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Markets to Watch:
Carbon Removal Technologies

Executive Summary

One of the essential tools in limiting climate change in the future will be carbon dioxide removal (CDR)—that is, the removal of existing carbon dioxide (CO_2) from the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) projects that, by 2050, we'll need to be removing between 2 to 20 billion tons of CO_2 from the atmosphere per year.[1] On its own, carbon removal will not be sufficient to solve the climate crisis, but most experts believe that meeting climate targets cannot happen without carbon removal efforts, either.

Carbon removal methods include a range of approaches—from direct air capture (DAC) systems that draw air in with fans and remove CO_2 chemically, to strategies to enhance soil or ocean absorption of CO_2, and more. Many of these are not yet commercially viable, but the sector is getting a boost with advanced market commitments and offtake agreements from companies like Microsoft, Shopify, and Stripe, in addition to VC investment and incentive prizes like the $100 million XPRIZE for Carbon Removal. There will undoubtedly be unicorns in the carbon removal tech space. Who the winners will be—and, importantly, who the customers will be—for these solutions at scale is still evolving.

The Market

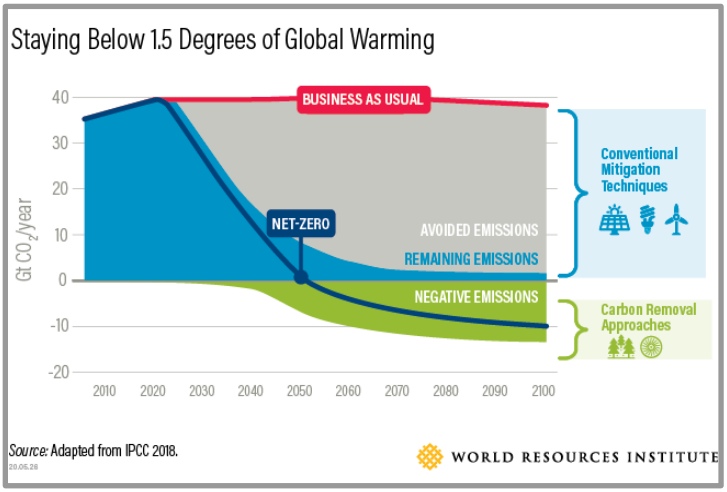
As businesses, investors, and governments are developing solutions to the problem of climate change, carbon dioxide removal (CDR)—taking existing carbon dioxide (CO_2) out of the atmosphere—will become a critical strategy in addition to mitigating (or slowing) the release of new CO_2. Because of this, CDR represents a significant market opportunity for investors and innovators, but it's still a nascent market.

Humans generate 36 billion tons of CO_2 annually.[2] In order to limit the increase in global warming to 1.5˚C, the Intergovernmental Panel on Climate Change (IPCC) projects that, by 2050, we'll need to be removing between 2 to 20 billion tons of CO_2 from the atmosphere per year.[3] On its own, carbon removal will not be sufficient to solve the climate crisis, but most experts believe that meeting climate targets cannot happen without carbon removal efforts. Besides removing "legacy" CO_2 which has already been emitted to the atmosphere, carbon removal is a strategy that will be necessary in some industries like steel and cement production (sometimes referred to as "hard to abate" sectors) that will rely on some method of removing CO_2 emitted through operations. The latest IPCC report states: "The deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved."[4]

Market size

Carbon removal technologies (also sometimes called "negative emissions technologies") face scientific, technological, business model, and market hurdles. Extracting CO_2 from the atmosphere mechanically is technologically challenging, energy-intensive, and expensive, while available biological solutions (such as reforestation) face challenges in measurement, monetization, and scaling. Many carbon removal technologies are early stage, and therefore difficult to assess in terms of market potential, but some experts believe the total addressable market ultimately may be on the order of $1 trillion per year, given the magnitude of climate crisis.[5]

Despite the lack of clarity in market size, VCs are betting big on carbon removal technologies because they believe that future policy interventions (like a carbon tax or mandatory cap-and-trade carbon market) or direct federal investment in carbon removal could rapidly create a market for these technologies. In 2021, 183 investors poured money into



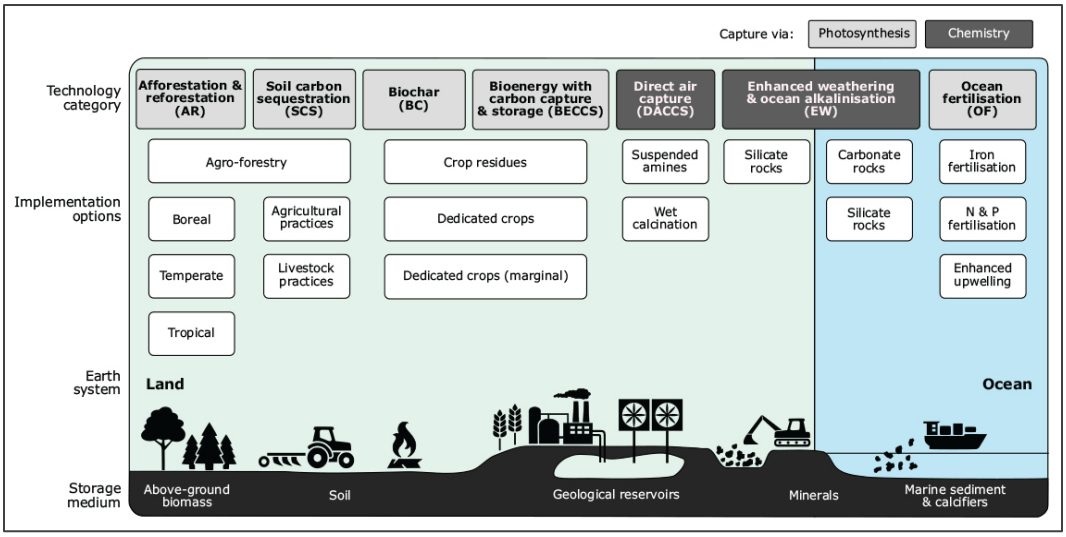
Source: World Resources Institute, https://www.wri.org/initiatives/carbon-removal

Lead Authors: Katie Kross, MBA, Managing Director, Center for Energy, Development, and the Global Environment (EDGE), Duke University and Graham Sinclair, MBA, Senior Responsible Investment Strategist, Parametric.

carbon tech startups, according to Climate Tech VC.[6] In early 2022, VC firm Lowercarbon Capital launched a $350 million fund dedicated to carbon removal investments.[7]

Methods

The primary objectives in carbon removal involve capturing CO_2 from the atmosphere, and either permanently sequestering it or using it as a product of value ("carbon-to-value" or "circular carbon"). In the following paragraphs, we summarize the most commonly pursued removal methods.



Source: Minx et al, "Negative emissions—Part 1: Research landscape and synthesis," 2018. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9b

Nature-based solutions. Trees, soils, rocks, and other natural systems including oceans already remove CO_2 from the atmosphere—they just can't remove it at a rate that matches humanity's current output. Not all natural carbon removal is created equal. For instance, pound for pound, mangroves can sequester more than four times more carbon than rainforests.[8] Nature-based approaches to carbon removal focus on expanding natural systems (for instance, planting trees, restoring forests) and/or enhancing the effectiveness of natural systems (for instance, adding silicate rock dust to soils in agricultural lands to boost their CO_2-absorbing power).[9]

Nature-based solutions are the most efficient and (generally) most cost-effective carbon removal strategies and are the most commonly used strategies for generating carbon credits for purchase today. But large-scale uptake faces complications including competition with other land uses (e.g., agriculture uses, timber), impermanence (e.g., susceptibility to damage from wildfires and other natural disasters), difficulty in measuring new/"additive" CO_2 removal, and lack of sufficient available land for projects. As the World Resources Institute points out, "natural carbon removal alone will likely not be sufficient to reach net-zero by 2050, or to address legacy emissions."[10]

Direct air capture (DAC) or direct air capture with carbon sequestration (DACCS). DAC systems are mechanical systems that pull air through a system (typically using giant fans) to capture CO_2 as it comes into contact with a chemical sorbent or solvent.[11] Once the CO_2 is captured, it can be pressurized for transport, converted into useful products, or injected into an underground geological formation for permanent storage ("sequestration"). DAC is promising in particular because the land area required for carbon removal is much less than that of nature-based solutions. However, these technologies need to come down the cost curve. Today, the costs for carbon removal with DAC are estimated at $250-600 per ton of carbon removed (versus $50 per ton for reforestation projects).[12]

Ocean-based carbon removal. The world's oceans absorb about 9 billion tons of CO_2 every year.[13] A variety of methods may be used to accelerate or enhance the ocean's rate of carbon removal. These strategies range from seaweed cultivation and ocean fertilization to direct capture of CO_2 from seawater using electrochemical methods. "Blue carbon" projects typically include investments in coastal ecosystem conservation and restoration.

Bio-energy with carbon capture and storage (BECCS). BECCS is a complicated solution that involves using biomass for energy, capturing its emissions before they are released back to the atmosphere, and then storing that captured CO_2. Because the biomass draws carbon from the atmosphere as it grows, BECCS can be considered a negative emissions technology.[14]

Enhanced mineralization. Certain minerals can also absorb CO_2. Enhanced mineralization strategies, which seek to speed up this process, include, for instance grinding basalt into powder and spreading the powder over soils, where it reacts with CO_2 in the air to form stable carbonate minerals.[15]

In reading about climate tech, another term you might hear is *"carbon capture, utilization, and storage (CCUS)"* or *"point source carbon capture."* This typically refers to capturing CO_2 at the point of emission before it is released into the atmosphere (for instance, at a refinery smokestack) and using and/or sequestering the carbon. This is an important strategy for *mitigation* (e.g., putting less CO_2 into the atmosphere), but is distinct from carbon removal, which aims to remove existing CO_2 from the atmosphere.

Trends & Uncertainties

With companies taking increasingly bold action on climate, as well as potential policy developments spurring more climate regulation, the landscape of carbon removal is shifting quickly. Breakthroughs in technology and/or policy incentives could change the market overnight, so following industry trends is essential.

Carbon markets & policy incentives

Currently, two types of carbon markets exist globally: compliance carbon markets and voluntary carbon markets, but participation in these is still relatively limited. Many experts agree that strong U.S. federal action to "put a price on carbon" through the creation of a carbon tax or a regulated cap-and-trade carbon market would have the greatest impact on the viability of carbon removal investments. Without mandatory participation by the world's largest carbon emitters, these markets tend to underprice carbon by orders of magnitude (see: for instance, Platts Carbon Prices pricing carbon credits at $12.70 per metric ton in Nov. 2021). Voluntary markets for corporate carbon removal purchases are smaller, but growing. Monitoring, reporting and verification (MRV) activities will also be critical drivers to encouraging demand in this type of market.

Direct government investment

The U.S. Infrastructure Investment and Jobs Act that passed in Nov. 2021 included some provisions for direct government investment in carbon removal, including $3.5 billion to lead the development of four regional DAC hubs, each with the capacity to capture 1 million metric tons of CO_2 per year.[16] Additional future legislation could further invest government dollars in carbon removal projects and infrastructure, spurring the market for these technologies.

Corporate investment and advanced market commitments

With consumer awareness and activist pressure for climate action increasing, more than 2,000 companies have set climate targets through the Science Based Targets initiative (SBTi). For many of these companies, meeting targets will require not only reducing their emissions (mitigation) but also purchasing carbon credits. Some companies are buying carbon credits today at high prices in order to bolster the nascent carbon removal market; for instance, Swiss Re committed in 2021 to a 10-year, $10 million purchase agreement for carbon offsets with Climeworks. In April 2022, a consortium called Frontier, which includes Alphabet, Meta, McKinsey, Shopify, and Stripe announced it would purchase $925 million in carbon removal over eight years.[17] This "advanced market commitment," along with the possible addition of offtake agreements for carbon removal projects, will be an important market driver.

Example Companies with Carbon Removal Targets

Intuit	Ikea
Interface	Microsoft
Shopify	Stripe
Drax Group Plc	Linkedin
Mitsui & Co.	Walmart
Cisco	FedEx
Volkswagen	Viridor
Ralph Lauren	
Royal Dutch Shell	
Boston Consulting Group	

Source: Circular Carbon Network Corporate Index, 2022.

R&D funding

New investment in carbon removal R&D from both government and private sources could advance technologies quickly. For instance, in 2021, Elon Musk sponsored a $100 million XPRIZE to incentivize the development of technologies that demonstrate CO_2 removal at the scale of at least 1,000 tons per year. The U.S. DOE has also been making funding available to scale up DAC technologies combined with carbon storage.

Breakthrough innovation

As investment in R&D grows, it is likely we will see technology breakthroughs in the next decade that will reshape the market. For instance, Y Combinator is investing in frontier carbon removal technologies like desert flooding and cell-free enzymatic CO_2 fixing systems.[18] Where these future breakthroughs occur and which technologies will be the biggest winners remains to be seen.

Business Opportunities

Though many are still in early stage development, carbon removal technologies represent significant future business opportunities for entrepreneurs and investors.

Direct air capture (DAC) technologies

In Sept. 2021, Climeworks started up its "Orca" project—the largest operating DAC facility at the time—to capture 4,000 tons of CO_2 annually. The project was built in Iceland to take advantage of geothermal energy to power the process as well as favorable geology for storing carbon underground. 1PointFive has announced plans together to build a larger system, DAC 1, with an anticipated capture capacity of one million tons of CO_2 each year when fully operational (expected to come online in 2024). Global Thermostat and others are also working on bringing DAC to scale.

CO_2 pipelines & transportation infrastructure

Scaling up DAC carbon removal and effectively putting captured CO_2 into use presents its own infrastructure opportunity; pipelines, trucks, and boats will be needed to move CO_2. For instance, Summit Carbon Solutions has proposed a $2 billion project in Iowa to collect captured CO_2 and inject it underground.[19]

Carbon sequestration technologies

In Iceland, startup Carbfix is partnering with DAC company Climeworks to pipe captured CO_2 underground for permanent sequestration.[20] Similarly, the startup 44.01, based in Oman, is sequestering carbon by accelerating reactions with the mineral peridotite.[21] Canadian startup CarbonCure Technologies has raised $12 million for its technology to trap CO_2 in concrete.

Mineralization technologies
Heirloom Carbon Technologies believes it can remove 1 billion tons of CO_2 from the atmosphere by 2035 for $50/ton at commercial scale using enhanced mineralization.[22]

Afforestation and reforestation
Microsoft said in early 2022 that it had contracts in place for 2.5 million metric tons of carbon removal, mainly from reforestation,[23] and Salesforce has set a goal of planting 100 billion trees by 2030.[24] The U.S. Infrastructure Investments and Jobs Act includes $400 million over five years for mine forestation and Tribal reforestation efforts.[25] These initiatives are creating opportunities for startups like DroneSeed and Land Life Company which are planting new forests using drones, as well as forest project developers like Finite Carbon and companies like Pachama that use remote sensing and monitoring to verify conservation projects.

Regenerative agriculture and soil MRV
"Regenerative agriculture" practices are farming techniques that leave more carbon in the soil—which if properly managed and quantified—can be sold as carbon credits that benefit farmers. Indigo Ag has raised $1.2 billion to advance regenerative ag practices, quantify, and create a market for the credits. In Europe, Soil Capital has a similar model. Larger companies like ADM are also making regenerative ag investments,[26] while other companies are finding opportunities in providing soil monitoring, reporting, and verification (MRV) services.[27]

Soil carbon and biochar
Another strategy to bolster the carbon-absorbing potential of soil is to add biochar (defined as "charcoal created when biomass from crop residues, grass, trees, or other plants is combusted at temperatures of 300–600˚C without oxygen"[28]) . Pacific Biochar and Carboculture are two leaders in this space.

Ocean carbon removal
Conserving and/or restoring coastal wetlands and mangroves creates opportunities for developers like France's BlueLeaf Conservation. Another startup, Project Vesta, is using olivine sand to accelerate ocean carbon sequestration using rock weathering.

Carbon offset marketplaces
To facilitate the carbon market, companies such as Nori, NCX, and Supercritical have built marketplaces to sell carbon credits. Puro.earth has created a marketplace exclusively for carbon removal, called CO_2 Removal Certificates (CORCs).

"Carbon-to-value" or "circular carbon" products
CO_2 can be transformed into a wide range of products—from fuels and fertilizers to plastics, consumer products, and even apparel (like Zara's dresses made from recycled carbon). In 2022, carbon tech startup Lanzatech went public in a merger with a special-purpose acquisition company valued at $2.2 billion.[29] In a recent report, Carbon180 estimates that the U.S. total available market (TAM) for carbon tech products at $1.07 trillion per year, and global TAM at $5.91 trillion per year.[30] Twelve, Kiverdi, and Made of Air are other startups working on carbon tech while accelerators like the Carbon to Value Initiative and programs like the Circular Carbon Network are spurring market development.

Frontier technologies
Other technologies will emerge with new potential for carbon removal, and startups that can pull carbon out of the atmosphere cost-effectively will find buyers in the future.

Takeaways for MBAs

1. Though technological and market hurdles exist, carbon removal is poised to be a trillion-dollar market, driven by the need to remove between 2 to 20 billion tons of CO_2 from the atmosphere per year to limit climate change.
2. Carbon removal at that scale faces several obstacles. With billions of dollars going into R&D and venture capital, it is expected that technologies will come down the cost curve and improve in effectiveness and viability. Innovation breakthroughs will also emerge.
3. The biggest challenge to market growth is the lack of customers with a willingness to pay for carbon removal. Policy interventions, like a carbon tax or mandated carbon market, would likely increase market interest and demand.

Further Reading

Carbon Negative by 2030: CO_2 removal options for an early corporate buyer, Lawrence Livermore National Lab, 2022.

Circular Carbon Network 2021 Report

Technological Carbon Removal in the United States, World Resources Institute, 2018.

Carbon Dioxide Removal Primer, 2021.

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