Direct Air Capture

Capitalizing on the Defining Decade
for Technology Development

Insight Brief / December 2021

Authors & Acknowledgments

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Cover image shows the Orca DAC plant in Iceland. Courtesy of Climeworks.

Acknowledgment

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About Third Derivative

Founded by RMI and New Energy Nexus in 2020, Third Derivative (D3) is an open, collaborative climate tech ecosystem that accelerates startups and moves markets.

By guiding and supporting climate tech entrepreneurs who are bringing new ideas and innovation to market, D3 is accelerating the clean future worldwide. Through a vast global network of deep experts, corporate partners, and investors, D3 helps startups go to market faster with their breakthrough ideas, create real impact, and transform markets.

About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and nongovernmental organizations (NGOs) to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

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Executive Summary

Meeting the global climate crisis calls for deep and rapid decarbonization of the economy. But with 1°C warming already by 2021, widespread decarbonization alone may not be enough.

According to the Intergovernmental Panel on Climate Change, starting in 2050 we may also need to remove 2 billion to 20 billion tons of carbon dioxide from the atmosphere per year to limit warming to 1.5°C (2.7°F).[i]

To reach this scale of negative emissions, we will need to deploy a portfolio of carbon dioxide removal approaches. As part of this portfolio of negative emissions technologies, direct air capture (DAC) is an imperative "insurance policy," given its potential to pull gigatons of CO_2 directly from the atmosphere every year and lock it up in permanent, sequestered storage.

Today's leading DAC technologies are far too expensive and energy-intensive to deploy at gigaton scale. However, new step-change technologies and significant improvements to existing technologies are on the horizon.

There are important opportunities for cost reductions across all three of DAC's main cost drivers:

1. Capital expenditures and operational expenditures for air contactor systems that bring atmospheric CO_2 into contact with the capture material
2. The cost of liquid solvents or solid "sorbent" capture materials that react with CO_2 to pull it from the air
3. The energy needed to regenerate and release the CO_2 from the capture material

Together, improvements in these areas could drop the cost of DAC by a factor of 5–10 in 10 years.

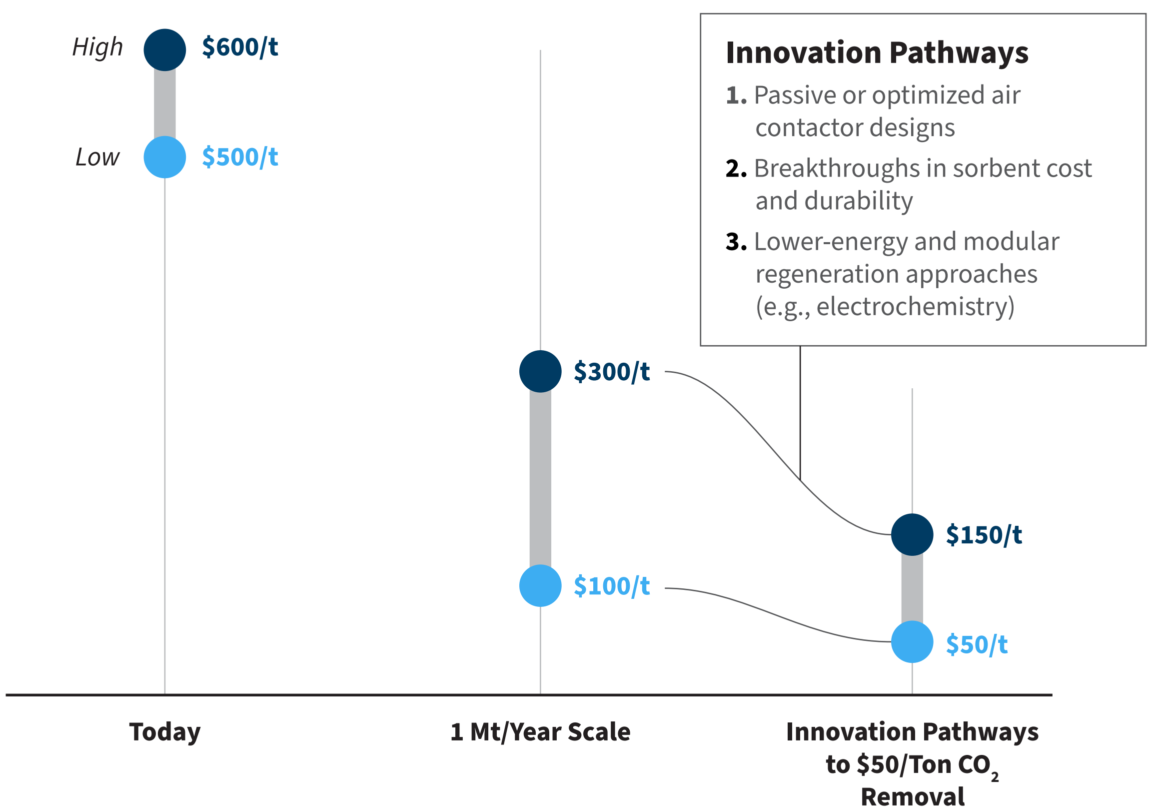
i The 2021 IPCC report states that we need to remove 100 billion to 1 trillion tons of CO_2 over the 21st century. This corresponds to 2-20 gigatons (Gt) of carbon dioxide removal (CDR) per year, starting in 2050. This CDR includes both natural and engineered solutions.

Based on our review of the current technology landscape, we arrived at the following key findings:

- Innovations are possible across all of the technology's top energy and cost drivers, which, at the most ambitious, could push costs to $50–$100/ton of CO_2 removed.
- DAC approaches that use optimized airflow systems have already dropped capital expenditures (capex) by more than 90%. New passive airflow systems could fully eliminate air contacting capex, up to 25% of the entire cost of capture.
- Emerging solid sorbent and electrochemical technologies could offer a lower-energy, fully electrified, lower-cost pathway to CO_2 removal.
- This is the defining decade for technology development: investment is needed now to drive down costs and enable DAC to reach gigaton scale when we need it.

Exhibit 1

Innovation Pathways to below $100/Ton CO_2 Removal



Note: Today's costs are based on reported costs for Climeworks with existing technologies at pilot scale. Costs at 1 Mt/year scale are based on company projected costs of existing technologies with learning effects. Innovation pathways offer a lower cost floor as shown in Exhibit 6.

Sources: Current costs and 1 Mt/year scale costs from "A Review of Direct Air Capture (DAC)," Noah McQueen et al., 2021, and *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda,* National Academy of Sciences, 2019

DAC: An "Insurance Policy" for the Climate

While decarbonizing emissions-heavy sectors such as power, mobility, buildings, and industry remains crucial for our climate's future, this alone may not be enough. A growing number of climate models indicate that society must be prepared to remove gigatons of the planet-warming carbon dioxide from the air to limit warming to 1.5°C (2.7°F). RMI will publish a deep dive on carbon removal in climate models in an upcoming insight brief in early 2022.

Engineered technologies for carbon removal are in their early stages of maturity, and the future roles of individual technologies and processes have not been clearly established. But the 2021 IPCC report indicates that we may need 2–20 gigatons (Gt) per year of CO_2 removal, requiring an all-of-the-above approach to the problem. This includes widespread use of nature-based solutions, such as tree planting, as well as the scale-up of engineered solutions for carbon removal.

Direct air capture, or DAC, is one such engineered solution that could provide an "insurance policy" for the climate. DAC offers the potential of gigaton-scale carbon capture with the ability to store that CO_2 over long timescales. As the name suggests, DAC technologies pull carbon dioxide directly from the air, chemically trapping it in fluids or solid filters. Once captured, the CO_2 can be used to synthesize fuels, chemicals, or other products. But more importantly, it can also be safely sequestered in geological formations for millennia.

We need to develop DAC solutions now to ensure that this insurance policy is available when the globe needs it. As of 2021, 19 DAC plants are in operation globally, but the cost of current technologies is much too high to deploy at gigaton scale. At today's costs, removing 10 gigatons of CO_2 per year from the atmosphere would cost at least $5 trillion—or one-quarter of US gross domestic product (GDP)—each year.

In this insight brief, we will explore some of the opportunities for innovation and scaling that could reduce the cost of DAC by an order of magnitude to close to $50 per ton of CO_2 removed. A future brief will compare DAC to other approaches to carbon removal, such as direct mineralization and nature-based solutions. We have chosen to focus this first brief on DAC because of its potential for gigaton-scale, verifiable, long-duration CO_2 capture and storage, and because it needs rapid innovation now for future deployment.

There are valid concerns about DAC, especially about its energy intensity while the grid is still reliant on fossil fuels. Further, point-source carbon capture and sequestration (CCS) projects have historically underperformed. We strongly believe all DAC innovation should be reviewed with a full carbon life-cycle assessment and with stringent ongoing monitoring and verification to ensure projects are, in fact, carbon negative. Further, innovators should focus on fully electrified processes that can couple with renewables.

To set the stage for that innovation, we will describe the current state of the art in DAC, the cost drivers of the technology, and the innovation areas that could enable critical cost reductions to unlock DAC's potential in the carbon removal portfolio.

DAC Today: Advancing but Still Too Costly

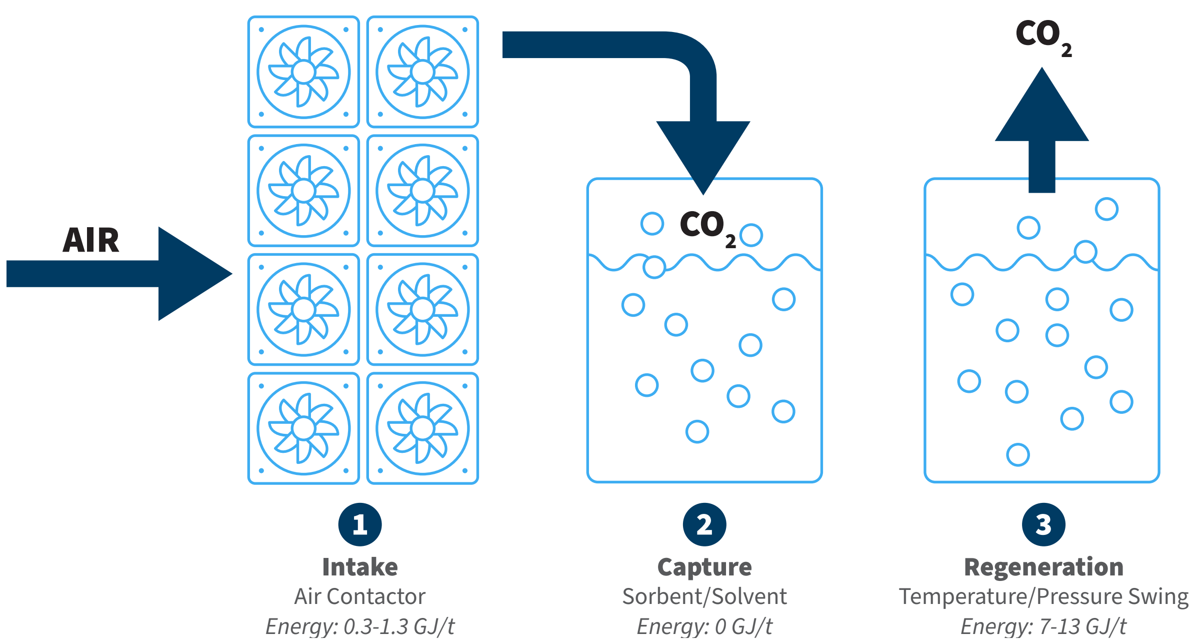
Direct air capture is a nascent technology with only a handful of plants in operation today. The 19 active DAC plants as of 2021 capture around 10,000 tons of CO_2 per year from the atmosphere—negating the tailpipe emissions of only about 2,000 passenger vehicles.

Current technologies have been limited by high costs (several hundred dollars per ton of CO_2 removed) and substantial energy requirements (more than 7 gigajoules, or GJ, of energy per ton of CO_2). As shown in Exhibit 2, DAC systems typically comprise three stages:

1. Air intake to bring dilute, atmospheric CO_2 into contact with a specialized carbon-capture material
2. Chemical capture of CO_2 using a high-pH liquid solvent or solid "sorbent" that captures CO_2 via an acid-base chemical reaction
3. Release of CO_2 from the capture material so it can be stored or used, and regeneration of the carbon-capturing material for future use

Exhibit 2

Typical Stages in a DAC System



Sources: Noah McQueen and National Academy of Sciences

Putting the energy demands into perspective, removing one gigaton of CO_2 with existing technologies would require 7–14 exajoules, or approximately 7%–13% of annual US primary energy consumption.

Today, the leaders in the field are Carbon Engineering, Climeworks, and Global Thermostat (Exhibit 3). Carbon Engineering uses a liquid solvent to capture CO_2, while Climeworks and Global Thermostat use a solid sorbent. Both Climeworks and Carbon Engineering have shown that DAC is possible at approximately the kiloton scale. However, the cost floor of the current technologies is about \$100–\$300 per ton based on the latest estimates (see Exhibit 3).

These approaches also require significant energy inputs (which includes burning natural gas in the Carbon Engineering approach). Putting the energy demands into perspective, removing one gigaton of CO_2 by these routes would require 7–14 exajoules, or approximately 7%–13% of annual US primary energy consumption. Further, it's important to consider the net cost of CO_2 removal; DAC technologies reliant on fossil fuel-based energy can emit 30%+ of the CO_2 that is removed.

Exhibit 3 Comparison of Leading DAC Approaches

	Liquid solvent (strong base)	Solid sorbent (weak base)
Example companies	Carbon Engineering	Climeworks
Sorbent regeneration (recycling) method	Temperature swing	Temperature swing under vacuum
Regeneration temperature	900°C	100°C (under vacuum)
Energy required	7–14 GJ/t CO_2	7–8 GJ/t CO_2
Current cost	Not publicly available (likely above \$500/t CO_2)	\$500–\$600/t CO_2
Company projected cost floor	\$100–\$230/t CO_2	\$100–\$300/t CO_2

Note: Global Thermostat is another solid sorbent startup at the pilot stage, but it has not made recent data publicly available.

Sources: Energy requirements and current costs from Noah McQueen, National Academy of Sciences, and "A Process for Capturing CO_2 from the Atmosphere," David Keith, 2018

Opportunities for Innovation

With only three companies having achieved pilot scale to date, and DAC technology developing rapidly, it is too early to predict which technologies or which companies will reach the scale needed to contribute meaningfully to global carbon removal. However, analysis of today's DAC landscape, as well as a consideration of technical limits and cost trends, points to several opportunities for advancement that can guide the market.

Exhibit 4 shows the capital expenditures (capex) and operational expenditures (opex) breakdown of DAC systems at a scale of 1 million tons of CO_2 removed per year. These represent a "middle of the road" set of cost improvement assumptions from scaling the current technologies, based on models provided by the National Academy of Sciences. NAS reports that the total energy consumption for a generic solid sorbent system will reach 4–6 GJ per ton of CO_2 at scale, compared with approximately 7 GJ per ton of CO_2 today. For the liquid solvent system using natural gas, approximately 30% process emissions elevates the net cost per ton of CO_2 removed. For the solid sorbent system, we assumed a $0.06 per kWh cost for electricity generated using renewable sources (e.g., solar, wind) without significant process emissions. Due to today's higher cost of renewable energy than natural gas, this pushes the energy cost per ton of the solid sorbent system over that of the liquid solvent system (despite requiring a lower temperature for regeneration).

Early investment can enable startups to pursue emerging opportunities for innovation, accelerating the technology toward maturity and potentially enabling gigaton-scale carbon removal when we need it.

A scale of 1 megaton (Mt) of carbon captured per year would represent an increase of two orders of magnitude over today's actual DAC capacity; these numbers will change with engineering realities. Nonetheless, with existing estimates and assumptions, current DAC technologies are headed toward costs of roughly net $230 per ton of CO_2 for the solid sorbent system and roughly net $300 per ton of CO_2 for the liquid solvent system. A key difference between the company projected costs and the net costs presented in Exhibit 4 is the adjustment for process emissions for the liquid solvent systems. Liquid solvent systems can be coupled with point source carbon capture to reduce process emissions. These costs do not include compression, transport, or sequestration.

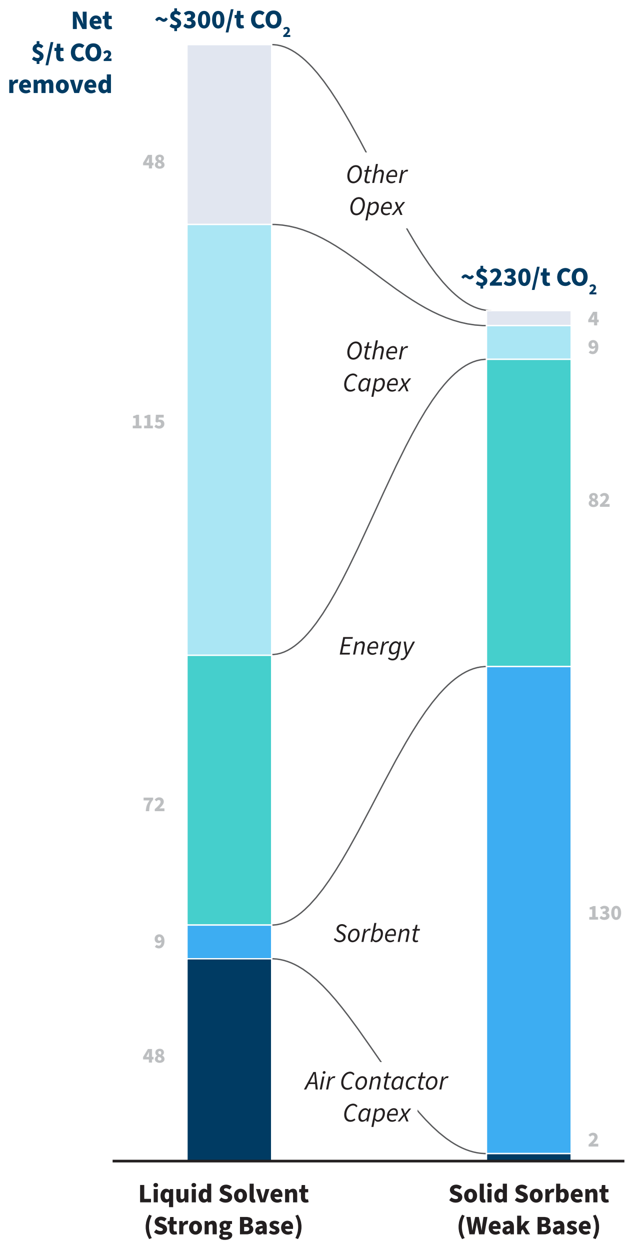
Importantly, the cost stack shows that there are opportunities to reduce costs across the three main cost drivers of DAC technology, which correspond to the three stages of DAC:

- The air contactor system and operation (primarily for liquid solvent DAC)
- Cost of the liquid solvent or solid sorbent material
- Energy use for the release of CO_2 and regeneration of the capture material

From a survey of the startup landscape, lab research, and experts, we find innovations emerging across all three major drivers of cost, beyond what is represented by the current leaders. Innovations in these

Exhibit 4

DAC Cost Breakdown at 1 Mt/Year Scale



Note: Liquid solvent assumptions: natural gas is used for the thermal energy sources with 30% process CO_2 emissions. Other capital expenses include the calciner, slaker, air separation unit, and other equipment associated with the liquid solvent system. Other operating expenses include labor and maintenance. All other capital and operating expenses are the midpoints of the range reported by NAS, with a 12% fixed charge factor to determine annualized capex. Renewable electricity is taken at $0.06/kWh and does not contribute to process emissions.

Solid sorbent assumptions: electricity is taken at $0.06/kWh generated from renewable sources and therefore does not contribute to process emissions. All other capital and operating expenses are the midpoints of the range reported by NAS, with a 12% fixed charge factor to determine annualized capex. The solid sorbent cost component was calculated using the base case values shown in the sensitivity analysis (Exhibit 6).

Source: National Academy of Sciences

areas could enable a steep drop in DAC cost. The US Department of Energy announced at COP26 its ambition to reach less than net $100 per ton of CO_2 by 2030, a step change from current costs. This is an ambitious but feasible goal, and with additional step-change innovations and learning effects, $50–$100 per ton of CO_2 may be possible. The US House Ways and Means Committee has considered a substantial increase in the Section 45Q tax credit for DAC, from below $50 per ton of CO_2 today up to $180 per ton of CO_2. Such an increase would signal bipartisan willingness to pay that price in a small-scale, nascent market to help stimulate the development of the DAC ecosystem and drive down costs.

At $50 per ton, the world could achieve 10 gigatons of annual CO_2 removal at a cost below $500 billion per year. While this is still a large sum, we believe that humankind will increasingly realize the value of solutions to the climate crisis and, in turn, justify substantial investments in carbon removal technologies. This also presents a $500 billion to $1 trillion market opportunity for companies that are able to provide high-quality carbon removal services.

At Third Derivative, we see a need for investment in DAC technology development and de-risking now. Hard technologies like DAC take years to decades to develop. Early investment can enable startups to pursue the emerging opportunities for innovation outlined here, accelerating the technology toward maturity and potentially enabling gigaton-scale carbon removal when we need it.

Opportunity: Reducing Air Contactor Cost

Given airborne CO_2 concentrations of about 400 ppm (0.04%), a system would need to contact about 1.8 million cubic meters of air to capture one ton of CO_2, assuming a 75% capture rate. That is about 1.7 times the volume of the Empire State Building. DAC systems typically use massive fans to blow these large volumes of air across the capture solvent or sorbent. CO_2 capture rates for these types of active air contactor systems that blow air over sorbent beds typically range from 60% to 75%.

For 1 Mt/year solid sorbent systems, the National Academy of Sciences reports the relatively low total cost for an air contactor of $13 million to $84 million ($1–$8 per ton of CO_2 removed). Liquid solvent systems, such as Carbon Engineering's technology, have 10% of the surface area of solid sorbent systems, requiring air contactor capital expenses in the hundreds of millions of dollars to ensure sufficient CO_2 uptake.

Over the past decade, Carbon Engineering has used computational modeling to optimize design and materials with its solvent, publishing results that suggest the cost of the air contactor step can drop as low as $60 per ton of CO_2. That figure marks a 90% reduction in cost from estimates made 10 years ago, when papers reported costs of $600–$1,000 per ton of CO_2 for the air contactor alone. The Carbon Engineering innovations include changing the orientation of the airflow, using low-cost plastic packing spheres, and optimizing the design of the capture rate. However, even with these innovations, Carbon Engineering's air contactor is projected to cost $200 million to $400 million for a 1 Mt/year plant ($30–$60 per ton of CO_2 removed), showing further innovation is needed.

Given airborne CO_2 concentrations of about 0.04%, a system would need to contact about 1.7 times the volume of the Empire State Building to capture 1 ton of CO_2.

DAC startups can follow this optimization example by developing computational models to assess the technoeconomic potential of their own systems and optimize the design of their sorbent beds. These optimizations and trade-offs will vary (e.g., higher CO_2 adsorption and energy costs) with the characteristics of individual sorbents.

Passive Air Contactors

In contrast to active air contactors, passive air contactors rely on wind and natural airflow to capture CO_2. Reducing the need for massive airflow systems with the energy requirements of their massive fans can substantially reduce the cost of DAC systems—with the trade-off of slowing the CO_2 adsorption process.

Based on the analysis in Exhibit 4, the active air contactor represents 25% of the overall cost for liquid solvent-based DAC. If it were possible to completely replace the active air contactor with a passive air contactor, that would represent a 25% savings.

Avoiding the capital expense of the active air contactor can lower the capital intensity of DAC systems. Such passive systems could, therefore, be well suited for more modular and distributed installations. However, distributed systems may not be ideal for capturing and sequestering carbon because sequestration usually occurs at carefully selected geological sites rather than at scattered locales.

Passive air contacting brings less CO_2 into contact with the capture material over a given time frame. This can lead to a slower capture rate, which can still be economically feasible if paired with a low-cost sorbent that keeps ongoing costs down. The most promising passive air contacting innovations find ways to accelerate the adsorption of the CO_2 in the absence of powerful airflow systems. Startups pursuing passive air contacting approaches to DAC include Heirloom, Carbon Collect, Infinitree, and Noya. Heirloom says it has accelerated its CO_2 adsorption cycle from two years to two weeks, possibly due to an optimization of its grinding process. Noya piggybacks on existing infrastructure to increase airflow by retrofitting cooling towers for DAC.

The tailored regeneration of sorbents could further lower the energy required to release CO_2.

Opportunity: New Sorbent and Regeneration Approaches

As shown in Exhibit 2, a DAC system captures CO_2 via an acid-base reaction with a high-pH (basic) sorbent. Advances in sorbent chemistries show promise for lowering sorbent costs and increasing CO_2 adsorption.

Among the main players in today's DAC landscape, Carbon Engineering uses a liquid, caustic solvent to capture CO_2, whereas Climeworks, Global Thermostat, and numerous new startups rely on a solid sorbent (Exhibit 5). Whether solid or liquid, DAC approaches typically regenerate the capture material with a temperature and/or pressure swing—applying large amounts of energy to release the captured CO_2 and prepare the capture material for reuse.

Liquid solvents require a stronger base to capture CO_2, which necessitates a correspondingly higher regeneration energy to release the captured carbon. Solid sorbents can offer lower regeneration energies and more modular forms, potentially lowering the capital expense of producing them. But they typically require a batch process for regeneration that takes them temporarily out of service, extending the overall time it takes to capture and store a given quantity of CO_2.

The "tailored regeneration" of sorbents is a novel area of innovation that could further lower the energy required to release CO_2. Rather than heating an entire chamber to release CO_2 from a sorbent, for example, a tailored approach would more precisely apply energy to target the location of the CO_2 in the sorbent material. Examples include microwave wavelengths tailored to specific binding sites in a sorbent, moisture swings or acid baths to release CO_2, and electrochemical approaches.

Exhibit 5 Characteristics of Sorbents and Solvents Currently in Use

	Class of material[1]	Regeneration	Advantages	Constraints	Example startups
Liquid solvent	Alkali and alkaline-earth hydroxides[2]	Temperature swing (900°C)	• Low cost (<$1/kg) • High CO_2 reactivity • Low volatility and degradation	• High energy/ temperature for regeneration • High water loss, better suited to humid climates	Carbon Engineering
Solid sorbent	Alkaline earth oxides[3]	Temperature swing (600°–1,200°C)	• Low-cost feedstock (<$1/kg)	• High energy/ temperature for regeneration • Batch process	Heirloom
	Amines[4]	Humidity swing or temperature and pressure swing (100°C)	• Lower-temperature regeneration	• Expensive sorbents (>$50/kg) • Short sorbent lifetimes due to degradation (0-1 years) • Better suited to dry climates	Climeworks, Global Thermostat, Hydrocell
	Zeolites[5,6]	Humidity swing or temperature and pressure swing (~100°–350°C)	• High capacity, adsorption, and selectivity for CO_2 • Low cost ($2/kg)[7]	• Limited ability to handle contaminants • Water can foul the reaction • Batch process	Carbon Capture, Innosepra
	Metal-organic frameworks (MOFs)	Humidity swing or temperature and pressure swing (~100°C)[8,9]	• Ultra-high surface area and capacity • Highly tunable	• Durability concerns • Batch process • Difficult to manufacture	Mosaic Materials
Electrochemical	Variety	Electrochemical swing	• Modular (plug-and-play) • 100% electric	• Expensive catalyst materials • Low faradaic efficiency	Mission Zero, RepAir, Holy Grail

Note: Numbers for MOFs and zeolites come from academic papers, whereas figures for amines, alkali carbonates, and hydroxides come from the companies.

[1] Noah McQueen

[2] David Keith

[3] "Ambient weathering of magnesium oxide for CO_2 removal from air," Noah McQueen et al., 2020

[4] "The Swiss company hoping to capture 1% of global CO_2 emissions by 2025," CarbonBrief, 2017

[5] "Direct Dry Air Capture of CO_2 Using VTSA with Faujasite Zeolites," Wilson et al., 2020

[6] *Bench Scale Development and Testing of a Novel Adsorption Process for Post-Combustion CO_2 Capture*, Jain et al., 2015

[7] "Sorbents for the Capture of CO_2 and Other Acid Gases: A Review," Halliday et al., 2021

[8] "A Pilot-Scale Demonstration of Mobile Direct Air Capture Using Metal-Organic Frameworks," Sadiq et al., 2020

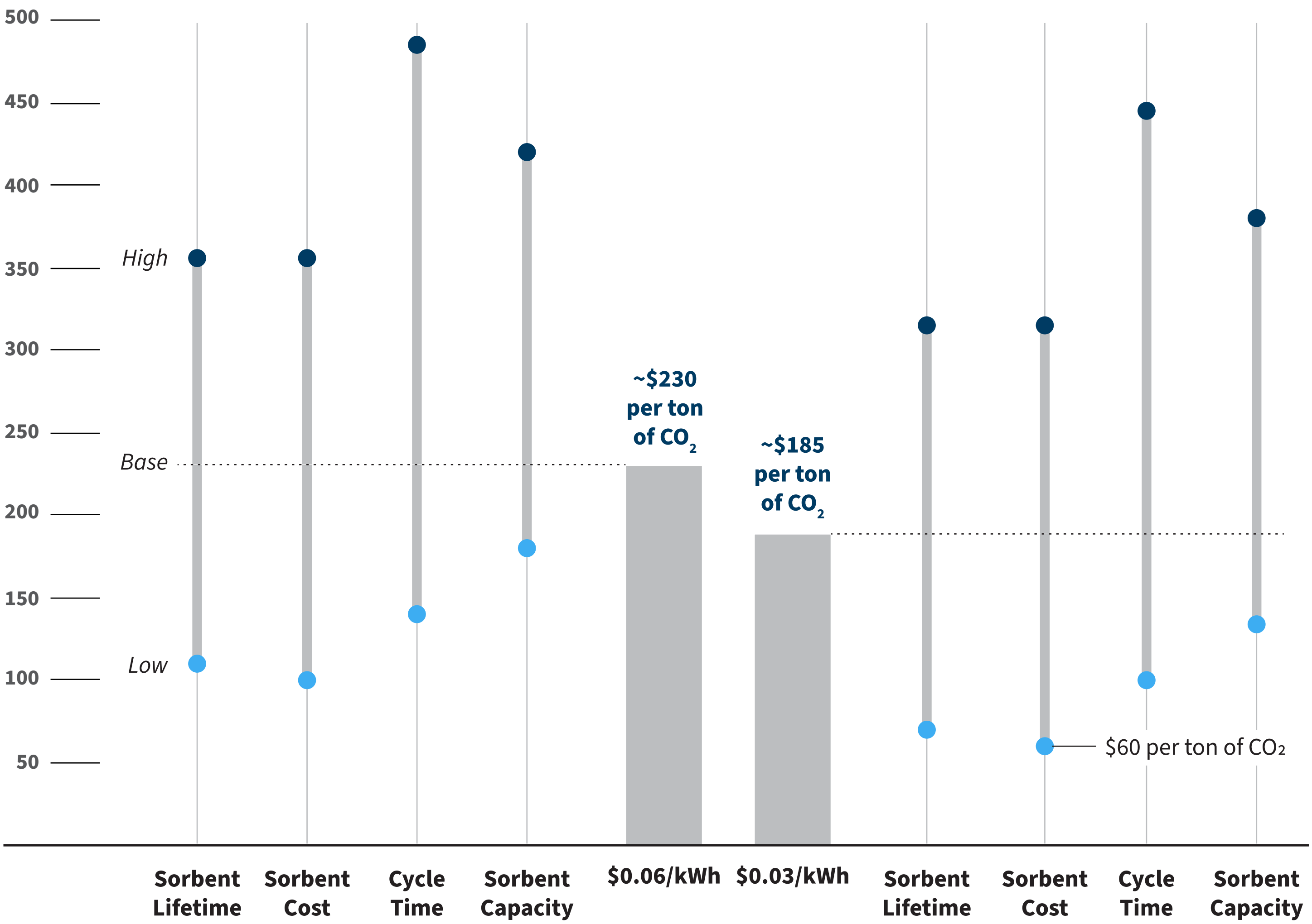
[9] "Flue-gas and direct-air capture of CO_2 by porous metal-organic materials," Madden et al., 2017

To quantify some of the innovation potential for solid sorbents, we looked at the impact of potential sorbent breakthroughs on the overall cost of CO_2 capture. Exhibit 6 shows that making the sorbent more durable (e.g., extending its lifetime to five years) or using sorbents with low upfront costs of less than $2/kg can lower the overall cost of CO_2 capture to nearly $100 per ton.

Pairing sorbent innovations with cheaper energy offers an even lower cost pathway for direct air capture. With a renewables cost of $0.03/kWh, coupled with advances in sorbent durability or cost, removing CO_2

Exhibit 6 Impact of Sorbent Breakthroughs on DAC Cost for Solid Sorbent System

Net cost of capture ($ per ton of CO_2)



Sorbent Lifetime
Low: 0.25, Base: 0.5, High: 5 yrs

Sorbent Cost
Low: $2, Base: $50, High: $100 per kg

Sorbent Capacity
Low: 0.5, Base: 1.25, High: 2 mol/kg

Cycle Time
Low: 10, Base: 30, High: 90 min

Note: The base case is calculated using the midpoint values for all characteristics, while the high and low ends are calculated using the high-end or low-end variable for that particular characteristic, along with the base case for each other characteristic. The high and low cases were typically calculated using the boundaries of the ranges reported by the National Academy of Sciences. Cycle time, sorbent cost, and capacity values were modified to incorporate frontier values from emerging startups. The total energy requirement is taken to be 5GJ/t CO_2 in line with the average value reported by NAS for a solar-powered solid sorbent system.

Sources: National Academy of Sciences, *Specification of the ECT Framework Methodologies for Direct Air Capture*, The Climate Disclosure Project, 2021, emerging startups.

from the atmosphere approaches $60/ton. Alternatively, positioning DAC systems near free sources of energy can eliminate the thermal energy part of the cost stack entirely. Climeworks currently uses low-grade excess heat from a municipal waste incinerator at one of its pilot plants at nearly no additional cost. Scaling eventually to gigaton per year removal will require detailed renewable energy sourcing and planning.

Electrochemical CO_2 Capture and Regeneration

At Third Derivative, we see a number of startups, including our portfolio company Mission Zero, leveraging electrochemistry in clever ways to lower the energy and cost required for CO_2 capture and regeneration. By harnessing clean electricity to drive chemical reactions, electrochemical approaches to DAC can achieve greater efficiencies and unlock novel system designs. Electrochemistry offers the potential to reduce the energy demands of direct air capture from 7+ gigajoules per ton of CO_2 today down to around 2 gigajoules per ton.

Electrochemistry is a promising pathway for DAC because units can be modular (and assembled in stacks like batteries or fuel cells) and 100% electric, without the need for high temperatures or fossil energy inputs. The designs of these systems are inspired by established technologies, such as fuel cells and electrodialysis, and can benefit from advances in electrochemical technologies such as hydrogen electrolysis and redox flow batteries.

However, electrochemistry approaches to DAC are in the early stages, and much work remains to be done to reach the potential of the technology. As shown in Exhibit 7, advances are needed in membrane cost, cell/stack design, durability, cost, and faradaic efficiency (the percentage of electricity converted into the desired electrochemical reaction).

Electrochemistry is a promising pathway for DAC because units can be modular and 100% electric without the need for high temperatures or fossil energy inputs.

For electrochemical cells, the main figures of merit in terms of regeneration energy are:

- **Faradaic efficiency:** the conversion efficiency of charge into the electrochemical system. Higher faradaic efficiencies require less input energy to produce a ton of CO_2.

- **Current density:** the amount of current flowing across the membrane in the system. Low current densities imply that large amounts of membrane (and large capital expenditures) are required to remove a ton of CO_2.

Today's approaches to electrochemical DAC are limited by low faradaic efficiency, low current density, overpotential (requiring surplus voltage needed to drive a chemical reaction), or all three. However, we see opportunities to overcome these limitations, some of which are actively being pursued by startups.

Membrane innovation is critical to enabling electrochemical DAC because membranes are the most expensive component of some electrochemical systems. This is an area where we are seeing exciting innovations from companies like Membrion and Versogen in Third Derivative's cohort.

Improved cell designs to eliminate parasitic reactions and improved electrode architecture to maximize surface area also can significantly reduce the cost relative to existing electrochemical systems.

One key challenge with a fuel cell–like design is that the CO_2 adsorption at the electrode is proportional to the output flux of the cell. Electrodes often are composed of expensive metals like platinum, so this can require an expensive cell to achieve sufficient CO_2 output. One promising approach to solve this challenge is to decouple the CO_2 adsorption step from the electrochemical CO_2 separation step. Electrodialysis, a mature technology for water purification, is one such design that decouples the CO_2 adsorption step at the electrode from the amount of membrane required. This could enable more cost-effective scaling.

Exhibit 7 Development Targets for Electrochemical DAC

	Membrane	Cell design/ engineering	Electrocatalysts	Projected by startups at scale	Example startups
Targets	Cost: <$10/t CO_2	Faradaic efficiency >50%	Earth-abundant catalysts (not iridium or platinum)	2 GJ/t CO_2 $50-$100/t CO_2	Mission Zero, RepAir, RedoxNRG, Holy Grail

Today's approaches to electrochemical DAC are limited by low faradaic efficiency, low current density, high overpotential, or all three.

Shaping the Defining Decade for DAC

With IPCC scenarios increasingly projecting the need to remove billions of tons of CO_2 annually by 2050, accelerating innovation in DAC is imperative if we are to close the gap on carbon removal technologies that we may need in our not-too-distant future. Even in the International Energy Agency's net-zero-by-2050 scenario, which calls for only 2.4 Gt/year of engineered carbon removal in 2050, we need to reach 85 Mt/year of DAC by 2030. We need to invest now to develop the necessary technologies and drive down the costs of carbon capture to approach this milestone.

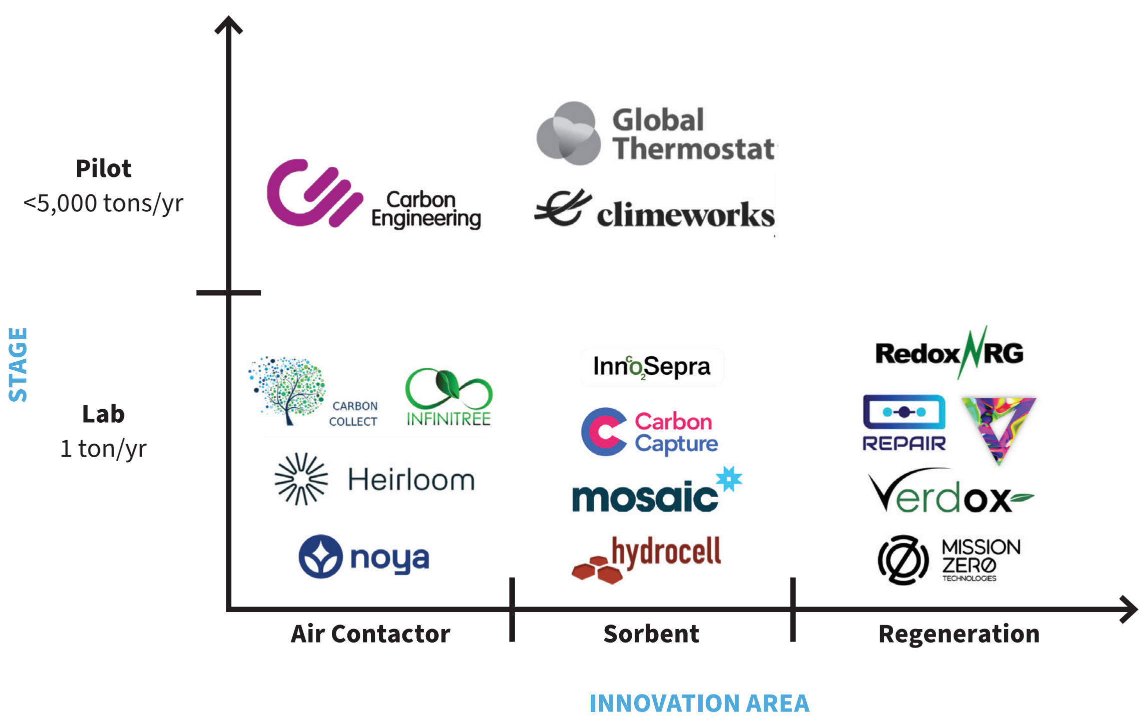
Importantly, the DAC market is rich with areas for investment and innovation. We see opportunities for innovation across the three main stages of DAC: in reducing the cost of air contacting, in developing new and more cost-effective sorbents, and in designing advanced regeneration approaches to release CO_2 for use or storage. Electrochemistry is one especially promising approach that can lower the energy and cost required for carbon capture and sorbent regeneration.

Fortunately, there are many exciting startups pursuing innovation around each of these opportunities for cost reduction and energy efficiency. Exhibit 8 shows some leading examples, but it is not a comprehensive depiction, and there are new entrants all the time.

Together, innovations in these technology areas could enable direct air capture to reach the cost target of \$50–\$100 per ton of CO_2 removed from the atmosphere. The faster the technology reaches this target—and the further costs fall past that point—the more insurance that direct air capture can provide against the perils of a warming world.

Exhibit 8

Select Companies Working on Core Innovations



THIRD DERIVATIVE

Third Derivative, in partnership with the Jeremy and Hannelore Grantham Environmental Trust, has launched First Gigaton Captured— a breakthrough initiative to find, fund, and scale the world's most promising carbon capture startups. Learn more on how to become involved at **https://third-derivative.org/firstgigaton**.

Dr. Eve Hanson, Sam Lefkofsky, Dr. Cyril Yee*, Direct Air Capture: Capitalizing on the Defining Decade for Technology Development,* RMI, 2021, **https://third-derivative.org/firstgigaton**.

All images are from iStock.com unless otherwise noted.

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