mafic and ultramafic rocks have the potential to react the greatest amount of CO_2. Strefler et al (2018) reports a theoretical value of 1.1 tCO_2 removed per ton of rock deployed. Campbell (2022) estimates 0.6-0.7 tCO_2 per ton of limestone. Renforth, 2012 estimates that appropriate feedstocks can capture between 0.3-1.25 tCO_2 per ton of mineral. [2]Alkaline minerals will not necessarily be generated or located in areas where they can be easily mineralized, and transportation costs may be too significant to balance removals. This paper describes a lifecycle assessment for enhanced rock weathering in Brazil. [3]According to the Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019), significant ultramafic mine tailings exist on mining sites but provide less than 10 Gt of total material. Furthermore, NAS (2019) estimates that annual production of new ultramafic mine tailings is about 200 Mt/y (p270). Based on our analysis in this section, we estimate that mines may generate up to 300 Mt/y of ultramafic minerals. In this figure, we have assumed a baseline production of 250 Mt/y of ultramafic mine tailings and 300 Mt/y of mineralization using previously existing mine tailing waste. We have also assumed that the supply of mafic rocks like basalt, specifically mined for gCDR, grows from zero in 2020 to 2.4 Gt/y in 2050, consistent with our TEW success story. The category of waste minerals is estimated from Renforth (2019), includes ash, concrete, and slag, and is tabulated in detail this gCDR section of the AIR. In this figure, we have assumed that only 30% of these waste material estimates will be usable for gCDR. [4]The energy transition minerals (minimum and high estimates) are estimates of the tailings from energy transition metal mining. These additional material estimates are calculated based on several data points. The IEA Net Zero in 2050 report that includes the future market size of 8 key energy transition ores: copper, lithium, nickel, graphite, cobalt, manganese, silicon, and rare earth metals. The total mass of these metals is expected to increase from 7.1 to 42.3 Mt/y in 2050 (p24). The 2030 datapoint was taken from the IEA WEO 2022 (Fig 1.11). Additional rock that these activities will generate was calculated based on the sum-product of the market share of each of the 8 minerals, their 2023 market price per ton, and the low and high ranges of the concentration of their respective ores in these rocks. Total mineral demand is expected to increase 2-3x by 2030 in the IEA's announced pledges scenario.

Global supply of waste materials[3] is enough to remove 2.6-3.8 $GtCO_2$/year by 2050

Waste mineral supply[3]	Current estimated production (Gt/y)	Projected production in 2100 (Gt/y)	Removal potential ($GtCO_2$/Gt material)[2]	gCDR applications[1]
Ash	**0.6-1** [13]	**0.13-4.2** [3]		
Biomass ash	*Unknown*	0.3-1.2 [3]	-0.3-1.8 [3]	Ex-situ, surficial
Fly ash (coal combustion)	0.42-0.6 [7]	*Unknown*	0.03-0.06 [15]	Ex-situ [15]
Fuel ash	0.4-0.6 [10,11]	0.13-4.2 [3]	0.07-0.25 [3]	Ex-situ
Concrete	**4.1** [13,14]	**7.5-40** [3]		
Cement	0.42-2.1 [10]	7.5 [3]	0.001-0.3 [10]	Ex-situ, surficial [15]
Kiln dust	0.25 [3]	0.25-1.1 [3]	0.33-0.53 [3]	Ex-situ, surficial [15]
Concrete (products & demolition waste)	0.3-5.8 [3,7,10]	7.5-40 [3]	0.08-0.1 [3]	Ex-situ, TEW, surficial [15]
Slag	**0.17-0.5** [9,12]	**5-15** [13]		
Furnace slag	*Unknown*	0.7 [3]	0.37-0.62 [3,5]	Ex-situ, surficial
Steel slag	0.17-0.25 [7]	2.2 [3]	0.37-0.62 [3]	Ex-situ,[3,4] surficial
Red mud/bauxite residue	0.12-0.15 [3,7]	0.5-1.1 [3]	0.05-0.44 [3]	Ex-situ, surficial
Waste rock, mine tailings	8.9-17 [6,8]	≤3.5 (ultrabasic) [3]	0.04-0.38 [3]	Ex-situ, surficial

Notes and sources: [1]This review accounts for potential removals without considering emissions reductions or mitigation of mining operations. Toxicity of waste minerals, form factor, source, etc. inform the type of gCDR approach. There is a separate question of what to do with the waste once it has been mineralized. [2]The removal potential range includes both carbonation and mineralization rates when available. [3]The negative emission potential of alkaline materials [4]Per [3], steel slag is usually stockpiled and has environmental risks of extreme pH and metal pollution. [5]Per [3], this is an average of blast, basic oxygen, and electric arc furnace slag. [6]Towards Zero Harm, Global Tailings Review [7]Alkaline residues and the environment [8]Global Carbon Dioxide Removal Potential of Waste Materials from Metal and Diamond Mining total potential; however, only a small percentage will carbonate within a few decades. [9]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [10]An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations [11]Waste production as coal ash [12]Geochemical Negative Emissions Technologies: Part I. Review (Campbell et at. 2022) [13]USGS Mineral Commodity Summaries 2023 [14]Global cement production in 2022, per [13], not including clinker or other wastes [15]Mineralization of Carbon Dioxide: Literature Review (Romanov et al., 2015)

Natural minerals useful for CDR are abundant on earth. Their commercial availability will be determined by limits on mining and mineral recovery

	NATURAL MINERAL SUPPLY	CURRENT MINING OR PRODUCTION (GT/Y)	ESTIMATED MAXIMUM REMOVALS ($GTCO_2$) [17]	ESTIMATED KNOWN FEEDSTOCK MATERIAL (GT)	REMOVAL POTENTIAL ($GTCO_2$/GT MATERIAL)	GCDR APPROACHES	SIGNIFICANT GEOGRAPHIES
Mafic rocks	Basalt (extracted)	*N/A*	4.9 [1]	~7% of Earth's crust [13]	0.2-0.3 [1]	Ex-situ, TEW,[2] surficial	
	Basalt (subsurface)	*N/A*	8-40E4 (total capacity) [11]			In-situ	Iceland, Kenya, US (Pacific Northwest)
Ultramafic rocks	Dunite	*Unknown*	1.9-95 [1]	*Unknown*	1.1 [1]	Ex-situ, TEW,[2] surficial	
	Kimberlite	0.02 (diamond) [6]		*Unknown*	~0.3 [16]	Ex-situ, surficial	South Africa, Botswana
	Olivine	0.06 [6]	10s [1,3,14]	10s [14]	0.3-0.6 [1,3]	Ex-situ, TEW,[1] surficial	US, Norway
	Peridotite (extracted)	0.009 [12]	*Not supply constrained*	10s-100s [3]		Ex-situ, surficial[4]	Oman, UAE, Papua New Guinea
	Peridotite (subsurface)	*N/A*	>100,000 (total capacity) [10]	6E4-1E8 [5,7]		In-situ	Oman, Coastal US
	Serpentine	<0.2 [6]	*Not supply constrained*	>3% of Earth's crust [9]	0.5 [3,5]	Ex-situ, surficial[4]	Canada, Afghanistan, US, South Africa, Zimbabwe
	Wollastonite	0.01 [8]	<0.04 [15]	>0.1 [8]	0.3-0.4 [5,6]	Ex-situ, surficial	US, Canada, China, India, Finland, Mexico

Notes and sources: [1]Potential and costs of carbon dioxide removal by enhanced weathering of rocks (Strefler et al., 2018) [2]On average, basalt contains less harmful elements, on average, than olivine (or other dunites) via [1]. [3]Engineered carbon mineralization in ultramafic rocks for CO2 removal from air: Review and new insights (Kelemen et al., 2020) [4]Per [3], Ni and Cr from peridotite and serpentinite may accumulate in soil or water over time, posing a hazard during enhanced weathering. [5] Mineralization Technology for Carbon Capture, Utilization, and Storage (Hills et al., 2020) [6]Global Carbon Dioxide Removal Potential of Waste Materials from Metal and Diamond Mining and Supplemental Material (Bullock et al., 2021) [7]This includes land and seafloor peridot aquifers with depth <3 km, per [5]. [8]USGS Mineral Commodity Summaries 2023 [9]Serpentinites [10]An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations (Kelemen et al., 2019) [11]Mineralization of Carbon Dioxide: Literature Review (Romanov et al., 2015) [12]Geological Mapping and Characterization of Possible Primary Input Materials for the Mineral Sequestration of Carbon Dioxide in Europe (Kremer et al., 2019) [13]Volcanic rock makes up about 8% of the Earth's crust, and 90% of that is comprised of basalt. [14]Peridotite is made up of at least 40% olivine. Given the abundance of peridotite [3], olivine has extensive potential feedstock. [15]If 100% of the 100 Mt of wollastonite [8] were fully carbonated at 0.4 tCO_2/t mineral, 0.04 $MtCO_2$ would be removed. [16]Evaluating feedstocks for carbon dioxide removal by enhanced row weathering and CO_2 mineralization (Paulo, et al. 2021) [17]Maximum removals were determined from capacity reported in literature or by calculating capacity from reported known feedstock material and removal potential of the material.

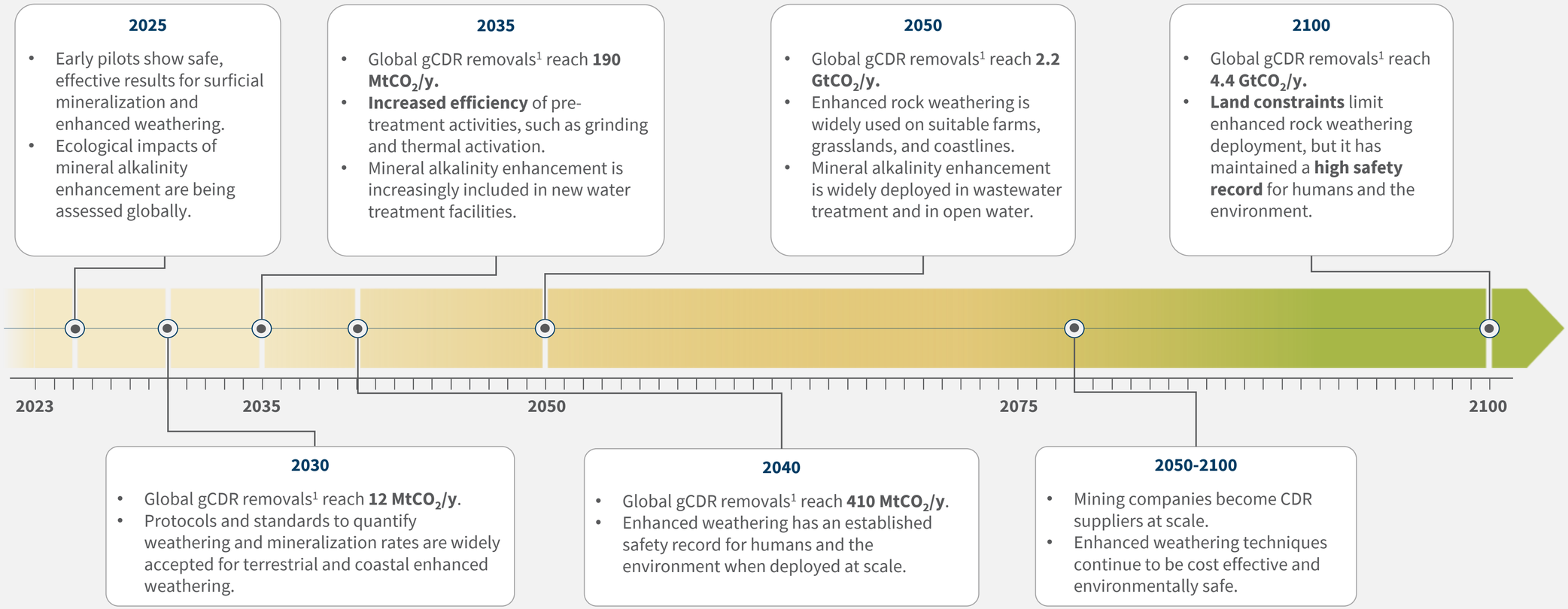
Geochemical CDR success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

The cumulative gCDR described below is the summation of the upper limit of CDR deployment taken from four individual CDR success stories from the AIR report.[1] The assumptions for each projection are based on a range of sources described in the individual CDR success stories.



Notes and sources: [1]The gCDR taxonomic area includes roadmaps of four unique approaches. The success story of each gCDR approach was assessed on its own. Details and growth assumptions for each individual pathway can be found in the individual approach success stories. As a reference point, geochemical reactions on the earth's surface naturally remove ~1.1 $GtCO_2/y$. [2]Because the total mineralizable rock on earth is essentially limitless, as described in our global mineral supply tables, we think that the total deployment will instead be limited by practical constraints such as the ability to grind and distribute feedstock. More detail on this is provided in the individual success stories for the four gCDR approaches.

4. Solid carbonate minerals

Approach seeks to enhance the formation of carbonate minerals under ambient conditions through the acceleration of natural reactions of alkaline materials with CO_2

INDEX	APPROACHES	DEFINITION
4.1	Surficial mineralization	Enhancing the natural capacity of excavated or processed alkaline feedstock to passively react with atmospheric CO_2 – through crushing, grinding, spreading, heating, or other physical or chemical means – to form carbonate minerals

RMI classifies solid carbonate mineral approaches as **geochemical**

Biogenic (bCDR)	Geochemical (gCDR)	Synthetic (sCDR)	Storage
Living biomass **1.1** Improved management **1.2** Conservation / protection **1.3** Restoration / creation **Stabilized biomass** **2.1** Biomass direct storage **2.2** Timber building products **2.3** Other biomass building products **2.4** Pyrolysis (biochar) and storage **2.5** Pyrolysis (bioliquid) and storage **2.6** Microalgae in ponds **2.7** Microalgae in open water **2.8** Macroalgae in open water **Sequestration of CO_2 from biomass** **3.1** BECCS to electricity **3.2** BECCS to fuels	**Solid carbonate minerals** **4.1** Surficial **Dissolved bicarbonate sequestration** **5.1** Terrestrial enhanced weathering **5.2** Coastal enhanced weathering **5.3** Mineral alkalinity enhancement	**Indirect water capture (IWC)** **6.1** CO_2 stripping **6.2** Electrochemical alkalinity production **Direct air capture (DAC)** **7.1-7.3** Liquid solvent **7.4-7.7** Solid sorbent **7.8-7.9** Membranes **7.10** Cryogenic	**Storage of CO_2** **8.1** Conventional CO_2 storage **8.2** In-situ mineralization **8.3** Ex-situ mineralization

SECTION 4.1

Surficial mineralization

SECTION	4.1
TAXONOMIC BUCKET	Geochemical
CDR CATEGORY	Solid carbonate minerals
APPROACH	Surficial mineralization

DEFINITION

Enhancing the natural capacity of excavated or processed alkaline feedstock to passively react with atmospheric CO_2 – through crushing, grinding, spreading, heating, or other physical or chemical means – to form carbonate minerals

EXAMPLE SCENARIOS

1) Crushing and spreading alkaline rocks from mine tailings to react with CO_2 and water in the environment to create solid carbonate minerals; 2) excavating alkaline rocks for CDR, then holding them on trays in greenhouse containers where they are passively heated to increase uptake of CO_2.

Section 4.1 overview

Surficial mineralization

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **None** • Key risks in scalability include energy, mineral, water, and land requirements as well as environmental impacts and storage locations
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is mass-customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot stage** • ~3 companies at pilot stage, with <$50M in funding each • Other notable RD&D activity includes the ARPA-E MINER program and field tests by LLNL and UBC
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **1.3 $GtCO_2$ by 2050** • Success is contingent on proof of safe and cost-competitive deployment, including the use of mining waste
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$150-300M over 7-20 years** • Key stage gates in measurement of removals and management of environmental impacts, especially at scale

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Medium risk:** Mining, grinding, transport, and subsequent stirring or spreading of feedstock will introduce constraints on scaling.	Grinding feedstock for efficient reactions is a key step that may require between 7.2-250 kWh (0.03-0.9 GJ) per tCO_2.[1] Using alkaline wastes to reduce additional mining or grinding as well as minimizing transport by carbonating and storing the minerals close to the source can all reduce energy requirements.[2,3,4]
	Mineral requirements	**Medium risk:** Industrial alkaline by-products alone have the potential to provide up to 7.5 Gt CO_2 global removals per year by 2100.	Industrial wastes and by-products, including slag or mine tailings, are favorable feedstocks as they can take advantage of pre-processing by other industries and are relatively low cost. Increased future material consumption will drive increased availability of wastes.[5] Purpose-mined reactant materials may be favorable for given locations but would come with the costs and constraints of additional extraction. [2,3,4]
	Water requirements	**Medium risk:** Water is a necessary additional input depending on climate conditions and process.	For mineralization sites located in arid and semi-arid regions, supplemental water may be necessary to overcome minimum humidity constraints of 55-60%, or to improve process efficiencies.[2] 20% of existing mine sites are located in regions under extreme water stress and 27% are located in regions where water risk is expected to increase by 2030.[5]
	Land requirements	**Medium risk:** Mineral distribution over a large area may be needed for efficient carbon removal at scale.	Mineralization can occur in piles and utilize existing industrial waste storage sites; however, mineral surfaces must be exposed to water and CO_2 during the process, requiring regular stirring of piles or extensive land area for rapid mineralization at scale. This could potentially require 14 million km^2 per $GtCO_2$.[2,3,4]
	Environmental impacts	**Medium risk:** Groundwater contamination risks are possible.	Implementation sites are likely close to water resources and must be managed to avoid surface and groundwater contamination.[2,3,4,6] However, there is also potential for positive impacts related to mitigating environmental concerns from industrial wastes.
	Storage location	**Medium risk:** Each $GtCO_2$ captured generates many km^3 of mineral products.	Large volumes of mineralized material will need to be either stored or utilized,[3,4] though the additional mass generated from the mineralization process is not expected to be problematic for existing industrial waste storage sites.
Secure storage for 100+ years		**Low risk:** Carbonates are long-lived and secure.	Carbonate mineral storage is highly durable, though careful site selection and ongoing monitoring will be required to avoid potential reversal due to strong acid weathering, e.g., at relevant mine sites.[3,7]
Path to measurement at scale		**Medium risk:** There is uncertainty in kinetics, assessing baseline mineralization rates, and implementing scalable measurement and monitoring in open environments.	Techniques for assessing mineralization rates do exist, but measurement and monitoring must be adapted for scale. [8] There are uncertainties in kinetics, especially in open environments.[2] Assessing baseline rates to determine additionality is not always straightforward.
Pathway to full costs <$100/$tCO_2$		**Low risk:** Appropriate feedstock sources are low cost.	Depending on feedstock and processing, costs range from $55-500/$tCO_2$.[3] The use of industrial wastes can provide low-cost feedstock.[2] Costs are likely to depend on process innovation rather than new technology.[9]

Notes and sources: [1]An LCA by Lefebvre et al. (2019) estimated comminution power requirements of 5.45 kWh/t feedstock. Kelemen et al. (2020) reports power requirements of 10-100 kWh/t feedstock. Using carbon mineralization capacities for various mine tailing feedstocks of removals of 0.4-0.76 tCO_2/t mineral from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019), the energy requirements are 7.2-250 kWh or 0.026-0.9 GJ per tCO_2. For comparison, the energy consumption of an average American home for 1 day is ~29 kWh, per the U.S. Energy Information Administration. [2]Geochemical Negative Emissions Technologies: Part I. Review (Campbell et al., 2022) [3]Engineered carbon mineralization in ultramafic rocks for CO_2 removal from air: Review and new insights (Kelemen et al., 2020) [4]NAS 2019 [5]Climate Related Considerations In the Metals and Mining Sector (Bullock, 2020) [6]Per sources [1,2,3], carbon mineralization processes can reduce acidity of wastes, reduce mobility of toxic metals, and destroy asbestiform aspects of some mine tailings, but approaches must be thoroughly tested. [7]The negative emission potential of alkaline materials (Renforth, 2019) [8]Measurements in Geochemical Carbon Dioxide Removal (Campbell et al., 2023) [9]Some reviewers consider this to be medium risk, given the variability in feedstocks, high-cost uncertainties, and low TRLs in this pathway.

Potential for cost improvement

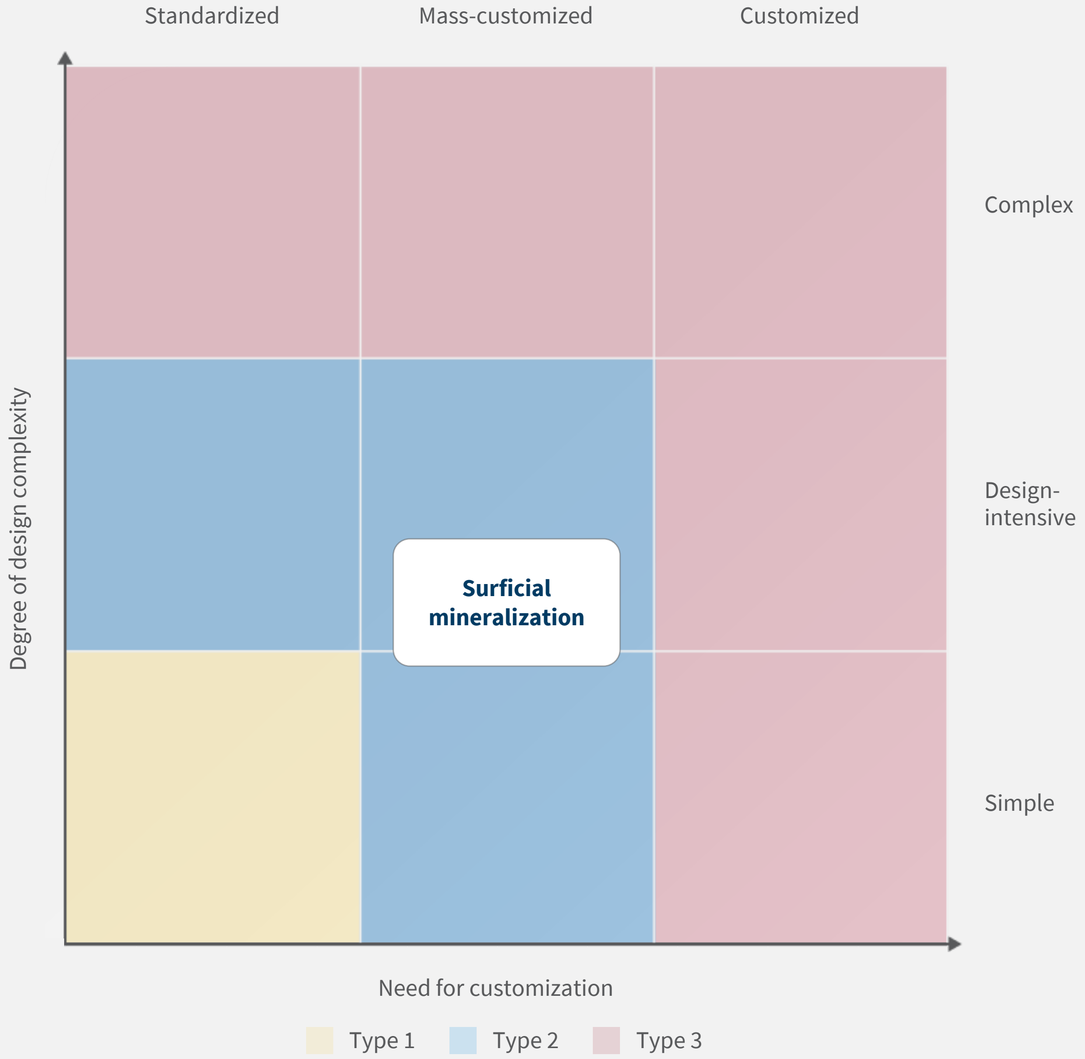
An assessment of two key drivers of learning rates

SECTION 4.1

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Solid carbonate minerals

APPROACH Surficial mineralization



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive
- **Rationale:** Processes for mineralizing feedstock may differ depending on existing material flows or stockpiles. Measurement and monitoring must account for open environments and complex kinetics.[2] Assessing baselines will depend on local circumstances.

NEED FOR CUSTOMIZATION

- **Rating:** Mass-customized
- **Rationale:** Different material sources, environmental conditions, and mineralization procedures all need to be addressed at each project site. Measurement and monitoring may be addressed via a variety of approaches and may need to be customized.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]The degree of design complexity may be much lower in practice; however, we lean towards a conservative assessment given the lack of data on process integration at scale.

Current state of RD&D

A mapping of companies, plus other notable activities

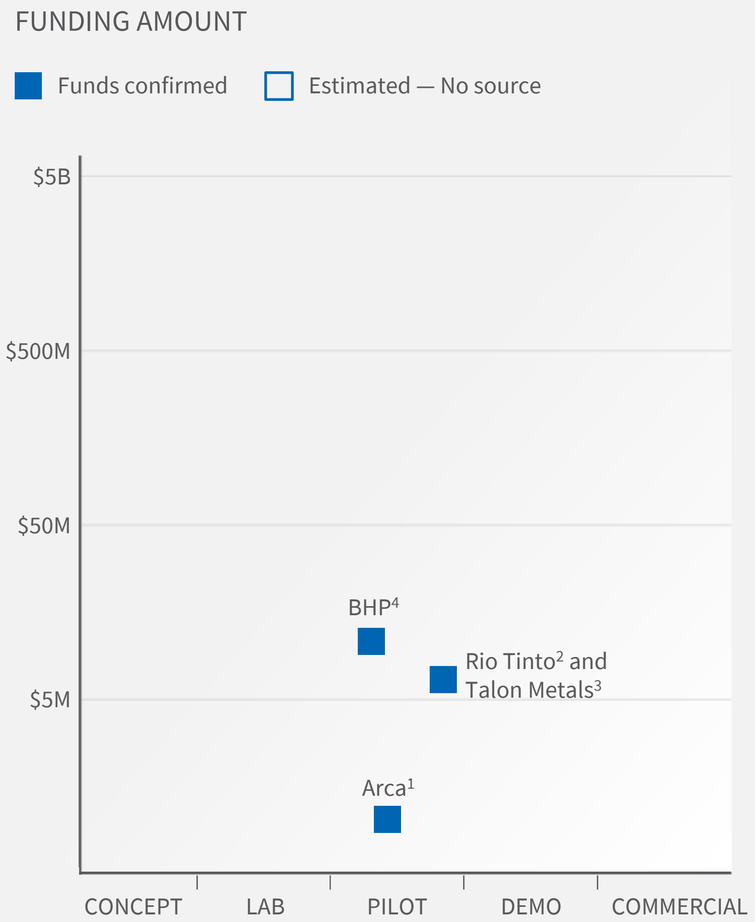
NOT EXHAUSTIVE

SECTION 4.1

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Solid carbonate minerals

APPROACH Surficial mineralization



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Arca (formerly Carbin Minerals): Accelerating mineralization of ultramafic mine tailings[1]	$2M (2022)[5]	• 200 tCO_2 partnership with Shopify • 380 tCO_2 Frontier purchase (2022) • XPRIZE Milestone winner[5]
Rio Tinto and Talon Metals: Pilot project in Minnesota at a nickel, copper, cobalt mine with ultramafic rock[2,3]	$2.2M (DOE) $4M (Rio Tinto)[6]	• Rio Tinto, Talon Metals, and other partners are exploring carbon storage through mineralization at a mining site and may include surficial and in-situ mineralization with CO_2 injection.
BHP: Australian mining company working at multiple locations on mineralization[4]	$15M investment[7]	• Conducting trials at Mount Keith tailings dam at Nickel West[8] • Signed a deal with China's HBIS group, a steelmaker, to pilot slag mineralization[7]
Other companies and activities: Rockfix,[9] Alkali Earth,[10] De Beers' CarbonVault research program[11,12,13]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
ARPA-E MINER (Mining Innovations for Negative Emissions Resource Recovery)[14]	$39M announced for projects in Oct 2022[14]	• ARPA-E MINER has 17 ongoing research projects that connect mining operations to carbon negative technologies through mineralization.[15]
Lawrence Livermore National Lab and **University of British Columbia:** KCAC field tests	$5M	• Surficial mineralization field tests to evaluate multiple approaches for carbon mineralization on asbestos mine sites.

Notes and sources: [1]Arca [2]Rio Tinto [3]Talon Metals [4]BHP [5]$1M XPRIZE Milestone winner [6]Rio Tinto pilot funding [7]BHP investment with HSIB [8]BHP investigating Nickel West [9]RockFix [10]Alkali Earth [11]De Beers is conducting a pilot to assess weathering of kimberlite mine tailings through its CarbonVault research program. [12]Grant for carbon-capture research [13]This program is assessing weathering of kimberlite mine tailings, researched in "Potential for offsetting diamond mine carbon emissions through mineral carbonation of processed kimberlite: an assessment of De Beers mine sites in South Africa and Canada" (Mervine et al., 2017). [14]ARPA-E MINER program and funds [15]List of 17 ongoing ARPA-E MINER projects [16]KCAC field tests by LLNL and UBC

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

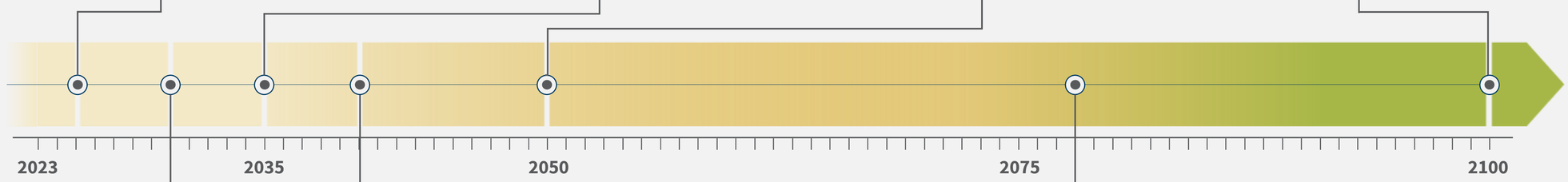
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 4.1

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Solid carbonate minerals

APPROACH Surficial mineralization



2025

- Early industrial pilots at the kiloton scale show safe, effective removals, prompting multiple industries to begin implementing waste mineralization demonstrations.
- Total measured global removals[1] from surficial mineralization are 160 $ktCO_2/y$ but growing quickly as more mining companies recognize the market potential of this approach.

2030

- Total measured global removals[1] from surficial mineralization are 5 $MtCO_2/y$.
- Carbonated wastes are certified as building materials.
- A database of current and projected mineral and waste resource availability is created and leads to identification of optimal deployment sites.
- Large scale mineralization projects are increasingly scoped alongside new mines.

2035

- Total measured global removals[1] from surficial mineralization reach 160 $MtCO_2/y$. This requires approximately 400 Mt ultramafic rock per year.[2]
- The total global supply of ultramafic rock has increased due to new supply driven by the energy transition.[3]
- Improvements in pre-treatment activities, such as heating, grinding, comminution, and microwaving, have led to improvements in carbon mineralization rates.

2040

- Total measured global removals[1] from surficial mineralization reach 330 $MtCO_2/y$.
- Surficial mineralization has become common in the mining industry as means of generating revenue from mine tailing waste.
- Carbonated wastes are integrated into building material aggregate, reducing storage needs.

2050

- Total measured global removals[1] from surficial mineralization reach 1.3 $GtCO_2/y$.
- At this rate of mineralization, use of legacy mine tailings has been maximized and some additional mineral feedstock is excavated expressly for mineralization.

2050-2100

- Almost all suitable industrial mineral waste continues to be utilized as part of the mineralization process.
- Breakthroughs in recycling of rare earth metals and new sources of rare earth metals, as well as pressure to decrease mining operations, have decreased the amount of secondary material available for surficial mineralization.

2100

- Total measured global removals[4] from surficial mineralization reach 3 $GtCO_2/y$ and require around 7.5 Gt per year of rock, comparable to the global coal industry today.[5]
- Surficial mineralization is further increased by the development of dedicated mines for CDR.

Notes and sources: [1]Future estimated global deployment assumes a starting point of 40 $ktCO_2/y$ removals based on press coverage of BHP's activities at the Mt Keith tailings dam in Western Australia. Future estimated deployment assumes a 100% growth rate from 2023 to 2035 followed by a 15% y-o-y growth rate from 2035 until 2050. [2]Renforth (2019) estimates 0.62 tCO_2/t of olivine reactant, 0.76 tCO_2/t of brucite reactant, and approximately 0.4 to 0.5 tCO_2/t of pyroxene and serpentine. Here we assume 0.4 tCO_2/t rock. [3]According to Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019), significant ultramafic mine tailings exist on mining sites but consists of less than 10 Gt of total material. Furthermore, annual production of new ultramafic mine tailings is about 200 Mt/y (p270). The total production of ultramafic mine tailings is expected to increase due to demand for minerals as part of the energy transition. [4]The magnitude of removals in 2100 varies considerably by source. Campbell et al., (2022) estimates that total removals could reach up to 7.5 $GtCO_2/y$. The NAS 2019 report notes that cumulative annual production of mine tailings is estimated to have a total CO_2 uptake capacity of 0.5-1 $GtCO_2/y$ (p269). [5]The IEA reports that the global coal industry in 2023 is around 8 Gt/y of coal. Coal is currently the most mined commodity on earth and is mined all over the world.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

TRL

CRITICAL PATH ACTIVITIES

$150-300 million | **7-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Environmental impact assessment**: Assessments of ecological impacts, including heavy metal leaching and water contamination
- **Site selection:** Identification of four demonstration sites with adequate feedstock, land, and water availability
- **MRV:** Development of scalable measurement techniques and monitoring for mineralization and removal rates; robust LCAs and TEAs

$50-100 million | **6-10 years**

- ✓ Environmental impacts are manageable at selected demonstration sites.
- ✓ Measurement techniques can quantify carbon removals and are ready to test at scale.
- ✓ TEA demonstrates a path to market competitive costs.

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **4x projects across multiple industrial sectors:** Demonstration of carbon mineralization using waste material, efficient integration into existing industrial and material handling processes; assessment of potential reduction of environmental risks
- **MRV:** Demonstration of measurement and monitoring at scale, protocol development, and further development of LCAs and TEAs

$100-200 million | **7-10 years**

- ✓ Carbon mineralization is effective and measurable at scale.
- ✓ Environmental impacts during processing and subsequent storage are manageable, or even favorable, at scale.
- ✓ Challenges for integrating mineralization steps into industrial processes have been addressed.
- ✓ Removals are demonstrated at market competitive costs.

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

SECTION 4.1

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Solid carbonate minerals

APPROACH Surficial mineralization

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$30-60 million | **5-10 years**

- Create a resource database assessing potential feedstock sourcing for legacy, actively produced, and projected wastes; identification of optimal sites for demonstration scale experiments.
- Test industrial waste as a weathering feedstock.
- Investigate process improvements and pre-treatments.
- Assess and improve reaction kinetics of mineralization.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Market competitive costs
- CO_2 removal rates are well-quantified at scale.
- Environmental and safety impacts across the entire process and storage chain are well-characterized and manageable.
- Feedstock sourcing and industrial integration has proven economically feasible.

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Site identification	Identify four demonstration sites that combine: • Adequate land area for effective mineralization • Mineral feedstock sources and disposal • Appropriate ambient humidity or available water At least two sites should provide direct integration with existing material handling.[1]	✓ Environmental impacts at selected pilot sites have been assessed and are manageable. ✓ Metals can be effectively immobilized, providing a pathway for reduction of environmental risks. ✓ Demonstration sites identified	1-2	$0.5-1M/y[2]	1-3 y	$2-3M
Field testing	Pilot scale field tests	Conduct trials to confirm that mineralization takes place on reasonable time scales, and determine environmental impacts in the field and mitigation approaches, including: • Effects of waste mineral storage (especially leakage into water systems) • Alkaline material exposure impacts, such as those due to airborne particulates		4-6	$0.5-1M/y[3]	6-10 y	$20-40M
Desktop research / field testing	Measurement and monitoring	Identify measurement approaches for inputs (CO_2, water, power, mineral feedstock, etc.) and feedstock mineralization rate monitoring to determine CO_2 captured. Utilize measured data to develop accurate modeling of weathering rates at scale.	✓ Measurement techniques provide reliable mineralization rate monitoring and associated CO_2 removals. ✓ Models can determine CO_2 removal rates and are ready to be tested at scale.	4	$0.5-1M/y[3]	5-10 y	$10-40M
MRV	LCA and TEA development	Develop robust methods to inform lifecycle accounting and technoeconomic assessments. • Approaches should develop tools, including models, that combine empirical data validation and analytical measurement methods for MRV protocols. • Approaches should be open source to invite collaboration and consolidation around best practices	✓ At least one open source MRV methodology that combines empirical and analytical techniques to verify removals is under development ✓ TEAs can assess and indicate a pathway to removals for <$100/t$CO_2$	3-5	$1-2M/y	4-8 y	$20-40M[4]

Notes and sources: [1]Direct waste stream integration includes approaches such as mineralization of mine tailings on-site or within existing material handling pathways. ICEF Recommends in their Carbon Mineralization Roadmap (2021) that mining and manufacturing companies look for carbon mineralization opportunities in their exploration and production activities [2]Cost estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Carbon Mineralization Research Agenda Budget (Table 6.3, p314), "Scoping for pilot sites." [3]Estimates based on a combined range of averages from NAS 2019 budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [4]Estimated budgets are based on NAS 2019 IAM model building of ~$1-3M/y/project for up to 8 years.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Industrial integration: 4+ demonstrations at distinct sites in industrial settings to investigate carbon mineralization for alkaline wastes, including: • Impact of local environmental conditions and seasonal effects on mineralization rates • Efficacy of CO_2 removal for existing wastes, and potential for improvements through additional grinding or pre-processing • Feasibility of integrating mineralization processes into existing material handling procedures and optimization of mine tailing rotations • Environmental hazard monitoring and mitigation	100 kt – 1 $MtCO_2/y$ [1,2]	✓ Carbon can be efficiently mineralized on a reasonable timescale, with existing waste, at low CO_2 concentrations ✓ Measurement is reliable at scale ✓ Environmental impact across the entire processing and storage chain, are manageable ✓ Achieves market competitive costs for CDR	4	$3-5M/y	7-10 y	$80-150M[3]
MRV	Demonstration of scalable techniques to quantify removals by: • Building on the pre-demonstration mineralization measurement development • Combining empirical measurements and any required modeling • Consolidating around standard, accepted protocols that are developed specifically for surficial measurement techniques	N/A	✓ MRV protocols based on empirical data and numerical modeling can attest to accurate mineralization rates and are accepted across the field.	3-6	$1M/y	7-10 y	$30-60M[4]

Notes and sources: [1]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) recommends kt-Mt/y field experiments based on the existing research on this approach. ICEF Recommends in their Carbon Mineralization Roadmap (2021) up to 25 full scale mineralization projects be launched across geochemical CDR approaches before 2030 [2]Campbell et al. (2022) reports surficial mineralization provides CO_2 removals within weeks to months. Assuming mineralization capacities for various mine tailing feedstocks of 0.4-0.76 tCO_2/t of feedstock (NAS 2019), then 130-250 kt of feedstock will be required for 100 $ktCO_2$ removals. [3]Cost estimates based on NAS 2019 Carbon Mineralization Research Agenda Budget for "Mine tailings, alkaline wastes" pilot studies. [4]Projects and costs are based on NAS 2019 Table 6.3 for numerical modeling for carbon mineralization.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Field testing	Waste stream integration	Pilot or demonstration scale projects that utilize legacy alkaline waste stores, including abandoned mine tailings, as feedstock, especially where toxicity can be mitigated through carbon mineralization	2-3	$0.25-0.5M/y[1]	5-8 y	$2.5-12M
Desktop research	Resource database	Creation of a database of current and projected mineral and waste resource availability, as well as identification of optimal sites for deployment based on climate, available processing energy sources, and environmental risk considerations	1-2	$0.5-1M/y	3-5 y	$4-8M[2]
Desktop research / field testing	Pre-treatment process improvements and improvements in reaction kinetics	Conduct and utilize experimental measurements and modeling of reaction kinetics to understand dissolution and mineralization rates as a factor of environmental conditions, mineral type, processing, and reaction stage.[3] This work should be complemented by investigation of pre-treatment activities[6], such as heating, grinding, comminution, microwave, and biotic interactions (either through engineered conditions or engineered microorganisms) that can enhance carbon mineralization.	5-8	$1M/y[4,5]	5-10 y	$25-80M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include new legal frameworks and permitting.*

Notes and sources: [1]Cost estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) "Mine tailings, alkaline wastes" Pilot Studies from Carbon Mineralization Research Agenda Budget (Table 6.3, pg316). [2]Cost estimates based on NAS 2019 Carbon Mineralization Research Agenda Budget. [3]Environmental conditions include temperature, pressure, humidity, and pH. Preprocessing approaches include heating and grinding. Reaction stage should include any existing mineralization and passivation effects. [4]Cost estimates based on averages from NAS 2019 budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [5]Cost estimates based on NAS 2019 Kinetics research from Carbon Mineralization Research Agenda Budget (Table 6.3, p314). [6]Pre-treatment processes may change the feedstock categorization and the associated permitting or regulatory approvals necessary for deployment. ICEF identifies in their Carbon Mineralization Roadmap (2021) that pretreatments for accelerating mineralization rates are a cross-cutting research priority.

5. Dissolved bicarbonate sequestration

Approaches seek to react alkaline materials with CO_2 to produce dissolved bicarbonates that are ultimately stored in the ocean or other bodies or water

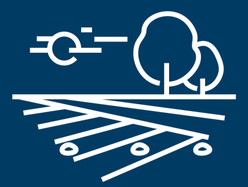
INDEX	APPROACHES	DEFINITION
5.1	Terrestrial enhanced weathering	Acceleration of the natural geologic weathering process through the spreading of finely ground alkaline materials in agricultural, urban, or forest soils, where it reacts with CO_2 and water to produce dissolved inorganic carbon
5.2	Coastal enhanced weathering	Distribution of crushed or pulverized alkaline minerals onto beaches and coastal shelves where it reacts under water with CO_2 to produce dissolved inorganic carbon
5.3	Mineral alkalinity enhancement	Direct addition of alkaline minerals to lakes, oceans, rivers, wastewaters, or other bodies of water to increase the alkalinity of the water and its capacity to absorb CO_2

RMI classifies solid carbonate mineral approaches as **geochemical**

Biogenic (bCDR)	Geochemical (gCDR)	Synthetic (sCDR)	Storage
Living biomass **1.1** Improved management **1.2** Conservation / protection **1.3** Restoration / creation **Stabilized biomass** **2.1** Biomass direct storage **2.2** Timber building products **2.3** Other biomass building products **2.4** Pyrolysis (biochar) and storage **2.5** Pyrolysis (bioliquid) and storage **2.6** Microalgae in ponds **2.7** Microalgae in open water **2.8** Macroalgae in open water **Sequestration of CO_2 from biomass** **3.1** BECCS to electricity **3.2** BECCS to fuels	**Solid carbonate minerals** **4.1** Surficial **Dissolved bicarbonate sequestration** **5.1** Terrestrial enhanced weathering **5.2** Coastal enhanced weathering **5.3** Mineral alkalinity enhancement	**Indirect water capture (IWC)** **6.1** CO_2 stripping **6.2** Electrochemical alkalinity production **Direct air capture (DAC)** **7.1-7.3** Liquid solvent **7.4-7.7** Solid sorbent **7.8-7.9** Membranes **7.10** Cryogenic	**Storage of CO_2** **8.1** Conventional CO_2 storage **8.2** In-situ mineralization **8.3** Ex-situ mineralization

SECTION 5.1

Terrestrial enhanced weathering



SECTION	5.1
TAXONOMIC BUCKET	Geochemical
CDR CATEGORY	Dissolved bicarbonate sequestration
APPROACH	Terrestrial enhanced weathering

DEFINITION

Acceleration of the natural geologic weathering process through the spreading of finely ground alkaline materials in agricultural, urban, or forest soils, where it reacts with CO_2 and water to produce dissolved inorganic carbon

EXAMPLE SCENARIOS

1) Spreading crushed basalt on farmlands, or 2) adding crushed basalt as a soil treatment during reforestation – where, in both scenarios, the basalt reacts with carbonic acid produced by soil CO_2 and rain or irrigation water, creating dissolved bicarbonate that eventually flows into riverine systems.

Section 5.1 overview

Terrestrial enhanced weathering

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability** • Key risks include the environmental impacts of heavy metal leaching from certain feedstocks
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is mass-customized and simple
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab to demo stage** • ~6 companies at lab to demo stages with <$50M in funding each • Other notable RD&D activity includes the DOE Technology Commercialization Fund and LLNL's "Microbes Persist" focus area
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **470 $MtCO_2$ by 2050** • Success is contingent on the approach proving safe for humans and the environment at scale
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$250-700M over 7-20 years** • Key stage gates in monitoring of environmental and crop impacts and measurement of removals at scale

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Medium risk:** Grinding and transporting feedstock to weathering sites is necessary for deployment.	Mineral feedstock transport has an offsetting distance of 990 km.[1,2,3] Long distance transport is currently unusual, so the logistics of scaling must be considered. Grinding feedstock to a suitable size for efficient reactions in soils can consume energy in the range of 4-333 kWh (0.02-1.2 GJ) per tCO_2.[4]
	Mineral requirements	**Low risk:** Appropriate feedstock materials are abundant.	There are abundant mafic and ultramafic feedstocks with the theoretical potential to remove 0.3-1.25 tCO_2/t of mineral dissolved,[1] but additional mining may be required for gigaton scale removals.[5]
	Water requirements	**Low risk:** Little to no additional water is required.	The carbon mineralization process occurs primarily through rainfall and existing irrigation practices.[1]
	Land requirements	**Low risk:** Significant land area (including agricultural and forest) is suitable without land use conversion.	Urban, agricultural, and forested (especially during reforestation or other treatments) land can be employed without land use conversion, potentially with co-benefits to soils.[1]
	Environmental impacts	**High risk:** Heavy metal leaching from certain feedstocks is a significant concern.	Depending on the feedstock,[6] heavy metal leaching, especially nickel and chromium,[7] could cause hazardous levels in groundwater and agricultural soils.[1,8,9,10] Changes in pH may also affect freshwater ecosystems.[1] More environmental impact studies are needed to assess lifecycle risks.
Secure storage for 100+ years		**Low risk:** High proportions of carbon stored as bicarbonate are very stable.	Carbon is stored as dissolved bicarbonate and is transported through watersheds to rivers, where a small fraction may be re-released due to local river pH. Most bicarbonate makes its way to oceans, where it can be stored for >10,000 years.[2,5,11,12,13]
Path to measurement at scale		**Medium risk:** Measuring field scale removals that occur over multiple years is challenging.	Existing measurement techniques are labor intensive. Characterizing large-area, open systems with soil, riverine, and marine interactions and losses requires significant new development.[1,2,11,14] Complex models will need to be developed in order to assess removals at scale.
Pathway to full costs <$100/$tCO_2$		**Low risk:** Costs are already approaching $100/$tCO_2$, depending on location.	Current costs are estimated as $25-190/$tCO_2$, depending on country where deployment occurs.[1,8] Transportation cost is likely to be a limiting factor, requiring feedstock, soil, and environmental conditions to be considered when developing transportation networks. MRV costs are also higher for early deployments.

Notes and sources: [1]Geochemical Negative Emissions Technologies: Part I. Review (Campbell et al., 2022) [2]Geochemical Negative Emissions Technologies: Part II. Roadmap (Maesano et al., 2022) [3]Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment (Lefebvre et al., 2019) [4]An LCA by Lefebvre et al. (2019) estimated comminution power requirements of 5.45 kWh/t feedstock. Kelemen et al. (2020) reports power requirements of 10-100 kWh/t. Using 0.3-1.25 tCO_2 removal per t of mineral feedstock (from Campbell et al., 2022), the energy requirements are 4.4-333 kWh/tCO_2 or 0.02-1.2 GJ/tCO_2. For comparison, the energy consumption of an average American home for 1 day is about 30 kWh, per the U.S. Energy Information Administration. [5]The potential of enhanced weathering in the UK (Renforth, 2012). [6]A reviewer notes that some silicates, such as basalt and wollastonite, may present low risk for heavy metal leaching, as they are well within applicable limits for fertilizers and lime. [7]Other trace metals from ore and mining waste includes arsenic, beryllium, cadmium, lead, manganese, mercury, selenium, thorium, uranium (Gomes et al., 2016). [8]Engineered carbon mineralization in ultramafic rocks for CO_2 removal from air: Review and new insights (Kelemen et al., 2020) [9]As noted by a reviewer, the degree of leaching may be affected by increasing soil sorption capacity during weathering. [10]A reviewer notes that ongoing research indicates this risk may be lower. [11]The efficacy of enhancing carbonate weathering for carbon dioxide sequestration (Knapp & Tipper, 2022) [12]Enhanced weathering depends on numerous factors including mineral type, soil pH, temperature, material grain size, biological and chemical interaction resulting in complete weathering requiring 2.5 to 15+ years. [13]Per [11] of this slide, a factor of x0.86 is used to account for carbonate equilibria factors in riverine systems, but the rest of the carbon is permanently stored. [14]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [15]Global olivine production is 7.8-9 Mt/y (Kremer et al., 2019)

Potential for cost improvement

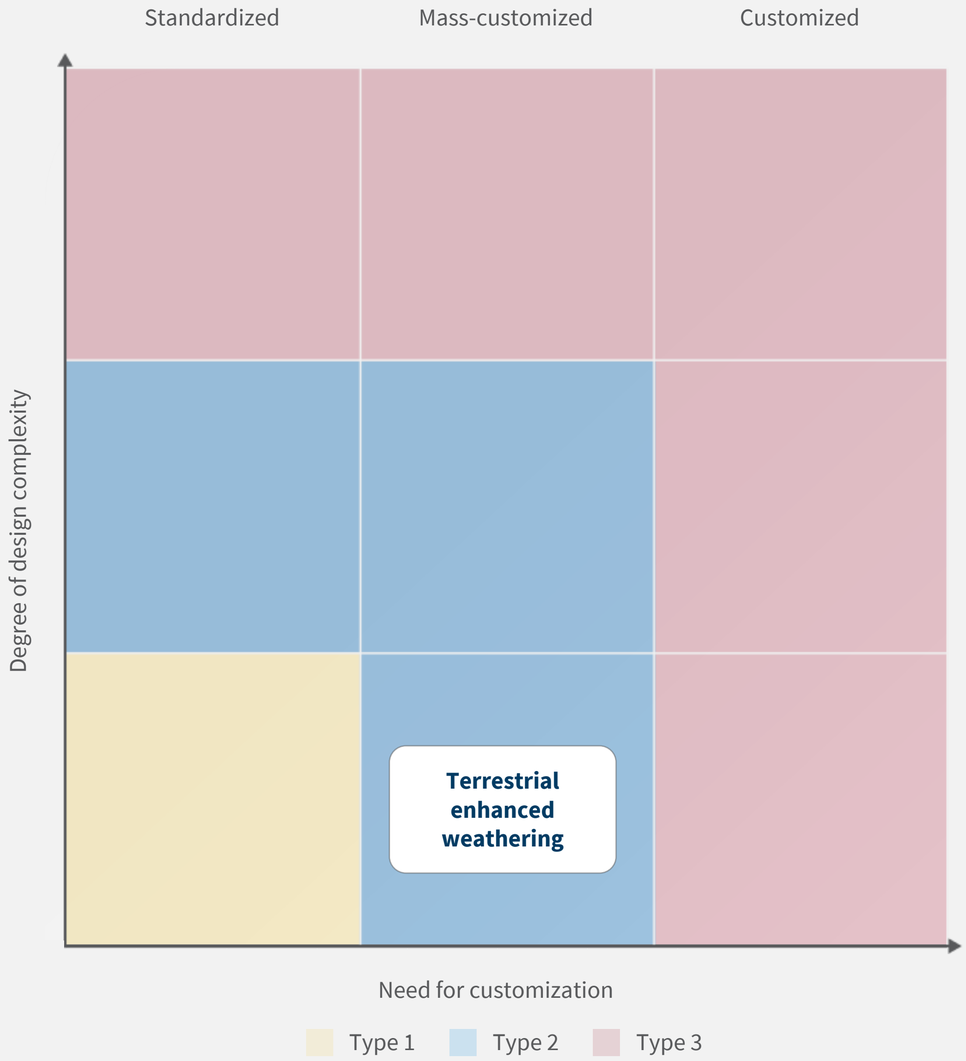
An assessment of two key drivers of learning rates

SECTION 5.1

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Terrestrial enhanced weathering



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 **Medium**

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Simple to design-intensive
- **Rationale:** Production and deployment of feedstock utilizes existing technologies. Substantial challenges exist in developing broadly deployable monitoring approaches with respect to both field measurements and accounting for overall system losses.

NEED FOR CUSTOMIZATION

- **Rating:** Standardized to mass-customized
- **Rationale:** Material sourcing and deployment will need to be tailored to each site, but with more projects, deployment under analogous conditions will provide increasing efficiency. Measurement techniques are likely to be highly repeatable across mineral types and deployment sites, and assessing baselines should be straightforward.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix .

Current state of RD&D

A mapping of companies, plus other notable activities

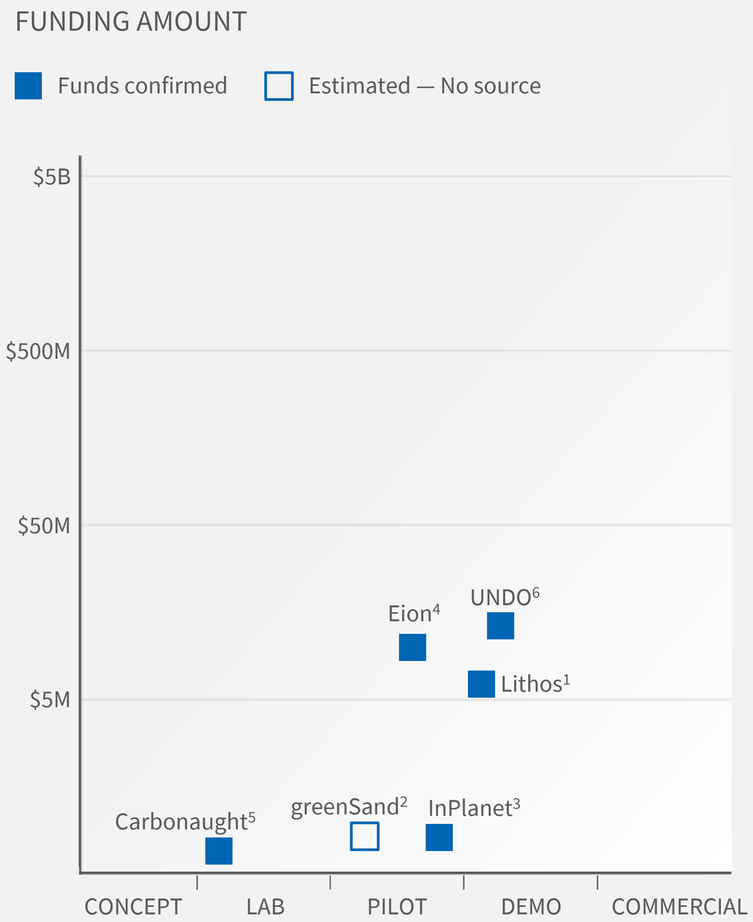
NOT EXHAUSTIVE

SECTION 5.1

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Terrestrial enhanced weathering



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Lithos: Deploying basalt for mineral weathering on croplands[1]	$6.3M seed round (Oct 2022)[7]	• Deployed ~47 kt of minerals as of June 2023 across range of crop, soil, and feedstocks (2500 ha total) • 640 tCO_2 removals supplied to Frontier Climate[8]
greenSand: Producing olivine and CO_2 certificates from enhanced weathering[2]	Equity crowdfunding + commercial	• Partner in two-year field trial[9]
InPlanet: Deploying rock powder on agricultural lands in tropical climates[3]	€1.2M (Jan 2023, pre-seed)[10]	• Projects[11] in Brazil with 15-1000 tonnes of alkaline mineral deployment and project CDR potentials of 1-176 tCO_2
Eion: Replacing agricultural lime as soil pH amendment[4]	$12M (Series A)[12]	• 2021 purchase agreement with Stripe
Carbonaught: Tracking feedstock deployment and removal technology for farms[5]	$900K[13]	• XPRIZE Carbon Removal Challenge Finalist • Technology is pending patent
UNDO: Spreading crushed basalt rock on farmlands[6]	$17M[14,15,16]	• Current pilots in Scotland and Washington with other pilots planned in England, North Carolina • 165 kt of basalt deployed[16]
Other companies and activities: Everest Carbon,[17] Green Sequest,[18] Rock Dust Local,[19] Silicate,[20] Mati,[21] Verde AgriTech[22]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
"Microbes Persist" Soil Microbiome Focus Area[23]	N/A	• Assessment of primary weathering rates,[24] LLNL program funded by the DOE Office of Biological and Environmental Research
DOE Technology Commercialization Fund	Portion of $15M[25]	• Developing an adaptive MRV framework for mineralization-based carbon dioxide removal pathways[25]

Notes and sources: [1]Lithos [2]greensand [3]InPlanet [4]Eion [5]Carbonaught [6]UNDO [7]Dealroom estimate for Lithos [8]Lithos Launch News, reviewer inputs [9]Olivine weathering in field trials [10]Inplanet Press Release [11]Inplanet Projects [12]Crunchbase funding estimate for Eion [13]Crunchbase funding estimate for Carbonaught [14]Crunchbase funding estimate for UNDO [15]AgFax article on UNDO [16]Funding and deployment informed by personal communication with UNDO. [17]Everest Carbon [18]Green Sequest [19]Rock Dust Local Enhanced Weathering [20]Silicate [21]Mati [22]Verde AgriTech [23]LLNL Microbes Persist consists of a mix of commercial (industrial) farm demonstrations alongside ongoing agronomic and CO_2 removal field trials to simultaneously validate operational, stakeholder, and practical feasibility. [24]Soil carbon storage rocks [25]DOE Funding Announcement

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

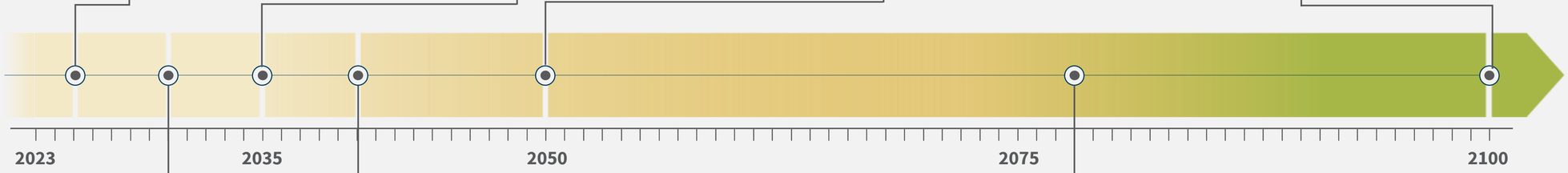
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 5.1

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Terrestrial enhanced weathering



2025

- 10+ demonstrations across 50 kha are funded and underway along with accompanying MRV development.
- 850 kt of alkaline material is deployed annually[2] generating approximately 170 $ktCO_2$/y of removals.
- Significant funding is allocated to develop and test sensors and measurement techniques for enhanced weathering.

2030

- At least 10 large (10 kha+) and 200 medium (500-2500 ha) deployments are underway over multiple crop types, forestry, and grassland with half using industrial waste rather than purpose-mined feedstock.[3]
- Total TEW application reaches 30 Mt of alkaline material per year, including appropriate reapplications.[2] Global CDR from TEW[2] reaches 5 $MtCO_2$/y.

2035

- Successful deployment of 82 Mt of material on several million hectares of land[3]
- Total global CDR from TEW[2] reaches 17 $MtCO_2$/y.
- Multiple feedstocks are used worldwide.
- Pay for practice policy incentives are beginning to yield further deployment.
- Protocols for testing alkaline feedstock to assess quality and safety are widely accepted.

2040

- Enhanced weathering has become common practice in agricultural activities.
- Enhanced weathering has been shown to be safe for humans and the environment when deployed at scale.
- 250 Mt of alkaline material is applied annually around the world on croplands and other lands.
- Total global CDR from TEW[2] reaches 50 $MtCO_2$/y.

2050

- Roughly 2.4 Gt of alkaline material is deployed globally each year for total global removals of 470 $MtCO_2$/y.
- Multiple feedstocks are in use.
- Deployments are optimized for appropriate land use, agricultural needs, local production, and transport.

2050-2100

- Deployment rates stabilize at ~3 Gt of alkaline material deployed globally each year. This mass is about half the size of the current coal industry, the largest currently mined commodity on earth, extracting ~8 Gt per year.[1] This scale provides around 600 $MtCO_2$/y of removals and would require distribution[4] over a land area of 3 million km^2 every year. This is equivalent to the land mass of India.

2100

- Terrestrial enhanced weathering approaches have the potential to supply ~2 $GtCO_2$/y of global removals which would require around 10 Gt of alkaline material.[1] Actual deployment will likely be limited to around 3 Gt of feedstock per year (600 $MtCO_2$/y) due to land constraints for application.[4]
- Enhanced weathering continues to be deployed in a manner that is safe for humans and the environment.

Notes and sources: [1]Beerling et al., (2020) estimates up to 2 $GtCO_2$/y removals can be achieved by 2050. With removals of 0.2 tCO_2/t of alkaline material, this would require ~10 Gt feedstock/y. For context, the IEA reports the global coal industry will produce about 8 Gt in 2023. [2]Optimistic deployment assumes 212 kt/y of feedstock deployed in 2023. Total CO_2 removed is based on estimates: (1) potential removals of about 0.2 tCO_2/t of basalt, based on data from UNDO that it will distribute 25 kt basalt to remove about 5 $ktCO_2$; and (2) total feedstock deployed, based on Lithos reviewer input that they have 2,500 ha of projects underway using 47 kt of basalt and on direct input from UNDO that they expect to complete 165 kt of basalt deployment by the end of 2023. More optimistic estimates exist in academic literature, including Renforth (2012), estimating removals of 0.3-1.25 tCO_2/t of mineral feedstock, and Strefler et al., (2018), noting a theoretical value of ~0.3 tCO_2/t of basalt. Private discussions with practitioners suggest the value may be lower than 0.2 tCO_2/t of basalt. Finally, dispersed alkaline minerals do not weather immediately but can take many years. More studies are needed to understand timelines and CO_2 reaction rates. Future growth assumes 100% y-o-y growth from 2023-2030 and 25% y-o-y growth from 2030-2050. [3]The United States has 166 million ha of cropland and the USFS manages 78 million ha of National Forests and Grasslands. EW may be more effectively deployed with reforestation/afforestation efforts than in mature forests. [4]This assumes 10 t of feedstock distributed per hectare of land, based on the Inplanet Projects report, which assumes ~4-10 t of feedstock per hectare. Some companies, including UNDO, are deploying at higher rates (20+ t/ha), but others think deployment may be limited by constraints on bicarbonate levels in local water. TEW may also be constrained by the volume and logistics of excavating and deploying feedstock.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 5.1

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Terrestrial enhanced weathering

TRL

CRITICAL PATH ACTIVITIES

$250-700 million | **7-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Environmental impact assessment**: Assess ecological impacts and implications for crop production.
- **Measurement technology:** Develop measurement and ongoing monitoring techniques for weathering rates, CO_2 removals, and environmental conditions.
- **MRV development:** Develop weathering measurement and modeling procedures to confirm CO_2 removals.

$50-100 million | **5-10 years**

✓ Demonstration sites are identified, and any negative ecosystem impacts are determined to be manageable.

✓ Weathering from other acids, e.g., nitric acid, as well as any secondary effects, are minimal.

✓ Reliable measurements and models suggest that net CO_2 removals can be verified, and large-scale modeling is possible.

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Agriculture based demonstrations:** Perform large scale studies on industrial farms across multiple crop types.
- **Feedstock based demonstrations:** Evaluate identical alkaline feedstocks across varying geographical and soil conditions.
- **MRV:** Develop scalable measurement and monitoring techniques along with LCAs and TEAs.

$200-600 million | **7-10 years**

✓ Ecosystem and crop impacts have been quantified with ongoing monitoring and negative impacts mitigated.

✓ Measurement and modeling of weathering rates and carbon removals can be verified at scale and is widely accepted.

✓ Market competitive costs achieved.

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$30-100 million | **5-10 years**

- Create a database of aggregate geospatial assessments for potential sourcing and deployment sites.
- Assess quality and safety of alkaline feedstocks with procedures for mineral processing and spreading.
- Test industrial waste as a weathering feedstock.
- Investigate process improvements through feedstock pre-treatments.
- Assess and improve mineralization reaction kinetics.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- CO_2 removal rates are well-quantified and verified at scale.
- Mineral spreading is safe for local and downstream environments.
- Feedstock transport to weathering sites is optimized for cost and emissions.
- Cost of removals is market competitive.

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Site identification	Identify 15-30 potential agricultural demonstration sites with distinct climate conditions and proximity to mineral feedstocks.	✓ Ecosystem impacts, especially around potential metal leaching, have been determined to be neutral or manageable at potential demonstration sites and downstream waterways. ✓ Weathering rates prove significant and cost effective.	1-3	$0.5-1M/y[1]	1-3 y	$2-3M
Field testing	Pilot scale field tests	Conduct trials to confirm that weathering occurs and bicarbonate is created while assessing the risks and co-benefits of mineral dissolution on deployment sites, downstream environments, existing soil organisms, and crop production at 10+ sites across geographic and environmental conditions. Tests should also include distinct mineral types to identify environmental impacts of various feedstocks and incorporate ongoing environmental monitoring to assess longer term impacts.		4-6	$0.5-1M/y[2]	5-10 y	$20-40M[2]
Desktop research / field testing	Measurement and modeling	Develop and test sensors and measurement techniques to assess weathering rates, environmental changes, and inform modeling approaches for deployment at scale.[3] • Investigate and assess weathering rates as a function of grain size and environmental conditions. • Assess the extent of weathering caused by strong acids, secondary precipitation, and clay formation.[4] • Constrain estimates of downstream leakage and impacts through watershed-scale assessments. • Utilize measured data to develop accurate modeling of weathering rates at scale.	✓ Models can determine CO_2 removal rates and are ready to be tested at scale. ✓ Key environmental conditions are known and can be monitored to track weathering rates over time.	8-10	$1-2M/y[2]	2-5 y	$15-40M
MRV	LCA and TEA	Develop robust methods to inform lifecycle accounting and technoeconomic assessments.[5] • Approaches should seek to develop tools that combine empirical measurements and analytical models. • Approaches should be open source to invite collaboration and consolidation around best practices.[6]	✓ At least one open source MRV methodology that combines empirical and analytical methods to verify removals is under development. ✓ TEAs can assess and indicate a pathway to market competitive costs.	1-3	$1-3M/y	4-8 y	$20-30M[7]

Notes and sources: [1]Cost estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Carbon Mineralization Research Agenda Budget (Table 6.3, p314) "Scoping for pilot site." [2]Values based on averages from NAS 2019 budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. The total cost is comparable to half the $30M total cost for the "Soils, beaches" pilot studies in the NAS 2019 Carbon Mineralization Research Agenda Budget (Table 6.3, p316). [3]Development of sensors and empirical monitoring protocols (measurement in the field) are essential to establishing an MRV framework. This step is a precursor to the following MRV line item for LCA and TEA development. [4]Strong acids in soils can preferentially weather alkaline material and essentially consume it. Removal efficiency decreases when secondary precipitation of carbonates occur or through the formation of clays (i.e., reverse weathering). [5]MRV for EW presents at least 2 major challenges: (1) It will not be possible to measure every field, so empirical data will not be enough to conduct MRV at scale. (2) The weathering process is non-linear and variable by field via conditions such as temperature, rainfall, pH, rate of application, type of feedstock, timing of application, depth of application, etc. Adjacent farms, for example, can have different capture rates. Some companies, such as Lithos, as described in an OpenAir Collective webinar, are taking empirical soil measurements and coupling this with machine learning to determine actual rates of weathering. This or a similar approach will likely be necessary for EW to scale. [6]The EW field is not yet ready for standardization; however, it should advance in this direction within the next 10 years. [7]Estimated budgets are based on NAS 2019 IAM model building of ~$10M/y per project for 10 years.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Demonstrations of 1,000-2,000 ha on industrial farms testing one of three different crops[1] to assess: • Weathering performance and ecosystem impact at scale • Nutrient transfer from feedstock to crops, potential fertilizer reduction, and lime replacement • Feedstock impacts based on crop type • Large scale measurement and modeling	10-20 $ktCO_2/y$[2,3]	✓ Environmental and crop performance impacts have been quantified and are manageable. ✓ Reliable measurement and modeling of reaction kinetics exist at scale such that weathering rates can be reasonably estimated based on feedstock, soil, and climate conditions. ✓ Optimal feedstock dosing, including seasonal effects, is understood. ✓ Market competitive costs are achieved.	6-10	$1-3M/y[4]	5-10 y	$90-300M
Demo	Large-scale, standardized demonstrations of 1,000-2,000 ha of identical feedstocks in varied climate and soil conditions across the US to test and compare: • Climate implications for weathering, dosing, reapplication rates, and carbon storage limits • Chemical and microbial soil interactions • Validation of measurement capabilities and models • Impacts in forestry compared to agricultural land use	10-20 $ktCO_2/y$[2,3]		10-15	$1-2M/y[4]	5-10 y	$75-300M
MRV	Numerical modeling to validate removals in the above demonstration projects, MRV should: • Build on the pre-demonstration work for enhanced weathering • Combine empirical measurements with analytical models and validate against the heterogeneity of site conditions • Consolidate around standard, accepted MRV protocols that are developed in parallel with geochemical CDR practices	N/A	✓ Robust measurement protocols based on empirical data and numerical modeling are verified and accepted across the field.	3-6	$1M/y	7-10 y	$30-60M[5]

Notes and sources: [1]Likely crop types are soy, corn, and wheat due to their prevalence in US farming. [2]Based on "The potential of enhanced weathering in the UK" (Renforth, 2012), appropriate feedstocks can capture between 0.3-1.25 tCO_2/t of mineral feedstock; however, this removal occurs over a period of years, not instantaneously upon feedstock deployment. 8-33 kt of mineral feedstock would be required for 10 $ktCO_2$ removal. Lithos reported 11 kt of minerals deployed in 2022. [3]Inplanet Projects reports approximately 4-10 tonnes of feedstock distributed per ha of land (across agroforestry, mixed crops and fruit trees, corn, and soy plantings) using a variety of alkaline feedstocks. Using the higher spreading rate of 10 t feedstock per ha applied twice over the duration of demonstrations and 8 demonstrations of 200 ha each (10 t feedstock * 2 applications * 1600 ha), a total of 32 kt of feedstock would be applied. This can provide a total of 9.6-40 $ktCO_2$ removals. [4]Project cost minimums based on "Soils, beaches" pilot studies in the Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Carbon Mineralization Research Agenda Budget (Table 6.3, p316). [5]Project costs are based on NAS (2019) Table 6.3 for numerical modeling for carbon mineralization.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Protocol development	Establish protocols for testing alkaline feedstock to assess quality and safety before processing and spreading.[1]	1-2	$0.5-1M/y[2]	3-5 y	$4-10M
Field testing	Waste stream implementation and environmental impact	Test industrial wastes (including slag, mining, and concrete waste) as feedstock to determine: • Safety of waste feedstocks • Pre-processing steps to ensure safety • Potential improvements in soil heath and crop yield • Financial advantages of using waste feedstocks	3-5	$0.5-1M/y[2]	5-10 y	$10-40M
Desktop research	Resource database	Create a database of geospatial assessments for potential siting, resource extraction, available energy sources, transport networks, and environmental impact concerns.	1-2	$0.5-1M/y	1-3 y	$2-3M[3]
Desktop research / field testing	Process improvements and reaction kinetics	Conduct and utilize experimental measurements and modeling of reaction kinetics to understand dissolution and mineralization rates as a factor of environmental conditions, mineral type, processing, and reaction stage.[4] This work should be complemented by investigation of pre-treatment activities[6] that can enhance carbon mineralization, such as heating, grinding, comminution, microwave treatment, and biotic interactions through engineered conditions or engineered microorganisms.	5-8	$1M/y[2,5]	5-10 y	$25-80M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include new legal frameworks, permitting, and policy analysis for distinct feedstock types and usage.*

Notes and sources: [1]Safety standards for related industries, especially mining and agriculture, can inform occupational hazards related to dust exposure and any feedstock specific contaminants. [2]Estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]Cost estimates based on NAS (2019) Kinetics research from Carbon Mineralization Research Agenda Budget (Table 6.3, p314). [4]Environmental conditions include temperature, pressure, humidity, and pH. Processing approaches include heating and grinding. Reaction stage considerations should include any mineralization and passivation effects. [5]Values based on averages from NAS 2019 budgets for desktop and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [6]Pre-treatment processes may change the feedstock categorization and the associated permitting or regulatory approvals necessary for deployment. ICEF identifies in their Carbon Mineralization Roadmap (2021) that pretreatments for accelerating mineralization rates are a cross-cutting research priority.

SECTION 5.2

Coastal enhanced weathering

SECTION	5.2
TAXONOMIC BUCKET	Geochemical
CDR CATEGORY	Dissolved bicarbonate sequestration
APPROACH	Coastal enhanced weathering

DEFINITION

Distribution of crushed or pulverized alkaline minerals onto beaches and coastal shelves where it reacts under water with CO_2 to produce dissolved inorganic carbon

EXAMPLE SCENARIOS

1) Adding mined and crushed olivine to beach nourishment projects, or 2) adding crushed olivine minerals to coastal shelves – where, in both scenarios, these minerals can react with dissolved CO_2 in ocean water to create bicarbonate.

Section 5.2 overview

Coastal enhanced weathering

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk, across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and path to measurement at scale** • Key risks include the environmental impacts on marine ecosystem balance and measurement at scale to validate net CO_2 removals
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is mass-customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot stage** • ~2 companies at pilot stage with <$5M in funding each
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **270 $MtCO_2$ by 2050** • Success is contingent on the approach proving cost effective, environmentally safe, and widely deployed across multiple continents
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$250-630M over 7-20 years** • Key stage gates in the measurement and modeling of removals and mitigation of ecosystem impacts

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

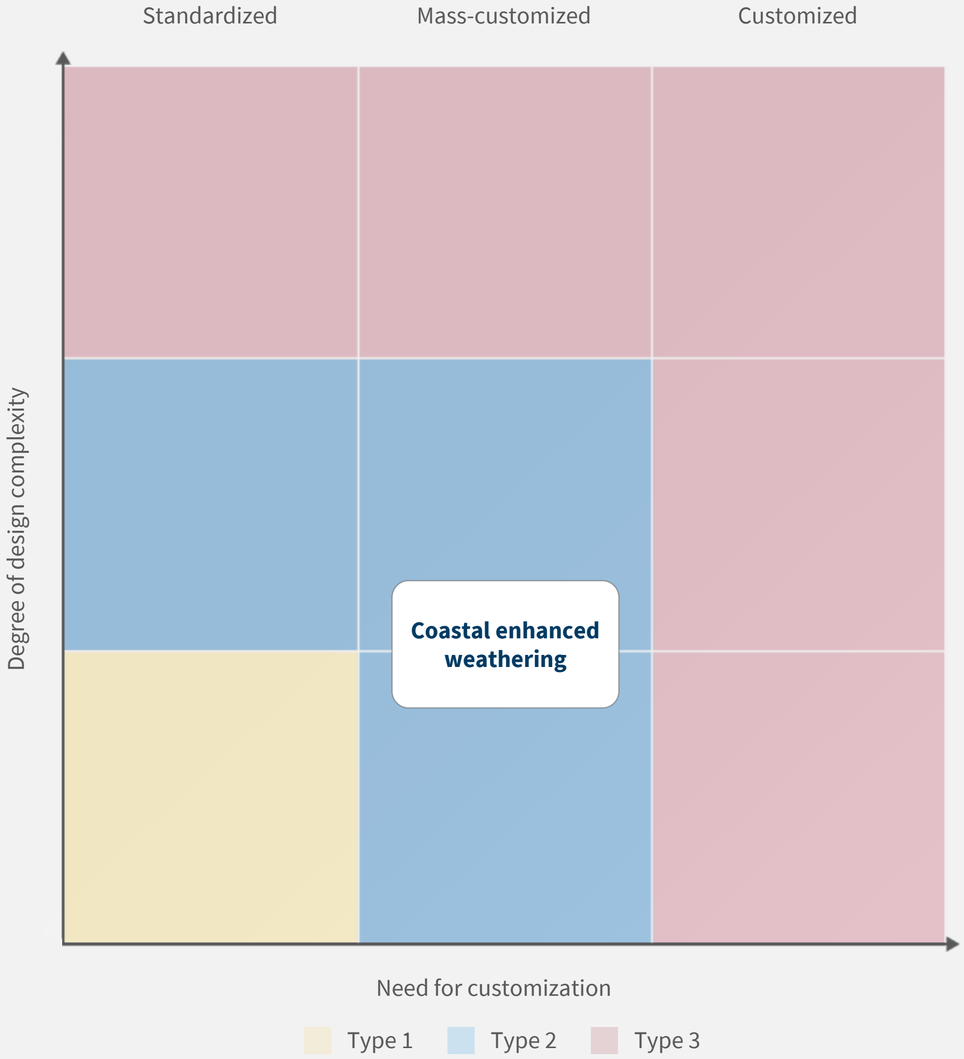
Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Medium risk:** Grinding and transporting feedstock may require significant energy.	Feedstock may require mining and grinding to a suitable size. Grinding requires 4-333 kWh (0.02-1.2 GJ) per tCO_2.[1,2,3,4] Transportation method and distance are also significant factors.[5,6]
	Mineral requirements	**Medium risk:** Abundant suitable feedstock sources exist, though mining will be required for gigaton scale removals.	There are abundant mafic and ultramafic feedstocks, but gigaton scale removals will require additional mining.[7,8] The theoretical potential to remove 0.3-1.25 tCO_2/t of mineral dissolved[1,9] is not yet observed in practice.
	Water requirements	**Low risk:** Feedstock sourcing requires mining, but no additional water is needed during weathering.	Water is required during mining and for dust control during grinding.[5] Feedstock deployment occurs along coastlines or coastal shelves, so additional water is not required.[1]
	Land requirements	**Low risk:** Beach nourishment activities or coastal shelves can occur without changing land use.	Feedstock deployment along coastal shelves or for beach nourishment[2] does not require land use conversion unless environmental impacts are severe.[2,5] Access and use by local populations should not be affected.
	Environmental impacts	**High risk:** There is a high rate of uncertainty as to unintended imbalances in marine ecosystems.	Enhanced weathering can reduce ocean acidification, providing marine environmental benefits, but nickel leaching is a significant risk.[2,5] Local spikes in ocean alkalinity resulting from over deployment would be detrimental to marine life.[10]
	Storage location	**Medium risk:** Significant coastline and coastal shelf areas exist, but suitability varies by site.	Many coastal sites are potentially suitable,[1,2,3] with an estimated 28M km^2 of global continental shelf area.[11] Environmental impacts and weathering conditions must be assessed for each site.
Secure storage for 100+ years		**Medium risk:** Bicarbonate residence time in the ocean is hundreds to thousands of years, however secondary precipitation is possible.	The mineralization process occurs in open, uncontrolled environments over long time periods (1-240 years)[12,13] and will result primarily in durable storage; however, secondary precipitation can occur due to induced pH swings, releasing CO_2. This has not been quantified in open settings.[1, 10]
Path to measurement at scale		**High risk:** Weathering occurs in open environments over several years.	Given the weathering time frame of years in open, uncontrolled environments, quantification is difficult and will require further innovation in measurement and modeling.[1]
Pathway to full costs <$100/$tCO_2$		**Low risk:** Process cost estimates are in line with a pathway to <$100/$tCO_2$.	Grinding costs are estimated at $10/t of feedstock.[14] Estimated academic process cost projections are low ($20-100/$tCO_2$),[15] although costs of MRV are still unknown. Total costs may be ultimately be determined by integration into existing activities, e.g., beach nourishment.

Notes and sources: [1]Geochemical Negative Emissions Technologies: Part I. Review (Campbell et al., 2022) [2]Engineered carbon mineralization in ultramafic rocks for CO_2 removal from air: Review and new insights (Kelemen et al., 2020) [3]A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022) [4]An LCA by Lefebvre et al. (2019) estimated comminution power requirements of 5.45 kWh/t feedstock. Kelemen (2020) reports power requirements of 10-100 kWh/t. Using 0.3-1.25 tCO_2 removal per tonne of feedstock (from Campbell et al., 2022), the energy requirements are 4.4-333 kWh/tCO_2 or 0.02-1.2 GJ/tCO_2. For comparison, the energy consumption of an average American home for 1 day is about 30 kWh, per the U.S. Energy Information Administration. [5]Life Cycle Assessment of Coastal Enhanced Weathering for Carbon Dioxide Removal from Air (Foteinis et al., 2023) [6]Increasing transportation of feedstock from 50 km to 250 km increases the environmental footprint by 23% (Foteinis et al., 2023) [7]The potential of enhanced weathering in the UK (Renforth, 2012) [8]Fewer mineral feedstocks are suitable for coastal enhanced weathering than for terrestrial enhanced weathering. [9]Global olivine production is 7.8-9 Mt/y (Kremer et al., 2019) [10]Kinetics of Olivine Weathering in Seawater: An Experimental Study (Fuhr et al., 2022) [11]Deriving Nickel (Ni(II)) and Chromium (Cr(III)) Based Environmentally Safe Olivine Guidelines for Coastal Enhanced Silicate Weathering (Flipkins et al., 2021) [12]The time scale of the silicate weathering negative feedback on atmospheric CO_2 (Colbourn et al., 2015) [13]Rolling stones; fast weathering of olivine in shallow seas for cost-effective CO_2 capture and mitigation of global warming and ocean acidification (Schuiling & De Boer, 2011) [14]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [15]Assessing ocean alkalinity for carbon sequestration (Renforth & Henderson, 2017)

Potential for cost improvement

An assessment of two key drivers of learning rates



SECTION 5.2

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Coastal enhanced weathering

OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Simple to design-intensive
- **Rationale:** Initial environmental and feasibility studies are complex; however, the technology needed for crushing and spreading rock is well established and not straightforward. MRV may be more complex based on measurement and modeling challenges in the open ocean.

NEED FOR CUSTOMIZATION

- **Rating:** Mass-customized
- **Rationale:** Material sourcing, deployment technologies, and measurement approaches must be tailored to each site, but as deployment increases, analogous conditions will decrease the need for novel customization.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix

Current state of RD&D

A mapping of companies, plus other notable activities

NOT EXHAUSTIVE

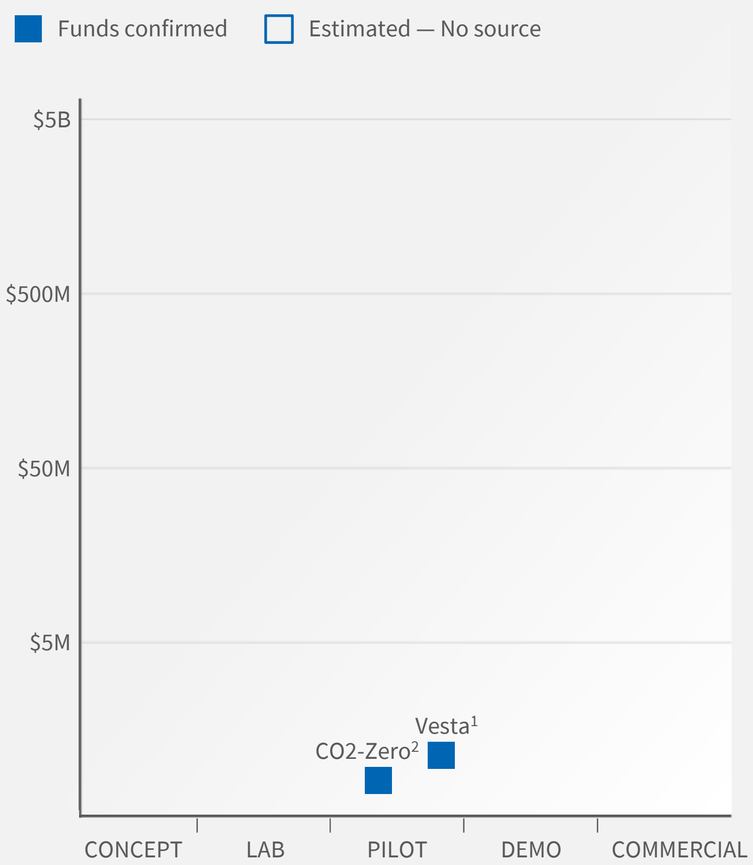
SECTION 5.2

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Coastal enhanced weathering

FUNDING AMOUNT



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Vesta: Providing coastal restoration through enhanced weathering[1]	$1.6M[3]	• 5% of a beach nourishment project in Southampton, NY[4] • Partnering with Great Lakes Dredge and Dock for research in US[5] • Partnering with The Aspen Institute to develop a code of conduct for ocean CDR[5]
CO2-Zero: Aggregating mineral rights to source feedstock for potential EW deployment[2]	£89k (Oct 2020)[6]	• Pilot project at Torbalı-Izmir • Negotiating an Atlantic coastline industrial facility[6]
Other companies and activities: Ocean Visions[7]		

Notes and sources: [1]Vesta [2]CO2-Zero [3]Crunchbase funding estimate for Vesta. [4]Project Vesta Field Pilots [5]Vesta collaborations [6]CO2-ZERO Press Releases [7]A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by 2030 (Ocean Visions, 2023) outlines several funding opportunities and programs that are relevant across multiple CDR approaches that occur in the ocean, including MRV research, field trials, and spatial planning.

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

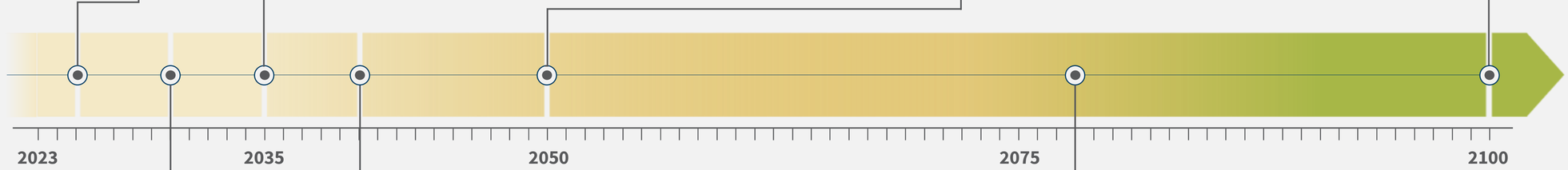
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 5.2

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Coastal enhanced weathering



2025

- Beach and coastal pilot studies of CEW are underway in parallel with development of measurement and monitoring techniques.
- Global deployment of olivine for coastal enhanced weathering reaches 5 kt rock/y.
- Significant funding is allocated for measurement, modeling, and verification of removals.

2030

- Larger demonstrations of coastal weathering are underway and are proving safe for marine ecosystems.
- Globally, 1.3 Mt of feedstock is being deployed each year in coastal environments for weathering for around 1.4 $MtCO_2$/y removals.[1]
- MRV methodologies are widely accepted.

2035

- Olivine coastal replenishment is widely accepted and globally deployed.
- 4.9 Mt of alkaline feedstock are deployed annually on coastlines around the world for total removals of around 5.4 $MtCO_2$/y.[1]
- Novel mineral distribution approaches and feedstocks are expanded, and sourcing efforts are scaling.

2040

- Annual deployment of approximately 18 Mt of feedstock per year for removals of 20 $MtCO_2$/y.[1]
- Deployments are made across at least 5 continents using multiple deployment approaches.
- CEW continues to be widely accepted, safe, and effective as a CDR approach.

2050

- Global deployments reach 250 Mt of feedstock per year for total removals of 270 $MtCO_2$/y.[1]
- Deployments for CEW continue to grow based on demand for beach nourishment, coastal deployment, and novel approaches.[1]

2050-2100

- CEW continues to be used as a primary process for beach nourishment and land creation. CEW continues to be cost effective and environmentally safe.

2100

- Coastal enhanced weathering continues to be deployed for land nourishment and extension.
- Total global removals have stabilized at around 300 $MtCO_2$/y based on yearly deployments of around 300 Mt of rocks per year.[2]

Notes and sources: [1]Future estimated global deployment assumes 200% y-o-y growth from 2023-2030 and 30% y-o-y growth from 2030-2050. The initial deployment is estimated at 0.6 kt alkaline minerals in 2023 based on estimates from Vesta's Southampton project in which 500 yd^3 of olivine, or approximately 0.6 kt. We assume a mineralization rate of 1.1 tCO_2 removed per tonne of feedstock deployed, which is the theoretical value reported by Strefler et al. (2018). Finally, dispersed feedstock does not mineralize immediately but can take many years and is dependent on exposure conditions. More studies are needed to understand the timelines and CO_2 reaction rates. [2]The A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) report suggests a combined potential for all mineral alkalinity enhancement approaches, including coastal enhanced weathering, in the range of 0.1-1 Gt CO_2/y. Similar to terrestrial enhanced weathering, the limiting factor on future growth will not be the amount of appropriate feedstock, but our ability to safely and cost effectively deploy them in the environment.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 5.2

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Coastal enhanced weathering

TRL

CRITICAL PATH ACTIVITIES

$250-630 million | **7-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Site identification:** Select test sites with appropriate environmental conditions and proximity to feedstock.
- **Environmental impact assessment:** Determine environmental risks, including ecotoxicology, marine population shifts, and other ecological effects of olivine dissolution are manageable.
- **MRV development:** Develop weathering measurement and modeling procedures to confirm net CO_2 removals over multi-year timescales.

$100-180 million | **6-10 years**

- ✓ Ecosystem impacts are quantifiable and manageable.
- ✓ CO_2 removals are not significantly negated via secondary effects.
- ✓ Weathering models are ready for testing at scale.
- ✓ Reliable TEA demonstrates a pathway to removals at <$100/$tCO_2$

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Beach nourishment demonstration:** Perform 3-4 site demonstrations to assess beach nourishment at scale.
- **Coastal shelf demonstrations:** Perform 10 standardized demonstrations using comparable feedstock along environmentally diverse coastal shelf locations.
- **MRV:** Develop scalable measurement and monitoring techniques, along with LCAs and TEAs.

$150-450 million | **7-10 years**

- ✓ Negative ecosystem impacts have been quantified and mitigated, including heavy metal contamination.
- ✓ Models and measurements are reliable at scale.
- ✓ Safe integration into existing coastal management activities.
- ✓ Established cost of removals <$100/$tCO_2$.

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$20-120 million | **5-10 years**

- Create a database of aggregate geospatial assessments for potential sourcing and deployment sites
- Develop guidance for safety, deployment, and monitoring
- Investigate process improvements through biological interactions and feedstock pre-treatment
- Assess and improve reaction kinetics through pre-treatments and optimizing deployment conditions

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated costs are <$100/$tCO_2$.
- Reliable, safe application in marine environments with little to no negative impact on relevant ecosystems.
- Scalable measurement techniques are verified, and models can reliably quantify CO_2 removals.
- Feedstock sourcing has proven economically feasible.

RMI

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Site identification	Identify four beach and ten coastline demonstration sites with distinct geographic and marine conditions and with proximity to suitable feedstocks.	✓ Net weathering rates are significant and cost effective ✓ Ecosystem impacts, especially due to nickel and heavy metal leaching, are determined to be manageable. ✓ Interactions of silicate minerals with marine environment and life and are known and manageable.	1-2	$0.5-1M/y[1]	1-3 y	$2-3M
Field testing	Pilot scale field tests	Conduct trials to confirm the weathering process occurs and to assess the risks and co-benefits of alkaline mineral dissolution on the marine environment at potential demonstration sites, including detailed studies on: • Ecotoxicological impacts during olivine dissolution, especially from metal leaching • Direct or indirect impacts on organisms from environmental or physical changes due to alkaline mineral addition and dissolution[2]		4	$0.5-1M/y[3]	6-10 y	$20-40M
Desktop research / field testing	Measurement and modeling	Develop appropriate sensing capabilities to provide reliable, multi-year measurement of dissolution rates and local environmental conditions. • Investigate and assess weathering rates as a function of grain size plus environmental and coastal conditions. • Determine the risk for secondary precipitation and formation of clays. • Utilize measured data to develop accurate modeling of weathering rates at scale.	✓ Measurement and modeling techniques can track weathering rates over time. ✓ Models can reliably estimate CO_2 removal rates and are ready to be tested at scale. ✓ Key environmental marine conditions are known and can be monitored.	4-8	$1-2M/y[3]	5-10 y	$20-50M
MRV	LCA and TEA	Develop robust methods to inform lifecycle accounting and technoeconomic assessments.[4] • Approaches should seek to develop tools that combine empirical and analytical measurement methods for robust MRV protocols. • Approaches should be open source to invite collaboration and consolidation around best practices.[5]	✓ At least one open source MRV protocol that combines empirical and analytical methods to verify removals is under development ✓ TEAs can assess and indicate a pathway to removals at market competitive costs.	2	$4-6M/y	5-10 y	$70-100M[6]

Notes and sources: [1]Cost estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Carbon Mineralization Research Agenda Budget (Table 6.3, p314). [2]Environmental changes may include variation in conditions such as beach and water temperature, pH, salinity, increase in silicate material presence, and turbidity. Physical environmental conditions include sand grain size and color, and secondary mineralization of clays. [3]Estimates based on averages from NAS 2019 budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [4]MRV for EW approaches presents at least 2 major challenges: (1) It will not be possible to measure every beach, so empirical data will not be enough to conduct MRV at scale. (2) The weathering process is non-linear and variable by beach as qualities such as temperature, pH, rate of application, type of alkaline feedstock, timing of application, depth of application, particle size, particle porosity, etc., can all affect weathering rates. Geographically close beaches can, as a result, have different capture rates. [5]The EW field is not yet ready for standardization; however, it should advance in this direction within the next 10 years. [6]Estimated budgets are based on NAS 2019 IAM model building ~$10M/y per project for 10 years.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Demonstrate beach nourishment with fractional deposits to test and confirm: • Alkaline feedstock dissolution rates when deployed in combination with other beach nourishment material • Nickel, cobalt, and other heavy metals contamination levels • Manageable ecosystem disturbances	10 $ktCO_2$ [1,2]	✓ Ecosystem impacts have been quantified and mitigated ✓ Nickel and heavy metal leaching at scale has been determined to be inconsequential ✓ Weathering rates can be reliably tracked for deployment at scale ✓ LCA, TEA, and MRV verified at scale ✓ CEW has a pathway to achieve market competitive costs	3-4[1]	$3-4M/y[3]	5-10 y	$30-120M
Demo	Perform large-scale, standardized demonstrations along coastal shelves. Tests should utilize identical feedstocks deployed globally with varying climate and ocean conditions to measure and compare: • Variations in weathering rates • Required dosing and reapplication rates • Environmental impacts, including nickel and cobalt contamination levels	5 $ktCO_2$ [1,2]		10	$1-2M/y[3]	5-10 y	$100-300M
MRV	Consolidated numerical modeling to validate removals in the above demonstration projects. MRV should: • Build on the pre-demonstration work on coastal enhanced weathering. • Combine empirical and analytical measurements to develop robust models. • Consolidate around standard, accepted MRV protocols that are developed in line with geochemical CDR practices.	N/A	✓ Robust MRV based on empirical data and numerical modeling is verified and accepted across the field	3-6	$1M/y	7-10 y	$30-60M[4]

Notes and sources: [1]Based on construction and landscaping guidelines, estimating approximately 100 lb/ft^3, a cubic yard of olivine has a mass of ~1.23 t). Using the 0.3-1.25 tCO_2 removal per tonne of feedstock value from Renforth (2012), each yd^3 can remove 0.27-1.5 tCO_2. Using the top of the range, removing 10 $ktCO_2$ requires 6.7 kt or 12,300 yd^3. As reported in Vesta's Southampton Field Pilot page, over the last 10 years, the state of New York alone has deployed more than 25M yd^3 of sand to restore coastlines. If all the deployed sand was olivine, that volume of sand could remove 2 $MtCO_2$ at the upper range of carbon capture. However, in the Southampton project, 500 yd^3 of olivine were deployed in 2022, about 3% of the 15,000 yd^3 deployed. Beach nourishment projects intended to provide shore protection benefits include 0.3-1M m^3 (0.39-1.3M yd^3) of sand. Assuming ~3% olivine content (comparable to the Southampton deployment), a 0.4M yd^3 deployment could capture an estimated 3-18 $ktCO_2$. Using the lowest end of this estimate, 3-4 beach nourishment projects will provide 10 $ktCO_2$ removals. Coastal shelf demonstrations are expected to be considerably smaller, providing data from more locations with smaller potential environmental impacts. [2]Based on "The potential of enhanced weathering in the UK" (Renforth, 2012), appropriate feedstocks can capture between 0.3-1.25 tCO_2/t of mineral feedstock; however, this removal occurs over a period of years, not instantaneously upon feedstock deployment. [3]Data from the ASBPA Nationwide Renourishment Database reports a volume of 1.6B yd^3 of renourishment projects since the 1920s at a total cost of $8.7B, or $5.40/$yd^3$, with a mix of offshore, nearshore, and upland sand sourcing. More recent estimates from a 2-year project in North Carolina had a cost of $8.50/$yd^3$ with offshore sand sourcing (based on 5.2M yd^3 deployed for a total cost of $44.3M). Based on the more recent cost, 4 beach projects of 0.4M yd^3 would cost $13.6M, not including the costs of measurement and monitoring or additional years of beach nourishment. [4]Projects and costs are based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Table 6.3 for numerical modeling for carbon mineralization.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Resource database	Create a database and geospatial assessment for potential siting, including information on locations in need of beach nourishment or coastal management intervention.	1-2	$0.5-1M/y	1-3 y	$2-3M[1]
Lab / field testing	Protocol development	Establish robust protocols for safe deployment, including: • Quality and safety assessment of alkaline feedstock before application • Safe quantities and rates of feedstock application • Environmental measurement and monitoring, including contaminant levels and ecosystem disturbance • Weathering measurement and monitoring to track CO_2 fluxes and mineralization rates	3-4	$1-2M/y[2]	5-10 y	$20-40M
Field testing	Pre-treatment process improvements	Conduct and utilize experimental measurements and modeling of reaction kinetics to understand dissolution and mineralization rates as a factor of environmental conditions, mineral type, processing, and reaction stage.[4] This work should be complemented by investigation of pre-treatment activities that can enhance carbon mineralization and weathering,[3] such as heating, grinding, comminution, microwave treatment, and biotic interactions through engineered conditions or engineered microorganisms.	5-8	$1M/y[2,5]	5-10 y	$25-80M[5]

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include early and on-going community engagement, as well as new legal frameworks and permitting.*

Notes and sources: [1]Projects and costs are based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019)(p314) for development of a resource database for carbon mineralization. [2]Estimates based on combined averages from NAS 2019 budgets for lab and desktop R&D funding. Details of this estimation can be found in the AIR Appendix. [3]Pre-treatment processes may change the feedstock categorization and the associated permitting or regulatory approvals necessary for deployment. ICEF identifies in their Carbon Mineralization Roadmap (2021) that pretreatments for accelerating mineralization rates are a cross-cutting research priority. [4]Environmental conditions include temperature, pressure, humidity, and pH. Preprocessing approaches include heating and grinding. Reaction stage should include any existing mineralization and passivation effects. [5]Cost estimates based on NAS 2019 kinetics research from Carbon Mineralization Research Agenda Budget (Table 6.3, p314).

SECTION 5.3

Mineral alkalinity enhancement

SECTION	5.3
TAXONOMIC BUCKET	Geochemical
CDR CATEGORY	Dissolved bicarbonate sequestration
APPROACH	Mineral alkalinity enhancement

DEFINITION

Direct addition of alkaline minerals to lakes, oceans, rivers, wastewaters, or other bodies of water to increase the alkalinity of the water and its capacity to absorb CO_2

EXAMPLE SCENARIOS

1) Spreading purified and crushed alkaline mine tailings in the open ocean to reduce acidity and convert dissolved CO_2 into bicarbonates; 2) adding alkaline minerals to water or wastewater treatment processes in order to reduce acidity and take up more CO_2 in the effluent.

Section 5.3 overview

Mineral alkalinity enhancement

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and path to measurement at scale** • Key risks include energy requirements from feedstock production and distribution, environmental impacts on marine ecosystems, and measurement at scale of long-term CO_2 removals in open environments
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • The approach is mass-customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot stage** • ~2 companies at pilot stage with <$10M in funding each • Other notable RD&D activity includes the Carbon to Sea Initiative and an EU OceanNets work package
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **130 $MtCO_2$ by 2050** • Success is contingent on the approach proving safe and cost effective, including along shipping routes and in wastewater processing
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$250-500M over 15-20 years** • Key stage gates in the measurement of removals and ecosystem impacts for different materials and environment conditions

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**High risk:** Feedstock extraction, production, transport, and distribution require significant energy inputs.	Mining or quarrying, pulverizing feedstocks, calcination of calcium carbonate for lime, transport to ports, and dispersal in oceans and other bodies of water all require significant energy.[1,2]
	Mineral requirements	**Medium risk:** Abundant feedstock sources exist but require mining to access.	Abundant suitable alkaline feedstocks exist globally;[10] however, mining requirements may be on the order of 2-7 Gt alkaline minerals per year, comparable with the global cement industry.[1,3,4]
	Water requirements	**Medium risk:** Production of alkaline feedstock may require water inputs, but opportunities exist to integrate with wastewater processing.	Water may be required to store CO_2 produced via calcination of lime. Water is also needed for slaking lime before distribution and possibly in the production of other alkaline feedstocks.[1,3,5,6] Several startups are beginning to pursue opportunities for deployment within wastewater treatment facilities, which would reduce this risk.
	Land requirements	**Medium risk:** Land may be required for additional feedstock mining.	Land is not consumed for feedstock distribution, but adequate feedstock supply will likely require expanded mining with associated land use.[1]
	Environmental impacts	**High risk:** There are numerous potential unintended impacts to marine environments.	There are substantial risks[7] for potential harm to aquatic life and environments, especially in marine environments that have little capacity to contain potential issues. These environments have limited potential for reversals and significant knowledge gaps about impacts at scale. Expanded mining operations will also have environmental implications.[1]
Secure storage for 100+ years		**Medium risk:** Modeling indicates high potential for secure removal.	Permanent carbon storage is dependent on water column properties and requires additional R&D assessment to determine secondary precipitation effects.[1,8,11]
Path to measurement at scale		**High risk:** MRV in open environments over long time scales will require breakthroughs in measurement and modeling.	Given the removal timeframe of months to years[9] occurring in open uncontrolled environments, measurement is difficult and will require dedicated effort, but can build on existing ocean modeling efforts.[1,12]
Pathway to full costs <$100/$tCO_2$		**Medium risk:** Full scale costs have addressable uncertainties toward full costs <$100/$tCO_2$.	Process estimates (not including MRV and infrastructure expansion) are $100-150/$tCO_2$. 2013 ocean liming costs were estimated at $120/$tCO_2$ using oxy-fuel limestone calcination. Different calcination methods or feedstocks offer potential cost reductions.[1,13]

Notes and sources: [1]A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) [2]Ocean liming requires ~5 GJ/tCO_2 of process heat and 150–300 kWh (0.18-0.36 GJ) of electricity for limestone calcination, lime distribution, and geological storage of the produced gas. Distribution of 1 Gt of mineral per year may require 1,000 dedicated vessels, especially without integration into existing freight pathways (NAS, 2022). [3]Geochemical Negative Emissions Technologies: Part I. Review (Campbell et al., 2022) [4]CO_2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems (Bach et al., 2019) [5]Slaking or hydrating lime produces calcium hydroxide. [6]Water demand may be lower depending on feedstock. [7]Risks include severe carbonate imbalances after alkalinity enhancement until equilibrium with air can occur (NAS, 2022) [8]Permanent carbon storage considers the CO_2 conversion into inorganic carbon compounds to be stable for >100 years, which is affected by dissolution kinetics, precipitation of carbonate (which leads to the release of CO_2), organic matter affecting mineral aggregation, grazing or consumption by lifeforms, and ocean current dynamics and physical processes (NAS, 2022). [9]Per Campbell et al. (2022), CO_2 removal takes place within weeks, but the stability of the removal over time depends on additional environmental factors, described in (NAS, 2022) and note [7]. [10]Alkaline feedstocks include hydrated lime, magnesium hydroxide, sodium carbonate, etc. [11]Reviewers assess this risk as ranging from low to high. [12]Some reviewers consider MRV a tractable challenge and rate the overall risk for MRV as medium. [13]Engineering challenges of ocean liming (Renforth et al., 2013)

Potential for cost improvement

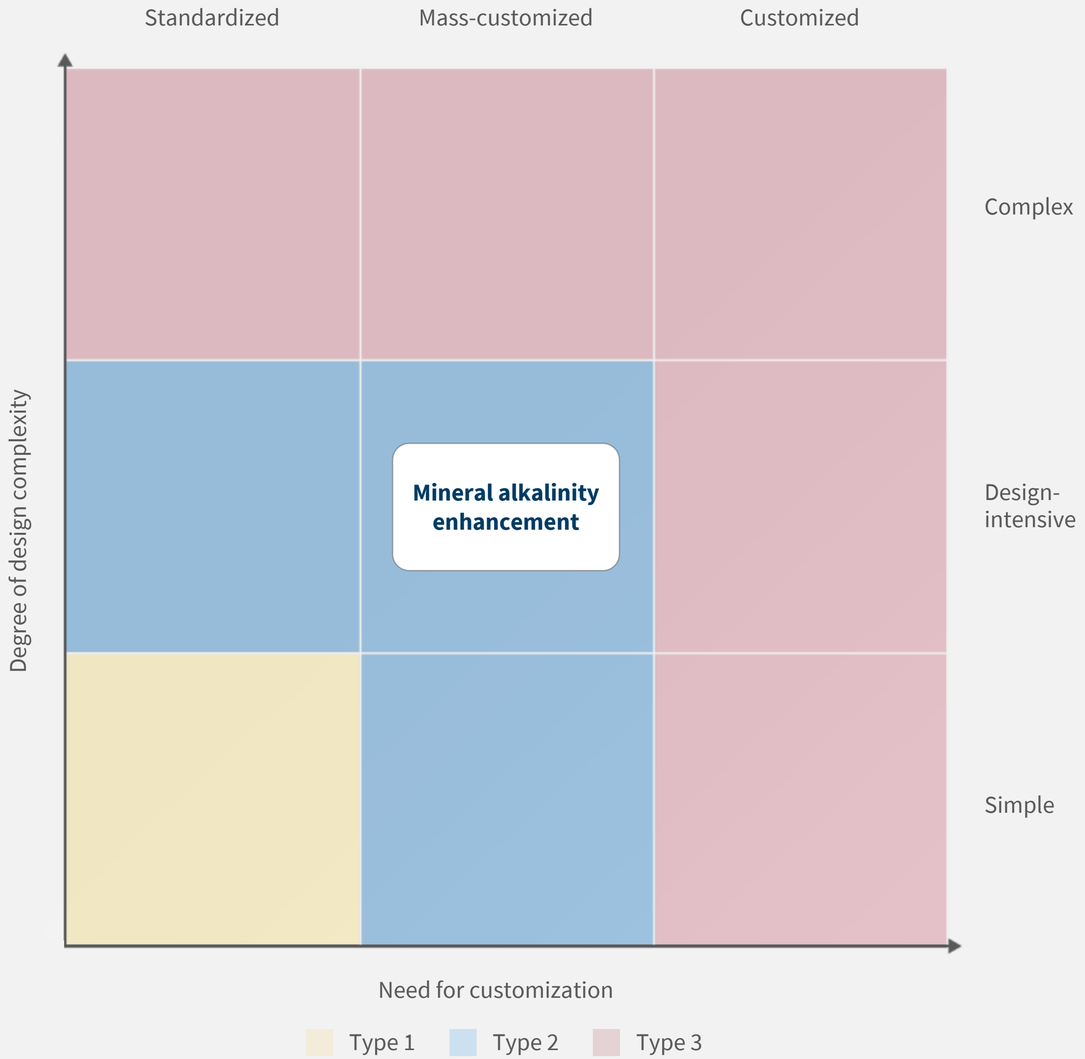
An assessment of two key drivers of learning rates

SECTION 5.3

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Mineral alkalinity enhancement



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive to complex
- **Rationale:** Feedstock sourcing, transport, and distribution must be all be addressed for deployment. Substantial technical and logistical considerations need to be addressed to solve complex challenges in measurement and monitoring.[2]

NEED FOR CUSTOMIZATION

- **Rating:** Mass-customized
- **Rationale:** Local conditions need to be individually assessed before dispersion of alkalinity, but, as deployment increases, analogous conditions will decrease the need for new customization on deployment and measurement approaches.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]MRV for electrochemical ocean CDR approaches (both the CO_2 stripping approaches and the precipitation approaches) is expected to be the same as for mineral alkalinity enhancement. Details of this process can be found here.

Current state of RD&D

A mapping of companies, plus other notable activities

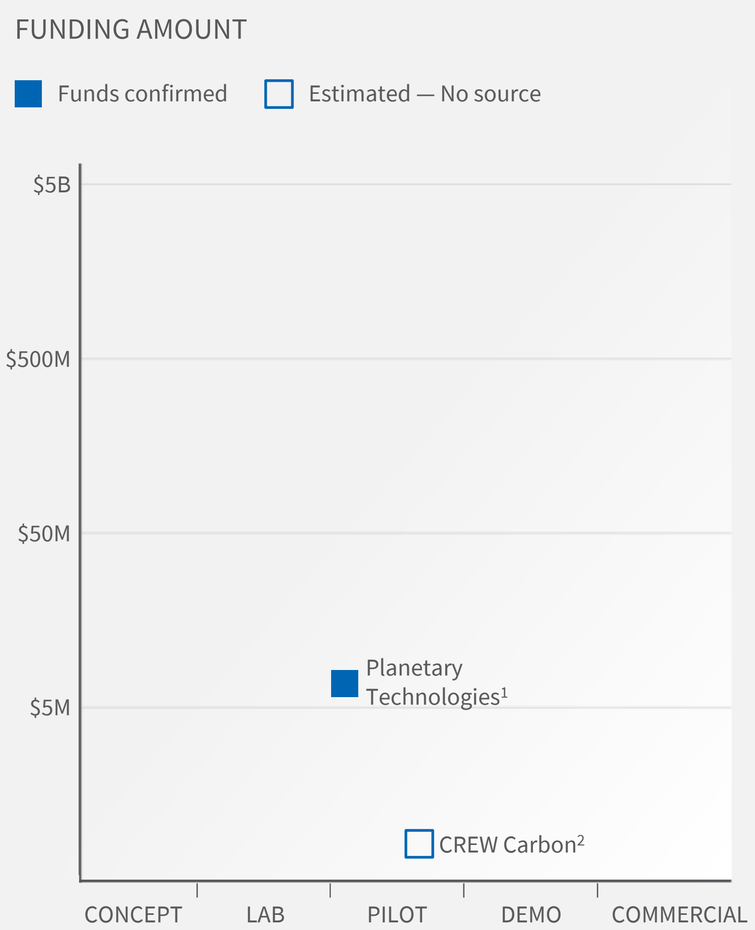
NOT EXHAUSTIVE

SECTION 5.3

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Mineral alkalinity enhancement



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Planetary Technologies: Purifying alkaline rocks after mining to use for ocean alkalinity enhancement[1]	$7.8M[3]	• Small site project in Cornwall, UK beginning in 2023[4] • Goal of removing 1 $MtCO_2$/y by 2028 and up to 1 $GtCO_2$/y by 2050[5] • Published an MRV protocol for ocean-based CDR
CREW Carbon: Deploying containerized weathering for CO_2 mineralization[2]	Frontier – Fall 2022 purchases[6]	• 615 tCO_2 purchased
Other companies and activities: CarbonRun,[7] Aquarry,[8] Origen,[9] Ocean Visions[10]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Carbon to Sea Initiative[11]	$22M	• Nine ocean alkalinity enhancement research or technology awards for 18 month to 5-year projects[11]
NOAA Pacific Marine Environmental Laboratory[12]	N/A	• PMEL's Ocean Carbon program includes research on the potential for ocean alkalinity enhancement to address ocean acidification[12]
OceanNETs: EU-funded work packages focused on CDR that occurs in the ocean	€7M for whole program	• Work package 5 is focused on ocean alkalinization through mineral additions[13] • Work package 6 is focused on ocean alkalinization case studies[14]
Pacific Northwest National Laboratory: Ocean Alkalinity Enhancement[15]	$2M from the DOE	• Evaluating the effectiveness and impact of OAE through coastal areas in the US

Notes and sources: [1]Planetary Technologies [2]CREW Carbon website [3]Planetary Technologies funding as covered by Business Wire [4]Planetary's Cornwall Project [5]Carbon Herald [6]Frontier purchases from CREW Carbon [7]CarbonRun is dissolving alkalinity into rivers, reducing their acidity and leading to the uptake of terrestrial and atmospheric carbon. [8]Aquarry is using alkalinity enhancement to treat pit lakes. [9]Origen Carbon Solutions is producing net-zero lime. The company was shortlisted for the UK Industrial Carbon Capture Hubs Phase 2 and has a Frontier project with DAC company Calcite to deliver carbon removals. Although they are not performing MAE as a CDR approach, the production of alkaline feedstocks is a critical activity to enable MAE at scale. [10]A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by 2030 (Ocean Visions, 2023) outlines several funding opportunities and programs that are relevant across multiple CDR approaches that occur in the ocean, including MRV research, field trials, and spatial planning. [11]Carbon to Sea Initiative [12]PMEL [13]OceanNETs Work package 5 [14]OceanNETs work package 6 [15]DOE announced $36M for CDR in marine environments, including $2M for the PNNL to conduct Ocean Alkalinity Enhancement experiments.

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

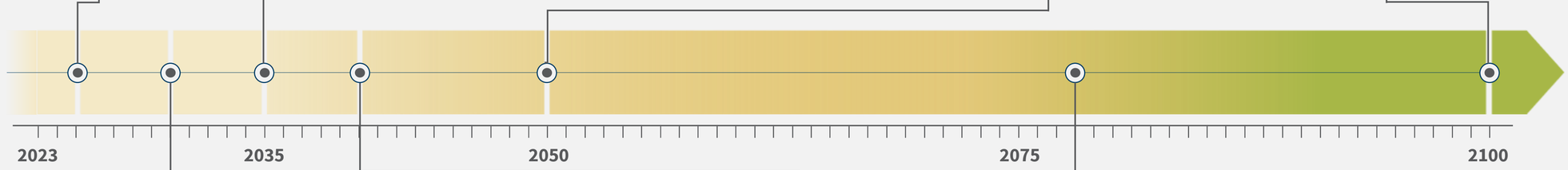
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 5.3

TAXONOMIC BUCKET Geochemical

CDR CATEGORY Dissolved bicarbonate sequestration

APPROACH Mineral alkalinity enhancement



2025

- Pilot scale studies of mineral alkalinity enhancement are funded and underway. These studies include carveouts to assess ecological impacts of ocean alkalinity enhancement.
- Significant trials begin adding minerals to wastewater in treatment facilities.
- Sufficient sites are identified for demonstration scale deployment.

2030

- Controlled field trials are planned, funded, and being deployed at small scales of 1-5 kt of alkaline material per project.
- Total deployment of mineral alkalinity enhancement globally reaches 160 kt of feedstock, which provides ~80 ktCO_2/y of removals.[1]
- New feedstocks are being tested in parallel with new measurement and modeling techniques to assess net CO_2 drawdown and ecological impacts while reducing feedstock energy requirements.

2035

- Total global deployment of mineral alkalinity enhancement reaches 5.1 Mt of alkaline material, providing approximately 2.5 MtCO_2/y of removals.[1]
- Sensing and monitoring systems are implemented in several deployment environments, including water treatment and desalination facilities and on maritime vessels.
- Shipping routes are initially tested for alkaline mineral distribution. These approaches are developed to avoid negatively affecting other ocean CDR approaches.[2]

2040

- Total deployment of mineral alkalinity enhancement globally reaches 19 Mt of material, providing ~9.5 MtCO_2/y of removals with minimal environmental impacts.[1]
- Validated monitoring and modeling systems inform the establishment of international standards for monitoring and deployment.

2050

- Total deployment of mineral alkalinity enhancement globally reaches 260 Mt of feedstock, providing around 130 MtCO_2/y of removals.[1]
- Mineral alkalinity is included in wastewater processes globally and fleets of repurposed ships are deploying material in the open ocean with increasingly accurate global monitoring to assess ocean conditions.

2050-2100

- Dedicated ships for mineral distribution increase total deployment.[3]
- Alternative approaches to mineral alkalinity enhancement have also become common.
- Total deployment of minerals begins to level off just short of 1 Gt of material per year.

2100

- Mineral alkalinity enhancement has leveled off at around 500 MtCO_2/y of removals or around 1 Gt per year of alkaline minerals deployed.[3,4]
- MAE approaches are commonly integrated with water treatment.

Notes and sources: [1]Future estimated global deployment assumes 100% y-o-y growth from 2030-2040, with an initial deployment of 5 kt feedstock, and 30% y-o-y growth from 2040-2050. Total removals are assumed to be 0.5 tCO_2/t of feedstock based on several estimates for the types of minerals that would be expected to be deployed: (Campbell, 2022) estimates 0.6-0.7 tCO_2/t of limestone; (Renforth, 2012) estimates that appropriate feedstocks can capture between 0.3-1.25 tCO_2/t of mineral feedstock. [2]It may be the case that $Mg(OH)_2$ is relatively safe compared to $Ca(OH)_2$ and NaOH with respect to marine microalgae. [3]Distributing alkaline materials at the scale of 1 billion t/y may require 1,000 dedicated vessels, especially without integration into existing freight pathways, per A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022), (Caserini et al., 2021). [4]The NAS (2022) report indicates that between 0.5-1 GtCO_2/y removals may be achieved by OAE while others, such as NOAA and Ocean Visions, estimate that up to 15 GtCO_2/y may be possible.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

SECTION	5.3
TAXONOMIC BUCKET	Geochemical
CDR CATEGORY	Dissolved bicarbonate sequestration
APPROACH	Mineral alkalinity enhancement

CRITICAL PATH ACTIVITIES

$250-500 million | **15-20 years**

TRL

TRL 1–6

PRE-DEMONSTRATION WORK

- **Environmental impact assessment:** Confirm risks from alkaline mineral dissolution are manageable.
- **Field and pilot testing mineral interaction:** Assess reaction kinetics, biological interactions, and optimal dispersal rates.
- **MRV:** Ensure removals can be measured and validated, with a pathway to scalable quantification.

$130-210 million | **5-10 years**

- ✓ Demonstration sites are identified.
- ✓ Pilot tests confirm environmental impacts are quantifiable and manageable.
- ✓ Distribution approaches for mineral dissolution indicate pathway to market competitive costs.[2]

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Large-scale comparative demonstrations:** Evaluation of different feedstocks across dispersal locations to assess environmental impacts while optimizing alkalinity enhancement processes and deployment logistics.
- **MRV:** Scalable measurement and monitoring techniques developed, along with LCAs and TEAs.

$130-300 million | **10 years**

- ✓ Ecosystem impacts are manageable at scale.
- ✓ Optimal feedstock dosing and dispersal are understood.
- ✓ MRV at scale can verify carbon removals based on material and open environment conditions.
- ✓ TEAs show a pathway to market competitive costs.[2]

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[3]

$110-250 million | **6-10 years**

- Aggregate geospatial assessments for deployment routes, approaches, and timing.
- Establish safe deployment guidelines for relevant deployment areas.
- Determine new infrastructure needed to deploy alkaline material for Gt scale removal.
- Investigate process improvements through feedstock pre-treatment.
- Assess and improve reaction kinetics.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[3]

- Empirical studies have proven the safety and efficacy of dispersing alkaline material into open systems.
- CO_2 removal rates are well-quantified at scale and have achieved market competitive costs.
- Feedstock production and transport is economically feasible when optimized for cost and emissions.

CRITICAL PATH RATING[1]

#	Current TRL
	Estimated cost
	Timeline to complete

1	Pre-demo only
2	Pre-demo and demo together, demo is FOAK
3	Pre-demo and demo together, demo is NOAK
4	Demo only
5	Path-boosting only

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Potential co-benefits, especially in the case of wastewater treatment, may lower the near-term deployment costs. However, long-term removal costs should be independent of ancillary products or co-benefits. [3]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION[9]	TOTAL COST
Desktop research	Site identification	Identify potential land-based dispersion sites, as well as shipping routes that have favorable environmental, seasonal, ocean, and cost conditions for demonstrations at scale.	✓ Sites with favorable environmental and logistical conditions are identified	1-2	$0.5-1M/y	1-3 y	$2-3M
Field testing	Pilot scale field tests	Comparative demonstrations of 1-5 kt[1] of alkaline feedstock (such as hydrated lime,[2] ikaites and other alkaline minerals[3]) at separate test sites with long- and short-term monitoring of environmental impacts, reaction kinetics, and biological interactions in pilot scale tests to assess: • Mineral dissolution and carbon removal rates[4] • Post-dispersal particulate aggregation and mitigation • Biotic and abiotic precipitation of carbonates • Key parameters for scale measurement and modeling	✓ Demonstration of measurable net carbon removal ✓ Dispersed material can be kept within optimal depth for dissolution ✓ Costs and environmental assessments indicate readiness for larger scale demonstration	5-10	$3-5M/y	5-10 y	$50-80M[5]
Field testing	Environmental impacts[8]	Test and assess the risks and co-benefits of alkalinity additions on marine environments, including: • Carbon cycle impacts • Duration and effects of carbonate imbalances • Growth impacts on calcifiers and silicifiers • Impacts to population dynamics of microorganisms, including algae blooms • Penetration of mineral particles into respiratory systems (human and animal)[6]	✓ Environmental impacts have been assessed and determined to be manageable.	5-10	$1-2M/y	5-10 y	$40-60M[5]
MRV	Measurement and modeling	Develop regional and global measurement, monitoring, and modeling activities for ocean dynamics and biogeochemistry.	✓ Confidence in predictions of alkalinity distribution, including residence time near the ocean surface	4-8	$1-3M/y[7]	5-10 y	$30-50M
MRV	LCA and TEA	Develop robust lifecycle accounting and technoeconomic assessments capable of evaluating and comparing distinct deployment conditions.	✓ TEAs can assess and indicate a pathway to market competitive costs.	3-5	$0.5-1M/y	5-10 y	$10-20M[5]

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include new legal frameworks and permitting for ocean activities.[8]*

Notes and sources: [1]Planetary's Cornwall project is using 100-550 t of magnesium hydroxide for its 2023 tests. [2]Potential of Maritime Transport for Ocean Liming and Atmospheric CO_2 Removal (Caserini et al., 2021) [3] Using ikaite and other hydrated carbonate minerals to increase ocean alkalinity for carbon dioxide removal and environmental remediation (Renforth et al., 2022) [4]Particle depth changes occur due to numerous factors, such as ocean temperature and dynamics, biological activity, and timing of deployment, and affects dissolution and environmental interactions. Measurements may include the rate of particle export to depth and parameters of the water column. [5]Budget estimates from A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) Table 7.5 "Research and Development Needs: Ocean Alkalinity Enhancement", p207 [6]Mineral particles in seawater can penetrate deeply into respiratory tissue, especially when particle sizes are smaller than 10 µm EPA Particulate Matter Basics via NAS 2022 [7]Estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [8]In the white paper Depending on the Ocean, released in May 2023, Carbon180 calls for more robust policies and legal frameworks. [9]A reviewer suggests that pre-demonstration should be complete within five years.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Perform comparative demonstrations of different alkaline feedstocks (hydrated lime,[1] ikaites,[2] dissolved olivine, magnesium hydroxide,[3] etc.) across distinct locations with long- and short-term monitoring to assess: • Feedstock dosing (amount over a given area, frequency of distribution, and impacts of different types of feedstock) • Consistent, predictable results in terms of pH increases and environmental impacts at large scales, including outside the immediate feedstock distribution area • The spread of alkaline plumes in the ocean • Potential albedo effects from particulate matter • Logistics of distribution through wastewater facilities and by different ships, routes, and discharge types • Reliability of MRV at scale	25-40 $ktCO_2/y$ [4]	✓ Changes to pH and ecosystem responses are consistently within acceptable limits ✓ Measurements at scale are effective and models assessing CO_2 drawdown are reliable ✓ Optimal feedstock dosing is understood for varying environmental, season, and feedstock conditions ✓ Approach is shown to achieve market competitive costs	5-10	$2.5-5M/y	10 y	$100-250M[5]
MRV	Validation of models to estimate removals and other environmental impacts in the above demonstration projects. MRV should: • Build on pre-demonstration work for all alkalinity enhancement approaches, including electrochemical approaches • Refine models based on ground / marine-based measurements and any relevant remote measurements to develop robust models and quantify uncertainties. • Consolidate around standard, accepted MRV protocols that are developed in line with geochemical and other enhanced alkalinity CDR practices.	N/A	✓ Models are quantitatively verified at relevant deployment scales ✓ Robust protocols are developed based on empirical data and numerical modeling that are verified and accepted across the field	3-6	$1M/y	10 y	$30-60M[6]

Notes and sources: [1]Potential of Maritime Transport for Ocean Liming and Atmospheric CO_2 Removal (Caserini et al., 2021) [2]Using ikaite and other hydrated carbonate minerals to increase ocean alkalinity for carbon dioxide removal and environmental remediation (Renforth et al., 2022) [3]Planetary's Cornwall project is using 100-550 t of magnesium hydroxide for its 2023 pilot tests. [4]Using estimates from Caserini et al. (2021) of 1.1 $GtCO_2$ removals with 1.3 Gt calcium hydroxide ($CA(OH)_2$), removals are estimated as 0.85 tCO_2 per t feedstock, or 0.6-0.7 tCO_2 per t of limestone (from Campbell et al., 2022). Caserini et al., also provides estimates of ~15 exploitable travels per year for container and bulk carriers ships, able to discharge 140 kt and 90 kt of lime, respectively, over those travels. Only 1/3 of this amount is assumed to be discharged to provide for more time for data collection between liming events, providing 25-40 $ktCO_2$ removals/year, as removals occur within weeks of the lime discharge into the ocean (Renforth et al., 2022). [5]Budget estimates from A Research Strategy for Ocean Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2022) Table 7.5 "Research and Development Needs on Ocean Fertilization," p100, used as comparable to the scale of ocean liming demonstrations. [6]Projects and costs are based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Table 6.3 for numerical modeling for carbon mineralization.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Site mapping	Perform ocean mapping detailing ocean alkalinity, carbon cycles, and natural feedback mechanisms, including modeling to predict how perturbations in alkalinity impact Earth systems and assess ocean zones favorable to alkalinity amendments. Additional mapping should also assess wastewater treatment facilities and other potential deployment sites, such as pit lakes or rivers.[1]	4-6	$1-2M/y[2]	5-10 y	$20-40M
Lab	Feedstock improvements	Develop feedstock production process improvements, including: • Identification of novel alkaline feedstocks and production opportunities • Energy reductions during pre-processing, such as calcination and grinding	10-15	$1-2M/y[2]	5-10 y	$50-100M
MRV	Protocol development	Establish protocols to address safe feedstock quantities, contaminant levels and ecosystem monitoring that consider international regulations for deployment beyond coastal zones.	2-3	$0.5-1M/y[2]	6-10 y	$10-20M
Desktop research	Industrial integration	Assess and plan for optimal integration of mineral distribution into the wastewater, shipping, and other industries, including: • Inclusion of mineral process steps in wastewater treatment • Optimal pre-processing of feedstock, including onshore and offshore options • Adaptation of cargo ships to disperse material along existing routes • Retrofitting of decommissioned ships or need for construction of new ships • Studies on adapting ports to include relevant infrastructure for mineral loading and processing	2-4	$1-2M/y[2]	3-5 y	$6-20M
Desktop research / field testing	Process improvements and reaction kinetics	Conduct and utilize experimental measurements and modeling of reaction kinetics to understand dissolution and mineralization rates as a factor of environmental conditions, mineral type, processing, and reaction stage.[4] This work should be complemented by investigation of pre-treatment activities[3] that can enhance carbon mineralization, such as heating, grinding, comminution, microwave treatment, and biotic interactions through engineered conditions or engineered microorganisms.	5-8	$1M/y[2,5]	5-10 y	$25-80M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include new legal frameworks, permitting, and policy analysis for distinct feedstock types and usage.*

Notes and sources: [1]New companies such as Aquarry and CarbonRun are looking to employ MAE approaches in acidic water bodies other than oceans. [2]Estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for desktop and lab R&D funding. Details of this estimation can be found in the AIR appendix. [3]Pre-treatment processes may change the feedstock categorization and the associated permitting or regulatory approvals necessary for deployment. ICEF identifies in their Carbon Mineralization Roadmap (2021) that pretreatments for accelerating mineralization rates are a cross-cutting research priority. [4]Environmental conditions include temperature, pressure, humidity, and pH. Preprocessing approaches include heating, grinding. Reaction stage should include any existing mineralization and passivation effects. [5]Cost estimates based on NAS 2019 Kinetics Research from Carbon Mineralization Research Agenda Budget (Table 6.3, p314).

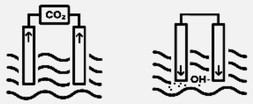
Intro to synthetic CDR (sCDR)

DEFINITION: *sCDR approaches use engineered systems powered by low carbon energy to directly separate CO_2 from the air and capture it, or to alter water chemistry to indirectly remove CO_2 from the air.*

We break sCDR into two sub-categories, based on how the carbon dioxide is removed from the atmosphere:

Indirect water capture

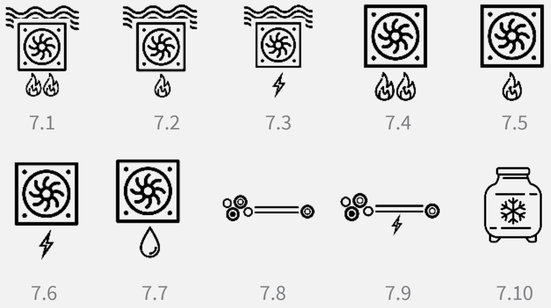
Approaches that indirectly remove CO_2 from the air by altering water chemistry.



6.1 6.2

Direct air capture

Approaches that use machines to capture CO_2 from the atmosphere in a concentrated stream.



7.1 7.2 7.3 7.4 7.5

7.6 7.7 7.8 7.9 7.10

sCDR definitions and example scenarios

6. Indirect water capture: Approaches that indirectly remove CO_2 from the air by altering water chemistry.

INDEX	APPROACHES	DEFINITION	EXAMPLE SCENARIOS
6.1	CO_2 stripping	Electrochemical processes that split water from oceans, lakes, or other bodies of water into acid and base streams, then use the acid stream to push dissolved CO_2 out of the water to be captured, and finally, recombine the acid and base streams to re-neutralize the water and return it to the source	1) Drawing ocean water into a membrane system that produces a small acid stream, adding the acid to a sealed container of water to bubble out the CO_2 for capture and storage, then the base stream is added back to the chamber of water and the water is deposited back into the ocean; 2) using light and a photocatalyst to split ocean water into acid and base streams, instead of electricity and membranes.
6.2	Electrochemical alkalinity production	The use of electrochemistry to create alkalinity that is added to the ocean or another body of water, enabling it to absorb additional CO_2	1) Changing the pH of a stream of water with electricity in a wastewater treatment facility to enable the water to uptake additional CO_2; 2) splitting ocean water into acid and base streams with electricity, then using the base stream to lower the pH of seawater locally while the acid stream is removed or disposed of elsewhere.

7. Direct air capture: Approaches that use machines to capture CO_2 from the atmosphere in a concentrated stream.

INDEX	APPROACHES	DEFINITION	EXAMPLE SCENARIOS
7.1	Absorption and high-grade heat regeneration	CO_2 absorption with an alkaline solvent (where CO_2 is dissolved or diffused in a liquid to form a solution), followed by a desorption process in which CO_2 is mineralized out of the solution and then regenerated by high-grade heat (700-900 °C)	Fans pull air over a potassium hydroxide solution that chemically binds with CO_2 in air to form potassium carbonate that then is regenerated with calcium hydroxide. This produces mineralized CO_2 that is processed at high temperatures to release concentrated CO_2 for storage.
7.2	Absorption and low-grade heat regeneration	CO_2 absorption with a liquid solvent (e.g., amines or amino acids, where CO_2 is dissolved or diffused in a liquid to form a solution), followed by a desorption process in which low-grade heat (120 °C or lower) is used to release the captured CO_2 and regenerate the solvent	Fans pull air over an amino acid solution that chemically binds with CO_2 in air. The resulting CO_2-rich liquid is then processed at low temperatures (<120C) to release the CO_2 for storage and regenerate the amino acid solution.
7.3	Absorption and electrochemical regeneration	CO_2 absorption with an alkaline solvent (where CO_2 is dissolved or diffused in a liquid to form a solution) followed by CO_2 release and solvent regeneration in an electrochemical cell where a change in voltage is used to separate CO_2 from the solvent	Fans pull air over potassium hydroxide that chemically binds with CO_2 in air and forms potassium carbonate. The carbonate is electrochemically processed to release concentrated CO_2 for storage and regenerate the hydroxide solution.

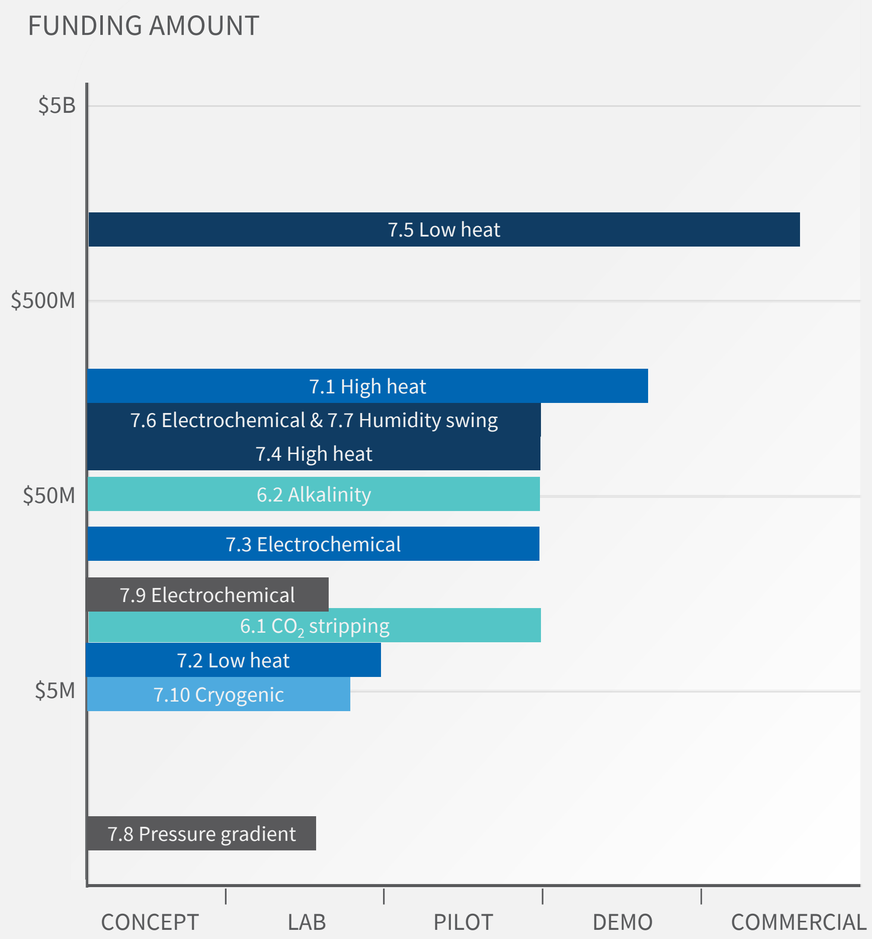
sCDR definitions and example scenarios

7. Direct air capture: Approaches that use machines to capture CO_2 from the atmosphere in a concentrated stream.

INDEX	APPROACHES	DEFINITION	EXAMPLE SCENARIOS
7.4	Adsorption and high-grade heat regeneration	CO_2 adsorption onto a solid mineral sorbent (where CO_2 is captured on the surface of a solid material) followed by a desorption process in which high-grade heat (600-1200 °C) is used to separate CO_2 from the mineral	Crushed calcium oxides chemically bind with CO_2 in air to form limestone, which is then processed at high temperatures to release concentrated CO_2 for storage and regenerate the calcium oxides.
7.5	Adsorption and low-grade heat regeneration	CO_2 adsorption onto the surface of a solid sorbent material (where CO_2 is captured on the surface of a porous solid material), followed by a desorption process where mainly low-grade heat (<120 °C) is used to release the CO_2 from the sorbent	Fans pull air over solid particles with high surface area that is used to physically or chemically bind with CO_2 from air and release it in the presence of higher temperature and/or lower pressure.
7.6	Adsorption and electrochemical regeneration	CO_2 adsorption onto a solid sorbent (where CO_2 is captured on the surface of a solid material), followed by CO_2 release and sorbent regeneration in an electrochemical cell in which a voltage change is used to separate the CO_2 from the sorbent	1) Ambient air is channeled through a stack of electrodes in which CO_2 is adsorbed, then a voltage is applied through the stack to release concentrated CO_2 for storage; 2) electrochemically reduced organic solids like quinones are used to chemically bind with CO_2 from air and electrochemically oxidized to release CO_2 for storage.
7.7	Adsorption and humidity / water regeneration	Adsorption onto a solid sorbent (where CO_2 is captured on the surface of a solid material) followed by a desorption step in which a swing in humidity (high humidity for regeneration) is used to separate CO_2 from the sorbent (i.e., a resin); further purification of CO_2 may be necessary, depending on the water concentration in the product stream	CO_2 is passively captured on a filter coated with resins that chemically bind with CO_2 in air, then water is added, causing the filter to release the CO_2 in an aqueous form and allowing the coated filter to be reused. Further treatment of the solution releases the CO_2 as a gas for storage.
7.8	Membrane: pressure gradient separation	Polymeric membrane separation in which the CO_2 is separated from other gases via differences in the molecular ability to pass through a polymer membrane (i.e., permeability); multiple capture stages, in which several membrane units are stacked together, may be required to achieve a concentrated CO_2 product	CO_2 in air permeates through a series of membranes, becoming increasingly concentrated until it can be utilized or stored.
7.9	Membrane: electrochemical separation	Ion-exchange membrane separation in which the CO_2 is separated from other gases in an electrochemical cell by means of a membrane and electron transfer	Electrochemically generated ions bind with CO_2 in air and selectively permeate through a membrane to electrochemically release CO_2 for storage.
7.10	Cryogenic: phase separation (vapor-solid)	Cryogenic separation in which very low temperatures enable a phase separation of CO_2 from other gases by deposition (a phase transition of CO_2 from vapor to solid)	At very low temperatures, CO_2 in air solidifies as dry ice on the surface of heat exchangers and then is removed through sublimation, resulting in concentrated CO_2 for storage.

Right now, sCDR is led by low temperature DAC approaches

NOT EXHAUSTIVE



	APPROACH	FUNDS COMMITTED[1]	SIGNIFICANT DEPLOYMENTS
IWC	CO_2 stripping (6.1)	>$12M[2]	**Captura** is launching a 1kt CO_2/y pilot with Equinor in Norway.[14]
	Electrochemical alkalinity production (6.2)	>$50M[3]	**Equatic** has launched two pilots in LA and in Singapore that each remove 100 kg CO_2/day.[15]
Absorption	Absorption and high-grade heat regeneration (7.1)	>$110M[4]	**Carbon Engineering** began construction of STRATOS in TX (500 ktCO_2/y) in 2022.[16]
	Absorption and low-grade heat regeneration (7.2)	>$7M[5]	**Rolls Royce and CSIRO's** Project ENCORE will have a larger field pilot by end of 2023.[17]
	Absorption and electrochemical regeneration (7.3)	>$33M[6]	**Capture6** has announced Project Monarch to provide water treatment and CDR in Palmdale, CA.[18]
Adsorption	Adsorption and high-grade heat regeneration (7.4)	>$80M[7]	**Heirloom's** first pilot to store CO_2 in concrete completed in 2023, capacity of 1ktCO2/y.[19]
	Adsorption and low-grade heat regeneration (7.5)	>$1B[8]	**Climeworks'** Mammoth plant, has been designed with a capacity of 36 ktCO_2/y.[20]
	Adsorption and electrochemical regeneration (7.6)	>$110M[9]	**Verdox** lab prototypes have proven successful and are exploring field opportunities.[21]
	Adsorption and humidity / water regeneration (7.7)	>$90M[10]	**Avnos** has begun building two pilot plants with support from the US government.[22]
Membrane	Membrane: pressure gradient separation (7.8)	>$1M[11]	**Innosense, LLC** received grant to research lab fabrication of membranes.[23]
	Membrane: electrochemical separation (7.9)	>$11M[12]	**RepAir** joined RMI's Third Derivative accelerator cohort in 2022.[24]
Cryo	Cryogenic: phase separation (7.10)	>$6M[13]	**Sustainable Energy Solutions** has combined cryogenic tech with concrete production in pilot in 2022.[25]

Notes and sources: [1]Total funding includes seed funding, grants, and investments in CDR-relevant projects that have been disclosed by companies included in the AIR. It does not include government funding towards research institutions. As companies reach later stages of development, they also disclose less financial information, so the actual funds committed to each of these approaches is likely higher than shown. [2]$12M sum based on disclosed funding from 1 company. [3]$50M sum based on disclosed funding from 2 companies. [4]$110M sum based on disclosed funding from 1 company. [5]$7M sum based on disclosed funding from 2 companies. [6]$33M sum based on disclosed funding from 6 companies. [7]$80M sum based on disclosed funding from 3 companies. [8]$1B sum based on disclosed funding from 15+ companies. [9]$110M sum based on disclosed funding from 5 companies. [10]$90M sum based on disclosed funding from 2 companies. [11]$1M sum based on disclosed funding from 1 company. [12]$11M sum based on disclosed funding from 1 company. [13]$6M sum based on disclosed funding from 1 company. [14]Captura pilot projects [15]Equatic website [16]STRATOS project [17]Project ENCORE [18]Project Monarch [19]Heirloom successful pilot [20]Climeworks plant Mammoth [21]Verdox website [22]Avnos pilot plants [23]Innosense, LLC research announcement [24]RepAir in Third Derivative cohort [25]SES pilot

Public and private funding for sCDR is significant and growing

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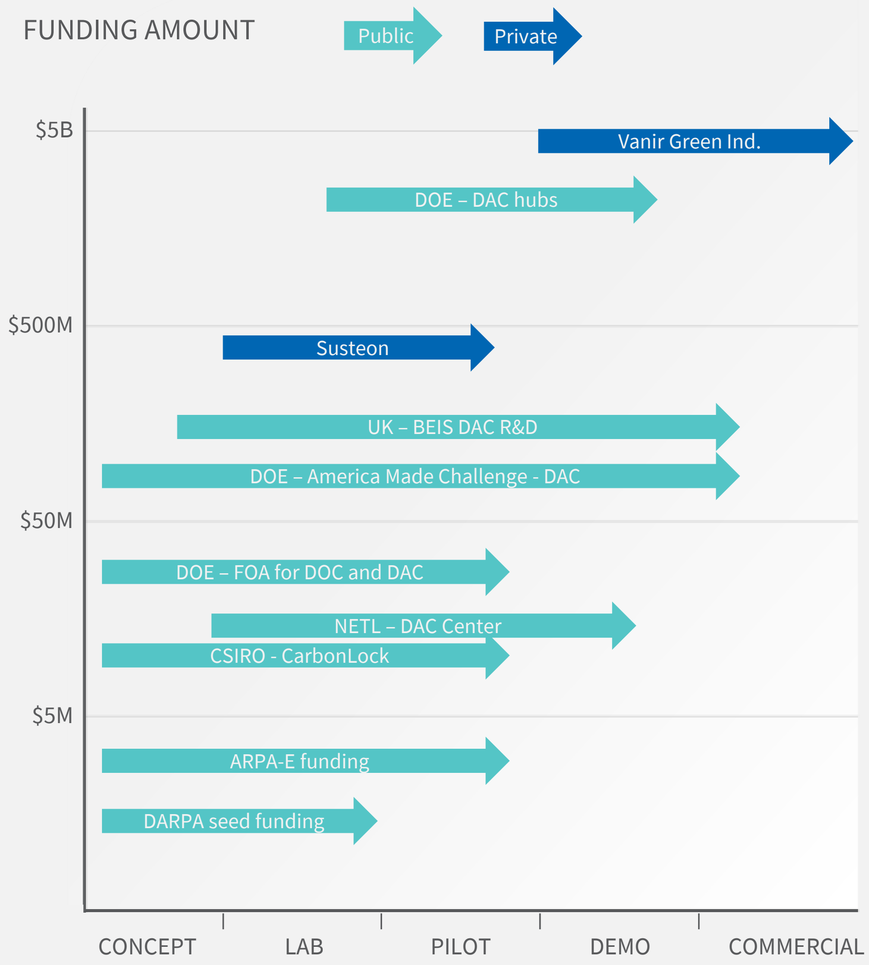
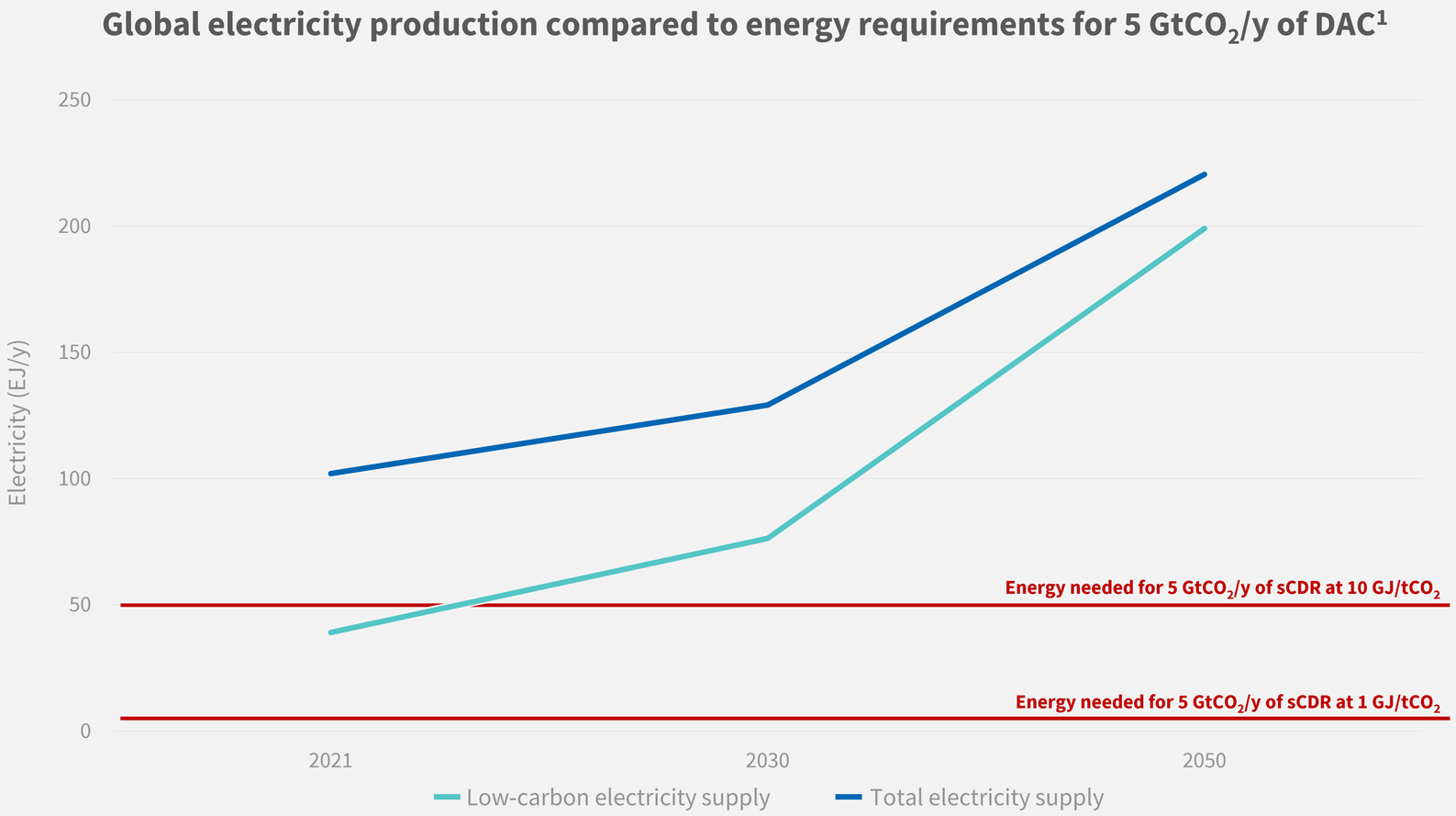


NOTABLE PUBLIC AND PRIVATE FUNDING	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
US NETL – DAC Center	$25M[1]	• Starting 2024 – enable tech developers to accelerate commercialization of DAC tech beyond the conceptual phase • Researching the ideal operating conditions for various DAC technologies across different climates
US DOE – DAC hubs	$3.5B[2]	• Established by the Bipartisan Infrastructure Law in 2021 • Supporting the creation of four regional DAC hubs across the US
US DOE – American Made Challenge	$100M	• Pre-commercial prize focuses on new tech ideation phase[3] • Pre-commercial EPIC prize focuses on DAC ecosystem enhancement[4] • DAC commercial prize awards established tech entities along their scaling path towards commercialization[5]
DOE – FOA for DOC and DAC	$30M	• Develop conceptual design studies followed by field validation[6]
ARPA-E Exploratory Projects and DOC Research Projects	$500k $3M	• $500k grant to Captura for development of hollow fiber membranes[7] • $3M to three projects at MIT, Cal Tech, and U. North Dakota for different electrochemical CDR approaches[8]
DARPA seed funding	<$400k <500k	• Funding to study regeneration of CO_2 gas from DAC[9] • Funding to research CO_2 extraction from seawater using bipolar membrane electrodialysis[10]
UK- BEIS	£100M	• 2020 initiated a competitive grant funding for R&D projects[11] • 2022 Phase 2 awarded ~£3M per each of the 4 DAC projects[12]
Australia- CSIRO	$20M[13]	• March 2023, CSIRO launched $20M research program, CarbonLock • Goal to minimize DAC energy requirements and costs while exploring co-benefits and new storage technologies[14]
Susteon	$500M to energy technologies	• Focus on early innovations (TRL 3-4), bridging over the valley of death for technology development[15] • Spin-out, Sustaera, is an adsorption and low-heat regeneration pilot
Vanir Green Industries[16]	N/A	• Private investment of green industries projects, including DAC • Funds Removr, an adsorption and low-heat regeneration plant[17]

Notes and sources: [1]NETL - DAC Center announcement. [2]DOE DAC Hubs [3]DAC Pre-commerical tech prize [4]Pre-commerical Energy Program for Innovation Clusters (EPIC) awards cash prizes to regional incubator teams that submit creative and impactful plans to support entrepreneurs and innovators in the DAC space and create meaningful community engagement. It aims to support both emerging and established DAC incubators and accelerators in implementing those plans to develop strong clusters, resources, and connections for energy startups and entrepreneurs. [5]DAC- commercial prize [6]DOE Office of Carbon Management FOA number: DE-FOA-0002614 [7]ARPA-E funding to Captura [8]ARPA-E DOC research projects [9]This funding led to the publications of several papers including Eisaman et al., "CO2 separation using bipolar membrane electrodialysis," (2011), and Eisaman et al., "CO2 desorption using high-pressure bipolar membrane electrodialysis" (2011). [10]This funding led to the publication of Eisaman et. al., "CO2 extraction from seawater using bipolar membrane electrodialysis," (2012). [11]UK BEIS fund for DAC and engineered CDR tech [12]UK – BEIS Phase 2 awards summary [13]CSIRO CarbonLock [14]CarbonLock research focuses [15]Susteon [16]Vanir Green Industries [17]Removr

Low-carbon energy is the key input for sCDR

Low-carbon electricity generates ~40 EJ/y today with the ability to rise to ~200 EJ/y by 2050



Notes and context

- The IEA estimates that total low-carbon electricity generation will grow from 39 EJ in 2021 to 199 EJ in 2050.[1]
- Low-carbon electricity availability is constrained by supply chains, resource constraints, and land use constraints.[1]
- Many other aspects of the energy transition are dependent on low-carbon electricity and will compete for supply.[1,2]
- All additional electricity for sCDR must come from additional, purpose-built generation, otherwise it is likely to hamper mitigation elsewhere

Notes and sources: [1]Electricity generation in the IEA Announced Pledges Scenario (APS) from the 2022 WEO (Table A.3b, p443). Here, we include the categories of "Renewables," "Nuclear," and "Fossil fuels with CCUS" in our definition of low-carbon electricity. [2]Carbon Brief summarizes the IPCC AR6 WGIII report by showing that rapid electrification is required across nearly all end use sectors to achieve long term goals.

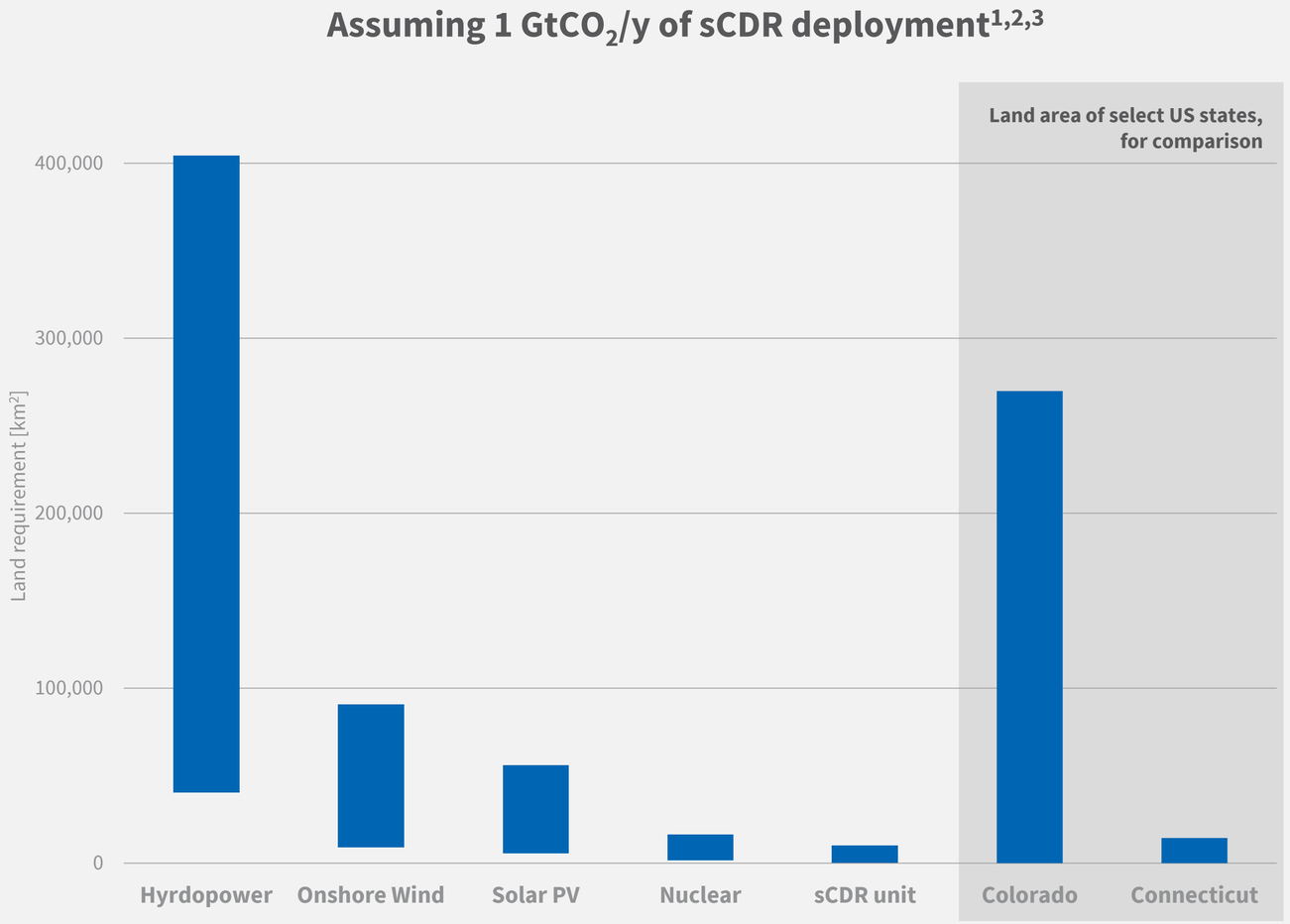
Land requirements for low-carbon energy to power sCDR facilities may also limit deployment

Land requirements for low-carbon-energy to power sCDR facilities can be large

Onshore wind and solar PV may require much more land than hydropower or nuclear power.

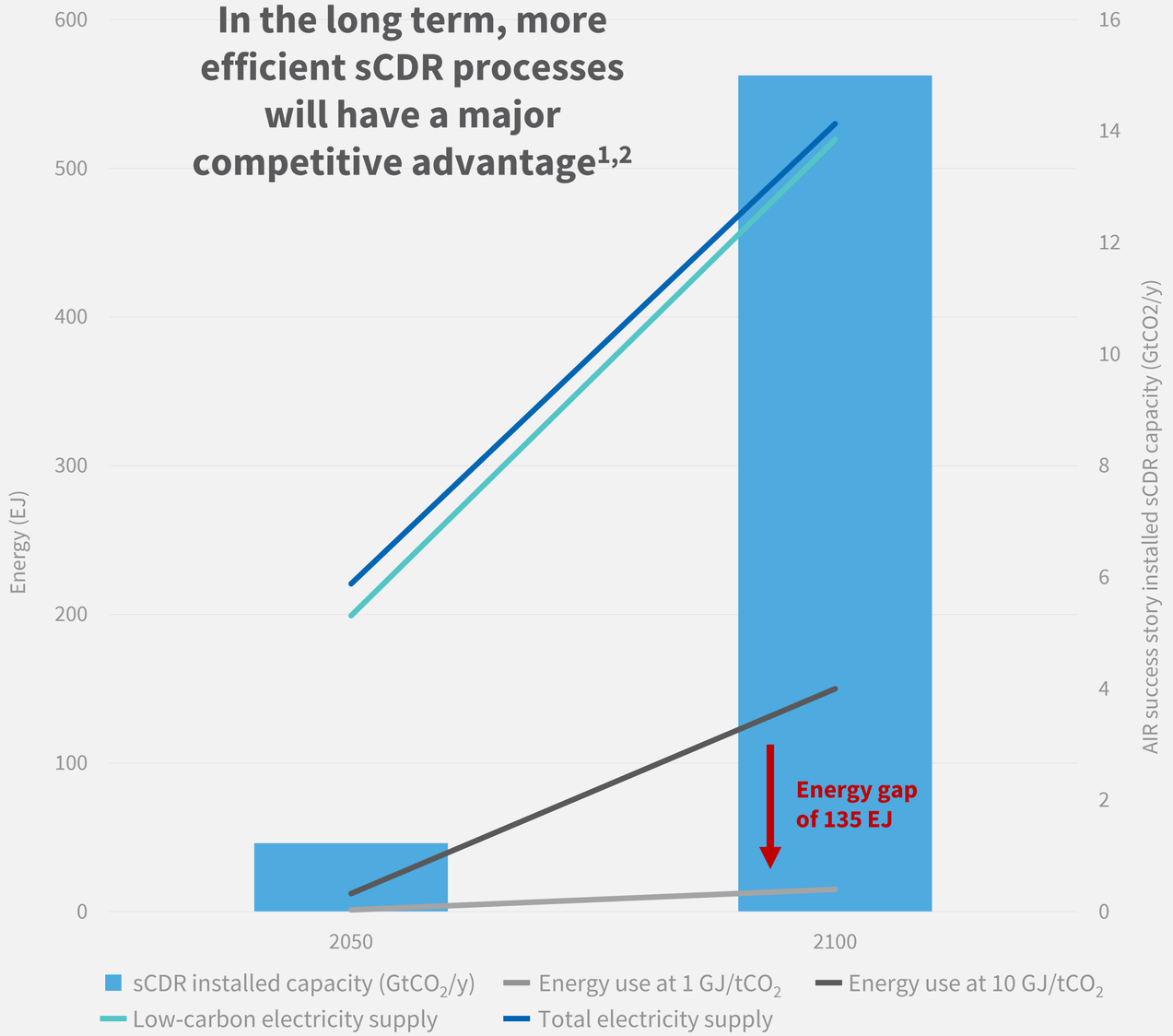
The efficiency of the sCDR process has significant impact on land requirements

Higher sCDR process efficiency results in lower demand for low-carbon-energy and thus less land use.



Notes and sources: [1]Land requirements for the DAC unit are taken from Küng et al. (2023). Land requirements for sCDR facilities are relatively small. Facilities can require between 10-10,000 $km^2/GtCO_2$. [2]The land requirements per low-carbon energy source are taken from Strata report (2017): Nuclear (12.7 acres/MW), solar PV (43.5 acres/MW), onshore wind (70.6 acres/MW), hydropower (315.2 acres/MW). [3]Lower and upper ranges for the land for low carbon energy are based on sCDR facility efficiencies of 1 GJ/tCO_2 and 10 GJ/tCO_2.

sCDR could achieve scale in 2050 with <3% of global electricity, if its energy intensity can be driven down



Notes and context

- In 2050, the energy required to run the maximum amount of sCDR, as described by our success stories, is only 1-3% of total global low-carbon electricity supply.[1]
- In 2100, the efficiency of the sCDR processes matters much more. Based on the AIR success story deployment trajectories, sCDR processes may consume between 7-29% of total global low carbon energy depending on whether they achieve 1 GJ/tCO_2 or 10 GJ/tCO_2.

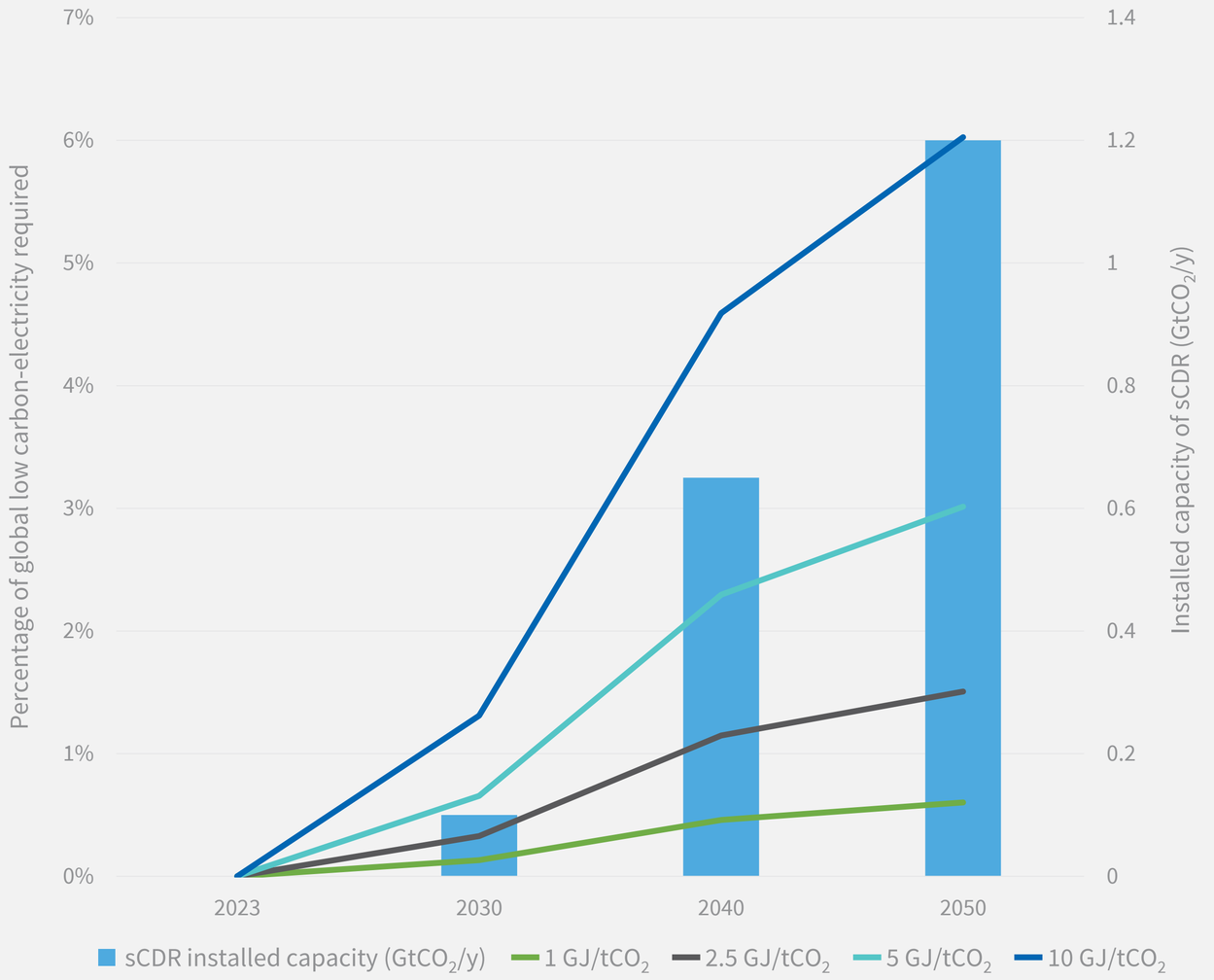
Notes and sources: [1]Electricity generation in 2050 is taken from the IEA Announced Pledges Scenario (APS) from the 2022 WEO (Tables A.3b p443). Electricity data for 2100 is taken from IPCC AR6 WG3 (Figure 3.23, p342) which indicates total electricity generation of 530 EJ/y, 98% of which is low carbon. [2]The installed sCDR capacity for sCDR in 2050 and 2100 is taken from the sum of all sCDR success stories.

Several factors will determine sCDR winners, but none more than process energy efficiency

Qualities that will determine sCDR winners:

- **Process energy efficiency:** The most important driver of an sCDR approach's competitiveness will be how well it can use low-carbon electricity. The efficiency of the system will also dictate how much land is required for low carbon energy. The most efficient systems are likely to win out.
- **Modularity:** Approaches that are more modular are more likely to come down in cost, as they can be rapidly improved by continual manufacturing iterations.
- **Scalability:** Successful sCDR approaches will be able to scale on their own terms and not be limited by access to certain locations or configurations.
- **Technical limitations:** Successful sCDR approaches will function as easily in the field as they do in theory. Approaches that are negatively affected by impurities, pollution, variability in ambient conditions, and other environmental qualities will struggle to compete.

More efficient CDR processes will consume significantly less energy



Notes and sources: [1]Electricity generation is taken from the IEA Announced Pledges Scenario (APS) from the 2022 WEO. (WEO 2022 Table A.3b p445). [2]The installed sCDR capacity for sCDR is taken from the sum of all sCDR success stories. Energy requirements in GJ/tCO_2 are all hypothetical.

Synthetic CDR success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

The cumulative sCDR described below is the summation of the upper limit of CDR deployment taken from individual CDR success stories from the AIR report.[1] The assumptions for each projection are based on a range of sources described in the individual CDR success stories.

2025

- Funding is allocated for R&D advances in sCDR materials, process design, equipment, and system integration.
- Development of ocean models and sensors for indirect water capture MRV is funded and progressing.

2035

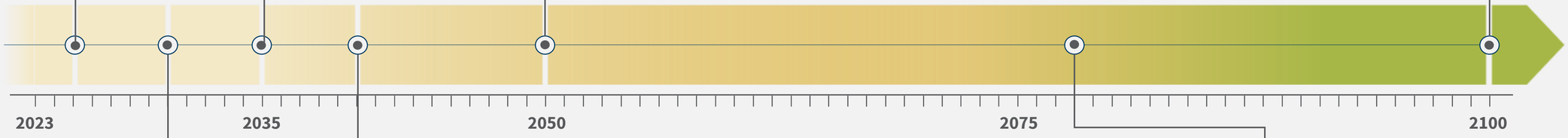
- Global sCDR removals[1] reach **190 $MtCO_2/y$**.
- DAC demonstration data identifies the **best approaches** for further development.
- Basic R&D to achieve breakthroughs in **process efficiency** is well-funded for all sCDR.

2050

- Global sCDR removals[1] reach **1.2 $GtCO_2/y$** with increasing reductions in cost.
- The most **energy efficient** and cost-optimized sCDR approaches have emerged as market leaders.

2100

- Global sCDR removals[1] reach **15 $GtCO_2/y$**.
- sCDR facilities are operational all around the world.
- The cost of sCDR is less than $\$100/tCO_2$ (adjusted to 2023 dollars).



2030

- Global sCDR removals[1] reach **60 $MtCO_2/y$**, mostly from DAC.
- Ten indirect water capture facilities are funded or operational, with at least 100 $ktCO_2/y$ combined capacity.
- MRV is established for **indirect water capture**.

2040

- Global sCDR removals[1] reach **600 $MtCO_2/y$.**
- sCDR facilities are increasingly sited to take advantage of **process and siting synergies** with industrial hub clusters and storage infrastructure.

2050-2100

- sCDR plants scale rapidly in accordance with climate objectives.
- New facilities are built **all around the world.**

Notes and sources: [1]We have assessed all DAC approaches in this Applied Innovation Roadmap (AIR) under a single growth paradigm. Each indirect ocean capture approach was assessed independently. Details and growth assumptions for each individual pathway can be found in the individual approach success stories.

6. Indirect water capture (IWC)

Approaches that indirectly remove carbon from the air by altering water chemistry

Index	Approaches	Definition
6.1	CO_2 stripping	Electrochemical processes that split water from oceans, lakes, or other bodies of water, into acid and base streams, then use the acid stream to push dissolved CO_2 out of the water to be captured, and finally, recombine the acid and base streams to re-neutralize the water and return it to the source
6.2	Electrochemical alkalinity production	The use of electrochemistry to create alkalinity that is added to the ocean or another body of water, enabling it to absorb additional carbon dioxide

RMI classifies indirect water capture (IWC) approaches as **synthetic**

Biogenic (bCDR)	Geochemical (gCDR)	Synthetic (sCDR)	Storage
Living biomass **1.1** Improved management **1.2** Conservation / protection **1.3** Restoration / creation **Stabilized biomass** **2.1** Biomass direct storage **2.2** Timber building products **2.3** Other biomass building products **2.4** Pyrolysis (biochar) and storage **2.5** Pyrolysis (bioliquid) and storage **2.6** Microalgae in ponds **2.7** Microalgae in open water **2.8** Macroalgae in open water **Sequestration of CO_2 from biomass** **3.1** BECCS to electricity **3.2** BECCS to fuels	**Solid carbonate minerals** **4.1** Surficial **Dissolved bicarbonate sequestration** **5.1** Terrestrial enhanced weathering **5.2** Coastal enhanced weathering **5.3** Mineral alkalinity enhancement	**Indirect water capture (IWC)** **6.1** CO_2 stripping **6.2** Electrochemical alkalinity production **Direct air capture (DAC)** **7.1-7.3** Liquid solvent **7.4-7.7** Solid sorbent **7.8-7.9** Membranes **7.10** Cryogenic	**Storage of CO_2** **8.1** Conventional CO_2 storage **8.2** In-situ mineralization **8.3** Ex-situ mineralization

SECTION 6.1

CO_2 stripping

SECTION	6.1
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	Indirect water capture
APPROACH	CO_2 stripping

DEFINITION

Electrochemical processes that split water from oceans, lakes, or other bodies of water, into acid and base streams, then use the acid stream to push dissolved CO_2 out of the water to be captured, and finally, recombine the acid and base streams to re-neutralize the water and return it to the source

EXAMPLE SCENARIOS

1) Drawing ocean water into a membrane system that produces a small acid stream, adding the acid to a sealed container of water to bubble out the CO_2 for capture and storage, then the base stream is added back to the chamber of water and the water is deposited back into the ocean; 2) using light and a photocatalyst to split ocean water into acid and base streams, instead of electricity and membranes.

Section 6.1 overview

CO_2 stripping

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/t$CO_2$** • Key risks in scalability include energy requirements for water pumping and electrochemistry • Cost estimate risks are due to energy requirements and capex
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is mass-customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Concept to pilot stage** • ~4 companies at concept to pilot stages, each with <$15M in funding • Other notable RD&D activity includes the ARPA-E Exploratory Project and DARPA seed funding
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **63 MtCO_2 by 2050** • Success is contingent on breakthroughs in energy efficiency of the process
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$300-550M over 15-20 years** • Key stage gates in validating significant net CO_2 removals and efficient use of low-carbon energy

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**High risk:** Water pumping and electrochemistry require significant energy inputs.	The energy requirement for CO_2 stripping is estimated to be 3.1 MWh/tCO_2 (11.2 GJ/tCO_2) removed.[1,2,3,10] Captura estimates 100-150 MWh (360-540 GJ) will be required for a 1 MtCO_2/y plant.[4] High energy use is the biggest challenge facing all sCDR options at scale.
	Land requirements	**Low risk:** To reach gigaton scale, this approach could require a significant footprint, but could be developed offshore.	The availability of cost-effective, appropriately-zoned coastal sites may limit scaling, but off-shore deployment is also being developed and would mitigate this risk.[1,2]
	Reliance on other infrastructure	**Medium risk:** This approach may be critically dependent on other infrastructure.	The ultimate scalability of this method could be limited by other infrastructure, such as desalination plant capacity.[5] There are also unsolved questions about CO_2 offtake processes, including pipeline, shipping, and other transportation methods, especially for offshore facilities.
	Environmental impacts	**Medium risk:** Water intake and effluent management at high volume creates localized environmental risk.	There are a variety of potential environmental issues, including intake and discharge complications.[1] More research on macro- and micro-ocean ecosystem impacts is required.[1]
Secure storage for 100+ years		**Low risk:** Storage of CO_2 can be long-lived and secure, similar to DAC approaches.	Stripped CO_2 is stored via geological sequestration or in-situ mineralization, which are considered permanent storage approaches.[1]
Path to measurement at scale		**Medium risk:** Measurement to inform MRV may require extensive development at several levels.	MRV may require measurement of (1) evolved CO_2, (2) verification of restored ocean alkalinity in effluent water, and (3) the oceanic reuptake of CO_2 from air to replace the stripped CO_2.[6,7]
Pathway to full costs <$100/t$CO_2$		**High risk:** Current cost estimates are high due to energy requirements and capex.	Energy requirements, material costs, and capital costs are all significant and difficult to reduce.[1,2,8] Captura, by contrast, estimates that major cost reductions are possible.[9]

Notes and sources: [1]A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022) [2]Indirect ocean capture of atmospheric CO_2: Part I. Prototype of a negative emissions technology (Lannoy et al., 2018) and Indirect ocean capture of atmospheric CO_2: Part II. Understanding the cost of negative emissions (Eisaman et al., 2018). Part II includes a detailed TEA. [3]Captura website [4]This is CDR Ep.38 Captura. CEO Steve Oldham notes that this energy requirement assumes 50% efficiency reduction from what they are observing in their lab scale facility. During peer review of the AIR, Captura representatives indicated that they believe this cost can continue to come down. [5]According to NAS (2022), a facility designed to remove 0.1 MtCO_2/y would need to treat about 3 Mt of seawater per day, about 5-10 times more than the world's largest desalination facilities. [6]Henry's law states that the amount of dissolved gas in a liquid is directly proportional to its partial pressure. Here, as evolved gas is stripped from seawater, Henry's law describes the process by which the ocean would re-absorb CO_2 from the atmosphere, thus drawing down atmospheric concentrations. However, uncertainties regarding air-sea gas exchange require modeling to verify efficacy and timing of carbon drawdown. [7]The "CO_2 stripping" process uses the acid to first shift dissolved inorganic carbon to dissolved CO_2 and then vacuum strips out the CO_2 as a gas. This acidification reduces the alkalinity, so a base is then used to restore the alkalinity back to where it started, guaranteeing that additional CO_2 from the air will backfill the stripped CO_2. Without restoring the lost alkalinity and verifying that this led to CO_2 uptake equivalent to the amount stripped, this scheme would acidify the oceans and strip them of DIC, its capacity to safely store carbon. But with the alkalinity restoration step, this scheme is a sustainable closed loop, effectively using the ocean to pump CO_2 from the air. A detailed description of this process can be found here. [8]Significant science breakthroughs are required to enable costs <$100: e.g., via novel membranes (especially BPM and AM), alternative modes of acid generation (e.g., photo-excitable acids) or similar. [9]Captura estimates that sub-$100 costs would be achieved at Mt-scale when using retired offshore oil and gas platforms. They note that capex is 1/5 that of DAC since air contractors and absorbents are not necessary, ~40% of their costs are for maintenance and replacement of bi-polar membranes and membrane contactors, there are no by-products to dispose of, and lower energy use with the ability to utilize off-peak and intermittent energy. [10]NAS (2022), p.228

Potential for cost improvement

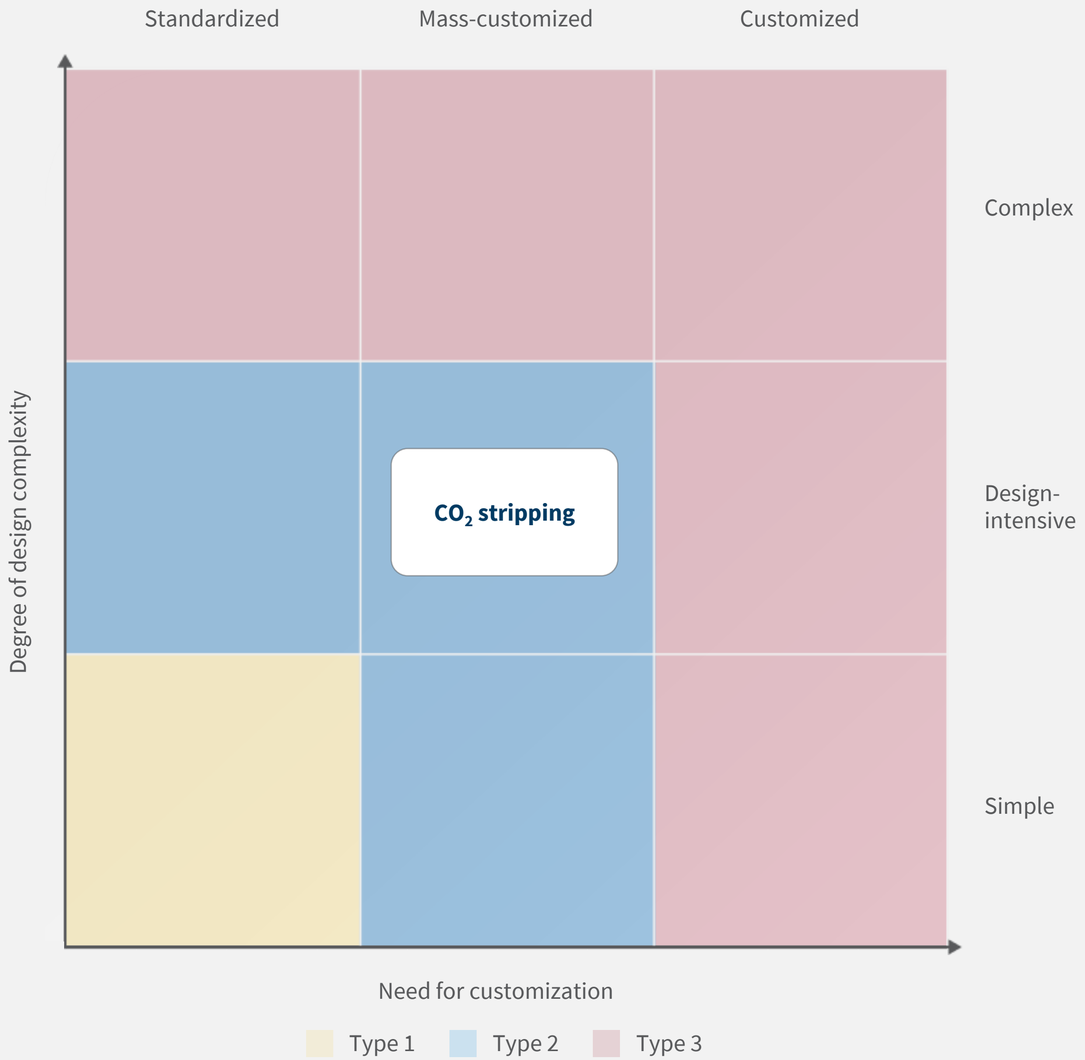
An assessment of two key drivers of learning rates

SECTION 6.1

TAXONOMIC BUCKET Synthetic

CDR CATEGORY Indirect water capture

APPROACH CO_2 stripping



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive
- **Rationale:** CO_2 stripping requires building specialized industrial plants that are paired with energy sources, supply chains, and CO_2 storage options.[2] MRV is expected to be the same as mineral alkalinity enhancement (approach 5.3).[3]

NEED FOR CUSTOMIZATION

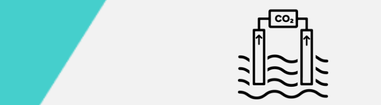
- **Rating:** Mass-customized
- **Rationale:** Once technologies are mature, plants will benefit from largely standardized designs with customization for siting, plant size, energy, and storage requirements and constraints.[2] Some customization may be required to handle differences in water pH, temperature, alkalinity, ion presence, and ion concentrations.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]According to review provided by Captura, the currently active version of this technology (and all components that make it up) are optimized, readily-available, commercial off-the-shelf pieces of machinery, including water pumping, filtration, and commercial bipolar membranes. The new capability of the technology provided by Captura is the proprietary bipolar membranes within the electrodialysis unit and the membrane contractor that Captura is developing. [3]MRV for electrochemical ocean CDR approaches (both the CO_2 stripping approach and the electrochemical alkalinity production approach) is expected to be the same as for mineral alkalinity enhancement, described in approach 5.3. Details of this process can be found in Monitoring, Reporting, and Verification for Ocean Alkalinity, preprint (Ho, et al. 2023).

Current state of RD&D

A mapping of companies, plus other notable activities

NOT EXHAUSTIVE

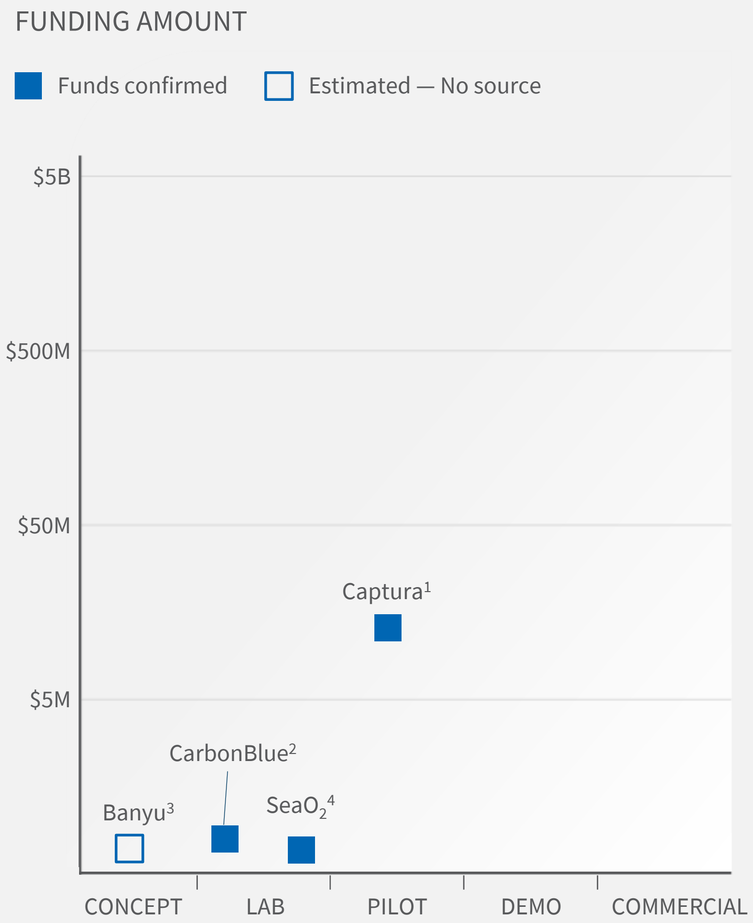


SECTION 6.1

TAXONOMIC BUCKET Synthetic

CDR CATEGORY Indirect water capture

APPROACH CO_2 stripping



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Captura: Vacuum assisted acid evolution of CO_2 from seawater[1]	$12 M series A[1,6] $500k from ARPA-E[7]	• Pilot project underway in Newport Beach California since August 2022 • 100 tCO_2 system to launch in 2023 in Los Angeles[8] • Partnering with Equinor on 1ktCO2/y pilot in Norway[9] • XPrize milestone winner[1,10] • Frontier pre-purchase winner
CarbonBlue: Marine calcium looping[2]	$100k[11]	• No projects listed
Other companies and activities: Banyu,[3] $SeaO_2$,[4] Ocean Visions[5]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
ARPA-E Exploratory Project	$500k grant to Captura[7]	• Development of Thin Film Composite Hollow Fiber Membranes for Captura
DARPA seed funding to Palo Alto Research Center, Inc. (PARC)	$472k	• 2010 – CO_2 extraction from seawater using bipolar membrane electrodialysis[12]

Notes and sources: [1]Captura website [2]CarbonBlue website [3]Banyu uses sunlight to drive a chemical reaction that causes CO_2 to be released from the ocean and generate solar energy. [4]$SeaO_2$ website, Pitchbook company funding estimate [5]A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by 2030 (Ocean Visions, 2023) outlines several funding opportunities and programs that are relevant across multiple CDR approaches that occur in the ocean, including MRV research, field trials, and spatial planning. [6]Captura funding raised [7]ARPA-E funding to Captura [8]Captura will demonstrate efficient CO_2 stripping from oceanwater using low-cost thin film composite hollow fiber membranes. [9]Equinor and Captura pilot project [10]This is CDR Ep. 38 Captura [11]Pitchbook funding estimate for Carbon Blue [12]This funding led to the publication of "CO_2 extraction from seawater using bipolar membrane electrodialysis" (Eisaman et al., 2012).

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

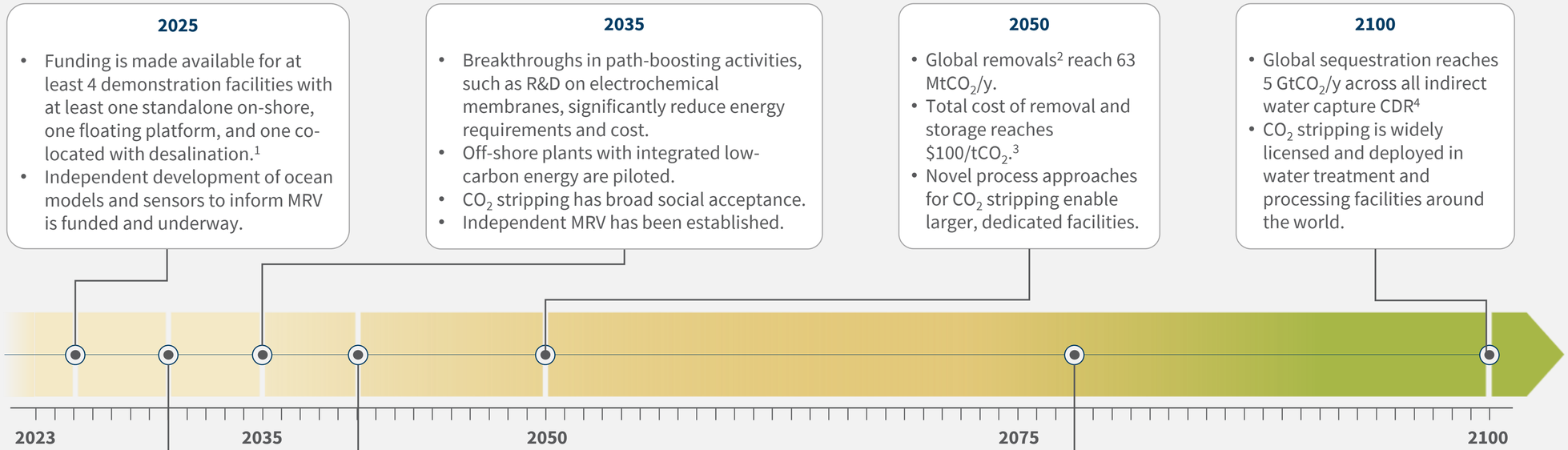
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 6.1

TAXONOMIC BUCKET Synthetic

CDR CATEGORY Indirect water capture

APPROACH CO_2 stripping



2025

- Funding is made available for at least 4 demonstration facilities with at least one standalone on-shore, one floating platform, and one co-located with desalination.[1]
- Independent development of ocean models and sensors to inform MRV is funded and underway.

2035

- Breakthroughs in path-boosting activities, such as R&D on electrochemical membranes, significantly reduce energy requirements and cost.
- Off-shore plants with integrated low-carbon energy are piloted.
- CO_2 stripping has broad social acceptance.
- Independent MRV has been established.

2050

- Global removals[2] reach 63 $MtCO_2/y$.
- Total cost of removal and storage reaches $\$100/tCO_2$.[3]
- Novel process approaches for CO_2 stripping enable larger, dedicated facilities.

2100

- Global sequestration reaches 5 $GtCO_2/y$ across all indirect water capture CDR[4]
- CO_2 stripping is widely licensed and deployed in water treatment and processing facilities around the world.

2030

- Global siting is established for CO_2 stripping facilities.
- 10+ facilities, each ≥10 $ktCO_2/y$, are funded or operational and answering engineering challenge and ecosystem impact questions.
- Adjacent infrastructure such as desalination and water treatment facilities are regularly scoped and built to include CO_2 stripping capabilities.
- CO_2 equilibrated from the atmosphere is validated on emissions relevant timescales.

2040

- Global removals[2] reach 10 $MtCO_2/y$.
- At least 10 on-shore plants utilizing extensive CO_2 transportation and storage networks and another 3-5 standalone off-shore plants are operational.[2]

2050-2100

- Continued scaling of this approach in accordance with climate objectives
- Financial modeling incorporates co-benefits such as microplastics removal
- CO_2 stripping competes with other CDR approaches that use electricity as a primary input.

Notes and sources: [1]Ocean Visions overview for electrochemical ocean capture [2]Future deployment is based on 100% y-o-y growth from 2030-2040 and 20% growth from 2040-2050 based on a starting point of 10 $ktCO_2/y$ in 2030. Some reviewers of the AIR think that these numbers will be dampened by the time necessary to assess environmental impacts. [3]Captura's TEA (provided for review of this roadmap) indicates that they will reach $\$100/tCO_2$ when they achieve a 1 $MtCO_2/y$ system. Other reviewers think that $\$100/tCO_2$ will be challenging to achieve. [4]Total deployment in 2100 is capped at 5 $GtCO_2/y$, which is the upper limit used by the Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022) report and Ocean Visions roadmap for electrochemical ocean capture.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost[2]
- Timeline to complete[2]

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 6.1

TAXONOMIC BUCKET Synthetic

CDR CATEGORY Indirect water capture

APPROACH CO_2 stripping

TRL

CRITICAL PATH ACTIVITIES

$300-550 million | **15-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Site selection:** Identify global sites with potential to implement CO_2 stripping.
- **Environmental impact assessment:** Determine potential environmental impacts and methods for mitigating them.
- **Develop ocean models to inform MRV:** Develop software models along with in-field sensors and data collection tools to quantify removals.

$25-50 million | **5-10 years**

- ✓ Demonstration sites have been identified
- ✓ Environmental impacts at demonstration sites have been assessed and are manageable
- ✓ LCA validates high net negativity

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Deployment of key plant designs** (e.g., standalone on-shore, standalone off-shore, co-location with desalination / thermal power)
- **MRV**: Verification of net atmospheric CO_2 removal under operating conditions
- **Storage / utilization:** Successfully pair removal with scalable storage / utilization partners

$250-500 million | **10 years**

- ✓ Pathway to market competitive costs
- ✓ Independent verification of CO_2 removal
- ✓ Manageable environmental impacts on biodiversity, ecology, habitat, and water quality

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[3]

$45-110 million | **10 years**

- Perform continual marine ecosystem monitoring and techno-economic analysis of costs
- Assess standalone and connected low-carbon platforms for powering plants
- Explore process and material improvements

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[3]

- Carbon removal in active demonstration projects is verified
- Verified carbon storage by independent accounting organization
- Total costs are competitive with leading DAC approaches
- Demonstrated manageable impacts on ecosystems

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Estimates based on A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022). [3]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research[3]	Site identification	Identify sites for various IWC configurations, including: (1) stand alone on-shore, (2) co-location with desalination, (3) co-location with thermal power, and (4) standalone off-shore (decommissioned oil platform). Siting should consider opportunities near clean energy sources and deep ocean mixing.	✓ Sufficient sites are identified to support a potential industry of at least 100 $MtCO_2$/y removals	1-2	$0.5-1M/y	1-3 y	$1-3M
Field testing	Environmental impact assessment	Assess potential environmental impacts for various siting and plant design configurations with focus on effluent / acid management in accordance with local, state, and federal regulations, and with broader ocean ecosystem considerations.[4]	✓ Environmental impacts at scale are determined to be manageable	1-2	$2-3M/y[2]	1-3 y	$6-9M
MRV	Development of ocean models for measurement and monitoring	Demonstrate the efficacy of atmospheric CO_2 uptake over realistic timeframes, with uncertainty bounds.[5] Initial funding should seek to demonstrate this theory in practice with (1) dedicated field testing and (2) dedicated modeling of removals.[6] This is cross-cutting with all CDR approaches that modify open water chemistry.	✓ Verification that CO_2 is equilibrated from the atmosphere on an emissions-relevant timescale[7]	1-2	$2-4M/y	5-10 y	$20-40M[6]

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include new legal frameworks and permitting for ocean activities.*[8]

Notes and sources: [1]During review of these materials in July 2023, representatives from Captura indicated that they have made significant headway on these pre-demonstration activities, including (1) identifying multiple global sites for commercial systems, (2) assessing environmental impacts through a pilot program, and (3) testing bi-polar membranes to improve efficiency and lifetime. [2]Baseline costing estimates are based on A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022). The number of facilities is based on an average of sources. Costing estimates are described in the AIR Appendix. [3]The desktop research portions of this approach can be done simultaneously for CDR approaches that modify ocean chemistry. [4]Captura is working with Ocean Visions to determine what the environmental impacts are and how to manage them, This is CDR Ep.38 Captura [5]It is expected that the amount of CO_2 removed from the atmosphere will likely be lower than that removed from the ocean given that ocean mixing can carry CO_2 depleted water to lower layers or equilibrate part of the depleted water with non-atmospheric sources. [6]One of the AIR reviewers is currently building a suite of software modeling tools for ocean CDR MRV. The 7-year budget of the project is >$50M. [7]Current estimates are that CO_2 equilibrates over 2 weeks to 4 months. [8]In the white paper Depending on the Ocean released in May 2023, Carbon180 calls for more robust policies and legal frameworks.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS[1]	PROJECT BUDGET[1]	DURATION	TOTAL COST
Demo	Scaled deployment of key plant designs:[2] Up to 4 demonstration plants in different bodies of water, with demonstrations to consider facilities that are: • Standalone on-shore • Standalone off-shore (fixed / floating) • Co-located with desalination • Co-located with thermal power Demonstration projects should perform their own measurement, LCA, and environmental monitoring and impact analyses. Additional analyses will be performed by third-parties.	10 $ktCO_2/y$ (per plant)	✓ Pathway to total costs (including storage) are competitive with DAC approaches ✓ Manageable environmental impacts for plant designs	4-6	$10M/y *Most cost is upfront rather than annual*	5-8 y	$200-400M
Demo	Storage / utilization demonstrations: Each demonstration plant should be paired with a utilization or storage partner.[3] Storage and utilization should be scaled to be able to successfully process all CO_2 production from the demonstration projects, and investigate: • Offtake of CO_2 for direct use • Permanent storage / sequestration of CO_2 • Utilization of CO_2 for synthetic fuels or chemicals	N/A	✓ Efficient utilization / storage partnerships are established and contribute to market competitive costs	1-4	$0.5-2M/y	5-8 y	$5-40M
MRV	Measurement and modeling to inform MRV: MRV should build on the pre-demonstration work of building sensors and software models. It should be performed by an independent third party, but in concurrence with the demonstration projects above.[4,5]	N/A	✓ Verification of CO_2 uptake from the atmosphere over realistic timeframes, with uncertainty bounds	1-2	$3-4M/y	10 y	$30-70M[6]

Notes and sources: [1]Baseline costing estimates are based on A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022). The number of facilities is based on an average of sources. Costing estimates are described in the AIR Appendix. [2]General siting considerations include: (1) seawater access, (2) low-carbon energy supply, (3) infrastructure for raw material sourcing and waste disposal, and (4) labor. [3]Scaled deployment will require, among other things, co-location or a transportation network to acceptable utilization / storage assets. For gas or liquid generating approaches this may include pipelines. For solid generating approaches this may include landfill or other disposal options. Securing offtake is not trivial; it must overcome permitting, scoping, and liability concerns. [4]MRV requires verification that the restored alkalinity resulted in an equivalent amount of CO_2 was drawn into the ocean from the atmosphere as was stripped out. [5]Conducted in conjunction with demonstrations but administered as a separate process [6]Some reviewers thought that even this estimate was too low and should be higher to account for the development of sensors, frameworks, and models.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[1]	DURATION[1]	TOTAL COST
Desktop research	Improved lifecycle analysis, technoeconomic analyses, and accounting for emissions and energy[1]	Use demonstration data to continually update the (1) lifecycle assessment and (2) technoeconomic analysis. Use this to further refine CO_2 stripping deployment.	1-2	$0.5-1M/y	10 y	$5-10M
Field testing	Test different electric power supply approaches, including standalone and connected low-carbon platforms	Demonstrate both off-shore low-carbon plants combined with decommissioned oil platforms, floating islands, etc. and on-shore grid connected and disconnected power sources.	1-2	$2-10M/y	4 y	$8-40M
Field testing	Ongoing marine ecosystem monitoring	Perform continual assessment of key marine ecosystem metrics near demonstration sites to ensure regulatory compliance, low impact, and support transparency / social acceptance.	2-4	$1-2M/y	10 y	$10-20M
Lab	Novel and improved electrodes, bi-polar membranes, and membrane materials[2]	Research to improve key technologies driving efficiency and reduce capex, including: • Electrodes (low-cost electrodes, reaction selectivity, reaction density, large form factors, manufacturability) • Electrochemical membranes (reduced cost, higher durability, improved conductivity, permeability, and selectivity)	2-10	$1-2M/y	7-10 y	$20-40M
Lab	Explore alternative modes of pH swing	Investigate alternative methods that may consider novel electrochemical stack designs or photo-active acid / base chemistry instead of using bipolar membranes	1-4	$0.5M/y	5-10 y	$2-6M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include new legal frameworks and permitting for ocean activities.*[3]

Notes and sources: [1]Estimates based on A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022) [2]Captura estimates that ~40% of their costs are for maintenance and replacement of bi-polar membranes and membrane contactors and that an R&D focus on improving lifetime and efficiency will drive this cost down. [3]In the white paper Depending on the Ocean, released in May 2023, Carbon180 calls for more robust policies and legal frameworks.

SECTION 6.2

Electrochemical alkalinity production

SECTION	6.2
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	Indirect water capture
APPROACH	Electrochemical alkalinity production

DEFINITION

The use of electrochemistry to create alkalinity that is added to the ocean or another body of water, enabling it to absorb additional carbon dioxide

EXAMPLE SCENARIOS

1) Changing the pH of a stream of water with electricity in a wastewater treatment facility to enable the water to uptake additional CO_2; 2) splitting ocean water into acid and base streams with electricity, then using the base stream to lower the pH of seawater locally while the acid stream is removed or disposed of elsewhere.

Section 6.2 overview

Electrochemical alkalinity production

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/t$CO_2$** • Key risks in scalability include energy requirements for water pumping and electrochemistry • Cost estimate risks are due to energy requirements and capex
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is mass-customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot stage** • ~2 companies at pilot stage, with <$50M in funding each • Other notable RD&D activity includes ARPA-E DOC research projects and an EU OceanNETs work package
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment: **160 MtCO_2 by 2050** • Success is contingent upon energy efficiency gains including the ability to integrate with other water infrastructure
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$250-650M over 11-20 years** • Key stage gates in materials R&D, market competitiveness, and measurement of CO_2 removals

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**High risk:** Pumping water and electrochemical processes require significant energy inputs.	The current estimated energy requirements are 4.4 MWh/tCO_2 (15.8 GJ/tCO_2) removed,[1,9] and Equatic states 2 MWh/tCO_2 (7.2 GJ/tCO_2).[2] At scale, energy could be a significant cost driver and thus limit scalability.[3]
	Land requirements	**Low risk:** This approach could require significant area footprint but may be deployed offshore.	The availability of cost effective, appropriately-zoned coastal sites may limit scaling, but off-shore deployment is being developed and would mitigate this risk.[1,4]
	Reliance on other infrastructure	**Medium risk:** This approach may be critically dependent on other infrastructure.	The ultimate scalability of this method could be limited by other infrastructure.[5] Facilities are currently being co-sited with desalination facilities.
	Environmental impacts	**Medium risk:** Potential changes to ocean water chemistry may have environmental impacts.	The environmental impacts of the base approach are poorly understood, requiring further study, but are potentially lower risk than mineral alkalinity enhancement.[1] Safe disposal of acid is also required for this pathway.
Secure storage for 100+ years		**Low risk:** Storage of CO_2 in carbonates and bicarbonates is stable and long lived.	Electrochemical alkalinity production locks CO_2 into the long carbon cycle by either creating bicarbonates that are stable for at least 10,000 years or precipitating carbonates that are stable for at least 100,000 years.[6]
Path to measurement at scale		**Medium risk:** Measurement to inform MRV may require extensive development on several levels.	Some companies indicate that measurement will be as straightforward as weighing the precipitated carbonates,[5] although implementation will likely be more complex.[7] MRV for electrochemical ocean approaches is similar to that of other ocean chemistry approaches, such as mineral alkalinity enhancement.[8]
Pathway to full costs <$100/t$CO_2$		**High risk:** Current cost estimates are high due to high energy requirements and capex.	Energy use is the key challenge to achieving costs under $100/t$CO_2$.[1,4] There could be a shorter path to $100/t$CO_2$ for approaches that include co-product revenue, such as the production of hydrogen or disposal / utilization of wastes.

Notes and sources: [1]A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022) [2]Equatic as described by Forbes, April 2023 [3]Some reviewers note that companies are reporting values closer to 1 MWh/tCO_2, but public data is not yet available to validate this. [4]Indirect ocean capture of atmospheric CO_2: Part I. Prototype of a negative emissions technology (Lannoy et al., 2018) and Indirect ocean capture of atmospheric CO_2: Part II. Understanding the cost of negative emissions (Eisaman et al., 2018). Part II includes a detailed TEA. [5]The Equatic website lists a simple set of dimensional analysis on a mass of precipitated carbonates as proof of removals. However, other sources indicate that this process is more complicated and the uncertainties regarding air sea gas exchange require modeling to verify the efficacy and timing of carbon drawdown. [6]The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System (Falkowski et al., 2000) [7]The electrochemical precipitation process uses added alkalinity to force the precipitation of dissolved inorganic carbon in seawater as carbonate solids. The precipitation process itself removes alkalinity from the seawater, so after precipitation, alkalinity must be added to restore the alkalinity levels back to initial levels, guaranteeing that additional CO_2 from the air will backfill the stripped DIC. It may also be necessary to monitor calcium and magnesium depletion from seawater. As such, these approaches may require (1) weighing of precipitated carbonates, (2) verification of restored ocean alkalinity in effluent water, and (3) measurement of the oceanic reuptake of stripped CO_2. [8]Verifying that alkalinity restoration results in additional CO_2 backfilling is the same MRV that is required for mineral alkalinity enhancement. [9]NAS (2022), p.229

Potential for cost improvement

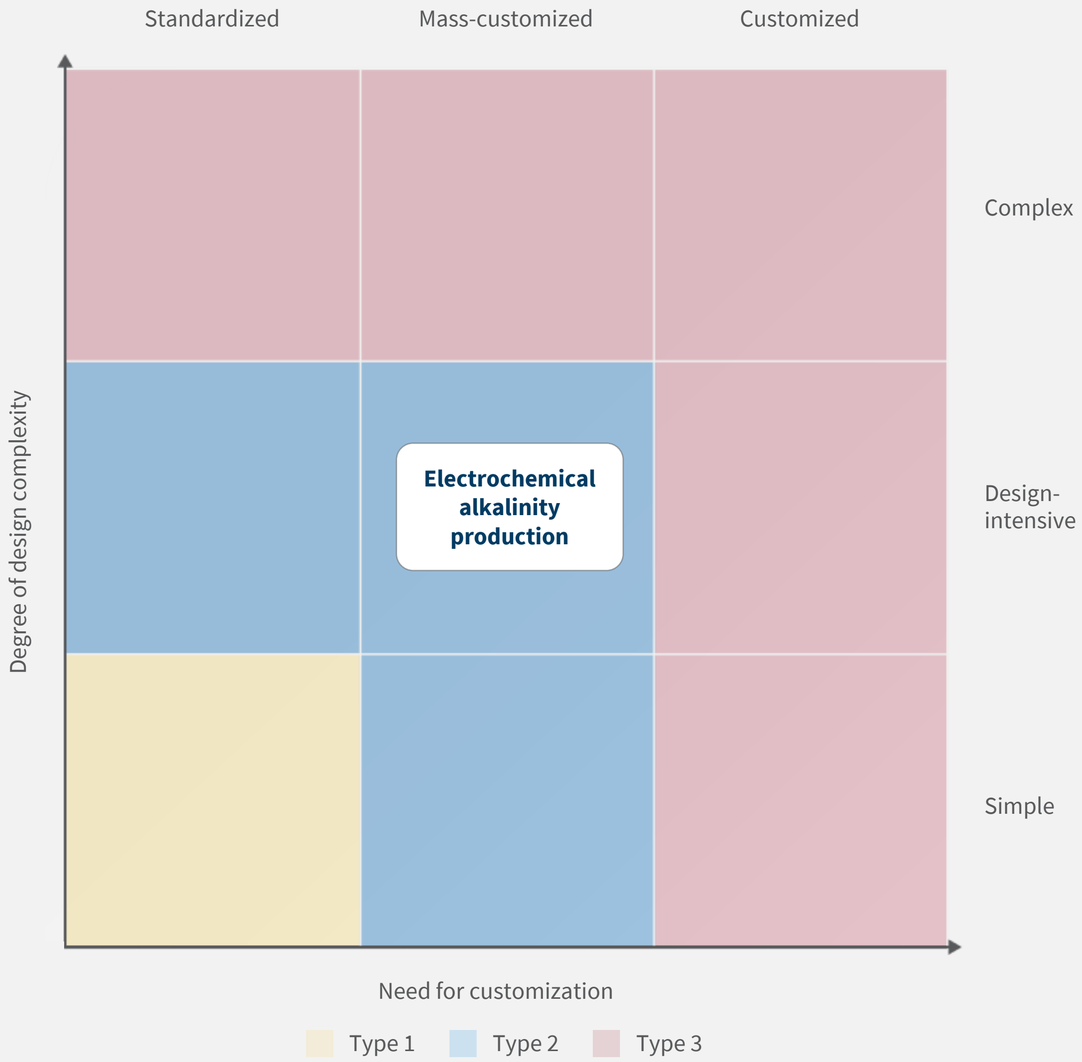
An assessment of two key drivers of learning rates

SECTION 6.2

TAXONOMIC BUCKET Synthetic

CDR CATEGORY Indirect water capture

APPROACH Electrochemical alkalinity production



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive
- **Rationale:** Electrochemical alkalinity productions require specialized industrial plants that are integrated with energy sources, supply chains, and possibly industrial co-location. MRV is expected to be the same as for mineral alkalinity enhancement, described in approach 5.3.[2]

NEED FOR CUSTOMIZATION

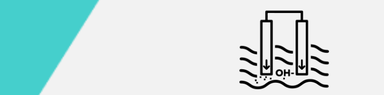
- **Rating:** Mass-customized
- **Rationale:** Once technologies are mature, plants will benefit from standardized designs with customization for siting, plant size, energy, and storage requirements. Some customization may be required to handle differences in pH, temperature, alkalinity, ion presence, and ion concentration.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]Details of this process can be found in Monitoring, Reporting, and Verification for Ocean Alkalinity, preprint (Ho, et al. 2023).

Current state of RD&D

A mapping of companies, plus other notable activities

NOT EXHAUSTIVE



SECTION 6.2

TAXONOMIC BUCKET Synthetic

CDR CATEGORY Indirect water capture

APPROACH Electrochemical alkalinity production

NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Equatic (formerly SeaChange): Precipitation of CO_2 as carbonates, plus H_2 production[1,3]	$30M[4] ($735K[5])	• Pilot facilities in Singapore and Los Angeles can remove 100 $kgCO_2$ (0.1 tCO_2) per day • 2024 – Demonstration in Singapore for 3.5 $ktCO_2$/y at desalination co-location; Stripe commitment to purchase at $1,370/$tCO_2$
Ebb Carbon: Storage of CO_2 as bicarbonates[2]	$20M[6]	• Sold $1.5 million in removals to Stripe • Operating a 100 tCO_2/y facility at PNNL-Sequim[7]
Other companies and activities: [C]worthy,[8] Carbon to Sea Initiative (Additional Ventures),[9] Pronoe,[10] Deep Sky,[11] Kepler Recapture,[12] OceanVisions[13]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
ARPA-E DOC Research Projects[14]	~$3M	• Three funded projects at MIT, Cal Tech, and U. North Dakota focused on demonstrating different electrochemical CDR approaches
OceanNETs: EU-funded work packages focused on CDR that occurs in the ocean	€7M	• Work package 5 is focused on ocean alkalinization through mineral additions[15] • Work package 6 is focused on ocean alkalinization case studies[16]

Notes and sources: [1]Equatic website [2]Ebb Carbon website [3]Saline Water-Based Mineralization Pathway for Gigatonne-Scale CO_2 Management (La Plante et al., 2021) [4]Equatic as described by Forbes, April 2023 [5]Carbon Herald [6]In April 2023, Ebb Carbon raised $20M in Series A funding. [7]Full steam ahead: Ebb's ocean carbon removal solution is up and running at PNNL-Sequim [8][C]worthy is developing MRV for these processes. [9]The Carbon to Sea Initiative is evaluating alkalinity production as a CDR solution. [10]Pronoe received $15k from Ocean Visions. [11]Deep sky is a venture supporting DAC and IWC. [12]Kepler Recapture is developing fully autonomous deep water spar platforms. [13]A Comprehensive Program to Prove or Disprove Marine Carbon Dioxide Removal Technologies by 2030 (Ocean Visions, 2023) outlines several funding opportunities and programs that are relevant across multiple CDR approaches that occur in the ocean, including MRV research, field trials, and spatial planning. [14]ARPA-E DOC research projects [15]OceanNETs work package 5 [16]OceanNETs work package 6

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

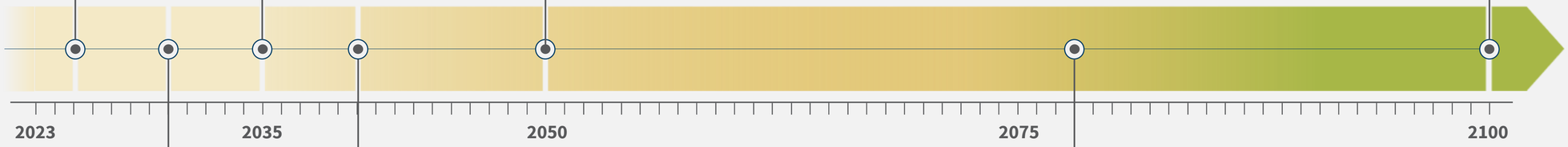
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 6.2

TAXONOMIC BUCKET Synthetic

CDR CATEGORY Indirect water capture

APPROACH Electrochemical alkalinity production



2025

- Early pilot facilities have successfully removed CO_2.
- 4+ demonstration facilities are publicly funded, including at least one standalone and one co-located with desalination.[1]
- Sufficient funding is allocated to develop ocean models for MRV.

2030

- 4-10 demonstration facilities of at least 5 $ktCO_2/y$ are operational.
- Adjacent infrastructure, such as desalination and water treatment facilities, are regularly scoped and built to include CDR.
- Measurement and modeling establishes that CO_2 is equilibrated from the atmosphere on emissions-relevant timescales.

2035

- At least 10 commercial facilities are operational.
- Path-boosting breakthroughs, such as R&D on electrochemical membranes, significantly reduce the energy requirements and cost of removals.
- Global removals[2] reach 10 $MtCO_2/y$.

2040

- Global removals[2] reach 25 $MtCO_2/y$.
- Environmental impacts are managed and public acceptance for these approaches is high.
- New facilities are being built on several continents and electrochemical alkalinity production reaches a scale and price point that is competitive with DAC.

2050

- Global removals[2] reach 160 $MtCO_2/y$.
- Novel process approaches for electrochemical alkalinity production allow for larger, dedicated facilities.

2050-2100

- Rapid scaling of this approach continues in line with long term climate goals and a diversified CDR portfolio.
- This approach competes with other CDR approaches that use electricity as a primary input.

2100

- 5 $GtCO_2/y$ is sequestered across all indirect water capture CDR approaches.[3]
- Indirect water capture approaches are competitive with leading DAC approaches on cost and energy use.

Notes and sources: [1]Ocean Visions Electrochemical Ocean Carbon Dioxide Removal Overview [2]Future deployment is based on 100% y-o-y growth from 2025-2035 and 20% growth from 2035-2050 based on a starting point of 10 $ktCO_2/y$ in 2025. Some reviewers think that these numbers will be reduced due to the time needed to assess environmental impacts. [3]Total deployment in 2100 is capped at 5 $GtCO_2/y$, which is the upper limit used by A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022) report and Ocean Visions roadmap for Electrochemical CDR roadmap for water capture.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost[2]
- Timeline to complete[2]

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

TRL

CRITICAL PATH ACTIVITIES

$250-650 million | **11-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Site selection:** Identify adequate siting with potential to grow the approach to gigaton scale.
- **Environmental impact assessment:** Determine if impacts on relevant ecosystems are manageable.
- **Ocean models to inform MRV:** Develop software models as well as in-field sensors and data collection tools.

$40-70 million | **5-10 years**

- ✓ Sites for demonstrations have been identified.
- ✓ Environmental impacts are expected to be manageable at scale.
- ✓ Pathway to effective MRV protocols at scale

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Scaled deployment of key plant designs:** At least 4 demonstration facilities with different operating conditions and locations are built
- **MRV and environmental monitoring:** Implement concurrent MRV and environmental monitoring of the demonstration facilities to ensure removals are verified and environmentally managed.

$200-550 million | **6-10 years**

- ✓ Pathway to market competitive costs
- ✓ Acceptable infrastructure durability, capex, and maintenance requirements
- ✓ Successful measurement of CO_2 removal
- ✓ Manageable environmental impacts on biodiversity, ecology, habitat, and water quality

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

SECTION 6.2

TAXONOMIC BUCKET Synthetic

CDR CATEGORY Indirect water capture

APPROACH Electrochemical alkalinity production

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[3]

$30-70 million | **10 years**

- Improve electrode and membrane materials to reduce energy and equipment costs
- Develop improved bi-polar membranes and membrane contactors
- Perform continual techno-economic analysis of costs
- Perform ongoing marine ecosystem monitoring

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[3]

- Total costs are competitive with leading DAC approaches
- Measured carbon removal in demonstration projects
- Carbon removal verified by independent accounting organization
- Demonstrated manageable impacts on ecosystems

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Estimates based on A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022). [3]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS[1]	PROJECT BUDGET[1]	DURATION	TOTAL COST
Desktop research[2]	Site identification	Identify sites for alkalinity creation and coastal dispersion in accordance with local, state, and federal regulations. Site identification[3] should consider: • Standalone seawater / freshwater locations • Co-location with desalination / thermal power	✓ Sites have the cumulative potential to reach gigaton scale with a pathway to market competitive costs ✓ Sites and CDR processes have manageable environmental impacts	1-2	$0.5-1M/y	1-3 y	$1-3 M
Field testing	Environmental impact assessment	Assess potential environmental impacts for various siting and dispersion approaches with both local and broader ocean ecosystem considerations.		1-2	$2-3M/y[1]	1-3 y	$6-9 M
Field testing	Assessment of alkalinity dispersion	Assess the efficacy and environmental impact of various alkalinity dispersion methods, such as coastal, ship-based, co-location with desalination or water treatment, etc.		2-4	$1M/y[1]	1-5 y	$10-20 M
MRV	Development of ocean models	Demonstrate the efficiency of atmospheric CO_2 uptake over realistic timeframes with uncertainty bounds.[4] Initial funding should seek to demonstrate this in practice to inform MRV with (1) dedicated field testing and (2) dedicated modeling of removals.[5] This is cross-cutting with all CDR approaches that modify open water chemistry.	✓ Verification that CO_2 is equilibrated from the atmosphere on an emissions-relevant timescale[6]	1-2	$2-4M/y	5-10 y	$20-40 M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include new legal frameworks and permitting for ocean activities,[7] as well as community support.*

Notes and sources: [1]Costing estimates are based on A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022); the number of facilities is based on an average of sources. Costing estimates are described in the AIR Appendix. [2]The desktop research portions of this approach can be performed collaboratively with the CO_2 stripping and alkalinity production approaches. [3]General siting considerations include: (1) seawater access, (2) low-carbon energy supply, (3) infrastructure for the supply of raw materials and waste disposal, and (4) labor. Assessment informed by the NAS (2022). [4]It is expected that the amount of CO_2 removed from the atmosphere will likely be less than that removed from the ocean, given that ocean mixing can carry CO_2 depleted water to lower layers or equilibrate part of the depleted water with non-atmospheric sources. [5]One of the AIR reviewers is currently building a suite of software modeling tools for ocean CDR MRV. The 7-year budget of the project is >$50M. [6]Current estimates are that CO_2 equilibrates over two weeks to four months. [7]In the white paper Depending on the Ocean (May 2023), Carbon180 calls for more robust policies and legal frameworks.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS[1]	PROJECT BUDGET[1]	DURATION	TOTAL COST
Demo	Scaled deployment[2] of key plant designs at 4 sites with a combination of: • Standalone seawater / freshwater • Co-location with desalination / thermal power • In-process mineralization / post-process mineralization in seawater Demonstration projects should perform their own measurement, LCA, and environmental monitoring and impact analyses. Additional analyses will be performed by third-parties.	4-6 demonstration plants, each with at least 5 $ktCO_2/y$ capacity	✓ Pathway to total costs (including storage) is competitive with DAC approaches ✓ Manageable environmental impacts for plant designs and deployment	4-6	$10-15M[3] *Most cost is upfront rather than annual*	6-10 y	$200-500M
Demo	Dispersion method assessments: Scaled deployment to assess efficacy and environmental impact of various dispersion methods (coastal, ship-based, shared, co-located with desalination or water treatment, etc.) in conjunction with demonstrations	N/A	✓ Various dispersion methods can scale with manageable environmental impacts	1-4	$0.25M	6-10 y	$2.5-10M
MRV	Ocean models to inform MRV: Development of ocean models to (1) build on the pre-demonstration MRV workstream and (2) be performed by a separate entity than the demonstration team, but in concurrence with the demonstration projects listed above. Activities may utilize significant funding for software-based ocean models as well as in-field sensors.[4]	N/A	✓ Verification of (1) storage of CO_2 and (2) ocean uptake of equivalent amounts of CO_2 from the air	1-2	$1-5M	6-10 y	$10-50M

Notes and sources: [1]Baseline costing estimates are based on A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022).The number of facilities is based on an average of sources. Costing estimates are described in the AIR Appendix. [2]Scaled deployment will require, among other things, co-location or transportation network to acceptable utilization or storage assets. This may include pipelines for gas or liquid generating approaches and landfill or other disposal options for solid generating approaches. [3]NAS (2022) allocates $30M/y for 5 years for electrochemical DOC (IWC) processes. For comparison, the Capture 6 Commercialization Industrial Decarbonization (CID) Program grant recently awarded $8M for a fully integrated water management and carbon dioxide removal plant, though this plant is expected to be much smaller than 10 $ktCO_2/y$. [4]Quantification costs depend on the CDR process. If co-located with water processing facilities, measurement might be simple and inexpensive. If done in open water, it may require more extensive ocean modeling and measurements.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS[1]	PROJECT BUDGET[1]	DURATION	TOTAL COST
Desktop research	Continual lifecycle analysis and accounting for emissions and energy	Use demonstration data to continually update the (1) lifecycle assessment and (2) technoeconomic analysis. Use this to further refine deployment of electrochemical alkalinity production.	1-2	$0.5-1M	10 y	$5-10 M
Field testing	Ongoing marine ecosystem monitoring	Perform continual assessment of key marine ecosystem metrics near demonstration sites to ensure regulatory compliance, low impact, and to support transparency / social acceptance.	2-4	$1-2M	10 y	$10-20 M
Lab	Novel and improved electrodes, bi-polar membranes, and membrane materials	Research to improve key technologies that drive efficiency and reduce capex, including: • Electrodes (low-cost electrodes, reaction selectivity, reaction density, large form factors, manufacturability) • Electrochemical membranes (reduced cost, higher durability, improved conductivity, permeability, and selectivity)[2]	2-10	$1-2M	7-10 y	$20-40 M
Cross-cutting research	Market research and development for use of acid byproducts	Because approaches that produce solid carbonates also produce acid as a side product, the development of new markets for HCl or H_2 and Cl_2 would help offtake co-products. This could include industrial co-processes and other operations on site.	1-2	$0.5M	2-5 y	$2-3M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include new legal frameworks and permitting for ocean activities,[3] as well as community support.*

Notes and sources: [1]Baseline costing estimates are based on A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS), 2022). The number of facilities is based on an average of sources. Costing estimates are described in the AIR Appendix. [2]Captura estimates that ~40% of their costs are for maintenance and replacement of bi-polar membranes and membrane contactors; an R&D focus on improving lifetime and efficiency will drive this cost down. [3]In the white paper Depending on the Ocean, released in May 2023, Carbon180 calls for more robust policies and legal frameworks.

7. Direct air capture (DAC), 7.1-7.5

Approaches that use machines to capture CO_2 from the atmosphere in a concentrated stream

Index	Approaches	Definition	TRL
7.1	Absorption and high-grade heat regeneration	CO_2 absorption with an alkaline solvent (where CO_2 is dissolved or diffused in a liquid to form a solution), followed by a desorption process in which CO_2 is mineralized out of the solution and then regenerated by high-grade heat (700-900 °C)	> 6
7.2	Absorption and low-grade heat regeneration	CO_2 absorption with a liquid solvent (e.g., amines or amino acids, where CO_2 is dissolved or diffused in a liquid to form a solution), followed by a desorption process in which low-grade heat (120 °C or lower) is used to release the captured CO_2 and regenerate the solvent	≤ 6
7.3	Absorption and electrochemical regeneration	CO_2 absorption with an alkaline solvent (where CO_2 is dissolved or diffused in a liquid to form a solution) followed by CO_2 release and solvent regeneration in an electrochemical cell where a change in voltage is used to separate CO_2 from the solvent	≤ 6
7.4	Adsorption and high-grade heat regeneration	CO_2 adsorption onto a solid mineral sorbent (where CO_2 is captured on the surface of a solid material) followed by a desorption process in which high-grade heat (600-1200 °C) is used to separate CO_2 from the mineral	≤ 6
7.5	Adsorption and low-grade heat regeneration	CO_2 adsorption onto the surface of a solid sorbent material (where CO_2 is captured on the surface of a porous solid material), followed by a desorption process where mainly low-grade heat (<120 °C) is used to release the CO_2 from the sorbent	> 6

RMI classifies direct air capture (DAC) approaches as **synthetic**

Biogenic (bCDR)	Geochemical (gCDR)	Synthetic (sCDR)	Storage
Living biomass **1.1** Improved management **1.2** Conservation / protection **1.3** Restoration / creation **Stabilized biomass** **2.1** Biomass direct storage **2.2** Timber building products **2.3** Other biomass building products **2.4** Pyrolysis (biochar) and storage **2.5** Pyrolysis (bioliquid) and storage **2.6** Microalgae in ponds **2.7** Microalgae in open water **2.8** Macroalgae in open water **Sequestration of CO_2 from biomass** **3.1** BECCS to electricity **3.2** BECCS to fuels	**Solid carbonate minerals** **4.1** Surficial **Dissolved bicarbonate sequestration** **5.1** Terrestrial enhanced weathering **5.2** Coastal enhanced weathering **5.3** Mineral alkalinity enhancement	**Indirect water capture (IWC)** **6.1** CO_2 stripping **6.2** Electrochemical alkalinity production **Direct air capture (DAC)** **7.1-7.3** Liquid solvent **7.4-7.7** Solid sorbent **7.8-7.9** Membranes **7.10** Cryogenic	**Storage of CO_2** **8.1** Conventional CO_2 storage **8.2** In-situ mineralization **8.3** Ex-situ mineralization

7. Direct air capture (DAC), 7.6-7.10

Approaches that use machines to capture CO_2 from the atmosphere in a concentrated stream

Index	Approaches	Definition	TRL
7.6	Adsorption and electrochemical regeneration	CO_2 adsorption onto a solid sorbent (where CO_2 is captured on the surface of a solid material), followed by CO_2 release and sorbent regeneration in an electrochemical cell in which a voltage change is used to separate the CO_2 from the sorbent	≤ 6
7.7	Adsorption and humidity / water regeneration	Adsorption onto a solid sorbent (where CO_2 is captured on the surface of a solid material) followed by a desorption step in which a swing in humidity (high humidity for regeneration) is used to separate CO_2 from the sorbent (i.e., a resin); further purification of CO_2 may be necessary, depending on the water concentration in the product stream	≤ 6
7.8	Membrane: pressure gradient separation	Polymeric membrane separation in which the CO_2 is separated from other gases via differences in the molecular ability to pass through a polymer membrane (i.e., permeability); multiple capture stages, in which several membrane units are stacked together, may be required to achieve a concentrated CO_2 product	≤ 6
7.9	Membrane: electrochemical separation	Ion-exchange membrane separation in which the CO_2 is separated from other gases in an electrochemical cell by means of a membrane and electron transfer	≤ 6
7.10	Cryogenic: phase separation (vapor-solid)	Cryogenic separation in which very low temperatures enable a phase separation of CO_2 from other gases by deposition (a phase transition of CO_2 from vapor to solid)	≤ 6

RMI classifies direct air capture (DAC) approaches as **synthetic**

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SECTION 7.1

Absorption and high-grade heat regeneration

SECTION	7.1
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Absorption and high-grade heat regeneration

DEFINITION

CO_2 absorption with an alkaline solvent (where CO_2 is dissolved or diffused in a liquid to form a solution), followed by a desorption process in which CO_2 is mineralized out of the solution and then regenerated by high-grade heat (700-900 °C)

EXAMPLE SCENARIO

Fans pull air over a potassium hydroxide solution that chemically binds with CO_2 in air to form potassium carbonate that then is regenerated with calcium hydroxide. This produces mineralized CO_2 that is processed at high temperatures to release concentrated CO_2 for storage.

Section 7.1 overview

Absorption and high-grade heat regeneration

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability** • Key risks in scalability include energy requirements of solvent regeneration and water requirements to replace evaporation losses
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Low** • This approach is mass-customized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Demonstration stage** • 1 company demo stage with ~$0.5M and ~$100M in funding respectively
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment across all DAC approaches: **1 $GtCO_2$ by 2050** • Success is contingent on breakthroughs in materials, process design, and equipment, as well as siting synergies and increased cost effectiveness as compared to other DAC approaches
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$2-3B over 13-20 years** • Key stage gates in cost reductions by equipment and process optimization

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Very high risk:** Solvent regeneration by calcination is extremely energy intensive.	Energy needs meet our DAC criteria for "very high risk" (>5 GJ/tCO_2 and needs high-grade heat).[1] Capture and solvent regeneration alone require approximately 6-10 GJ/tCO_2. The full pathway will require additional energy (e.g., compression, transport, and storage).[2,3]
	Land requirements	**Low risk**: Significant land areas are suitable for DAC siting.	These DAC plants have minimal footprint per capture capacity (~16 $km^2/GtCO_2$) compared to other CDR solutions and can be deployed on most types of land. The footprint is larger if land use for energy production is considered.[4]
	Water requirements	**High risk:** Large volumes of water are evaporated when operating the plant.	This DAC technology requires large amounts of water (~5 $GtH_2O/GtCO_2$), which restricts deployment to locations with low water stress indices.[2] However, water requirements vary depending on local conditions.
	Material requirements	**Low risk:** No rare materials are required.	Beyond basic construction materials (e.g., steel, cement), this solution requires raw material inputs that are relatively abundant (KOH and $CaCO_3$ solutions).[2]
	Co-location of DAC and storage	**Low risk:** Co-location of DAC and storage is relatively easy.	The DAC unit should not be situated in dry and hot environments due to the high requirements for water. However, there is sufficient geological storage in water-rich areas, so co-location should not be a problem. Easy co-location with storage is also favorable due to high CO_2 purity from the DAC unit.[2,5]
	Environmental impacts	**Low risk:** No environmental impacts anticipated beyond effects from energy and water intensity.	LCA exists for this technology. Methane leakage during transport is a potential risk, if natural gas is the source of high-grade heat.[2,6] Apart from impacts associated with energy, water, and material requirements, minimal other impacts are anticipated.
Secure storage for 100+ years		**Low risk:** Storage is durable.	Geological sequestration or in-situ mineralization (primary storage options) are considered permanent storage approaches.[3]
Path to measurement at scale		**Low risk:** Measurement to inform MRV is straightforward.	DAC+S measurement and monitoring is straightforward, as capture occurs in a controlled environment, and geological injection has established monitoring standards.[2]
Pathway to full costs <$100/$tCO_2$		**Medium risk:** Technology is modular across certain components with cost estimates at $100-500/$tCO_2$.	Rating is based on cost estimates for FOAK plants and the data quality used for these estimates. Different cut-offs for modular / non-modular technologies were applied, as modular approaches are comparatively less expensive and easier to scale. This technology meets our criteria for "medium" risk (FOAK: >10 $ktCO_2$; $100-500/$tCO_2$ plus available plant data).[2,3,7,8]

Notes and sources: [1]Methods and criteria used to assign DAC ratings are found in the AIR appendix. [2]A Roadmap for Achieving Scalable, Safe and Low-cost Direct Air Carbon Capture and Storage (Küng et al., 2023) [3]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [4]The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis (Viebahn et al., 2019) [5]There is a risk of CO_2 leakage if DAC and storage are not co-located. [6]Life cycle carbon efficiency of Direct Air Capture systems with strong hydroxide sorbents (de Jonge et al., 2019) [7]The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy (Young et al., 2022) [8]The price of available electricity will have a significant impact on the cost estimate.

Potential for cost improvement

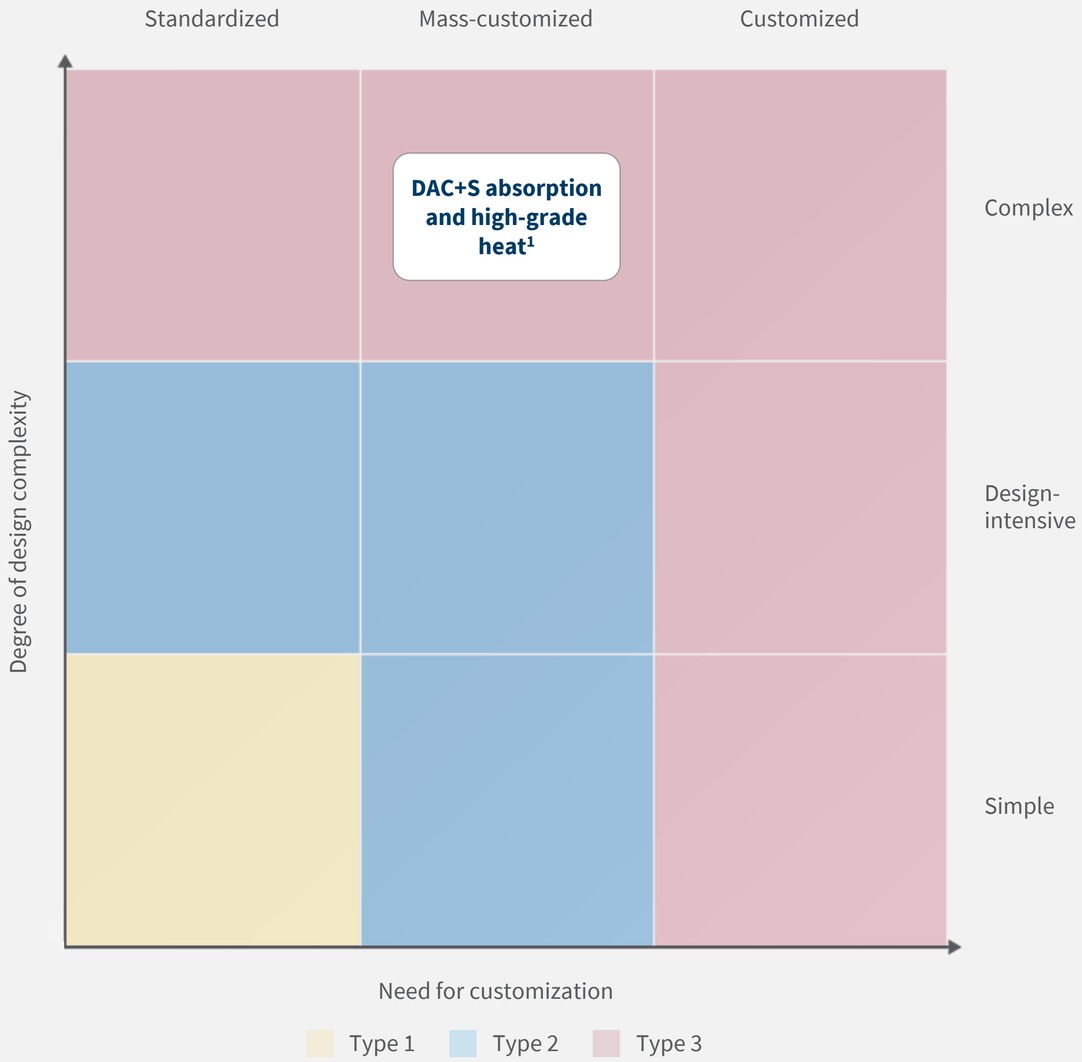
An assessment of two key drivers of learning rates

SECTION 7.1

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and high-grade heat regeneration



OVERALL RATING

Type 3[2]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Complex
- **Rationale:** DAC+S absorption with high-grade heat is a highly complex system as it requires multiple independent steps of chemical processing with large, CAPEX-intensive equipment, such as calciners and pellet reactors.[3]

NEED FOR CUSTOMIZATION

- **Rating:** Mass-customized
- **Rationale:** There is a need for equipment customization and adaptation to specific sites and ambient conditions (primarily to address varying evaporation rates), despite some standardization of components.[3]

Notes and sources: [1]Reviewers have pointed out that Carbon Engineering (CE) could have a lower degree of design complexity as its design is based on a process configuration of pre-existing industrial equipment, and each component has well developed supply chains and extensive global application in various industries. [2]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [3]Overall sCDR assessment on cost improvement is based on "Lessons for Direct Air Capture from the History of Nitrogen Synthesis: High rates of deployment are possible, with strong support" (Roberts and Nemet, Pre-print 2023).

Current state of RD&D

A mapping of companies, plus other notable activities

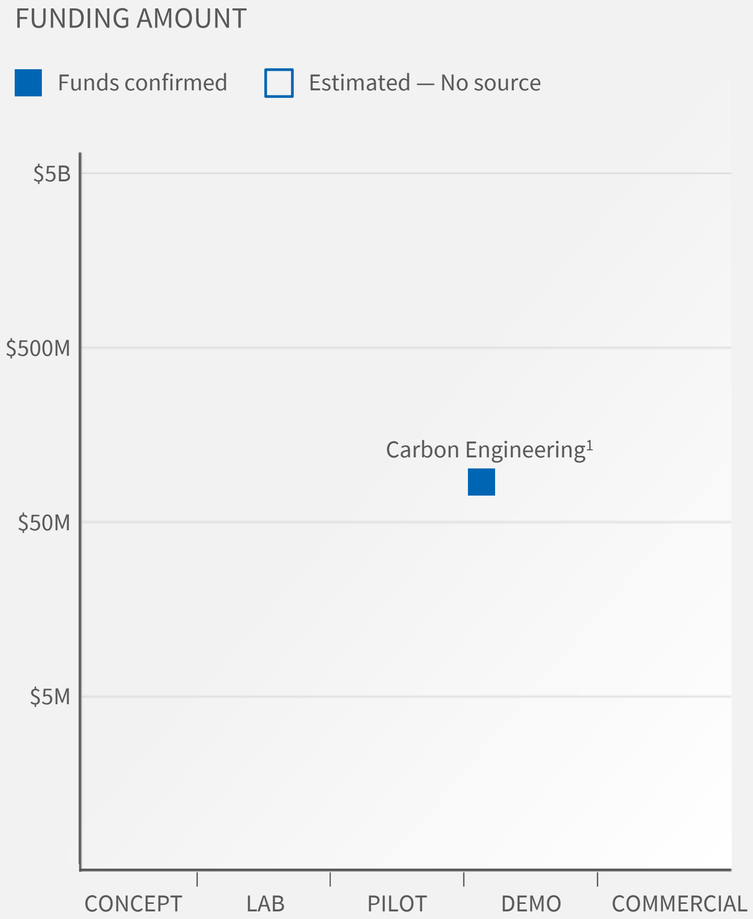
NOT EXHAUSTIVE

SECTION 7.1

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and high-grade heat regeneration



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Carbon Engineering (to be acquired by Occidental Petroleum): Four major pieces of equipment that capture, purify, and compress CO_2[1]	$110.4M[2]	• 2022 — started construction of first large-scale demonstration project (500 $ktCO_2/y$) “STRATOS” in Texas[3]

Notes and sources: [1]Carbon Engineering is one of the pioneering companies in the DAC sector; their technology is deployable only in large-scale plants. Occidental Petroleum (Oxy) will acquire Carbon Engineering after the companies have worked together for years to advance DAC technology. [2]Crunchbase funding estimate for Carbon Engineering [3]The Carbon Engineering demonstration project is designed to become the anchor for future deployment of megaton scale DAC plants in the gulf region.

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

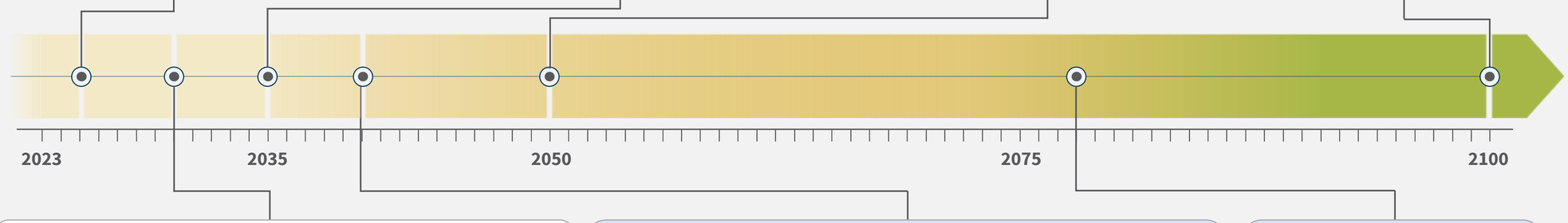
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 7.1

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and high-grade heat regeneration



2025

- 2-3 non-Carbon Engineering (CE) demonstration plants are funded using alternative designs.
- All currently announced CE projects are proceeding to operation without delays.[2]
- Additional funding is allocated for R&D advances in materials, process design, equipment, and system integration.
- A global database of R&D gaps is created. This database directs researchers and funders to the most critical open questions / R&D projects that need to be addressed.[3]

2030

- At least 10 operational commercial facilities[2]
- Breakthroughs in materials, process design, and equipment have brought CAPEX costs down by at least 50%.
- Plant data from CE's now-operational facility, other demonstrations, and the state of other DAC approaches begin to determine the extent of future investments made in this approach.

- Total global capture[1] for all DAC operations reaches 60 $MtCO_2/y$. This approach contributes significantly to that total.

2035

- This DAC approach is built into industrial clusters to take advantage of existing resources and other siting synergies.
- Plant data from CE's demonstration plant, other demonstrations, and the rest of the DAC space indicates whether this approach should be scaled widely or give way to other, more competitive DAC approaches.

- Total global capture[1] for all DAC operations reaches 180 $MtCO_2/y$.

2040

- Total global capture[1] for all DAC operations reaches 560 $MtCO_2/y$.
- DAC facilities are synergistically sited alongside other industrial facilities as part of the energy transition.
- DAC facilities increasingly take advantage of new low-carbon energy generation, including non-peak electricity loads.
- A "fail fast" methodology applied across the DAC space has led to consolidated funding directed toward the most effective approaches. Unpromising approaches are no longer funded.

2050

- Total capture[1] from all forms of DAC reaches 1 $GtCO_2/y$.
- Breakthroughs in DAC R&D continue to drive down the cost of removals.
- Due to decades of competition, the most energy efficient and cost-optimized DAC approaches have become market leaders.
- DAC clusters have emerged in industrial corridors, some of which remove 10-100 $MtCO_2/y$.

These story elements are common to all DAC approaches.

2100

- Capture from all forms of DAC reaches 10 $GtCO_2/y$.[1]
- DAC facilities are operational globally.
- The cost of DAC is less than \$100/tCO_2 (adjusted to 2023 dollars).

2050-2100

- There is continued rapid scaling of DAC plants in accordance with climate objectives.
- Breakthroughs in DAC design and deployment lead to new facilities being built in widely distributed locations around the world.

Notes and sources: [1]We have assessed all DAC approaches in the AIR under a single growth paradigm. Our growth paradigm therefore is representative of the DAC field, not a specific DAC approach. We assumed a starting deployment of 60 $MtCO_2/y$ in 2030, which is the amount of DAC in the IEA Net Zero scenario in 2030, based on 130 proposed plants the IEA is tracking. We then assume that this 60 $MtCO_2/y$ grows at 25% per year from 2030 to 2040 and then 6% per year from 2040 to 2050. This growth paradigm includes 3 phases: (1) an initial period of rapid growth to 2030 where many new standalone facilities are built, (2) a second period of growth from 2030-2040 characterized by supply chain management, workforce development, and addressing other scaling challenges, and (3) a sustained period of long-term growth characterized by more complex supply chains and large-scale systems. This multi-phase growth methodology is used in other AIR success stories and has also been recently modeled in academic papers, such as Roberts and Nemet, Pre-print 2023. [2]The Oxy/1PointFive facility is due to begin construction in 2024. It will have a capacity of 500 $ktCO_2/y$ with scalability to 1 $MtCO_2/y$. Oxy has announced that it plans to have 100 high-temperature liquid solvent DAC facilities operating by 2035. [3]A similar database has already been initiated by Frontier.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 7.1

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and high-grade heat regeneration

TRL

CRITICAL PATH ACTIVITIES

$2-3 billion | **13-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Lab – materials R&D:** Identify optimal materials and test for performance, durability, and degradation
- **Lab and pilot – process and equipment:** Optimize contactor and causticizer designs and operation; test optimal operation and configurations
- **Lab and pilot – system integration:** Conduct independent TEA, LCA, climate sensitivity, and supply chain studies

$100-200 million | **5-10 years**

- ✓ Pathway to significant CAPEX & OPEX cost reductions via optimized equipment and process operation
- ✓ Reduced electricity and heat requirements with potential to reach theoretical maximum efficiency
- ✓ Demonstrated ability to scale: e.g., CO_2 purity >85%

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Demonstration – DAC+S:** Fund / support either novel configurations (that no company is currently pursuing) OR collaborate with entities already pursuing opportunities to scale
- **MRV:** Measurement and verification should be performed by an independent entity

$2-3 billion | **8-10 years**

- ✓ Cost requirements: $100-500/tCO$_2$[3]
- ✓ Energy requirements: <7.5 GJ/tCO$_2$[4]
- ✓ Reduced water requirements

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$40-60 million | **5-10 years**

- Create a DAC R&D gap database to direct researchers and funders to the most critical open questions and R&D projects.
- Perform planning studies for industrial clusters to facilitate the use of potentially available resources and existing CCS infrastructure.
- Investigate the use of CO_2 for valuable products such as chemicals and fuels.
- Assess water risks to enable better siting decisions.
- Establish industry standards with open-access designs for major equipment.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Carbon storage verified by an independent third-party
- Low-carbon / green energy sourcing and low energy requirements
- Industry and consumer acceptance
- Long-term safety record with net carbon removal and durable storage
- Financing costs in line with commercially accepted technologies

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development. [3]Based on the assumptions in the "Pathway to full costs <$100/tCO$_2$" presented in appendix. [4]DAC energy requirements of 7.5 GJ/tCO$_2$ require the equivalent of about 2.5 months of energy consumption for the average American household, and removing a gigaton of CO_2 would require about half the total energy consumed by the US in 2022.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK[1]	WORKSTREAM[2]	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Lab	R&D: Materials	Identify optimal materials and tradeoffs between material properties: • Model and measure relevant material performance parameters for optimal solvents, caustics, and minerals for regeneration • Establish frameworks for selection of optimal materials	✓ Identify at least 3-5 high performing solvents for testing at pilot scale ✓ Demonstrate improved material characteristics ✓ Validate expected material lifetimes	2-4	$0.5-2M/y	2-4 y	$10-20M
		Assess material durability and recyclability: • Conduct long-term testing for material loss and degradation • Explore the effects of climate and harsh operational conditions on materials					
Lab / pilot	R&D: Process design	Simulate and conduct synergistic material and process optimization, including heat recovery, for each configuration	✓ Identify and validate performance of 2-3 configurations that reduce energy and cost	2-4	$1-3M/y	3-5 y	$20-30M
		Design alternative regeneration methods to oxy-fired calciners (e.g., electric calciner, syngas) and experimentally validate process performance					
Lab / pilot	R&D: Equipment	Simulate and test alternative contactor designs (e.g., shallow contactor designs, cross flow contactors, etc.)	✓ Prototype at least 2-3 alternative contactor designs that enable modularity	2-4 (lab)	$1-3M/y	3-5 y	$20-30M
		Test alternative calcination options (e.g., oxy-fired, electric, syngas calciners)	✓ Validate performance and path to scalability for the most promising calcination options	2-4 (pilot)	$5-10M/y	5-10 y	$50-100M
		Perform comparative studies for process design and primary equipment					
Lab / pilot	R&D: System level studies	Conduct independent TEA, LCA, local / regional climate sensitivity studies, and supply chain analysis on the full DAC system (including material synthesis, transportation, and disposal)	✓ Independent estimates show costs and environmental impact are manageable	2-4	$0.5-2M/y	2-4 y	$10-20M

Notes and sources: [1]Components of the technology are very mature and used in other industrial process, so the focus of the pre-demonstration workstream is to adopt and optimize materials, equipment, and process for DAC purposes. [2]The recommended workstreams and budgets are adopted from Küng et al. (2023).

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	DAC+S: Fund 2-3 demonstrations of the most promising configurations optimized for energy and cost reduction (using alternative materials, operational strategies, and optimized equipment)[1]	1 $MtCO_2/y$ [2]	✓ Demonstrate CAPEX and OPEX cost improvements[2] towards an all-in cost <$100/$tCO_2$ ✓ Demonstrate energy requirement reduction to <7.5 GJ/tCO_2, with potential for additional improvements (<2.5 GJ/tCO_2 for market acceptance) ✓ Demonstrate negligible water evaporation rates, i.e., minimal water consumption per tCO_2	2-4	$100M/y	8-10	$2,000-3,000M
MRV	Measurement, reporting, and verification protocols are established and validated by an independent third party.	N/A	✓ Verification of CO_2 storage and full life cycle removals for DAC+S	1-3	$2-5M/y	5-10	$20-50M

Notes and sources: [1]Given the high likelihood of candidate demonstration projects overlapping with an existing startup approach, collaboration on demonstration projects should be investigated. This can reduce the overall price tag per demonstration project, especially with regard to public funding, and generally accelerate the pathway for unique DAC+S demonstration projects. A key of objective of these collaborations should be data transparency incentivized by public funding. [2]The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy. Young et al. (2022) describes potential economies of scale due to major equipment, such as the as calciner and slaker.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

☐ Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research	DAC R&D gap database[3]	Create a global database of R&D gaps to accelerate DAC deployment by directing researchers and funders to the most critical open questions and R&D projects that need to be addressed.	1	$0.2-0.5M/y	3-5 y	$1-5M
Desktop research	Industrial cluster planning[4]	The most cost-effective DAC typically benefits from co-location with industrial clusters using CCS for integration with existing storage reservoirs. This workstream should also seek to identify clusters producing high-grade heat for co-location of DAC.	1-3	$0.5-2M/y[5]	5-10 y	$10-20M
Desktop research	Establish industry standards	Build industry commitments for open-access designs of major process equipment. Shared designs and coordinated improvements could lower the cost of DAC.	1-3	$0.5-2M/y	5-10 y	$10-20M
Lab	DAC and utilization (DAC+U)[4]	Explore the possibility of using CO_2 products as feedstock to produce other chemicals and fuels. CO_2 utilization has the potential to de-risk and accelerate DAC deployment at scale by creating new demand for CO_2.	2-4	$0.5-2M/y	5-10 y	$20-30M
Desktop research	Water risk assessments	Perform desktop research to generate risk assessments of water sourcing and usage to enable better siting decisions.	1-3	$0.5-2M/y	3-5 y	$5-10M

Note: *There are non-RD&D gaps that are critical to the success of this approach. These include knowledge transfer and social license.*

Notes and sources: [1]A reviewer suggested a workstream to establish test centers and advanced manufacturing facilities that could help accelerate the development and testing of new materials. [2]Cost estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field, lab, and desktop R&D funding. Details of this estimation can be found in the AIR Appendix. [3]A similar database has already been initiated by Frontier. [4]Project planning and management are path-boosting activities for pre-demonstration and demonstration projects. [5]A reviewer notes that subsidies my be necessary to incentivize co-location for industrial clusters, which could significantly increase this cost.

SECTION 7.2

Absorption and low-grade heat regeneration

SECTION	7.2
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Absorption and low-grade heat regeneration

DEFINITION

CO_2 absorption with a liquid solvent (e.g., amines or amino acids, where CO_2 is dissolved or diffused in a liquid to form a solution), followed by a desorption process in which low-grade heat (120 °C or lower) is used to release the captured CO_2 and regenerate the solvent

EXAMPLE SCENARIO

Fans pull air over an amino acid solution that chemically binds with CO_2 in air. The resulting CO_2-rich liquid is then processed at low temperatures (<120 °C) to release the CO_2 for storage and regenerate the amino acid solution.

Section 7.2 overview

Absorption and low-grade heat regeneration

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk, across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/tCO$_2$** • Key risks in scalability include energy requirements, water requirements, and environmental impacts
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Low** • This approach is mass-customized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab to pilot stage** • ~2 companies at lab and pilot stages with <$50M in funding each
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment across all DAC approaches: **1 GtCO$_2$ by 2050** • Success is contingent on breakthroughs in materials, process design, and equipment, as well as siting synergies and increased cost effectiveness as compared to other DAC approaches
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$1-2B over 13-20 years** • Key stage gates in cost reductions by equipment and process optimization

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk Medium risk High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Very high risk:** Low-grade heat solvent regeneration is very energy intensive.	Energy needs meet our DAC criteria for "very high risk" (>10 GJ/tCO_2).[1] Capture and solvent regeneration alone require approximately 10-17 GJ/tCO_2. The full pathway will require additional energy (e.g., compression, transport, and storage).[2,3]
	Land requirements	**Low risk:** Significant land areas are suitable for DAC siting.	This approach has a higher footprint per capture capacity than other DAC approaches, but optimal designs can reduce it. The footprint is larger if land use for energy production is considered.[2,3]
	Water requirements	**High risk:** Large volumes of water are evaporated when operating the facility.	This DAC technology requires large amounts of water (~3-6 $GtH_2O/GtCO_2$), which restricts deployment to locations with low water stress indices.[4]
	Material requirements	**Low risk:** No rare materials are required.	Apart from basic construction materials (e.g., steel, cement), this solution requires chemicals (e.g., amines or amino acids) that need to be synthesized and purchased.[2] However, these materials are readily available.
	Co-location of DAC and storage	**Low risk:** Co-location of DAC and storage is relatively easy.	Performance of DAC can be affected by local conditions such as access water. However, CO_2 storage is widely available, so co-location can be easily achieved.[2,3,5]
	Environmental impacts	**High risk:** No / incomplete data available. Risk due to amine volatility exists but is manageable.	No LCA exists for this technology. Impacts associated with energy, water, and material requirements are expected to be significant but manageable. Risks associated with amine volatility and toxicity should be easily controllable using a water washing column or non-volatile and non-degradable solvents.[6]
Secure storage for 100+ years		**Low risk:** Storage is durable.	Geological sequestration or in-situ mineralization (the primary storage options) are considered permanent storage approaches.[3]
Path to measurement at scale		**Low risk:** Measurement is straightforward.	DAC+S measurement and monitoring is straightforward. Capture occurs in a controlled environment, and geological injection has established monitoring standards.[2]
Pathway to full costs <$100/$tCO_2$		**High risk:** The technology is non-modular and cost estimates are >$500/t.[7]	Rating is based on the cost estimates for FOAK plants & the data quality used for these estimates. Different cut-offs for modular / non-modular technologies were applied, as modular approaches are comparatively cheaper and easier to scale. This technology meets our criteria for "high" risk (FOAK: >10 $ktCO_2$; >$500/$tCO_2$ plus available plant data).[1,2,8,9,10]

Notes and sources: [1]Methods and criteria used to assign DAC ratings are found in the AIR appendix. [2]A Roadmap for Achieving Scalable, Safe and Low-cost Direct Air Carbon Capture and Storage (Küng et al., 2023) [3]Techno-Economic Assessment for CO_2 Capture From Air Using a Conventional Liquid-Based Absorption Process (Kiani et al., 2020) [4]Project ENCORE (2021) Final report [5]There is a risk of CO_2 leakage if DAC and storage are not co-located. [6]Results of the 18-month test with MEA at the post-combustion capture pilot plant at Niederaussem – new impetus to solvent management, emissions and dynamic behaviour (Moser et al., 2020) [7]A reviewer notes that this may be very high risk as developers of this technology who are building plants consider meeting the <$100/$tCO_2$ threshold by 2050 to be extremely challenging. [8]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [9]The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy (Young et al., 2022) [10]The price of available electricity will have a significant impact on the cost estimate.

Potential for cost improvement

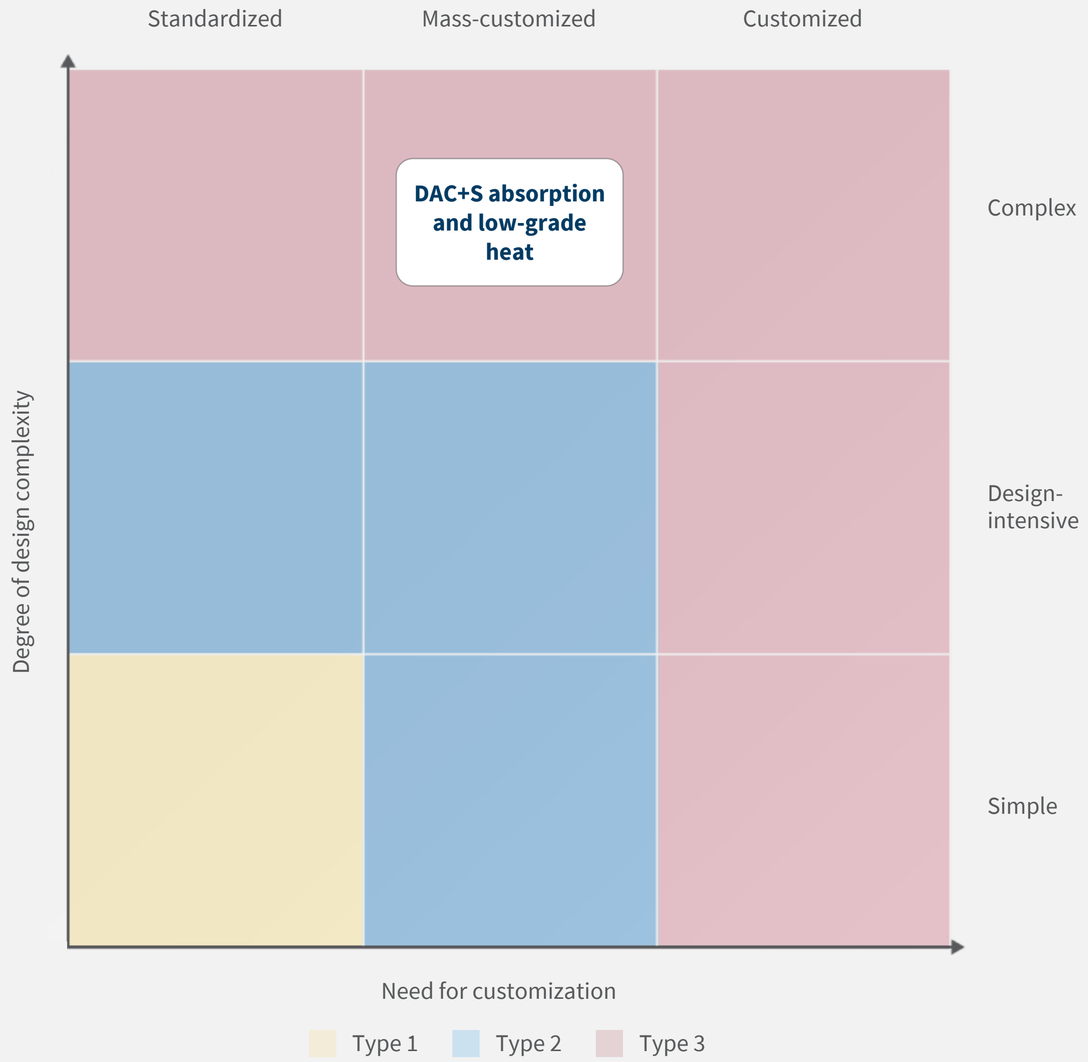
An assessment of two key drivers of learning rates

SECTION 7.2

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and low-grade heat regeneration



OVERALL RATING

Type 3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Complex
- **Rationale:** Multiple independent steps of chemical processing, such as post-combustion amine-based CCS technology, make this a highly complex approach.[2]

NEED FOR CUSTOMIZATION

- **Rating:** Mass-customized
- **Rationale:** This approach needs equipment customization and adaptation to specific, but repeatable, sites and ambient conditions (primarily dealing with evaporation rates).[2]

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]Overall sCDR assessment on cost improvement is based on Roberts and Nemet, "Lessons for Direct Air Capture from the History of Nitrogen Synthesis: High rates of deployment are possible, with strong support" (Roberts and Nemet, Pre-print 2023).

Current state of RD&D

A mapping of companies, plus other notable activities

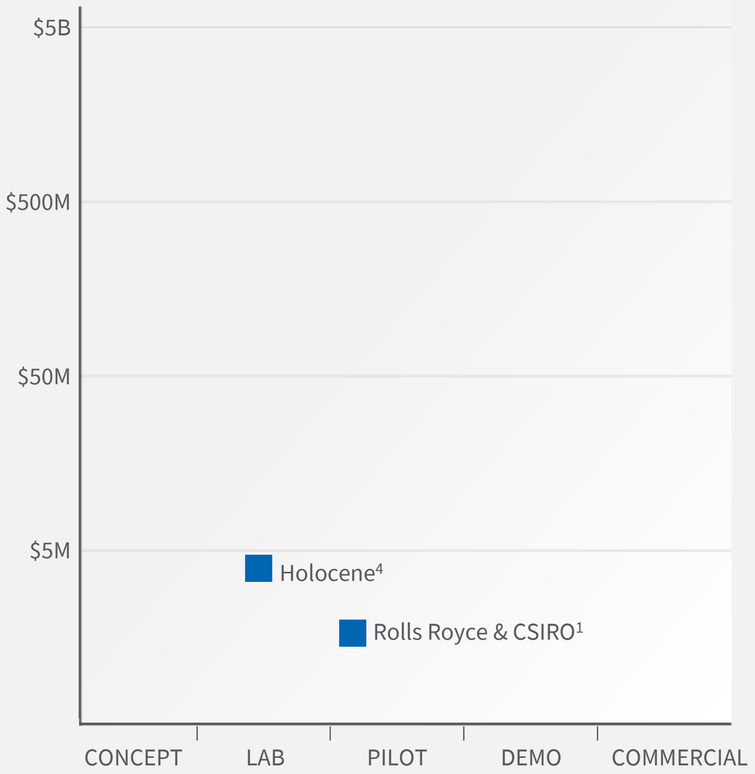
NOT EXHAUSTIVE

SECTION 7.2

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and low-grade heat regeneration



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Rolls Royce & CSIRO: Project ENCORE[1]	£2.8M[2]	• 2021 — Lab scale prototype in Australia used to optimize solvent and process operation • By end of 2023, a larger field pilot will be deployed at the Rolls Royce testing site “Test Bed 52” near Derby, UK[3]

Other companies and activities:

- Holocene[4]
- Other activities / research are being developed in parallel, e.g., research on improving the contactor design to achieve a better contact between the dilute CO_2 and the capture liquid.[5]
- This DAC approach can benefit from decades of learnings from post-combustion carbon capture.[6]

Notes and sources: [1]Project ENCORE led by Rolls Royce and CSIRO [2]This project won two grants from the UK department BEIS as part of the Net Zero Innovation Portfolio funding scheme: Phase 1 £0.25M; Phase 2 £2.81M [3]Press release (Jul 2022) [4]Holocene was awarded $4.5M from LaunchTN. [5]Case for Direct Air Capture (DAC) (Labib et al.) [poster] [6]Results of the 18-month test with MEA at the post-combustion capture pilot plant at Niederaussem – new impetus to solvent management, emissions and dynamic behavior (Moser et al., 2020)

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

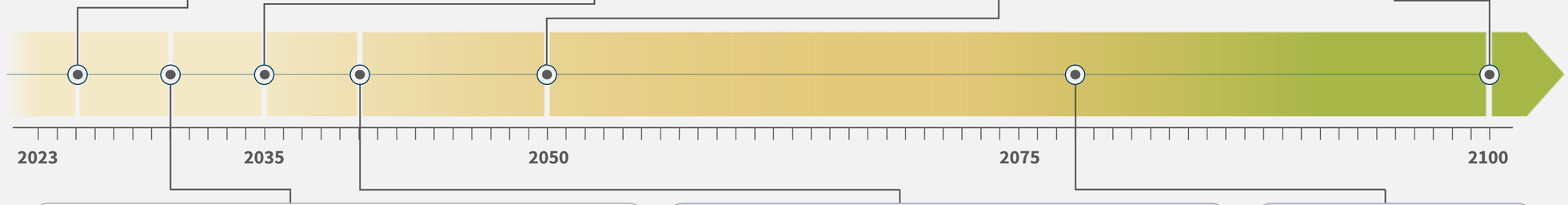
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 7.2

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and low-grade heat regeneration



2025

- Significant funding is allocated for R&D projects to advance materials, process design, equipment, and systems integration of this approach.
- A global database of R&D gaps is created. This database directs researchers and funders to the most critical open questions / R&D projects that need to be addressed.[1]
- 1-3 pilot plants with various process designs, contactor designs, and regeneration methods are being planned or under construction.

2030

- R&D breakthroughs in materials, process design, equipment, and systems integration lead to significant cost declines for this approach.
- Plant data from SCIRO's pilot plant and 1-3 additional pilots with alternative configurations inform future funding decisions for this DAC approach.

- Total global capture[2] for all DAC operations reaches 60 $MtCO_2$/y. This approach is not yet mature enough to contribute significantly to that total.

2035

- Early R&D, pilot, and demonstration data from this approach is used to inform future funding decisions. This approach is either being scaled widely or giving way to other, more competitive DAC approaches.

- Total global capture[2] for all DAC operations reaches 180 $MtCO_2$/y.

2040

- Total global capture[2] for all DAC operations reaches 560 $MtCO_2$/y.
- DAC facilities are synergistically sited alongside other industrial facilities as part of the energy transition.
- DAC facilities increasingly take advantage of new low-carbon generation, including non-peak electricity loads.
- A "fail fast" methodology applied across the DAC space has led to consolidated funding directed toward the best approaches. Unpromising approaches are no longer funded.

2050

- Total capture[2] from all forms of DAC reaches 1 $GtCO_2$/y.
- Breakthroughs in DAC R&D continue to drive down the cost of removals.
- Due to decades of competition, the most energy efficient and cost-optimized approaches to DAC have emerged as market leaders.
- DAC clusters have emerged in industrial corridors, some of which remove 10-100 $MtCO_2$/y.

These story elements are common to all DAC approaches.

2050-2100

- There is continued rapid scaling of DAC plants in accordance with climate objectives.
- Breakthroughs in DAC design and deployment lead to new facilities being built in widely distributed locations all around the world.

2100

- Capture from all forms of DAC reaches 10 $GtCO_2$/y.[2]
- DAC facilities are operational globally.
- The cost of DAC is less than \$100/tCO_2 (adjusted to 2023 dollars).

Notes and sources: [1]A similar database has already been initiated by Frontier. [2]We have assessed all DAC approaches in the AIR under a single growth paradigm. Our growth paradigm therefore is representative of the DAC field, not a specific DAC approach. We assumed a starting deployment of 60 $MtCO_2$/y in 2030, which is the amount of DAC in the IEA Net Zero scenario in 2030, based on 130 proposed plants the IEA is tracking. We then assume that this 60 $MtCO_2$/y grows at 25% per year from 2030 to 2040 and then 6% per year from 2040 to 2050. This growth paradigm includes 3 phases: (1) an initial period of rapid growth to 2030 where many new standalone facilities are built, (2) a secondary period of growth from 2030-2040 characterized by supply chain management, workforce development, and other scaling challenges, and (3) a sustained period of long-term growth characterized by more complex supply chains and large-scale systems. This multi-phase growth methodology is used in other AIR success stories and has also been recently modeled in academic papers, such as Roberts and Nemet, Pre-print 2023.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 7.2

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and low-grade heat regeneration

TRL

CRITICAL PATH ACTIVITIES

$1-2 billion | **13-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Lab – materials R&D:** Identify and assess optimal materials for performance, durability, and degradation
- **Lab and pilot – process and equipment:** Optimize contactor (absorber) and reactor / stripper designs and operation; test optimal operation and configurations
- **Lab and pilot – system integration:** Conduct independent TEA, LCA, climate sensitivity, and supply chain studies

$60-100 million | **5-10 years**

- ✓ Pathway to significant CAPEX and OPEX cost reductions via optimal equipment and process operation
- ✓ Reduced electricity and heat requirements with potential to reach theoretical maximum efficiency
- ✓ Demonstrated ability to scale: e.g., CO_2 purity >85%[3]

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Demonstration – DAC+S:** Fund / support either novel configurations (that no company is currently pursuing) OR collaborate with entities already pursuing opportunities to scale
- **MRV:** Measurement and verification should be performed by an independent entity

$1-2 billion | **8-10 years**

- ✓ Cost requirements: $100-500/tCO$_2$[4]
- ✓ Energy requirements: <7.5 GJ/tCO$_2$[5]
- ✓ Reduced water requirements

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$40-60 million | **5-10 years**

- Create a DAC R&D gap database to direct researchers and funders to the most critical open questions / R&D projects.
- Perform planning studies for industrial clusters to facilitate use of potentially available resources and existing CCS infrastructure.
- Investigate the use of CO_2 for valuable products such as chemicals and fuels.
- Assess water risks to enable better siting decisions.
- Establish industry standards with open-access designs for major equipment

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Carbon storage verified by a third-party accounting organization
- Low-carbon / green energy sourcing and low energy requirements
- Industry and consumer acceptance
- Long-term safety record with net carbon removal and durable storage
- Financing costs in line with commercially accepted technologies

RMI

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development. [3]Below this threshold, density changes, mostly due to the presence of non-condensable impurities (e.g., N_2, O_2, Ar) that cannot be liquified at ambient temperature, can affect storage capacity, injectivity, and buoyancy. More information found here. [4]Based on the assumptions in the "Pathway to full costs <$100/tCO$_2$" presented in the AIR Appendix. [5]DAC energy requirements of 7.5 GJ/tCO$_2$ require the equivalent of about 2.5 months of energy consumption for the average American household, and removing a gigaton of CO_2 would require about half the total energy consumed by the US in 2022.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK[1]	WORKSTREAM[2]	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Lab	R&D: Materials	Identify optimal materials and tradeoffs between material properties: • Model and measure all relevant material performance parameters for optimal CO_2 solubility, kinetics, and regeneration • Establish frameworks for selection of optimal materials	✓ Identify at least 3-5 high performing solvent materials for testing at pilot scale ✓ Demonstrate improvements in material characteristics to reduce volatility, degradation, heat demand and enhance CO_2 uptake and kinetics ✓ Validate material lifetimes	1-3	$0.5-2M/y	2-4 y	$5-10M
		Assess material recyclability and elimination of material loses: • Conduct long-term degradation studies • Assess the effects of climate and harsh operational conditions					
Lab / pilot	R&D: Process design	Simulate and conduct synergistic material and process optimization, including heat recovery, for each configuration considering different climate conditions and CO_2 purity targets, depending on CO_2 destination	✓ Identify and validate performance of 2-3 configurations to reduce material losses, energy, and cost	1-3	$1-3M/y	2-4 y	$10-20M
		Design alternative regeneration methods (e.g., crystallization, pH swings, electrochemical conversion, etc.) and experimentally validate process performance					
Lab / pilot	R&D: Equipment	Optimize contactor design and geometry to achieve: • Higher mass transfer of the diluted CO_2 into the liquid • Optimal packing design	✓ Prototype at least 2-3 alternative contactor designs that enable modularity	1-3 (lab)	$1-3M/y	2-4 y	$10-20M
		Optimize large-volume crystallizers and solid-liquid separators specific to amino acid capture	✓ Validate performance and path to scalability for the most promising regeneration options	1-3 (pilot)	$5-10M/y	5-10 y	$30-50M
		Perform comparative studies for process design and primary equipment					
Lab / pilot	R&D: System level studies	Conduct independent TEA, LCA, local / regional climate sensitivity studies, and supply chain analysis on the full DAC system (including material synthesis, transportation, and disposal)	✓ Independent estimates show costs and environmental impact are manageable	1-3	$0.5-2M/y	2-4 y	$5-10M

Notes and sources: [1]This CDR approach is rated TRL 6 as aspects of the technology are very mature and used in other industrial process, thus the focus of the pre-demonstration workstream is to adopt and optimize materials, equipment, and process for DAC purposes. [2]List of recommended workstreams and budgets is adopted from Küng et al. (2023).

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	DAC+S: Fund 2-3 demonstration projects of the most promising optimized configurations for energy and cost reduction using alternative materials, operational strategies, and optimized equipment[1]	1 $MtCO_2/y$ [2]	✓ Demonstrate CAPEX and OPEX cost improvements[2] towards an all-in cost <$100/$tCO_2$ ✓ Demonstrate energy requirements reduced to <7.5 GJ/tCO_2, with potential for further reduction (<2.5 GJ/tCO_2 for market acceptance) ✓ Demonstrate negligible water evaporation rates, i.e., minimal water consumption per tCO_2	1-3	$100M/y	8-10 y	$1,000-2,000M
MRV	Measurement, reporting, and verification protocols are established and validated by an independent third party.	N/A	✓ Verification of CO_2 storage and full life cycle removals for DAC+S	1-3	$2-5M/y	5-10 y	$20-50M

Notes and sources: [1]Given the high likelihood of candidate demonstration projects overlapping with an existing startup approach, collaboration on demonstration projects should be investigated. This can reduce the overall price tag per demonstration project, especially with regard to public funding, and generally accelerate the pathway for unique DAC+S demonstration projects. A key of objective of these collaborations should be data transparency incentivized by public funding. [2]The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy. Young et al. (2022) describes potential economies of scale due to major equipment, such as the as calciner and slaker.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research	DAC R&D gap database[3]	Create a global database of R&D gaps to accelerate DAC deployment by directing researchers and funders to the most critical open questions / R&D projects that need to be addressed.	1	$0.2-0.5M/y	3-5 y	$1-5M
Desktop research	Industrial cluster planning[4]	The most cost-effective DAC typically benefits from co-location with industrial clusters using CCS so that it can integrate with existing storage reservoirs. This workstream should also seek to identify clusters producing low-grade heat for co-location with DAC.	1-3	$0.5-2M/y[5]	5-10 y	$10-20M
Desktop research	Establish industry standards	Build industry commitments for open-access designs of major process equipment. Shared designs and coordinated improvements could lower the cost of DAC.	1-3	$0.5-2M/y	5-10 y	$10-20M
Lab	DAC and utilization (DAC+U)[4]	Explore the possibility of using CO_2 products as feedstock to produce other chemicals and fuels. CO_2 utilization has the potential to de-risk and accelerate DAC deployment at scale by selling CO_2-based products, creating a new demand for CO_2, and thus reducing the cost of DAC.	2-4	$0.5-2M/y	5-10 y	$20-30M
Desktop research	Water risk assessments	Perform desktop research to generate risk assessments of water sourcing and usage to enable better siting decisions.	1-3	$0.5-2M/y	3-5 y	$5-10M

Notes and sources: [1]A reviewer suggested a workstream to establish test centers and advanced manufacturing facilities that could help accelerate the development and testing of new materials. [2]Cost estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]A similar database has already been initiated by Frontier. [4]Project planning and management are path-boosting activities for pre-demonstration and demonstration projects. [5]A reviewer notes that subsidies my be necessary to incentivize co-location for industrial clusters, which could significantly increase this cost.

SECTION 7.3

Absorption and electrochemical regeneration

SECTION	7.3
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Absorption and electrochemical regeneration

DEFINITION

CO_2 absorption with an alkaline solvent (where CO_2 is dissolved or diffused in a liquid to form a solution) followed by CO_2 release and solvent regeneration in an electrochemical cell where a change in voltage is used to separate CO_2 from the solvent.

EXAMPLE SCENARIO

Fans pull air over potassium hydroxide that chemically binds with CO_2 in air and forms potassium carbonate. The carbonate is electrochemically processed to release concentrated CO_2 for storage and regenerate the hydroxide solution.

Section 7.3 overview

Absorption and electrochemical regeneration

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/tCO$_2$** • Key risks include energy requirements, water requirements, cost, and limited data available to characterize environmental impacts
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium to low** • This approach is mass-customized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab to pilot stage** • ~6 companies at lab and pilot stages with <$10M in funding each
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment across all DAC approaches: **1 GtCO$_2$ by 2050** • Success is contingent on breakthroughs in materials, process design, and equipment, as well as siting synergies and increased cost effectiveness as compared to other DAC approaches
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$1-3B over 13-20 years** • Key stage gates in cost reductions by equipment and process optimization

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk Medium risk High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**High risk:** Electrochemical solvent regeneration is very energy intensive.	Energy needs meet our DAC criteria for "high risk" (>5 GJ/tCO_2).[1] Capture and solvent regeneration require approximately 7.8 GJ/tCO_2.[2] The full DAC+S pathway will require additional energy (e.g., compression, transport, and storage).[3]
	Land requirements	**Low risk:** Significant land areas are suitable for DAC siting.	The DAC plant is expected to have minimal footprint per capture capacity compared to other CDR solutions and can be deployed on most types of land. The footprint is expected to be larger if land for energy production is considered.[3]
	Water requirements	**High risk:** Large volumes of water are evaporated when operating the facility.	This DAC technology requires large amounts of water. The magnitude is unknown but is expected to be comparable to other liquid solvent technologies, especially "absorption and high-grade heat regeneration."[3]
	Material requirements	**Medium risk:** High-demand materials are required.	Apart from basic construction materials (e.g., steel, cement), this solution requires solvents, high-demand materials for electrodes, and membranes that need to be synthesized and / or purchased.[3]
	Co-location of DAC and storage	**Low risk:** Co-location of DAC and storage is relatively easy.	The DAC unit should not be situated in hot and dry environments due to high water requirements. However, there is sufficient geological storage in water-rich areas that co-location should not be a problem.[3,4]
	Environmental impacts	**High risk:** No / incomplete data available.	Apart from impacts associated with energy, water, and material requirements, including sourcing high-demand materials for the electrodes, no other impacts are anticipated. However, no LCA study is currently available for this solution.[3]
Secure storage for 100+ years		**Low risk:** Storage is durable.	Geological sequestration or in-situ mineralization (primary storage options) are considered permanent storage approaches.[5]
Path to measurement at scale		**Low risk:** Measurement to inform MRV is straightforward.	DAC+S measurement and monitoring is straightforward. Capture occurs in a controlled environment and geological injection has established monitoring standards.[3]
Pathway to full costs <$100/t$CO_2$		**High risk:** Technology is modular across certain components with cost estimates >$500/t$CO_2$.	Rating is based on the cost estimates for FOAK plants and the data quality used for these estimates. Different cut-offs for modular / non-modular technologies were applied, as modular approaches are comparatively cheaper and easier to scale. This technology meets our criteria for "high risk" (FOAK: >10 ktCO_2; >$500/t$CO_2$ plus available plant data).[1,3,6,7,8]

Notes and sources: [1]Methods and criteria used to assign DAC ratings are found in the AIR Appendix. [2]Mission Zero Technologies: Phase 1 Final Report. [2]A Roadmap for Achieving Scalable, Safe and Low-cost Direct Air Carbon Capture and Storage (Küng et al., 2023) [4]There is a risk of CO_2 leakage if DAC and storage are not co-located. [5]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [6]The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy (Young et al., 2022) [7]Reviewers note that this risk is likely to improve as plant data becomes available. [8]The price of available electricity will have a significant impact on the cost estimate.

Potential for cost improvement

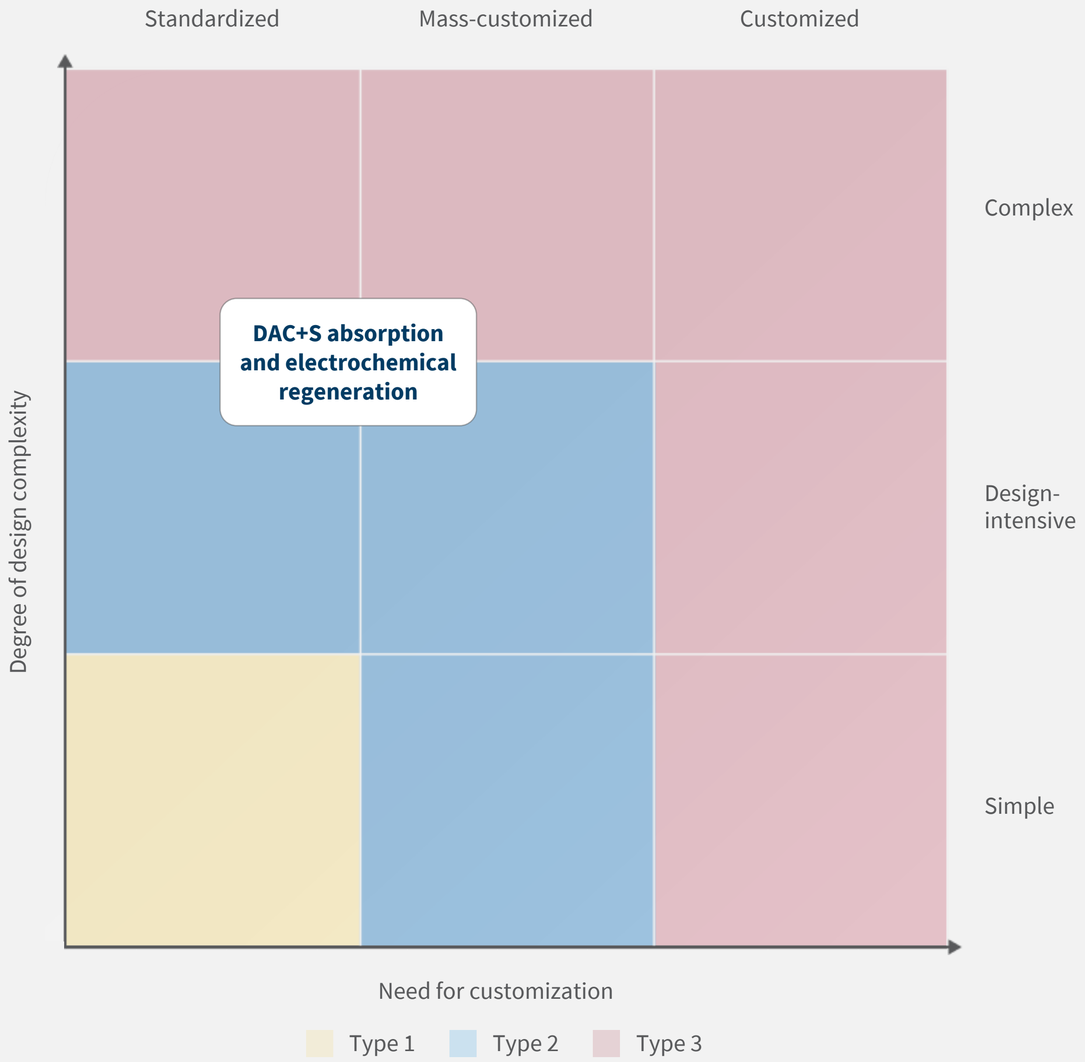
An assessment of two key drivers of learning rates

SECTION 7.3

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and electrochemical regeneration



OVERALL RATING

Type 2-3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 **Medium**

Type 3 **Low**

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design intensive - complex
- **Rationale:** Liquid-based DAC systems are complex as they require multiple independent steps of chemical processing. However, electrochemical cells have less complex designs.[2]

NEED FOR CUSTOMIZATION

- **Rating:** Mass-customized - standardized
- **Rationale:** Most components are modular for liquid-based systems. However, material customization is still needed based on plant location and climate conditions, primarily dealing with high evaporation rates.[2]

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]Overall sCDR assessment on cost improvement is based on Roberts and Nemet, "Lessons for Direct Air Capture from the History of Nitrogen Synthesis: High rates of deployment are possible, with strong support", (Roberts and Nemet, Pre-print 2023).

Current state of RD&D

A mapping of companies, plus other notable activities

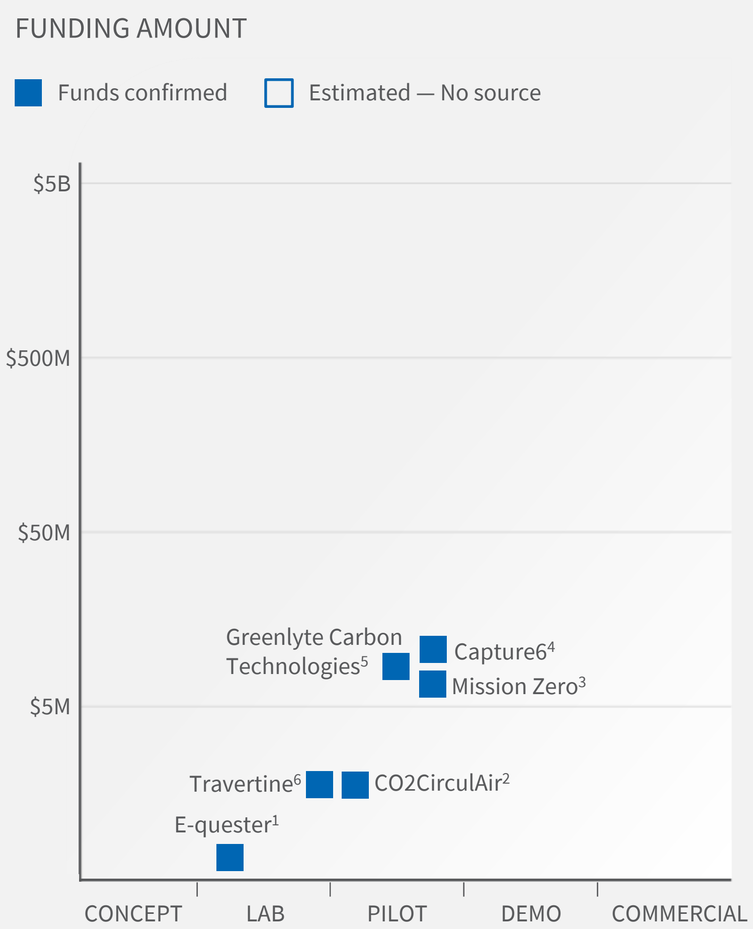
NOT EXHAUSTIVE

SECTION 7.3

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and electrochemical regeneration



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
E-quester: Electrochemical regeneration system fully powered by clean energy[1]	$250k[7]	• Team of students conducting lab work at the University of Toronto • XPRIZE Carbon Removal Top 60[8] • XPRIZE student award winner[7]
CO2CirculAir: Modular units using passive airflow[2]	£3M[9]	• 2022 — Began a small pilot project (<100 tCO_2/y)[10]
Mission Zero Technologies: Continuous process using ion-selective electrochemical separation[3]	$9.2M[11]	• 2022 — Established plans for two pilot projects: a small project DRIVE in the UK (100 tCO_2/y)[12] and Project Hajar in partnership with 44.01 in Oman (1 $ktCO_2/y$)[13]
Capture6: Electrochemical processes to split sodium hydroxide from salt water during water treatment[4,26]	$6.3M[14] in funding plus $8M from California Energy Commission[15]	• Project Monarch[16] was announced in July 2023 to provide water treatment[17] and carbon dioxide removal to the Palmdale water district.
Greenlyte Carbon Technologies: Developing low temperature, energy efficient DAC[5]	€8M[18]	• Pilot plant construction underway in 2023 • Plans to construct demonstration plant in 2024/2025 • Plans to commission kiloton-scale FOAK plant in 2026/2027
Travertine: DAC that utilizes ex-situ mineralization reactors as their storage step[6,26]	$3M (seed)[19]	• Pilot demonstration at mine site by end of 2023[20]
Other companies and activities: Carbon Blade,[21] Carbon Utility,[22] Carbon Atlantis,[23,26] Yuanchu Tech,[24] EDAC Labs[25,26]		

Notes and sources: [1]E-quester website [2]CO2CirculAir website [3]Mission Zero Technologies (MZT) website [4]Capture6 website [5]Greenlyte Carbon Technologies website [6]Travertine website [7]XPRIZE student winners [8]XPRIZE top 60 [9]Little public information is available except one UK government grant award of £3M. [10]UK's GGR innovation program public 2022 report [11]CrunchBase reports five rounds of mixed funding government grants, and seed funding. [12]MZT pilot Project DRIVE [13]MZT pilot project Hajar [14]CrunchBase funding estimate for Capture6 [15]Announcement of the Capture 6 Commercialization Industrial Decarbonization (CID) Program grant for $8M for a fully integrated water management and carbon dioxide removal plant [16]Project Monarch [17]Capture6 is using saltwater at a water treatment plant. [18]Funding raised by Greenlyte Carbon Technologies, (Tech EU) [19]Crunchbase estimate for Travertine [20]Canary Media [21]Carbon-Blade website [22]Carbon Utility [23]Carbon Atlantis is currently in pre-seed funding. [24]Yuanchu Tech was a top 60 XPRIZE finalist. [25]EDAC Labs entered Third Derivative's accelerator program, cohort 23-3, funding estimate [26]These companies do not use electrochemistry for CO_2 release, but for acid and base production. The produced materials can be used in a DAC unit for absorption-based CO_2 capture and potentially for critical minerals mining and ocean alkalinity enhancement.

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

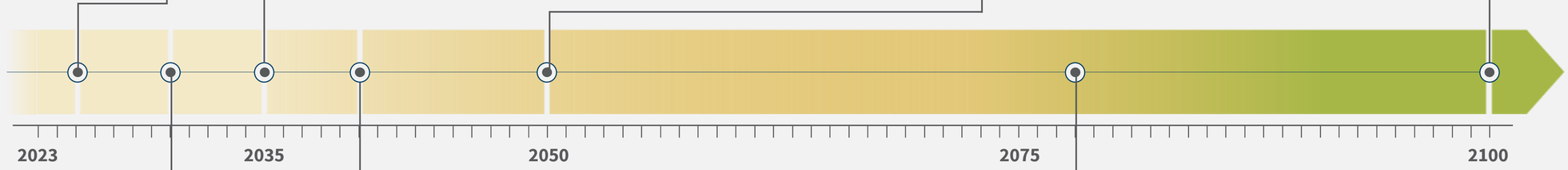
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 7.3

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and electrochemical regeneration



2025

- Significant funding is allocated for R&D projects to advance materials, process design, equipment, and systems integration of this approach.
- A global database of R&D gaps is created. This database directs researchers and funders to the most critical open questions / R&D projects that need to be addressed.[1]
- 2-4 pilot plants with alternative process designs to Mission Zero's are planned or under construction (e.g., alternative contactor designs, solvent, or regeneration methods).

2030

- R&D breakthroughs in materials, process design, equipment, and systems integration lead to significant cost declines for this approach.
- Plant data from 2-4 demonstrations and the state of other DAC approaches indicate the potential of this approach and inform future funding decisions.

- Total global capture[2] for all DAC operations reaches 60 $MtCO_2/y$. This approach is not yet mature enough to contribute significantly to that total.

2035

- Early R&D, pilot, and demonstration data from this approach is used to inform future funding decisions. This approach is either being scaled widely or giving way to other, more competitive DAC approaches.

- Total global capture[2] for all DAC operations reaches 180 $MtCO_2/y$.

2040

- Total global capture[2] for all DAC operations reaches 560 $MtCO_2/y$.
- DAC facilities are synergistically sited alongside other industrial facilities as part of the energy transition.
- DAC facilities increasingly take advantage of new low-carbon generation, including non-peak electricity loads.
- A "fail fast" methodology applied across the DAC space has led to consolidated funding directed toward the best approaches. Unpromising approaches are no longer funded.

2050

- Total capture[2] from all forms of DAC reaches 1 $GtCO_2/y$.
- Breakthroughs in DAC R&D continue to drive down the cost of removals.
- Due to decades of competition, the most energy efficient and cost-optimized approaches to DAC have emerged as market leaders.
- DAC clusters have emerged in industrial corridors, some of which remove 10-100 $MtCO_2/y$.

2050-2100

- There is continued rapid scaling of DAC plants in accordance with climate objectives.
- Breakthroughs in DAC design and deployment lead to new facilities being built in widely distributed locations all around the world.

These story elements are common to all DAC approaches.

2100

- Capture from all forms of DAC reaches 10 $GtCO_2/y$.[2]
- DAC facilities are operational globally.
- The cost of DAC is less than $\$100/tCO_2$ (adjusted to 2023 dollars).

Notes and sources: [1]A similar database has already been initiated by Frontier. [2]We have assessed all DAC approaches in the AIR under a single growth paradigm. Our growth paradigm therefore is representative of the DAC field, not a specific DAC approach. We assumed a starting deployment of 60 $MtCO_2/y$ in 2030, which is the amount of DAC in the IEA Net Zero scenario in 2030, based on 130 proposed plants the IEA is tracking. We then assume that this 60 $MtCO_2/y$ grows at 25% per year from 2030 to 2040 and then 6% per year from 2040 to 2050. This growth paradigm includes 3 phases: (1) an initial period of rapid growth to 2030 where many new standalone facilities are built, (2) a secondary period of growth from 2030-2040 characterized by supply chain management, workforce development, and other scaling challenges, and (3) a sustained period of long-term growth characterized by more complex supply chains and large-scale systems. This multi-phase growth methodology is used in other AIR success stories and has also been recently modeled in academic papers, such as Roberts and Nemet, Pre-print 2023.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 7.3

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Absorption and electrochemical regeneration

TRL

CRITICAL PATH ACTIVITIES

$1-3 billion | **13-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Lab – materials R&D:** Synthesize new solvent blends and membrane materials
- **Lab and pilot – process & equipment:** Optimize contactor and electrochemical cell design and operation; test optimal configurations
- **Lab and pilot – system integration:** Conduct independent TEA, LCA, climate sensitivity, and supply chain studies

$120-200 million | **5-10 years**

- ✓ Pathway to significant CAPEX and OPEX cost reductions via optimal equipment and process operation
- ✓ Reduced electricity requirements with potential to reach theoretical maximum efficiency
- ✓ Demonstrated ability to scale: e.g., CO_2 purity >85%[3]

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Demonstration – DAC+S:** Fund / support either novel configurations (that no company is currently pursuing) OR collaborate with entities already pursuing opportunities to scale
- **MRV:** Measurement and verification should be performed by an independent entity

$1-3 billion | **8-10 years**

- ✓ Cost requirements: \$100-500/tCO_2[4]
- ✓ Energy requirements: <7.5 GJ/tCO_2[5]
- ✓ Reduced water requirements
- ✓ Minimum operating current density: 50-100 mA/cm^2

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$40-60 million | **5-10 years**

- Create a DAC R&D gap database to direct researchers and funders to the most critical open questions / R&D projects.
- Perform planning studies for industrial clusters to facilitate use of potentially available resources and existing CCS infrastructure.
- Investigate the use of CO_2 for valuable products such as chemicals and fuels.
- Assess water risks to enable better siting decisions.
- Establish industry standards with open-access designs for major equipment

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Verified carbon storage by a third-party accounting organization
- Low-carbon / green energy sourcing and low energy requirements
- Industry and consumer acceptance
- Long-term safety record with net carbon removal and durable storage
- Financing costs in line with commercially accepted technologies

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development. [3]Below this threshold, density changes, mostly due to the presence of non-condensable impurities (e.g., N_2, O_2, Ar) that cannot be liquified at ambient temperature, can affect storage capacity, injectivity, and buoyancy. More information found here. [4]Based on the assumptions in the "Pathway to full costs <\$100/tCO_2" presented in the AIR Appendix. [5]DAC energy requirements of 7.5 GJ/tCO_2 require the equivalent of about 2.5 months of energy consumption for the average American household, and removing a gigaton of CO_2 would require about half the total energy consumed by the US in 2022.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK[1]	WORKSTREAM[2]	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Lab	R&D: Materials	Identify and test new solvent blends that maximize kinetics and CO_2 solubility, and optimize for low degradation, volatility, and regeneration energy	✓ Identify at least 3-5 high performing solvents for testing at pilot scale ✓ Validate expected material lifetime	2-4	$0.5-2M/y	2-4 y	$10-20M
Lab	R&D: Materials	Improve specific membrane and electrocatalysts characteristics, such as lower resistance and increased selectivity Conduct long term studies on the degradation of critical materials (especially in the presence of oxygen)	✓ Identify at least 3-5 high performing membranes and electrocatalysts for testing at pilot scale ✓ Validate expected material lifetime	2-4	$0.5-2M/y	2-4 y	$10-20M
Lab / pilot	R&D: Process design	Simulate and conduct synergistic material and process optimization for each configuration Study alternatives to electrodialysis for regeneration methods (e.g., electrolysis, capacitive deionization, reversible proton coupled electron transfer) and experimentally validate performance Demonstrate operation at industrially relevant current densities (>100 mA/cm^2)	✓ Identify and validate performance of 2-3 configurations that reduce energy and cost	2-4	$1-3M/y	2-4 y	$20-30M
Lab / pilot	R&D: Equipment	Simulate and test alternative contactor designs, including shallow contactor designs, cross flow contactors, etc.	✓ Prototype at least 2-3 alternative contactor designs that enable modularity	2-4 (lab)	$1-3M/y	2-4 y	$20-30M
		Develop high pressure electrochemical cells to reduce resistance in the electrolyte[3] and advance stack engineering Comparative studies for process and equipment design	✓ Develop optimized electrochemical cells (including the use of multiple cells in series)	2-4 (pilot)	$5-10M/y	5-10 y	$50-100M
Lab / pilot	R&D: System level studies	Conduct independent TEA, LCA, local / regional climate sensitivity studies, and supply chain analysis on the full DAC system, including material synthesis, transportation and disposal	✓ Independent estimates show costs and environmental impact are manageable	3-5	$0.5-2M/y	2-4 y	$10-20M

Notes and sources: [1]Several companies are actively pursuing pilot to demonstration scale projects and, therefore, this approach is currently at TRL 6. Components of the technology are very mature and used in other industrial process, so the focus of the pre-demonstration workstream is to adopt and optimize materials, equipment, and process for DAC purposes. [2]List of recommended workstreams and budgets is adopted from Küng et al. (2023). [3]Reviewers have pointed out that developing a high-pressure electrochemical cell may or may not be necessary, depending on the nature of gas evolution in the process. If the approach does not evolve gases within the cell, then high pressure is not necessary and will add an unnecessary energetic cost.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	DAC+S: Fund 2-4 demonstration projects of the most promising optimized configurations for energy and cost reduction using alternative materials, operational strategies, and optimized equipment[1]	46 $ktCO_2/y$ [2,3]	✓ Demonstrate CAPEX and OPEX cost improvements[2] towards an all-in cost <$100/$tCO_2$ ✓ Demonstrate energy requirements reduced to <7.5 GJ/tCO_2, with potential for further reduction (<2.5 GJ/tCO_2 for market acceptance) ✓ Demonstrate negligible water evaporation rates, i.e., minimal water consumption per tCO_2 ✓ Demonstrate minimum operating current density of 50-100 mA/cm^2	2-4	$50-100M/y	8-10 y	$1,000-3,000M
MRV	Measurement, reporting, and verification protocols are established and validated by an independent third party.	N/A	✓ Verification of CO_2 storage and full lifecycle removals for DAC+S	1-3	$2-5M/y	5-10 y	$20-50M

Notes and sources: [1]Given the high likelihood of candidate demonstration projects overlapping with an existing startup approach, demonstration project collaboration should be investigated. This can reduce the overall price tag per demonstration project, especially with regard to public funding, and generally accelerate the pathway for unique DAC+S demonstration projects. A key of objective of these collaborations should be data transparency incentivized by public funding. [2]The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy. Young et al. (2022) describes potential economies of scale due to major equipment, such as the calciner and slaker. [3]Companies currently working on this approach noted that a scale of 10-100 $ktCO_2/y$ can be achieved, which will reduce the total cost for demonstration plants.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

☐ Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research	DAC R&D gap database[3]	Create a global database of R&D gaps to accelerate DAC deployment by directing researchers and funders to the most critical open questions / R&D projects that need to be addressed.	1	$0.2-0.5M/y	3-5 y	$1-5M
Desktop research	Industrial cluster planning[4]	The most cost-effective DAC typically benefits from co-location with industrial clusters using CCS so that it can integrate with existing storage reservoirs. This workstream should seek to identify clusters with access to competitive low-carbon and low-cost electricity contracts / sources, which should significantly improve costs and LCA.	1-3	$0.5-2M/y[5]	5-10 y	$10-20M
Desktop research	Establish industry standards	Build industry commitments to open-access designs of major process equipment. Shared designs and coordinated improvements could lower the cost of DAC.	1-3	$0.5-2M/y	5-10 y	$10-20M
Lab	DAC and utilization (DAC+U), including H_2 production[4]	Explore the possibility of using CO_2 products as feedstock to produce other chemicals and fuels. H_2 production is also possible. CO_2 utilization and H_2 production have the potential to de-risk and accelerate DAC deployment at scale by selling CO_2-based products, creating a new demand for CO_2 and H_2, thus reducing the cost of DAC.	2-4	$0.5-2M/y	5-10 y	$20-30M
Desktop research	Water risk assessments	Perform desktop research to generate risk assessments of water sourcing and usage to enable better siting decisions.	1-3	$0.5-2M/y	3-5 y	$5-10M

Notes and sources: [1]A reviewer suggested a workstream to establish test centers and advanced manufacturing facilities that could help accelerate the development and testing of new materials. [2]Cost estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]A similar database has already been initiated by Frontier. [4]Project planning and management are path-boosting activities for pre-demonstration and demonstration projects. [5]A reviewer notes that subsidies my be necessary to incentivize co-location for industrial clusters, which could significantly increase this cost.

SECTION 7.4

Adsorption and high-grade heat regeneration

SECTION	7.4
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Adsorption and high-grade heat regeneration

DEFINITION

CO_2 adsorption onto a solid mineral sorbent (where CO_2 is captured on the surface of a solid material) followed by a desorption process in which high-grade heat (600-1200 °C) is used to separate CO_2 from the mineral

EXAMPLE SCENARIO

Crushed calcium oxides chemically bind with CO_2 in air to form limestone, which is then processed at high temperatures to release concentrated CO_2 for storage and regenerate the calcium oxides.

Section 7.4 overview

Adsorption and high-grade heat regeneration

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/tCO$_2$** • Key risks include the energy requirements of sorbent regeneration and environmental impacts are yet to be characterized
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is mass-customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab to pilot scale** • ~3 companies at lab and pilot stage with <$60M in funding each
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment across all DAC approaches: **1 GtCO$_2$ by 2050** • Success is contingent on breakthroughs in materials, process design, and equipment, as well as siting synergies and increased cost effectiveness as compared to other DAC approaches
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$2-3B over 13-20 years** • Key stage gates in cost reductions by equipment and process optimization

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**High risk:** Sorbent regeneration by calcination is extremely energy intensive, but heat recovery is possible.	Energy needs meet our criteria for “very high risk” (>5 GJ/tCO_2 and needs high-grade heat).[1] However, since the capture and sorbent regeneration alone require approximately 6-9 GJ/tCO_2 and there is the possibility of heat recovery in the calcination and hydration steps, we assigned this a lowered risk rating of "high risk." The full DAC+S pathway will require additional energy (e.g., compression, transport, and storage).[2]
	Land requirements	**Low risk:** Significant land areas are suitable for DAC siting.	This approach has a higher footprint per capture capacity than other DAC approaches, as some solutions require large land areas, (~6000 $km^2/GtCO_2/y$ to expose and weather minerals), but optimal designs, such as the use of vertically-stacked trays, can reduce those requirements. The footprint is larger if land use for energy production is considered.[2,3]
	Water requirements	**Medium risk:** Large volumes of water are needed to enable mineralization.	This DAC technology requires large amounts of water (2.5-5 t of H_2O per t CaO) as humidity is needed for the process to work. However, the water used can be recycled. The amount of water may vary depending on mineral used ($CaCO_3$ or $MgCO_3$). High water requirements restrict deployment to locations with low water stress indices.[2]
	Material requirements	**Low risk:** No rare materials are required.	Beyond basic construction materials (e.g., steel, cement), this technology relies on abundant minerals that can be reused ($CaCO_3$ or $MgCO_3$).[2]
	Co-location of DAC and storage	**Low risk:** Co-location of DAC and storage is relatively easy for this technology.	The DAC unit shouldn’t be situated in dry and hot environments due to high water requirements. However, there is sufficient geological storage in water-rich areas so co-location should not be a problem.[2,4]
	Environmental impacts	**High risk:** No / incomplete LCA data available.	No LCA exists for this technology. However, apart from impacts associated with energy, water and material requirements, minimal to no other impacts are anticipated.[2]
Secure storage for 100+ years		**Low risk:** Storage is durable.	Geological sequestration or in-situ mineralization (primary storage options) are considered permanent storage approaches.[3]
Path to measurement at scale		**Low risk:** Measurement to inform MRV is straightforward.	DAC+S measurement and monitoring is straightforward. Capture occurs in a controlled environment and geological injection has established monitoring standards.[2]
Pathway to full costs <$100/$tCO_2$		**Medium risk:** Technology can be modular across certain components with cost estimates in the $100-500 range.	We base our rating on cost estimates for FOAK plants and the quality of these estimates. We apply different cut-offs for modular / non-modular technologies as modular approaches are comparatively less expensive and easier to scale. This technology meets our criteria for “medium” risk (FOAK >10 $ktCO_2$; $100-500 plus available plant data).[1,2,5]

Notes and sources: [1]Methods and criteria used to assign DAC ratings are found in the AIR Appendix. [2]A Roadmap for Achieving Scalable, Safe and Low-cost Direct Air Carbon Capture and Storage (Küng et al., 2023) [3]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [4]There is a risk of CO_2 leakage if DAC and storage are not co-located. [5]The price of available electricity will have a significant impact on the cost estimate.

Potential for cost improvement

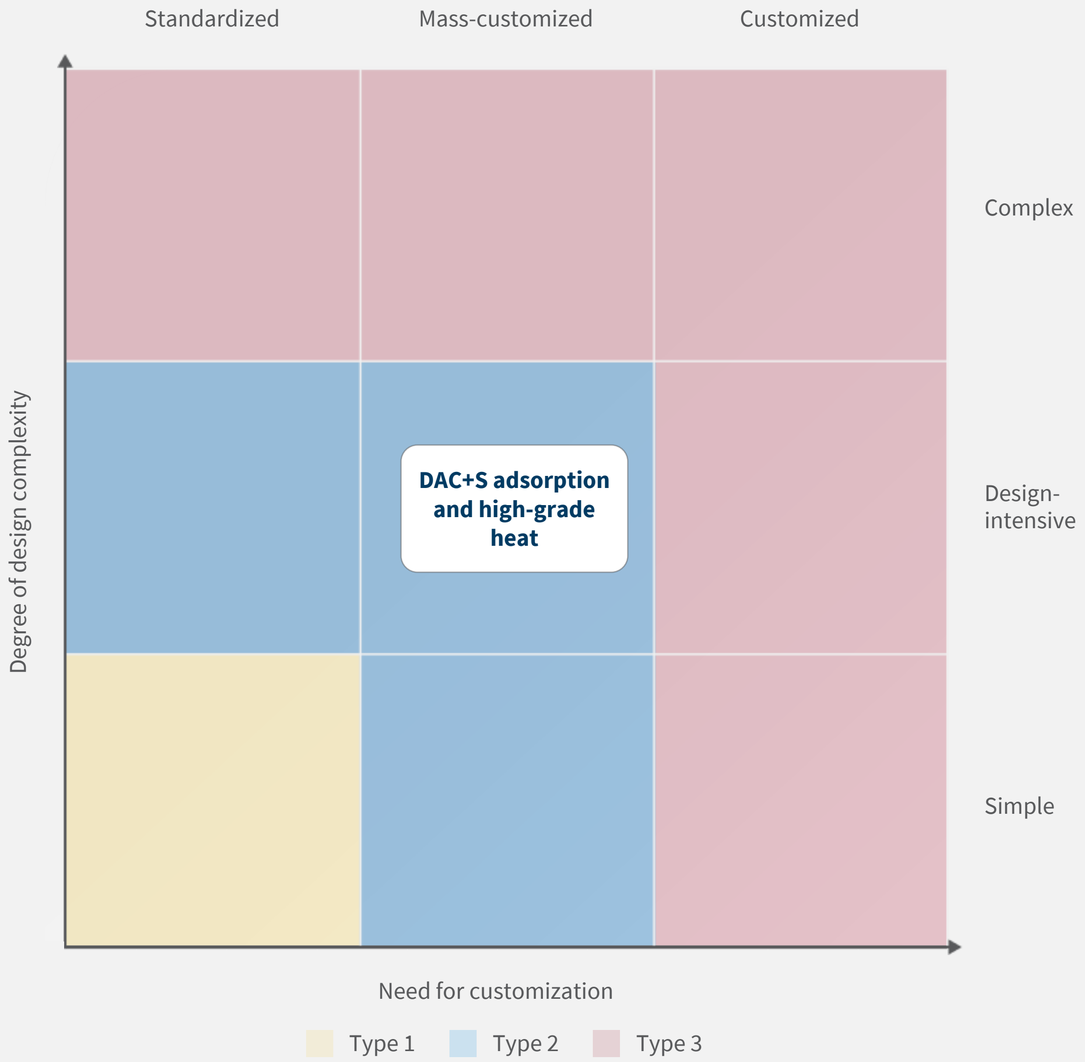
An assessment of two key drivers of learning rates

SECTION 7.4

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and high-grade heat regeneration



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive
- **Rationale:** Several physical moving pieces contribute to the design intensity. However, there is less complexity as compared to absorption with high-grade heat approaches since liquid pumping is not necessary.

NEED FOR CUSTOMIZATION

- **Rating:** Mass-customized
- **Rationale:** There is some standardization of necessary components, but there is also a need for equipment customization based on the DAC plant site and mineral sourcing.[2]

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]Overall sCDR assessment on cost improvement is based on Roberts and Nemet, "Lessons for Direct Air Capture from the History of Nitrogen Synthesis: High rates of deployment are possible, with strong support", (Roberts and Nemet, Pre-print 2023).

Current state of RD&D

A mapping of companies, plus other notable activities

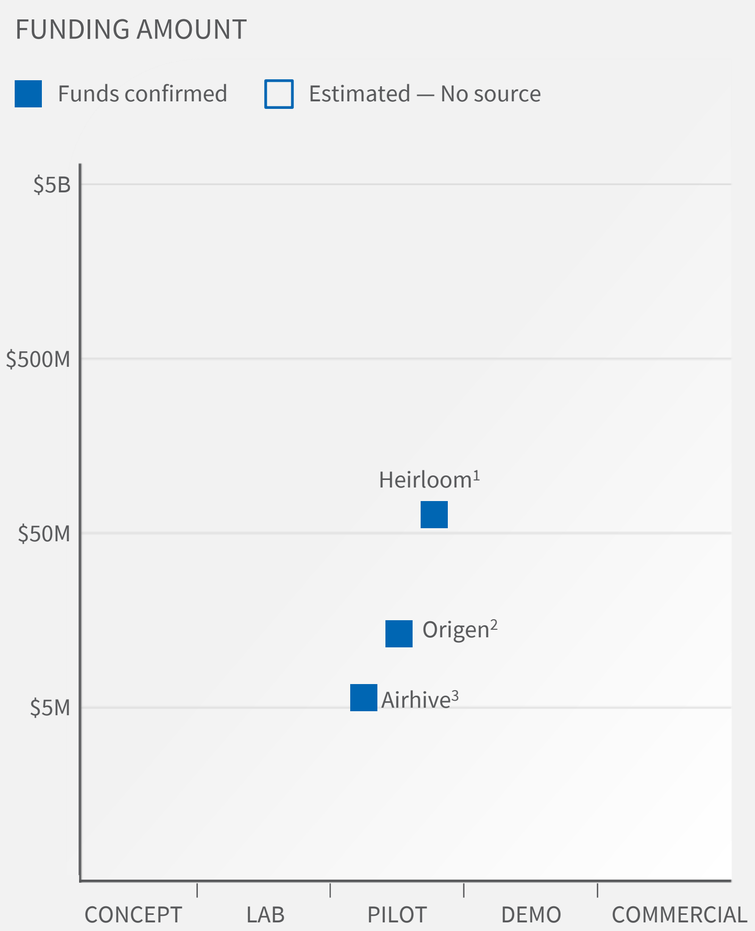
NOT EXHAUSTIVE

SECTION 7.4

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and high-grade heat regeneration



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Heirloom: Modular circulated and electrified system[1]	$54.3M[4]	• 2022 — Completed pilot proof of concept and prototype system funded by ARPA-E[5] • 2023 — First pilot of CO_2 stored in limestone, with a capacity of 1 $ktCO_2/y$[6]
Origen: Large scale process; oxy-fueled combustion and flash calcination[2]	$20M[7]	• January 2023 — Completed construction of first pilot facility in the UK
Airhive: Building geochemical-DAC tech[3]	$6M[8]	• Currently building a 50 tCO_2-scale project
Other companies and activities: 8 Rivers Capital – Calcite[9]		

Notes and sources: [1]Heirloom [2]Origen [3]Airhive [4]Crunchbase reports 5 rounds of pre-seed, seed, private grant, government grant, and Series A fundraising [5]ARPA-E pilot completed [6]Heirloom announced their successful pilot in collaboration with CarbonCure. [7]Origen's funding is a mix of equity and grant funds (~$20M). They also have pre-purchase agreements with Frontier. [8]Per reviewer comments, Airhive has raised $6M in equity and grants. [9]8 Rivers Capital, 8 Rivers capital holds and support a portfolio of technology solutions. They invested in Calcite's early phases of technology innovation at the lab phase and now license it to other partners to scale it.

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

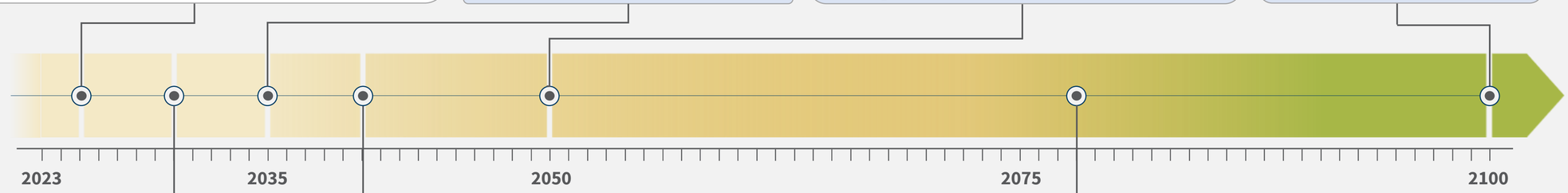
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 7.4

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and high-grade heat regeneration



2025

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- 2-4 pilot plants with alternative process designs from Heirloom (e.g., alternative contactor designs, mineral choice or regeneration methods) are under construction.

2030

- R&D breakthroughs in materials, process design, equipment, and systems integration lead to significant cost declines for this approach.
- Plant data from 3-5 demonstrations, including Heirloom's 2022 pilot and upcoming demonstration plant(s), indicate the potential of this DAC approach and are used to inform future funding decisions.

- Total global capture[2] for all DAC operations reaches 60 $MtCO_2$/y. This approach contributes significantly to that total.

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- Early R&D, pilot, and demonstration data from this approach is used to inform future funding decisions. This approach is either being scaled widely or giving way to other, more competitive DAC approaches.

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- DAC facilities increasingly take advantage of new low-carbon generation, including non-peak electricity loads.
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- Total capture[2] from all forms of DAC reaches 1 $GtCO_2$/y.
- Breakthroughs in DAC R&D continue to drive down the cost of removals.
- Due to decades of competition, the most energy efficient and cost-optimized approaches to DAC have emerged as market leaders.
- DAC clusters have emerged in industrial corridors, some of which remove 10-100 $MtCO_2$/y.

2050-2100

- Continued rapid scaling of DAC plants in accordance with climate objectives.
- Breakthroughs in DAC design and deployment lead to new facilities being built in widely distributed locations all around the world.

These story elements are common to all DAC approaches.

2100

- Capture from all forms of DAC reaches 10 $GtCO_2$/y.[2]
- DAC facilities are operational globally.
- The cost of DAC is less than \$100/tCO_2 (adjusted to 2023 dollars).

Notes and sources: [1]A similar database has already been initiated by Frontier. [2]We have assessed all DAC approaches in the AIR under a single growth paradigm. Our growth paradigm therefore is representative of the DAC field, not a specific DAC approach. We assumed a starting deployment of 60 $MtCO_2$/y in 2030, which is the amount of DAC in the IEA Net Zero scenario in 2030, based on 130 proposed plants the IEA is tracking. We then assume that this 60 $MtCO_2$/y grows at 25% per year from 2030 to 2040 and then 6% per year from 2040 to 2050. This growth paradigm includes 3 phases: (1) an initial period of rapid growth to 2030 where many new standalone facilities are built, (2) a secondary period of growth from 2030-2040 characterized by supply chain management, workforce development, and other scaling challenges, and (3) a sustained period of long-term growth characterized by more complex supply chains and large-scale systems. This multi-phase growth methodology is used in other AIR success stories and has also been recently modeled in academic papers, such as Roberts and Nemet, Pre-print 2023.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 7.4

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and high-grade heat regeneration

TRL

CRITICAL PATH ACTIVITIES

$2-3 billion | **13-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Lab – materials R&D:** Optimize adsorption minerals
- **Lab and pilot – process & equipment:** Optimize performance of the contactor and calciner units; test optimal configuration and regeneration strategies
- **Lab and pilot – system integration:** Conduct independent TEA, LCA, climate sensitivity, and supply chain studies

$100-200 million | **5-10 years**

✓ Pathway to significant CAPEX and OPEX cost reductions via optimal equipment and process operation

✓ Reduced electricity and heat requirements with potential to reach theoretical maximum efficiency

✓ Demonstrated ability to scale: e.g., CO_2 purity >85%[3]

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Demonstration – DAC+S:** Fund / support either novel configurations (that no company is currently pursuing) OR collaborate with entities already pursuing opportunities to scale
- **MRV:** Measurement and verification should be performed by an independent entity

$2-3 billion | **8-10 years**

✓ Cost requirements: $100-500/tCO$_2$[4]

✓ Energy requirements: <7.5 GJ/tCO$_2$[5]

✓ Reduced water requirements

✓ Reduced land requirements

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$40-60 million | **5-10 years**

- Create a DAC R&D gap database to direct researchers and funders to the most critical open questions / R&D projects.
- Perform planning studies for industrial clusters to facilitate use of potentially available resources and existing CCS infrastructure.
- Investigate the use of CO_2 for valuable products such as chemicals and fuels.
- Assess water risks to enable better siting decisions.
- Establish industry standards with open-access designs for major equipment

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Verified carbon storage by a third-party accounting organization
- Low-carbon / green energy sourcing and low energy requirements
- Industry and consumer acceptance
- Long-term safety record with net carbon removal and durable storage
- Financing costs in line with commercially accepted technologies

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development. [3]Below this threshold, density changes, mostly due to the presence of non-condensable impurities (e.g., N_2, O_2, Ar) that cannot be liquified at ambient temperature, can affect storage capacity, injectivity, and buoyancy. More information found here. [4]Based on the assumptions in the "Pathway to full costs <$100/tCO$_2$" presented in the AIR Appendix. [5]DAC energy requirements of 7.5 GJ/tCO$_2$ require the equivalent of about 2.5 months of energy consumption for the average American household, and removing a gigaton of CO_2 would require about half the total energy consumed by the US in 2022.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK[1]	WORKSTREAM[2]	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Lab	R&D: Materials	Optimize adsorption minerals, including type and grain size, for maximum CO_2 uptake under a range of ambient weather conditions for diminished degradation, increased recyclability, and reduced heat demand for regeneration	✓ Identify ideal grain size for at least 2-3 different minerals ✓ Validate expected material lifetimes	2-4	$0.5-2M/y	2-4 y	$10-20M
		Conduct accelerated durability testing on degradation of critical materials					
Lab / pilot	R&D: Process design	Simulate and conduct synergistic material and process optimization, including heat recovery, for each configuration considering different climate conditions and CO_2 purity targets, depending on CO_2 destination	✓ Identify and validate performance of 2-3 configurations that reduce energy and cost	2-4	$1-3M/y	2-4 y	$20-30M
		Design regeneration methods as alternatives to oxy-fired kiln (e.g., electric kiln, syngas), study process intensification, and experimentally validate process performance					
Lab / pilot	R&D: Equipment	Optimize contactor design and geometry through simulation and testing for maximum CO_2 uptake per unit of land / feedstock across variable ambient conditions and mineral types	✓ Prototype at least 2-3 alternative contactor designs that enable modularity	2-4 (lab)	$1-3M/y	2-4 y	$20-30M
		Test alternative calcination options (e.g., oxy-fired, electric, syngas calciners)[1]	✓ Validate performance and path to scale for the most promising regeneration options	2-4 (pilot)	$5-10M/y	5-10 y	$50-100M
		Perform comparative studies for process design and primary equipment					
Lab / pilot	R&D: System level studies	Conduct independent TEA, LCA, local / regional climate sensitivity studies, and supply chain analysis on the full DAC system, including material synthesis, transportation, and disposal	✓ Independent estimates show costs and environmental impact are manageable	2-4	$0.5-2M/y	2-4 y	$10-20M

Notes and sources: [1]Heirloom, a leading company advancing this approach, uses an electric kiln for regeneration. The company's pilot proof of concept and prototype system was developed in 2022 and funded by ARPA-E. The company is actively pursuing a demonstration project and, therefore, its approach is currently at TRL 6. It is crucial that newly funded R&D projects focus on advancing unknown or alternative elements to this DAC approach. [2]List of recommended workstreams and budgets is adopted from Küng et al. (2023).

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	DAC+S: Fund 2-4 demonstration projects of the most promising optimized configurations for energy and cost reduction using alternative materials, operational strategies, and optimized equipment[1]	1 $MtCO_2/y$[2]	✓ Demonstrate CAPEX and OPEX cost improvements[2] towards an all-in cost <$100/$tCO_2$ ✓ Demonstrate energy requirements reduced to <5 GJ/tCO_2, with potential for further reduction ✓ Demonstrate minimal water consumption per tCO_2 ✓ Reduce land requirements to <3 $km^3/MtCO_2$	2-4	$100M/y	8-10 y	$2,000-3,000M
MRV	Measurement, reporting, and verification protocols are established and validated by an independent third party.	N/A	✓ Verification ofCO_2 storage and net lifecycle removals for DAC+S	1-3	$2-5M/y	5-10 y	$20-50M

Notes and sources: [1]Given the high likelihood of candidate demonstration projects overlapping with an existing startup approach, demonstration project collaboration should be investigated. This can reduce the overall price tag per demonstration project, especially with regard to public funding, and generally accelerate the pathway for unique DAC+S demonstration projects. A key of objective of these collaborations should be data transparency incentivized by public funding. [2]The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy. Young et al. (2022) describes potential economies of scale due to major equipment, such as the as calciner and slaker.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

☐ Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research	DAC R&D gap database[3]	Create a global database of R&D gaps to accelerate DAC deployment by directing researchers and funders to the most critical open questions / R&D projects that need to be addressed.	1	$0.2-0.5M/y	3-5 y	$1-5M
Desktop research	Industrial cluster planning[4]	The most cost-effective DAC typically benefits from co-location with industrial clusters using CCS so that it can integrate with existing storage reservoirs. This workstream should seek to identify clusters producing high-grade heat for co-location of DAC.	1-3	$0.5-2M/y[5]	5-10 y	$10-20M
Desktop research	Establishing industry standards	Building industry commitments to open-access designs of major process equipment. Shared designs and coordinated improvements could lower the cost of DAC.	1-3	$0.5-2M/y	5-10 y	$10-20M
Lab	DAC and utilization (DAC+U), including byproducts[4]	Explore the possibility of using CO_2 products as feedstock to produce other chemicals and fuels and producing net zero quicklime. CO_2 utilization and quicklime production have the potential to de-risk and accelerate DAC deployment at scale by selling CO_2-based products, creating a new demand for CO_2 and quicklime, thus reducing the cost of DAC.	2-4	$0.5-2M/y	5-10 y	$20-30M
Desktop research	Water risk assessments	Desktop research to generate risk assessments of water sourcing and usage to enable better siting decisions.	1-3	$0.5-2M/y	3-5 y	$5-10M

Notes and sources: [1]A reviewer suggested an additional workstream to establish test centers and advanced manufacturing facilities that could help accelerate the development and testing of new materials. [2]Cost estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]A similar database has already been initiated by Frontier. [4]Project planning and management are path-boosting activities for pre-demonstration and demonstration projects. [5]A reviewer notes that subsidies my be necessary to incentivize co-location for industrial clusters, which could significantly increase this cost.

SECTION 7.5

Adsorption and low-grade heat regeneration

SECTION	7.5
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Adsorption and low-grade heat regeneration

DEFINITION

CO_2 adsorption onto the surface of a solid sorbent material (where CO_2 is captured on the surface of a porous solid material), followed by a desorption process where mainly low-grade heat (<120 °C) is used to release the CO_2 from the sorbent

EXAMPLE SCENARIO

Fans pull air over solid particles with large surface area that is used to physically or chemically bind with CO_2 from air and release it in the presence of higher temperature and/or lower pressure.

Section 7.5 overview

Adsorption and low-grade heat regeneration

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/tCO$_2$** • Key risks include the energy requirements of sorbent regeneration and the high costs of modular technology
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Low** • This approach is standardized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab to commercial stage** • ~10 companies at lab to commercial stages with funding ranging from $1M to $1B
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment across all DAC approaches: **1 GtCO$_2$ by 2050** • Success is contingent on breakthroughs in materials, process design, and equipment, as well as siting synergies and increased cost effectiveness as compared to other DAC approaches
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$500M-$1B over 13-20 years** • Key stage gates in sorbent material R&D and process optimization

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk Medium risk High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**High risk:** Sorbent regeneration by low grade heat is very energy intensive.	The required energy meets the DAC criteria for "high risk" (>5 GJ/tCO_2).[1] The capture and sorbent regeneration alone require approximately 5-11 GJ/tCO_2. The full removal pathway will also require additional energy (e.g., compression, transport, and storage).[2]
	Land requirements	**Low risk:** Significant land areas are suitable for DAC siting.	These DAC plants have a small footprint (100 - 2000 km^2/GtCO_2/y) compared to other CDR solutions and can be deployed on most types of land. The footprint is larger if land use for energy production is considered.[2]
	Water requirements	**Low risk:** The volume of water needed for operation is insignificant.	Steam may be required for sorbent regeneration, but it is not expected to be a limiting consideration, especially since water may be recovered from ambient air.[2]
	Material requirements	**Low risk:** No rare materials are required.[4]	Beyond basic construction materials (e.g., steel, cement), this solution requires chemicals (e.g., functionalized amine adsorbents, zeolites, MOFs) that need to be synthesized and purchased but are not rare.[2,3]
	Co-location of DAC and storage	**Low risk:** Co-location of DAC and storage is relatively easy for this approach.	DAC performance might be affected by different climate conditions. However, these units can easily be deployed in favorable climates. Straightforward co-location with storage is also favorable given the high CO_2 purities from the DAC unit.[2,5]
	Environmental impacts	**Low risk:** No environmental impacts are anticipated beyond concerns from energy intensity.	Minimal to no environmental impacts are anticipated, apart from those associated with energy, water, and material requirements.[5,6]
Secure storage for 100+ years		**Low risk:** Storage is durable.	Geological sequestration or in-situ mineralization (the primary storage options) are considered permanent storage approaches.[3]
Path to measurement at scale		**Low risk:** Measurement to inform MRV is straightforward.	Measurement and monitoring for DAC+S is straightforward. Capture occurs in a controlled environment and geological injection has established monitoring standards.[2]
Pathway to full costs <$100/t$CO_2$		**High risk:** The technology is modular; cost estimates are greater than $600/t$CO_2$.	Ratings are based on cost estimates for FOAK plants and the quality of these estimates. Different cut-offs were applied for modular / non-modular technologies. For modular technologies, iteration is simpler and comparatively cheap. This technology meets the AIR criteria for "high" risk (FOAK <10 ktCO_2; >$600/t$CO_2$ plus plant data available).[1,2,3,7,8]

Notes and sources: [1]Methods and criteria used to assign DAC ratings are found in the AIR Appendix. [2]A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage (Küng et al., 2023) [3]Shedding Light on the Stakeholders' Perspectives for Carbon Capture (Charalambous et al., 2023) [4]Approaches with high requirements for rare materials are not expected to be successful at scale since the cost and environmental impacts of the system would be significant. [5]There is a risk of CO_2 leakage if DAC and storage are not co-located. [6]Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption (Deutz & Bardow, 2021) [7]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [8]The price of available electricity will have a significant impact on the cost estimate.

Potential for cost improvement

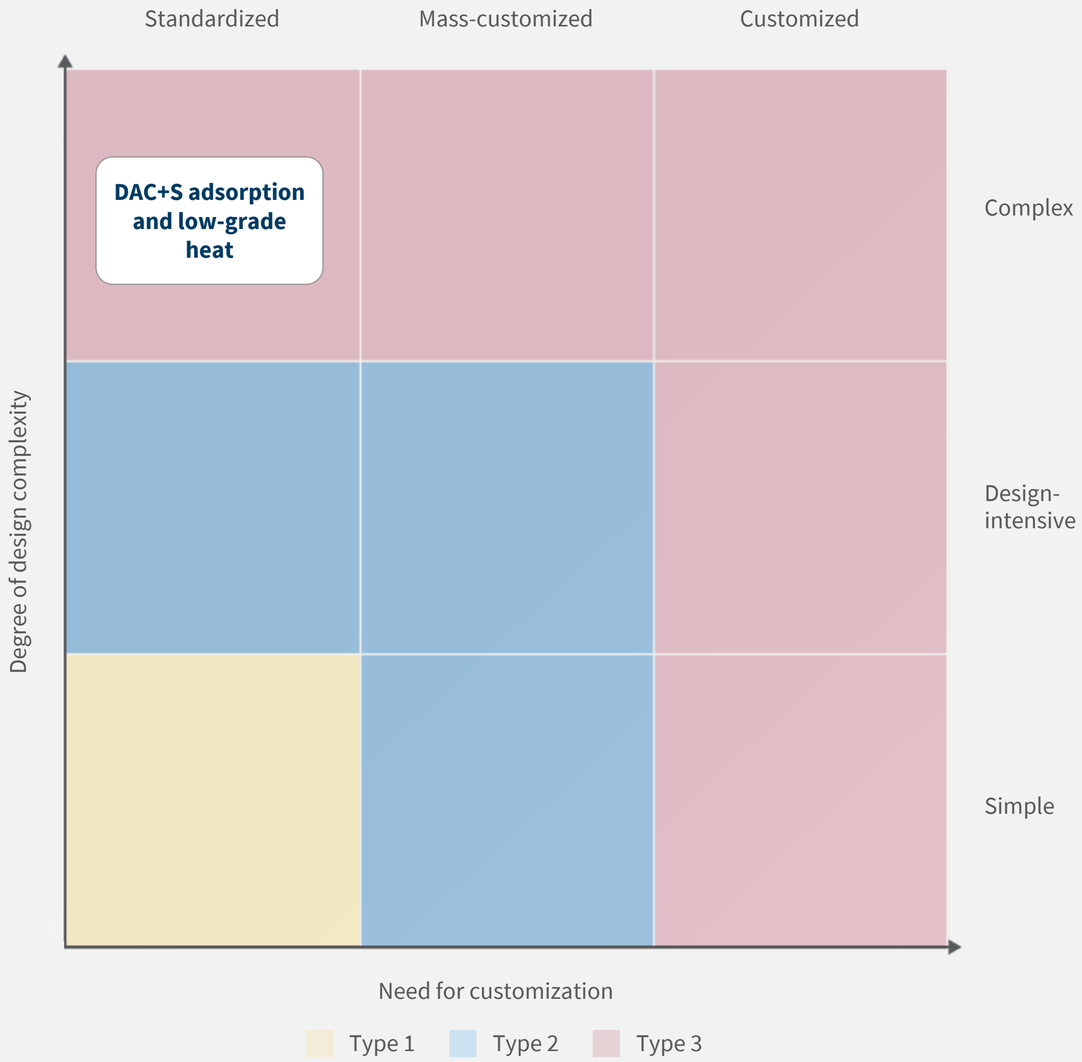
An assessment of two key drivers of learning rates

SECTION 7.5

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and low-grade heat regeneration



OVERALL RATING

Type 3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Complex
- **Rationale:** Design requirements for continuous operation of adsorption-desorption cycles are complex and require multiple steps of chemical processing.[2] Multiple parameters, such as heat recovery, must be addressed.

NEED FOR CUSTOMIZATION

- **Rating:** Standardized
- **Rationale:** Systems are modular, designed to take place in smaller, less centralized facilities than liquid-based systems. However, specific material considerations are needed based on plant location and climate conditions.[2]

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]Overall sCDR assessment on cost improvement is based on "Lessons for Direct Air Capture from the History of Nitrogen Synthesis: High rates of deployment are possible, with strong support" (Roberts & Nemet, Pre-print 2023).

THE APPLIED INNOVATION ROADMAP FOR CDR

Current state of RD&D

A mapping of companies, plus other notable activities

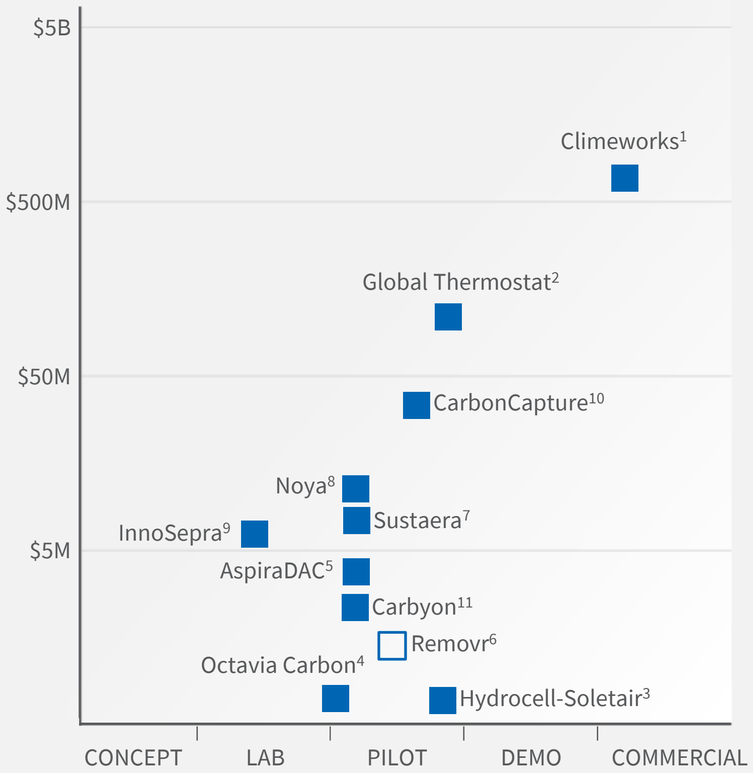
NOT EXHAUSTIVE

SECTION 7.5

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and low-grade heat regeneration



SUB APPROACHES	NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Amine	**Climeworks[1]**	$833M[1]	• 2021 – FOAK commercial plant (Orca)[1] • 2023 – Selected for Department of Energy DAC Hub[23]
	Global Thermostat[2]	>$70M[2]	• 2023 — Opened largest DAC plant in US, (kiloton-scale pilot plant)[20] • 2021 — MOU for projects with Exxon and Black & Vetch[21]
	Hydrocell-Soletair[3]	$1.6M[3]	• 2022 — FAOK commercial project[3]
	Octavia Carbon[4]	$0.5M[4]	• Pilot plant scheduled for completion in 2024[4]
MOF	**AspiraDAC[5]**	$4.7M[4]	• 2022 — Small pilot (310 tCO_2/y)
Zeolites	**Removr[6]**	N/A	• By 2022 — Completed 4 small pilots
Alkali Carbonate	**Sustaera[7]**	$11M[6]	• 2022 — Completed lab-scale pilot
Unknown	**Noya[8]**	$12.2M[7]	• 2022 — Changed approach from retrofitting cooling towers to standalone units[7]
	InnoSepra[9]	$6M[8]	• 2023 — Lab-scale project planned[22]
	CarbonCapture[10]	$47M[9]	• 2023 — Leading Project Bison DAC hub[9]

Other companies and activities: Carbyon,[11] TerraFixing,[12] Skytree,[13] Aircapture,[14] Emissol,[15] Airthena,[16] Spiritus,[17] ReCarbn,[18] There are also novel technologies within this approach that are not currently pursued by any company.[19]

Notes and sources: [1]Climeworks website, funding data from Crunchbase; CDR.fyi indicates the sale of 69k carbon credits by Climeworks, with estimated prices of $500-1000/$tCO_2$, which are not included in the total funding. [2]Global Thermostat website, limited information is available, but Bloomberg Green quoted at least $70M raised in 2021. [3]Hydrocell is a technology developer who licensed its DAC solution to Soletair Power; Crunchbase funding estimate for Soletair Power. [4]Octavia Carbon, Crunchbase funding estimate for Octavia Carbon, Why Kenya could take the lead in carbon removal (The Economist, 2023) [5]AspiraDAC (a subsidiary of Corporate Carbon) developed the technology behind the small solar PV encased units which are exclusively licensed it to Southern Green Gas for deployment. Technology development was funded by the Australian government. Other funding includes a CCUS grant, Corporate Carbon and Southern Green Gas funding, and a removal contract. [6]Removr is owned by Vanir Green Industries (60%) and GreenCap Solutions (40%), who developed the underlying DAC technology. [7]Sustaera spun out of Susteon, funded by DOE seed funding, Series A, and an XPRIZE milestone award. [8]Noya originally designed DAC retrofits to industrial cooling towers, but based on a recent post, they have updated their approach. According to CDR.fyi they sold 1472 credits at estimated price of $2300/$tCO_2$; funding information via Crunchbase [9]InnoSepra has specialized in CCS technology since 2007, and in recent years, has completed R&D projects funded by US government. [10]CarbonCapture is developing open architecture modular units (Project Bison) that can use any sorbent-based contactor. Funding information is via Crunchbase and DAC hub funding reporting. [11]Carbyon website, Crunchbase estimates $3M of funding. [12]TerraFixing website [13]Skytree website, Crunchbase estimates $6M in funding. [14]Aircapture and partners were awarded $2.9M from the DOE for a DAC hub. [15]Emissol received $1.65M from the DOE. [16]Airthena – CSIRO website [17]Spiritus raised $11M during a September 2023 seed round. [18]ReCarbn website [19]Adsorption artificial tree for atmospheric carbon dioxide capture, purification and compression (Santori et al., 2018) [20]Largest DAC plant in US [21]Limited media has covered project agreements but have not provided status updates (Exxon Mobile; Black & Vetch). [22]The project is a collaboration with National Carbon Capture Center in Wilsonville, Alabama. [23]Climeworks DOE Notification of Selection announcement

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

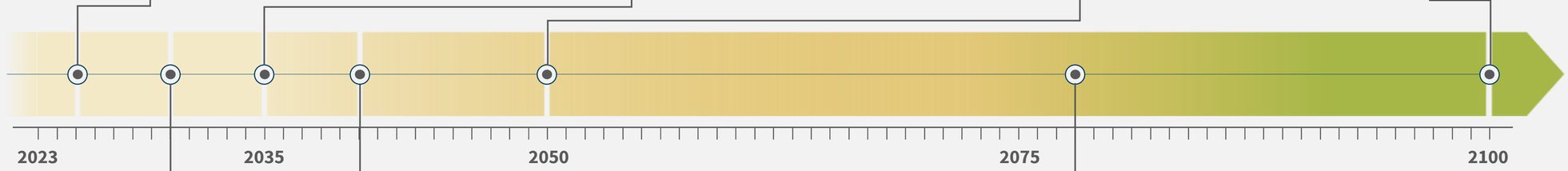
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 7.5

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and low-grade heat regeneration



2025

- Climeworks' Mammoth facility is operational at 36 $ktCO_2/y$.[1]
- 2-4 non-Climeworks demonstrations using this DAC approach are planned, funded, or underway.
- Significant funding is allocated for R&D projects to advance materials, process design, equipment, and systems integration for this approach.
- A global database of R&D gaps is created. This database directs researchers and funders to the most critical open questions and R&D projects that need to be addressed.[2]

2030

- R&D breakthroughs in materials, process design, equipment, and systems integration lead to significant cost improvements for this approach.
- Data from the Climeworks demonstration plant, other demonstrations, and the rest of the DAC space begin to inform future investment decisions in this DAC approach.

- Total global capture[3] for all DAC operations reaches 60 $MtCO_2/y$. This approach contributes significantly to that total.

2035

- Plant data from the Climeworks demonstration plant, other demonstrations, and the rest of the DAC space inform a decision on whether this approach should be pursued further or give way to other, more promising DAC approaches.
- If successful, this DAC approach is built into industrial clusters to take advantage of colocation with industrial heat and other siting synergies.

- Total global capture[3] for all DAC operations reaches 180 $MtCO_2/y$.

2040

- Total global capture[3] for all DAC operations reaches 560 $MtCO_2/y$.
- DAC facilities are synergistically sited alongside other industrial facilities as part of the energy transition.
- DAC facilities increasingly take advantage of new low-carbon energy generation, including non-peak electricity loads.
- A "fail fast" methodology applied across the DAC space has led to consolidated funding directed toward the best approaches. Unpromising approaches are no longer funded.

2050

- Total capture[3] from all forms of DAC reaches 1 $GtCO_2/y$.
- Breakthroughs in DAC R&D continue to drive down the cost of removals.
- Due to decades of competition, the most energy efficient and cost-optimized approaches to DAC have emerged as market leaders.
- DAC clusters have emerged in industrial corridors, some of which remove 10-100 $MtCO_2/y$.

These story elements are common to all DAC approaches.

2050-2100

- There is continued rapid scaling of DAC plants in accordance with climate objectives.
- Breakthroughs in DAC design and deployment lead to new facilities being built in widely distributed locations around the world.

2100

- Capture from all forms of DAC reaches 10 $GtCO_2/y$.[3]
- DAC facilities are operational globally.
- The cost of DAC is less than $\$100/tCO_2$ (adjusted to 2023 dollars).

Notes and sources: [1]Climeworks Mammoth facility is currently under construction. [2]A similar database has already been initiated by Frontier. [3]We have assessed all DAC approaches in the AIR under a single growth paradigm. Our growth paradigm therefore is representative of the DAC field, not a specific DAC approach. We assumed a starting deployment of 60 $MtCO_2/y$ in 2030, which is the amount of DAC in the IEA Net Zero scenario in 2030, based on 130 proposed plants the IEA is tracking. We then assume that this 60 $MtCO_2/y$ grows at 25% per year from 2030 to 2040 and then 6% per year from 2040 to 2050. This growth paradigm includes 3 phases: (1) an initial period of rapid growth to 2030 where many new standalone facilities are built, (2) a secondary period of growth from 2030-2040 characterized by supply chain management, workforce development, and addressing other scaling challenges, and (3) a sustained period of long-term growth characterized by more complex supply chains and large-scale systems. This multi-phase growth methodology is used in other AIR success stories and has also been recently modeled in academic papers, such as Roberts & Nemet (pre-print 2023).

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
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SECTION 7.5

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and low-grade heat regeneration

TRL

CRITICAL PATH ACTIVITIES

$500M-$1B **13-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Lab – materials R&D:** Identify, validate, and optimize performance of new sorbent materials
- **Lab and pilot – process & equipment:** Optimize performance of the contactor unit; test optimal process configurations and regeneration strategies
- **Lab and pilot – system integration:** Conduct independent TEA, LCA, climate sensitivity, and supply chain studies

$100-200 million **5-10 years**

✓ Pathway to significant CAPEX and OPEX cost reductions via optimal equipment and process operation

✓ Reduced electricity and heat requirements with potential to reach theoretical maximum efficiency

✓ Demonstrated ability to scale: e.g., CO_2 purity >85%[3]

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Demonstration – DAC+S:** Fund / support either novel configurations (that no company is currently pursuing) OR collaborate with entities already pursuing opportunities to scale
- **MRV:** Measurement and verification should be performed by an independent entity

$400-850 million **8-10 years**

✓ Cost requirements: $200-600/tCO$_2$[4]

✓ Energy requirements: <7.5 GJ/tCO$_2$[5]

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$30-50 million **5-10 years**

- Create a DAC R&D gap database to direct researchers and funders to the most critical open questions / R&D projects.
- Perform planning studies for industrial clusters to facilitate the use of potentially available resources and existing CCS infrastructure.
- Investigate the use of CO_2 for valuable products such as chemicals and fuels.
- Establish industry standards with open-access designs for major equipment.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Verified carbon storage by a third-party accounting organization
- Low-carbon / green energy sourcing and low energy requirements
- Industry and consumer acceptance
- Long-term safety record with net carbon removal and durable storage
- Financing costs in line with commercially accepted technologies

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development. [3]Below this threshold, density changes, mostly due to the presence of non-condensable impurities (e.g., N_2, O_2, Ar), which cannot be liquified at ambient temperature, can affect storage capacity, injectivity, and buoyancy. More information found here. [4]Based on the assumptions in the "Pathway to full costs <$100/tCO$_2$" presented in the AIR Appendix. [5]DAC energy requirements of 7.5 GJ/tCO$_2$ require the equivalent of about 2.5 months of energy consumption for the average American household, and removing a gigaton of CO_2 would require about half the total energy consumed by the US in 2022.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK[1]	WORKSTREAM[2]	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Lab	R&D: Materials	Identify and test new sorbent materials and configurations that improve mass transfer, leverage water co-adsorption, reduce heat capacities, enhance conductivity, enhance cyclic CO_2 working capacity, etc. The best candidates will reduce heat demand and enhance CO_2 uptake.	✓ Identify at least 3-5 high performance sorbent materials for testing at pilot scale[1] ✓ Validate expected material lifetimes and manufacturing requirements	2-4	$0.5-2M/y	2-4 y	$10-20M
		Assess material durability, recyclability, and manufacturing: • Conduct long-term material stability and degradation studies • Explore the effects of climate and harsh operational conditions • Evaluate sorbent manufacturing and recycling / reuse / disposal					
Lab / pilot	R&D: Process design	Simulate and conduct synergistic material and process optimization, including heat recovery, that considers different climate conditions and CO_2 purity targets.[3]	✓ Identify and validate performance of 2-3 configurations for low material losses, energy, and cost	2-4	$1-3M/y	2-4 y	$20-30M
		Study alternatives to direct heating for regeneration methods (e.g., indirect, microwave and joule heating, steam stripping, etc.) and experimentally validate process performance.					
Lab / pilot	R&D: Equipment	Simulate and test alternative contactor designs (e.g., shallow contactor designs, cross flow contactors, etc.) for increased mass and heat transfer and lower energy requirements, especially due to pressure drop.	✓ Develop at least 2-3 alternative contactor designs that enable modularity	2-4 (lab)	$1-3M/y	2-4 y	$20-30M
		Improve process intensification for all equipment.	✓ Identify promising configurations for improved process and performance	2-4 (pilot)	$5-10M/y	5-10 y	$50-100M
		Perform comparative studies for process design and primary equipment.					
Lab / pilot	R&D: System level studies	Conduct independent TEA, LCA, local / regional climate sensitivity studies, and supply chain analysis for the full DAC system (including material synthesis, transportation, and disposal).	✓ Independent estimates show costs and environmental impact are manageable	2-4	$0.5-2M/y	2-4 y	$10-20M

Notes and sources: [1]This CDR approach is already categorized at TRL 9, given that commercial projects (e.g., Climeworks) have already been deployed. However, major knowledge gaps remain as companies have advanced faster than academia. Alternative opportunities for reducing energy demand and cost remain unexplored. [2]List of recommended workstreams and budgets is adopted from Küng et al. (2023). [3]Leveraging AI and ML can help assess new / optimal sorbent materials.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Fund 2-3 DAC+S demonstration projects for the most promising optimized configurations across energy and cost reduction using alternative materials, operational strategies, and optimized equipment[1]	1 $ktCO_2/y$[2]	✓ Demonstrate CAPEX and OPEX cost improvements[2] for an all-in cost <$\$100/tCO_2$ ✓ Demonstrate reduction in energy requirements to <$7.5GJ/tCO_2$, with potential for further reduction (<$2.5GJ/tCO_2$ for market acceptance)	2-4	$20M/y	8-10 y	$350-800M
MRV	Measurement, reporting, and verification protocols are established and validated by an independent third party.	N/A	✓ Verification of CO_2 storage and net lifecycle removals for DAC+S	1-3	$2-5M/y	5-10 y	$20-50M

Notes and sources: [1]Given the high likelihood of candidate demonstration projects overlapping with an existing startup approach, demonstration project collaboration should be investigated. This can reduce the overall price tag per demonstration project, especially with regard to public funding, and generally accelerate the pathway for unique DAC+S demonstration projects. A key of objective of these collaborations should be data transparency incentivized by public funding. [2]The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy. Young et al. (2022) describes potential economies of scale due to major equipment such as the calciner and slaker.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research	DAC R&D gap database[3]	Create a global database of R&D gaps to accelerate DAC deployment by directing researchers and funders to the most critical open questions and R&D projects that need to be addressed.	1	$0.2-0.5M/y	3-5 y	$1-5M
Desktop research	Industrial cluster planning[4]	The most cost-effective DAC typically benefits from co-location with industrial clusters using CCS and co-siting to integrate DAC with existing storage reservoirs. This workstream should seek to identify clusters producing low-grade heat for co-location of DAC.	1-3	$0.5-2M/y[5]	5-10 y	$10-20M
Desktop research	Establishing industry standards	Build industry commitments to open-access designs of major process equipment. Shared designs and coordinated improvements may lower the cost of DAC.	1-3	$0.5-2M/y	5-10 y	$10-20M
Lab	DAC and utilization (DAC+U)[4]	Explore the possibility of using CO_2 products as feedstock to produce other chemicals and fuels. CO_2 utilization has the potential to de-risk and accelerate DAC deployment at scale by selling CO_2-based products, creating a new demand for CO_2, thus reducing the cost of DAC.	2-4	$0.5-2M/y	5-10 y	$20-30M

Notes and sources: [1]A reviewer suggested an additional workstream to establish test centers and advanced manufacturing facilities that could help accelerate the development and testing of new materials. [2]Cost estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]A similar database has already been initiated by Frontier. [4]Project planning and management are path-boosting activities for pre-demonstration and demonstration projects. [5]A reviewer notes that subsidies my be necessary to incentivize co-location for industrial clusters, which could significantly increase this cost.

SECTION 7.6

Adsorption and electrochemical regeneration

SECTION	7.6
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Adsorption and electrochemical regeneration

DEFINITION

CO_2 adsorption onto a solid sorbent (where CO_2 is captured on the surface of a solid material), followed by CO_2 release and sorbent regeneration in an electrochemical cell in which a voltage change is used to separate the CO_2 from the sorbent

EXAMPLE SCENARIOS

1) Ambient air is channeled through a stack of electrodes in which CO_2 is adsorbed, then a voltage is applied through the stack to release concentrated CO_2 for storage; 2) electrochemically reduced organic solids like quinones are used to chemically bind with CO_2 from air and electrochemically oxidized to release CO_2 for storage.

Section 7.6 overview

Adsorption and electrochemical heat regeneration

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/tCO$_2$** • Key risks include energy requirements of sorbent regeneration and limited data available to characterize environmental impacts and cost
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium to low** • This approach is standardized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab to pilot stage** • ~5 companies at lab to pilot stages with funding ranging from $0.1-100M
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment across all DAC approaches: **1 GtCO$_2$ by 2050** • Success is contingent on breakthroughs in materials, process design, and equipment, as well as siting synergies and increased cost effectiveness as compared to other DAC approaches
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$500M-$1B over 13-20 years** • Key stage gates in materials, process, and equipment development

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**High risk:** High energy requirements for sorbent regeneration are expected.	High energy requirements for electrochemical CO_2 release are expected. Although lower energy values have been reported (~1 GJ/tCO_2), we classify this approach as high risk as limited data is currently available for a more rigorous assessment.[1] DAC+S will also require additional energy (e.g., compression, transport, and storage), which is not included in the publicly available energy data.[2]
	Land requirements	**Low risk:** Significant land areas are suitable for DAC siting.	These DAC plants are expected to have minimal footprint per capture capacity compared to other CDR solutions and can be deployed on most types of land. However, there is no public data regarding land requirements for this approach. The footprint is expected to be larger if land for energy production is considered.[2]
	Water requirements	**Low risk:** No water is required.	Water is not used in this process and therefore it is not expected to be a risk.[2]
	Material requirements	**Medium risk:** High-demand materials are required.	Apart from basic construction materials (e.g., steel, cement), this solution requires chemicals (e.g., quinones) that need to be synthesized or purchased (for scalability, supply chains need to be in place) and high-demand materials for electrodes.[2]
	Co-location of DAC and storage	**Low risk:** Co-location of DAC and storage is relatively easy for this technology.	The DAC unit performance may be affected by different climate conditions. However, easy co-location with storage can be achieved due to the high CO_2 purities from the DAC unit.[2,3]
	Environmental impacts	**High risk:** No / incomplete LCA data available.	No LCA is currently available. However, apart from the impacts associated with energy, water, and material requirements, minimal to no other impacts are anticipated.[2]
Secure storage for 100+ years		**Low risk:** Storage is durable.	Geological sequestration or in-situ mineralization (primary storage options) are considered permanent storage approaches.[4]
Path to measurement at scale		**Low risk:** Measurement to inform MRV is comparatively straightforward.	DAC+S measurement and monitoring is straightforward. Capture occurs in a controlled environment and geological injection has established monitoring standards.[2]
Pathway to full costs <$100/t$CO_2$		**Very high risk:** Not enough reliable data is available to assign a lower rating.[4]	FOAK plants are expected at <10 ktCO_2; process data is limited and no data on cost is available; net FOAK capture cost is expected to be very high risk at >$600/t$CO_2$ (excluding compression, transport, and storage).[1,2,5]

Notes and sources: [1]Methods and criteria used to assign DAC ratings are found in the AIR appendix. [2]A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage (Küng et al., 2023) [3]There is a risk of CO_2 leakage if DAC and storage are not co-located. [4]To the best of our knowledge, there is limited publicly available data. [5]The price of available electricity will have a significant impact on the cost estimate.

Potential for cost improvement

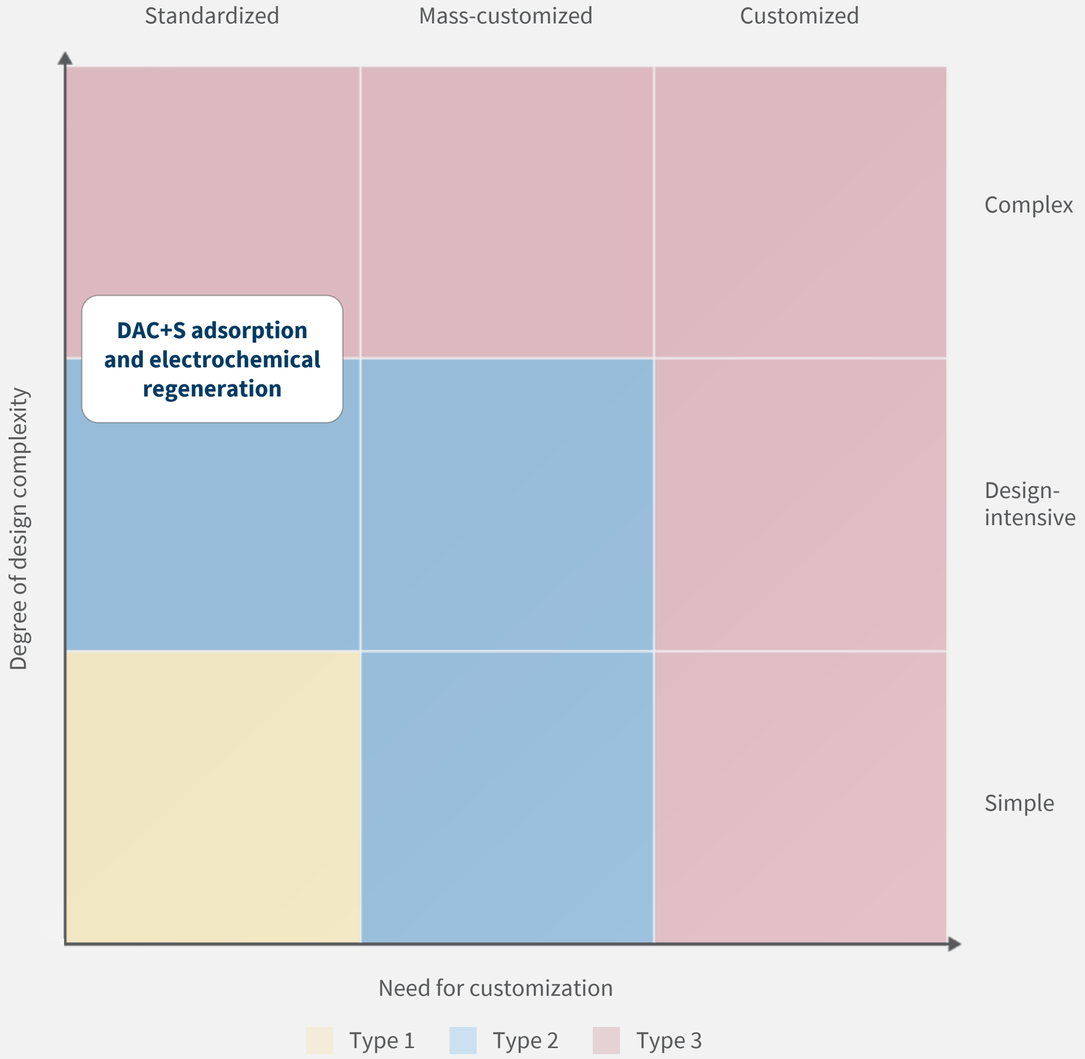
An assessment of two key drivers of learning rates

SECTION 7.6

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and electrochemical regeneration



OVERALL RATING

Type 2-3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive - complex
- **Rationale:** Solid-based DAC systems require complex designs for continuous process operation. However, electrochemical cells have a less complex design.

NEED FOR CUSTOMIZATION

- **Rating:** Standardized
- **Rationale:** Systems are modular and designed to take place in smaller, less centralized facilities than liquid-based systems. However, material customization is still needed based on plant location and climate conditions.[2]

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]Overall sCDR assessment on cost improvement is based on Roberts and Nemet, "Lessons for Direct Air Capture from the History of Nitrogen Synthesis: High rates of deployment are possible, with strong support", (Roberts and Nemet, Pre-print 2023).

Current state of RD&D

A mapping of companies, plus other notable activities

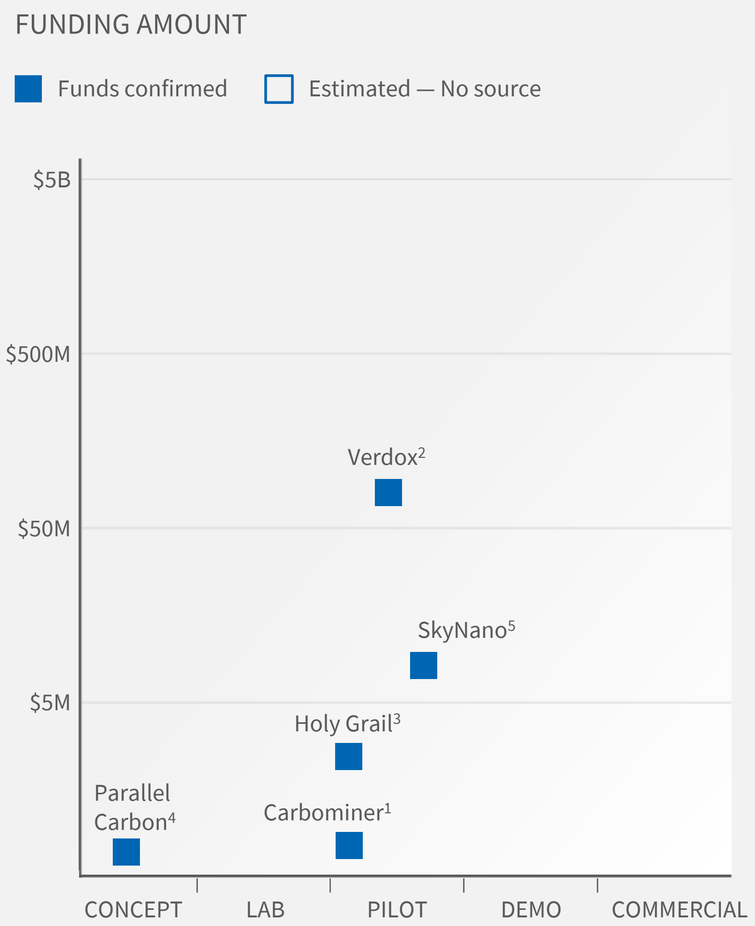
NOT EXHAUSTIVE

SECTION 7.6

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and electrochemical regeneration



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Carbominer: Electrodialysis system with pH swing for regeneration[1]	$1M[6]	• Lab prototype development in June 2022[7]
Verdox: Electro-swing adsorption[2]	$100M[8]	• Lab prototype development in 2022, now exploring field pilot opportunities[9]
Holy Grail: Modular electrochemical CO2 removal with above-ground storage[3]	$3M[10]	• Operational scrubber in California, USA • Planning pilot Project Moonstone in Fremont, CA[11]
Parallel Carbon: Passive geochemical capture with electrolysis regeneration[4]	$127k[12]	• Top 60 XPRIZE Carbon Removal[4]
SkyNano: Modular technology developed at Vanderbilt University[5]	$8.5M[13]	• First production of carbon nanotubes from flue gas, obtained from Tennessee Valley Authority's John Sevier Combined Cycle Plant[14] • Top 60 XPRIZE Carbon Removal

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
DARPA seed funding to Palo Alto Research Center, Inc. (PARC) in 2009	$392k	• Studying the use of electrodialysis to regenerate CO_2 gas from a DAC capture solution[15]

Notes and sources: [1]A Ukrainian based startup, Carbominer builds modular units with four stages, including active contacting using fans and two capture steps of passive ion-exchange sorbents, later flushed with solvent to isolate CO_2. After the final electrochemical desorption and regeneration step, the solvent is recycled. They are currently targeting industrial indoor agriculture as an entry market with plans to focus on long term storage via larger capacity and passive tower-like units. [2]Verdox website [3]Holy Grail website [4]Parallel Carbon website describes their process of a passive capture phase via geochemistry ($CaCO_3$) that then goes into a nitric acid solution to pH-swing out the CO_2. Electrolysis regenerates the nitric acid. In the process they also produce green hydrogen, tapping into two markets and improving the DAC economics. [5]SkyNano website [6]Crunchbase estimate for Carbominer [7]Company blog post [8]Dealroom estimate for Verdox [9]Little public information is available about Verdox's progress, but it is known that they have built prototypes and are looking for field pilots. [10]Based on Crunchbase [11]Project Moonstone information [12]Based on Crunchbase [13]SkyNano Forbes article [14]Company blog [15]This funding led to the publications of several papers including "CO_2 separation using bipolar membrane electrodialysis" (Eisaman et al., 2011) and "CO_2 desorption using high-pressure bipolar membrane electrodialysis" (Eisaman et a., 2011).

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

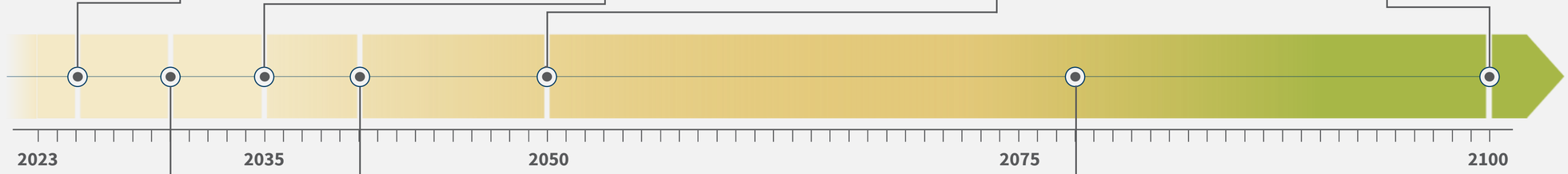
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 7.6

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and electrochemical regeneration



2025

- Significant funding is allocated for R&D projects to advance materials, process design, equipment, and systems integration of this approach.
- A global database of R&D gaps is created. This database directs researchers and funders to the most critical open questions / R&D projects that need to be addressed.[1]
- 2-4 pilot plants are under construction including alternative contactor designs, materials, and operational strategies distinct from Verdox.

2030

- Breakthroughs in materials, process design, equipment, and systems integration lead to significant cost improvements for this approach.
- Data from pilots, demonstration facilities, and the state of other DAC approaches begin to determine ongoing investments in this approach.

- Total global capture[2] for all DAC operations reaches 60 $MtCO_2/y$. This approach is not yet mature enough to contribute significantly to that total.

2035

- Early R&D, pilot, and demonstration data from this approach is used to inform future funding decisions. This approach is either being scaled widely or giving way to other, more competitive DAC approaches.

- Total global capture[2] for all DAC operations reaches 180 $MtCO_2/y$.

2040

- Total global capture[2] for all DAC operations reaches 560 $MtCO_2/y$.
- DAC facilities are synergistically sited alongside other industrial facilities as part of the energy transition.
- DAC facilities increasingly take advantage of new low-carbon generation, including non-peak electricity loads.
- A “fail fast” methodology applied across the DAC space has led to consolidated funding directed toward the best approaches. Unpromising approaches are no longer funded.

2050

- Total capture[2] from all forms of DAC reaches 1 $GtCO_2/y$.
- Breakthroughs in DAC R&D continue to drive down the cost of removals.
- Due to decades of competition, the most energy efficient and cost-optimized approaches to DAC have become market leaders.
- DAC clusters have emerged in industrial corridors, some of which remove 10-100 $MtCO_2/y$.

These story elements are common to all DAC approaches.

2050-2100

- There is continued rapid scaling of DAC plants in accordance with climate objectives.
- Breakthroughs in DAC design and deployment lead to new facilities being built in widely distributed locations all around the world.

2100

- Capture from all forms of DAC reaches 10 $GtCO_2/y$.[2]
- DAC facilities are operational globally.
- The cost of DAC is less than $\$100/tCO_2$ (adjusted to 2023 dollars).

Notes and sources: [1]A similar database has already been initiated by Frontier. [2]We have assessed all DAC approaches in the AIR under a single growth paradigm. Our growth paradigm therefore is representative of the DAC field, not a specific DAC approach. We assumed a starting deployment of 60 $MtCO_2/y$ in 2030, which is the amount of DAC in the IEA Net Zero scenario in 2030, based on 130 proposed plants the IEA is tracking. We then assume that this 60 $MtCO_2/y$ grows at 25% per year from 2030 to 2040 and then 6% per year from 2040 to 2050. This growth paradigm includes 3 phases: (1) an initial period of rapid growth to 2030 where many new standalone facilities are built, (2) a secondary period of growth from 2030-2040 characterized by supply chain management, workforce development, and other scaling challenges, and (3) a sustained period of long-term growth characterized by more complex supply chains and large-scale systems. This multi-phase growth methodology is used in other AIR success stories and has also been recently modeled in academic papers, such as Roberts and Nemet, Pre-print 2023.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 7.6

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and electrochemical regeneration

TRL

CRITICAL PATH ACTIVITIES

$500M - $1B | **13-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Lab – materials R&D:** Perform materials discovery, optimization, and performance evaluation and validation
- **Lab and pilot – process & equipment:** Optimize performance of the contactor unit; test optimal process configurations and regeneration strategies
- **Lab and pilot – system integration:** Perform independent TEA, LCA, climate sensitivity, and supply chain studies

$100-200 million | **5-10 years**

- ✓ Pathway to significant CAPEX and OPEX cost reductions via optimal equipment and process operation
- ✓ Reduced electricity requirements with potential to reach theoretical maximum efficiency
- ✓ Demonstrated ability to scale: e.g., CO_2 purity >85%[3]

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Demonstration – DAC+S:** Fund / support either novel configurations (that no company is currently pursuing) OR collaborate with entities already pursuing opportunities to scale
- **MRV:** Measurement and verification should be performed by an independent entity

$400-850 million | **8-10 years**

- ✓ Cost requirements: $200-600/tCO$_2$[4]
- ✓ Energy requirements: <7.5 GJ/tCO$_2$[5]
- ✓ Reduced water requirements

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$30-50 million | **5-10 years**

- Create a DAC R&D gap database to direct researchers and funders to the most critical open questions / R&D projects.
- Perform planning studies for industrial clusters to facilitate the use of potentially available resources and existing CCS infrastructure.
- Investigate the use of CO_2 for valuable products such as chemicals and fuels.
- Establish industry standards with open-access designs for major equipment.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Verified carbon storage by a third=party accounting organization
- Low-carbon / green energy sourcing and low energy requirements
- Industry and consumer acceptance
- Long-term safety record with net carbon removal and durable storage
- Financing costs in line with commercially accepted technologies

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development. [3]Below this threshold, density changes, mostly due to the presence of non-condensable impurities (e.g., N_2, O_2, Ar), which cannot be liquified at ambient temperature, can affect storage capacity, injectivity, and buoyancy. More information found here. [4]Based on the assumptions in the "Pathway to full costs <$100/tCO$_2$" presented in the AIR Appendix. [5]DAC energy requirements of 7.5 GJ/tCO$_2$ require the equivalent of about 2.5 months of energy consumption for the average American household, and removing a gigaton of CO_2 would require about half the total energy consumed by the US in 2022.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK[1]	WORKSTREAM[2]	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Lab	R&D: Materials	Identify and test new sorbent and membrane materials and electrodes to maximize CO_2 uptake and achieve high durability in the presence of relevant gases, high permeability through the membrane (if applicable), rapid kinetics, low voltage requirements, etc. The best candidates will reduce heat demand and enhance CO_2 uptake.	✓ Identify at least 3-5 high performing sorbents and membranes (if applicable) for testing at pilot scale[1] ✓ Validate material lifetime and manufacturing requirements	2-4	$0.5-2M/y	2-4 y	$10-20M
		Assess material durability, recyclability, and manufacturing: • Conduct long-term degradation studies • Explore the effects of climate and harsh operational conditions • Study sorbent manufacturing and recycling / reuse / disposal					
Lab / pilot	R&D: Process design	Simulate and conduct synergistic analysis and optimization between electrodes, electrolytes, and electrochemical systems that assess different climate conditions and CO_2 purity targets.	✓ Identify and validate performance for 2-3 configurations with expected low material losses, energy, and cost	2-4	$1-3M/y	2-4 y	$20-30M
		Study alternative CO_2 transfer methods (e.g., cation exchange membrane, pH swing, electrochemically mediated separation, etc.) and experimentally validate process performance.					
Lab / pilot	R&D: Equipment	Simulate and test alternative electrochemical cell designs for lower energy requirements, especially due to pressure drop, and higher operational performance.	✓ Identify at least 2-3 alternative electrochemical cell designs	2-4 (lab)	$1-3M/y	2-4 y	$20-30M
		Improve process intensification for all equipment.	✓ Identify promising configurations for improved process and performance	2-4 (pilot)	$5-10M/y	5-10 y	$50-100M
		Perform comparative studies for process design and primary equipment.					
Lab / pilot	R&D: System level studies	Conduct independent TEA, LCA, local / regional climate sensitivity studies, and supply chain analysis on the full DAC system, including material synthesis, transportation, and disposal.	✓ Independent estimates show costs and environmental impact are manageable	2-4	$0.5-2M/y	2-4 y	$10-20M

Notes and sources: [1]Verdox is the leading startup advancing this approach and is exploring pilot to demonstration projects (TRL 6). There is very limited data available about Verdox's process, making it difficult to assess unknown areas for further research and avoiding duplication of efforts. [2]List of recommended workstreams and budgets is adopted from Küng et al. (2023).

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	DAC+S: Fund 2-3 demonstration projects of the most promising optimized configurations for energy and cost reductions using alternative materials, operational strategies, and optimized equipment.[1]	1 $ktCO_2/y$ [2]	✓ Demonstrate CAPEX and OPEX cost improvements[2] towards an all-in cost <$100/$tCO_2$ ✓ Demonstrate reduction in energy requirements to <7.5 GJ/tCO_2, with potential for further reduction (<2.5 GJ/tCO_2 for market acceptance) ✓ Demonstrate minimum operating current density of 50-100 mA/cm^2	2-4	$20M/y	8-10 y	$350-800M
MRV	Measurement, reporting, and verification protocols are established and validated by an independent third party.	N/A	✓ Verification of CO_2 storage and net lifecycle removals for DAC+S	1-3	$2-5M/y	5-10 y	$20-50M

Notes and sources: [1]Given the high likelihood of candidate demonstration projects overlapping with an existing startup approach, demonstration project collaboration should be investigated. This can reduce the overall price tag per demonstration project, especially with regard to public funding, and generally accelerate the pathway for unique DAC+S demonstration projects. A key of objective of these collaborations should be data transparency incentivized by public funding. [2]Assumed similar FOAK scale as 'Adsorption and low-grade heat regeneration' approach.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research	DAC R&D gap database[3]	Create a global database of R&D gaps to accelerate DAC deployment by directing researchers and funders to the most critical open questions / R&D projects that need to be addressed.	1	$0.2-0.5M/y	3-5 y	$1-5M
Desktop research	Industrial cluster planning[4]	The most cost-effective DAC typically benefits from co-location with industrial clusters using CCS so that it can integrate with existing storage reservoirs. This workstream should seek to identify clusters with access to competitive low-carbon and low-cost electricity contracts / sources which should significantly improve costs and LCA.	1-3	$0.5-2M/y[5]	5-10 y	$10-20M
Desktop research	Establishing industry standards	Build industry commitments to open-access designs of major process equipment. Shared designs and coordinated improvements could lower the cost of DAC.	1-3	$0.5-2M/y	5-10 y	$10-20M
Lab	DAC and utilization (DAC+U) (including H_2 production)[4]	Explore the possibility of using CO_2 product as feedstock for chemicals and fuels and H_2 production. CO_2 utilization and H_2 production have the potential to de-risk and accelerate DAC deployment at scale by creating new demand for CO_2 and H_2.	2-4	$0.5-2M/y	5-10 y	$20-30M

Notes and sources: [1]A reviewer suggested an additional workstream to establish test centers and advanced manufacturing facilities that could help accelerate the development and testing of new materials. [2]Cost estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]A similar database has already been initiated by Frontier. [4]Project planning and management are path-boosting activities for pre-demonstration and demonstration projects. [5]A reviewer notes that subsidies my be necessary to incentivize co-location for industrial clusters, which could significantly increase this cost.

SECTION 7.7

Adsorption and humidity / water regeneration

SECTION	7.7
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Adsorption and humidity / water regeneration

DEFINITION

Adsorption onto a solid sorbent (where CO_2 is captured on the surface of a solid material) followed by a desorption step in which a swing in humidity (high humidity for regeneration) is used to separate CO_2 from the sorbent (i.e., a resin); further purification of CO_2 may be necessary, depending on the water concentration in the product stream

EXAMPLE SCENARIO

CO_2 is passively captured on a filter coated with resins that chemically bind with CO_2 in air, then water is added, causing the filter to release the CO_2 in an aqueous form and allowing the coated filter to be reused. Further treatment of the solution releases the CO_2 as a gas for storage.

Section 7.7 overview

Adsorption and humidity/water regeneration

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability, secure storage, and pathway to full costs <$100/tCO$_2$** • Key risks include the energy requirements of sorbent regeneration, storage of low-purity CO_2, and limited data available to characterize environmental impacts and cost
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium to low** • This approach is standardized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot stage** • ~4 companies at concept to pilot stages, with funding <$100M for each
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment across all DAC approaches: **1 GtCO$_2$ by 2050** • Success is contingent on breakthroughs in materials, process design, and equipment, as well as siting synergies and increased cost effectiveness as compared to other DAC approaches
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$500M-$1B over 13-20 years** • Key stage gates in materials, process, and equipment development

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk Medium risk High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Very high risk:** There is no data available on energy needs to achieve high purity CO_2.	Reported energy requirements are relatively low (1.2 GJ/tCO_2) due to passive contacting and no heat requirements for regeneration. However, more energy will be needed to adequately purify the CO_2 product stream and the full DAC+S pathway will require additional energy (e.g., compression, transport, and storage). [1,2,3,4]
	Land requirements	**Low risk:** Significant land areas are suitable for DAC siting.	Limited information is publicly available but, based on pilot plants (at 80 km^2/GtCO_2/y), it is expected that the plant footprint will be very competitive with other DAC approaches and can be deployed on most types of land. The footprint is larger if land use for energy production is considered.[1]
	Water requirements	**Low risk:** Modest volumes of water are needed for operation.	This process relies on water for the humidity swing. Water needs to be recycled for the water requirements not to become excessive.[1] This approach should be deployed only in favorable environmental conditions in areas with low risk of water stress.
	Material requirements	**Low risk:** No rare materials are required.	Apart from basic construction materials (e.g., steel, cement), this solution requires chemicals (ion exchange resin powder (I200) from polypropylene with ammonium) that need to be synthesized and purchased.
	Co-location of DAC and storage	**Low risk:** Co-location of DAC is relatively easy if high CO_2 purities can be achieved.	From publicly available data, this approach can only be deployed in dry areas. However, CO_2 storage is widely available. Therefore, easy co-location can be achieved if high CO_2 purities can be obtained from the DAC unit.[1,5]
	Environmental impacts	**High risk:** No / incomplete LCA data is available.	No LCA is currently available. Apart from impacts associated with energy, water and material requirements, minimal to no other impacts are foreseen.[1]
Secure storage for 100+ years		**High risk:** Scalable, permanent options for low purity DAC are underdeveloped	Geological sequestration or in-situ mineralization (primary storage options) are considered permanent storage approaches. However, high CO_2 purity DAC output needs to be achieved first, and there is low certainty as to whether durable or permanent storage for low purity DAC output is feasible.[6,7]
Path to measurement at scale		**Low risk:** Measurement to inform MRV is straightforward.	DAC+S measurement and monitoring is straightforward. Capture occurs in a controlled environment and geological injection has established monitoring standards.[1]
Pathway to full costs <$100/t$CO_2$		**Very high risk:** Cost data is incomplete.[4]	A FOAK plant is expected at <10 ktCO_2; however, plant data is not yet available. Net FOAK capture cost is expected to be >$600/t$CO_2$ (excluding compression, transport, and storage).[1,8,9]

Notes and sources: [1]A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage (Küng et al., 2023) [2]Methods and criteria used to assign DAC ratings are found in the AIR appendix. [3]Reviewers noted that lower energy risk is possible, but the lack of publicly available data places this solution within the "very high risk" category. [4]To the best of our knowledge, there is limited publicly available data on the current cost of this solution. [5]There is a risk of CO_2 leakage if DAC and storage are not co-located. [6]Moisture Swing Sorbent for Carbon Dioxide Capture from Ambient Air (Wang et al., 2013) [7]Carbon Dioxide capture from air: a simple analysis (Brandani , 2012) [8]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [9]The price of available electricity will have a significant impact on the cost estimate.

Potential for cost improvement

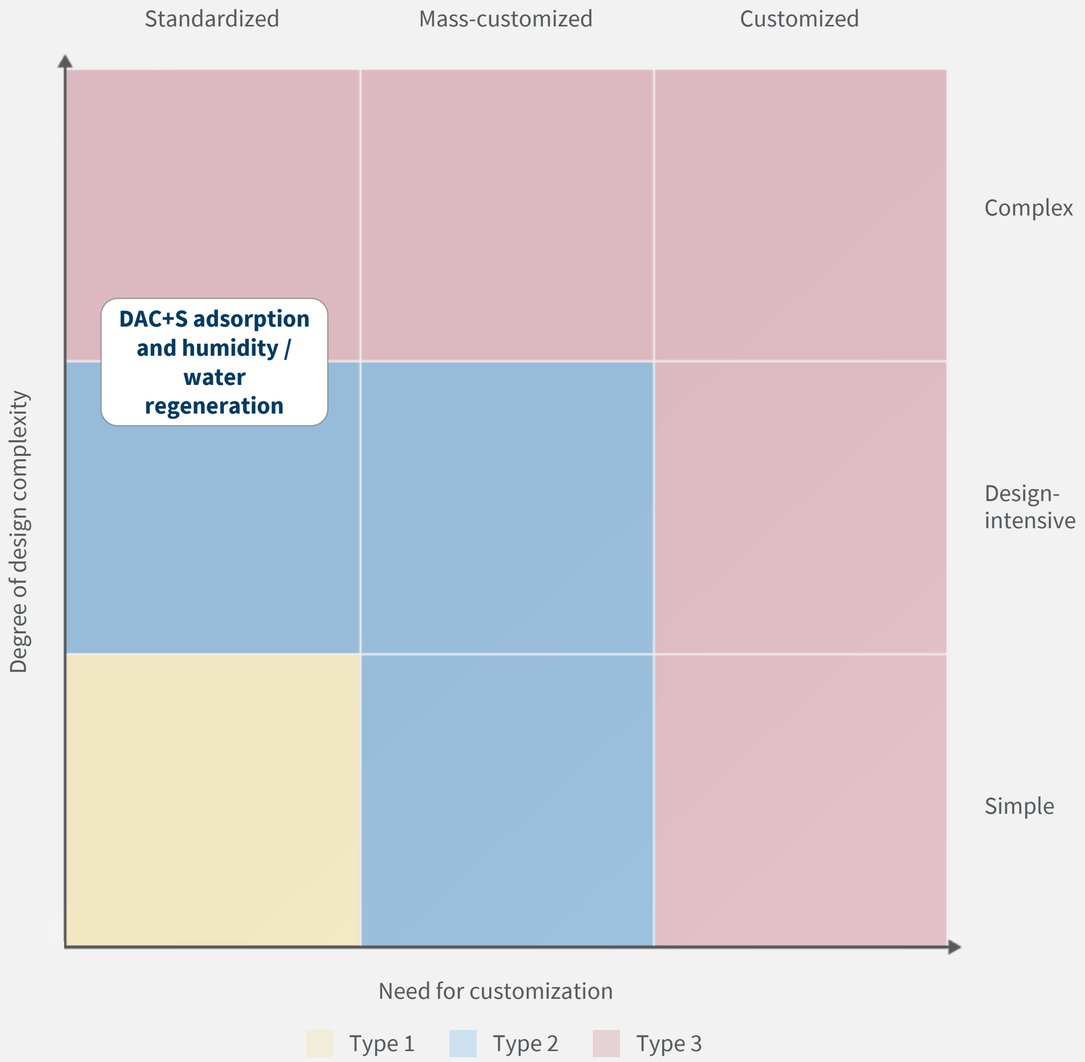
An assessment of two key drivers of learning rates

SECTION 7.7

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and humidity / water regeneration



OVERALL RATING

Type 2-3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive – complex
- **Rationale:** The design requirements for continuous operation of adsorption-desorption cycles for solid-based DAC systems are complex. In addition, high purity output has not yet been achieved. However, regeneration with water has less complex design considerations.

NEED FOR CUSTOMIZATION

- **Rating:** Standardized
- **Rationale:** Systems are modular, designed to take place in smaller, less centralized facilities than liquid-based systems. However, material customization is still needed based on plant location and climate conditions.[2]

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]Overall sCDR assessment on cost improvement is based on Roberts and Nemet, "Lessons for Direct Air Capture from the History of Nitrogen Synthesis: High rates of deployment are possible, with strong support", (Roberts and Nemet, Pre-print 2023).

Current state of RD&D

A mapping of companies, plus other notable activities

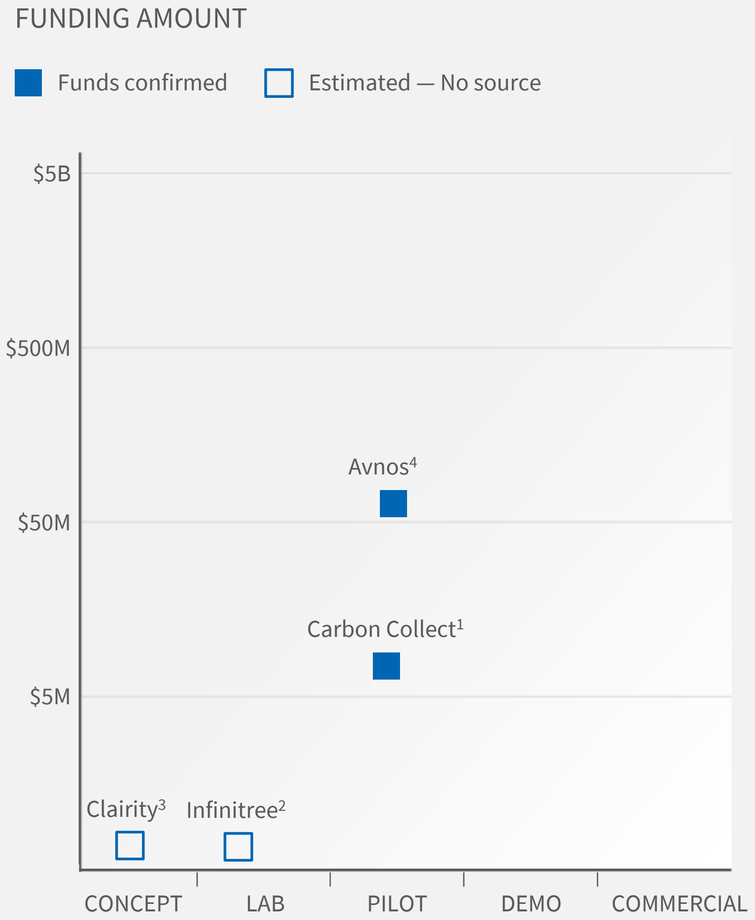
NOT EXHAUSTIVE

SECTION 7.7

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and humidity / water regeneration



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Carbon Collect – Mechanical Tree: Passive capture in closed units[1]	$14.5 M[5]	• 2022 — First field pilot deployed in Tempe, Arizona[6]
Infinitree: Passive contacting system[2]	N/A	• 2014 — Founded, but very limited public information about the company and its activity is available
Clairity: Material science for sorbent identification[3]	N/A	• 2023 — Currently building out 100 tCO_2/y pilot plant[7]
Avnos: Low energy HDAC that produces water[4]	$80M[8]	• Building two pilot projects with support from the US government[4] • Pilot unit produces ~300 t water/y and captures ~33 tCO_2/y[8]
Other companies and activities: Arbon,[9] Zero Carbon Production[10]		

Notes and sources: [1]Mechanical Tree is now owned by Carbon Collect in Ireland, previously Silicon Kingdom Holdings. The system captures CO_2 passively via ion-exchange resin and uses water for CO_2 desorption. The process results in low CO_2 concentrations, and the only energy demand is for final post-capture processing of water with CO_2. [2]Based on the company website, Infinitree targets low CO_2 concentration for utilization in the indoor agriculture industry. [3]Based on the company website, Clairity's focus is on material science to identify the optimal sorbent for a non-passive contacting system design. [4]Avnos company website [5]Based on several news reports, fundraising is a mix of grants, and dedicated fundraising. [6]Based on news report [7]From Clarity About page [8]Avnos signed multiple partnerships amounting to $80M, which they will use to build commercial HDAC units by the end of 2025. [9]Arbon website [10]Zero Carbon Production website

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

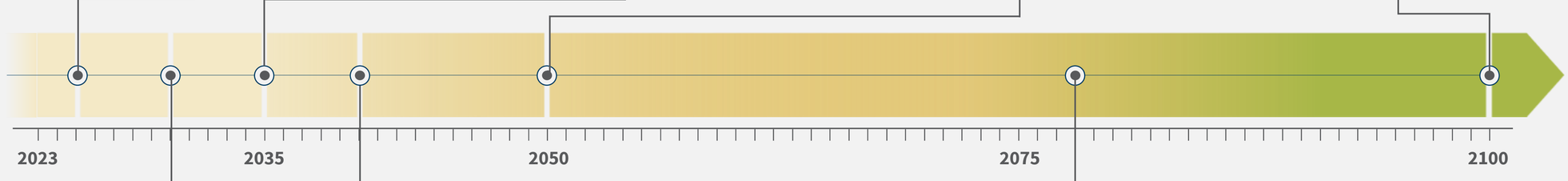
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 7.7

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and humidity / water regeneration



2025

- Significant funding is allocated for R&D projects to advance materials, process design, equipment, and systems integration for this approach.
- A global database of R&D gaps is created. This database directs researchers and funders to the most critical open questions / R&D projects that need to be addressed.[1]
- 2-4 pilot plants are under construction, including alternative contactor designs to Mechanical Trees that use distinct materials or regeneration methods and target high purity CO_2.

2030

- R&D breakthroughs in materials, process design, equipment, and systems integration lead to significant cost improvements for this approach.
- Plant data from several pilots, demonstration facilities, and the state of other DAC approaches begin to inform future funding decisions for this approach.

- Total global capture[2] for all DAC operations reaches 60 $MtCO_2$/y. This approach is not yet mature enough to contribute significantly to that total.

2035

- Early R&D, pilot, and demonstration data from this approach is used to inform future funding decisions. This approach is either being scaled widely or giving way to other, more competitive DAC approaches.

- Total global capture[2] for all DAC operations reaches 180 $MtCO_2$/y.

2040

- Total global capture[2] for all DAC operations reaches 560 $MtCO_2$/y.
- DAC facilities are synergistically sited alongside other industrial facilities as part of the energy transition.
- DAC facilities increasingly take advantage of new low-carbon generation, including non-peak electricity loads.
- A "fail fast" methodology applied across the DAC space has led to consolidated funding directed toward the best approaches. Unpromising approaches are no longer funded.

2050

- Total capture[2] from all forms of DAC reaches 1 $GtCO_2$/y.
- Breakthroughs in DAC R&D continue to drive down the cost of removals.
- Due to decades of competition, the most energy efficient and cost-optimized approaches to DAC have emerged as market leaders.
- DAC clusters have emerged in industrial corridors, some of which remove 10-100 $MtCO_2$/y.

2050-2100

- There is continued rapid scaling of DAC plants in accordance with climate objectives.
- Breakthroughs in DAC design and deployment lead to new facilities being built in distributed locations around the world.

These story elements are common to all DAC approaches.

2100

- Capture from all forms of DAC reaches 10 $GtCO_2$/y.[2]
- DAC facilities are operational globally.
- The cost of DAC is less than \$100/tCO_2 (adjusted to 2023 dollars).

Notes and sources: [1]A similar database has already been initiated by Frontier. [2]We have assessed all DAC approaches in the AIR under a single growth paradigm. Our growth paradigm therefore is representative of the DAC field, not a specific DAC approach. We assumed a starting deployment of 60 $MtCO_2$/y in 2030, which is the amount of DAC in the IEA Net Zero scenario in 2030, based on 130 proposed plants the IEA is tracking. We then assume that this 60 $MtCO_2$/y grows at 25% per year from 2030 to 2040 and then 6% per year from 2040 to 2050. This growth paradigm includes 3 phases: (1) an initial period of rapid growth to 2030 where many new standalone facilities are built, (2) a secondary period of growth from 2030-2040 characterized by supply chain management, workforce development, and other scaling challenges, and (3) a sustained period of long-term growth characterized by more complex supply chains and large-scale systems. This multi-phase growth methodology is used in other AIR success stories and has also been recently modeled in academic papers, such as Roberts and Nemet, Pre-print 2023.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 7.7

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Adsorption and humidity / water regeneration

TRL

CRITICAL PATH ACTIVITIES

$500M - $1B | **13-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Lab – materials R&D:** Perform materials discovery, optimization and performance evaluation and validation
- **Lab and pilot – process & equipment:** Optimize performance of the contactor unit; test optimal process configurations and regeneration strategies
- **Lab and pilot – system integration:** Perform independent TEA, LCA, climate sensitivity, and supply chain studies

$100-200 million | **5-10 years**

- ✓ Pathway to significant CAPEX and OPEX cost reductions via optimal equipment and process operation
- ✓ Reduced electricity requirements with potential to reach theoretical maximum efficiency
- ✓ Demonstrated ability to scale: e.g., CO_2 purity >85%[3]

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Demonstration – DAC+S:** Fund / support either novel configurations (that no company is currently pursuing) OR collaborate with entities already pursuing opportunities to scale
- **MRV:** Measurement and verification should be performed by an independent entity

$400-850 million | **8-10 years**

- ✓ Cost requirements: $200-600/tCO$_2$[4]
- ✓ Energy requirements: <7.5 GJ/tCO$_2$[5]
- ✓ Reduced water requirements

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$40-60 million | **5-10 years**

- Create a DAC R&D gap database to direct researchers and funders to the most critical open questions / R&D projects.
- Perform planning studies for industrial clusters to facilitate the use of potentially available resources and existing CCS infrastructure.
- Investigate the use of CO_2 for valuable products such as chemicals and fuels.
- Establish industry standards with open-access designs for major equipment.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Verified carbon storage by a third-party accounting organization
- Low-carbon / green energy sourcing and low energy requirements
- Industry and consumer acceptance
- Long-term safety record with net carbon removal and durable storage
- Financing costs in line with commercially accepted technologies

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development. [3]Below this threshold, density changes, mostly due to the presence of non-condensable impurities (e.g., N_2, O_2, Ar), which cannot be liquified at ambient temperature, can affect storage capacity, injectivity, and buoyancy. More information found here. [4]Based on the assumptions in the "Pathway to full costs <$100/tCO$_2$" presented in the AIR Appendix. [5]DAC energy requirements of 7.5 GJ/tCO$_2$ require the equivalent to about 2.5 months of energy consumption for the average American household, and removing a gigaton of CO_2 would require about half the total energy consumed by the US in 2022.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK[1]	WORKSTREAM[2]	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJEC BUDGET[2]	DURATION	TOTAL COST
Lab	R&D: Materials	Identify and test new sorbent materials (i.e., resins) and form factors to achieve high durability in the presence of gases, maximize CO_2 uptake, fast kinetics, high efficiency in both wet and dry atmospheric conditions, etc. The best candidates will reduce heat demand in enhance CO_2 uptake.	✓ Identify at least 3-5 high performing sorbent materials to test at pilot scale[1] ✓ Validate expected material lifetime and manufacturing requirements	2-4	$0.5-2M/y	2-4 y	$10-20M
		Assess material stability, recyclability, and manufacturing: • Conduct long-term degradation studies • Explore the effects of climate and harsh operational conditions • Study sorbent manufacturing and recycling / reuse / disposal					
Lab / pilot	R&D: Process design	Simulate and conduct synergistic material and process optimization, including water recycling, that considers different climate conditions and CO_2 purity targets.	✓ Identify and validate performance of 2-3 configurations for low material losses, energy, and cost	2-4	$1-3M/y	2-4 y	$20-30M
		Assess alternative regeneration methods to humidity swing (e.g., combination of humidity with temperature / pressure swings) to achieve competitive CO_2 purity levels and validate process performance.					
Lab / pilot	R&D: Equipment	Simulate and test alternative contactor designs for high mass and heat transfer with lower energy requirements, such as passive vs active flow, and especially due to pressure drop.	✓ Develop at least 2-3 alternative contactor designs that enable modularity	2-4 (lab)	$1-3M/y	2-4 y	$20-30M
		Improve process intensification for all equipment and integrate CO_2 purification.	✓ Identify promising configurations for improved process and performance	2-4 (pilot)	$5-10M/y	5-10 y	$50-100M
		Perform comparative studies for process design and primary equipment.					
Lab / pilot	R&D: System level studies	Conduct independent TEA, LCA, local / regional climate sensitivity studies, and supply chain analysis on the full DAC system, including material synthesis, transportation, and disposal.	✓ Independent estimates show costs and environmental impact are manageable	2-4	$0.5-2M/y	2-4 y	$10-20M

Notes and sources: [1]This CDR approach is at TRL 6, given that pilot projects (i.e., Carbon Collect (Mechanical Tree™), Avnos) have already been deployed. Major knowledge gaps remain, primarily linked to the currently low CO_2 purity levels of the technology. Alternative opportunities for reducing energy demand and cost remain unexplored. [2]List of recommended workstreams and budgets is adopted from Küng et al. (2023).

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	DAC+S: Fund 2-3 demonstration projects of the most promising optimized configurations for energy and cost reduction using alternative materials, operational strategies, and optimized equipment.[1]	1 $ktCO_2/y$[2]	✓ Demonstrate CAPEX and OPEX cost improvements toward an all-in cost <$100/$tCO_2$ ✓ Demonstrate reduction in energy requirements to <7.5 GJ/tCO_2, with potential for further reduction (<2.5 GJ/tCO_2 for market acceptance) ✓ Demonstrate negligible water evaporation rates, i.e., minimal water consumption per tCO_2	2-4	$20M/y	8-10 y	$400-800M
MRV	Measurement, reporting, and verification protocols are established and validated by an independent third party.	N/A	✓ Verification of CO_2 storage and full lifecycle removals for DAC+S	1-3	$2-5M/y	5-10 y	$20-50M

Notes and sources: [1]Given the high likelihood of candidate demonstration projects overlapping with an existing startup approach, demonstration project collaboration should be investigated. This can reduce the overall price tag per demonstration project, especially with regard to public funding, and generally accelerate the pathway for unique DAC+S demonstration projects. A key of objective of these collaborations should be data transparency incentivized by public funding. [2]Assumed similar FOAK scale as 'Adsorption and low-grade heat regeneration' approach.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

☐ Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research	DAC R&D gap database[3]	Create a global database of R&D gaps to accelerate DAC deployment by directing researchers and funders to the most critical open questions / R&D projects that need to be addressed.	1	$0.2-0.5M/y	3-5 y	$1-5M
Desktop research	Industrial cluster planning[4]	The most cost-effective DAC typically benefits from co-location with industrial clusters using CCS so that it can integrate with existing storage reservoirs. This workstream should seek to identify clusters with access to competitive low-carbon and low-cost electricity contracts / sources which should significantly improve costs and LCA.	1-3	$0.5-2M/y[5]	5-10 y	$10-20M
Desktop research	Establishing industry standards	Build industry commitments to open-access designs of major process equipment. Shared designs and coordinated improvements could lower the cost of DAC.	1-3	$0.5-2M/y	5-10 y	$10-20M
Lab	DAC and utilization (DAC+U)[4]	Explore the possibility of using CO_2 products as feedstock to produce other chemicals and fuels. CO_2 utilization has the potential to de-risk and accelerate DAC deployment at scale by selling CO_2-based products, creating a new demand for CO_2, thus reducing the cost of DAC.	2-4	$0.5-2M/y	5-10 y	$20-30M
Desktop research	Water risk assessments	Desktop research to generate risk assessments of water sourcing and usage to enable better siting decisions.	1-3	$0.5-2M/y	3-5 y	$5-10M

Notes and sources: [1]A reviewer suggested an additional workstream to establish test centers and advanced manufacturing facilities that could help accelerate the development and testing of new materials. [2]Cost estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]A similar database has already been initiated by Frontier. [4]Project planning and management are path-boosting activities for pre-demonstration and demonstration projects. [5]A reviewer notes that subsidies my be necessary to incentivize co-location for industrial clusters, which could significantly increase this cost.

SECTION 7.8

Membrane: pressure gradient separation

SECTION	7.8
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Membrane: pressure gradient separation

DEFINITION

Polymeric membrane separation in which the CO_2 is separated from other gases via differences in the molecular ability to pass through a polymer membrane (i.e., permeability); multiple capture stages, in which several membrane units are stacked together, may be required to achieve a concentrated CO_2 product

EXAMPLE SCENARIO

CO_2 in air permeates through a series of membranes, becoming increasingly concentrated until it can be utilized or stored.

RMI

Section 7.8 overview

Membrane: pressure gradient separation

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability, secure storage, and pathway to full costs <$100/tCO$_2$** • Key risks include the energy requirements of membrane separation, storage of low-purity CO_2, and limited data available to characterize environmental impacts and cost
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium to low** • This approach is standardized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab stage** • ~2 companies at lab stage with funding <$15M each
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment across all DAC approaches: **1 GtCO$_2$ by 2050** • Success is contingent on breakthroughs in basic research with sufficient pre-demonstration funding prove cost effectiveness
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$400-750M over 13-20 years** • Key stage gates in materials, process, and equipment development

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk Medium risk High risk

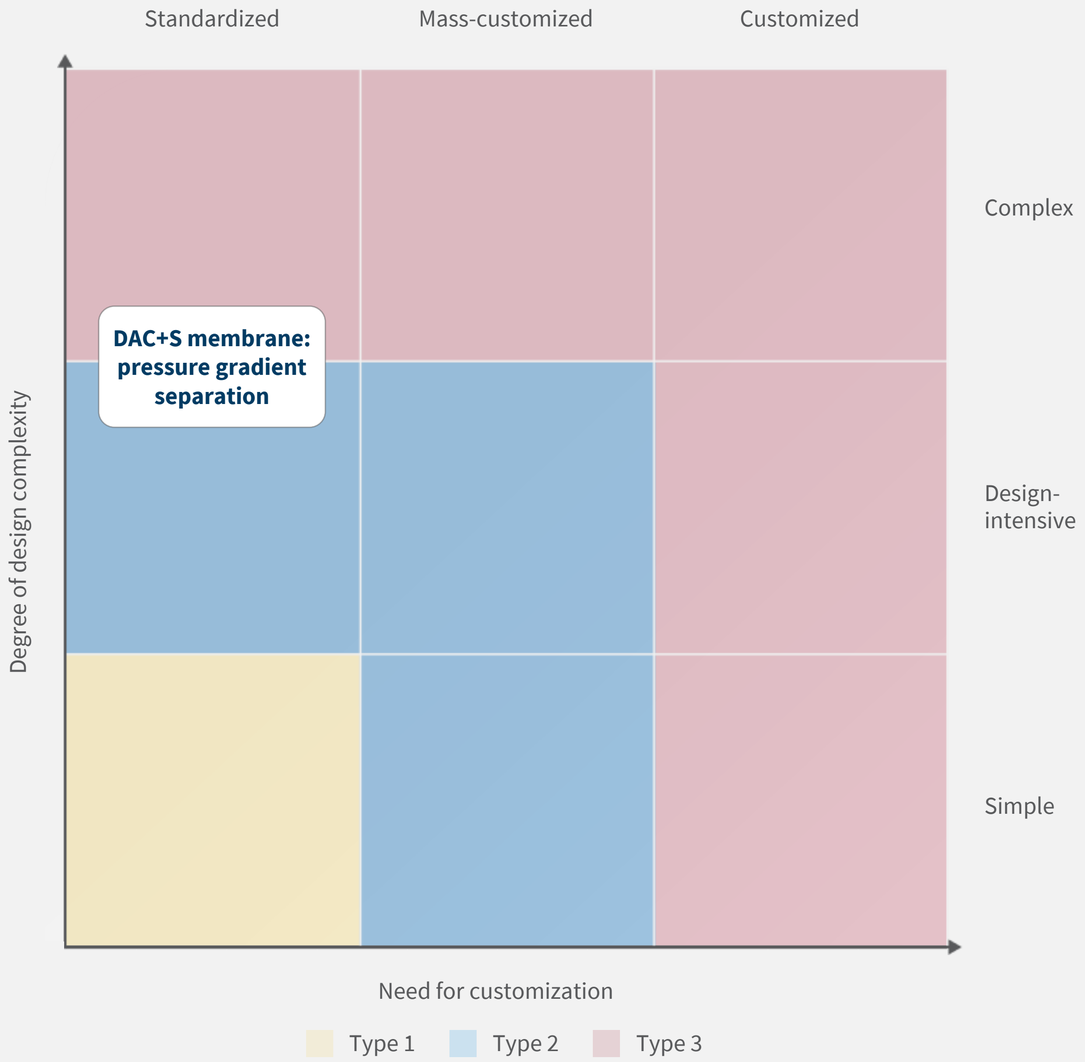
CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Very high risk:** Membrane separation is extremely energy intensive.	Energy needs meet our criteria for "very high risk" (>10 GJ/tCO_2).[1] Membrane separation alone requires approximately 44-62 GJ/tCO_2. More energy will be needed to further purify the CO_2 product stream (currently at 40-60% CO_2). The full pathway will require additional energy (e.g., compression, transport, and storage).[2]
	Land requirements	**Low risk:** Significant land areas are suitable for DAC siting.	No information is publicly available, but it is expected that plant footprints will be very competitive with other DAC approaches. The footprint will be larger if land use for energy production is considered.[2]
	Water requirements	**Low risk:** No water is required.	No water is required to perform this DAC approach.[2]
	Material requirements	**Low risk:** No rare materials are required.	Apart from basic construction materials (e.g., steel, cement), this solution requires chemicals (e.g., organic polymer membranes) that need to be synthesized and purchased.[3]
	Co-location of DAC and storage	**Medium risk:** Co-location is challenging due to the low purity DAC output.	Co-location with storage is challenging due to the currently low CO_2 purities obtained from the DAC unit.[2,4]
	Environmental impacts	**High risk:** No / incomplete LCA data is available.	No LCA is currently available. Apart from impacts associated with energy and material requirements, minimal to no other impacts are foreseen.[2]
Secure storage for 100+ years		**High risk:** Scalable, permanent options for low purity DAC are underdeveloped.	Geological sequestration or in-situ mineralization (primary storage options) are considered permanent storage approaches. However, high CO_2 purity DAC output needs to be achieved first, and there is low certainty as to whether durable or permanent storage is feasible for low purity DAC outputs.[3]
Path to measurement at scale		**Low risk:** Measurement is straightforward.	DAC+S measurement and monitoring to inform MRV is straightforward. Capture occurs in a controlled environment and geological injection has established monitoring standards.[2]
Pathway to full costs <$100/t$CO_2$		**Very high risk:** Cost data is incomplete.[5]	FOAK plant is expected at <10 ktCO_2; however, plant data is not available. Low CO_2 purities (40-60%) contribute to cost uncertainty. The net FOAK capture cost is expected to be at >$600/t$CO_2$ (excluding compression, transport, and storage).[1,2,4,7]

Notes and sources: [1]Methods and criteria used to assign DAC ratings are found in the AIR Appendix. [2]A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage (Küng et al., 2023) [3]A new strategy for membrane-based direct air capture (Fujikawa et al., 2020) [4]There is a risk of CO_2 leakage if DAC and storage are not co-located. [5]To the best of our knowledge, there is limited publicly available data. [6]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [7]The price of available electricity will have a significant impact on the cost estimate.

Potential for cost improvement

An assessment of two key drivers of learning rates

SECTION	7.8
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Membrane: pressure gradient separation



OVERALL RATING

Type 2-3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 **Medium**

Type 3 **Low**

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Complex
- **Rationale:** Membrane technologies are well understood, but design-intensive to complex design is required due to the multiple membrane stacks needed to reach acceptable process performance (higher CO_2 purity levels).

NEED FOR CUSTOMIZATION

- **Rating:** Standardized
- **Rationale:** Systems are modular, designed to take place in smaller, less centralized facilities than liquid-based systems. However, some material customization is still needed based on plant location and climate conditions.[2]

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]Overall sCDR assessment on cost improvement is based on Roberts and Nemet, "Lessons for Direct Air Capture from the History of Nitrogen Synthesis: High rates of deployment are possible, with strong support," (Roberts and Nemet, Pre-print 2023).

Current state of RD&D

A mapping of companies, plus other notable activities

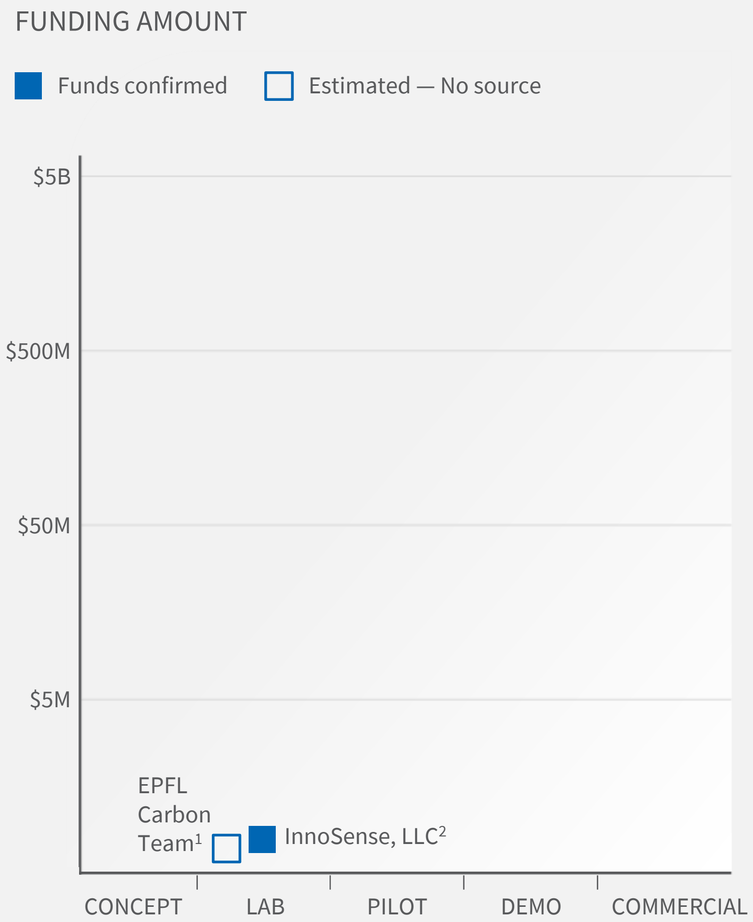
NOT EXHAUSTIVE

SECTION 7.8

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Membrane: pressure gradient separation



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORKS
EPFL Carbon Team: Nano-porous single-layer graphene membranes[1]	N/A	• Conducting research including adsorbent synthesis and characterization, adsorbent structurization, optimal heat transfer, graphene manufacturing
InnoSense, LLC: Lab fabrication of membranes[2]	$1M[3]	• Received NETL grant to research CO_2-selective, ultra-thin, functionalized hybrid polymer membranes integrated with carbon materials[3] • Research ended in May 2023
Other companies and activities: SUNY at Buffalo[4]		

Notes and sources: [1]EPFL Carbon Team website [2]InnoSense website [3]NETL project funding page for High-Performance, Hybrid Polymer Membrane for Carbon Dioxide Separation from Ambient Air [5]NETL project funding for State University of New York at Buffalo project on developing an integrated adsorption system enabled by solar heating and radiative cooling.

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

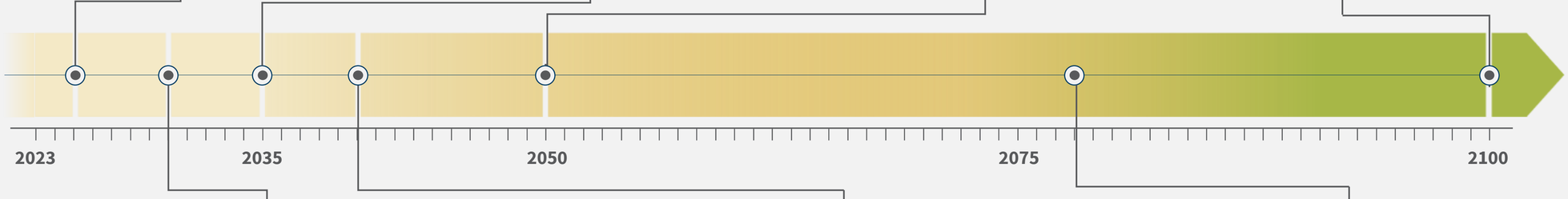
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 7.8

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Membrane: pressure gradient separation



2025

- Significant funding is allocated for R&D projects to advance materials, process design, equipment, and systems integration for this approach.
- A global database of R&D gaps is created. This database directs researchers and funders to the most critical open questions / R&D projects that need to be addressed.[1]
- Breakthroughs in basic research remain the focus of funding for this approach.

2030

- Membrane pressure gradient DAC approaches have been proven in the lab thanks to sufficient pre-demonstration funding.
- Given lab scale successes, this approach has cleared significant early TRL stage gates and warrants sufficient funding to be tested at the pilot scale.

- Total global capture[2] for all DAC operations reaches 60 $MtCO_2/y$. This approach is not yet mature enough to contribute significantly to that total.

2035

- The membrane pressure gradient approach either continues to receive funding based on promising R&D or it begins giving way to other, more competitive DAC approaches.

- Total global capture[2] for all DAC operations reaches 180 $MtCO_2/y$.

2040

- Total global capture[2] for all DAC operations reaches 560 $MtCO_2/y$.
- DAC facilities are synergistically sited alongside other industrial facilities as part of the energy transition.
- DAC facilities increasingly take advantage of new low-carbon generation, including non-peak electricity loads.
- A "fail fast" methodology applied across the DAC space has led to consolidated funding directed toward the best approaches. Unpromising approaches are no longer funded.

2050

- Total capture[2] from all forms of DAC reaches 1 $GtCO_2/y$.
- Breakthroughs in DAC R&D continue to drive down the cost of removals.
- Due to decades of competition, the most energy efficient and cost-optimized approaches to DAC have emerged as market leaders
- DAC clusters have emerged in industrial corridors, some of which remove 10-100 $MtCO_2/y$.

2050-2100

- Continued rapid scaling of DAC plants in accordance with climate objectives.
- Breakthroughs in DAC design and deployment lead to new facilities being built in distributed locations around the world.

These story elements are common to all DAC approaches.

2100

- Capture from all forms of DAC reaches 10 $GtCO_2/y$.[2]
- DAC facilities are operational globally.
- The cost of DAC is less than $\$100/tCO_2$ (adjusted to 2023 dollars).

Notes and sources: [1]A similar database is already initiated by Frontier. [2]We have assessed all DAC approaches in the AIR under a single growth paradigm. Our growth paradigm therefore is representative of the DAC field, not a specific DAC approach. We assumed a starting deployment of 60 $MtCO_2/y$ in 2030, which is the amount of DAC in the IEA Net Zero scenario in 2030, based on 130 proposed plants the IEA is tracking. We then assume that this 60 $MtCO_2/y$ grows at 25% per year from 2030 to 2040 and then 6% per year from 2040 to 2050. This growth paradigm includes 3 phases: (1) an initial period of rapid growth to 2030 where many new standalone facilities are built, (2) a secondary period of growth from 2030-2040 characterized by supply chain management, workforce development, and other scaling challenges, and (3) a sustained period of long-term growth characterized by more complex supply chains and large-scale systems. This multi-phase growth methodology is used in other AIR success stories and has also been recently modeled in academic papers, such as Roberts and Nemet, Pre-print 2023.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 7.8

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Membrane: pressure gradient separation

TRL

CRITICAL PATH ACTIVITIES

$400 - 750 million | **13-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Lab – materials R&D:** Perform materials discovery, optimization, and performance evaluation and validation
- **Lab and pilot – process & equipment:** Design and optimize the separation unit; test optimal process configurations and CO_2 concentration strategies
- **Lab and pilot – system integration:** Conduct independent TEA, LCA, climate sensitivity, and supply chain studies

$60-110 million | **5-10 years**

- ✓ Pathway to significant CAPEX and OPEX cost reductions via optimal equipment and process operation
- ✓ Reduced electricity requirements with potential to reach theoretical maximum efficiency
- ✓ Demonstrated ability to scale: e.g., CO_2 purity >85%[3]

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Demonstration – DAC+S:** Fund / support either novel configurations (that no company is currently pursuing) OR collaborate with entities already pursuing opportunities to scale.
- **MRV:** Measurement and verification should be performed by an independent entity.

$300-650 million | **8-10 years**

- ✓ Cost requirements: $200-600/tCO$_2$[4]
- ✓ Energy requirements: <7.5 GJ/tCO$_2$[5]

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$30-50 million | **5-10 years**

- Create a DAC R&D gap database to direct researchers and funders to the most critical open questions / R&D projects.
- Perform planning studies for industrial clusters to facilitate use of potentially available resources and existing CCS infrastructure.
- Investigate the use of CO_2 for valuable products such as chemicals and fuels.
- Establish industry standards with open-access designs for major equipment.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Verified carbon storage by a third-party accounting organization
- Low-carbon / green energy sourcing and low energy requirements
- Industry and consumer acceptance
- Long-term safety record with net carbon removal and durable storage
- Financing costs in line with commercially accepted technologies

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development. [3]Below this threshold, density changes, mostly due to the presence of non-condensable impurities (e.g., N_2, O_2, Ar), which cannot be liquified at ambient temperature, can affect storage capacity, injectivity, and buoyancy. More information found here. [4]Based on the assumptions in the "Pathway to full costs <$100/tCO$_2$" presented in the AIR Appendix. [5]DAC energy requirements of 7.5 GJ/tCO$_2$ require the equivalent of about 2.5 months of energy consumption for the average American household, and removing a gigaton of CO_2 would require about half the total energy consumed by the US in 2022.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK[1]	WORKSTREAM[2]	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Lab	R&D: Materials	Identify and test new membranes that improve material properties, such as CO_2 permeability, selectivity, kinetics, and achieve high purity targets without placing tens of membranes in series (which leads to substantial drops in pressure).	✓ Identify at least 3-5 high performing membranes to test at pilot scale[1] ✓ Validate expected material lifetime and manufacturing	1-3	$0.5-2M/y	2-4 y	$5-10M
		Assess material stability, recyclability, and manufacturing: • Conduct long-term degradation studies • Explore the effects of climate and harsh operational conditions • Study sorbent manufacturing and recycling / reuse / disposal					
Lab / pilot	R&D: Process design	Simulate and conduct synergistic material and process optimization considering different climate conditions and CO_2 purity targets.	✓ Identify and validate the performance of 2-3 configurations for low energy and cost	1-3	$1-3M/y	2-4 y	$10-20M
		Study alternative configurations (e.g., membranes stacked in series or in parallel) and experimentally validate process performance.					
Lab / pilot	R&D: Equipment	Simulate and test the most promising contactor designs (e.g., hollow fiber, spiral wound, etc.) for more efficient CO_2 permeability.	✓ Prototype at least 2-3 alternative unit designs that enable modularity	1-3 (lab)	$1-3M/y	2-4 y	$10-20M
		Improve process intensification for all equipment and test different connected membranes to reduce energy requirements, especially due to pressure drop.	✓ Validate performance of the most promising connected membranes	1-3 (pilot)	$5-10M/y	5-10 y	$30-50M
		Perform comparative studies for process design and primary equipment.					
Lab / pilot	R&D: System level studies	Conduct independent TEA, LCA, local / regional climate sensitivity studies, and supply chain analysis for the full DAC system (including material synthesis, transportation, and disposal).	✓ Independent estimates show costs and environmental impact are manageable	1-3	$0.5-2M/y	2-4 y	$5-10M

Notes and sources: [1]This CDR approach is underdeveloped / researched, rated as TRL 2. Some membrane components of the technology may be mature and used in other industrial process, so the focus of the pre-demonstration workstream is to adopt and optimize materials, equipment, and processes for DAC purposes. [2]List of recommended workstreams and budgets is adopted from Küng et al. (2023).

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	DAC+S: fund 2-3 demonstration projects of the most promising optimized configurations for energy and cost reduction using alternative materials, operational strategies, and optimal equipment.	1 $ktCO_2/y$ [1]	✓ Demonstrate CAPEX and OPEX cost improvements to an all-in cost <$100/$tCO_2$ ✓ Demonstrate reduction in energy requirements to <7.5 GJ/tCO_2, with potential for further reduction (<2.5GJ/tCO_2 for market acceptance)	1-3	$20M/y	8-10 y	$300-600M
MRV	Measurement, reporting, and verification protocols are established and validated by an independent third party.	N/A	✓ Verification of CO_2 storage and full lifecycle removals for DAC+S	1-3	$2-5M/y	5-10 y	$20-50M

Notes and sources: [1]Assumed similar FOAK scale as 'Adsorption and low-grade heat regeneration' approach.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research	DAC R&D gap database[3]	Create a global database of R&D gaps to accelerate DAC deployment by directing researchers and funders to the most critical open questions / R&D projects that need to be addressed.	1	$0.2-0.5M/y	3-5 y	$1-5M
Desktop research	Industrial cluster planning[4]	The most cost-effective DAC typically benefits from co-location with industrial clusters using CCS so that it can integrate with existing storage reservoirs (if this solution can succeed in reaching high purities in the product stream). This workstream should seek to identify clusters with access to competitive low-carbon and low-cost electricity contracts / sources which should significantly improve costs and LCA.	1-3	$0.5-2M/y[5]	5-10 y	$10-20M
Desktop research	Establishing industry standards	Build industry commitments to open-access designs of major process equipment. Shared designs and coordinated improvements could lower the cost of DAC.	1-3	$0.5-2M/y	5-10 y	$10-20M
Lab	DAC and utilization (DAC+U)[4]	Explore the possibility of using CO_2 products as feedstock to produce other chemicals and fuels. CO_2 utilization has the potential to de-risk and accelerate DAC deployment at scale by selling CO_2-based products, creating a new demand for CO_2, thus reducing the cost of DAC.	2-4	$0.5-2M/y	5-10 y	$20-30M

Notes and sources: [1]A reviewer suggested an additional workstream to establish test centers and advanced manufacturing facilities that could help accelerate the development and testing of new materials. [2]Cost estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]A similar database has already been initiated by Frontier. [4]Project planning and management are path-boosting activities for pre-demonstration and demonstration projects. [5]A reviewer notes that subsidies my be necessary to incentivize co-location for industrial clusters, which could significantly increase this cost.

SECTION 7.9

Membrane: electrochemical separation

SECTION	7.9
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Membrane: electrochemical separation

DEFINITION

Ion-exchange membrane separation in which the CO_2 is separated from other gases in an electrochemical cell by means of a membrane and electron transfer

EXAMPLE SCENARIO

Electrochemically generated ions bind with CO_2 in air and selectively permeate through a membrane to electrochemically release CO_2 for storage.

RMI

Section 7.9 overview

Membrane: electrochemical separation

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/tCO$_2$** • Key risks include the energy requirements of electrochemical cells and limited data available to characterize environmental impacts and cost
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium to low** • This approach is standardized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab stage** • 1 company at lab stage, with funding <$15M each
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment across all DAC approaches: **1 GtCO$_2$ by 2050** • Success is contingent on breakthroughs in basic research with sufficient pre-demonstration funding prove cost effectiveness
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$500M-$1B over 13-20 years** • Key stage gates in materials, process, and equipment development

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Very high risk:** Electrochemical cells have extremely high energy requirements.[1]	Energy needs meet our DAC criteria for "very high risk" (>10 GJ/tCO_2).[2] The contacting and the electrochemical cell alone requires approximately 41-62 GJ/tCO_2. DAC+S will require additional energy (e.g., compression, transport, and storage), which is excluded rom the publicly available energy value.[3]
	Land requirements	**Low risk:** Significant areas are suitable for DAC siting.	No information is publicly available, but it is expected that plant footprint will be very competitive with other DAC approaches. The footprint is larger if land use for energy production is considered.[3]
	Water requirements	**Medium risk:** Humidity / water may be required.	Depending on the specific configuration, humidity / water may be required.[4,8] However, there is a lack of publicly available data.
	Material requirements	**Medium risk:** High-demand materials are required.	Apart from basic construction materials (e.g., steel, cement), this solution relies on shortened membranes. If fuel cell electric vehicles scale significantly, expanding the supply chain would be considerably easier, but high demand materials for electrodes are required.[3]
	Co-location of DAC and storage	**Low risk:** Co-location of DAC and storage is relatively easy.	Can be located all around the globe. Humid environments are preferable for the RepAir configuration.[4,5]
	Environmental impacts	**High risk:** No/incomplete LCA data is available.	No LCA is currently available. Apart from impacts associated with energy and material requirements (including disposal and recycling), minimal to no other impacts are anticipated.[3]
Secure storage for 100+ years		**Low risk:** Storage is durable.	Geological sequestration or in-situ mineralization (primary storage options) are considered permanent storage approaches.[4]
Path to measurement at scale		**Low risk:** Measurement is straightforward.	DAC+S measurement and monitoring to inform MRV is straightforward. Capture occurs in a controlled environment and geological injection has established monitoring standards.[3]
Pathway to full costs <$100/$tCO_2$		**Very high risk:** Cost data is incomplete.[1,6]	We base our rating on cost estimates for FOAK plants and the quality of these estimates. We apply different cut-offs for modular / non-modular technologies, as modular approaches are comparatively less expensive and are easier to scale. This technology meets our criteria for "very high risk" (FOAK <10 ktCO_2; >$600 with incomplete data).[2,3,7]

Notes and sources: [1]RepAir claims much lower energy requirements (<2.5 GJ/tCO_2) but due to the lack of publicly available comparative studies, we rely only "A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage" (Küng et al., 2023). If data becomes available, the risk for the pathway to full costs <$100/$tCO_2$ will be reduced. [2]Methods and criteria used to assign DAC ratings are found in the AIR Appendix. [3]A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage (Küng et al., 2023) [4]Electrochemical Devices and Fuel Cell Systems (Yan et al., 2020) [patent] [5]There is a risk of CO_2 leakage if DAC and storage are not co-located. [6]To the best of our knowledge, there is limited publicly available data. [7]The price of available electricity will have a significant impact on the cost estimate. [8]See the RepAir configuration

Potential for cost improvement

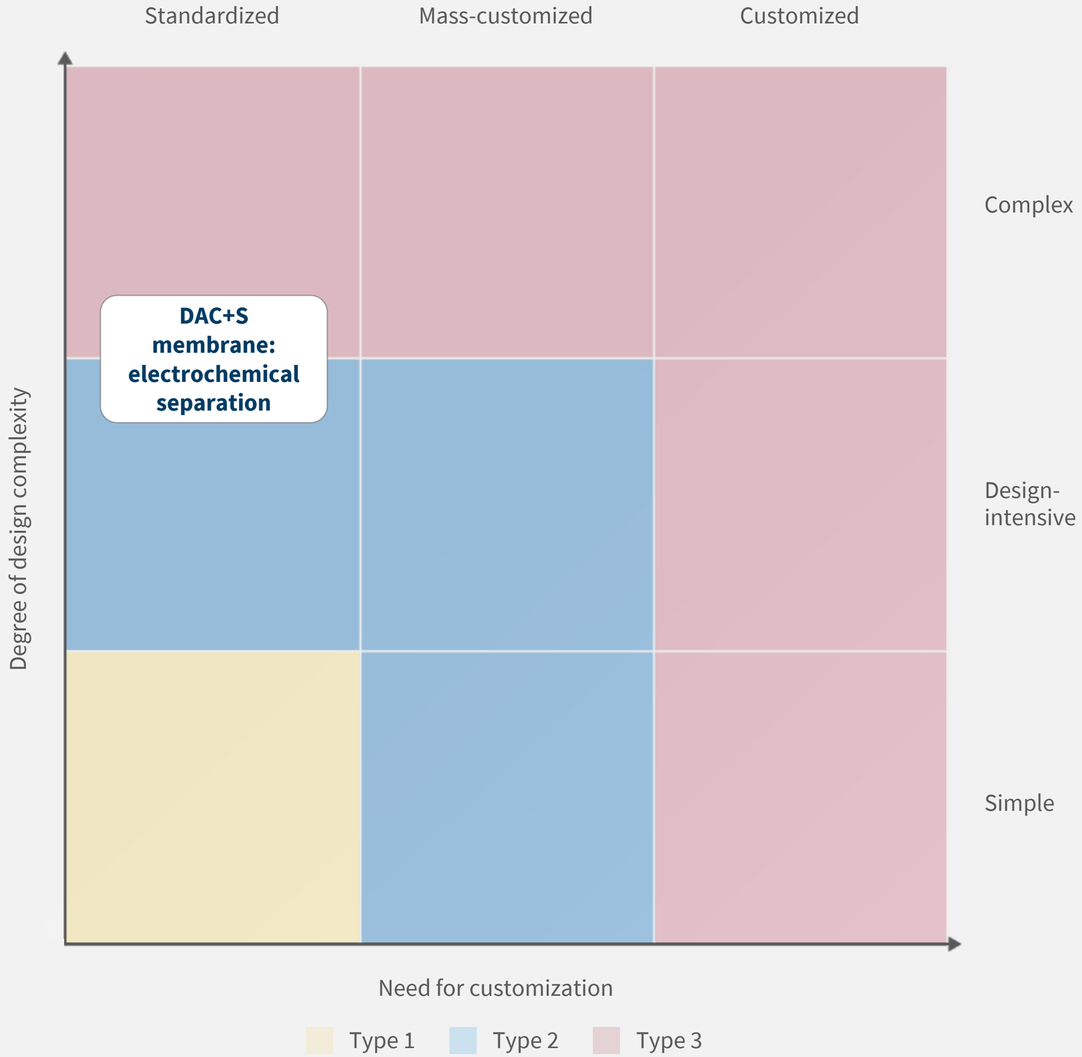
An assessment of two key drivers of learning rates

SECTION 7.9

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Membrane: electrochemical separation



OVERALL RATING

Type 2-3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 **Medium**

Type 3 **Low**

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive – complex
- **Rationale:** Membrane and electrochemical cell technologies are well understood, but design-intensive to complex designs are required (e.g., multiple membrane stacks in a row) to reach acceptable process performance.

NEED FOR CUSTOMIZATION

- **Rating:** Standardized
- **Rationale:** Systems are modular, designed to take place in smaller, less centralized facilities than liquid-based systems.[2]

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A mapping of companies, plus other notable activities

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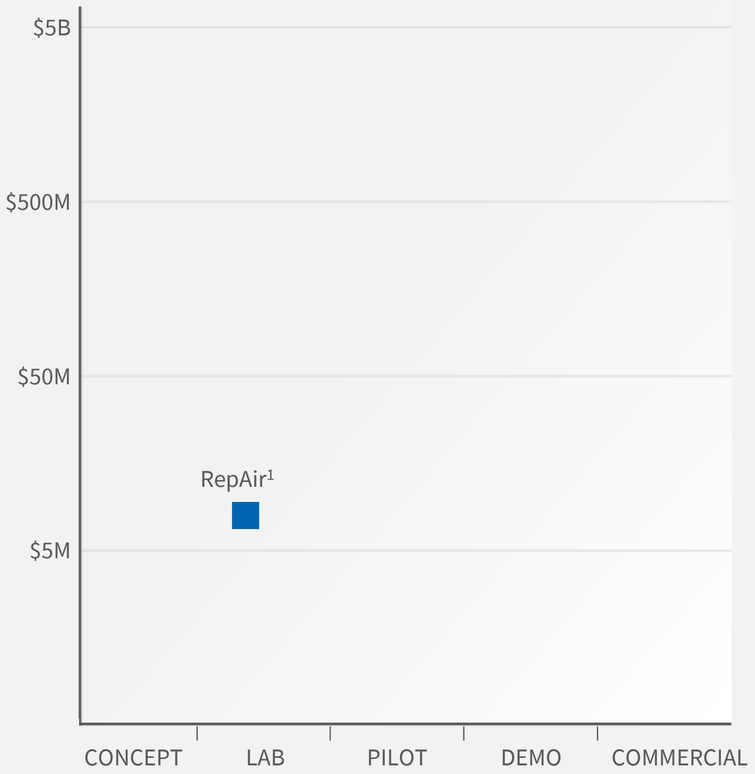

NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
RepAir: Using selective membranes and electricity to separate CO_2 from ambient air[1]	$11.5M[2]	• 2022 — Joined RMI Third Derivative accelerator cohort[3]

Notes and sources: [1]RepAir website [2]Crunchbase estimate for RepAir [4]RMI FGC Cohort 2

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What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
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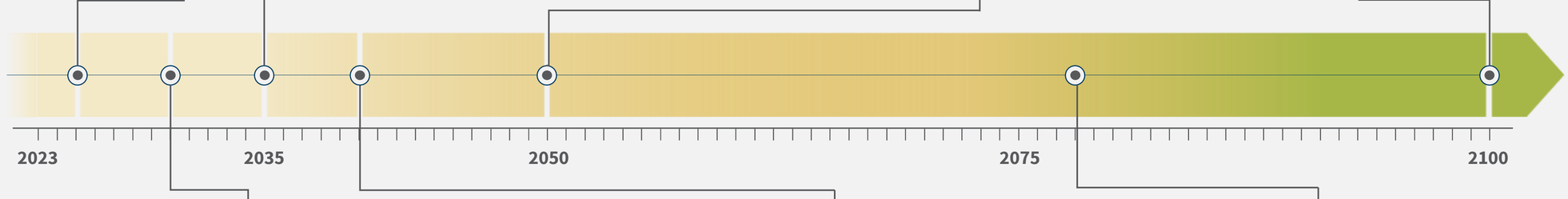

2025

- A global database of R&D gaps is created. This database directs researchers and funders to the most critical open questions / R&D projects that need to be addressed.[1]
- Breakthroughs in basic research remain the focus of funding for this approach.
- At least one pilot plant is under construction to determine the viability of this approach.

2030

- Sufficient pre-demonstration funding has enabled membrane electrochemical DAC approaches to be proven in a lab setting.
- Lab and pilot scale testing begin to inform future funding decisions for this DAC approach.

- Total global capture[2] for all DAC operations reaches 60 $MtCO_2/y$. This approach is not yet mature enough to contribute significantly to that total.

2035

- The membrane electrochemical gradient approach either continues to receive funding based on promising RD&D or it begins giving way to other, more competitive DAC approaches.

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- Total capture[2] from all forms of DAC reaches 1 $GtCO_2/y$.
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- DAC clusters have emerged in industrial corridors, some of which remove 10-100 $MtCO_2/y$.

2050-2100

- There is continued rapid scaling of DAC plants in accordance with climate objectives.
- Breakthroughs in DAC design and deployment lead to new facilities being built in widely distributed locations all around the world.

These story elements are common to all DAC approaches.

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$100-200 million | **5-10 years**

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$400-850 million | **8-10 years**

- ✓ Cost requirements: \$200-600/tCO_2[4]
- ✓ Energy requirements: <7.5 GJ/tCO_2[5]
- ✓ Low water requirements
- ✓ Minimum operating current density: 50-100 mA/cm^2

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

SECTION 7.9

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Membrane: electrochemical separation

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$40-60 million | **5-10 years**

- Create a DAC R&D gap database to direct researchers and funders to the most critical open questions / R&D projects.
- Perform planning studies for industrial clusters to facilitate the use of potentially available resources and existing CCS infrastructure.
- Investigate the use of CO_2 for valuable products such as chemicals and fuels.
- Assess water risks to enable better siting decisions.
- Establish industry standards with open-access designs for major equipment.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Verified carbon storage by a third-party accounting organization
- Low-carbon / green energy sourcing and low energy requirements
- Industry and consumer acceptance
- Long-term safety record with net carbon removal and durable storage
- Financing costs in line with commercially accepted technologies

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development. [3]Below this threshold, density changes, mostly due to the presence of non-condensable impurities (e.g., N_2, O_2, Ar), which cannot be liquified at ambient temperature, can affect storage capacity, injectivity, and buoyancy. More information found here. [4]Based on the assumptions in the "Pathway to full costs <\$100/tCO_2" presented in the appendix. [5]DAC energy requirements of 7.5 GJ/tCO_2 require the equivalent of about 2.5 months of energy consumption for the average American household, and removing a gigaton of CO_2 would require about half the total energy consumed by the US in 2022.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK[1]	WORKSTREAM[2]	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Lab	R&D: Materials	Identify and test new membranes that improve CO_2 permeability and reach high purity targets without placing tens of membranes in a series, which leads to higher electrical potential to electro-migrate the carbon species across. Assess material stability, recyclability, and manufacturing: • Conduct long-term degradation studies • Explore the effects of climate and harsh operational conditions • Study sorbent manufacturing and recycling / reuse / disposal	✓ Identify at least 3-5 high performing membranes to test at pilot scale[1] ✓ Validate expected material lifetime and manufacturing requirements	2-4	$0.5-2M/y	2-4 y	$10-20M
Lab / pilot	R&D: Process design	Simulate and conduct synergistic material and process optimization that considers different climate conditions and CO_2 purity targets. Assess alternative configurations (e.g., flat plate, spirally wound), electrode current density, uniformity, and flat plate tolerances, and experimentally validate process performance.	✓ Identify and validate performance of 2-3 configurations for expected low energy and cost	2-4	$1-3M/y	2-4 y	$20-30M
Lab / pilot	R&D: Equipment	Simulate and test optimal contactor designs for pilot scale and demonstration scale electrochemical cell stacks.	✓ Prototype at least 2-3 contactor designs that enable modularity[3]	2-4 (lab)	$1-3M/y	2-4 y	$20-30M
		Improve process intensification for all equipment and test different connected membranes for lower energy requirements, especially due to pressure drop. Perform comparative studies for process design and primary equipment.	✓ Identify at least 2-3 alternative electrochemical cell designs[3]	2-4 (pilot)	$5-10M/y	5-10 y	$50-100M
Lab / pilot	R&D: System level studies	Conduct independent TEA, LCA, local / regional climate sensitivity studies, and supply chain analysis on the full DAC system, including material synthesis, transportation, and disposal.	✓ Independent estimates show costs and environmental impact are manageable	2-4	$0.5-2M/y	2-4 y	$10-20M

Notes and sources: [1]The approach is currently rated at TRL 3 after RepAir proved the concept in the lab, although there are no publicly announced pilot or demonstration projects. Major knowledge gaps remain since there is limited public data available. Alternative opportunities for reducing energy demand and cost remain unexplored. [2]List of recommended workstreams and budgets is adopted from Küng et al (2023). [3]Integration of the air contactor and the electrochemical cell is also possible.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	DAC+S: Fund 2-3 demonstration projects of the most promising optimized configurations for energy and cost reduction using alternative materials, operational strategies, and optimized equipment.[1]	1 $ktCO_2/y$[2]	✓ Demonstrate CAPEX and OPEX cost improvements toward an all-in cost <$100/$tCO_2$ ✓ Demonstrate reduction in energy requirements to <7.5 GJ/tCO_2, with potential for further reduction (<2.5 GJ/tCO_2 for market acceptance) ✓ Demonstrate negligible water consumption per tCO_2 ✓ Demonstrate a minimum operating current density of 50-100 mA/cm^2	2-4	$20M/y	8-10 y	$400-800M
MRV	Measurement, reporting, and verification protocols are established and validated by an independent third party.	N/A	✓ Verification of CO_2 storage and full lifecycle removals for DAC+S	1-3	$2-5M/y	5-10 y	$20-50M

Notes and sources: [1]Given the high likelihood of candidate demonstration projects overlapping with an existing startup approach, demonstration project collaboration should be investigated. This can reduce the overall price tag per demonstration project, especially with regard to public funding, and generally accelerate the pathway for unique DAC+S demonstration projects. A key of objective of these collaborations should be data transparency incentivized by public funding. [2]Assumed similar FOAK scale as 'Adsorption and low-grade heat regeneration' approach.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

☐ Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research	DAC R&D gap database[3]	Create a global database of R&D gaps to accelerate DAC deployment by directing researchers and funders to the most critical open questions / R&D projects that need to be addressed.	1	$0.2-0.5M/y	3-5 y	$1-5M
Desktop research	Industrial cluster planning[4]	The most cost-effective DAC typically benefits from co-location with industrial clusters using CCS so that it can integrate with existing storage reservoirs. This workstream should seek to identify clusters with access to competitive low-carbon and low-cost electricity contracts / sources which should significantly improve costs and LCA.	1-3	$0.5-2M/y[5]	5-10 y	$10-20M
Desktop research	Establishing industry standards	Build industry commitments to open-access designs of major process equipment. Shared designs and coordinated improvements could lower the cost of DAC.	1-3	$0.5-2M/y	5-10 y	$10-20M
Lab	DAC and utilization (DAC+U)[4]	Explore the possibility of using CO_2 products as feedstock to produce other chemicals and fuels or unique end-uses with durable forms of storage (as this approach may only make sense when downstream compression and purification is skipped). CO_2 utilization has the potential to de-risk and accelerate DAC deployment at scale by selling CO_2-based products, creating a new demand for CO_2, and thus reducing the cost of DAC.	2-4	$0.5-2M/y	5-10 y	$20-30M
Desktop research	Water risk assessments	Desktop research to generate risk assessments of water sourcing and usage to enable better siting decisions.	1-3	$0.5-2M/y	3-5 y	$5-10M

Notes and sources: [1]A reviewer suggested an additional workstream to establish test centers and advanced manufacturing facilities that could help accelerate the development and testing of new materials. [2]Cost estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]A similar database has already been initiated by Frontier. [4]Project planning and management are path-boosting activities for pre-demonstration and demonstration projects. [5]A reviewer notes that subsidies my be necessary to incentivize co-location for industrial clusters, which could significantly increase this cost.

SECTION 7.10

Cryogenic: phase separation (vapor-solid)

SECTION	7.10
TAXONOMIC BUCKET	Synthetic
CDR CATEGORY	DAC
APPROACH	Cryogenic: phase separation (vapor-solid)

DEFINITION

Cryogenic separation in which very low temperatures enable a phase separation of CO_2 from other gases by deposition (a phase transition of CO_2 from vapor to solid)

EXAMPLE SCENARIO

At very low temperatures, CO_2 in air solidifies as dry ice on the surface of heat exchangers and then is removed through sublimation, resulting in concentrated CO_2 for storage.

RMI

Section 7.10 overview

Cryogenic: phase separation (vapor-solid)

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **Scalability and pathway to full costs <$100/tCO$_2$** • Key risks include energy requirements of cryogenic separation and limited data available to characterize environmental impacts and cost
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Low** • This approach is standardized and complex
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Lab and pilot stages** • ~2 companies at lab and pilot stages with funding <$50M each
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Deployment across all DAC approaches: **1 GtCO$_2$ by 2050** • Success is contingent on breakthroughs in materials, process design, and equipment, as well as siting synergies and increased cost effectiveness as compared to other DAC approaches
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$1-2B over 13-20 years** • Key stage gates in cooling liquid and process

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk Medium risk High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**High risk:** Cryogenic separation is very energy intensive.	Energy needs meet our DAC criteria for "high risk" (>5 GJ/tCO_2).[1] Contacting and cooling alone require approximately 5 GJ/tCO_2.[2]
	Land requirements	**Medium risk:** Deployment may be limited to very cold regions to avoid massive energy requirements.	No information is available, but it is expected that cryogenic DAC plants will have a larger footprint than other DAC approaches due to the number of precooling units, separation units, compressors, and condensers that will be required. The footprint will be greater if land use for energy production is considered.[3,4,5] Also, in the case of deployment in remote regions, dedicated energy infrastructure will be difficult to access.
	Water requirements	**Low risk:** Water is not expected to be required in significant quantities.	No information is available, but water is not expected to be an issue.[2]
	Material requirements	**Low risk:** No rare materials are required.	Apart from basic construction materials (e.g., steel, cement), this solution does not require the use of physical or chemical solvents or sorbents. If applicable, cryogenic liquids will be required.[3,5]
	Co-location of DAC and storage	**Medium risk:** Co-location may be challenging.	Remote regions can make co-location challenging, although the technology can produce CO_2 outputs suitable for long-term storage.[2,6]
	Environmental impacts	**High risk:** No / incomplete LCA data available.	No LCA is currently available. Beyond impacts associated with energy and material requirements, no other impacts are anticipated.[2]
Secure storage for 100+ years		**Low risk:** Storage is durable.	Geological sequestration or in-situ mineralization (primary storage options) are considered permanent storage options.[3,4,5]
Path to measurement at scale		**Low risk:** Measurement is straightforward.	DAC+S measurement and monitoring to inform MRV is straightforward. Capture occurs in a controlled environment and geological injection has established monitoring standards.[2]
Pathway to full costs <$100/t$CO_2$		**Very high risk:** Incomplete cost data[7]	We base our rating on cost estimates for FOAK plants and the quality of these estimates. We apply different cut-offs for modular / non-modular technologies, as iteration is easy and comparatively inexpensive for modular technologies. This technology meets our criteria for "very high risk" (FOAK <10 ktCO_2; >$500 with incomplete data).[1,2,8]

Notes and sources: [1]Methods and criteria used to assign DAC ratings are found in the AIR Appendix. [2]A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage (Küng et al., 2023) [3]Cryogenic-based CO_2 capture technologies: State-of-the-art developments and current challenges (Song et al., 2019) [4]Thermal removal of carbon dioxide from the atmosphere: energy requirements and scaling issues (von Hippel, 2018) [5]Review of Cryogenic Carbon Capture Innovations and Their Potential Applications (Font-Palma et al., 2021) [6]There is a risk of CO_2 leakage if DAC and storage are not co-located. [7]To the best of our knowledge, there is limited publicly available data. [8]The price of available electricity will have a significant impact on the cost estimate.

Potential for cost improvement

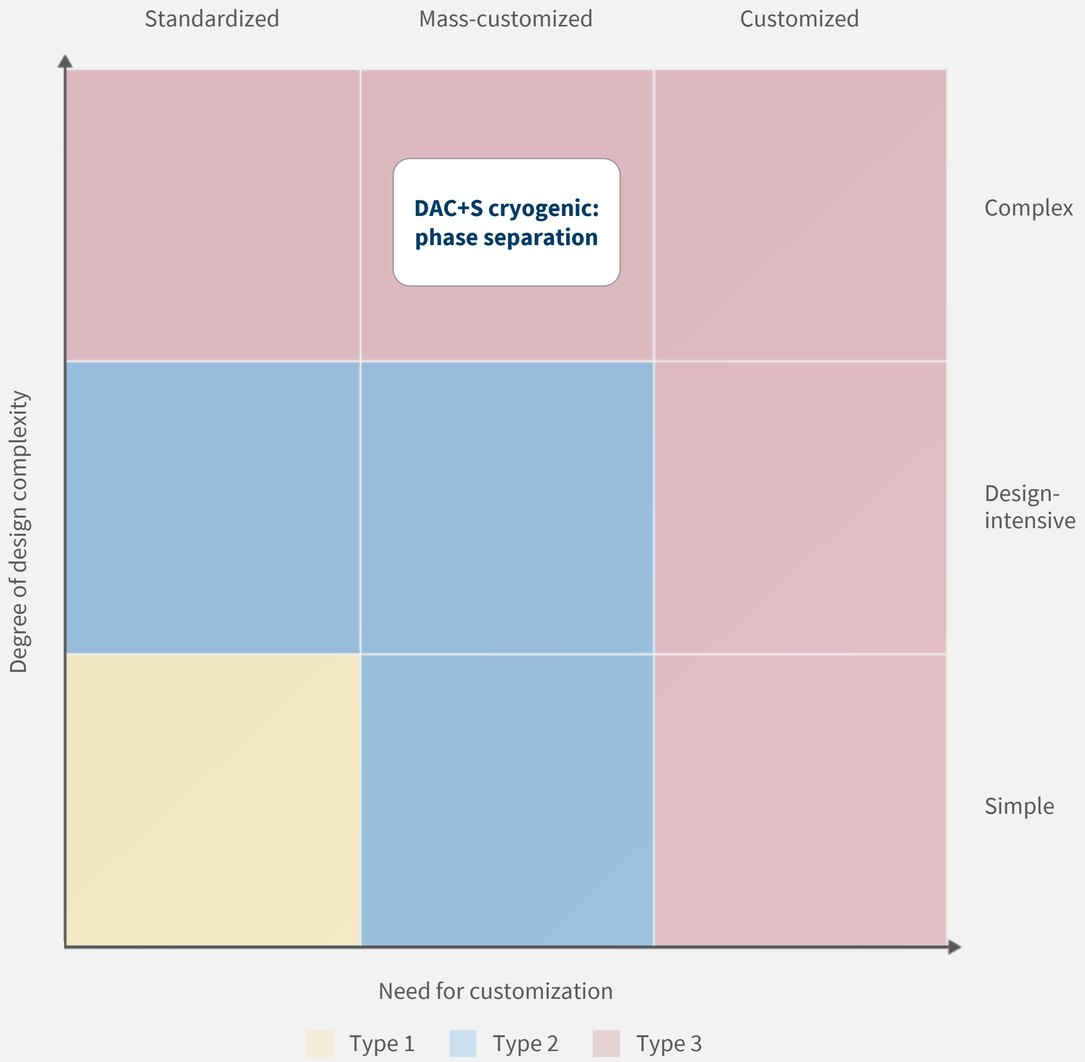
An assessment of two key drivers of learning rates

SECTION 7.10

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Cryogenic: phase separation (vapor-solid)



OVERALL RATING

Type 3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Complex
- **Rationale:** This approach utilizes a complex process that includes multiple compression stages, separation units, and condensers (e.g., multiple heat exchangers are required for CO_2 defrosting). This follows the conventional cryogenic post-combustion CCS approach.[2]

NEED FOR CUSTOMIZATION

- **Rating:** Mass-customized
- **Rationale:** There is a need for equipment customization and adaptation to specific sites and ambient conditions, despite some standardization of components.[2]

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix. [2]Overall sCDR assessment on cost improvement is based on Roberts and Nemet, "Lessons for Direct Air Capture from the History of Nitrogen Synthesis: High rates of deployment are possible, with strong support", (Roberts and Nemet, Pre-print 2023).

Current state of RD&D

A mapping of companies, plus other notable activities

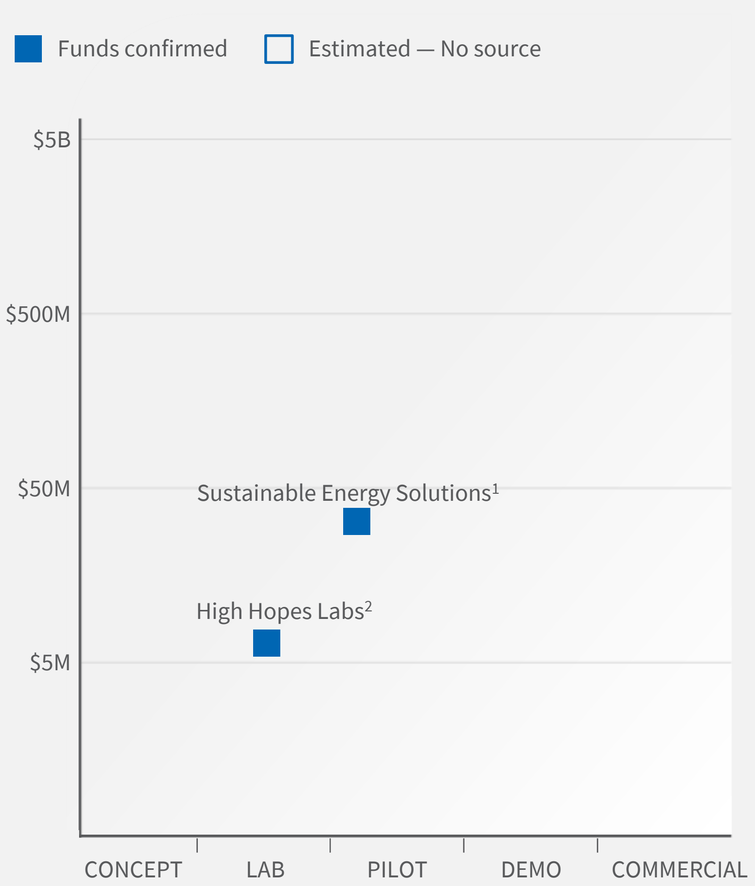
NOT EXHAUSTIVE

SECTION 7.10

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Cryogenic: phase separation (vapor-solid)



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Sustainable Energy Solutions: Developed cryogenic technology to freeze out, liquify, and store CO_2[1]	Acquired for $45M[3]	• Completed a pilot in 2022 combining cryogenic technology and cement / concrete production, proved to capture 96-98% of CO_2 treated from flue gas[4]
High Hopes Labs: Developed "High Altitude Carbon Capture" (HACC) approach[2]	$6M	• Received patent from US Patent and Trademark Office in 2022

Notes and sources: [1]Sustainable Energy Solutions website [2]High Hopes Labs website, approach called "High Altitude Carbon Capture" (HACC), they are developing a passive capture system that leverages ideal conditions at high altitude ~15km above ground where extreme freezing temperatures turn CO_2 to a solid and windy conditions allow for passive capture. Their system is based on weather observation balloons. Based on limited information online, High Hopes Labs has raised $6M. They received a patent for balloon technology, Carbon Herald. [3]Chart Industries acquired Sustainable Energy Solutions for $45M. [4]Sustainable Energy Solutions pilot project description

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

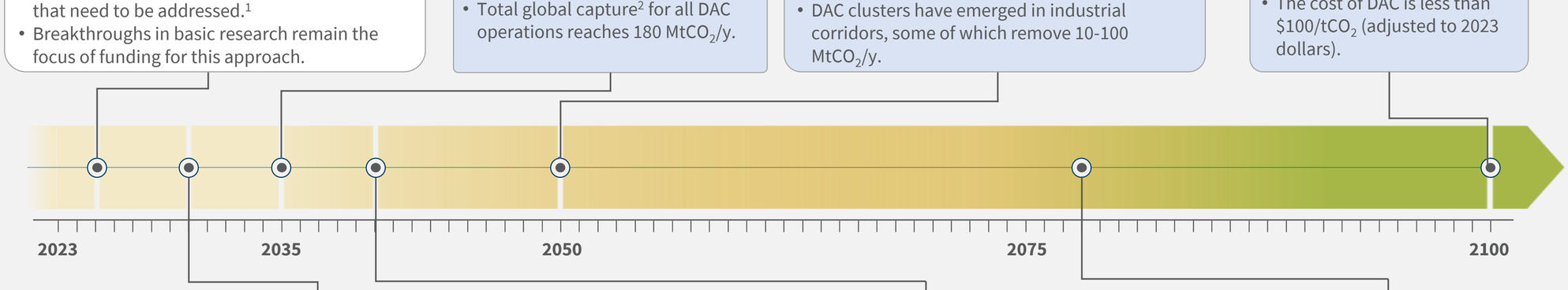
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 7.10

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Cryogenic: phase separation (vapor-solid)



2025

- Significant funding is allocated for R&D projects to advance materials, process design, equipment, and systems integration for this approach.
- A global database of R&D gaps is created. This database directs researchers and funders to the most critical open questions / R&D projects that need to be addressed.[1]
- Breakthroughs in basic research remain the focus of funding for this approach.

2030

- R&D breakthroughs in materials, process design, equipment, and systems integration lead to significant cost improvements for this approach.
- With lab scale successes, this approach clears significant early TRL stage gates and warrants sufficient funding to be tested at the pilot scale.

- Total global capture[2] for all DAC operations reaches 60 $MtCO_2/y$. This approach is not yet mature enough to contribute significantly to that total.

2035

- The cryogenic DAC approach either continues to receive funding based on promising R&D and pilots, or it begins giving way to other, more competitive DAC approaches.

- Total global capture[2] for all DAC operations reaches 180 $MtCO_2/y$.

2040

- Total global capture[2] for all DAC operations reaches 560 $MtCO_2/y$.
- DAC facilities are synergistically sited alongside other industrial facilities as part of the energy transition.
- DAC facilities increasingly take advantage of new low-carbon generation, including non-peak electricity loads.
- A “fail fast” methodology applied across the DAC space has led to consolidated funding directed toward the best approaches. Unpromising approaches are no longer funded.

2050

- Total capture[2] from all forms of DAC reaches 1 $GtCO_2/y$.
- Breakthroughs in DAC R&D continue to drive down the cost of removals.
- Due to decades of competition, the most energy efficient and cost-optimized approaches to DAC have emerged as market leaders.
- DAC clusters have emerged in industrial corridors, some of which remove 10-100 $MtCO_2/y$.

2050-2100

- There is continued rapid scaling of DAC plants in accordance with climate objectives.
- Breakthroughs in DAC design and deployment lead to new facilities being built in distributed locations around the world.

These story elements are common to all DAC approaches.

2100

- Capture from all forms of DAC reaches 10 $GtCO_2/y$.[2]
- DAC facilities are operational globally.
- The cost of DAC is less than $\$100/tCO_2$ (adjusted to 2023 dollars).

Notes and sources: [1]A similar database has already been initiated by Frontier. [2]We have assessed all DAC approaches in the AIR under a single growth paradigm. Our growth paradigm therefore is representative of the DAC field, not a specific DAC approach. We assumed a starting deployment of 60 $MtCO_2/y$ in 2030, which is the amount of DAC in the IEA Net Zero scenario in 2030, based on 130 proposed plants the IEA is tracking. We then assume that this 60 $MtCO_2/y$ grows at 25% per year from 2030 to 2040 and then 6% per year from 2040 to 2050. This growth paradigm includes 3 phases: (1) an initial period of rapid growth to 2030 where many new standalone facilities are built, (2) a secondary period of growth from 2030-2040 characterized by supply chain management, workforce development, and other scaling challenges, and (3) a sustained period of long-term growth characterized by more complex supply chains and large-scale systems. This multi-phase growth methodology is used in other AIR success stories and has also been recently modeled in academic papers, such as Roberts and Nemet, Pre-print 2023.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 7.10

TAXONOMIC BUCKET Synthetic

CDR CATEGORY DAC

APPROACH Cryogenic: phase separation (vapor-solid)

TRL

CRITICAL PATH ACTIVITIES

$1-2 billion | **13-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Lab – materials R&D:** Identify optimal cryogenic liquids; evaluate and validate their performance
- **Lab and pilot – process & equipment:** Optimize performance of the CO_2 cooling method; test optimal operational strategies and process design
- **Lab and pilot – system integration:** Conduct independent TEA, LCA, climate sensitivity, and supply chain studies

$60-110 million | **5-10 years**

- ✓ Pathway to significant CAPEX and OPEX cost reductions via optimal equipment and process operation
- ✓ Reduced electricity and heat requirements with potential to reach theoretical maximum efficiency
- ✓ Demonstrated ability to scale: e.g., CO_2 purity >85%[3]

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Demonstration – DAC+S:** Fund / support either novel configurations (that no company is currently pursuing) OR collaborate with entities already pursuing opportunities to scale
- **MRV:** Measurement and verification should be performed by an independent entity

$1-2 billion | **8-10 years**

- ✓ Cost requirements: $100-500/tCO$_2$[4]
- ✓ Energy requirements: <7.5 GJ/tCO$_2$[5]

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$30-50 million | **5-10 years**

- Create a DAC R&D gap database to direct researchers and funders to the most critical open questions / R&D projects.
- Perform planning studies for industrial clusters to facilitate use of potentially available resources and existing CCS infrastructure.
- Investigate the use of CO_2 for valuable products such as chemicals and fuels.
- Assess water risks to enable better siting decisions.
- Establish industry standards with open-access designs for major equipment.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Demonstrated market competitive costs
- Verified carbon storage by a third-party accounting organization
- Low-carbon / green energy sourcing and low energy requirements
- Industry and consumer acceptance
- Long-term safety record with net carbon removal and durable storage
- Financing costs in line with commercially accepted technologies

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development. [3]Below this threshold, density changes, mostly due to the presence of non-condensable impurities (e.g., N_2, O_2, Ar), which cannot be liquified at ambient temperature, can affect storage capacity, injectivity, and buoyancy. More information found here. [4]Based on the assumptions in the "Pathway to full costs <$100/tCO$_2$" presented in the AIR Appendix. [5]DAC energy requirements of 7.5 GJ/tCO$_2$ require the equivalent of about 2.5 months of energy consumption for the average American household, and removing a gigaton of CO_2 would require about half the total energy consumed by the US in 2022.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK[1]	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	R&D: Materials	Identify optimal cryogenic liquids for nonconventional alternative methods to heat exchangers. Liquids should enable direct contact with atmospheric air, causing the air to form solid CO_2 particles in a staged de-sublimation column.	✓ Identify 2-3 cryogenic liquids to test at pilot scale if this alternative method is viable ✓ Validate expected cryogenic liquid lifetime	1-3	$0.5-2M/y	2-4 y	$5-10M
		Ensure material recyclability by minimizing loss of contact liquid in the solid CO_2 filtration step, conducting long degradation studies, and exploring the effects of climate and harsh operational conditions.					
Lab / pilot	R&D: Process design	Simulate and conduct process optimization and energy intensification for each configuration to overcome challenges related to the availability of cold energy sources, capture costs, storage, and impurities.[2]	✓ Identify and validate performance of 2-3 configurations with expected low energy and cost (e.g., reduced cooling duties, increased heat transfer)	1-3	$1-3M/y	2-4 y	$10-20M
		Design alternative CO_2 cooling methods for heat exchangers (e.g., packed beds and cryogenic liquids) and experimentally validate process performance, including determining the effect of humidity and harsh operational conditions.					
Lab / pilot	R&D: Equipment	Simulate and test cost-effective heat exchanger designs and materials (e.g., coil-wound, plate heat, and regenerative heat exchangers)	✓ Prototype at least 2-3 alternative heat exchanger or CO_2 cooling designs and solid CO_2 handling solutions	1-3 (lab)	$1-3M/y	2-4 y	$10-20M
		Optimize auxiliary equipment (e.g., condensers and compressors) and identify solid CO_2 handling solutions.					
		Test alternative CO_2 cooling methods (e.g., packed beds and cryogenic liquids).	✓ Validate the performance of the most promising methods for CO_2 cooling and solid CO_2 solutions handling	1-3 (pilot)	$5-10M/y	5-10 y	$30-50M
		Perform comparative studies for process design and primary equipment.					
Lab / pilot	R&D: System level studies	Conduct independent TEA[3], LCA, local / regional climate sensitivity studies, and supply chain analysis on the full DAC system, including material synthesis, transportation, and disposal.	✓ Independent estimates show costs and environmental impact are manageable	1-3	$0.5-2M/y	2-4 y	$5-10M

Notes and sources: [1]This CDR approach underdeveloped / researched, rated as TRL 4. Components of the technology are very mature and used in other industrial process, so the focus of the pre-demonstration workstream is to adopt and optimize materials, equipment, and process for DAC purposes. [2]This workstream should also make use of insights from conventional and nonconventional cryogenic methods developed in flue gas-based carbon capture processes. [3]This workstream can also identify opportunities for cryogenic separation to enhance the techno-economics of other DAC systems.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	DAC+S: Fund 2-3 demonstration projects of the most promising optimized configurations for energy and cost reduction using alternative materials, operational strategies, and optimized equipment.[1,2]	1 $MtCO_2/t$[3,4]	✓ Demonstrate CAPEX and OPEX cost improvements toward an all-in cost <$100/$tCO_2$ ✓ Demonstrate reduction in energy requirements to <7.5 GJ/tCO_2, with potential for further reduction (<2.5 GJ/tCO_2 for market acceptance)	1-3	$100M/y	8-10 y	$1,000-2,000M
MRV	Measurement, reporting, and verification protocols are established and validated by an independent third party.	N/A	✓ Verification of CO_2 storage and full lifecycle removals for DAC+S	1-3	$2-5M/y	5-10 y	$20-50M

Notes and sources: [1]Given the high likelihood of candidate demonstration projects overlapping with an existing startup approach, demonstration project collaboration should be investigated. This can reduce the overall price tag per demonstration project, especially with regard to public funding, and generally accelerate the pathway for unique DAC+S demonstration projects. A key of objective of these collaborations should be data transparency incentivized by public funding. [2]There are opportunities for this technology to supplement other DAC systems. [3]Assumed a similar DAC scale as 'Absorption and high-grade heat regeneration' approach. [4]A reviewer noted that 980 $ktCO_2/y$ is likely quite large for a demonstration plant. Industrial scale cryogenic air separation plants might process the equivalent of 25-125 $ktCO_2e/y$ worth of air. It would be worthwhile to understand what the minimum-viable scale for these plants needs to be in to evaluate the economies of scale.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

☐ Cross-cutting method

TYPE OF WORK	WORKSTREAM[1]	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET[2]	DURATION	TOTAL COST
Desktop research	DAC R&D gap database[3]	Create a global database of R&D gaps to accelerate DAC deployment by directing researchers and funders to the most critical open questions / R&D projects that need to be addressed.	1	$0.2-0.5M/y	3-5 y	$1-5M
Desktop research	Industrial cluster planning[4]	The most cost-effective DAC typically benefits from co-location with industrial clusters using CCS so that it can integrate with existing storage reservoirs. This workstream should seek to identify clusters with access to competitive low-carbon and low-cost electricity contracts / sources that could significantly improve costs and LCA.	1-3	$0.5-2M/y[5]	5-10 y	$10-20M
Desktop research	Establishing industry standards	Build industry commitments to open-access designs of major process equipment. Shared designs and coordinated improvements could lower the cost of DAC.	1-3	$0.5-2M/y	5-10 y	$10-20M
Lab	DAC and utilization (DAC+U)[4]	Explore the possibility of using CO_2 products as feedstock to produce other chemicals and fuels. CO_2 utilization has the potential to de-risk and accelerate DAC deployment at scale by selling CO_2-based products, creating a new demand for CO_2, thus reducing the cost of DAC.	2-4	$0.5-2M/y	5-10 y	$20-30M

Notes and sources: [1]A reviewer suggested an additional workstream to establish test centers and advanced manufacturing facilities that could help accelerate the development and testing of new materials. [2]Cost estimates based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]A similar database has been already initiated by Frontier. [4]Project planning and management are path-boosting activities for pre-demonstration and demonstration projects. [5]A reviewer notes that subsidies my be necessary to incentivize co-location for industrial clusters, which could significantly increase this cost.

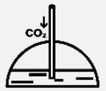
Intro to storage of CO_2

DEFINITION: *Storage of CO_2 approaches store captured and concentrated streams of CO_2 through trapping, mineralization, or other physical or chemical processes.*[1]

CO_2 storage includes conventional storage and unconventional storage, but we consider all three of these approaches under a common CO2 storage section:

Conventional storage

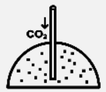
Storage of CO_2 in structural or mineral traps.



8.1

Unconventional storage

Any CO_2 storage that is not conventional. This includes storage of CO_2 by in-situ and ex-situ mineralization.



8.2

8.3

Notes and sources: These approaches do not capture CO_2 from the atmosphere but instead provide storage concentrated streams of captured CO_2. Captured CO_2 can come from BECCS units, electrochemical ocean stripping, DAC units, or any other process that produces a highly concentrated stream of CO_2.

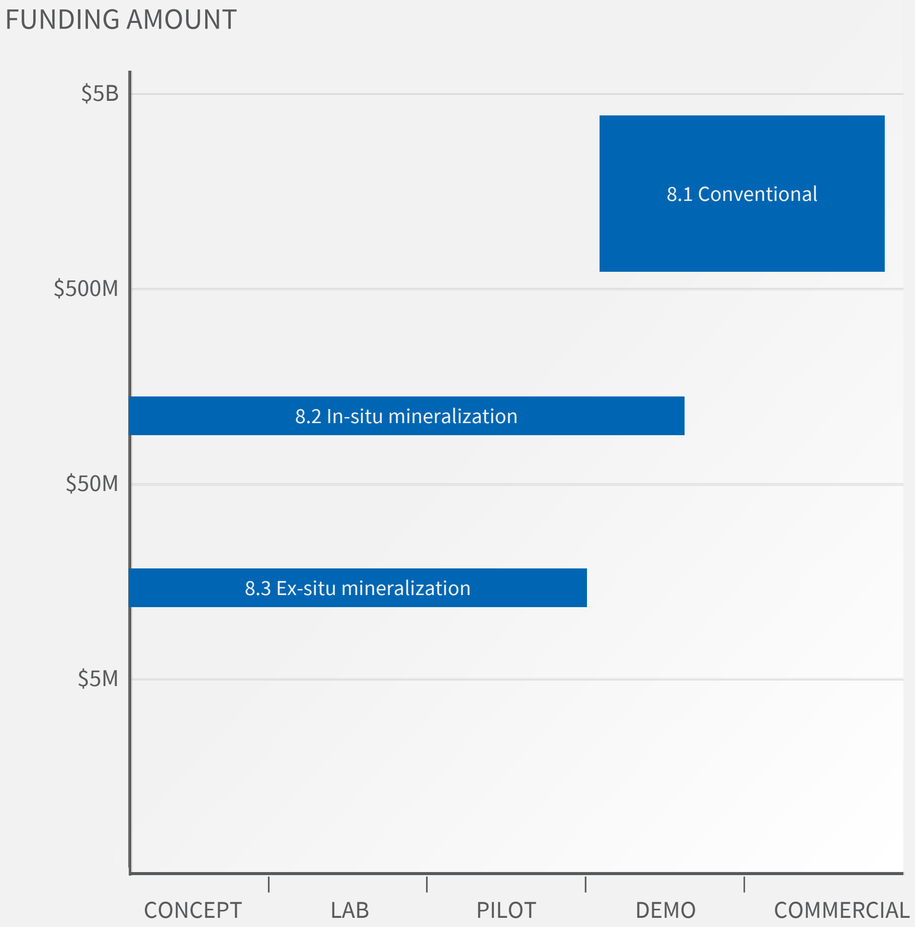
CO_2 storage definitions and example scenarios

8. CO_2 storage: Approaches that are used to store captured and concentrated streams of CO_2.

INDEX	APPROACHES	DEFINITION	EXAMPLE SCENARIOS
8.1	Conventional CO_2 storage	Storage of CO_2 by injection into depleted oil and gas reservoirs, saline aquifers, and other pore spaces with slow mineralization rates in order to confine the CO_2 underground via structural, residual, or solubility trapping	1) Injecting a stream of CO_2 gas into a saline aquifer thousands of feet below the surface of the earth and below a cap rock to prevent future leakage; 2) Storing a stream of CO_2 gas in a man-made holding tank or a salt cavern.
8.2	In-situ mineralization	Circulation of either supercritical CO_2 or CO_2-rich fluid through subsurface alkaline rocks, stabilizing carbon underground for durable storage via mineral trapping, i.e., conversion to solid carbonate minerals	1) Injecting a stream of captured CO_2 that is mixed with water into porous basaltic rock formations where it reacts with the rocks to create solid carbonate minerals; 2) injecting a supercritical stream of captured CO_2 into a peridotite mineral formation with moisture present, where the CO_2 reacts to form solid carbonate minerals
8.3	Ex-situ mineralization	Reacting CO_2 with either natural alkaline minerals or artificial alkaline by-products and wastes in engineered reactors, rather than under ambient conditions. These reactions typically go to completion within minutes using high temperatures, pressures, electrochemistry, and/or pH changes to accelerate the mineralization process.	1) Integrating an industrial waste stream of CO_2 into a reactor in which reactions with alkaline minerals are accelerated, forming carbonate minerals in minutes and storing the waste stream CO_2.

Conventional CO_2 storage is at commercial scale, and mineralization approaches are also receiving significant funding

NOT EXHAUSTIVE

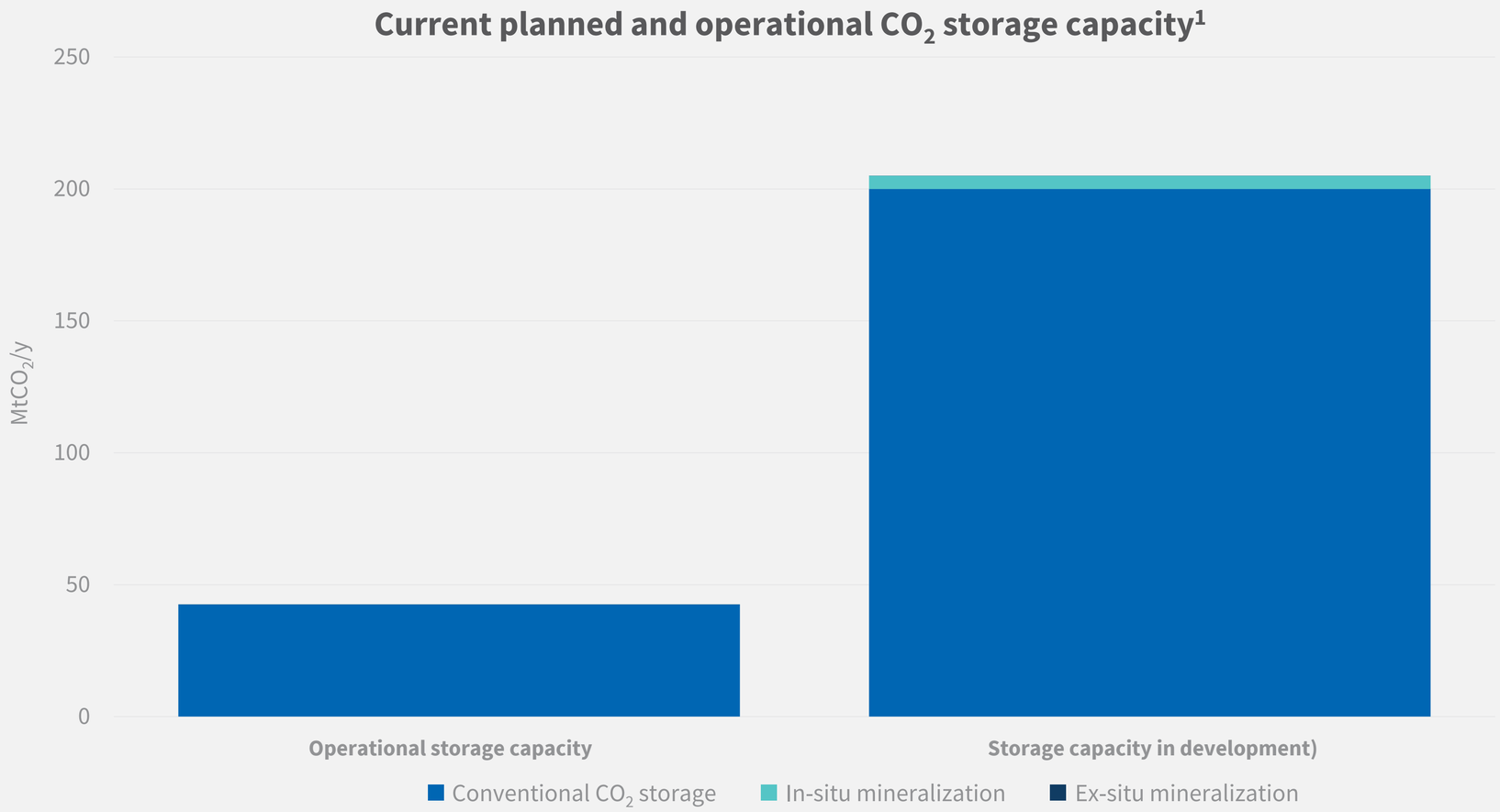


	APPROACH	FUNDS COMMITTED[1]	SIGNIFICANT DEPLOYMENTS
Storage	Conventional storage (8.1)	Commercial	**Gulf Coast Sequestration** signed an MOU with Climeworks to transport captured CO_2 from Project Cypress, a result of the DOE's DAC hub grant, and store it.[4]
	In-situ mineralization (8.2)	>$125M[2]	**Carbfix,** alongside RMI and PNNL, was awarded a grant from the DOE to develop a DAC hub in the US Pacific Northwest.[5]
	Ex-situ mineralization (8.3)	>$37M[3]	**MCi Carbon**, in partnership with RHI Magnesita, is planning to open a demonstration plant in 2024 in Australia.[6]

Notes and sources: [1]Total funding includes seed funding, grants, and investments in CDR-relevant projects that have been disclosed by companies included in the AIR. It does not include government funding towards research institutions. As companies reach later stages of development, they also disclose less financial information, so the actual funding committed to each of these approaches is likely higher than shown. [2]The $125M sum for in-situ mineralization is based on 3 companies. [3]The $37M sum for ex-situ mineralization is based on 8 companies. [4]Gulf Coast Sequestration and Climeworks [5]Carbfix DAC hub [6]MCi Carbon and RHI Magnesita project

Suitable geologic reservoirs are the key requirement for CO_2 storage

Today, there is only 42.5 $MtCO_2$/year of operational capacity at existing sites

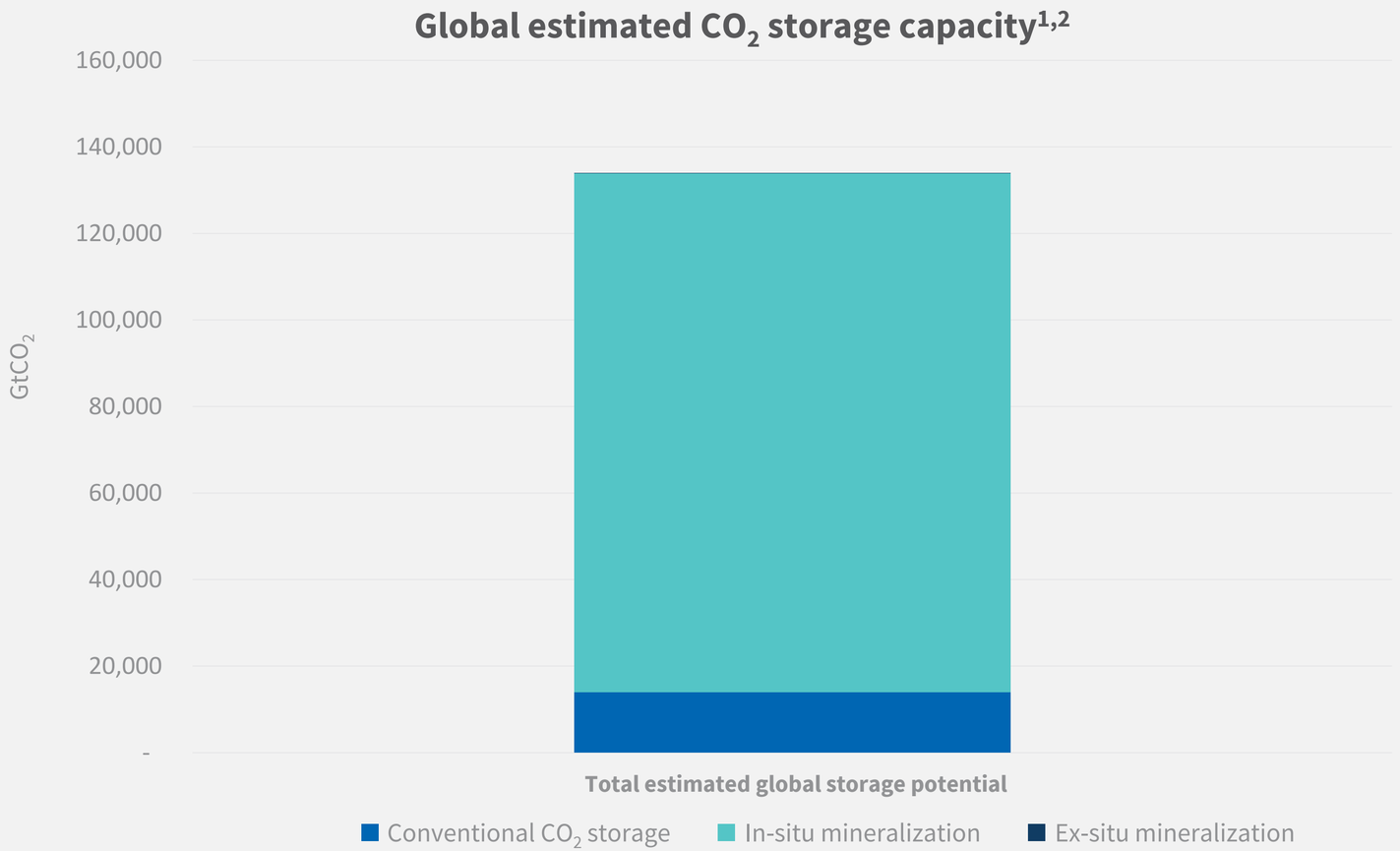


Notes and context

- According to the Global CCS Institute, operational CCS capacity has been largely constant for the last ten years.[1]
- Current operational capacity of CO_2 storage sites has the potential to grow far beyond future projections of CO_2 supply.
- The biggest challenge to conventional storage is the speed at which we can (1) validate and (2) operationalize CO_2 storage reservoirs.

Notes and sources: [1]Global CCS Institute Global Status of CCS 2022 estimates that there are currently around 42.5 $MtCO_2$/y of operational conventional CO_2 storage. Appendix 6.1 of the report explains the four types of geological CO_2 storage in detail.

The estimated physical potential of CO_2 storage is thousands of gigatons, but economic and regulatory constraints may limit access



Notes and context

- Total global conventional CO_2 storage capacity is estimated to be in the tens of thousands of gigatons.[1]
- Total global potential for mineralized storage is estimated to be in the hundreds of thousands of gigatons.[2]
- Potential CO_2 storage sites are widely geographically distributed, meaning that CO_2 storage should be possible in most regions.[3]
- Policy structures, permitting requirements, and public acceptance of CO_2 infrastructure build out differ by country and region and could potentially limit ability to utilize available pore space.[4]
- For some countries, build out of carbon capture, transport and storage infrastructure will likely be a significant percentage of GDP, which could make it hard to invest in and deploy as much storage capacity as is needed to achieve net-zero.
- Organization and systematic basin delivery will be necessary in order to realize the total estimated storage potential.

Notes and sources: [1]The CO2 Storage Resource Catalogue – Cycle 3 Report (2022) estimates that total global storage capacity for conventional CO_2 storage is around 14,000 $GtCO_2$, of which 577 $GtCO_2$ has been validated. [2]In-situ and ex-situ mineralization estimates are detailed and cited in the gCDR overview section of this Applied Innovation Roadmap under the section for global supply of natural materials. Estimates are around 100,000 $GtCO_2$ of peridotite capacity and an additional 20,000 $GtCO_2$ of basalt capacity based on the composition of the earth's crust (see gCDR summary slides). [3]An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations provides a map of potential in-situ and ex-situ storage basins. The CDR primer also provides a map of where some of these storage sites might be located. [4]Global CCS institute regional overview.

The expected timeline to develop CO_2 storage projects is between 7-8 years

The process timeline can require seven to eight years as potential project sites are assessed and down-selected.

Site Screening
Duration: 1 year
Cost: $1M
Sites: 20

Feasibility study
Duration: 0.5 years
Cost: $1M
Sites: 3-4

Appraisal phase
(includes data acquisition)
Duration: 1-2 years
Cost: $1-10M
Sites: 1

Conceptual phase
Duration: 0.5 years
Cost: $2-4M
Sites: 1

FEED phase
Duration: 1 year
Cost: $2-6M
Sites: 1

Construction phase
Duration: 2 years
Cost: $20-100M[2]
Sites: 1

Notes and sources: [1]This flow of information based on expert interviews conducted by RMI with CO_2 storage experts. [2]The Negative Emissions Technologies and Reliable Sequestration (2019) report notes that new wells can be drilled and completed at a cost of around $5M per well but that this does not include other infrastructure such as roads and power connections (p347)

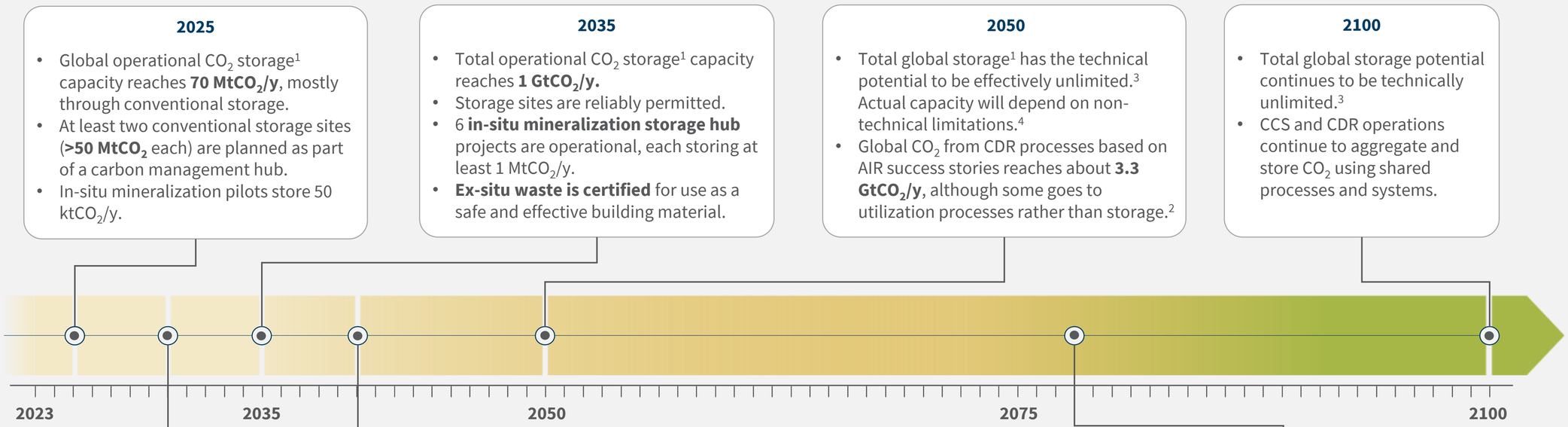
CO_2 storage success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

The cumulative CDR storage described below is the summation of the upper limit of deployment taken from three individual success stories from the AIR report.[1] The assumptions for each projection are based on a range of sources described in the individual approach success stories.



2025

- Global operational CO_2 storage[1] capacity reaches **70 $MtCO_2$/y**, mostly through conventional storage.
- At least two conventional storage sites (**>50 $MtCO_2$** each) are planned as part of a carbon management hub.
- In-situ mineralization pilots store 50 $ktCO_2$/y.

2030

- Global operational CO_2 storage[1,3] capacity reaches **270 $MtCO_2$/y**, primarily as conventional storage with 3 $MtCO_2$/y of in-situ storage.
- Seismic and **environmental assessments** are being performed for demonstration facilities.

2035

- Total operational CO_2 storage[1] capacity reaches **1 $GtCO_2$/y.**
- Storage sites are reliably permitted.
- 6 **in-situ mineralization storage hub** projects are operational, each storing at least 1 $MtCO_2$/y.
- **Ex-situ waste is certified** for use as a safe and effective building material.

2040

- Total global operational CO_2 storage[1] capacity reaches **3.8 $GtCO_2$/y.**
- Breakthroughs in **modeling of mineralization reaction kinetics** improve assessments and increase in-situ permitting.

2050

- Total global storage[1] has the technical potential to be effectively unlimited.[3] Actual capacity will depend on non-technical limitations.[4]
- Global CO_2 from CDR processes based on AIR success stories reaches about **3.3 $GtCO_2$/y**, although some goes to utilization processes rather than storage.[2]

2050-2100

- Conventional storage continues to be the primary method for storing captured CO_2.
- In-situ mineralization grows as a secondary means of CO_2 storage.

2100

- Total global storage potential continues to be technically unlimited.[3]
- CCS and CDR operations continue to aggregate and store CO_2 using shared processes and systems.

Notes and sources: [1]The CO_2 storage taxonomic category includes roadmaps for three unique approach. The growth trajectory of each of these three approaches was assessed separately. Details and growth assumptions for each individual pathway can be found in the individual approach success stories. [2]The main sources of CO_2 for storage are sCDR approaches (DAC and indirect water capture) and BECCS. By 2050, the AIR success story for sCDR results in 1.2 $GtCO_2$/y of removals. Our two BECCS approaches contribute an additional 2.1 $GtCO_2$/y for a total CDR storage requirement of around 3.3 $GtCO_2$/y in 2050. [3]Jordan Kearns et al. (2017) predict 8,000–55,000 $GtCO_2$ of feasible global geological storage potential. The National Academies of Science Negative Emissions Technologies Report (2019) quotes 25,000 $GtCO_2$ of total potential. [3]The IEA CCUS Handbook on CO2 storage (2022) estimates that annual CO_2 injection capacity will grow to 110 $MtCO_2$ by 2030. [4]Non-technical limitations include permitting and financial considerations, such as the marginal cost of new capacity generation.

8. Storage of CO_2

Approaches that are used to store captured and concentrated streams of CO_2

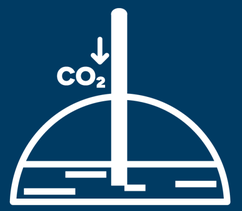
Index	Approaches	Definition
8.1	Conventional CO_2 storage	Storage of CO_2 by injection into depleted oil and gas reservoirs, saline aquifers, and other pore spaces with slow mineralization rates in order to confine the CO_2 underground via structural, residual, or solubility trapping
8.2	In-situ mineralization	Circulation of either supercritical CO_2 or CO_2-rich fluid through subsurface alkaline rocks, stabilizing carbon underground for durable storage via mineral trapping, i.e., conversion to solid carbonate minerals
8.3	Ex-situ mineralization	Reacting CO_2 with either natural alkaline minerals or artificial alkaline by-products and wastes in engineered reactors, rather than under ambient conditions. These reactions typically go to completion within minutes using high temperatures, pressures, electrochemistry, and/or pH changes to accelerate the mineralization process.

RMI classifies storage of CO_2 approaches as **storage**

Biogenic (bCDR)	Geochemical (gCDR)	Synthetic (sCDR)	Storage
Living biomass **1.1** Improved management **1.2** Conservation / protection **1.3** Restoration / creation **Stabilized biomass** **2.1** Biomass direct storage **2.2** Timber building products **2.3** Other biomass building products **2.4** Pyrolysis (biochar) and storage **2.5** Pyrolysis (bioliquid) and storage **2.6** Microalgae in ponds **2.7** Microalgae in open water **2.8** Macroalgae in open water **Sequestration of CO_2 from biomass** **3.1** BECCS to electricity **3.2** BECCS to fuels	**Solid carbonate minerals** **4.1** Surficial **Dissolved bicarbonate sequestration** **5.1** Terrestrial enhanced weathering **5.2** Coastal enhanced weathering **5.3** Mineral alkalinity enhancement	**Indirect water capture (IWC)** **6.1** CO_2 stripping **6.2** Electrochemical alkalinity production **Direct air capture (DAC)** **7.1-7.3** Liquid solvent **7.4-7.7** Solid sorbent **7.8-7.9** Membranes **7.10** Cryogenic	**Storage of CO_2** **8.1** Conventional CO_2 storage **8.2** In-situ mineralization **8.3** Ex-situ mineralization

SECTION 8.1

Conventional CO_2 storage



SECTION	8.1
TAXONOMIC BUCKET	Storage
CDR CATEGORY	Storage of CO_2
APPROACH	Conventional CO_2 storage

DEFINITION:

Storage of CO_2 by injection into depleted oil and gas reservoirs, saline aquifers, and other pore spaces with slow mineralization rates in order to confine the CO_2 underground via structural, residual, or solubility trapping

EXAMPLE SCENARIOS

1) Injecting a stream of CO_2 gas into a saline aquifer thousands of feet below the surface of the earth and below a cap rock to prevent future leakage; 2) storing a stream of CO_2 gas in a man-made holding tank or a salt cavern.

Section 8.1 overview

Conventional CO_2 storage

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **None** • Key risks are in the energy and land requirements for scalability
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Low** • This approach is customized and simple
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Commercial stage** • ~5 companies at commercial stage • Other notable RD&D activity includes the DOE FECM program
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Capacity: **Not limited by 2050** • Success is contingent on safe, scalable, and measurable storage as well as enough storage capacity for all CO_2 captured by CDR approaches
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$600-850M over 13-20 years** • Key stage gates in geologic risk evaluation and mitigation as well as measurement of long-term performance

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Land requirements*	**Medium risk:** Conventional CO_2 storage has a small land footprint compared to the amount of CO_2 injected and can be co-located with other industrial activities.	Storage occurs underground, so injection site access is the primary land requirement.[1] Capacity estimates for sites are ~0.5-5 tCO_2/m^2 or approximately 1 km^2 for a 1 $MtCO_2/y$ injection site.[7] Depending on the legal rights of a land area, the government could either implement eminent domain or prevent usage of pore space entirely.[2]
	Energy requirements	**Medium risk:** The total energy required for CO_2 compression and injection is small but not negligible.	Several LCA studies show the total energy demand range for compression and injection to be between 100-155 kWh (0.36-0.54 GJ) per tCO_2.[3,4] This would cost about \$5-10/tCO_2, which could be important for certain processes.
	Water requirements	**Low risk:** Conventional CO_2 storage uses no or minimal water.	Structural trapping compresses and injects CO_2 at a supercritical phase of approximately 600 kg CO_2/m^3 without additional water.[5]
	Environmental impacts	**Low risk:** Environmental impacts can be avoided at the surface and underground.	Subsurface storage has been performed safely and effectively since the 1990s and utilizes more than 150 years of oil and gas (O&G) industrial knowledge.[3] Additional work should be done to characterize and mitigate the impacts of accidental leakage.
Secure storage for 100+ years		**Low risk:** Conventional storage is highly durable.	Storage is very secure if performed at appropriate injection sites with impermeable caprock.[1,3,6]
Path to measurement at scale		**Low risk:** Injection of CO_2 is easy to measure and verify, and monitoring approaches exist.	Sensors are commonly used to measure and track the stability of storage sites. Nascent companies are patenting new sensors to further improve the efficiency of measurement and longer-term monitoring.
Pathway to full costs <\$100/tCO_2		**Low risk:** CO_2 storage is expected to be cost effective, especially at scale.	The current average cost for US onshore storage is approximately \$10/tCO_2.[8]

Note: *A skilled workforce is generally not considered a limitation for this approach. Instead, this is viewed as a possible benefit for the workforce transition pathway from O&G extraction to the CO_2 storage industry, and there is a great need and potential to expedite workforce upskilling or transition, especially in developing countries.*

Notes and sources: [1]The CO_2 Storage Resource Catalogue – Cycle 3 Report (2022) identified 96 $GtCO_2$ of known storage capacity for defined projects. [2]Within the USA, or anywhere with Napoleonic vs Crown law, it may be necessary to aggregate enough landowners to agree to storage. However, because it is not possible to control the migration of CO_2 in the subsurface, discontinuous storage may arise. In the case of discontinuous storage, the government would either (1) implement eminent domain rules or (2) prevent the use of any connecting pore space for storage. [3]CO_2 storage resources and their development (IEA, 2022) [4]Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption (Deutz & Bardow, 2021) [5]The National Energy Technology Laboratory Carbon storage webpage [6]Global Status of CCS (2022) [7]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [8]The IEA cites <\$10/tCO_2 for onshore storage in the US. This is based on data from the past decade. The DOE Pathways to Commercial Liftoff: Carbon Management also puts the range as \$5-15/tCO_2. Transportation costs are listed as \$5-25/tCO_2. NAS (2019) list the cost range between \$1-18/tCO_2.

Potential for cost improvement

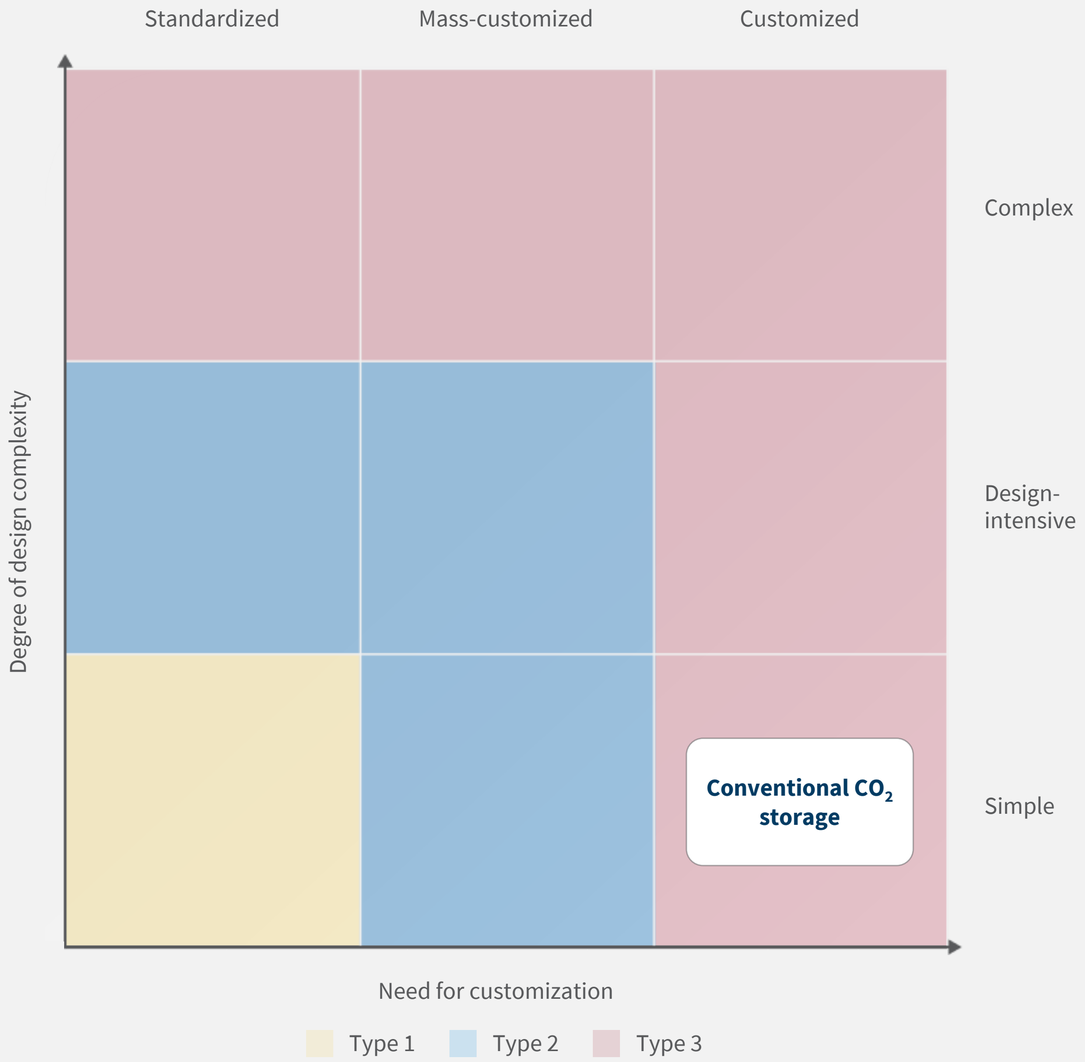
An assessment of two key drivers of learning rates

SECTION 8.1

TAXONOMIC BUCKET Storage

CDR CATEGORY Storage of CO_2

APPROACH Conventional CO_2 storage



OVERALL RATING

Type 3[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Simple
- **Rationale:** The conventional storage process is simple and easily replicated, utilizing standard industrial materials and equipment such as drills, pipes, compressors, and sensors.

NEED FOR CUSTOMIZATION

- **Rating:** Highly customized
- **Rationale:** Due to the multitude of technical variables per site, including variations in geology, hydrology, system integration with CO_2 transport modes, and local legal frameworks, deployment is highly customized, as are its risks and MRV implementation.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

Current state of RD&D

A mapping of companies, plus other notable activities

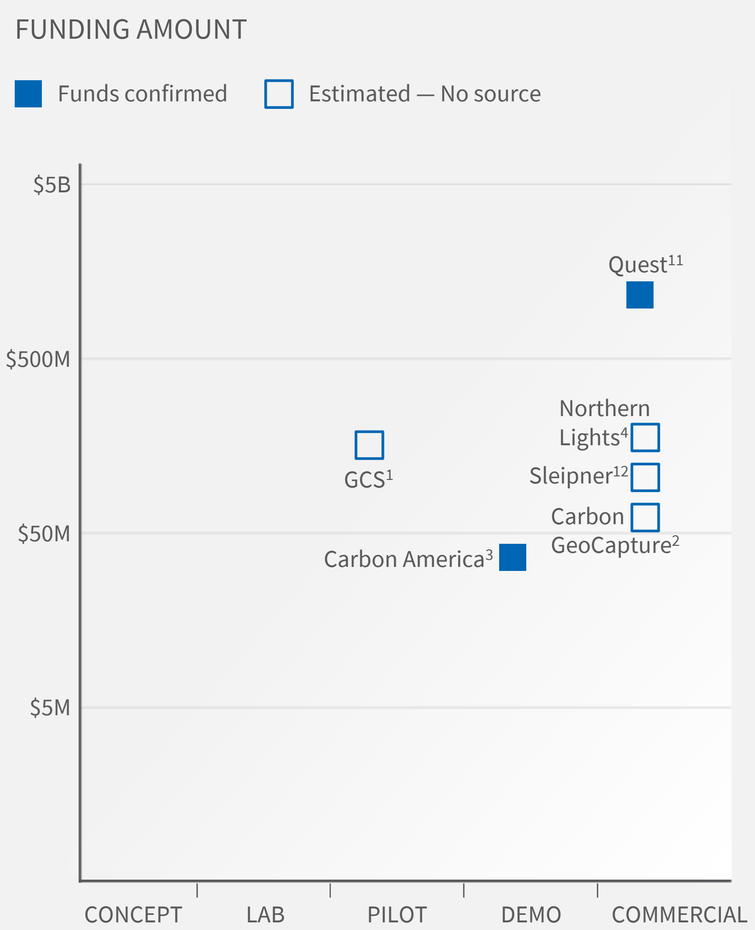
NOT EXHAUSTIVE

SECTION 8.1

TAXONOMIC BUCKET Storage

CDR CATEGORY Storage of CO_2

APPROACH Conventional CO_2 storage



NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Gulf Coast Sequestration (GCS): Storage hub developer[1]	Portion of $600M	• 2022 — Signed MOU with Climeworks to transport captured CO_2 from Project Cypress and store it[5]
Carbon GeoCapture: CCS developer[2]	N/A	• 2016 — Partnered with the DOE funded Carbon SAFE project in Wyoming
Carbon America: CCS super developer[3]	$40M[6]	• 2023 — Started operation of two ethanol CCS projects[7] • A secondary CCS project for an ethanol plant is in permitting[8]
Northern Lights: CO_2 transport and storage service provider[4]	€4M; 2.5B NOK[9]	• 2023 — Entered into transport and storage agreement with Ørsted[10] • 2024 — Starting operation of FOAK (Longship Project) cross-border and open-source infrastructure network
Quest: CCS facility operated by Shell Canada[11]	$1,310M[13]	• 2015-2020 — Captured and stored 5 $MtCO_2$ [14]
Sleipner: world's first CO_2 storage project, operated by Equinor[12]	857M NOK[15,16]	• 2019 — Accompanying CO_2 storage data program[15] • 2020 — Partial electrification approved[16] • Captured and stored over 19 $MtCO_2$ since 1996[12]
Other companies and activities: Storegga Geotechnologies[17]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
DOE – FECM carbon storage research[18]	$93M[19]	• CarbonSAFE Initiative (2023) Phase 2: Storage Complex Feasibility Projects[20]

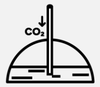
Notes and sources: [1]Gulf Coast Sequestration [2]Carbon Geocapture injects CO_2 into uneconomical coal seams. [3]Carbon America [4]Nortern Lights webpage [5]GCS and Climeworks funding from DOE, 2023 [6]Crunchbase assessment of Carbon America [7]CCS project on two ethanol plants: "Carbon America will finance, build, own and operate the CCS system, and monitor the geologic storage site, over 4,000 feet underground, using advanced seismic, air and water monitoring technology." [8]Carbon America's upcoming CCS project [9]Although no exact finance data is available, Northern Lights received €4 million from the European Commission and major European O&G companies invested in the Northern Lights project, including Shell, Equinor, and TotalEnergy. Further, the company has received over 2.5B NOK from state support. [10]Ørsted website [11]Quest CCS facility is operated by Shell Canada. [12]Sleipner was the world's first CO_2 storage project. Operated by Equinor, it has stored over 19M tCO_2 since 1996. [13]Quest funding [14]5-year anniversary of Quest [15]Sleipner funding for data program [16]Sleipner funding for electrification [17]Storegga website [18]The DOE – FECM has been investing billions of dollars of funding into carbon storage since 1997. [19]The DOE awarded eleven projects as part of the CarbonSAFE Phase 2. [20]The CarbonSAFE initiative has been operating since 2016, funded by the DOE and managed by the National Energy Technology Laboratory (NETL). Phase 2 is focused on full feasibility analysis across 6 geographies in the US, including technical, legal, and public outreach.

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

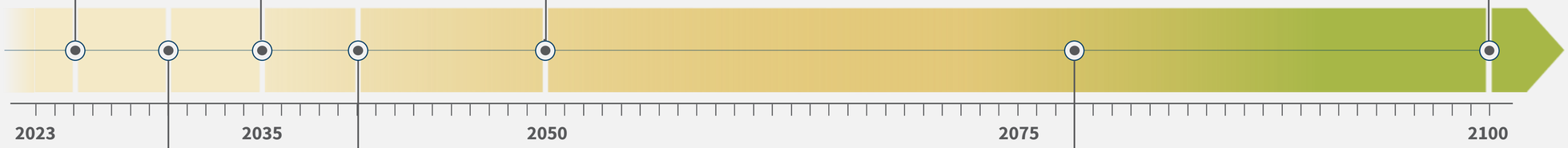


SECTION 8.1

TAXONOMIC BUCKET Storage

CDR CATEGORY Storage of CO_2

APPROACH Conventional CO_2 storage



2025

- Major increases in funding are made for simulation models to assess reservoir characteristics, seismic risks, and to improve MRV to validate an industry that can reach gigaton scales of sequestration.
- Several larger injection sites are planned as part of carbon management hubs.

2030

- Conventional CO_2 storage has scaled to provide 270 $MtCO_2$/y storage capacity globally.[1]
- Improved measurement and physical transport models ensure a high degree of confidence in CO_2 storage, MRV, and increase public acceptance.
- Storage sites and class VI wells are now regularly permitted in the US.

2035

- Conventional CO_2 storage approaches have scaled to provide 1 $GtCO_2$/y of global storage capacity and are growing quickly to meet demand.[1]
- Processes for engaging communities on pore space laws and pipeline permitting are established in collaboration with relevant communities.
- There are industrial clusters around the world with significant CO_2 storage capacity.
- Large injection wells emerge in industrial corridors. These allow smaller CCS and CDR operations to feed CO_2 into shared sequestration systems.

2040

- Conventional CO_2 storage approaches have scaled to provide 3.7 $GtCO_2$/y of storage.[1]
- Improved measurements and modeling with years of safe deployment have made public acceptance and permitting simpler, and no longer limiting to CCS or CDR projects.

2050

- Viable, permitted storage capacity is not a constraint to scaling of CCS or CDR.[1] There are effectively unlimited sites and available capacity for storage all around the world.
- Best practices for permitting and MRV are deployed globally.

2050-2100

- Conventional CO_2 storage, rather than in-situ or ex-situ mineralization, continues to serve as the main method for storing captured CO_2.
- Smaller, more disperse CO_2 storage and injection well infrastructure becomes possible, allowing sequestration in more remote facilities without the need for extensive CO_2 transport.

2100

- Conventional storage approaches sequester 10-20 $GtCO_2$/y that has been removed from the atmosphere by CDR. This CO_2 is supplied largely from BECCS, DAC, and indirect water capture approaches.
- The amount of CO_2 sequestered from CCS processes may reasonably equal or exceed this annual amount.[3]

Notes and sources: [1]According to the Global CCS Institute Global Status of CCS report 2022, there is 42.5 $MtCO_2$ capture capacity operational globally as of 2022. We use this as a starting point and apply a 30% y-o-y growth rate from 2023-2040. This growth rate is aggressive by historical standards; however, injection sites are expected to be able to scale non-linearly. Additionally, demand for CCS is expected to outpace CDR in the near term and will be responsible for most near term CO_2 injections. [2]The main sources of CO_2 for storage are from sCDR approaches such as DAC and indirect water capture CDR. [3](Kearns et al., 2017) predict 8,000–55,000 $GtCO_2$ of global feasible geological storage potential. The Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) quotes 25,000 $GtCO_2$ of total potential.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

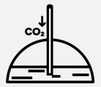
Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL[1]
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[2]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only



SECTION 8.1

TAXONOMIC BUCKET Storage

CDR CATEGORY Storage of CO_2

APPROACH Conventional CO_2 storage

TRL

CRITICAL PATH ACTIVITIES

$600-850 million | **13-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Reduce geologic risk:** Improve the understanding of geologic risks and mitigation, such as seismicity and wellbore leakage.
- **Improve simulation models:** Simulate the coupled physical processes that influence the fate and transport of CO_2 in sedimentary rocks.

$150-250 million | **5-10 years**

✓ Geologic concerns are understood with identified mitigation strategies

✓ Methods for predicting post-injection performance are reliable enough to inform and support regulatory decisions

STAGE GATES[2]

TRL 7-9

DEMONSTRATION PROJECTS

- **Expand CarbonSAFE:** Demonstrate and assess storage performance across distinct geological conditions with 2-4 active sites with >200 $MtCO_2$ combined capacity.[3]
- **MRV:** Establish measurement, modeling and monitoring regimes to viably measure storage rates and monitor for safety.

$450-600 million | **8-10 years**

✓ Models and measurements can be reliably scaled

✓ Injection of CO_2 is safe for local and global environment

✓ Robust MRV based on empirical data and numerical modeling accuracy is verified and accepted across the field

STAGE GATES[2]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[4]

$120-250 million | **5-10 years**

- Improve the understanding of secondary processes in CO_2 trapping
- Reduce MRV cost and increase quality of and access to information about stored CO_2 through monitoring
- Increase effectiveness of site characterization to better understand which sites are likely to provide the most secure and reliable CO_2 sequestration

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[4]

- MRV approaches are validated and widely accepted.
- Storage is demonstrated as safe and permanent via extensive monitoring and performance programs.
- Financing for storage is established and in line with low interest infrastructure projects.

Notes and sources: [1]Despite being rated MRL 10+, conventional storage needs pre-demonstration and demonstration work to prove that the approach works safely, at scale, under varying deployments and conditions. [2]Stage gates and critical path ratings are explained in the AIR Appendix. [3]The CarbonSAFE program is US-based, but it can also be used as a model for global demonstration project deployment. [4]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Field testing	Reducing geologic risks	Conduct studies seeking to reduce geologic risk and improve early-phase site assessments. Studies should:[1] • Improve understanding and reduce the risks of induced seismicity at geological sequestration sites • Improve capacity estimates by expanded site screening • Improve the understanding of wellbore leakage and poor geological conformance / containment • Quantify the risk of leakage from fault slippage / reactivation • Develop methods for mitigating geologic risks	✓ Geologic concerns are understood, and any necessary mitigation strategies can be implemented	1-3	$5-15 M/y[1,2]	5-10 y	$120-200M
Desktop research	Improved simulation models	Refine models for simulating the coupled physical processes that influence the fate and transport of CO_2 in sedimentary rocks.[3] These models should consider: • Site selection and storage engineering • Injection parameters, such as rate, volume, and injectivity • Risk assessment • Project performance	✓ Methods for predicting post-injection performance are reliable enough to support and inform regulatory decisions ✓ Methods are developed to inform and address the technical challenges associated with large commercial scale CO_2 injection projects	1-4	$1-2 M/y[1,2]	2-5 y	$15-30M
Desktop research / field testing	Reservoir injection planning	Conduct studies to understand the pressure front from large scale injections of CO_2. This includes the Joule Thompson effect of injecting pressurized CO_2 into depleted fields as well as pressure interactions with legacy wells and other projects.		2-3	$2-3M/y	5-8 y	$20-30M

Notes and sources: [1]Scoping cost estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Table 7.5, Costs and Components for a Geologic Sequestration Research Agenda (p339). [2]Estimates based on a combined range of averages from NAS (2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]The scope of this activity is based on the NAS (2019), p346 assessment activity.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Expand the CarbonSAFE program to include 2-4 active sites with total combined sequestration capacity of at least 200 $MtCO_2$.[1] Demonstration sites should seek to increase the efficiency and accuracy of site selection. Outputs should build on pre-demonstration work where appropriate and include: • Efficient and effective methods for characterizing geological sequestration sites • Methods for identifying and characterizing faults in seals and basement rocks • Methods of characterizing geological heterogeneity for trapping CO_2 • Publicly available data as specified by the NAS, e.g., through the NETL EDX platform, USGS, and university data	4x 50 $MtCO_2$ [1]	✓ Storage sites with at least 200 $MtCO_2$ combined capacity are operational and cost effective ✓ All operations continue to be safely and reliably deployed	2-4	$20-25M/y	8-10 y	$400-500M[1]
MRV	Refine and develop novel measurement, modeling, and monitoring practices to inform MRV and reduce costs. This work should: • Build on the pre-demonstration work • Validate models at scale across deployment conditions • Result in standard, accepted MRV protocols that are developed in parallel with in-situ CO_2 mineralization techniques • Model CO_2 plumes, pressure fronts, early indicators of leaks, etc.	N/A	✓ Measurement and modeling techniques are reliable at scale ✓ Protocols based on demonstrated quantification approaches are widely accepted	3-6	$2-3M/y[2]	8-10 y	$50-80M
Desktop research	Assess and plan for basin optimization and offset distancing. This will allow regulators to effectively plan licensing rounds and maximize capacity.	N/A	✓ Methods have been developed to optimize storage basins and offset distances	1-2	$1-2M/y	3-5 y	$10-15M

Notes and sources: [1]Projects and costs are based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Table 7.5 (p339). More details can be found in this report. [2]Estimates based on a combined range of averages from NAS (2019) budgets. Details of this estimation can be found in the AIR Appendix.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

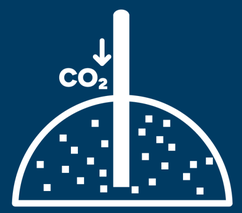
TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
R&D / field testing	Improved trapping predictions and techniques	Quantify the effectiveness of natural and accelerated trapping of post-injection CO_2 and improve the understanding of secondary processes in CO_2 trapping.[1]	4-6	$1-2M/y[2,3]	5-10 y	$20-40M
Field testing	Improved monitoring and decrease costs for MRV	Demonstrate approaches that can reduce costs while increasing the quality of and access to information about stored CO_2.[1] Some examples include: • Improved physical transport models of injected CO_2 • Improved monitoring of CO_2 saturation and mass balance • Site specific uncertainties and risks • Advanced methods for locating and characterizing risks	4-6	$5-8M/y[2,4]	5-10 y	$80-150M
Desktop research	Increasing the effectiveness of site characterization	Develop greater understanding of which sites might provide the most secure and reliable CO_2 sequestration.[1] This research could include: • Demonstration of effective site characterization • Identifying faults that might induce leakage • Imaging faults within igneous and metamorphic formations • Developing public datasets on geological heterogeneity in reservoirs	2-8	$0.5-1M/y[2]	5-10 y	$10-25M
Desktop research	Assessing and managing risks in compromised sequestration systems	Improve the understanding of impacts from leakage of CO_2 on groundwater systems and the vadose zone.[5] Determine the risks to local environments as well as to the atmosphere.	2-5	$1-2M/y[2,5]	5-10 y	$10-20M

Note: *There are non-RD&D gaps that are critical to the success of this approach. This includes CO_2 transportation infrastructure.*

Notes and sources: [1]Scoping and cost estimates are based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Table 7.5, Costs and components for a geologic sequestration research agenda (p339). [2]Estimates based on a combined range of averages from NAS (2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [3]Note that NAS (2019) lists the cost here as $25M/y for 10 years. [4]Note that NAS (2019) lists the cost here as $50M/y for 10 y. [5]This project is scoped directly from the NAS (2019) Table 7.5.

SECTION 8.2

In-situ mineralization



SECTION	8.2
TAXONOMIC BUCKET	Storage
CDR CATEGORY	Storage of CO_2
APPROACH	In-situ mineralization

DEFINITION

Circulation of either supercritical CO_2 or CO_2-rich fluid through subsurface alkaline rocks, stabilizing carbon underground for durable storage via mineral trapping, i.e., conversion to solid carbonate minerals

EXAMPLE SCENARIOS

1) Injecting a stream of captured CO_2 that is mixed with water into porous basaltic rock formations where it reacts with the rocks to create solid carbonate minerals; 2) injecting a supercritical stream of captured CO_2 into a peridotite mineral formation with moisture present, where the CO_2 reacts to form solid carbonate minerals

Section 8.2 overview

In-situ mineralization

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **None** • Key risks are in scalability and include energy and water requirements, environmental impacts on groundwater, and seismic activity
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is mass-customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Pilot to commercial stage** • ~3 companies at pilot to commercial stages • Other notable RD&D activity includes the DOE FECM program and studies by the Pacific Northwest National Laboratory
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Capacity: **1.2 $GtCO_2$ by 2050** • Success is contingent on improved knowledge of mineralization kinetics and seismic impacts, as well as verification
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$350-750M over 18-20 years** • Key stage gates in environmental risk evaluation and mitigation, site selection, and measurement of long-term performance

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Medium risk:** Current power requirements for multiple stages of the process are significant.	One approach requires about 2,000 kWh (7.2 GJ) of thermal energy and 650 kWh (2.3 GJ) of electricity per tCO_2 captured.[3,4] Additional energy is required for any required transport of the CO_2 and water pumping for injection.[1,2] Multiple wells may be required to avoid limitations due to passivation and clogging, thus requiring more drilling.
	Mineral requirements	**Low risk:** Suitable mafic and ultramafic rock formations are abundant and distributed globally.	There is global abundance of mafic and ultramafic rock formations,[5] although ultramafic rocks are usually at greater depths and the greatest capacity is offshore in seafloor basalt.[1,2,6,7,8,9] At scale, fracture networks may be required in order to overcome clogging and permeability issues.
	Water requirements	**Medium risk:** Significant water supply is necessary, but not all water is consumed in the process – some can be recycled.	Water demand can be significant, with up to 25-30 tons of H_2O/tCO_2 for the Carbfix Orca method.[1,2,10] Water may potentially be sourced from the target reservoir,[1] and some can be reused rather than consumed with the stored CO_2. Additional alternatives are being tested, including direct injection of CO_2 or co-injection with seawater.[1]
	Land requirements	**Low risk:** Land requirements are low but must consider spacing of injection and monitoring wells.	The required land footprint is minimal since storage is underground.[11] The process requires access to injection and monitoring wells as well as some surrounding area for pumping infrastructure. If the CO_2 source is co-located or close to the injection well, minimal land is required for transport infrastructure such as pipelines.[1,2,6]
	Environmental impacts	**Medium risk:** Risks of increased seismic activity and impacts to groundwater must be assessed and addressed.	Any CO_2 injection has a risk of induced seismicity, which is potentially greater with injection of dissolved CO_2 because of the volume of fluid to be injected.[12] The initial injection phase can also mobilize metals that may contaminate groundwater. Stringent, site-specific geologic assessments of potential injection sites and permitting are essential,[11] followed by long-term water and geologic monitoring during and after injection.[1,2,7]
Secure storage for 100+ years		**Low risk:** Carbon is converted to a solid carbonate mineral.	Mineralization has low risk of leakage and a reduced need for long-term monitoring compared to conventional structural trapping, especially if CO_2 is pre-dissolved before injection.[1,2,13,14,15]
Path to measurement at scale		**Low risk:** Several measurement and monitoring approaches have been successfully deployed, and new methods may be feasible.	Established methods for mineralization site monitoring, such as the SF_6 tracer technique, exist. New approaches, especially to determine mineralization rates, may be needed at scale.[16] Long-term monitoring of CO_2 may not be necessary for all sites.[2,17]
Pathway to full costs <$100/$tCO_2$		**Low risk:** Pilot projects on land have demonstrated very low costs.	Demonstrated costs for terrestrial sites have been \$10-50/tCO_2[6,17] and costs are estimated at \$200-400/tCO_2 for marine sites.[6,14] Costs will also be affected by required transportation and infrastructure.

Notes and sources: [1]Carbon dioxide storage through mineral carbonation (Snæbjörnsdóttir et al., 2020) [2]Geochemical Negative Emissions Technologies: Part I. Review (Campbell et al., 2022) [3]Energy requirements from Carbfix project via Geoengineering Monitor. Capturing 4 $ktCO_2$ is estimated to require more energy than all households in Iceland. Reviewers note that the energy requirements and associated risks are lower for supercritical CO_2 injection. [4]The high energy requirements highlight the importance of low-carbon energy, especially for offshore deployments. [5]A reviewer notes that less is known about the efficacy of CO_2 sequestration in basalt formations outside of Iceland and the Pacific Northwest (USA). [6]Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) [7]US Geological Survey (USGS) "CO_2 Mineralization feasibility study" [8]Carbfix Atlas [9]A reviewer notes that the theoretical mineralization capacity of ultramafic rocks, like peridotite, is large enough (500-600 kg/t) that even relatively small deposits offer significant CO_2 mineralization potential. [10]Geochemical Negative Emissions Technologies: Part II. Roadmap (Maesano et al., 2022) [11]New well drilling would increase land requirements and environmental risks. [12]A reviewer notes that seismicity risk may be low, depending on site selection. [13]Structural trapping is storage of CO_2 in rock pores and structural spaces. Injected CO_2 is structurally contained and takes thousands of years to mineralize, so the injection site must be contained with an impermeable cap-rock. [14]The permanence of CO_2 storage after mineralization reduces the need for long term monitoring and insurance, potentially reducing associated costs. [15]Per NAS (2019), Ch 6, carbon mineralization rates for H_2O-bearing supercritical CO_2 and carbonation rates for the same materials in aqueous fluid with the same pressure are comparable. [16]Techniques like muon tomography and other underground imaging methods are currently underexplored in the context of carbon storage. [17]Engineered carbon mineralization in ultramafic rocks for CO_2 removal from air: Review and new insights (Kelemen et al., 2020)

Potential for cost improvement

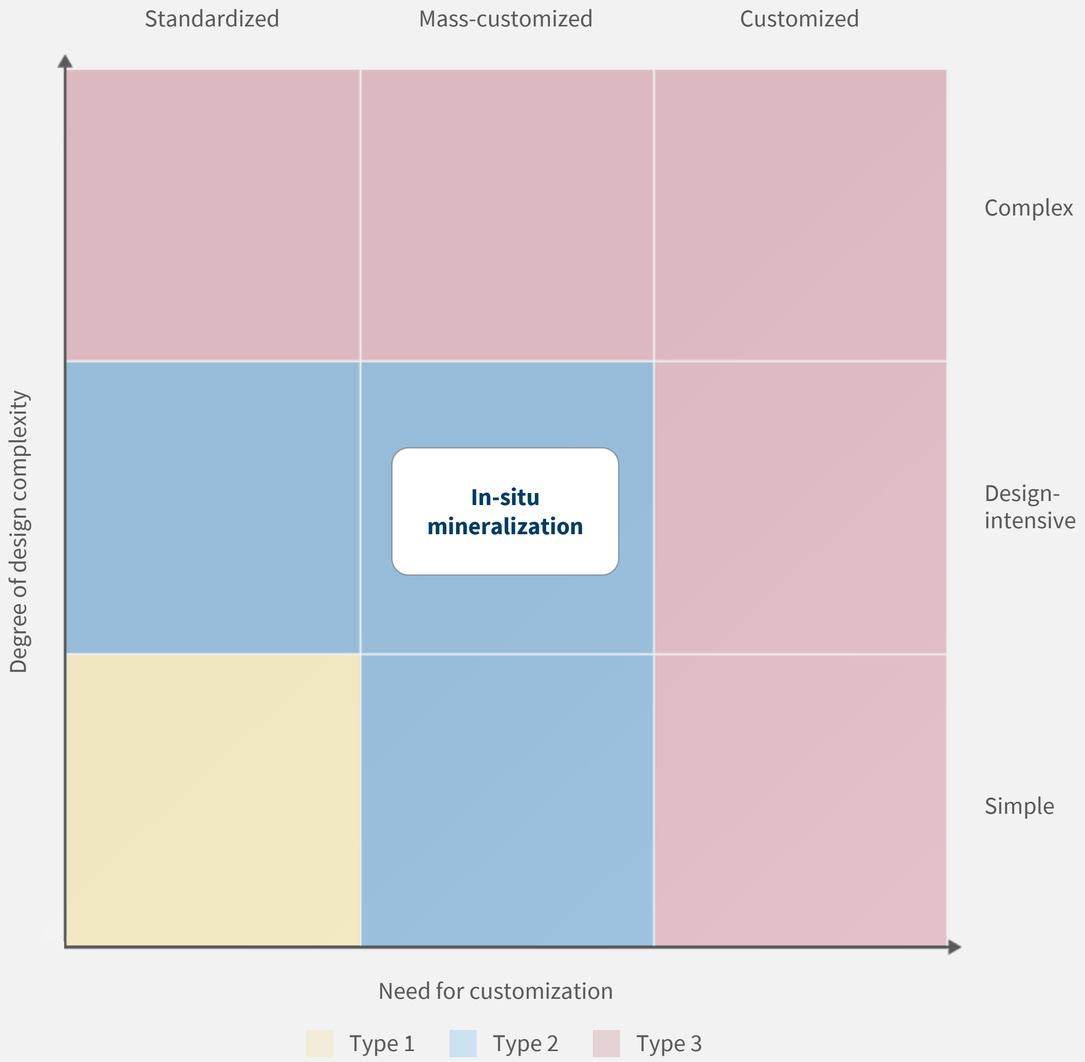
An assessment of two key drivers of learning rates

SECTION 8.2

TAXONOMIC BUCKET Storage

CDR CATEGORY Storage of CO_2

APPROACH In-situ mineralization



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Design-intensive
- **Rationale:** This storage process relies on existing industrial equipment, including drilling equipment, CO_2 pipelines, water pumps, and sensor and tracer technologies. However, pumping water and managing adequate subsurface pressure increases the design complexity.

NEED FOR CUSTOMIZATION

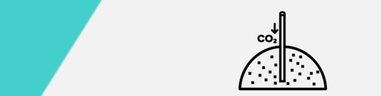
- **Rating:** Mass-customized
- **Rationale:** This approach requires customized technology due to the multitude of technical variables that vary between sites, including variations in geology, hydrology, system integration with CO_2 transportation, and the local legal framework.

Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

Current state of RD&D

A mapping of companies, plus other notable activities

NOT EXHAUSTIVE



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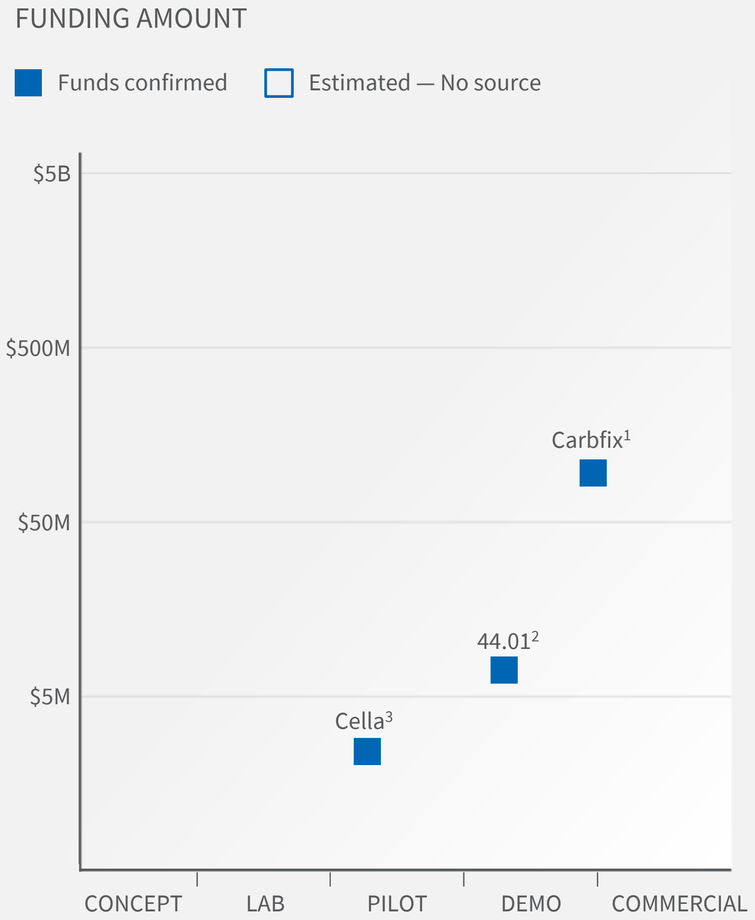


NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Carbfix: Developing carbon mineralization technology[1]	$117M[4]	• Multiple projects are currently operating with several more in development[5] • Carbfix, alongside RMI and PNNL, was awarded $3M from the DOE to develop a DAC hub in the US Pacific Northwest[6]
44.01: Injecting carbonated fluid into peridotite formations[2]	$6.2M[7] includes £1M Earthshot grant	• 2023 — Announcement of the first pilot outside Oman and expansion into the UAE[8] • 2024 — First commercial-scale demonstration project in Oman
Cella: Co-locating with geothermal power plant for clean energy and water[3]	$3.3M[9]	• Building a pilot in Kenya where a large of amount of basaltic rock is available[10] • Implementing DAC in 2024[10]
Other companies and activities: Yale Carbon Containment Lab: Carbon TrapRock Project,[11] Solid Carbon[12]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
DOE – FECM Carbon storage research[13]	$93M[13]	• 2023 — CarbonSAFE Phase 2: Storage Complex Feasibility Projects[14]
Pacific Northwest National Laboratory (PNNL)[15]	N/A	• 2015 — Small field pilot project completed in Eastern WA[16] • 2022 — Published study results on mineralization kinetics[15]

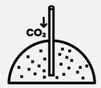
Notes and sources: [1]Carbfix website [2]44.01 website [3]Cella website [4]Crunchbase estimate [5]Carbfix project list [6]RMI, Carbfix, and PNNL DAC hub announcement [7]Crunchbase estimate [8]44.01 news [9]Cella funding, Carbon Herald [10]Cella pilot [11]Carbon Traprock [12]Solid Carbon is a team of researchers from the US, Canada, and Europe led by Oceans Network Canada. It integrates 6 technologies to capture carbon from the air, inject it underground, and transform it into rock. Plans are underway for a demonstration project in the Cascadia Basin. [13]The DOE – FECM has been investing billions of dollars of funding in carbon storage since 1997. The DOE awarded 11 projects as part of the CarbonSAFE Phase 2. [14]The CarbonSAFE initiative has been operating since 2016, funded by DOE and managed by the National Energy Technology Laboratory (NETL). Phase 2 is focused on feasibility analysis across six geographies in the US and includes technical, legal, and public outreach considerations. [15]PNNL lab research and recommendations for future R&D include kinetics integrated modeling and laboratory experiments. [16]PNNL Wallula Basalt pilot project

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR



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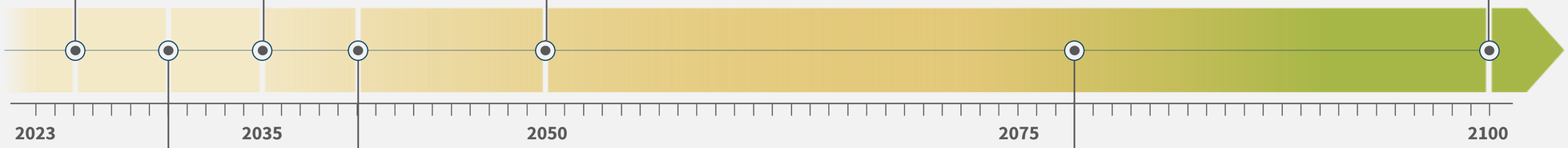


2025

- A global open-source integrated model improves understanding of mineralization kinetics under real conditions.
- Significant new funding is dedicated to better modeling and measuring in-situ mineralization inputs as well as verifying mineralization rates and CO_2 storage.
- Early demonstrations of in-situ mineralization with DAC facilities reach 50 $ktCO_2$ of sequestration.[1]

2030

- In-situ mineralization storage provides 3 $MtCO_2$/y of sequestration globally.[1]
- Continued pilot and demonstration scale activities lead to improvements of injection energy and water requirements.
- Seismic and environmental assessments are underway for demonstration facilities.
- Several demonstration or commercial scale facilities are sited and scoped for in-situ mineralization storage of more than 1 $MtCO_2$/y per site.

2035

- In-situ mineralization storage provides up to 23 $MtCO_2$/y of sequestration globally.[1]
- 6 fully independent 1 $MtCO_2$/y demonstration storage hub projects are operational.
- At least 1 offshore storage well with in-situ mineralization is being tested.
- Energy, water, and environmental impacts are sufficiently mitigated.

2040

- In-situ mineralization storage provides up to 85 $MtCO_2$/y of sequestration globally.[1]
- In-situ sites are operating at cost parity with conventional storage sites.
- Environmental and geological impacts continue to be minimal.
- Breakthroughs in modeling reaction kinetics lead to improved MRV protocols and increased permitting.

2050

- In-situ mineralization storage provides up to 1.2 $GtCO_2$/y of sequestration globally.[1,2]
- DAC and IWC facilities are commonly co-located with in-situ injection sites.
- In-situ mineralization has become a market competitor with conventional CO_2 injection. CO_2 from CCS operations is regularly used as input for in-situ mineralization.

2050-2100

- The storage system efficiency and cost effectiveness of in-situ mineralization makes it a co-leader with conventional CO_2 storage approaches.
- In-situ mineralization storage has the potential to provide several $GtCO_2$/y of storage.

2100

- In-situ mineralization continues to provide as needed CO_2 storage, with gigaton scale annual capacity.
- In-situ mineralization storage approaches continue to be cost competitive with conventional CO_2 injection.

Notes and sources: [1]Deployment estimates are based on 50% y-o-y growth from 2026-2035 and 30% growth from 2035-2050 with a starting point of 600 $ktCO_2$/y in 2026. The starting point of 600 $ktCO_2$/y is based on Carbfix's storage hub in Hellisheiði plus the announced Coda terminal. [2]Estimates for the total amount of CO_2 that will need to be sequestered in 2050 range up to 10 $GtCO_2$/y or higher, with the majority of that CO_2 coming from CCS operations. Conventional CO_2 injections are likely to sequester most of this CO_2 given a large head start; however, if in-situ mineralization approaches prove to be safer, more cost competitive, or to have other advantages, they could constitute a significant portion of sequestration in the second half of the century.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 8.2

TAXONOMIC BUCKET Storage

CDR CATEGORY Storage of CO_2

APPROACH In-situ mineralization

TRL

CRITICAL PATH ACTIVITIES

$350-750 million | **18-20 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Site selection:** Identify onshore and offshore demonstration sites with adequate geologic, energy, and water conditions.
- **Environmental impacts:** Assess seismicity and ecological impacts of water use, including metal mobilization during injection.
- **MRV:** Develop robust measurement and assessment pathways, as well as LCAs and TEAs.

$60-100 million | **8-10 years**

✓ Identification of demonstration sites with adequate water, energy, and storage conditions

✓ Manageable environmental risks and seismicity concerns

✓ TEAs indicate a path for verifiable storage at market competitive costs

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Onshore and offshore demonstrations:** Demonstrate and assess storage performance through 3-5 projects across distinct geological conditions.
- **MRV:** Incorporate empirical measurement techniques and analytical modeling for MRV protocol development.

$300-650 million | **10 years**

✓ Water requirements and usage impacts are manageable

✓ No induced seismicity or other geological risks

✓ Measurements are reliable at scale with mineralization rates comparable to smaller pilots

✓ Pathway to costs that are competitive with conventional geological storage

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$80-140 million | **10 years**

- Create a database of geospatial resource assessments, including potential storage sites, low-carbon energy sources, potential for co-located DAC or IWC, and adequate water availability.
- Investigate process improvements through feedstock pre-treatment and integration with the underground biome.
- Assess and improve mineralization reaction kinetics.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Safety risks and environmental impacts are manageable
- Storage cost is competitive with conventional storage
- Measurement and modeling approaches are widely validated and accepted
- CO_2 transport is optimized for cost and safety and potentially co-located with capture

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research / field testing	Site selection	Identification of at least 3 onshore sites and 3 offshore sites with: • Favorable geologic conditions for in-situ mineralization • Adequate energy, water, and access to CO_2 inputs for pumping CO_2-rich fluid underground,[1] including co-injection with water / seawater or direct injection into water-bearing pore spaces • Geological stability during injection and storage, including cap rock for supercritical CO_2 injection as necessary	✓ Water use for mineralization is manageable for local conditions[1] ✓ Seismic concerns are understood, and any necessary mitigation strategies can be implemented	1-2	$0.5-1M/y[2]	2-3 y	$3-5M
Field testing	Pilot scale field tests	Perform field tests to understand injection rates, mineralization rates, passivation, clogging, and other effects. Determine environmental impacts in the field, including: • Effects on nearby water tables or marine ecosystems resulting from seawater use • Metal mobilization during initial injection • Induced seismicity	✓ Ecosystem impacts are manageable ✓ Trace metals do not contaminate nearby water supplies ✓ Seismicity impacts are manageable	3-6	$3-5M/y	5-10 y	$30-50M[3]
Desktop research / field testing	Measurement and modeling	Reactive transport modeling and geochemical system modeling to explore potential issues with passivation and clogging and other geophysical effects that could impact injectivity and the number of drill sites required. Identify measurement approaches for relevant inputs (CO_2 concentrations, water, power, etc.) and mineralization rate monitoring to verify carbon storage.[4]	✓ Mineralization occurs as expected under target demonstration conditions ✓ Passivation and clogging are not constraints to developing larger scale storage sites ✓ Measurement techniques are capable of reliable carbon accounting at demonstration scale.	2-4	$1-2M/y[5]	3-6 y	$10-20M
MRV	LCA and TEA development	Develop robust protocols, lifecycle accounting, and technoeconomic assessments.[2] • Approaches should combine up to date empirical measurements and monitoring approaches. • Approaches should be open source to encourage collaboration and consolidation around best practices.·	✓ Open-source protocols that combine empirical and analytical techniques to verify removals are under development ✓ TEAs can assess and indicate a pathway to market competitive costs	3-5	$0.5-1M	8-10 y	$20-30M[4]

Note: *There are non-RD&D gaps that are critical to the success of this approach. This includes pathways to permitting.*

Notes and sources: [1]Water requirements for supercritical CO_2 injection can differ significantly from CO_2-rich water injection, which should be considered during project siting. Projects assessing the use of seawater, such as Carbfix Seastone, are also underway. [2]Cost estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Carbon Mineralization Research Agenda Budget "Scoping for pilot sites," Table 6.3; however, a reviewer suggested this cost could be up to 10x higher. [3]Cost estimates based on (NAS 2019) Carbon Mineralization Research Agenda Budget "Studying the environmental impact of mineral addition to terrestrial, coastal and marine environments," Table 6.3, with several projects being completed each year and new projects added. [4]PNNL recommends development of integrated lab and field project models. Although all published results from field pilot projects indicate efficient mineralization process, PNNL suggests that integrated models of lab and field tests will help expedite new project evolutions and development. [5]Estimates based on a combined range of averages from NAS (2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix. [6]Estimated budgets are based on NAS (2019), IAM model building at $10M/y per project for 10 years.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	3-6 demonstration sites across different onshore and offshore geological formations, injecting both CO_2-rich fluid and supercritical CO_2, to assess: • Efficacy and safety of mineralization in distinct geologic formations • Performance of injection technologies and opportunities to reduce total water and energy consumption • Any additional fracturing necessary to overcome passivation and clogging issues • Reliability of measurements and monitoring at scale • Total removal costs Sited demonstrations should be capable of scaling to >1 $MtCO_2$/y to take advantage of established permitting and infrastructure.	50-100 $ktCO_2/y$[1]	✓ Manageable water demand and environmental impacts for target implementation sites ✓ Mineralization rates at demonstration scales do not significantly decline over the lifetime of the project ✓ Models and measurements can be reliably scaled ✓ Overall costs, including MRV and reversal insurance, are comparable to or better than those of conventional geological storage	3-6	$10M/y	10 y	$300-600M[2]
MRV	Reactive transport modeling and geochemical system modeling based on empirical measurements to validate successful carbon mineralization in the above demonstration projects. This work should: • Build on the pre-demonstration work on mineralization measurements • Validate models at scale • Result in standard, accepted MRV protocols that are developed along with surficial and ex-situ CO_2 mineralization techniques	N/A	✓ Reliable measurement and modeling techniques at scale ✓ Robust and accepted protocols based on demonstrated quantification	3-6	$1M/y	10 y	$30-60M[3]

Notes and sources: [1]Demonstration scale values were selected based on Carbfix injection of 90 $ktCO_2$ since 2014. Their current annual average per injection system (i.e., per well) is 12 $ktCO_2$/yr. Their entire storage hub in Hellisheiði should accommodate 40 $ktCO_2/y$ once the Climeworks' Mammoth facility comes online. This storage capacity will compete with some conventional storage sites. [2]Cost estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Carbon Mineralization Research Agenda Budget "In situ basalt" and "In situ peridotite" pilot studies, Table 6.3. [3]Projects and costs are based on NAS (2019) "Numerical Modeling for Carbon Mineralization," Table 6.3.

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

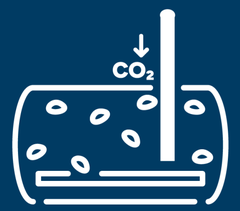
TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Resource database	Create a database with geological surveys, characterization, and monitoring to optimize potential siting, emphasizing resource availability such as low-carbon energy sources, water sources, and the potential for co-locating DAC and indirect water capture.	1-2	$0.5-1M/y[1]	2-3 y	$3-5M
Lab / field testing	Advance the understanding of underground biomes	Perform research to advance the interaction between of carbon mineralization and microorganisms.	5-8	$1M/y[2]	5-10 y	$25-80M
Desktop research	Studies to understand and improve reaction kinetics	Conduct experimental programs focused on reaction kinetics to understand mineralization rates as a factor of environmental conditions, mineral type, permeability, depth, and injection fluid composition.	8	$0.5-1M/y	10 y	$55M[3]

Note: *There are non-RD&D gaps that are critical to the success of this approach. This includes early and on-going community engagement, updated policy, pathways to permitting, social license, and open access to relevant datasets.*

Notes and sources: [1]Cost estimates based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) Carbon Mineralization Research Agenda Budget Table 6.3 "Development of a Resource Database for Carbon Mineralization" and historic government project funding with data platform estimated at $2.5M/y per project for 10 years and monitoring systems estimated at $5M/y per project for 5 years. [2]Estimates based on combined averages from NAS (2019) budgets for lab and desktop R&D funding. Details of this estimation can be found in the AIR Appendix. [3]Cost estimates based on NAS (2019), Table 6.3 "Kinetics research from Carbon Mineralization Research Agenda Budget."

SECTION 8.3

Ex-situ mineralization



SECTION	8.3
TAXONOMIC BUCKET	Storage
CDR CATEGORY	Storage of CO_2
APPROACH	Ex-situ mineralization

DEFINITION

Reacting CO_2 with either natural alkaline minerals or artificial alkaline by-products and wastes in engineered reactors, rather than under ambient conditions. These reactions typically go to completion within minutes using high temperatures, pressures, electrochemistry, and/or pH changes to accelerate the mineralization process.

EXAMPLE SCENARIOS

Integrating an industrial waste stream of CO_2 into a reactor in which reactions with alkaline minerals are accelerated, forming carbonate minerals in minutes and storing the waste stream CO_2.

Section 8.3 overview

Ex-situ mineralization

	DESCRIPTION*	KEY FINDINGS
Risk assessment	An assessment of risk across the factors essential for CDR approaches to achieve technical viability at scale	High risks: **None** • Key risks include energy, mineral, water, and land requirements, and environmental impacts through potential water and soil contamination
Cost improvement	An assessment of the potential for this approach to come down in cost	Potential learning rate: **Medium** • This approach is mass-customized and design-intensive
Current state	An overview of the state of this approach, including select companies and projects	Current TRL: **Concept to pilot stage** • ~5 companies at concept to pilot stage with <$10M in funding each • Other notable RD&D activity includes Australia's CCUS Development Fund
Success story	An optimistic scenario for the technical viability and deployment at scale of this approach	Capacity: **260 $MtCO_2$ by 2050** • Success is contingent on safe and effective deployment, especially as part of industrial waste streams and by capturing feedstocks unsuitable for enhanced weathering
RD&D roadmap	Roadmap of RD&D projects to best advance this approach toward technical viability at scale	Critical path projects: **$100-180M over 8-15 years** • Key stage gates in process performance, site selection, environmental risk evaluation and mitigation, and measurement of long-term performance

*Please see the **Appendix** for a description of how the results of each assessment are organized within this AIR, and the definitions, criteria, and methods used for each.

Risk assessment

An evaluation of risks to achieving technical viability at scale

Low risk | Medium risk | High risk

CRITERIA		RISK ASSESSMENT	RATIONALE AND SOURCE
Scalability	*Energy requirements*	**Medium risk:** Reactant minerals must be mined, ground, and transported to the reactor site. Additional energy is required to sustain temperature and pressure requirements.	Energy required for mining, grinding, and transportation is significant. Grinding uses 7.2-250 kWh (0.025-0.9 GJ) per tCO_2.[1,2] Using mine tailings reduces energy for mining and comminution.[3] Energy for reactor operation may be significant, though waste heat could reduce overall energy requirements.[3]
	Mineral requirements	**Medium risk:** Industrial alkaline by-products alone may provide up to 7.5 Gt CO_2 global removals per year by 2100.	Industrial wastes and by-products, including slag or mine tailings, are a promising feedstock as they can take advantage of pre-processing by other industries and are relatively low cost. Increased future material consumption will drive increased availability of wastes.[3,4,5,6] Purpose-mined reactant materials may be favorable for given locations but would come with the costs and constraints of additional extraction.[3,2,7]
	Water requirements	**Medium risk:** Reactors must have water access, especially if using CO_2 saturated water.	Feedstock is reacted with CO_2-rich fluid or gas, so access to sufficient water resources is important, but unlikely to be a limiting factor with appropriate siting.[3]
	Land requirements	**Medium risk:** Little land is required for ex-situ reactions, but storage of mineralized materials may require significant space.	Limited land is required for capture and processing, especially for reactors integrated at industrial sites,[3,5] If not used as a product, up to 5-50 Gt or 2-17 km^3 of tailings are produced and must be stored per gigaton of CO_2 captured, although storage of material is already accounted for through the mining process.[8] The estimated global storage potential is 100-200 Gt of ex-situ waste material.[9]
	Environmental impacts	**Medium risk:** Mining and storage of mineralized materials both pose risks for water and soil contamination.	Mining operations for feedstock sourcing and storage of waste products both have risks of contamination and heavy metal introduction into soils and water.[5,10]
Secure storage for 100+ years		**Low risk:** Geochemical storage of CO_2 is long-lived and secure, with only a small risk of reversal.	Carbonate mineral storage is highly durable, though careful site selection and ongoing monitoring will be required to avoid potential reversal due to strong acid weathering, e.g., at relevant mine sites.[3,6,7] For bicarbonate storage, the risk of reversal can be mitigated by managing disposal rates.
Path to measurement at scale		**Low risk:** Measurements are relatively straightforward in the controlled environment of reactors.	Engineered reactors provide controlled, closed environments that facilitate measurements.[7,9] Not all ex-situ approaches result in negative emissions, so a full analysis must be conducted.[9]
Pathway to full costs <$100/$tCO_2$		**Low risk:** Approaches utilizing different feedstock materials have been successfully demonstrated for <$100/$tCO_2$.	Process costs depend on energy for the reactor and feedstock and currently range from $10-600/$tCO_2$. High pressure and temperature systems cost $200-$600/tCO_2.[3,11] Current ex-situ approaches may cost up to 10x more than in-situ approaches.[12]

Notes and sources: [1]Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil (Lefebvre et al., 2019) [2]An LCA in Clearing the Air estimated comminution power requirements at 5.45 kWh/t feedstock. Kelemen et al. (2020) reports energy requirements of 10-100 kWh/t feedstock. Using mineralization capacities for various mine tailing feedstocks of 0.4-0.76 tCO_2 removal per ton mineral from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019), the energy requirements are 7.2-250 kWh/tCO_2. For comparison, the energy consumption of an average American home for 1 day is about 29 kWh, per the U.S. Energy Information Administration. [3]NAS (2019) [4]Rock Solid (EFI, 2020) [5]Clearing the Air (EFI, 2019) [6]The negative emission potential of alkaline materials (Renforth, 2019) [7]Engineered carbon mineralization in ultramafic rocks for CO_2 removal from air: Review and new insights (Kelemen et al., 2020) [8]Tailings volume estimate from "Enhanced Carbonation of Ultramafic Mine Tailings and Sediments" in NAS (2019), comparable to estimates for surficial mineralization. [9]Geochemical Negative Emissions Technologies: Part I. Review (Campbell et al., 2022) [10] Environmental impacts of carbon capture and utilization by mineral carbonation: A systematic literature review and meta life cycle assessment (Thonemann et al., 2022) [11]The mineralization approach and feedstock type both affect cost. Using elevated temperature and pressure requires greater energy and cost ($200-$600/tCO_2), while feedstock sourcing from waste streams (such as slag or demolition) are significantly cheaper than expressly mined materials. Processes that also produce value-added materials can offset some of the CO_2 storage costs for early development, per NAS (2019). [12]An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations (Kelemen et al., 2019)

Potential for cost improvement

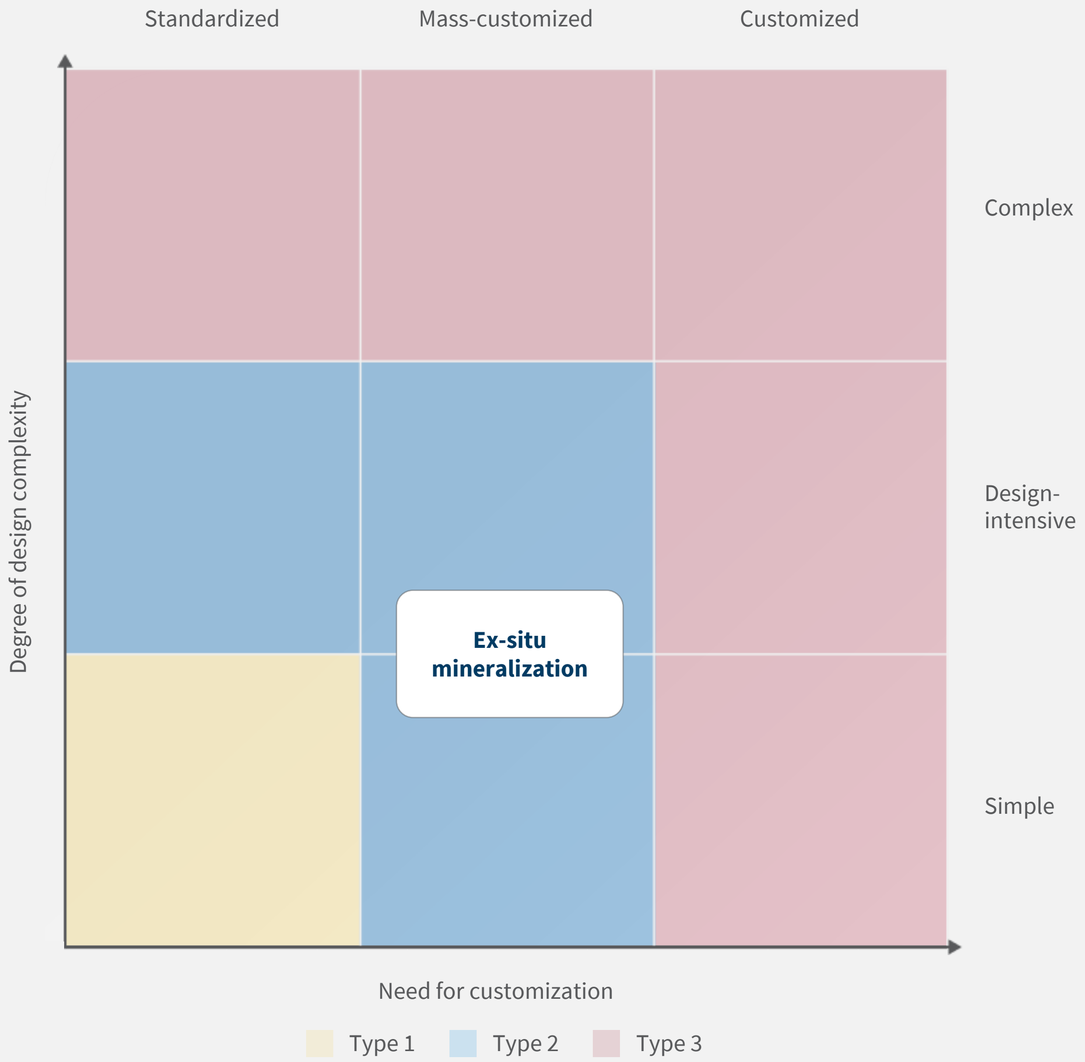
An assessment of two key drivers of learning rates

SECTION 8.3

TAXONOMIC BUCKET Storage

CDR CATEGORY Storage of CO_2

APPROACH Ex-situ mineralization



OVERALL RATING

Type 2[1]

POTENTIAL LEARNING RATE

Type 1 High

Type 2 Medium

Type 3 Low

RATIONALE FOR RATING

DEGREE OF DESIGN COMPLEXITY

- **Rating:** Simple to design-intensive
- **Rationale:** Reactors are based on a known technology. It is a closed system which enables straightforward measurement and quantification. Some complexity may be introduced with integration into existing industrial processes.

NEED FOR CUSTOMIZATION

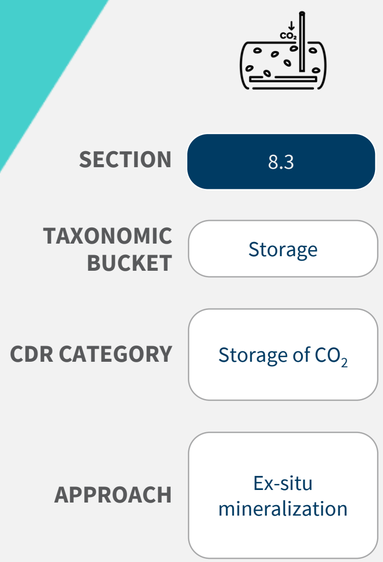
- **Rating:** Mass-customized
- **Rationale:** Diverse types of feedstocks with variation in potential contamination will likely require system customization. However, fundamental equipment can be standardized with tailored customization if necessary. Additional customization may be required when integrating into existing industrial processes.

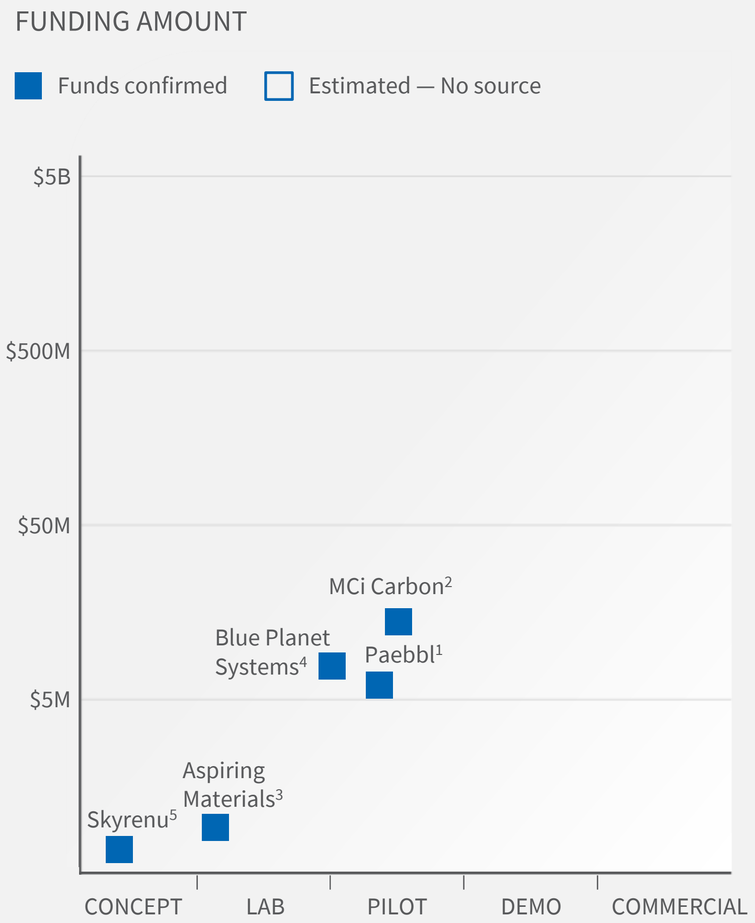
Notes and sources: [1]Table and analysis is based on Accelerating low-carbon innovation (Malhotra, Abhishek, and Tobias S. Schmidt, 2020). For more details on the typologies and their funding and development approaches, see the AIR Appendix.

Current state of RD&D

A mapping of companies, plus other notable activities

NOT EXHAUSTIVE





NOTABLE COMPANIES	FUNDS RAISED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Paebbl: Provides on-site mineralization units for DAC / CCS[1]	€8M (Oct 2022 seed)[6]	• Estimated 100 kg carbon-storing material/day produced in early 2023[6]
MCi Carbon (Mineral Carbonation): Produces reactors capable of processing multiple minerals in several industrial settings[2]	AUD 14.6M (2021)[7] $5M (2023)[8]	• Demonstration plant with RHI Magnesita in Newcastle, Australia (to kick-off in 2024)[9]
Aspiring Materials: Dissolves silicates with acid to separate silica, iron, and magnesium[3]	$1M (Oct 2021, seed)[10]	• XPRIZE Carbon Removal Top 60[3]
Blue Planet Systems: Combines CCS technologies with water and calcium to produce limestone aggregate[4]	$9.3M[4]	• CCS to concrete pilot occurring in Pittsburg, CA[4]
Other companies and activities: Skyrenu Technologies,[5] Blue Skies Minerals,[11] Rock Farm,[12] CO_2Lock,[13] Carbix Corp,[14] Neustark,[15] Cquestr8,[16] O.C.O Technology,[17] Carbon to Stone,[18] Carbon8[19]		

NOTABLE ACTIVITY OUTSIDE OF COMPANIES	FUNDS COMMITTED	SIGNIFICANT DEPLOYMENTS AND FUTURE WORK
Carbon Capture, Use, and Storage (CCUS) Development Fund (Australia)[20]	$25M for pilot / pre-commercial projects	• Support construction of a carbon dioxide storage facility on Kooragang Island in New South Wales[21]

Notes and sources: [1]Paebbl website [2]MCi Carbon website [3]Aspiring Materials website [4]Blue Planet Systems website, Crunchbase estimate of $9.3M and pilot description [5]Skyrenu Technologies website, Skyrenu won $250k from the XPRIZE student team competition. [6]Sifted funding announcement, "Carbon storage startup Paebbl raises €8M seed round" [7]AUD 14.6M investment, Industry and Energy [8]Crunchbase estimate for 2023 [9]RHI Magnesita News [10]Aspiring Materials News and Process [11]Blue Skies Minerals The Process [12]RockFarm [13]CO_2Lock [14]Carbix Corp Crunchbase estimate of $0.7M [15]Neustark, Crunchbase estimate of $0.02M; two projects by Neustark were chosen by Climate Cent Foundation to be awarded contracts with a combined 29,500 tCO_2 purchased. [16]Cquestr8, Crunchbase estimate of $0.3M [17]O.C.O website [18]Carbon to Stone [19]Carbon8 [20]CCUS Development Fund [21]Global Trade Alert

Success story

An optimistic scenario for technical viability and deployment of CDR in addition to, rather than as an alternative to, emissions reductions

What is a success story?

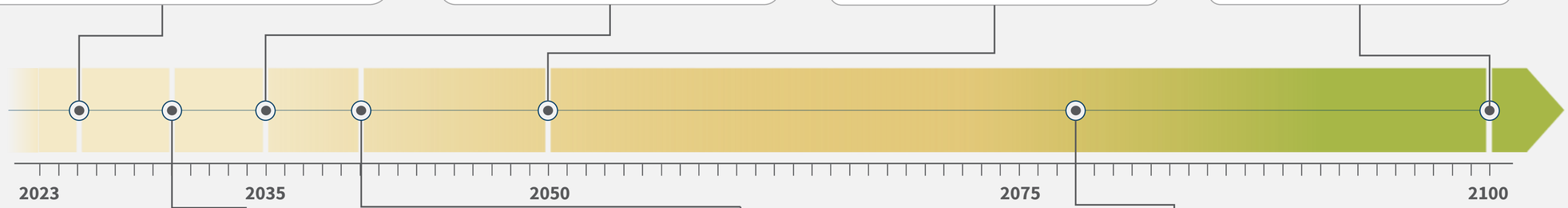
✓ Optimistic deployment projections	x Expected deployment projections
✓ What ***could*** happen in a best-case scenario	x What ***will*** happen in any scenario
✓ Independent of critical path spending estimates in the RMI AIR	x Based on critical path spending estimates in the RMI AIR

SECTION 8.3

TAXONOMIC BUCKET Storage

CDR CATEGORY Storage of CO_2

APPROACH Ex-situ mineralization



2025

- Ex-situ mineralization is used in small scale reactors for testing DAC pilot and demonstration facilities.
- DAC or other capture facilities are built near mineralizable wastes and ex-situ mineralization is used in part as a remediation strategy for reduced environmental impacts.
- New funding is set aside to test and study ex-situ reactor improvements.

2030

- Ex-situ mineralization provides 160 $ktCO_2$/y of sequestration.[1]
- Ex-situ mineralization reactors are built at industrial sites for mineralizing waste streams.
- Carbonated waste shows promise for alternative building materials.
- 4 industrial demonstration facilities of >100 $ktCO_2$/y are funded and sited.

2035

- Ex-situ mineralization provides 5 $MtCO_2$/y of sequestration.[1]
- Ex-situ waste has been shown to be safe and effective as an alternative building material and is in the process of being certified.
- DAC and other capture processes are co-located at mines with tailings and waste mineral streams.

2040

- Ex-situ mineralization provides approximately 20 $MtCO_2$/y of sequestration.[1]
- Continued R&D for this approach has led to improved reactor design and process conditions that have significantly reduced costs.[2]
- Waste feedstocks unsuitable for enhanced weathering are primarily utilized for ex-situ processing.[3]

2050

- Ex-situ mineralization provides 260 $MtCO_2$/y of sequestration.[1]
- Ex-situ reactors have achieved market dominance for neutralizing industrial waste streams and mine tailings on site.[2]

2050-2100

- Ex-situ mineralization continues to be used to neutralize wastes on site to produce building materials.
- Continued growth of this approach depends on the market competitiveness of mineralized building products as its own revenue stream.

2100

- Ex-situ has established itself based on its ability to produce saleable, value-added products.
- Ex-situ mineralization sequesters several hundred million tons of CO_2 per year.[4]

Notes and sources: [1]Annual storage estimates are in line with 100% y-o-y growth from 2025-2035 and 30% growth from 2035-2050 from a starting point of 5 $ktCO_2$/y in 2025. [2]Ex-situ mineralization is a useful storage option for novel DAC testing as it provides immediate storage for captured CO_2. It can also produce useful secondary products such as building materials, per Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) (p269). Ex-situ mineralization has significant process disadvantages as compared to conventional CO_2 storage and in-situ mineralization NAS (2019), p305. Notably, it may require several expensive steps such as excavating, grinding, and transporting feedstock, exposure to a concentrated stream of CO_2, and disposing of mineralized feedstock. These costs make it ~10 times more expensive than conventional CO_2 injection NAS (2019), p269. [3]Mineral feedstocks that contain heavy metals are unsuitable for enhanced weathering due to the risk of heavy metal leaching into soil or water. Ex-situ mineralization provides a more contained use-case, enabling secure storage while still utilizing these wastes for CO_2 removals. [4]Scale of upper limit for mineralization varies by source. NAS (2019) estimates that 0.5-1 $GtCO_2$/y may be possible. (Campbell, et al., 2022) estimates hundreds of millions of tons per year. Ultimately, total removals by ex-situ mineralization will be driven by market competitiveness. It is unlikely to compete as a CO_2 storage method at scale but may be able to compete on sales of ancillary products or in distinct geographies with no subsurface storage options.

THE APPLIED INNOVATION ROADMAP FOR CDR

Roadmap to technical viability

Timeline, scope, and funding for proposed RD&D activities

KEY

- # Current TRL
- Estimated cost
- Timeline to complete

CRITICAL PATH RATING[1]

1. Pre-demo only
2. Pre-demo and demo together, demo is FOAK
3. Pre-demo and demo together, demo is NOAK
4. Demo only
5. Path-boosting only

SECTION 8.3

TAXONOMIC BUCKET Storage

CDR CATEGORY Storage of CO_2

APPROACH Ex-situ mineralization

TRL

CRITICAL PATH ACTIVITIES

$100-180 million | **8-15 years**

TRL 1–6

PRE-DEMONSTRATION WORK

- **Site selection:** Identify demonstration sites with adequate alkaline feedstock and CO_2 sources with manageable environmental risks.
- **Reactor viability and scalability:** Verify process performance for net CO_2 removals from different reactor types.
- **MRV:** Develop robust measurement and assessment pathways as well as LCAs and TEAs.

$50-100 million | **5-10 years**

✓ Identification of demonstration sites and feedstock sources with manageable environmental risks

✓ Reactor performance is ready for demonstration scale testing

✓ Measurement techniques can verify carbon removals and are ready to test at scale

✓ TEA and LCA indicate a path to market competitive costs

STAGE GATES[1]

TRL 7-9

DEMONSTRATION PROJECTS

- **Industrial demonstrations:** Test and assess performance and industrial integration for carbon mineralization of wastes in controlled reactors. Identify process challenges, optimization for scaling, and opportunities for waste utilization.
- **MRV:** Demonstrate scalable measurement and monitoring, develop MRV protocols, and further refine LCAs and TEAs.

$50-80 million | **3-5 years**

✓ Robust MRV at scale with pathway to market competitive costs

✓ Manageable environmental impacts on air and water quality, including storage of carbonated wastes

STAGE GATES[1]

1 2 3 4 5 6 7 8 9 10

PATH-BOOSTING ACTIVITIES TRL 1–MRL 10+[2]

$40-120 million | **5-10 years**

- Assess potential feedstock sourcing from legacy, actively produced, and projected wastes to optimize deployment locations with climate, available energy, and environmental considerations.
- Investigate process improvements and feedstock pre-treatments.
- Assess and improve reaction kinetics of mineralization.

TECHNICAL VIABILITY AT SCALE TRL 9–MRL 10+[2]

- Carbon storage rates are well-quantified at scale and verified by a validated MRV methodology.
- Adequate safe storage for post-mineralization material is available as stockpiles and in use as construction materials.
- Feedstock transport is optimized for cost and emissions.
- Market competitive costs are achieved.

Notes and sources: [1]Stage gates and critical path ratings are explained in the AIR Appendix. [2]Market readiness involves activities that are beyond the scope of the AIR but may also require government support and targeted development.

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Desktop research	Site identification	Identify four demonstration sites for at least two different ex-situ reactor approaches that combine: • Access to appropriate CO_2 sources • Mineral feedstock sources and disposal capacity, including at least two that utilize existing alkaline waste stores[1] • Adequate water and power for relevant ex-situ reactor approaches[2]	✓ Environmental impacts at selected sites have been assessed and are manageable ✓ Appropriate mineral sources are proximate, and sourcing does not create added environmental or safety hazards	1-2	$0.5-1M/y[3]	1-2 y	$2-3M
Field testing	Environmental impact assessment	Determine positive and negative environmental impacts in the field, including: • Impacts resulting from mineralizing waste material • Stability of carbonates or disposal of bicarbonates		2-4	$0.5-1M/y[4]	2 y	$2-8M
Lab	Reactor viability demonstration	Verify performance for distinct reactor types, temperature, and pressure variations across all input parameters, including: • Determination of water use requirements and any resulting implications • Assessment of energy usage and possible improvements with scaling	✓ Net negativity is established and is expected to improve at scale.	3-5	$1-2M/y[4]	5-10 y	$30-50M
Desktop research / field testing	Measurement methodology	Test measurement approaches for all inputs (e.g., CO_2, water, power, mineral feedstock) and outputs (e.g., unconsumed gas, mineralized feedstock) to verify carbon stored.	✓ Measurement techniques are capable of reliable carbon accounting at demonstration scale	2-4	$0.5-1M/y[4]	5-10 y	$5-25M
MRV	LCA and TEA development	Develop robust lifecycle accounting and technoeconomic assessments for all relevant mineral feedstock sources.[1,2] • Approaches should combine empirical measurements and analytical modeling. • Approaches should be open source to invite collaboration and consolidation around a best practice.	✓ Open-source protocols under development that combine empirical and analytical techniques to verify removals. ✓ TEAs can assess and indicate a pathway to market competitive costs	1-3	$0.5-1M/y	4-8 y	$10-20M[5]

Notes and sources: [1]The use of legacy alkaline waste provides an opportunity to assess the extent to which waste toxicity can be mitigated through carbon mineralization. [2]Reactors can utilize different concentrations of CO_2 as inputs and may have a range of temperature and pressure conditions. [3]Cost estimates are based on Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) "Scoping for pilot sites," Table 6.3. [4]Estimates based on a combined range of averages from NAS (2019) budgets for field and lab R&D funding. Details of this estimation can be found in the AIR Appendix.

Demonstration projects

Scoping of demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	DESCRIPTION	SCALE	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Demo	Industrial integration: Perform at least four demonstrations in industrial settings to investigate the feasibility of mineralizing wastes in controlled reactors. These demonstrations should assess the following: • Efficacy of mineralizing existing wastes in reactors vs other processes, e.g., surficial mineralization • Potential process improvements such as reagents, further grinding or pre-processing, environmental controls, and varied CO_2 concentrations and impurities along with a sensitivity analyses to assess cost and performance tradeoffs • Integration of mineralization steps into existing industrial material handling processes, including mining operations • Use or management of carbonated wastes (e.g., for construction or stockpiling)[1]	100 $ktCO_2$ – 1 $MtCO_2/y$[1]	✓ LCAs and TEAs indicate a path to market competitive costs for combined capture and ex-situ mineralization storage at scale ✓ Disposal of mineralized product is environmentally safe at scale	4-6	$3-5M/y[2]	2-3 y	$40-50M
MRV	Demonstration of scalable techniques to quantify removals by: • Building on the pre-demonstration mineralization measurement, TEA, and LCA work • Combining empirical measurements and any required modeling • Consolidating around standard, accepted protocols that are developed along with in-situ and surficial mineralization	N/A	✓ Widely accepted MRV protocols based on empirical data and numerical modeling can accurately verify mineralization rates at scale	3-6	$1M/y	3-5 y	$10-20M[3]

Notes and sources: [1]Per Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019)), as much as 5-50 Gt or 2-17 km^3 of tailings are produced per $GtCO_2$ captured, if not used as a product. 100 $ktCO_2$-1 $MtCO_2$ of removals would produce between 0.5-50 Mt of carbonated tailings. [2]Projects and costs are based on NAS (2019) Table 6.3 "Ex situ pilot studies," but are increased here to account for larger sized projects. [3]Projects and costs are based on NAS (2019) Table 6.3 "Numerical modeling for carbon mineralization."

Path-boosting activities

Scoping of path-boosting activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	Reactor optimization	Explore creation of low-energy reactors,[5] and / or economic integration into existing industrial processes.	1-2	$2-4M/y[1]	3-5 y	$10-30M
Desktop research	Resource database	Create a database of current and projected mineral and waste resource availability, as well as identification of optimal sites for deployment based on climate, available processing energy sources, and environmental risk considerations.	1-2	$0.5-1M/y	3-5 y	$4-8M[2]
Desktop research / lab / field testing	Pre-treatment process and reaction kinetics improvements	Perform experimental measurements and modeling of reaction kinetics to understand dissolution and mineralization rates as a factor of environmental conditions, mineral type, processing, and reaction stage.[3] This work should be complemented by investigation of pre-treatment activities that can enhance carbon mineralization, such as heating, grinding, comminution, microwave treatment, or biotic interactions through engineered conditions or engineered microorganisms.	5-8	$1M/y[1]	5-10 y	$25-80M

Notes and sources: [1]Estimates are based on averages from Negative Emissions Technologies and Reliable Sequestration (National Academies of Sciences, Engineering, and Medicine (NAS) 2019) budgets for lab R&D funding. Details of this estimation can be found in the AIR Appendix. [2]Cost estimates based on NAS (2019) "Kinetics research from Carbon Mineralization Research Agenda Budget," Table 6.3. [3]Environmental conditions include temperature, pressure, humidity, and pH. Preprocessing approaches include heating, grinding, and biotic interventions. Reaction stage should include any existing mineralization and passivation effects. ICEF identifies in their Carbon Mineralization Roadmap (2021) that pretreatments for accelerating mineralization rates are a cross-cutting research priority. [4]Values are based on averages from NAS (2019) budgets for desktop and lab R&D funding. [5]Reactor design evaluation may include plug flow reactors, fluidized, and packed bed performance mapping.

Appendix

Risk assessment criteria

We determined four criteria for long-term CDR technical viability at scale based on the four US DOE Carbon Negative Shot goals

Four goals will guide US Department of Energy (DOE) efforts to advance technologies for both capture and storage:

1. Less than **$100/net metric ton CO_2e** for both capture and storage.
2. Robust **accounting of full lifecycle emissions** (i.e., ensures emissions created when running and building the removal technology are accounted for).
3. **Secure geologic storage or equivalent storage** with costs demonstrated for monitoring, reporting, and verification.
4. Enables necessary **gigaton-scale removal**. To put this into perspective, one gigaton of CO_2 is equivalent to the annual emissions from the U.S. light-duty vehicle fleet. This is equal to approximately 250 million vehicles driven in one year.

Influence on RMI criteria

1. Pathway to full costs <$100/t$CO_2e$
2. Path to measurement at scale
3. Ability to provide secure storage for 100+ years
4. Ability to scale to gigaton removals

Notes and sources: DOE Carbon Negative Shot

Risk definitions

We defined risk definitions for each of the four criteria, ranging from low risk to very high risk.

CRITERIA	SCALABILITY	SECURE STORAGE FOR 100+ YEARS	PATH TO MEASUREMENT AT SCALE	PATHWAY TO FULL & UNSUBSIDIZED COSTS <$100/TON[1]
Low risk	Gigaton scale CDR is achievable with high confidence. This includes minimal input challenges and low environmental impact.	The carbon storage phase is well understood with high confidence and is proven to be durable and permanent for >100 years.	There is an established carbon measurement methodology with high confidence of accuracy.	Costs today are near $\$100/tCO_2$ threshold OR near-term cost reduction pathways have been identified with high confidence. For DAC,[2] cost and energy data are available, outputs are high purity, and: FOAK demo $\leq$10 $ktCO_2$ capacity have cost estimates <$\$200/tCO_2$ OR FOAK demo with >10 $ktCO_2$ capacity with estimated costs <$\$100/tCO_2$
Medium risk	Gigaton scale CDR will encounter foreseeable input resource constraints, demand constraints, or environmental impacts that likely can be addressed.	Evidence of durable and permanent storage is limited. But additional RD&D could plausibly address issues and demonstrate durable and permanent storage.	Carbon measurement methodologies with acceptable accuracy are not yet established and do not have a clear path to being established.	Costs are high today, with mixed evidence for possible reduction to reach $\$100/tCO_2$ threshold. For DAC,[2] cost and energy data are available, outputs are high purity, and: FOAK demos with $\leq$10 $ktCO_2$ capacity have cost estimates $\$200-\$600/tCO_2$ OR FOAK demo with >10 $ktCO_2$ capacity with estimated costs $\$100-\$500/tCO_2$
High risk	Reaching gigaton scale CDR will only be possible if essential breakthroughs occur.	There is low certainty as to whether durable or permanent storage is feasible.	New carbon measurement methodologies and innovative technologies are required to establish accurate MRV protocols.	Costs today are very high or with wide range of uncertain estimates. New empirical evidence is required to clarify cost reduction pathway trajectories to $\$100/tCO_2$. For DAC,[2] limited cost and energy data are available, outputs are high purity, and: FOAK demos with $\leq$10 $ktCO_2$ capacity have cost estimates >$\$600/tCO_2$ OR FOAK demos with >10 $ktCO_2$ capacity with estimated costs >$\$500/tCO_2$
Very High Risk	There are significant hurdles to achieving gigaton scale CDR. No foreseeable solutions can overcome these hurdles in a reasonable amount of time.	Carbon storage is proven to lack durability and permanence, and no foreseeable solutions exist to overcome these issues.	Significant evidence indicates that a high standard of measurement is not technically achievable.	Significant evidence indicates that cost cannot be reduced to $\$100/tCO_2$ or there is no data available and no way to determine risk. For DAC,[2] limited / no cost and energy data are available, outputs are low purity, and: FOAK demos with $\leq$10 $ktCO_2$ capacity have cost estimates >$\$600/tCO_2$ OR FOAK demos with >10 $ktCO_2$ capacity with estimated costs >$\$500/tCO_2$

Notes and sources: [1]Costs per ton of CDR are meant to be inclusive of all the costs necessary to remove a ton of CO_2 from the atmosphere and durably store it. [2]The DAC cost requirements have more explicitly quantified scalability criteria than other AIR approaches. We have taken this approach because DAC approaches present a more tightly scoped engineering challenge than other approaches and can be assessed within the confines of their technical parameters.

Biogenic CDR scalability rubric

We further defined scalability criteria for bCDR approaches

SUB-CRITERIA	LOW RISK	MEDIUM RISK	HIGH RISK	VERY HIGH RISK
Scalability > 1 Gt/y	Gigaton scale CDR is achievable with high confidence. This includes minimal input challenges and low environmental impact.	Gigaton scale CDR will encounter foreseeable input resource constraints that can be addressed.	Reaching gigaton scale CDR will only be possible if essential breakthroughs are met.	There are significant hurdles to achieving gigaton scale CDR. No foreseeable solutions exist.
Water requirements	• At scale, would primarily require waste biomass that requires no additional water • Cultivation of crops occurs at locations with no water stress.	• Long term carbon removal at scale will require supplemental water or irrigation. This would only be needed in areas with low to no water stress.	• Long term carbon removal at scale will require supplemental water or irrigation. This would be needed in some areas of medium to high water stress.	• Long term carbon removal at scale will require supplemental water or irrigation in significant areas of medium to high water stress.
Land requirements	• No land-use conversion necessary (e.g., waste biomass) • Cultivation provides remediation of degraded lands. • High availability of suitable land at appropriate cultivation sites	• Land-use conversion is minimal. • Competition for land has local environmental or economic impacts.	• Likely requires material land-use change thus societal tradeoffs. • Competition for land has regional environmental or economic impacts.	• Unreasonable tradeoffs are necessary to produce biomass, such as pressure on food supply, environmental destruction, and community harm.
Fertilizer requirements	• At scale, would primarily require waste biomass that requires no additional fertilizer and does not impact on-site productivity with its removal	• Minimal additional fertilizer is required to produce biomass or restore soil fertility after harvest. • Fertilizer requirements do not affect regional demand.	• Fertilizer requirements affect sourcing or supply chain for adequate production and land treatment.	• Fertilizer requirements affect production of other cultivated crops or lead to environmental damage from increased production needs.
Environmental impact	• Environmental impacts are neutral or positive (such as remediation of degraded land, improved water quality).	• Cultivation affects local conditions in manageable ways, such as increased need for air quality management.	• Risks to health (e.g., decreased air quality), community or infrastructure (e.g., increased flooding), and environmental well-being (e.g., environmental destruction or species loss) are likely.	• Harm to the environment is unavoidable.

Geochemical CDR scalability rubric

We further defined scalability criteria for gCDR approaches

SUB-CRITERIA	LOW RISK	MEDIUM RISK	HIGH RISK	VERY HIGH RISK
Scalability > 1 Gt/y	Gigaton scale CDR is achievable with high confidence. This includes minimal input challenges and low environmental impact.	Gigaton scale CDR will encounter foreseeable input resource constraints that can be addressed.	Reaching gigaton scale CDR will only be possible if essential breakthroughs are met.	There are significant hurdles to achieving gigaton scale CDR. No foreseeable solutions exist.
Energy requirements	• Energy requirements do not impact local demand.	• Energy consumption requires additional capacity (e.g., power generation, transportation, etc.).	• Energy requirements affect local or regional power availability.	• Adequate energy cannot be provided at viable locations.
Water requirements	• Ambient conditions provide adequate water or humidity. • No additional water sourcing is needed.	• Optimal carbon capture requires supplemental water in locations with potential water stress.	• Carbon removals must occur with supplemental water in areas prone to water stress.	• Feedstock production or carbon removal process would cause or exacerbate water stress.
Land requirements	• No land-use conversion necessary for feedstock production, processing, or storage	• Land-use conversion is minimal.	• Necessary land-use change requires substantial tradeoffs. • Competition for land has regional environmental or economic impacts.	• Unreasonable tradeoffs are necessary at any stage of the CDR process, causing environmental destruction, food supply impacts, community harm, etc.
Mineral/feedstock requirements	• Adequate feedstock is already being produced or exists in waste backlogs.	• Feedstock is available but requires additional processing.	• Feedstock sourcing requires significant changes to other mining, mineral supply chain, or manufacturing needs.	• Feedstock supply interferes with critical supply chain elements.
Environmental impact	• Environmental impacts are neutral or positive (such as remediation of degraded land, immobilization of toxic waste constituents). • No additional mining is required.	• Mineralization or weathering affects local conditions in manageable ways, such as increased need for water quality monitoring.	• Risks to health, community or infrastructure (e.g., increased flooding), and environmental well-being (environmental destruction or species loss) are likely.	• Harm to the environment is unavoidable.

Synthetic CDR scalability rubric

We further defined scalability criteria for sCDR approaches

SUB-CRITERIA	LOW RISK	MEDIUM RISK	HIGH RISK	VERY HIGH RISK
Scalability > 1 Gt/y	Gigaton scale CDR is achievable with high confidence. This includes minimal input challenges and low environmental impact.	Gigaton scale CDR will encounter foreseeable input resource constraints, demand constraints, or addressable environmental impacts.	Reaching gigaton scale CDR will only be possible if essential breakthroughs are met.	There are significant hurdles to achieving gigaton scale CDR. No foreseeable solutions can overcome these hurdles in reasonable amount of time.
Energy requirements	• Energy requirements do not impact local demand. • DAC energy requirements are <2.5 GJ/tCO_2.[1,2]	• Energy consumption requires additional capacity. • DAC energy requirements are <5 GJ/tCO_2.[2]	• Energy requirements affect local or regional power availability. • DAC energy requirements are >5 GJ/tCO_2.[2]	• Adequate energy cannot be provided at viable locations. • DAC energy requirements are either >5 GJ/tCO_2 and high-grade heat, or >10 GJ/tCO_2, or produce low purity CO_2.[2]
Water requirements	• No additional water sourcing is needed.	• Optimal carbon capture requires supplemental water in locations with potential water stress.	• Carbon removals must occur with supplemental water in areas prone to water stress.	• Feedstock production or carbon removal process would cause or exacerbate water stress.
Land requirements	• Off-shore deployment mitigates issues with the land area footprint.	• Land-use conversion is minimal.	• Necessary land-use change requires substantial tradeoffs that have regional environmental or economic impacts.	• Unreasonable tradeoffs are necessary at any stage of CDR process.
Material requirements	• Adequate amounts of necessary material are already being produced.	• Material is available but requires additional production and processing.	• Material sourcing requires significant changes to supply chain or manufacturing needs.	• Material supply interferes with critical supply chain elements.
Environmental impacts	• Environmental impacts are neutral or positive.	• Technology affects local conditions in manageable ways, such as increased need for water quality monitoring.	• Risks to health, community or infrastructure, and environmental well-being are likely, or impacts are completely unknown.	• Harm to the environment is unavoidable.
Reliance on other infrastructure or storage	• For DAC, adequate land area with suitable environmental conditions and proximity to storage exists. High CO_2 purity makes storage straightforward. • For IWC, scalability is independent of other infrastructure.	• For DAC, co-location with storage is challenging due to low CO_2 purities. Suitable environmental conditions are limited or difficult to co-locate with storage. • For IWC, scalability could be limited by other infrastructure.	• For DAC, appropriate environmental conditions have limited co-location with any storage sites or reaching adequate CO_2 purity requires substantial technical challenges to be resolved. • For IWC, scalability will be limited by other infrastructure and needs to be built out alongside relevant facilities.	• For DAC, sufficient purity for CO_2 storage cannot be achieved or there are no locations suitable for both processing and storage. • For IWC, scalability will be limited by other infrastructure and there is no foreseeable solution to scaling.

Notes and sources: [1]The energy threshold value is calculated based on the thermodynamic minimum work of separation, second law efficiency (based on CCS), and compression work. [2]The DAC energy requirements have more explicitly quantified scalability criteria than other AIR approaches. We have taken this approach for two reasons. 1) DAC approaches present a more tightly scoped engineering challenge than other approaches and can be assessed within the confines of their technical parameters. 2) We expect DAC approaches to begin to compete with each other for available energy. Ultimately, the most energy efficient DAC approaches will win out within that category of CDR. By contrast, indirect water capture (IWC) approaches have significantly less deployment information and are expected to be deployed under different conditions than DAC. Therefore, they are not assessed against the same metrics.

CO_2 storage scalability rubric

We further defined scalability criteria for CO_2 storage approaches

SUB-CRITERIA	LOW RISK	MEDIUM RISK	HIGH RISK	VERY HIGH RISK
Scalability > 1 Gt/y	Gigaton scale storage is achievable with high confidence. This includes minimal input challenges and low environmental impact.	Gigaton scale storage will encounter foreseeable input resource constraints that can be addressed.	Reaching gigaton scale storage will only be possible if essential breakthroughs are met.	There are significant hurdles to achieving gigaton scale storage. No foreseeable solutions exist.
Energy requirements	• Energy requirements do not impact local demand.	• Energy consumption requires additional capacity (e.g., power generation, transportation, etc.).	• Energy requirements affect local or regional power availability.	• Adequate energy cannot be provided at viable locations.
Water requirements	• No additional water sourcing is needed.	• Optimal carbon storage requires supplemental water in locations with potential water stress.	• Carbon storage must occur with supplemental water in areas prone to water stress.	• Feedstock production or the carbon storage process would cause or exacerbate water stress.
Land requirements	• No land-use conversion necessary for feedstock production, processing, or storage.	• Land-use conversion is minimal.	• Necessary land-use change requires substantial tradeoffs. • Competition for land has regional environmental or economic impacts.	• Unreasonable tradeoffs are necessary at any stage of the CDR process, causing environmental destruction, food supply impacts, community harm, etc.
Mineral/feedstock requirements	• Adequate feedstock is already being produced or exists in waste backlogs or natural stores.	• Feedstock is available but requires additional processing.	• Feedstock sourcing requires significant changes to other mining, mineral supply chain, or manufacturing needs.	• Feedstock supply interferes with critical supply chain elements.
Environmental impact	• Environmental impacts are neutral or positive (such as use of legacy waste or infrastructure, immobilization of toxic waste constituents). • No additional mining is required.	• Mineralization or storage affect local conditions in manageable ways, such as increased need for water quality monitoring.	• Risks to health, community or infrastructure (e.g., increased flooding), and environmental well-being (environmental destruction or species loss) are likely.	• Environmental harm is unavoidable.

Reminder: *The CO_2 storage category in this report is comprised solely of approaches for storing CO_2 that has been captured from CDR activities in a concentrated form and now needs to be stored. These criteria are used to assess those approaches. They are not used to assess other forms of storage that are embedded within CDR approaches: for example, woody biomass sinking.*

Risk assessment implications

We use our risk assessment ratings to inform critical path stage gates in our roadmap assessments

CRITERIA	RISK ASSESSMENT EXPLANATION	IMPLICATION FOR ROADMAP
Low risk	There is no foreseeable risk, with high confidence, to achieving long-term deployment goals.	Minimal to no implications
Medium risk	**Critical path:** There are foreseeable challenges that should be addressed; however, they may not be critical to achieving long-term deployment goals. **Addressability:** These challenges are addressable with known or foreseeably achievable solutions.	These uncertainties are important to address but will not necessarily block the solution from technological success.
High risk	**Critical path:** Identified challenges are critical to achieving long-term deployment goals. **Addressability:** These challenges are addressable but with low certainty.	**These are stage gate concerns.** The roadmap must contain stage gates and RD&D projects configured to overcome these concerns for the technology to become technically viable at scale.
Very High Risk	**Critical path:** Identified challenges are critical to achieving long-term deployment goals. **Addressability:** These challenges are not addressable with high certainty.	The CDR pathway may need to be deprioritized due to its challenges in meeting long-term deployment goals. *If an approach receives a **"very high risk"** rating, it means that gigaton-scale CDR at less than $100/tCO$_2$e is not foreseeable. However, the approach may still be valuable for smaller scale removals in the near term.*

Criteria resulting in **"high risk"** lead to the creation of **stage gates** for pre-demo and demo work as shown in this example:

Risk assessment result

E.g., environmental impacts:

We assess potential impacts to the environment or to public health from poorly managed implementations of this approach.

→

Pre-demo stage gate

E.g., environmental impacts:

Pre-demo work must lead to high confidence that risks of environmental harm or harms to public health are manageable for larger-scale adoption.

→

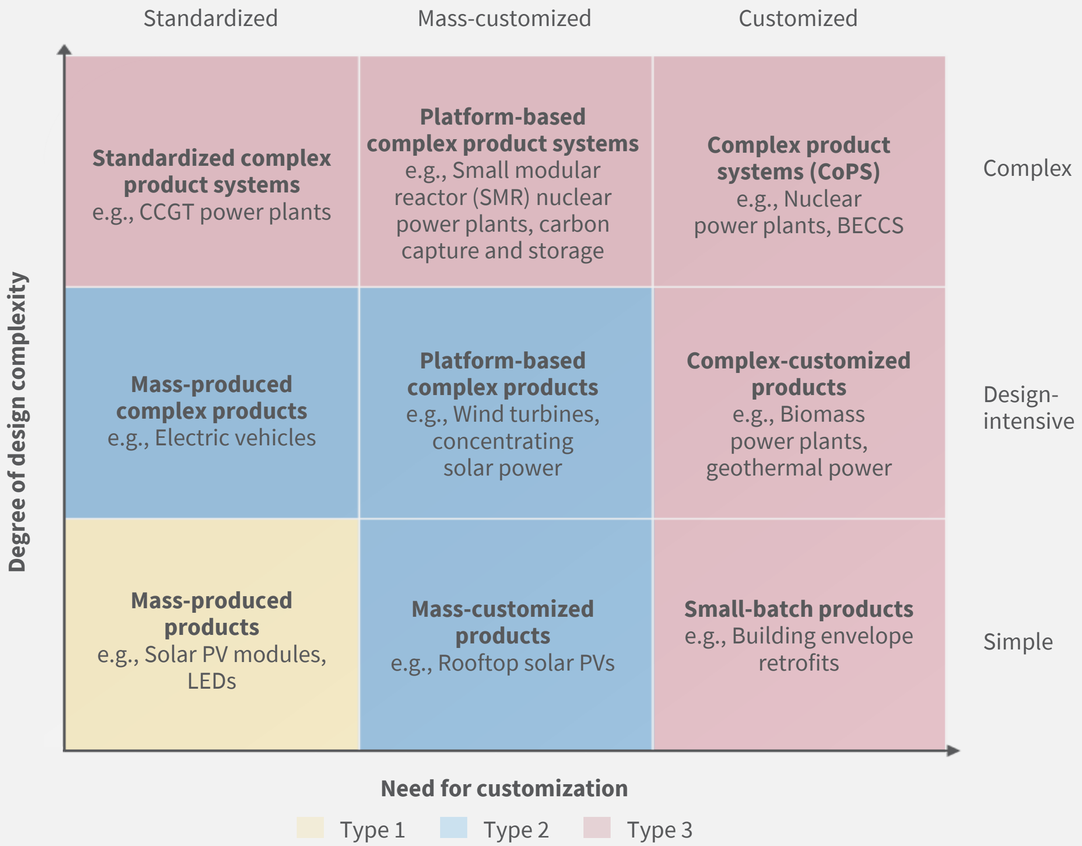
Demo stage gate

E.g., environmental impacts:

Demo work must have demonstrated that risks of environmental harm or harms to public health are manageable for broader deployment.

Cost improvement framework

We used the following framework to assess the potential of a CDR approach to come down in cost



In the words of the authors of the figure shown on the left:[1]

> *"In this perspective, we conduct a thorough review of experience rates of low-carbon technologies […] to develop a technology typology that helps explain systematic differences in technologies' experience rates by distinguishing between technologies on the basis of (1) their design complexity and (2) the extent to which they need to be customized."*

RMI is adapting this framework to assess **the potential of a CDR approach to come down in cost**.[3] The ability of a CDR approach to come down in cost is a critical factor in determining its long-term viability.

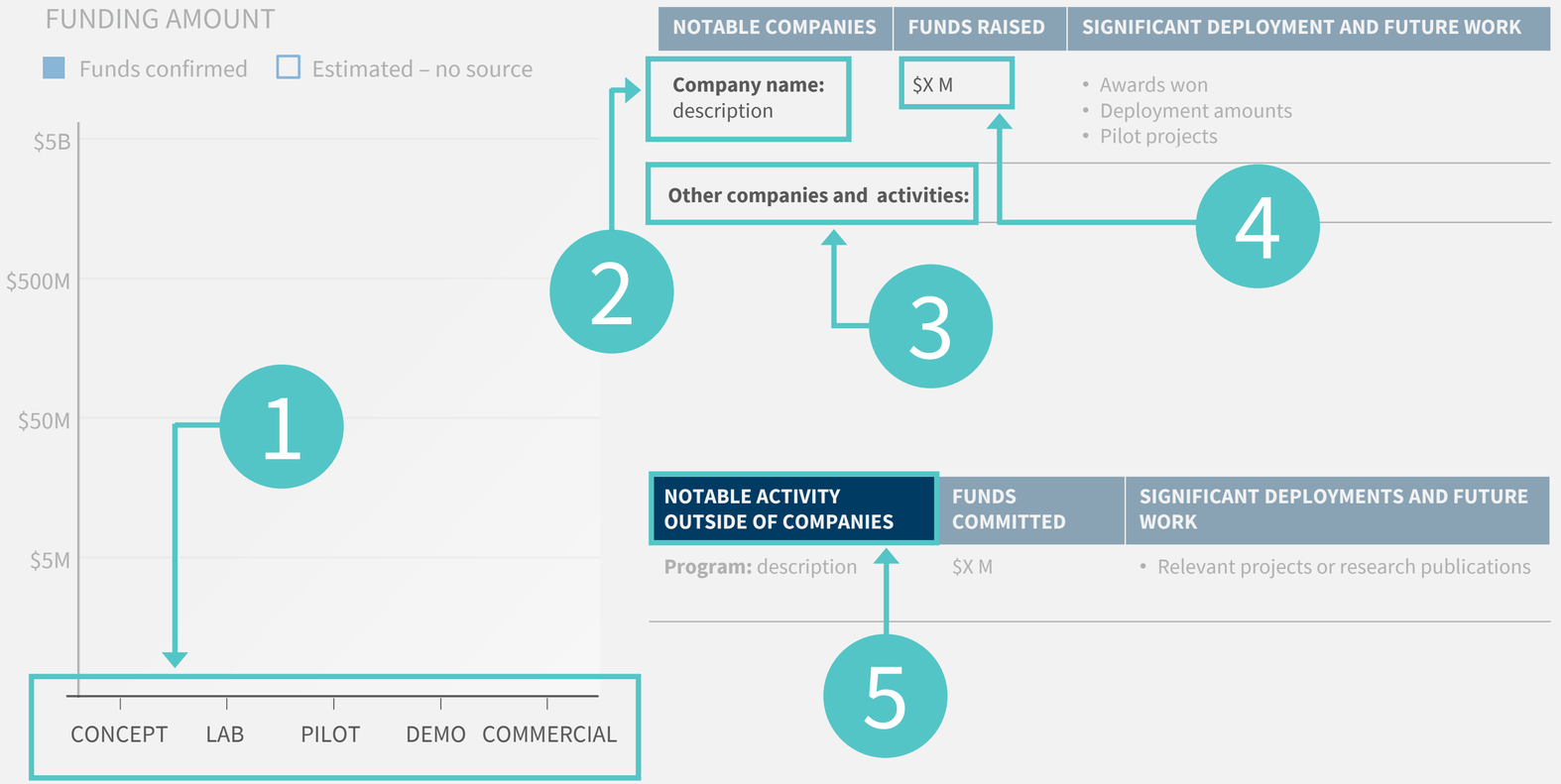
TYPE	EXPECTED LEARNING RATE	EXPLANATION[1]
Type 1	High	Simple, mass produced products have high learning rate potential
Type 2	Medium	More complex and customized products may not come down in price as quickly as type 1 technologies
Type 3	Low	Complex and/or customized technologies are the least likely to come down in cost

Notes and sources: [1]Malhotra, Abhishek, and Tobias S. Schmidt. "Accelerating low-carbon innovation." *Joule* 4.11 (2020): 2259-2267. The authors of the original paper suggest that Type 3 technologies often struggle to come down in cost (low learning rates) while Type 1 technologies often have higher learning rates. [2]Way, Rupert, et al. "Empirically grounded technology forecasts and the energy transition." *Joule* 6.9 (2022): 2057-2082. [3]Waterfall charts are commonly used to show where and how much a technology might come down in cost.

NOT EXHAUSTIVE

Current state slides

We used the following framework to assess the state of the field for each of our CDR approaches



1. We plotted companies along qualitative TRLs based on public information and information shared during the review process about deployment and projects.

2. For a company to be included, it needed to match several criteria:
   1. Accessible website
   2. Approach clearly outlined in enough detail to be categorized within our taxonomy
   3. Information on deployment or other progress, such as lab work or awards won

3. We included companies with early TRLs and less information about progress under additional activities, including supporting activities such as groups working on MRV. For commercial pathways, some large, well-funded companies were also listed here to ensure inclusion of smaller, innovative companies in the section above.

4. We estimated funds raised based on company websites, online sources, and personal communication.

5. Other programs (e.g., research, government funding) relevant to the CDR approach were included. However, these lists are not exhaustive.

Defining deployment

We qualitatively categorized company deployment to decide if a project was at pilot, demo, or commercial scale, which informed how we categorized TRLs and critical path ratings for an approach

PILOT

To be considered a pilot, projects need to be:

- One of a company's first projects in the field.
- Demonstrating that a technology works outside of lab conditions.
- Showcasing removal but not necessarily at scale.

Increase in scale but not market integration

DEMO

To be considered a demo, projects need to be:

- Functioning at commercial scale (representative amounts of feedstock, energy, labor that a commercial operation would need).
- Demonstrating not just that the technology works but that it works at scale.

Becomes integrated into the market and supply chains

COMMERCIAL

To be considered commercial, projects need to be:

- Fully functional on the market with products or services available for consumers.
- Fully incorporated into respective supply chains and workforces (i.e., conventional storage).

Highest company deployment[1]: Pilot
Critical path rating of
1 or 2

Highest company deployment[1]: Demo
Critical path rating of
3 or 4

Highest company deployment[1]: Commercial
Critical path rating of
3 or 4 or 5

Notes and sources: [1]These patterns are generally true, but not always depending on individual pathway needs. For more detailed information, see the executive summary slides on critical path ratings.

Success stories

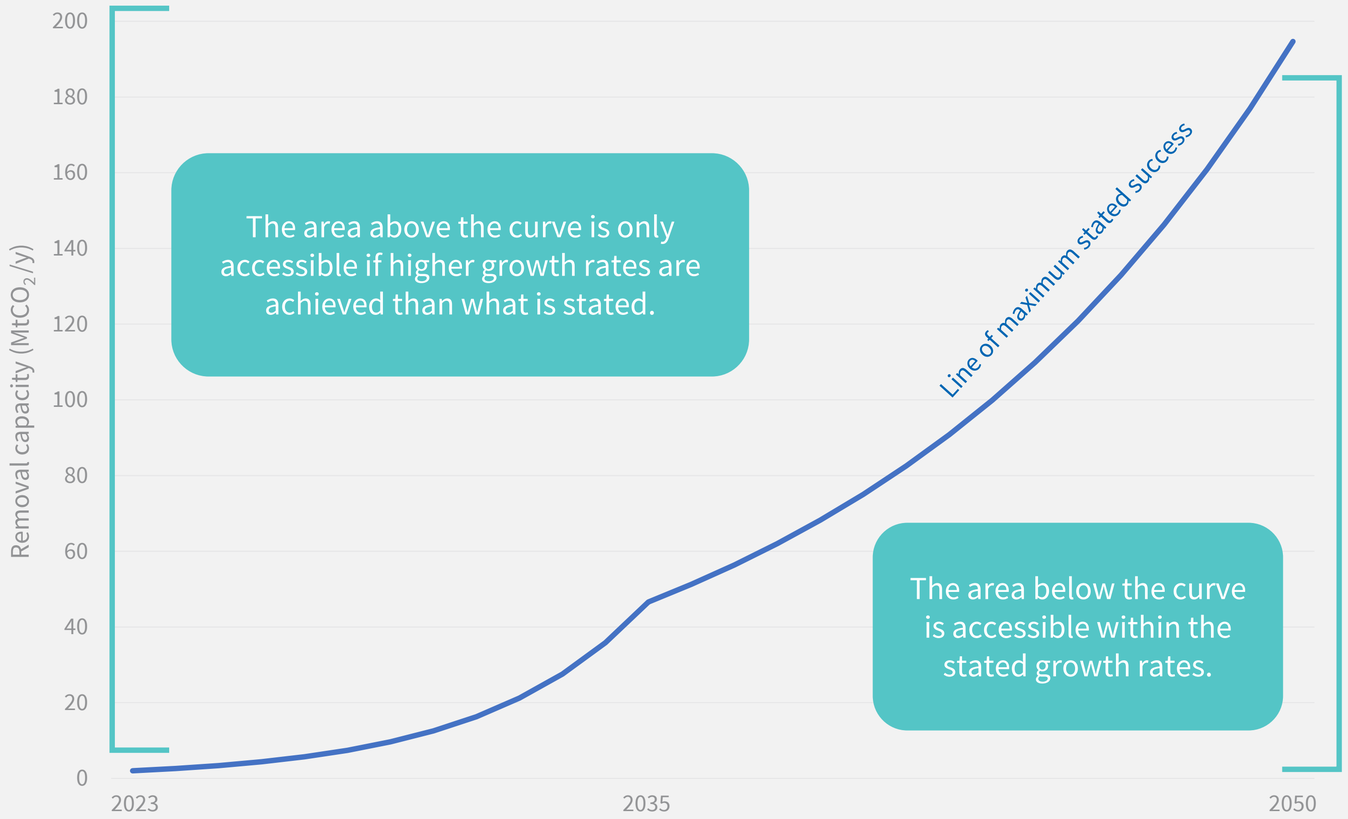
We include success stories to gain clarity on the optimistic upper bound given on where we are today

How our success stories should be interpreted

- Our success stories are not scenarios of what will happen. They are meant to represent the upper range of what could happen if all RD&D and scaling efforts go as well as possible.
- Any assertion of a scale of CDR that is higher than our success stories would require even faster growth rates than the ones we have characterized.
- Success stories are meant to illustrate the best-case scenario. They are also meant to preclude assertions of CDR scale that are higher than what is shown in the success story.

Example

Assumptions:
2023 starting point: **2 $MtCO_2$/y**
Annual growth, 2023-2035: **30%**
Annual growth, 2035-2050: **10%**

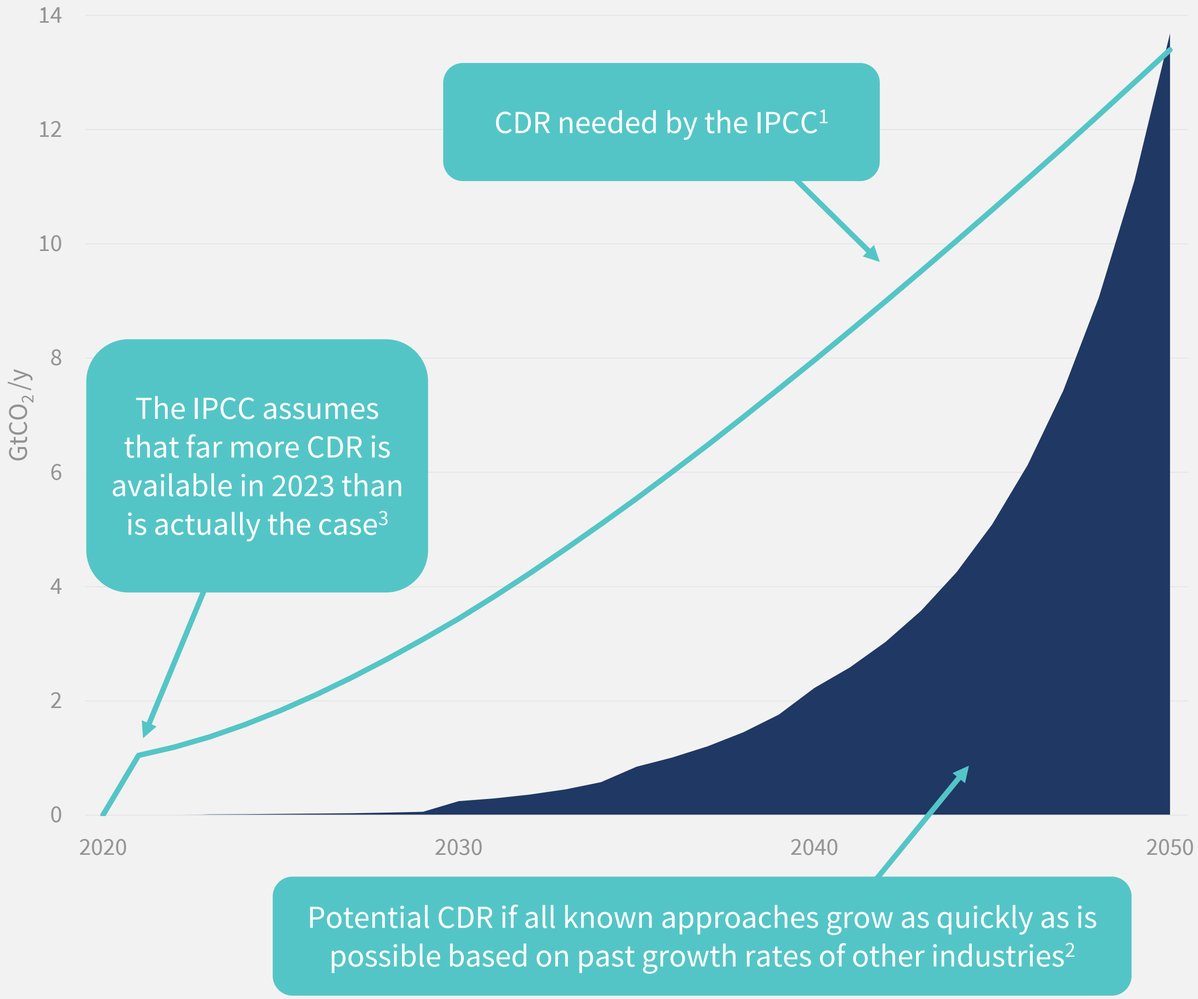


Success stories

Our success stories tell us that we will have less CDR than the IPCC says we need until at least 2050

- Outside of living biomass and timber wood products, intentional CDR activities are very small in scale today. (The Oxford State of CDR report estimates ~2.3 $MtCO_2/y$ in 2023, which is the same as our starting point in the AIR).[2]
- The IPCC AR6 report indicates that we need to achieve up to 13.4 $GtCO_2/y$ of CDR by 2050.[1]
- Achieving the scale of verified, durable, credited removals we need by 2050 will require an average yearly growth rate of around 35% from 2023-2050 across all of CDR.[2]

CDR required by IPCC vs. what might be supplied in the optimistic upper-bound scenario



Notes and sources: [1]The IPCC's sixth assessment report includes 8 categories of scenarios. C1 scenarios are those that limit warming to 1.5C by 2100 without overshooting in mid-century. C2 scenarios are those that limit warming to 1.5C by 2100 but "overshoot" in mid century and rely more heavily on CDR in the second half of the century. The line shown is C2 scenario requirement for CDR. Data was obtained from the AR6 Scenario Explorer and Database hosted by IIASA. [2]The State of CDR Report estimates that the total CDR from BECCS, biochar, and other "novel approaches" as 2.3 $MtCO_2/y$. We have estimated total CDR in 2023 as the sum of all measured and verified removals in our individual success stories. This includes roughly 2 $MtCO_2/y$ from BECCS to liquid fuels and 1 $MtCO_2/y$ from biochar. Growth in CDR shown here is the aggregate of all known CDR approaches modeled in the Applied Innovation Roadmap. [3]IPCC AR6 scenarios assume that we already have up to 1.4 $GtCO_2/y$ of carbon removals in 2023, largely from land use and afforestation.

Success stories

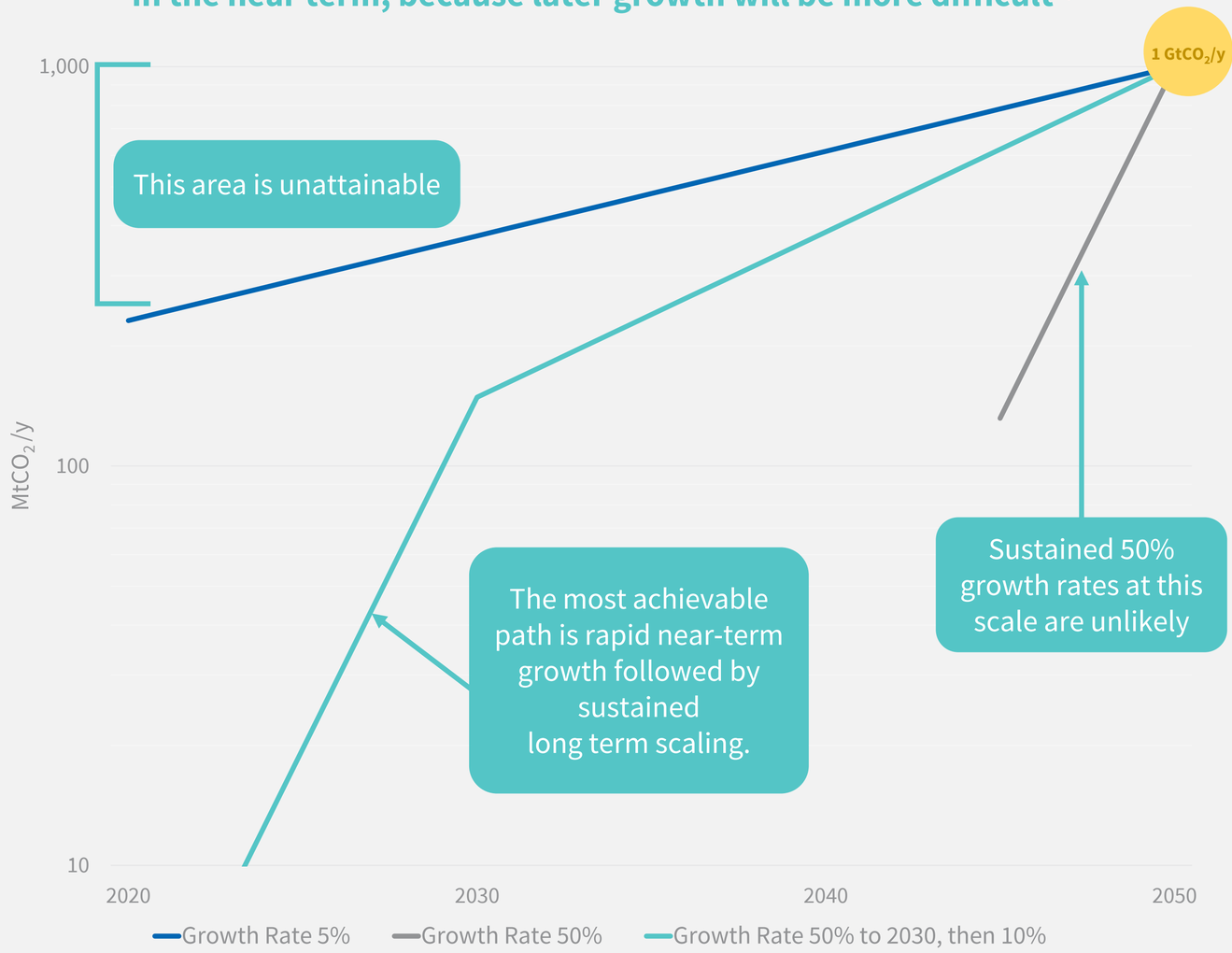
Our success stories include two growth paradigms: (1) an early period of rapid growth and (2) a later period of commercial scaling

Historically, growth in industries can start fast[1] but inevitably slows down to a long-term average of less than 5%.[2,3] Therefore, we have written our success stories to include two paradigms:

1. **An early period of rapid growth**: In this phase, the CDR is typically less than 50 $MtCO_2/y$ capacity. Yearly growth rates in this phase typically range from 20-50%. This phase is marked by fast technological adoption.

2. **A secondary period of scaling:** In this phase, the CDR approach has reached large commercial scale. Here its continued growth requires scaling of supply chains, building out workforce, and expanding operations into large new areas. Yearly growth rates slow to 5-20%.

To achieve our CDR targets, we need to scale quickly in the near term, because later growth will be more difficult[3,4]



Notes and sources: [1]IEA global sales market share of electric cars from 2010-2021 indicates that electric vehicle registrations grew 63% per year from 2011-2021. [2]According to CEIC data average US industrial growth from January 1920 to August 2023 averaged 3.3%. [3]In the paper Lessons for Direct Air Capture from the History of Nitrogen Synthesis, the authors write that ammonia production in several countries has achieved >20% for a decade or two, but only during early build-out periods. After that, growth rates have slowed to below 5%. They note that if DAC achieves the same rates of expansion as ammonia production, it can achieve gigaton scale in 2050. However, they also note that current RD&D efforts have been much slower for DAC than they were for nitrogen synthesis. [4]The numbers on this chart can be easily scaled by either multiplying or dividing all numbers by the same scaling value. For example, if you wanted to specify a target of 10 $GtCO_2/y$ in 2050, you would just multiply all the other numbers by 10 as well.

Success stories

Below are the guidelines we used when creating our success stories

Why create success stories?

Our goal is to shift the narrative mindset toward successful deployment of CDR:

- We aim to paint a plausible picture of how an unprecedented level of growth, at the scale required, **could feasibly be achieved**. Otherwise, we are just predicting the base-case future.
- We aim to **expand what's possible**, in terms of growth, compared to the past. Today, we know how to develop and deploy new technology quickly, as informed by prior experience; we have more people; we have better scientific tools and technologies; and it's a collective worldwide mission.

What makes a good success story?

Principles for creating good success stories include:

- Make **careful judgements**, based on data, to choose the most appropriate yet aggressive growth rates and trajectory for achievable scale from 2030-2050. These values define near-term aspirational deployment targets.
- Ground the story in **specific geographies, countries, applications, or synergies** with other shifts in the energy transition that support breakthrough deployment toward gigaton scale removals.
- Where appropriate, **name specific breakthroughs** resulting from successful demonstration projects.
- Where possible, **define the number of plants/facilities to be built or deployed**, especially if that is a critical path activity to advance the space.

RMI

Notes and sources: [1]These goals are all relevant to technical goals of success stories given the AIR's technical focus. However, there are other important reasons to create success stories including to create scenarios that global environmental justice, policy, workforce, and financing considerations can be mapped to.

Technology readiness levels

Using company deployment information and well-established technology readiness level (TRL) scales, we determined our own TRL scale unique to CDR and rated each approach based on it

CATEGORY	TRL/MRL	DEFINITION[1]	DEPLOYMENT LEVEL ACHIEVED	AIR CRITICAL PATH RATING
Market scaling	MRL 10+	**NOAK facilities** deployed commercially under **different conditions** and **geographies**	Commercial[2]	5
First deployment	9	Project is **fully operational** under real conditions and **first commercial activities** occur[3]	Commercial	3, 4
Technology demonstration	8	**Commercial scale** project undergoes **final stages** of testing and evaluation	Demo[2]	3, 4
	7	FOAK project occurs at **commercial scale** and under **relevant environmental conditions**	Demo	3, 4
Pilot validation	6	Project occurs at **pilot scale** and under **relevant environmental conditions;** FOAK commercial scale facility not completed	Pilot[2]	1, 2
Technology development	5	Project occurs at **lab scale** and under **relevant environmental conditions**	Lab	1
	4	**Components** of a project are **integrated** and tested at **lab scale**	Lab	1
Basic research	3	**Experimentation** occurs to test **proof of concept**	Concept	1
	2	**Conceptual research** applied to **practical applications**	Concept	1
	1	**Basic principles** and **concepts** of a project researched	Concept	1

Notes and sources: [1]We based our TRLs on two well-established scales. The DOE's Technology Readiness Level Scale which ranges from 1-9 and the DOE's technology risk scale which includes both technology readiness levels and market readiness levels. The scale shown above was designed to broadly cover all 32 of the CDR approaches mentioned in the AIR. For TRL scales pertaining to a specific technology, experts in the field may argue these definitions should shift slightly. [2]As defined in the appendix slide on defining deployment, 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 (i.e., biochar) or carbon removal credits, not including pre-purchases.

Roadmap timelines

We determined what work seems critical for an approach to scale, categorized the approach using critical path ratings, and determined timelines based on those ratings

What are critical path ratings?[1]

Critical path ratings were determined by a pathway's TRL/MRL as well as unique needs. The critical path rating indicates what type of work (pre-demo, demo, or path-boosting) and when that work (simultaneously or separately) is needed for an approach to scale up.

1 Pre-demo only

2 Pre-demo and demo can be done simultaneously - demo is FOAK

3 Pre-demo and demo can be done simultaneously - demo is new sites/conditions

4 Demo only

5 Path-boosting activities only

INDEX	APPROACH	CURRENT TRL/MRL	CRITICAL PATH RATING: WHAT IS NEEDED NEXT IN THE CRITICAL PATH
1.1	Living biomass	MRL 10+	Path-boosting activities only
2.1	Biomass direct storage	TRL 6	Pre-demo and demo can be done simultaneously - demo is FOAK
2.2	Timber building products	MRL 10+	Path-boosting activities only
2.3	Other biomass building products	TRL 9	Pre-demo and demo can be done simultaneously - demo is FOAK
2.4	Pyrolysis biochar	TRL 9	Demo only
2.5	Pyrolysis bioliquid	TRL 7	Pre-demo and demo can be done simultaneously - demo is new sites/conditions
2.6	Microalgae ponds	TRL 7	Demo only
2.7	Microalgae ocean	TRL 4	Pre-demo only
2.8	Macroalgae ocean	TRL 6	Pre-demo only
3.1	BECCS to electricity	TRL 6	Pre-demo and demo can be done simultaneously - demo is FOAK
3.2	BECCS to fuels	MRL 10+	Pre-demo and demo can be done simultaneously - demo is new sites/conditions
4.1	Surficial mineralization	TRL 6	Pre-demo and demo can be done simultaneously - demo is FOAK
5.1	Terrestrial enhanced weathering	TRL 7	Pre-demo and demo can be done simultaneously - demo is new sites/conditions
5.2	Coastal enhanced weathering	TRL 6	Pre-demo and demo can be done simultaneously - demo is FOAK
5.3	Mineral alkalinity enhancement	TRL 6	Pre-demo only
6.1	CO_2 stripping	TRL 6	Pre-demo and demo can be done simultaneously - demo is FOAK
6.2	Electrochemical alkalinity production	TRL 6	Pre-demo and demo can be done simultaneously - demo is FOAK
7.1	Absorption and high-grade heat regeneration	TRL 7	Pre-demo and demo can be done simultaneously - demo is new sites/conditions
7.2	Absorption and low-grade heat regeneration	TRL 5	Pre-demo only
7.3	Absorption and electrochemical regeneration	TRL 6	Pre-demo only
7.4	Adsorption and high-grade heat regeneration	TRL 6	Pre-demo and demo can be done simultaneously - demo is FOAK
7.5	Adsorption and low-grade heat regeneration	TRL 9	Pre-demo and demo can be done simultaneously - demo is new sites/conditions
7.6	Adsorption and electrochemical regeneration	TRL 6	Pre-demo only
7.7	Adsorption and humidity / water regeneration	TRL 6	Pre-demo only
7.8	Membrane: pressure gradient separation	TRL 2	Pre-demo only
7.9	Membrane: electrochemical separation	TRL 3	Pre-demo only
7.10	Cryogenic: phase separation	TRL 4	Pre-demo only
8.1	Conventional storage	MRL 10+	Pre-demo and demo can be done simultaneously - demo is new sites/conditions
8.2	In-situ mineralization	TRL 8	Pre-demo and demo can be done simultaneously - demo is new sites/conditions
8.3	Ex-situ mineralization	TRL 6	Pre-demo and demo can be done simultaneously - demo is FOAK

Notes and sources: [1]For more information on critical path ratings, see the executive summary slides that discuss each rating in more detail as well as which approach fits in to which category.

Roadmap timelines

We assessed timelines on multiple levels: (1) at the level of each individual activity, (2) at the level of pre-demo and demo work, and (3) at the level of the overall approach, using the methodology below

	PROCESS TO CREATE TIMELINES	CRITICAL PATH ACTIVITIES	PATH-BOOSTING ACTIVITIES
1 ACTIVITY LEVEL	**Timeline assessment individual AIR activities** • Pre-demo, demo, and path-boosting slides all include durations for each of the stated activities. • Durations for individual activities may include a range. This indicates uncertainty in the time required to complete an activity.	Pre-demo activity (2 to 4 years) Pre-demo activity (5 to 10 years) Pre-demo activity (1 to 3 years) Pre-demo activity (3 to 5 years) Demo activity (2 to 3 years) Demo activity (2 to 5 years) Demo activity (8 to 10 years) Demo activity (5 to 10 years)	Path-boosting activity (3 to 5 years) Path-boosting activity (4 to 5 years)
2 ROADMAP LEVEL	**Timeline assessment for pre-demo, demo, and path-boosting activities[1]** • The low end of the timeline is set by the activity that has the **longest low-end individual value**. • The high end of the timeline is set by the activity with the **longest high-end individual value**.	Pre-demo timeline: **5 to 10 years** Demonstration timeline: **8 to 10 years**	*Path-boosting activities have a separate timeline based on the time to complete*: **4 to 5 years**
3 OVERALL	**Timeline assessment for the overall approach** • The overall approach timeline is based on the timelines for the pre-demo and demonstration activities. • It is also based on the critical path rating, which is discussed in the previous slide and in the executive summary of the AIR. In some approaches, the pre-demo work can be done in parallel with the demonstration level work. In some approaches the pre-demonstration work must come first.	Overall approach timeline: **10 to 14 years** *Overall timeline depends on the critical path rating of the approach. In this example, some pre-demo and demo activities can be done in parallel. As a result, the low-end overall timeline (10 years) is less than the sum of the low-end timeline for pre-demo activities (5 years) and demo activities (8 years).*	

Notes and sources: [1]The critical path rating, presented in the executive summary, determines whether the pre-demo and demo activities must be done sequentially or whether they can be conducted in parallel.

Costing methodology

We used the following methodology to determine cost estimates on our roadmaps, pre-demo, demo, and path-boosting slides

All costs in the AIR are estimated by a combination of direct and indirect estimates, plus input from reviewers.

Direct cost estimates

- Directly quoted costs from academic publications, two National Academies of Science (NAS) reports,[1] and other publications
- Direct input or direct quotes from startups or researchers
- Direct input from thematic experts

Indirect cost estimates

- Indirect cost estimates from startups or experts (e.g., news articles)
- Estimates from third parties
- Estimated costs based on historic data and NAS ranges (shown in the following slides)[2]

The AIR includes ranges of costs (where applicable) based on (1) our assessment and (2) the input we received from reviewers

NOT INCLUDED

Calculated cost estimates

- Interpolation/estimation based on historical analyses of real costs analyzed in retrospect
- Bottom-up costing by individual component costs

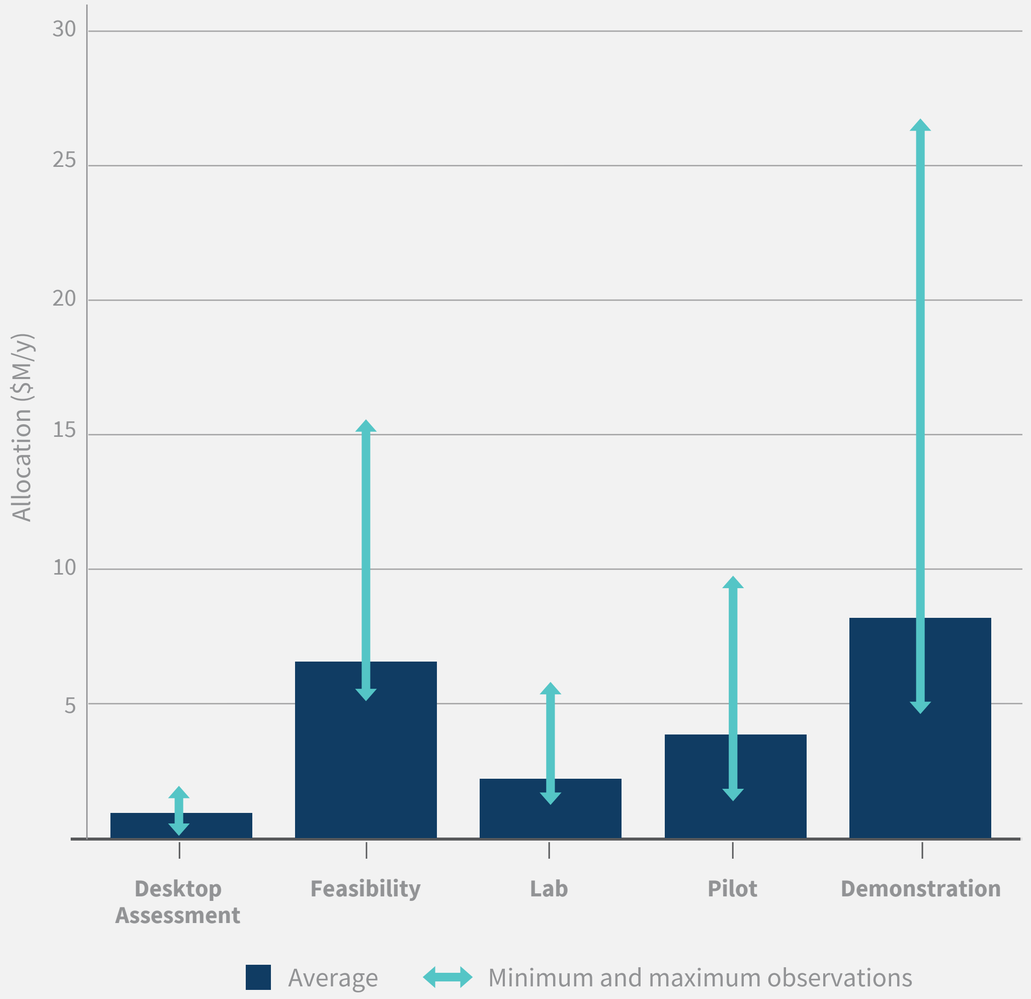
Notes and sources: [1]National Academies Ocean CDR (2022) and the National Academies Negative Emissions Technologies and Reliable Sequestration (2019) are the most important sources for grounding cost estimates in the AIR. [2]Values from the NAS (2019) report were aggregated and averaged (as shown on the next slide); however, values from NAS (2022) were directly referenced in the AIR.

Anchoring cost estimates

We averaged historic observations of various instances of government spending on CDR projects, shown in the chart and table below[1]

TYPE OF WORK	AVERAGE $M/year	MINIMUM $M/year	MAXIMUM $M/year
Desktop assessment	0.9	0.8	1.0
Feasibility	6.6	1.4	9.0
Lab	2.2	1.0	3.6
Pilot	3.9	2.4	6.0
Demonstration	8.2	3.6	18.5

Cost estimates are primarily based on US-centric sources and estimated in USD. This is currently the best available data, and most activities are currently in the US or are priced in USD.



Notes and sources: [1]This information represents averages of 78 individual funding line items. These individual line items were pulled from various sources including FOA 2614: CARBON MANAGEMENT, FOA 2610: CarbonSAFE Phase II - Storage Complex Feasibility, BBSRC - Research and Innovation Grant, UK Govt - Direct air capture and greenhouse gas removal programme - Phase 2, ARPA-E OPEN2021, and ARPA-E MINER.

Anchoring cost estimates

We aggregated and averaged values from NAS 2019 funding requests, shown in the charts below, which anchored cost estimates for projects in the AIR[1]

CATEGORY	REQUEST TYPE	$M/YEAR/SITE	NUMBER OF SITES	YEARS
Research funding	Field R&D	1.1	6.3	7.3
	Desktop R&D	1.3	2.9	10.1
	Lab R&D	1.0	19.0	10.0
	Social science R&D	3.0	1.0	6.5
	Grand goal R&D	60.0	1.0	15.0
	IAM modeling	10.0	1.0	10.0
Demo and pilot funding	Ecosystem demonstration	0.6	12.0	17.2
	Pilot	7.7	2.5	8.8
	DAC demonstration	100.0	1.0	10.0
Other funding	Environmental impact	0.8	12.0	10.0
	Data platform	2.5	2.0	10.0
	Monitoring system	5.0	1.0	5.0
	Engineering Design	5.0	1.0	10.0
	Test Center	15.0	1.0	10.0

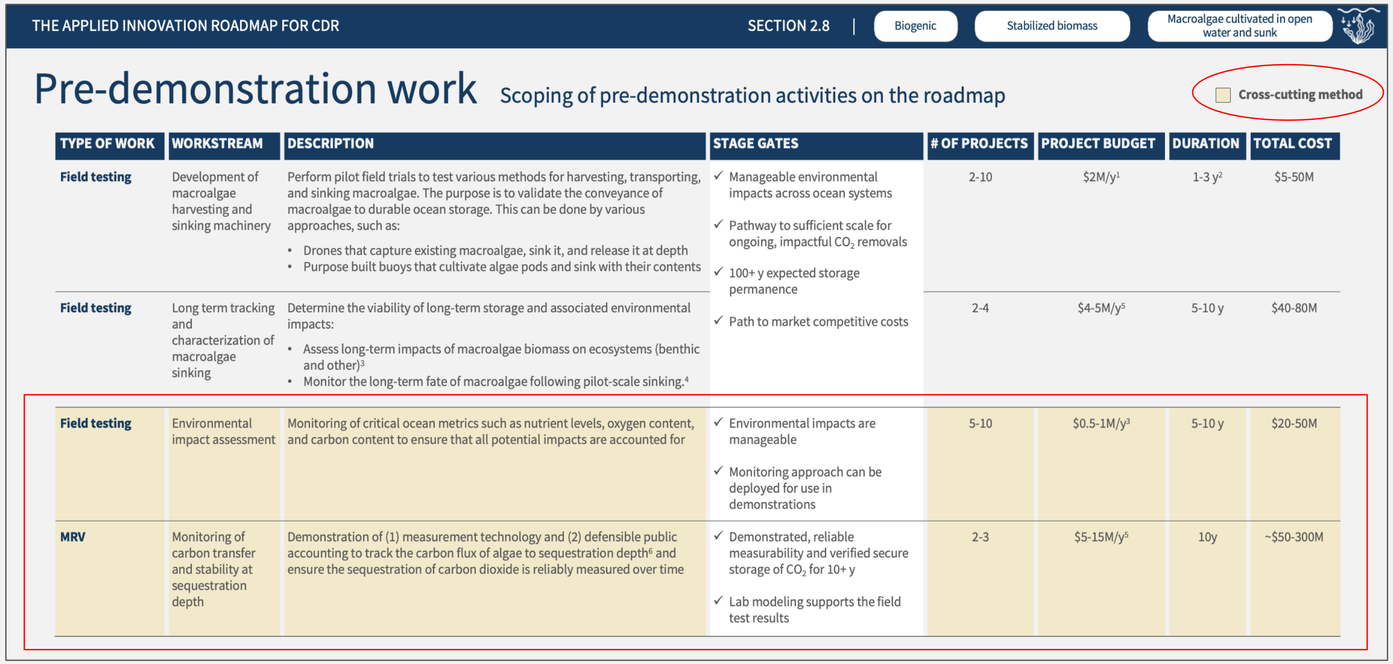
DAC-specific funding averages

Type	$M/year/site	Number of sites	Years
Lab R&D	1	30	10
Desktop R&D	3	1	10
Pilot	12	1	10
Engineering design	5	1	10
Pilot[2]	20	1	10
Test center	15	1	10
DAC demonstration[3]	100	1	10
Test center	15	1	10

Notes and sources: [1]Costs on this slide are averages of all the costs found in the National Academy of Sciences (2019) Table 8.3 (p368-380). These costs were aggregated and averaged in order to understand the general cost of various levels of project. In addition, these costs are in 2019 dollars and have not been adjusted to 2023 dollars. [2]The $20M over 10 years is expected to cover 3x 1 kt/y facilities. [3]Demonstration-scale plants of about 10 $ktCO_2/y$ would be of sufficient size to inform optimal siting for the various approaches. The $100M is expected to cover 2x 100 kt/y facilities.

Cross-cutting cost estimates

For some workstreams, costs were considered “cross-cutting.” We explain what this means and how it impacted cost estimations in our example below.



THE APPLIED INNOVATION ROADMAP FOR CDR SECTION 2.8 | Biogenic | Stabilized biomass | Macroalgae cultivated in open water and sunk

Pre-demonstration work

Scoping of pre-demonstration activities on the roadmap

Cross-cutting method

TYPE OF WORK	WORKSTREAM	DESCRIPTION	STAGE GATES	# OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Field testing	Development of macroalgae harvesting and sinking machinery	Perform pilot field trials to test various methods for harvesting, transporting, and sinking macroalgae. The purpose is to validate the conveyance of macroalgae to durable ocean storage. This can be done by various approaches, such as: • Drones that capture existing macroalgae, sink it, and release it at depth • Purpose built buoys that cultivate algae pods and sink with their contents	✓ Manageable environmental impacts across ocean systems ✓ Pathway to sufficient scale for ongoing, impactful CO_2 removals ✓ 100+ y expected storage permanence ✓ Path to market competitive costs	2-10	$2M/y[1]	1-3 y[2]	$5-50M
Field testing	Long term tracking and characterization of macroalgae sinking	Determine the viability of long-term storage and associated environmental impacts: • Assess long-term impacts of macroalgae biomass on ecosystems (benthic and other)[3] • Monitor the long-term fate of macroalgae following pilot-scale sinking.[4]		2-4	$4-5M/y[5]	5-10 y	$40-80M
Field testing	Environmental impact assessment	Monitoring of critical ocean metrics such as nutrient levels, oxygen content, and carbon content to ensure that all potential impacts are accounted for	✓ Environmental impacts are manageable ✓ Monitoring approach can be deployed for use in demonstrations	5-10	$0.5-1M/y[3]	5-10 y	$20-50M
MRV	Monitoring of carbon transfer and stability at sequestration depth	Demonstration of (1) measurement technology and (2) defensible public accounting to track the carbon flux of algae to sequestration depth[6] and ensure the sequestration of carbon dioxide is reliably measured over time	✓ Demonstrated, reliable measurability and verified secure storage of CO_2 for 10+ y ✓ Lab modeling supports the field test results	2-3	$5-15M/y[5]	10y	~$50-300M

What is a cross-cutting method?

Cross-cutting work can be done once and still apply to multiple approaches, which reduces overall costs.

Similar environmental impact assessments and MRV must be done for approaches 2.7 and 2.8, which makes these cross-cutting issues.

How does this impact cost?

Cross-cutting funding requirements are shared between pathways.

To avoid double-counting, the individual cost estimates were reduced for the relevant workstreams.

DAC roadmap rubric

Given similarity amongst DAC approaches, we outlined a DAC-specific roadmap based on previously mentioned cost and time estimates

TYPE OF WORK	STAGE GATES	NUMBER OF PROJECTS	PROJECT BUDGET	DURATION	TOTAL COST
Lab	**Energy reduction potential** **Cost reduction potential** **Scalability: CO_2 purity >85%**[1] **Cost:** • **\$200-600/tCO_2** (FOAK 0-10 $ktCO_2$) • **\$100-500/tCO_2** (FOAK >10 $ktCO_2$) **Energy: <7.5 GJ/tCO_2**[2] **Water requirements** **Land requirements**	**2-4**[3]	**\$0.5-2M/year**	**2-4 years**	**\$10-20M**[4]
Lab/Pilot		**2-4** (lab)[3]	**\$1-3M/year**	**2-4 years**	**\$20-30M**[4]
		2-4 (lab) – system[3]	**\$0.5-2M/year**	**2-4 years**	**\$10-20M**[4]
		2-4 (pilot)[3]	**\$5-10M/year**	**5-10 years**	**\$50-100M**[4]
Demo		**2-4**[4]	**\$20M/year** (FOAK 0-10 $ktCO_2$) **\$50-100M/year** (FOAK >10 $ktCO_2$, e-swing) **\$100M/year** (FOAK >10 $ktCO_2$)	**8-10 years** (FOAK 0-10 $ktCO_2$) **8-10 years** (FOAK >10 $ktCO_2$)	**\$400-800M** (FOAK 0-10 $ktCO_2$)[3] **\$1,000-3,000M** (FOAK >10 $ktCO_2$, e-swing) **\$2,000-3,000M** (FOAK >10 $ktCO_2$)[3]
MRV		**1-3** (MRV)	**\$2-5M/year**	**5-10 years**	**\$20-50M**
Path-boosting activities	n/a	**1-3** (per activity) **2-4** (DAC+U)	**\$0.5-2M/year** (per activity) **\$0.2-0.5M/year** (DAC database)	**5-10 years** (per activity) **3-5 years** (DAC database)	**\$10-20M** (per activity) **\$1-5M** (DAC database)**;** **\$20-30M** (DAC+U)

Notes and sources: [1]Below this threshold, density changes, mostly due to the presence of non-condensable impurities (e.g., N_2, O_2, Ar) which cannot be liquified at ambient temperature, can affect storage capacity, injectivity and buoyancy. More information can be found here. [2]DAC energy requirements of 7.5 GJ/tCO_2 require energy equivalent to about 2.5 months of energy consumption for the average American household. Removing one $GtCO_2$ would require about half the total energy consumed by the US in 2022. [3]The values are reduced for the "Absorption + Low-Grade Heat Regeneration", "Membrane: Pressure Gradient Separation", and "Cryogenic Separation" approaches.

Pre-demonstration activities

We assessed when pre-demonstration activities are necessary for each of our CDR approaches using the following framework

What is a pre-demonstration activity?

Activities that are necessary to prepare an approach for demonstration level projects.

Activities	Research and development; field validation and pilot facilities
Description	Basic concept to lab level research; prototype testing and pilot facilities
Target funders	Government, philanthropy

When do we need pre-demo activities?

Pre-demonstration work occurs at TRL 1-6, consisting of basic research, tech development, and pilot validation.

TRL and MRL	TRL 1-5	TRL 6

However, sometimes pre-demo work also needs to be done even when an approach is beyond TRL 6 to improve:

Safety | **Scale** | **Process efficiency** | **Siting decisions** | **MRV**

Defining successful demos

Demonstrations are needed in CDR, but they can fail for many reasons, including and sometimes especially if they are government-funded.[1] In scoping demos for the AIR, we applied these best practice design principles

General demonstration strategies[1]

1. Conduct demonstrations on **as small a scale** and with as little initial visibility as possible.
2. Do not emphasize large projects at the expense of small ones involving **incremental improvements** to existing products or processes.
3. Resist political pressure to demonstrate a technology **before it is well in hand**.
4. Allow **enough time** in the project's schedule for slippage, especially when undertaking large projects with significant technological uncertainty.

AIR demonstration approach implications

1. Keep **demo size as small** as possible.
2. Favor **incremental** improvements.
3. Ensure that **pre-demo work is complete** before moving to demonstration.
4. Allow for **slippage** in timeline and budget. Size up when in doubt.

Notes and sources: [1]This slide is quoted from: Analysis of Federally Funded Demonstration Projects: Executive Summary, Rand (1976)

Scoping successful demos

We applied general strategies for successful demonstration projects while scoping projects in the AIR

Demonstration Project

> Demonstrations help identify integration and deployment challenges, pinpoint opportunities for cost reduction and validate the maturity of a technology.[1]

Individual site sizing

Project sites should be sized to the minimum scale necessary to test all relevant properties at market viable scale

Project sizing considers scoping of demonstration from:

- National Academies reports
- Expert organizations
- Individual CDR experts
- Existing demonstration facilities within a CDR approach or in other CDR approaches

Number of project sites

Sometimes, more than one project site is necessary in order to demonstrate a technology under relevant conditions.

Project sites should be used to test demonstration scale facilities under all relevant and different deployment conditions, including:

- Different climates
- Different bodies of water
- Different sourcing of materials and feedstocks
- Different political and regulatory frameworks

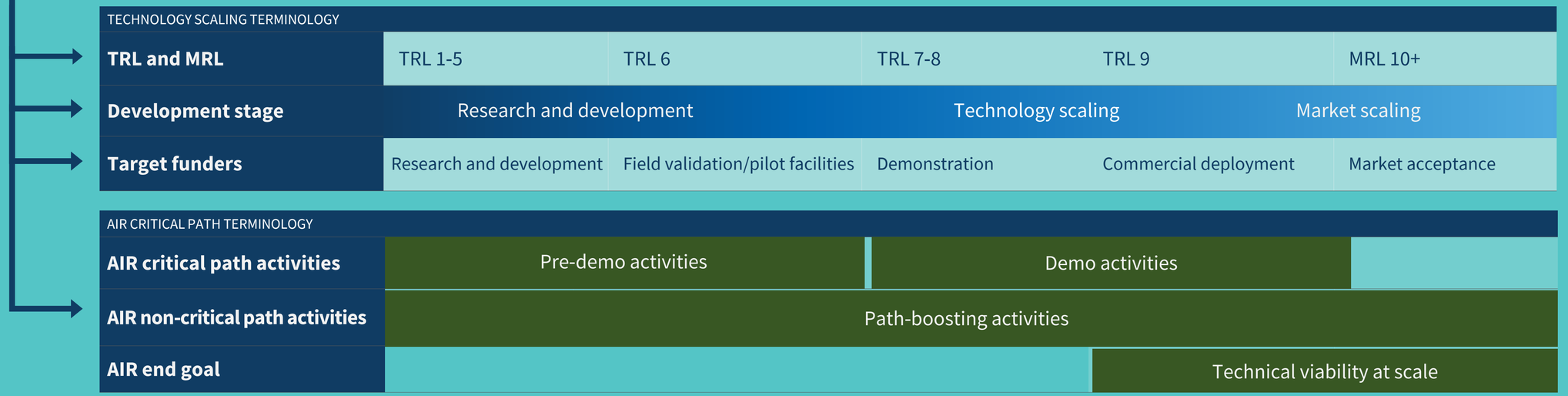
Notes and sources: [1]This slide is quoted from: Analysis of Federally Funded Demonstration Projects: Executive Summary, Rand (1976)

Path-boosting activities

We used the following framework to assess when and which path-boosting activities are necessary for each of the CDR approaches

What is a path-boosting activity?

Unlike pre-demo and demo work, which are vital to an approach's technical viability, path-boosting activities are non-critical but helpful to scaling.

When do we need path-boosting activities?

Because of their non-critical nature, path-boosting activities span all TRLs and all types of R&D and scaling activities.