BCG + XPRIZE CARBON REMOVAL | MUSK FOUNDATION

FROM SCIENCE TO SCALE:

How the XPRIZE Carbon Removal Finalists are Reducing Costs through Deployment

OCT 2025

WE GRATEFULLY ACKNOWLEDGE THE CONTRIBUTIONS OF ALL THOSE WHO MADE THIS REPORT POSSIBLE:

Authors

Karan Mistry, Managing Director and Partner, BCG - Author
Mike Matson, Partner and Associate Director, BCG - Author
Neil Slighton, Project Leader, BCG - Author
Paulina Ponce de Leon, Managing Director and Partner, BCG - Author
Habib Azarabadi, Manager, BCG Vantage - Author
Luke Chapman, Associate, BCG - Analyst

Nikki Batchelor, Executive Director, XPRIZE Carbon Removal - Author
Michael Leitch, Senior Technical Lead, XPRIZE Carbon Removal - Author

Design

Michael Mahaffey, Co-Founder, Tiny Giant – Report Design

Thanks to the XPRIZE Carbon Removal Finalists for the engagement on this report.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Between 6-10 gigatonnes per annum (Gtpa) of durable carbon dioxide removals (CDR) will be required by 2050 to stay in line with climate goals.[1] Beyond climate impact, durable CDR is beginning to create business value, improving margins, enabling differentiation, offering new businesses, and creating regulatory flexibility. However, last year the industry only delivered approximately 0.4 megatonnes (Mt) at prices far above what is viable at scale.[2] Durable CDR must scale by orders of magnitude and reduce costs by multiples to meet climate goals while also creating business value.

Awarded in April 2025, the $100 million XPRIZE Carbon Removal competition was a four-year contest to catalyze innovation in CDR and help build this nascent market. Of the over 1,300 entrants, 20 finalists were selected and challenged to remove and durably sequester over 1,000 tonnes of carbon dioxide (CO_2) while proposing how they would scale to a million and a billion tonnes. Application data from XPRIZE finalists offers a first-of-its-kind window into how leading CDR players plan to approach the scaling challenge.

This report analyzes finalists' data to provide a view of how CDR players envision scaling, as well as what it will take for the industry as a whole to unlock this growth. Despite the wide variety of technologies that can be employed for CDR, finalist strategies revolve around a common set of elements. To expand capacity and reduce costs, strategies are driven by combinations of **five growth levers:** future technology advancement, scaling, modularity, process optimization, and alternative revenue streams. Beyond levers that companies can directly control, CDR players also contend with **seven external risks** that shape both cost and scalability: financing costs, supply chain availability, logistics, energy, labor, water, and land. Below is a summary of the key trends in how XPRIZE finalists manage these levers and risks:

1. The challenge ahead is primarily focused on engineering and commercial optimization, rather than on technological or scientific breakthroughs.

Across the cohort, most strategies focus on commercial and engineering levers. Notably, only ~5% of projected cost reductions in finalist plans come from assumed future technological breakthroughs.

While technological innovation and scientific breakthroughs will continue to be important, the low planned contribution of future technology demonstrates that **the rapid maturation of CDR is achievable with the technology that exists today.** Technological improvements will continue and offer upside but companies are no longer relying on unpredictable technology breakthroughs to reach megatonne scale. Scaling strategies are instead grounded in commercial and engineering levers that offer more predictable maturation.

[1] BCG 2024 Boosting Demand for Carbon Dioxide Removal (based only on unabated emissions)
[2] CDR.fyi (September 2025)

2. There is a wide variety of credible approaches to scale, each with unique success factors and risks.

While technology variability is commonly discussed in CDR, strategic variance across providers is often underappreciated. Analysis of finalist submissions finds that **engineering and commercial strategies vary widely, even within common CDR pathways.** Some finalists plan to scale by developing large, highly optimized industrial facilities; others by managing wide networks or by mass manufacturing standardized units, a combination of these strategies, or other strategies entirely. Each approach has unique factors for success and varied risks. Notable findings include:

- Finalists that **scale** components and facilities must develop capabilities in large capital program management, skills that require significant experience to develop, while on a rapid startup timeline.
- Finalists who grow through **modularity** differentiate in their ability to manage the CAPEX intensity of modular component manufacturing and to handle the engineering and operational overhead created by modularity.
- **Process optimization and automation** amongst finalists rely on adopting standard best practices in industrial optimization and manufacturing. While these practices are simple in concept, they have challenged past novel industries and can be expensive to implement. As such, this challenge of process optimization is a pivotal journey in a company's growth.
- Companies with approaches that rely heavily on **byproducts** to drive down costs operate simultaneously as CDR and byproduct companies. Byproducts diversify revenues and offset costs but introduce operational complexity.
- There is no single way to **finance** CDR or even any individual CDR technology. Variability in commercial and engineering approaches opens an array of viable financial structures (e.g., project debt, credit revolvers, leaseback structures) and check sizes for CDR.
- **Partnerships** with industrials, energy producers, and offtakers will be powerful tools for CDR companies to **manage risks** such as financing, supply chain, energy, land, and water risks.

3. Regardless of individual strategy, the broader CDR ecosystem must grow.

To date, startups have led CDR growth as technology innovators and project developers. For these players to produce at the megatonne scale, and collectively at the gigatonne scale, the CDR industry will require an expanded ecosystem of feedstock suppliers, component manufacturers, EPC (engineering, procurement, and construction) partners, logistics providers, and plant operators.

Some of these roles may be filled by incumbents who expand into CDR, but others will require entirely new businesses. Growing this ecosystem represents both a risk for CDR and a major business opportunity.

These findings have several implications for CDR stakeholders:

- **CDR suppliers** can competitively position themselves using their engineering and commercial strategy as much as their technology. Critically though, they must mature specific internal capabilities and external partnerships needed to enact their strategy.

EXECUTIVE SUMMARY

- In this phase of commercialization, **offtakers** can consider areas where they have an opportunity to play a strategic role beyond just purchasing offtake. This can provide critical support to the CDR industry and also create business value for the offtaker.
- **Investors** can structure investments to manage the implementation-heavy risk profile of CDR (vs. technology risk). They can also utilize a wide range of investment structures tailored to the varied commercialization and engineering strategies of suppliers.

CDR LANDSCAPE AND THE ROLE OF XPRIZE

The Imperative for CDR

The importance of CDR in achieving climate goals is well-documented. Between 6-10 Gtpa of residual CO_2 emissions are likely to remain unabated globally in 2050.[1] Durable CDR will be a primary requirement for addressing these residual emissions.

As some of the first commercial-scale CDR plants emerge, the industry is also beginning to demonstrate its potential for business and economic development. This clear economic value will be essential for scaling this industry. In particular, CDR is beginning to provide companies with the following:

1. Increased Productivity

CDR can help buyers or partners increase revenue in existing businesses. **Mati Carbon** (the XPRIZE Grand Prize winner), for example, applies basalt rock dust to rice farms in India, improving soil health and boosting yields by ~20-30% on average while cutting reliance on synthetic fertilizers. Farmers saw a 20-25% increase in household incomes as a result.[3]

2. Product Differentiation

CDR can create market differentiation through sustainability to drive demand or premiums. For example, in Brazil, **NetZero** converts coffee husks into biochar that coffee companies return to their fields. This allows these coffee players to differentiate and drive a premium. For example, Marubeni (a large Japanese general trading company) paid ~30% premiums for coffee grown with **NetZero's** biochar.[4]

3. New Business Models

CDR can provide new business or services for companies to expand into. Several companies found complementary elements of the CDR value chain to create new businesses or features. For example, 3M, a materials conglomerate, has begun developing sorbent technology for direct air capture (DAC) applications.[5] Stripe, a financial software player, created a feature to allow companies and their customers to easily buy offsets.[6] Occidental Petroleum (Oxy) created the subsidiary 1PointFive, which is deploying Carbon Engineering's DAC technology to build six DAC plants and sequestration hubs.[7] Finally, Airbus purchased 400,000 tonnes of carbon removal credits and launched its Airbus Carbon Capture Offer (ACCO) to sell the credits to airlines as a reseller.[8, 9, 10]

[1] BCG 2024 Boosting Demand for Carbon Dioxide Removal (based only on unabated emissions)
[3] XPRIZE submission data
[4] MundoCoop.com, "Cooperativa negocia café produzido com Biochar com empresa do Japão"
[5] Nasdaq, "3M and Svante announce joint development agreement to develop and produce carbon dioxide removal products"
[6] Stripe, "Stripe launches world's first large-scale carbon removal purchase tool"
[7] 1PointFive, Projects in progress
[8] 1PointFive, "1PointFive announces agreement with Airbus for the purchase of 400,000 tonnes of carbon removal credits"
[9] Airbus Carbon Capture Offer
[10] Airbus, easyJet signs up to Airbus' pioneering carbon removal solution

4. Regulation Adaptation

CDR can help manage exposure to carbon pricing and evolving climate policies across regions by offsetting or insetting emissions. For example, Europe has enacted the Carbon Border Adjustment Mechanism (CBAM), a regulation that places a carbon price on imports of carbon-intensive goods. For aluminum, it is expected to levy 9% of the import value by 2035. Canadian aluminum, which often utilizes low carbon hydropower, in contrast, is projected to only see 3% levies, making it more financially attractive in Europe.[11, 12] As a result, Canadian plants are well-positioned to export to European buyers. While CBAM is still considering the allowance of CDR, the shift illustrates that sustainable products can strengthen competitiveness and create new market opportunities, while providing flexibility in response to evolving regional climate policies like CBAM or others like the EU's ETS and Japan's "GX-ETS."

The Current Challenge

CDR companies have made rapid progress in developing the industry. In less than two decades, CDR has progressed from a scientific concept to a nascent industry. Concurrently, demand for durable CDR has also accelerated rapidly, multiplying ~30x from just a few hundred tonnes purchased in 2019 to ~8 Mt bought in 2024.[13] Looking ahead, if companies deliver on sustainability goals, global demand is expected to rise to 40+ Mt annually by 2030, and by 2050, 6-10 Gt will be needed to meet global climate goals.[14, 15] CDR generation capacity will need to scale by orders of magnitude to meet this demand.

Furthermore, today, demand is driven by early adopters such as Microsoft, Stripe, Shopify, BCG, and coalitions such as Frontier, which are purchasing credits at significant premiums. These pioneers represent only a small fraction of potential buyers. For CDR to maintain demand growth beyond early buyers, solutions will need to reduce costs rapidly.[16] This dynamic exposes a fundamental challenge for CDR companies: **how can CDR providers expand capacity by orders of magnitude while cutting costs by multiples?**

The Role of the XPRIZE

The XPRIZE Carbon Removal competition was launched to accelerate this transition. From over 1,300 submissions across 88 countries, 20 finalists were selected based on technical rigor, scalability, and potential for impact. Finalists were required to run a year-long field trial to demonstrate at least 1,000 net tonnes of carbon removal, show at least 100-year durability of storage, and undergo third-party measurement, reporting, and verification (MRV).

As a part of their evaluation, **the cohort submitted qualitative roadmaps and quantitative techno-economic models** detailing their commercial and technical plans. These plans were specifically focused on what it would take to grow

[11] S&P Global, North American aluminum sector blindsided by tariff volatility, trade flow uncertainty
[12] Fastmarkets, CBAM is coming - can steel and aluminum supply chains bear the costs
[13] CDR.fyi (September 2025)
[14] BCG 2024, Boosting Demand for Carbon Dioxide Removal (based only on unabated emissions)
[15] BCG 2023, Climate Needs and Market Demand Drive Future for Durable CDR
[16] BCG & EDF 2023, In the Voluntary Carbon Market, Buyers Will Pay for Quality

from their kilotonne-scale demonstration to the megatonne-scale facilities they all plan to build from 2030-2035.[17] Techno-economic models included a detailed bill of materials (BOM), lifecycle inventory, mass balance, energy model, and costs for both their existing kilotonne plants and planned megatonne plants. These models were verified against their demonstrated performance in the field, as well as validated by independent third parties (350Solutions, Boundless Impact Research & Analytics, EcoEngineers, and Enegis).[18]

At its conclusion, the winners of the competition were **Mati Carbon** (Grand Prize), **NetZero**, **Vaulted Deep**, **UNDO Carbon**, **Planetary**, and **Project Hajar**, but all finalists put forward compelling solutions that demonstrate viable pathways to gigatonne scale.[19]

This rigorous process **created a uniquely granular dataset and offers a rare window into how leading innovators envision the pathway from early field demonstrations to industrial deployments.** This report synthesizes those submissions to extract lessons about how CDR can make the leap from science to commercialization, and what it will take for the sector to build megatonne-scale projects and reduce cost to a fraction of today's in only 5-10 years.

Note: *BCG authored this report in collaboration with the XPRIZE Foundation, and finalists were consulted to ensure accuracy. All finalists were generous with their information and time, but due to data privacy, data availability, and timing challenges, not all finalists are represented in data cuts. Quantitative analysis shown in this report draws from 15 out of the 20 finalists, including Airhive, Applied Carbon, Arca, Captura, Ebb Carbon, Heirloom, Kelp Blue, Mati Carbon, NetZero, Planetary, Project Hajar, Skyrenu, Takachar, UNDO Carbon, and Yuanchu.*

[17] Based on finalist submissions
[18] Note: The conclusions in this report are based on the independently-verified models provided by XPRIZE finalists; BCG did not validate the data
[19] XPRIZE 2025, XPRIZE Makes History, Awards $100M Prize for Groundbreaking Carbon Removal Solutions

CDR PATHWAYS

Before discussing the strategies of XPRIZE finalists, this section introduces the CDR technologies applied by the finalist cohort. First, it is worth noting that "Carbon Dioxide Removal" defines an outcome of a project that removes more CO_2 than it emits, not a specific class of technologies. As such, CDR encompasses a wide range of approaches from thermally decomposing plant matter to extracting CO_2 from ocean water. The 20 XPRIZE finalists span many of these technologies and can be categorized into four general pathways: Air, Land, Rocks, and Oceans. The table below summarizes the technologies represented by the finalists.[20]

Air:
Pulling CO_2 directly from the air

Direct Air Capture and Carbon Sequestration (DAC+S)

Description	Potential Co-Benefits	Potential Challenges
Capturing CO_2 directly from ambient air using a solvent or sorbents, then sequestering the CO_2 through mineralization or underground sequestration	CO_2 may be utilized to make construction material or to stabilize mine waste	High energy and capital requirements; significant infrastructure and siting needs

XPRIZE Finalist Cohort Companies: 44.01 + Aircapture, Airhive, Heirloom, Octavia Carbon + Cella, Skyrenu

[20] Only technologies represented by XPRIZE finalists are covered, not all durable CDR technologies.

Land:
Stabilizing carbon caught from organic materials like plants for the long term

Biochar

Description	Potential Co-Benefits	Potential Challenges
Converting biomass residue into a stable, carbon-rich solid via pyrolysis (heating in the absence of oxygen), then storing or applying the biochar to keep carbon out of the atmosphere	Improves soil fertility, moisture retention, and crop yields, while reducing the need for chemical fertilizers	Biomass availability; water and land use; challenges in quantifying and monitoring sequestration

XPRIZE Finalist Cohort Companies: Applied Carbon, net zero, MASH MAKES, TAKACHAR

Biomass Geological Storage

Description	Potential Co-Benefits	Potential Challenges
Storing biomass in engineered subsurface conditions that limit oxygen, moisture, and microbial activity to minimize decomposition and gas release	Reduces open burning, methane, and N_2O emissions, and can stabilize fire-prone or degraded lands	Biomass availability; uncertainty in long-term permanence without robust monitoring

XPRIZE Finalist Cohort Companies: vaulted deep

Rocks:
Accelerating the natural absorption of CO_2 in rocks

Enhanced Rock Weathering (ERW)

Description	Potential Co-Benefits	Potential Challenges
Accelerating natural weathering by spreading crushed minerals on land, which react with atmospheric CO_2 and store it safely in soil or oceans for thousands of years	Increases crop yields by reducing soil acidity, improving soil structure and water retention, boosting microbial activity, delivering essential micronutrients (e.g., magnesium, calcium), and reducing dependence on synthetic fertilizers and pesticides	Complex chemical management; difficulty monitoring sequestration at scale over the long term

XPRIZE Finalist Cohort Companies: LITHOS, Mati, Silicate, UNDO

Mine/Industrial Waste Mineralization

Description	Potential Co-Benefits	Potential Challenges
Reacting CO_2 with magnesium- or calcium-rich minerals in mine tailings or industrial residues to form stable solid carbonates	Stabilizes mine waste, reduces leaching of heavy metals, and improves geotechnical safety of mine tailings	Site limitations; complex chemical handling; uncertainty in long-term sequestration monitoring at scale

XPRIZE Finalist Cohort Companies: ARCA, 原初科技（北京）有限公司 Yuanchu Technology (Beijing) Co., Ltd.

CDR PATHWAYS

Oceans:
Leveraging the natural CO_2 absorption and sequestration qualities of the ocean

Macroalgae (Seaweed) Cultivation

Description	Potential Co-Benefits	Potential Challenges
Cultivating seaweed to take up CO_2 from the upper ocean via photosynthesis, then storing carbon in long-lived reservoirs (e.g., the deep ocean)	Improves biodiversity, reduces ocean acidification locally, and can create sustainable jobs in coastal economies	Access to suitable ocean surface area and sinking location at a large scale, nascent MRV; potential impact on native marine ecosystems at a large scale

XPRIZE Finalist Cohort Companies kelp blue

Ocean Alkalinity Enhancement (OAE)

Description	Potential Co-Benefits	Potential Challenges
Increasing the alkalinity of bodies of water by adding electrochemically generated alkaline solutions or dispersing alkaline minerals to enhance atmospheric CO_2 uptake	Counteracts ocean acidification, and improves marine ecosystem health. It also enables the reuse of industrial waste and provides long-term, low-footprint carbon storage. OAE can be co-located with a range of coastal outfalls (e.g., wastewater, power plant cooling, desalination)	Energy or feedstock requirements; need for robust measurement to confirm long-term CO_2 removal; potential for long-term ecological impacts

XPRIZE Finalist Cohort Companies ebb carbon PLANETARY

Direct Ocean Capture (DOC)

Description	Potential Co-Benefits	Potential Challenges
Extracting dissolved inorganic carbon from seawater (e.g., via electrodialysis), while compressing captured CO_2 for transport and storage	Potential for integration with other industries for high-value products (e.g., desalination, direct lithium extraction, etc.)	High energy and capital requirements; significant infrastructure and siting needs

XPRIZE Finalist Cohort Companies captura

As evident from the wide-ranging approaches represented across the XPRIZE finalists, CDR can be effectuated by a diversity of technology classes with distinct operating modes, maturities, and constraints. This makes CDR highly context-specific. No single approach fits every setting. Performance and scalability hinge on local conditions such as energy, land, water, feedstock, the surrounding policy, and permitting environment. Similarly, desired characteristics such as price, technology risk, quality, value chain (for insetting potential), and co-benefits may vary by buyer. Thus, certain pathways may excel in some situations and struggle in others.

Given these varied constraints, it is unlikely that a gigatonne-scale CDR industry will be built by any single class of technology. CDR, therefore, is not "winner-takes-all"—achieving the required scale will require multiple pathways and multiple providers. The central challenge is not identifying one "best" technology, but rather enabling many to scale, drive costs down, and improve MRV and durability over time. The next section of this report reviews how these technologies plan to do so.

PATHWAYS TO COST REDUCTION

INTERNAL LEVERS

XPRIZE finalists offer a best-in-class perspective on how CDR companies can rapidly scale up while reducing costs. A review of finalists' **strategic roadmaps** and kilotonne/megatonne **techno-economic BOMs** reveals commonalities across the cohort's growth plans. Finalists consistently use the same **five levers to mature their solutions:**

1. Future Technology Advancement: Developing novel materials or engineering designs.

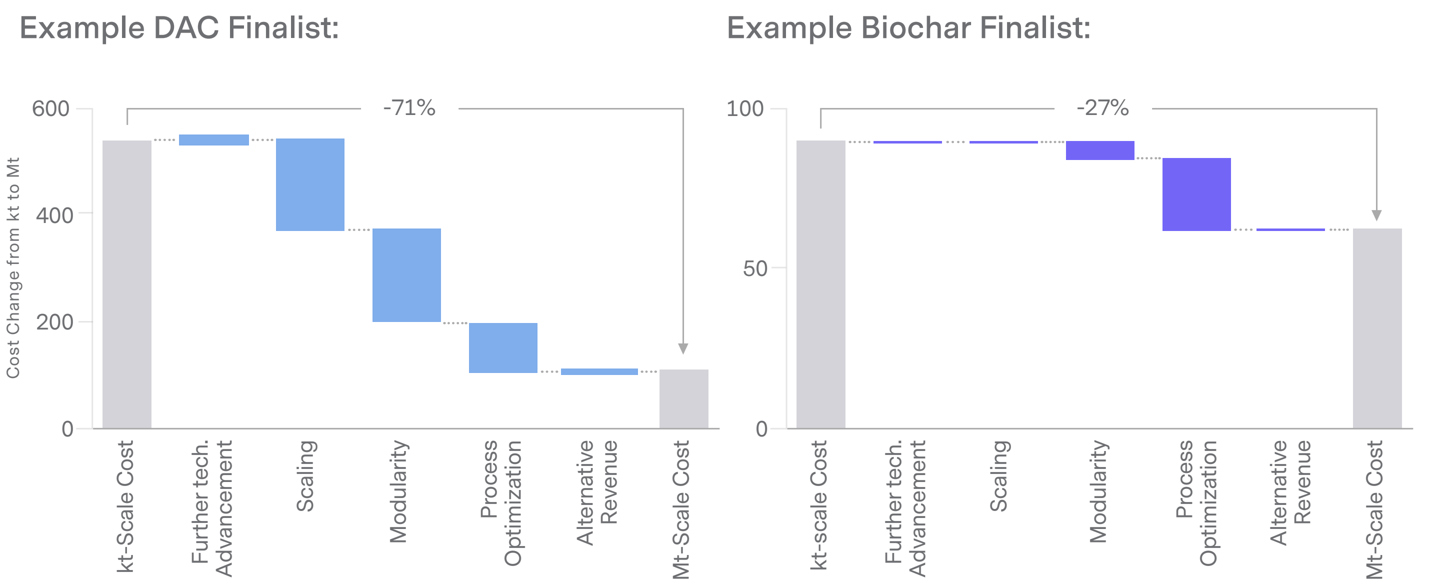
2. Scaling: Building larger operations, plants, or components to achieve economies of scale.

3. Modularity: Using standardized, repeatable units to lower costs through learning-curve benefits.

4. Process Optimization and Automation: Finding efficiencies in industrial systems, optimizing operational processes, and automating management of processes.

5. Alternative Revenue Streams: Generating income beyond carbon credits to cross-subsidize and/or reduce the credit sale price.

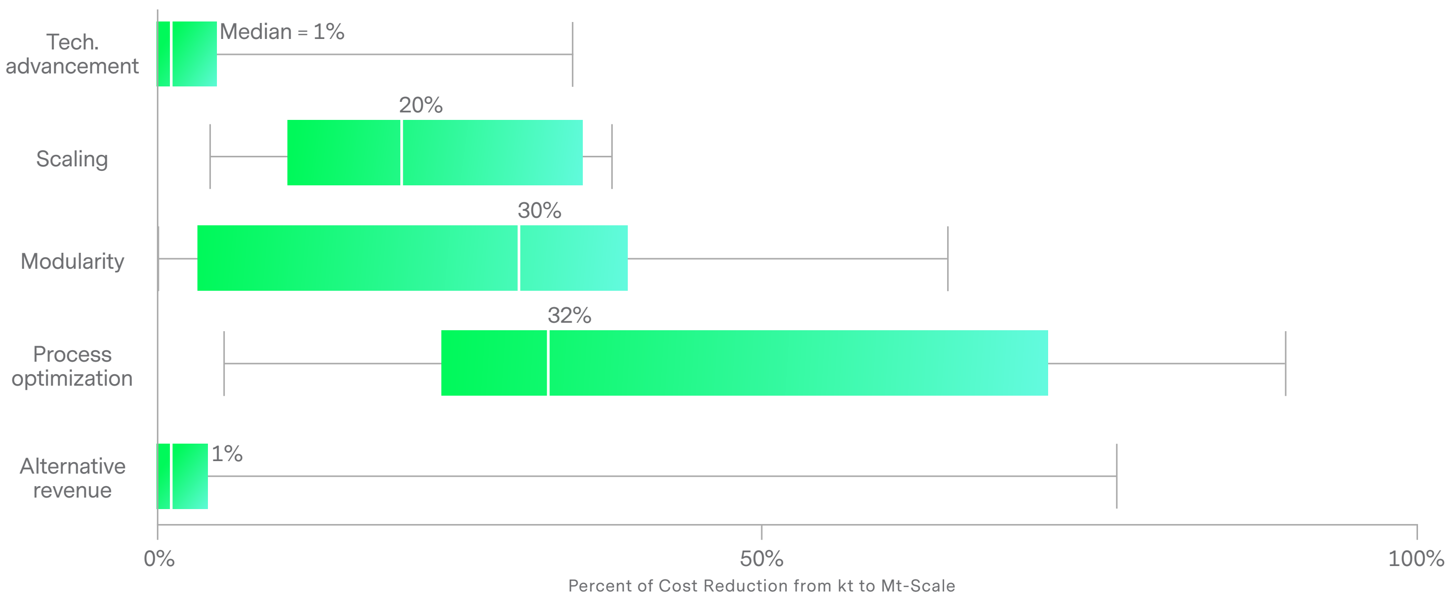
Share of Total Cost Reduction by Lever for Example DAC and Biochar Finalists



The figure illustrates how one DAC finalist and one biochar finalist plan to apply the five cost-reduction levers as they scale from kilotonne demonstrations to megatonne-scale commercial plants. The DAC finalist emphasizes modest refinement to its proprietary technology, significant scaling of balance-of-plant (BOP) systems, modularization of its core contactor units, and efficiency gains through automation. By contrast, the biochar finalist focuses primarily on process optimization, particularly through streamlining labor, while placing only moderate emphasis on modularity and minimal emphasis on scaling.

The application of these levers varies significantly across finalists. The figure below quantifies this variation, showing the percentage of projected cost reduction from the kilotonne to megatonne scale that can be attributed to each lever across all finalists.[21] The sections that follow dive deeper into each lever, examining why strategies diverge and what can be learned from both CDR leaders and other industries.

Share of Total Cost Reduction by Lever



Future Technology Advancement

As seen in the previous chart, the majority of finalist plans assume that future scientific and technological breakthroughs will contribute only a minor amount to their expected cost reduction trajectory. Further technology advancement's average cost reduction contribution across finalists is just 5%.
This is not to say that there will be minimal future technical advancement in CDR. Several teams discuss technical advancements that are directly on the horizon:

- **Arca** is preparing to pilot its Microwave Mineral Activation technology that uses high-intensity bursts of energy to disrupt the mineral lattice structure of abundant serpentine minerals, increasing the capacity for CDR by orders of magnitude.
- **Airhive** is refining its novel fluidized bed technology to more rapidly and efficiently capture CO_2 in DAC.

[21] The impact of each of these levers can be quantified by attributing how each line item evolves from a team's kilotonne BOM to megatonne BOM. Cost and scaling justifications provided by the teams for each line item describe what mechanisms, if any, are driving cost reduction when moving to megatonne scale.

- Yuanchu plans to develop technology to increase the interface area between particles and air to more rapidly capture CO_2.
- Silicate Carbon is advancing the science of ERW by focusing on soil water chemistry and building a dataset to maximize CDR by optimizing the selection and management of field sites.

The list continues.

The low reliance on future technology demonstrates that the **rapid maturation of CDR is achievable with the technology that exists today.** The challenge for CDR has shifted from a science problem to an engineering, execution, and commercial one. While technological improvements will continue and offer upside, companies are not relying on unpredictable technology breakthroughs to reach megatonne scale. Instead, their roadmaps are grounded in commercial and engineering levers that offer more regular and predictable maturation. This report explores these levers and the new requirements, challenges, and opportunities they bring.

Scaling and Modularization

Together, scaling and modularization provide complementary paths to expand CDR capacity.

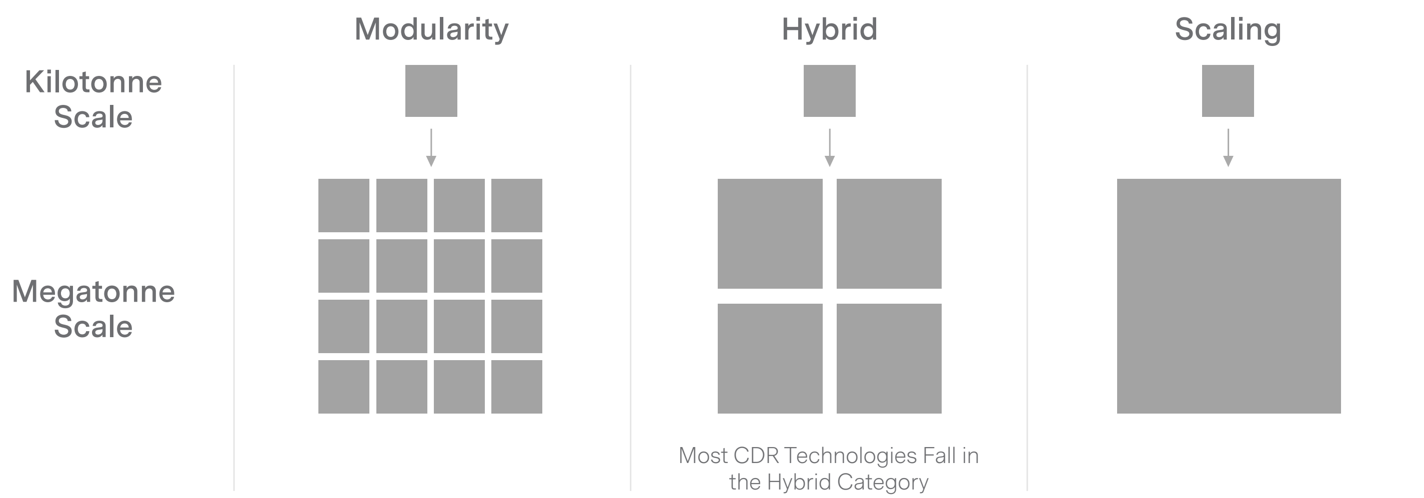
- **Scaling** is employed when bigger facilities and components are built to capture economies of scale. ERW companies such as UNDO Carbon and Mati Carbon, for instance, aim to grow their kilotonne demonstrations toward multi-megatonne plants by securing land through partnerships with farmers' cooperatives. UNDO Carbon's Ontario operations alone are targeting ~1 Mt of rock spread annually, creating savings in larger quarries and bigger spreading fleets. Larger operations create savings, as costs typically grow sub-linearly with unit size. This is often referred to as the "0.6 rule."[22] A 10× capacity ERW crushing facility may require only ~4x the footprint, saving on concrete pads and other balance of plant BOP elements, while improving unit economics.
- **Modularity** is leveraged by developing factory-built, repeatable units. MASH Makes shows this in practice by designing biofuel and biochar production systems that fit in a 40-foot shipping container. In their current design, ~50 sites would be deployed to reach the megatonne scale. Applied Carbon takes a similar approach, planning to build the same pyrolysis module several hundred times to reach megatonne scale. As such, Applied Carbon leverages modularity for up to 65% of its planned cost reduction because, with each unit built, it gains cost reduction through learning as well as mass production. [23]

Both modularity and scaling are often leveraged in conjunction. Most CDR systems scale up using a hybrid approach and rarely fit into purely modular or purely scaled models. Planetary, for example, plans to both scale the size of its deployments by 5x and deploy 20 modules to grow from its 10 kt demonstration to a 1Mt plant.

[22] Tribe and Alpine (1986), Scale economies and the "0.6 rule"
[23] BCG 1968, The Experience Curve

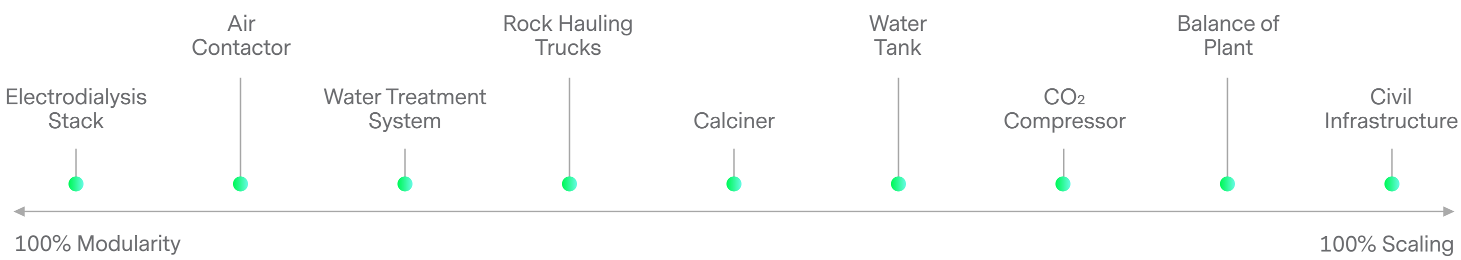
PATHWAYS TO COST REDUCTION

Scale-Up Approaches for Illustrative CDR Systems



At a more granular level, CDR systems comprise components that themselves scale either by increasing unit size or by increasing unit count. Components similarly span a spectrum from modularity-dominated to scaling-dominated, shaped by inherent characteristics and design choices. The diagram below positions common components along this spectrum. At the modularity-dominated end, electrodialysis stacks typically hold unit size relatively constant and scale by numbering up, often rising ~20–80x in count from kilotonne to megatonne plants. At the scaling-dominated end, civil infrastructure remains centralized and grows in size to serve megatonne throughput.

Illustrative View of Modularity vs. Scaling in Cost Reduction for Different System Components



Finalist plans combine various degrees of modularity and scaling at the plant and component level. For example, at the component level, Heirloom plans to modularize its tray contactor system while scaling the BOP around it. At the plant level, it plans to scale plant capacity with significantly larger deployment module, and build several of these modules to reach megatonne scale.

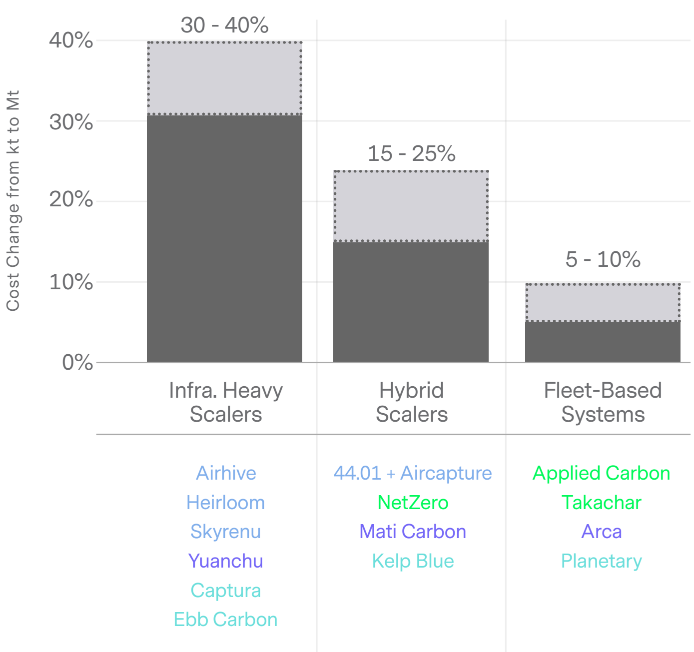
PATHWAYS TO COST REDUCTION

How CDR Companies Use Modularity and Scaling:

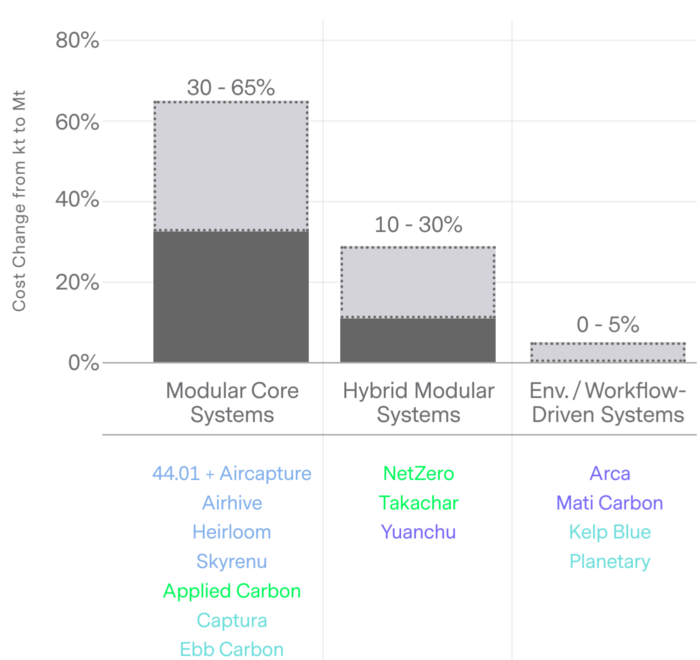
Finalists vary significantly in their application of scaling and modularity but tend to fall into indicative categories.

The use of scaling among finalists varies primarily with the geographic centralization of infrastructure. The teams that leverage scaling the most, **"infrastructure heavy scalers,"** tend to be large, engineered plants where the BOP or shared facilities dominate cost. Scaling contributes to over 30% of cost reduction for DAC players such as Skyrenu and Airhive. The most effective path to reduce costs for these systems is to build larger facilities and spread shared systems across a higher throughput. **"Hybrid scalers"** leverage a hub and spoke model, centralizing some infrastructure and distributing others. Mati Carbon, for instance, plans to employ a few central feedstock hubs, each of which is connected to a distributed network of spreading sites. These systems benefit from scaling the central "hub" systems, but less so their distributed "spoke" infrastructure. Finally, **"fleet-based systems"** rely on heavily distributed assets that see limited scale benefits. Takachar, as a distributed, on-farm biochar pyrolysis module, falls into this category.

Share of Total Cost Reduction Attributable to Scaling



Share of Total Cost Reduction Attributable to Modularity



The application of modularity increases when core components are highly optimized and diminishes when surrounding processes and operations add greater complexity. Companies in the **"modular core systems"** category rely on complex, heavily-engineered components such as electrodialysis stacks for Captura and pyrolysis reactors for Applied Carbon. These components benefit most from factory repetition and standardized interfaces. In contrast, **"environmental and workflow-driven systems"** see complexity in operations and processes rather than any single component. An example of this may be Arca, which prioritizes operational efficiency and optimization.

Interestingly, modularity and scaling **strategies often vary even within similar technologies**. As an example for biochar, **Applied Carbon** emphasizes fully modular mobile pyrolysis that converts residues into biochar in the field and on the move, leaning into unit-level repetition and rapid deployment. **NetZero**, another biochar player, standardizes mid-size, automated pyrolysis facilities and runs an integrated, end-to-end model near feedstock, which brings more scaling of site-level BOP and logistics into the cost reduction equation. **NetZero** falls into the hybrid category for both levers and equally benefits from modularity and scaling in its cost reduction journey, while **Applied Carbon** is a heavy user of modularity but makes limited use of scaling.

How to Unlock Scaling and Modularity:

While scaling and modularity are powerful levers, they do require specific capabilities to unlock and see risks in implementation.

Unlocking **scaling** revolves around building the experience and capabilities to manage large capital projects (for example, construction partnerships, permitting, financing, etc.), and gaining these experiences that typically have long lead times while on a rapid startup timeline. Finalists do this with the following practices.

- **Build in Parallel Steps:** Deploy successively larger plants (in parallel, where possible) to de-risk first-of-a-kind and get to nth-of-a-kind quickly. When **Heirloom's** first DAC plant started its operation in 2023, the company was already working on its next facility, aiming to achieve a ~300x increase in capacity.[24]
- **Partner for Delivery:** Form strategic relationships with experienced EPC partners and key suppliers suited for novel technologies to gain experience through partnerships. In the Carbon Capture and Storage (CCS) industry, for example, the demonstration Project Tundra leverages an EPC partner with previous experience with the Petra Nova CCS project.[25]
- **Standardize Trains and BOP:** Use a repeatable plant template to replicate quickly across new sites. **44.01's Project Hajar** illustrates this with standardized equipment for well designs that minimize variation and implementation risk in building the next scaled plant.

Unlocking **modularity** benefits relies on maximizing learning-by-doing by building the same module many times, as early as possible, with stable designs. Finalists maximize this with the following practices.

- **Converge to a Stable Module:** Settle on a single viable module design early to begin repetition as quickly as possible, while managing premature technology lock-in risks. This was done in the solar PV industry, where deployment and ultimately cost decline were accelerated by convergence toward dominant designs.[26]
- **Anchor Manufacturing:** Secure a long-term and consistent manufacturing partner or build an in-house line so learning moves upstream. **Captura**, for instance, has established an in-house manufacturing facility for commercial production of its proprietary electrodialysis.

[24] Heirloom Driving investment in America's energy capital
[25] Office of Clean Energy Demonstrations 2024, Portfolio Insight: Carbon Capture in the Power Sector
[26] Gregory Nemet (2009), How Solar Energy Became Cheap

- **Standardize Interfaces:** Share specs and interfaces across the industry to accelerate learning and deployment. For example, in the solar industry, nine major manufacturers have standardized on a 2,382 × 1,134 mm module format.[27]

Risks in Scaling and Modularity:

Scaling is a powerful cost reduction lever, but big plants mean long timelines, heavy capital, and resource-intensive siting. This can risk the following:

- **Design Lock-In:** Building large plants locks in early technology choices for decades. Given the fast pace of technological advancement, retrofitting outdated sorbents, reactors, or integration methods can be costly or infeasible.
- **Siting Challenges:** Land, water, and energy needs for large plants complicate permitting and community acceptance. Finalists have innovative strategies to manage this. For example, Ebb Carbon co-locates with desalination plants, using existing seawater intakes and outfalls to reduce new infrastructure and resource exposure.
- **Capital Burden:** Scaling requires billions in capital expenditure (CAPEX) and heavy project financing. Debt financing for unproven CDR technologies is limited and can be expensive.

Modularity and replication can drive learnings but tends to push risk to scaling manufacturing and managing overhead across sites.

- **CAPEX Hurdle:** Modularization requires an efficient mass manufacturing process, which in turn necessitates setting up manufacturing lines. Developing manufacturing is typically high CAPEX, making it prohibitively expensive for many early-stage companies and risky for established suppliers to fund.
- **Soft Costs:** In distributed modular systems, each new site could trigger fresh siting, permitting, interconnection, and financing steps that can dominate timelines and costs if unmanaged. Finalists address these challenges by standardizing plants to make development processes highly repeatable. They can also develop the capabilities to manage many plants by hiring requisite talent (e.g., financing experts) or automating development (e.g., using plant siting software). Other industries have found success with these approaches. According to the National Renewable Energy Laboratory, soft costs for residential solar systems declined by ~50% in the last decade.[28]
- **Fleet Complexity and Overhead:** Distributed fleets create high operations and maintenance (O&M) and MRV burdens. To address this, several finalist companies focus on early standardization or automation, cutting per-site overhead for distributed fleets or components. Heirloom pursues this objective by reducing costs through transition to a warehouse automation system for moving sorbent material between capture and regeneration across a heavily modularized contactor system.

[27] Trina Solar, company press release
[28] U.S. Department of Energy, Soft Cost

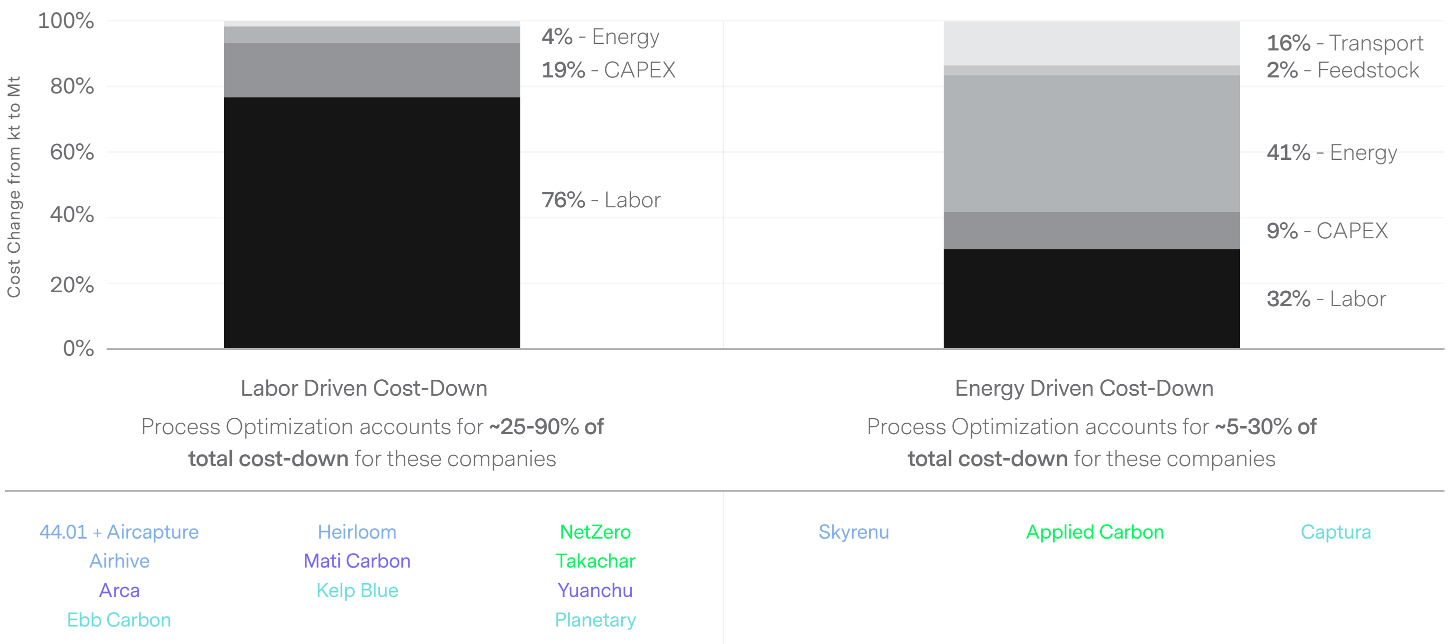
Process Optimization and Automation

Beyond finding savings by deploying larger or more modular systems, CDR companies must become more effective at operating those systems. Finalists do this by finding efficiencies in industrial systems, optimizing operational processes, and automating the management of such processes.

How CDR Companies Use Process Optimization:

Like scaling and modularity, finalists plan to leverage process optimization to varying degrees. Finalists leverage process optimization in two ways: some primarily aim to reduce labor costs, and others to reduce energy costs. The figure below shows the average cost category impact of process optimization for these groups. It is worth noting that a small number of companies do not fall into either of these buckets; instead, they tend to optimize their process equipment. For example, Project Hajar (a DAC + in-situ mineralization project between 44.01 and Aircapture) aims to increase the capacity utilization of its injection well, reducing its cost per tonne.

Share of Total Cost Reduction Attributable to Process Optimization



Energy savings tend to come from optimizing the engineering of facilities to run more efficiently. For example, ~35% of Yuanchu's cost reduction strategy is driven by implementing a proprietary reactor system, which can achieve high-efficiency reaction rates by finely controlling environmental parameters. Similarly, MASH Makes integrates pyrolysis gas recovery to generate electricity and heat for its own operations. However, companies whose process optimization cost reduction is energy-driven may also rely heavily on savings from labor, making labor efficiency the primary focus for process optimization.

Labor savings are typically driven by optimizing workforce schedules across multiple needs, such as installation scale, and automating/simplifying processes to require fewer operators. The focus on labor across finalists signals that process optimization in CDR is particularly focused on the shift from bespoke, human-driven operations to standardized, factory-style models. In other words, the challenge lies in applying existing practices in industrial optimization to CDR. Elements of these practices are introduced below.

How to Unlock Process Optimization:

- **Standardize Operations:** Standardizing playbooks, systems, and O&M routines early can prevent CAPEX lock-in around unique processes that depend on "linchpin employees." **Heirloom** illustrates this by moving from bespoke pilot tray-handling systems to standardized, off-the-shelf warehouse automation systems and modular plant layouts. This shift reduces tray handling manpower and ensures consistent expansion across future plants.
- **Optimize Standard Operations for Throughput and Flexibility:** Finalists are shifting from batch to continuous operations, balancing workloads across process lines, and enabling load shifting to respond to external factors such as energy price dynamics. In pilot operations, **Takachar** observed crew idle time between loading and unloading cycles. To optimize, they tested parallel deployment of multiple reactors per crew. Trials in California and India confirmed that shared crews not only boost throughput but also provide resilience if one unit requires servicing. This allows them to run continuously 24 hours a day, six days a week.
- **Automate Repetitive Tasks within Operations:** Identify elements of operations that are both repetitive and labor-heavy to automate to boost productivity and avoid labor bottlenecks that arise when scaling. **Kelp Blue**, for example, has introduced solar-powered, uncrewed harvesting vessels to replace manual boat crews for trimming kelp canopies, cutting labor intensity while maintaining efficiency at sea.
- **Integrate Digital Systems into Operations:** Embed sensors/SCADA (supervisory control and data acquisition) into components and structure the data collected flexibly and robustly, and leverage AI or analytics to continuously improve processes. **Vaulted Deep**, for example, has equipped its site with sensors across waste transport, processing, and injection systems and aggregate them in proprietary software. It uses this data to optimize waste sourcing, processing efficiency, and injection performance while ensuring transparent and accurate reporting.

Risks in Process Optimization:

While process optimization is a powerful tool for decreasing cost and increasing throughput, it also introduces risks. Several common challenges are the following:

- **Technology Lock-In:** Automating novel technologies can create rigidity. It crystallizes not just physical design but also the control logic and data flows, making retrofits costly when processes evolve. Small tweaks in one area can ripple across the facility, triggering costly replacements and delays. For example, the semiconductor industry once anticipated a shift to 450mm chips but required changes across every upstream and downstream tooling to implement. The cost and coordination burden ultimately stalled the transition.[29] Today's automation standards are more adaptable than in the past; modular PLCs, open data protocols, and

[29] Semiconductor Engineering, 450mm Silicon Wafer Issues Emerge

modular or more versatile robotics all support flexible upgrades and redeployment. Still, challenges may arise, particularly in more complex systems. To manage these risks, companies implement more adaptable practices and stage adoption (e.g., manual or semi-automated control in early phases or focusing on technologically stable processes first), so plants capture efficiency benefits without premature lock-in.

- **Brittle Operations:** Automated processes tend to be less flexible. Small disruptions such as wetter feedstock, sticky valves, or brief power dips can cascade into plant-wide disruptions. For example, Tesla initially aimed to completely automate its Model 3 manufacturing facility. This initial reliance on rigid, highly automated processes created major bottlenecks, leading to costly delays and workarounds.[30] The company eventually stabilized production by adding more human management to reintroduce flexibility. CDR companies can be wary of over-automation and include human talent in designs to maintain flexibility and reliability.
- **Workforce Readiness:** Even well-designed automation fails if it is not operated well. Thin staffing or limited training undermines trust in automation, leads to variability in product quality, and slows production. Initial high costs of training and slow learning curves may challenge early standard implementations. However, automation can lower workforce barriers by enabling low-skill operators to run complex systems, given proper training.

While the practices discussed in this section seem simple, new players across industries repeatedly struggle to adopt them. Industrial systems are tightly integrated and complex, and can be highly sensitive to errors. This challenge, paired with major investment requirements, makes the industrialization of operations a pivotal journey in a company's growth trajectory. Ultimately, other industries have eventually overcome this challenge but not without significant experience gained in trials. CDR players may benefit from sourcing this experience through partnerships or by building internal teams to navigate this common challenge.

Alternative Revenue Streams

How CDR Companies Use Alternative Revenues:

Many CDR approaches naturally generate useful byproducts and services that can be monetized and potentially used to subsidize the price of CDR credits. Mines/waste mineralization approaches, such as **Yuanchu's** and **Airhive's**, generate minerals that can be used in building and agricultural applications. Macroalgae cultivation processes, such as **Kelp Blue**, can generate biostimulants that support plant growth, creating a revenue opportunity 3x the cost of CDR. Biochar-based approaches, such as **NetZero**, generate biochar that can be used as a soil amendment to improve crop yields. Some biochar companies, such as **MASH Makes**, can also generate biofuels that could be used for shipping. The list of potential byproducts continues, including advanced materials, chemicals, chemical polymers, and more.[31]

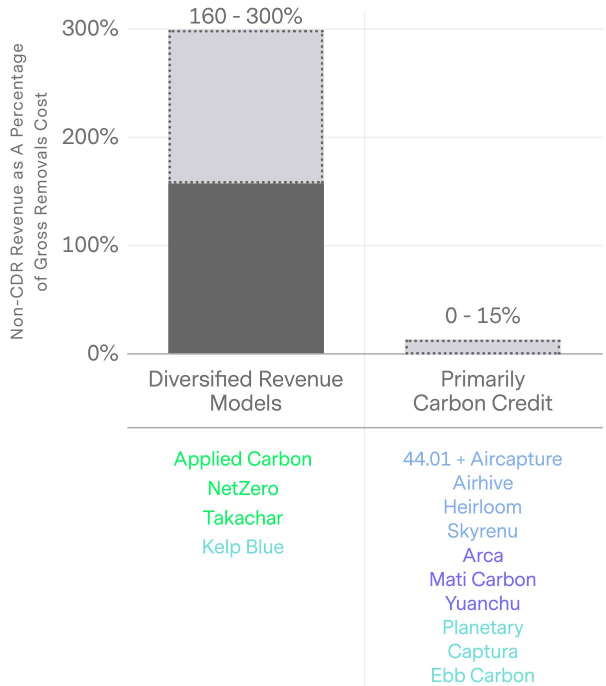
Beyond physical projects, certain approaches can generate revenue from services such as organic waste disposal from deep biomass storage by **Vaulted Deep** or mine tailings waste management for mineralization by **Skyrenu**. Finally, intellectual property can create a revenue stream as well. For example, **Captura** has developed a highly efficient proprietary electrodialysis technology with relevance to green hydrogen, battery recycling, and long-duration energy storage.

[30] Liu et al. (2025), The Rise and Recent Decline of Tesla's Share of the U.S. Electric Vehicle Market
[31] XPRIZE 2024, Carbon removal getting to gigatonne

CDR technologies that can generate and monetize co-benefits have significant advantages. In an uncertain policy environment, alternative revenues can de-risk the business case, cushion volatility, and improve financeability. They can also provide early revenues to offset funding needs or lower the breakeven carbon price. Many of these byproducts also create non-revenue co-benefits through local jobs, soil fertility, agricultural productivity, and ecosystem services that increase local support and adoption of CDR.

CDR players rely on alternative revenues to varying degrees.[32] Analysis of the finalist cohort points to two archetypes in alternative revenue use. For some companies, byproduct sales heavily impact unit economics, providing diversified revenue streams several times higher than total system costs. These companies' financials rely on alternative revenue streams even more than revenue from carbon removal. For most CDR companies, though, byproduct sales play a minor role in plans, as their economics significantly rely on carbon removal revenues with little to no alternative revenues.

Importance of Non-CDR Revenue Across Finalists



How to Unlock Alternative Revenues:

- **Prove Product Efficacy:** Secure third-party accreditation and regulatory clearance for the byproduct to build offtaker trust in a new product. **Takachar**, for example, demonstrates low impurity levels in its biochar through testing with a lab certified by Carbon Standard International and the International Biochar Initiative.
- **Build Sales and Lock Offtakes:** Stand up a product sales function and secure multi-year contracts to stabilize byproduct revenue streams. As an example, **Kelp Blue** has secured a six-year offtake commitment from blue chip buyers of its biostimulant byproduct.
- **Streamline Byproduct Logistics:** Design processes to minimize handling and transport so byproducts complement, instead of burden, CDR operations. For example, **Applied Carbon** integrates its biomass collection, pyrolysis, and distribution all on-farm to avoid haulage to a central pyrolysis facility.

Risks in Alternative Revenues

While byproducts offer significant advantages, not all companies that can generate co-benefits aim to monetize them. Alternative revenue streams can offset CDR costs, but they also add complexity. Teams that rely heavily on byproducts often devote a large, sometimes majority, share of total costs to managing them. A 10% swing in

[32] Plot only includes revenue from physical byproducts, not IP commercialization and waste handling services. Additionally, total plant cost includes additional CAPEX/OPEX for byproduct production.

byproduct margins could create a 15–30% swing in CDR costs for these companies. As such, biochar producers often operate as soil amendment companies as well as CDR firms. Similarly, macroalgae players may need to optimize operations around biostimulant manufacturing as much as carbon removal. Once a byproduct is monetized, companies must manage both byproduct generation and carbon removal. This creates several challenges:

- **Operational Complexity:** Monetizing byproducts often entails operating a parallel product business alongside the core CDR operation. Companies must manage a second logistics network, new regulatory/permitting requirements, additional customers, etc. For startups that often have limited resources, this additional complexity can be challenging.
- **Trade-Offs:** Optimizing the system for byproduct yield can reduce net removals. Tight co-location or exclusive offtakes for byproducts can also increase counterparty dependence.
- **Market Saturation:** At megatonne scale, byproduct volumes for some products can outrun regional or even global demand, capping potential alternative revenue streams. Market saturation risk can strand capacity or compress margins, ultimately weakening the CDR business case.
- **Carbon Accounting:** Companies that purchase CDR byproducts may advertise the clean origins of their materials. Selling byproducts creates a risk of double-counting environmental attributes between “clean” byproducts and the carbon credits. Leading carbon registries are managing this risk through clear methodologies and rigorous audits.

EXTERNAL FACTORS

Beyond the internal levers companies can directly control, CDR players must also contend with several external factors that shape both cost and scalability. These include **financing** costs, **supply chains**, **logistics**, **energy** prices, **land** cost and availability, and **water** availability. Controlling the cost sensitivities or bottleneck risks created by each of these factors is central to finalist deployment strategies. While the set of factors is common across companies, the exposure to these factors varies widely across companies (see the chart below). This section discusses the range of risks companies see and what finalists do to address each.

CDR Cost Sensitivity

	Engineered Solutions: Technology-intensive approaches that use industrial systems and equipment to capture and store CO_2		Biogenic Solutions: Nature-linked approaches that convert biomass into durable carbon storage forms		Geochemical Solutions: Mineral-based approaches that store CO_2 through accelerating natural chemical reactions with rocks or alkaline materials	
% Change in Variable	- 10%	+ 10%	- 10%	+ 10%	- 10%	+ 10%
Financing (CRF)[33]	-7%	7%	-4%	4%	-3%	3%
Supply Chain[34]	-6%	6%	-5%	5%	-4%	4%
Energy	-2%	2%	-1%	1%	-2%	2%
Land	-1%	1%	~0%	~0%	~0%	~0%
Labor	~0%	~0%	-2%	2%	-1%	1%
Logistics	~0%	~0%	-2%	2%	-2%	2%
Water	~0%	~0%	~0%	~0%	~0%	~0%
	44.01 + Aircapture, Airhive, Heirloom	Skyrenu, Captura, Ebb Carbon	Applied Carbon, NetZero, Takachar	Kelp Blue	Arca, Mati Carbon, UNDO Carbon	Yuanchu, Planetary

Note: *Groupings reflect the primary characteristics of each technology pathway for this analysis. Some teams may also share features with other categories.*

Financing

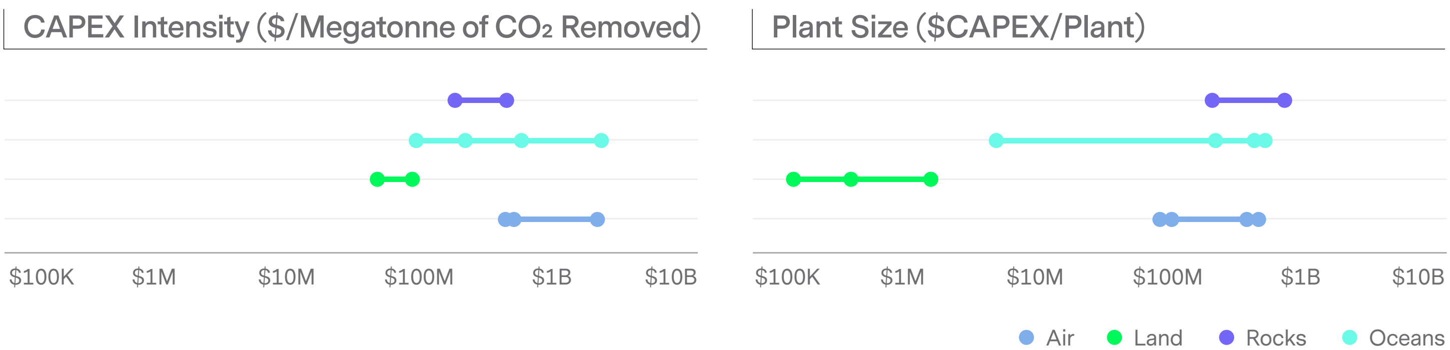
Financing is one of the most impactful external factors for CDR scale-up. Across the finalist cohort, cost of capital is a leading driver of levelized cost; getting financing strategy right is therefore critical, and a material competitive differentiator.

[33] Capital recovery factor, which converts upfront CAPEX into an equivalent uniform annual cost over the asset's life, determined mainly by weighted average cost of capital (WACC) and assets lifetime
[34] Supply chain sensitivity includes both component and feedstock costs

What Drives Financing Needs

Finalists vary significantly in their financing needs and strategies. These are determined by a range of characteristics of each company's approach. For example:

- The finalists' **CAPEX requirement** to build 1 Mt of removals ranges from $50 million to $2 billion. Financing $2 billion deployments with equity would be highly dilutive; therefore, cheaper project debt is relied on. In contrast, project financing may not be worth the effort for a $50 million project, so balance sheet financing may play a larger role.



- The projected **plant size** at the megatonne scale among finalists varies by three orders of magnitude from large $750 million facilities to small modular units costing $200 thousand each. Large plants that cost hundreds of millions of dollars will require bulk term loans to pay for construction at once, much like utility-scale solar developers. Investors for these plants will need to be equipped to offer large check sizes. In contrast, more modular companies can be financed by players that offer smaller checks or leverage revolving credit lines. These credit lines can be used to repeatedly draw smaller amounts of cash as individual units are built and use plant revenues for repayments, much like some distributed solar developers do. These smaller plants may even be able to have offtakers fund CAPEX with forward payments on credits or direct purchase of CAPEX.
- The percentage of CAPEX spent on **salable assets** informs the availability of asset-backed financing or leaseback structures. While most teams primarily spend CAPEX on plant components that have minimal value upon default, a handful spend 20–50% of CAPEX on salable assets such as cars or boats that can be resold upon default. These players may be able to access more favorable financing often used for vehicle fleets such as asset-backed loans or leaseback structures, as, in the worst-case scenario, investors can claim resale value.

How to Manage Financing Needs

Variations in these financing characteristics create a range of financing strategies among the finalists. For example, a DAC company pursuing large, centralized facilities will likely source project debt term loans. In contrast, a more modular company such as Takachar leverages smaller revolving credit lines. Takachar and its operating partner, Safi Organics, use a revolving debt facility to deploy their "Takavator" biochar units across Kenyan youth groups, who operate the machines and sell biochar back across Safi's fertilizer business. These revenues are used to service debt and pay for later units, allowing steady expansion without heavy upfront investment. NetZero, another company with a more modular approach, leverages a different financing strategy. It employs a franchise model whereby agricultural players themselves pay for CAPEX to own and operate their biochar sites with technical support from NetZero.

These financing characteristics may even diverge for companies of similar technology type. In contrast to certain DAC players that plan to grow to megatonne size by developing heavily scaled plants that cost many hundreds of millions, Skyrenu plans to scale with small, modular plants. Their megatonne-scale deployment plans consist of 400 x 2.5 kt modules deployed in sets of 20 around a mineralization reactor. Each batch of 20 deployments (50 kt) costs closer to ~$100M in CAPEX, potentially unlocking financiers with lower check sizes.[35]

Supply Chains

What Drives Supply Chain Risk

The primary supply chain risk for CDR companies lies in their dependence on bespoke or non-commoditized components and feedstocks. From a potential component provider's perspective, building out a new manufacturing line just to serve a novel technology startup is a highly risky investment. As such, supply chains for bespoke components and novel feedstocks are often thin. This increases costs, as suppliers increase premiums, prepayments, or minimum order volumes to offset risk. It also creates counterparty risk, with few suppliers a delay in one vendor's production may directly delay CDR operations.

Moreover, the globalized and highly leveraged nature of supply chains (employing just-in-time delivery) amplifies the impact of external disturbances. Disturbances such as wars, trade policy, natural disasters, and weather events can cascade across the system, causing supply to contract for extended periods. The COVID-19 pandemic, for example, disrupted global trade, constricting the supply of large power transformers for electricity transmission and distribution. Wait times for transformers extended from months to up to three years.[36] Even now, five years after COVID, the supply chain has not fully recovered.

Finalist reliance on bespoke/non-commoditized elements varies significantly. Captura's DOC system depends on custom-built electrodialysis membranes that are optimized for performance and cost targets at scale. In contrast, other finalists reduce risk by relying on abundant, commoditized inputs or off-the-shelf components. Airhive's DAC process runs on mineral sorbents that are commercially available and produced in hundreds of millions of tonnes globally each year. This allows for 100% of its feedstock to be commodities and ensures low cost and robust supply chain resilience.

In their submissions, finalists showed many different strategies to manage these costs and risks.

How to Manage Supply Chain Risk

- **Design Away Bespoke Elements:** Companies redesign components to remove unnecessary complexity, switch to off-the-shelf components, and commoditized feedstocks, making them easier and cheaper to

[35] This section surveys the range of CDR financing structures but does not delve into the many variations within each. For detailed treatments of creative project-finance strategies, see BCG reports here and here. Many XPRIZE finalists employ these approaches.
[36] NIAC 2024, Addressing the Critical Shortage of Power Transformers to Ensure Reliability of the U.S. Grid

procure and reducing the risk of being tied to niche suppliers. As discussed above, Airhive's DAC system relies on mineral sorbents made from globally abundant materials, avoiding dependence on specialized sorbent supply chains. Silicate Carbon relies on limestone over more exotic minerals in its ERW approach due to its global abundance and established use in the agriculture industry. However, bespoke components often offer significant advantages or create efficiencies that outweigh supply chain risk. In these cases, finalists use several other approaches to manage risk.

- **Engage Suppliers as Strategic Partners:** CDR firms address supplier wariness by sourcing partnerships instead of components. Suppliers are often treated as partners who are growing and sharing success. Finalists work hand in hand with suppliers, aligning innovation cycles while signing long-term deals. Heirloom, for example, co-designed and co-tested a kiln with manufacturing partners to de-risk commercial implementation.
- **Vertical Integration:** Wherever external sourcing is not feasible, bringing critical feedstocks or manufacturing in-house may be required. This approach can be expensive and risky if technologies shift, creating significant financing challenges, yet it has been applied successfully. MASH Makes designs and manufactures pyrolysis systems in the Global South, reducing dependence on OEMs, mitigating geopolitical risk, and achieving cost-competitive CAPEX. Captura has developed a manufacturing facility for its electrodialysis units, avoiding dependence on external suppliers.

Beyond CDR-specific solutions, finalists also benefit highly from **adopting standard supply chain practices** as they scale, for example:

- **Buffer Inventories:** Companies can establish stockpiles of high-risk components to solve temporary shortages or shipping delays. This practice, common in mature supply chains, helps reduce downtime from unexpected supply shocks. NetZero, for instance, stores coffee husks during harvest season to ensure steady biochar production year-round, insulating operations from seasonal variability.
- **Diversification:** Rather than relying on a single vendor, companies can aim to qualify three to four suppliers for each key input. This may be challenging for bespoke components that have a thin supply base, but it can be done for commodities. For example, Vaulted Deep has secured contracts with multiple waste suppliers, including stable suppliers such as municipalities and industrial operators, ensuring a steady and resilient flow of organic material for injection.
- **Redundant Supplier Qualification:** Instead of testing and purchasing from suppliers in series, companies pre-qualify multiple suppliers in parallel so that they can switch quickly whenever issues arise. This adds upfront cost but builds resilience. Ebb Carbon has tested dozens of different commercial electrodialysis membranes with multiple vendors, ensuring that it is not locked into one supplier when quality or pricing shifts.

While reducing dependency through design choices and vendor strategy can decrease costs and improve resilience, individual CDR companies have a limited ability to stabilize less mature supply chains on their own.

PATHWAYS TO COST REDUCTION

This is a common problem for novel industries. The solar industry, for example, addressed this challenge with cooperation across the ecosystem through the following:

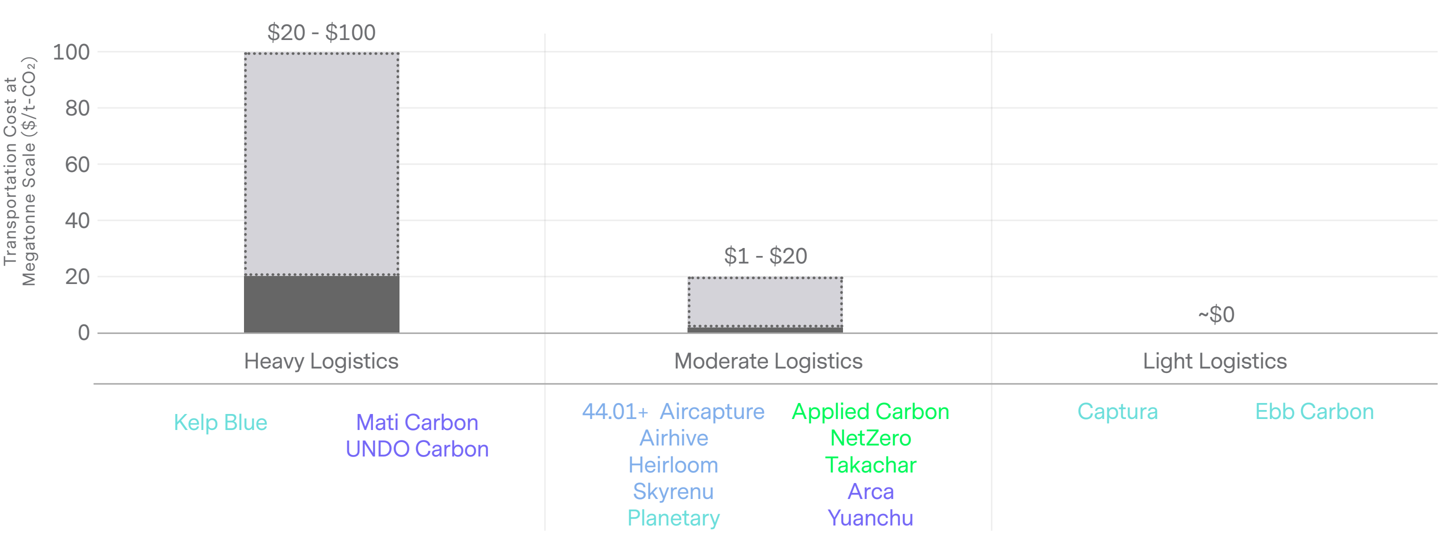
- **Standardization:** Aligning on shared specifications for key components across the solar industry allows it to diversify and expand the demand base for suppliers. For example, nine of the world's largest solar developers agreed to standardize module dimensions at 2384 mm × 1134 mm, enabling suppliers to consolidate around a single format.[37] This has reduced manufacturing complexity, lowered costs, and increased confidence for upstream suppliers to expand capacity. Similar alignment on key component specifications could reduce supplier risk and unlock scaling of new industries.
- **Aggregated Demand:** The industry also leverages buyer coalitions to pool procurement of scarce inputs, sending stronger signals to manufacturers and justifying investment in new production lines. For example, in recent years, several major U.S. developers formed a buyers' coalition and launched an aggregated RFP (request for proposal) to signal firm demand for U.S.-manufactured solar to manufacturers.[38]

While the diversity of CDR approaches makes the wide application of these levers challenging, these solutions could be employed for the components used across many CDR players (for example, monoliths, electrolyzers). For instance, Corning is currently developing monolith substrates to supply multiple DAC players with this standard component.

Logistics

CDR technologies rely on logistics networks to deliver feedstock, manage waste, and deliver CO_2. Logistics plays a minor cost role for most finalists, but is a primary cost for several, costing \$20–\$100 per tonne of CO_2 for the highest-need companies (see the figure below). Note that the data shown excludes the cost of CO_2 transportation since, at a megatonne scale, most finalists plan to pick locations in proximity to CO_2 storage sites.

Feedstock Transportation Cost Across Finalists



[37] PR Newswire, Trina Solar takes lead in standardization initiative to unify module dimensions
[38] Cypress Creek Renewables, Leading U.S. Solar Companies Announce Consortium to Spend over \$6 Billion on Solar Modules and Support Expansion of Domestic Supply Chain

What Drives Logistics Costs

Data from the finalist cohort suggests three archetypes by transportation demand:[39]

- **Light Logistics Need** systems require little feedstock or can strategically co-locate with sources; for example, ocean pathways that use seawater as the primary process feedstock site on the coast to limit water transport costs.
- **Moderate Logistics Need** systems move modest quantities of either light high-value feedstock, such as DAC, or bulky materials handled by distributed units placed near suppliers, such as biochar. These systems often prioritize siting for other factors (for example, energy or CO_2 storage) due to the lower impact of feedstock co-location.
- **Heavy Logistics Need** approaches are typically distributed or handle large tonnages that cannot be fully co-located. They rely on regional logistics networks, aggregation hubs, and long-haul bulk transport.

How to Manage Logistics Costs

XPRIZE finalists apply several levers to manage logistics costs, including the following:

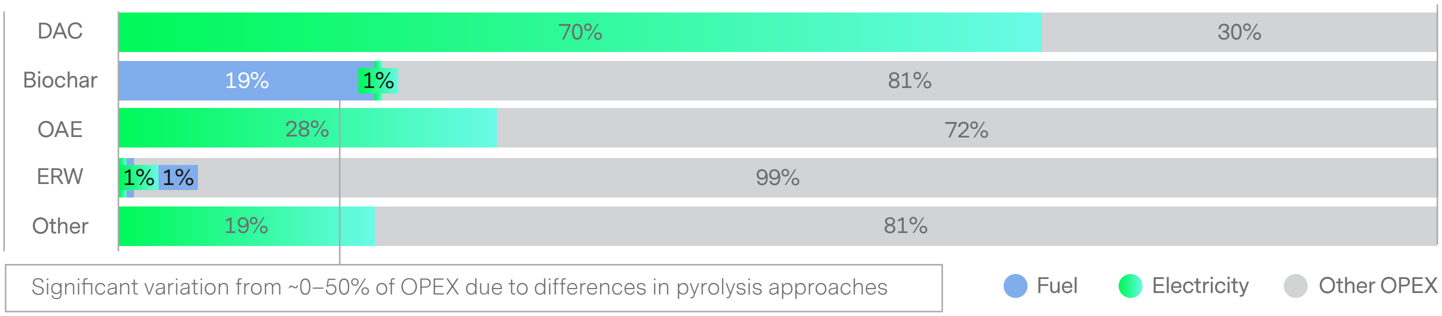
- **Design for Proximity:** Site facilities close to feedstocks and storage sinks to cut hauling distance and avoid redundant infrastructure. Kelp Blue, for example, sites facilities on the coast to minimize transport needs to algae cultivation sites. Similarly, Takachar and Applied Carbon both develop mobile pyrolysis systems to enable on-farm operations rather than requiring biomass to be transported back to stationary pyrolysis units.
- **Owning vs. Contracting Fleets:** Owning fleets can help companies control operations in remote or complex settings and can be more cost-effective for companies with very high logistics needs. Kelp Blue, for example, plans to purchase and own a fleet of trucks and installation barges. In contrast, contract third-party logistics is often used where existing transport infrastructure exists and can help minimize CAPEX needs. UNDO Carbon, for example, plans to outsource hauling of rock fines in its Canadian operations.
- **Digitize Field Logistics:** Use routing, clustering, and telematics to cut idle time and empty miles in distributed networks. Examples of this are Mati Carbon's proprietary MatiC software and UNDO Carbon's NEWTON. MatiC tracks geospatial data, transport logs, soil and rock sampling, and deployment details to create complete traceability and enable optimization.
- **Infrastructure Sharing Partnerships:** Work with industrial and municipal owners to tap existing infrastructure (such as intakes, outfalls, ports, and CO_2 pipelines), avoiding duplicate CAPEX and permits. Planetary, as an example, partners with industrial facilities that already transport alkaline products to mutually reduce logistics costs. Silicate Carbon takes advantage of limestone's current use in agriculture to leverage existing transport infrastructure, distribution equipment, and application practices for limestone-based ERW.

[39] The plot is not representative of all finalist companies.

Energy

Energy is one of the most critical external factors shaping the cost trajectory for many CDR technologies. Among the finalist cohort, energy is used in the form of either electricity or fuel. DAC, OAE, and DOC are electricity-intensive, with electricity and heat making up an average of 65% and a maximum of 98% of the operating expenditure (OPEX) per tonne of CO_2. The DAC finalists estimate that their megatonne plants will consume 1–2 TWh annually, equivalent to the electricity demand of a city the size of Geneva, Switzerland, or Reno, NV, or about eight average-sized data centers in the U.S.[40, 41, 42] Biochar and ERW finalists see higher energy costs from fuel but are generally less energy intensive (~10–40% of OPEX).[43, 44]

Average Energy Spend as a Percent of OPEX at Megatonne Scale



Note: *Numbers may not add up due to rounding.*

What Drives Energy Risk

Several trends make electricity one of the most volatile cost drivers for CDR:

- **Price Growth / Volatility:** Surging global electricity demand and generation interconnection delays may drive higher electricity prices while increasingly varied weather and renewables penetration increase price variability and outage rates. In European electricity markets, on ~70% of days, intra-day electricity price variation reaches ≥ €50 / MWh due to renewables variability and regional supply / demand mismatches.[45] For some DAC designs, this intraday volatility can swing CDR costs by ~40%. Long-term price growth could increase the costs of electricity-heavy CDR technologies, while cost variability or outages may create operational volatility that challenges cashflow management.

[40] Average U.S. data center is currently 40 MW (BCG, "Breaking Barriers to Data Center Growth"), and assumed to be running at 50% capacity (IDC, "IDC Report Reveals AI-Driven Growth in Datacenter Energy Consumption, Predicts Surge in Datacenter Facility Spending Amid Rising Electricity Costs" and Berkeley Lab, "2024 United States Data Center Energy Usage Report")

[41] World Bank Group, Electric power consumption

[42] IEA 2020, Specific energy consumption for CO_2 capture using current DAC technologies

[43] Technologies are less reliant on electricity and instead rely on fuel. To reduce their carbon intensity, many of these companies may transition to electric vehicles and could also become subject to electricity trends.

[44] For biochar companies, energy use typically breaks down to ~70% electricity and ~30% fuel, but reusing waste heat substantially reduces electricity demand, as shown in the energy chart.

[45] ACER 2025, Key developments in European electricity and gas markets

- **Regional Variability:** The varied regional availability of carbon-free energy, as well as increasingly varied regional energy policies, make both cost and carbon intensity of electricity diverge across geographies. This may increase regional competition for electricity.
- **Competition Risk:** Expanding demand from AI, electrification, and other heavy industries is intensifying competition for clean firm generation beyond the grid. By the end of 2024, U.S. data centers had contracted over 50 GW of clean energy, half of all U.S. clean energy procurement across the entire country that year.[46] CDR companies must often compete with these players to source clean energy.
- **Access Constraints:** Constrained distribution and transmission system buildout, paired with the rapid growth of new loads (for example, electric vehicles, data centers, industrial electrification), may force utilities to delay the interconnection of new loads. In California, industrial and commercial customers have faced grid-interconnection waits of up to two years.[47] Given the rapid timelines of startups, a multi-year delay could completely stall growth strategies.

How to Manage Energy Risk

While these dynamics pose major risks, they also create opportunities for strategic differentiation. The following strategies are employed by the finalists to manage these risks:

- **Adjust Tech or Operations to Reduce Energy Use:** Finalists, on average, reduce energy use per tonne of CO_2 removed by 65% when scaling from kilotonne to megatonne plants. Airhive, for example, uses a fluidized bed that makes it easier for air to flow through, so the fans do not have to use as much energy.
- **Adjust Operations to Flex Around Volatility:** Captura plans to overbuild its electrodialysis capacity to take advantage of price volatility. Electrodialysis runs during off-peak or curtailed power to produce acid and base that operate the system the rest of the day, effectively storing low- or zero-cost energy in chemical form.
- **Diversify Siting Strategy to Manage Grid Risk:** As CDR scales and matures, companies can reduce exposure to local energy market shocks by building across multiple geographies. In the more mature renewables industry, for example, developers operate across multiple geographies to capture diversification benefits.
- **Contract "Off-Grid" Clean Power to Stabilize Costs:** Octavia and Cella, for example, have co-located with a geothermal facility and contracted a long-term power purchase agreement (PPA) to firm low-carbon energy at stable costs off the standard grid. Similarly, Mati Carbon plans to establish small-scale solar power plants to power crushing facilities and reduce dependence on unstable grids in Africa.

Some of the most powerful strategies require strategic partnerships:

Reusing Energy Through Co-Location: Skyrenu, for example, notes that by strategically locating plants near industrial facilities, they could reuse low-grade waste heat and reduce energy needs by 30%. This strategy could be repeated for any major heat source; for example, Microsoft has piloted integrating DAC with data centers to reuse waste heat.[48]

[46] S&P Global, Data centers account for half of U.S. clean energy procurement but only 20% in Europe
[47] Press release, SB 83
[48] Microsoft, 2025 Environmental Sustainability Report

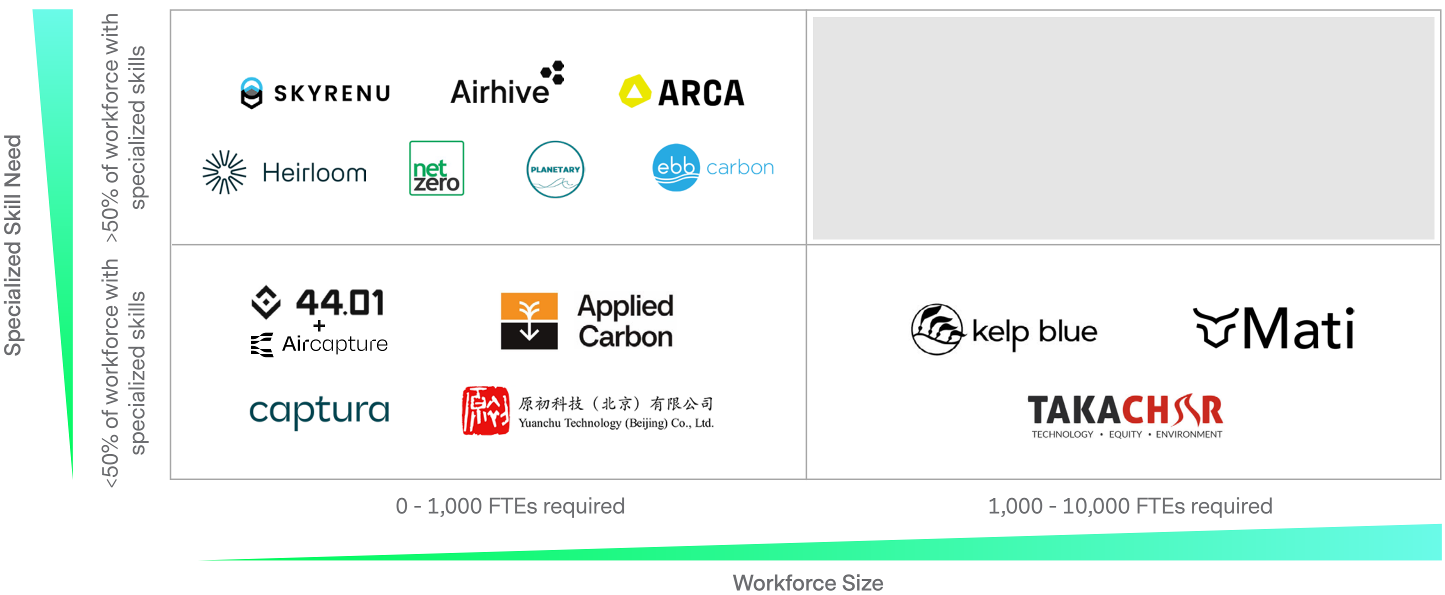
- **Secure Strategic Deals with Utilities:** Skyrenu has also partnered with Hydro-Québec to secure long-term, low-carbon hydropower blocks for its DAC + mineralization system. Similar clean energy tariffs are being developed for data centers, for example, the Clean Transition Tariff in Arizona.[49]

Ultimately, much of the energy risk is beyond the direct control of CDR players. Regulation can support energy stability by promoting the growth of transmission and distribution networks and expanding reliable, affordable, and clean generation capacity. Additionally, streamlining permitting/pre-permitting may alleviate bottlenecks (for example, Texas's Competitive Renewable Energy Zone and Colorado's siting of transmission on highway right of way).

Labor

Labor is a critical scaling constraint for CDR. Even as labor intensity per tonne falls with automation and process optimization, absolute headcount requirements rise sharply at megatonne scale. The challenge is twofold: ensuring sufficient numbers of workers for large-scale deployments, and sourcing the skills needed.

FTE Labor Breakdown by Income Level at Megatonne Scale



Note: *Specialized skills are defined as skilled labor roles that are the middle to top earning professions in their region, such as managers, technicians, machine operators, and service workers*

What Drives Labor Risk

XPRIZE teams vary in their labor needs but generally fall into three categories.

- **Companies with a small, non-specialist workforce** tend to have lighter labor needs.
- **Companies with a small, specialist workforce,** often DAC or OAE players, employ fewer people but depend heavily on highly trained engineers and technicians. These skills overlap with industries such as oil & gas operations and renewable energy, where expertise in running large industrial plants, managing fluid systems, and maintaining high-voltage equipment is in high demand. This competition makes it harder and more expensive to hire and retain the talent needed.

[49] SWEEP, Data centers: Power needs and clean energy challenges

- **Companies with a large, non-specialist workforce,** often based in biogenic processes, may require thousands of workers for positions such as logistics and field operations. Finding skills is less of a risk, but sourcing and retaining manpower (particularly in remote areas) can be a major constraint on scaling.

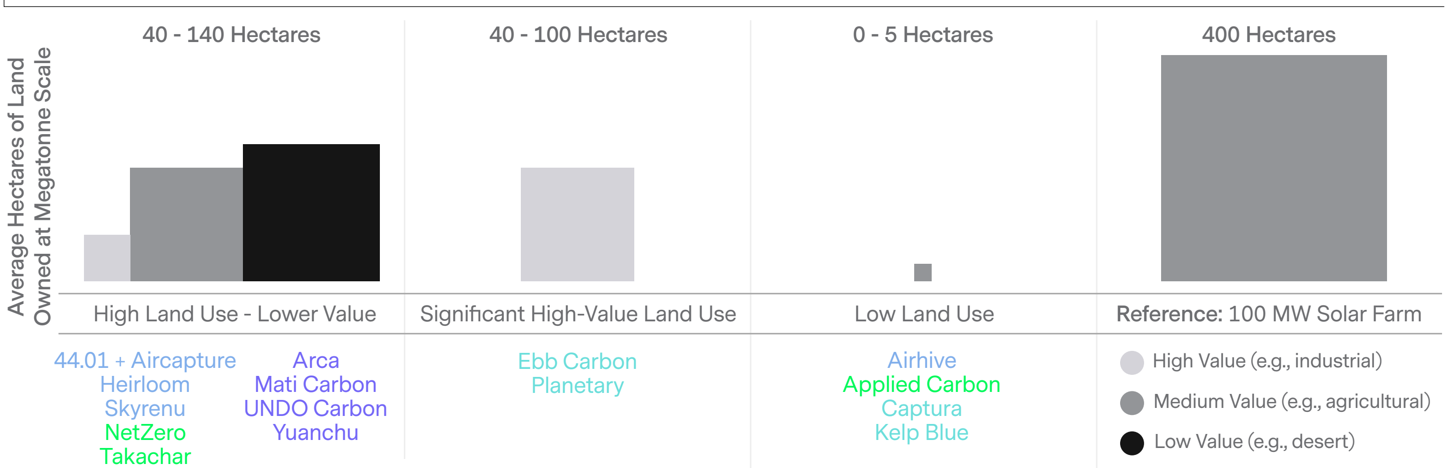
How to Manage Labor Risk

Labor is not just a cost factor; it is also a potential bottleneck to scale. To address these risks, companies have adopted a mix of solutions:

- **Optimize Workforce Efficiency:** Companies improve labor productivity by automating repetitive tasks, enabling remote monitoring, and streamlining deployment with mobile or clustered field teams (as discussed in the Process Optimization section).
- **Training and Upskilling Programs:** Companies such as Octavia and Cella are investing in local training (for example, community operator programs in Kenya) to build capacity from the ground up. Similarly, Kelp Blue is cross-training staff to handle farming, harvesting, and monitoring tasks in Namibia, creating multi-skilled crews and in-house training pipelines in regions with limited labor supply.
- **Standardize Operations:** Finalists simplify training by developing standard operating procedures (SOPs) across plants. Mati Carbon, for example, established SOPs for laboratories and created internal process training videos to maintain consistency in procedures and quality, reducing dependence on any individual employee.
- **Partnerships with Schools and Workforce Boards:** Collaborating with local educational institutions creates steady pipelines of skilled labor. Kelp Blue, for instance, works with the Lüderitz Blue School and Namibian universities via the Kelp Forest Foundation to seed local expertise in marine science and operations. These partnerships also strengthen community ties, making it easier to secure long-term land or resource access.
- **Clustering Facilities:** Locating projects close together allows companies to share skilled technicians, lowering costs and reducing exposure to labor shortages. Ebb Carbon and Captura pursue a similar strategy by co-locating with desalination plants, embedding into regions with existing industrial workforces rather than building new operator pools from scratch.

Land

Land Ownership for CDR at Megatonne Scale



Infrastructure with high land use may see bottlenecks in siting projects and can also create significant sustainability concerns from land-use change. For durable CDR, however, land use is rarely a binding constraint. Centralized systems (DAC, ocean solutions) occupy compact, dedicated parcels. For perspective, a typical 100 MW utility-scale solar plant requires ~3x more purchased land than even the most land-intensive CDR plants.[50, 51] Distributed approaches (ERW, biochar) operate across larger areas of working land, yet their purchased footprint is comparable to centralized plants because they rely on partner-owned farms, forests, and mine sites. One example of this is **Arca**, which integrates its operations directly into existing mine tailings sites, turning waste storage facilities into carbon removal assets without requiring new land purchases. Even with low land use, two recurring land-engagement challenges appear, and finalists are developing practical strategies to address them.

- **Sourcing High-Value Land:** Some finalists (DAC, OAE, and DOC) need to secure parcels with cheap electricity, ready grid interconnection, and industrial zoning. These plots of land are often in heavy competition with other industries (e.g., data centers, industrial operators). While footprints are compact, real estate may be expensive and hard to source. Moreover, OAE and DOC companies also need to purchase ocean-adjacent real estate, further constraining land parcel selection. Finalists address these siting considerations through co-location and reuse of existing assets. Ebb Carbon co-locates with desalination plants to use established intakes and outfalls. Planetary embeds with industrial facilities with existing water outfall.
- **Managing Distributed Land Partners:** ERW and biochar pathways operate across dispersed lands owned by farmers, foresters, and miners. At a megatonne scale, these systems require a network of fields or forest plots. Success depends first on trusted partnerships with landowners, co-ops, Indigenous groups, and other local stakeholders supported by standardized contracts and fair revenue sharing. Finalists resolve these needs through anchor partnerships, standardizing partner management, and digital operations. **UNDO Carbon**, for example, coordinates contractors and growers via its NEWTON platform, and both **UNDO Carbon** and **Mati Carbon** have explored anchor partnerships to access large, contiguous land blocks.

Water

Freshwater use is a second-order issue for most CDR approaches. Even the highest-using finalists use only 4–13 tonnes of water per tonne of CO_2 at megatonne scale, which is still 3–10x below the annual water consumption of an average-size natural gas power plant in the U.S.[52] In the finalist cohort, only two companies have a relatively high freshwater consumption, while the remaining consume less than 1.1 tonnes of water per tonne of CO_2 removed.

Still, water becomes a constraint in arid locations where freshwater is scarce and evaporative losses are high; in these situations, finalists make siting choices and refine engineering to reduce needs or adapt. Heirloom addresses this by siting megatonne projects in more humid regions to curb losses to the environment and lower make-up water needs. Similarly, 44.01 is redesigning its use of mineralization fluids and aiming to cut fresh water needs by more than half in Project Hajar.

[50] Based on a 10 ac/MW land footprint
[51] The comparison excludes land required to power CDR systems. CDR companies choose different strategies to power their systems. This includes different types of PPA, behind-the-meter generation, and strategic siting to tap into waste industrial heat.
[52] Assumed a 650 MW natural gas power plant with 75% capacity factor and water consumption of 2,800 gal/MWh (US EIA).

CONCLUSION

Durable CDR must scale by orders of magnitude and reduce costs by multiples to meet our climate goals and provide business value. Submissions from the XPRIZE Carbon Removal competition offer a unique window into how leading companies approach this challenge.

Finalists in the XPRIZE submitted **qualitative roadmaps** and **quantitative techno-economic models** detailing their strategic and technical plans to grow from existing kilotonne demonstrations to megatonne-scale plants. All submissions were underwritten by performance in year-long field demonstrations as well as validated by an independent third party.

Finalist submissions tended to discuss a common set of elements. First, strategies to grow are typically driven by combinations of the same five levers:

1. Further technical advancement, interestingly, plays a limited role in finalist calculations. While in all likelihood, technological innovation will continue to be an important part of cost-reduction strategies, finalist plans rely more on predictable engineering and commercial improvements that come from regular maturation. A rapid scaling of CDR can occur with existing technology; further technical innovation will provide additional upside.

2. Scaling plants or components to create economies of scale plays a major role, particularly in heavily engineered technologies with significant BOP (for example, DAC, OAE, DOC). Strategies to unlock scaling focus on building the experience and capabilities to manage large capital projects (for example, construction partnerships, permitting, and financing). These capabilities typically take direct experience and significant time to build. The challenge for CDR is acquiring these capabilities on a rapid startup timeline.

3. Modularization is leveraged by finalists across technology pathways to create repetition in components (for example, DAC contactors) or in plants (for example, biochar pyrolysis units). This maximizes learning rates and decreases manufacturing costs through volume but requires the development of a robust supply chain and management of overhead.

4. Optimizing or automating processes is widely used across all technologies and is particularly focused on reducing labor and energy requirements. The challenge revolves around adopting standard best practices in industrial optimization that are simple in concept but have challenged many novel industries in the past.

5. Expanding byproduct sales is a significant lever for a handful of finalists, sometimes providing revenues even greater than those from CDR. This can net-reduce carbon credit costs and diversify revenue streams but also creates complexity. Companies that leverage byproducts may have to operate as both a CDR and a byproducts company.

Beyond the internal levers that companies can directly control, finalists also plan around a consistent set of external factors that shape both cost and growth rates:

- **Financing** costs place a particular burden on CAPEX-intensive solutions. Finalists leverage a wide range of investment structures; interestingly, the financial structure that best suits a company varies based on its application of the five levers above, not necessarily its technology. There is no one-size-fits-all financing strategy for the CDR industry in general or for any individual CDR technology.

CONCLUSION

- **Supply chains** are a particular risk for companies that depend on bespoke or non-commoditized components and feedstocks. Manufacturing lines are expensive investments for suppliers to justify with risky offtake from a startup. Strategies to address this challenge focus on building supply chain partnerships, vertically integrating, or developing coalitions to pool demand.
- **Logistics** costs are minor for most finalists but a significant burden for several that have heavily distributed operations (for example, some biochar players) or players with significant feedstock needs and limited flexibility to co-locate with sources (for example, some ERW players). Management of these costs revolves around optimizing fleets, structuring fleet ownership, and sharing logistics infrastructure.
- **Energy** prices are a primary cost for DOC, DAC, and OAE and are projected to see significant variability in the near and mid-term as load growth, renewables penetration, and grid bottlenecks converge. CDR companies actively manage these risks by engineering-in energy efficiency and flexibility, selecting sites based on energy, and developing partnerships with energy players.
- **Labor** is a critical scaling constraint for CDR. Absolute headcount requirements must rapidly grow to produce at megatonne levels. Finalists tend to see one of two distinct challenges: expanding a large pool of general labor and building a base of skilled workers. They address these with industrial automation, training programs, co-location in talent hubs, standardization of process, and partnerships.
- **Land** ownership is a secondary problem for CDR but can pose challenges for specific technologies that must be sited on high-value land (for example, OAE, DOC) and technologies that must manage partnerships across many landowners (for example, ERW, biochar). Finalists explore co-location with landowners and automation of partnership management to deal with these challenges.
- **Water** is a minor challenge in most cases but can pose issues in geographies with low water availability or high evaporation rates. Finalists adjust plant designs or locations to manage this.

Across these strategies, several broad industry trends are apparent:

- Going forward, the growth of CDR is shifting from requiring novel technical/scientific breakthroughs to a more predictable expansion of engineering and commercial capabilities. In the future, strategic advantage will be found through implementational elements in the field as much as they are found in the lab.
- Commercial and engineering strategies vary significantly, even within technologies. There is a range of viable pathways to reduce costs and increase capacity, and each has its own requirements and risks.
- These varied strategies all share one requirement: they rely on a broader ecosystem of feedstock suppliers, component manufacturers, EPCs, logistics providers, and plant operators to support developers at scale. This creates a risk that the ecosystem will not materialize, but also provides a significant business opportunity in the development of this ecosystem.

This has several implications for players across the CDR industry,

CDR suppliers can competitively position themselves by using their engineering and commercial strategy as much as their technology. Enacting these strategies is not a trivial task, and requires companies to develop additional internal experience, corporate capabilities, and partnerships while taking advantage of new opportunities offered by the maturation of CDR. They can do the following:

- **Build capabilities to manage engineering and commercial challenges.** While tech advancements will continue to provide advantages, successful implementation will define the ability for CDR companies to scale. Companies can build teams with requisite experience (for example, hire talent with supply chain backgrounds), expand programs to build capabilities (for example, create technician training programs), and source partnerships for support (for example, clean firm electricity supply agreements with utilities). Critically, these actions are not one size fit all - they must be matched to the specifics of a company's commercial and engineering strategies, particularly the scaling levers applied, and external factors managed.
- **Take advantage of opportunities in the CDR supply chain.** As the CDR ecosystem expands, business opportunities will be created for dedicated feedstock suppliers, component manufacturers, EPCs, etc. CDR startups can mature into fields other than project development. For example, a startup with differentiating technology for a widely used component could evolve as a component supplier.
- **Continue to drive demand to meet supply growth.** This report discusses how CDR players can expand capacity at length. This supply side is critical, but ultimately must serve a demand. While not the focus of this report, developers should continue to focus on business development to ensure that the demand materializes to meet the supply scale-up.

In this new commercialization phase of CDR, large **offtakers** can consider areas where they have an opportunity to play a strategic role beyond just purchasing carbon credits, such as the following:

- **Sustainability teams** can consider opportunities to minimize CDR project risks, for example, by providing long-term offtake agreements for CDR or byproducts. They can also provide strategic financing, for example, through upfront CDR purchases, expand the CDR demand base through industry coalitions/offerings like the Airbus Carbon Capture Offer, or simplify offtake structuring, similar to what Google and LevelTen Energy did for renewables.
- **Strategy teams** can consider leveraging CDR to differentiate their product and drive a green premium, as some coffee players have successfully done. They can also expand into the new markets created by CDR, similar to what 3M did with sorbent technologies.
- Finally, **operational teams** can consider whether CDR can reduce feedstock requirements, as some agricultural players have done by using biochar to reduce fertilizer needs. They can also consider sharing infrastructure with CDR players, as some desalination plants have done by sharing their water management infrastructure with ocean CDR approaches. Finally, they can consider the opportunity to minimize environmental risks, as some mining companies have done by using waste mineralization CDR approaches to stabilize mine tailings.

Investors can structure investments to manage the implementation-heavy risk profile of CDR (vs. technology risk). They can also utilize a wide range of investment structures tailored to the varied commercialization and engineering strategies of suppliers.

CONCLUSION

- **Many CDR technologies can be successfully scaled without further technological or scientific breakthroughs.** Rapid growth and cost reductions in CDR can be achievable with today's technologies; the real challenges now lie in engineering, deployment, and commercialization. In this sense, the risk profile of the sector has shifted away from pure technology risk toward execution risk. Continued advances in technology, materials, and/or processes will certainly help, but they are accelerants, not prerequisites, for reaching scale. De-risking investment may evolve from managing technical risk to managing executional risk (e.g., engineering, construction, supply chains)
- **Financing structures vary widely even within the same technology category.** CAPEX needs, plant size, asset profile, and reliance on byproducts differ by orders of magnitude across finalists. These factors determine whether CDR players need checks of tens or hundreds of millions and shape the capital stack—from equity to project debt to instruments such as credit revolvers and asset backed loans. This variability complicates investor filtering but also creates room for financial innovation and a wide range of investment theses.

APPENDIX

Glossary

- **ACCO (Airbus Carbon Capture Offer):** Airbus's program to buy carbon removals to help decarbonize aviation
- **BBPIG (Germany's federal grid expansion law):** German law that fast-tracks major electricity grid projects
- **BOM (bill of materials):** A detailed list of parts, components, and materials needed to build a system or product
- **BOP (balance of plant):** All supporting equipment and systems needed to run a facility, aside from the main technology
- **CAPEX (capital expenditure):** Upfront costs of building or acquiring assets such as facilities, equipment, or infrastructure.
- **CBAM (Carbon Border Adjustment Mechanism):** A trade policy tool that puts a carbon price on imports into the EU
- **CREZ (Competitive Renewable Energy Zones):** Texas program that builds transmission lines to connect renewable energy to the grid
- **DAC (Direct Air Capture):** A technology that pulls CO_2 directly out of the air
- **DAC+S (Direct Air Capture with Carbon Storage):** DAC combined with storing captured CO_2 underground or in long-term products
- **DOC (Direct Ocean Capture):** Technology that removes CO_2 directly from seawater
- **Durable CDR (Carbon Dioxide Removal):** Technologies and practices that take CO_2 out of the atmosphere and durably store it
- **EPC (Engineering, Procurement, and Construction):** A common contract model in which one firm handles designing, sourcing, and building a project
- **ERW (Enhanced Rock Weathering):** Spreading crushed minerals to speed up natural CO_2-absorbing reactions
- **GW (Gigawatt):** A measure of power equal to one billion watts
- **Gtpa (Gigatonnes per Annum):** One billion tonnes of something (for example, CO_2) measured per year
- **ISO (Independent System Operator):** A regional organization that manages the power grid, balancing electricity supply and demand
- **kt (Kilotonne):** One thousand tonnes
- **MRV (Measurement, Reporting, and Verification):** The process of tracking, disclosing, and validating emissions or carbon removals

APPENDIX

- **Mt (Megatonne):** One million tonnes
- **MWh (Megawatt-Hour):** One million watt-hours of electricity
- **N_2O (Nitrous Oxide):** A potent greenhouse gas
- **OAE (Ocean Alkalinity Enhancement):** Adding alkaline materials to the ocean to boost its ability to absorb CO_2
- **O&M (Operations and Maintenance):** The ongoing work and costs to keep a facility running
- **OPEX (Operating Expenditure):** Day-to-day costs of running a business or facility
- **PPA (Power Purchase Agreement):** A contract between an energy generator and energy buyer, for the sale of electricity
- **SCADA (Supervisory Control and Data Acquisition):** Digital systems for monitoring and controlling industrial processes
- **TWh (Terawatt-Hour):** One trillion watt-hours of electricity

About the Authors

Boston Consulting Group partners with leaders in business and society to tackle their most important challenges and capture their greatest opportunities. BCG was the pioneer in business strategy when it was founded in 1963. Today, we work closely with clients to embrace a transformational approach aimed at benefiting all stakeholders—empowering organizations to grow, build sustainable competitive advantage, and drive positive societal impact. Our diverse, global teams bring deep industry and functional expertise and a range of perspectives that question the status quo and spark change. BCG delivers solutions through leading-edge management consulting, technology and design, and corporate and digital ventures. We work in a uniquely collaborative model across the firm and throughout all levels of the client organization, fueled by the goal of helping our clients thrive and enabling them to make the world a better place.

XPRIZE is the recognized global leader in designing and executing large-scale competitions to solve humanity's greatest challenges. With over $500 million in prizes over 30 years, our unique model has democratized crowdsourced innovation and scientifically scalable solutions that accelerate a more equitable and abundant future. Donate, learn more, and co-architect a world of abundance with us at xprize.org.

For more questions please contact:

Karan Mistry, Mistry.Karan@bcg.com
Paulina Ponce de Leon, PoncedeLeon.Paulina@bcg.com
Mike Matson, Matson.Mike@bcg.com
Michael Leitch, Michael.Leitch@xprize.org
Nikki Batchelor, Nikki.Batchelor@xprize.org

APPENDIX

Disclaimer

This document has been prepared in good faith on the basis of information available at the date of publication without any independent verification. BCG does not guarantee or make any representation or warranty as to the accuracy, reliability, completeness, or currency of the information in this document nor its usefulness in achieving any purpose. Readers are responsible for assessing the relevance and accuracy of the content of this document. It is unreasonable for any party to rely on this document for any purpose and BCG will not be liable for any loss, damage, cost, or expense incurred or arising by reason of any person using or relying on information in this document. To the fullest extent permitted by law, BCG shall have no liability whatsoever to any party, and any person using this document hereby waives any rights and claims it may have at any time against BCG with regard to the document. Receipt and review of this document shall be deemed agreement with and consideration for the foregoing.

This document is based on primary qualitative and quantitative research executed by BCG. BCG does not provide legal, accounting, or tax advice. Readers are responsible for obtaining independent advice concerning these matters. This advice may affect the guidance in the document. Further, BCG has made no undertaking to update the document after the date hereof, notwithstanding that such information may become outdated or inaccurate. BCG does not provide fairness opinions or valuations of market transactions, and this document should not be relied on or construed as such. Further, any evaluations, projected market information, and conclusions contained in this document are based upon standard valuation methodologies, are not definitive forecasts, and are not guaranteed by BCG. BCG has used data from various sources and assumptions provided to BCG from other sources. BCG has not independently verified the data and assumptions from these sources used in these analyses, including the accuracy or completeness of XPRIZE Carbon Removal application material. Changes in the underlying data or operating assumptions will clearly impact the analyses and conclusions.

This document is not intended to make or influence any recommendation and should not be construed as such by the reader or any other entity. This document does not purport to represent the views of the companies mentioned in the document. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by BCG.

BCG was not involved in the XPRIZE Carbon Removal selection, judging, or award decisions and does not speak on behalf of XPRIZE.