Scaling Carbon Dioxide Removal (CDR): Beyond Carbon Markets

by

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Masters project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of
Duke University

Executive Summary

Carbon dioxide removal (CDR) refers to processes that remove and durably store carbon dioxide (CO_2) from the atmosphere. Due to limited emissions abatement to date, the Intergovernmental Panel on Climate Change (IPCC) has found that capping global warming to 1.5°C with limited to no overshoot will require some degree of CDR. Exactly how much CDR will be required is correlated to the speed and degree to which emissions are abated, however, the need for billions of tons of CDR by 2050 is the consensus view of major climate-science institutions. To stay below 1.5°C of warming, average IPCC modeling estimates between 10.8-13.4 $GtCO_2$ must be removed via CDR annually by 2050.

CDR operates primarily as a waste management industry. One challenge for achieving CDR at scale is that most markets around the world lack mandates for managing CO_2 waste. As such, expected demand and deployment of CDR is currently on track to fall vastly short of required levels. In 2023, total CDR deployment was only 2 $GtCO_2$ and almost entirely generated from country-level land management activities. A small amount of CDR deployment is driven by private sector demand for carbon credits, but only 0.007 $GtCO_2$ have been sold to date. By 2050, potential combined growth in both public and private sector CDR demand may only reach 3.8 $GtCO_2$/y. This represents only 30% of required deployment levels to stay below 1.5°C of warming according to the low end of IPCC modeling, leaving a gap of at least 7 $GtCO_2$/y.

Given demand for CDR as a waste management product is insufficient, this research sought to characterize the potential for CDR demand from products that offer value beyond waste management. As such, this research explored four CDR approaches that generate one or more CDR-based products in addition to a carbon credit including: 1) bioenergy with carbon capture and storage (BECCS), which generates either electricity or fuel; 2) mineralized concrete, which provides building material products; 3) biochar, which produces a charcoal like substance primarily used in agriculture; and 4) enhanced rock weathering (ERW), a mineralization processes that could provide various services to agricultural markets.

This research found that none of the four CDR-based products can currently compete with substitute products on costs alone, but most are able to compete with a "green premium," or a customer's willingness-to-pay (WTP) for products with a low carbon footprint. Even with green premiums, however, suppliers of CDR-based products are still selling carbon credits to finance projects. While it does not free suppliers from reliance on carbon credit revenue, selling CDR-based products was observed to provide increased pricing flexibility and revenue generation, factors that could help suppliers scale more quickly. Additionally, some CDR-based products have the potential to replace or reduce the use of carbon-intensive products while also directly removing CO_2 from the atmosphere. As such, deployment of CDR-based products that result in the avoidance of carbon emissions via product substitution would provide more climate value than CDR approaches that only generate a carbon credit.

It is the conclusion of this research that until CDR-based products can compete with substitute products without the support of revenue from carbon credits, they are unlikely to represent a significant new demand center for deployment of CDR. This paradigm is likely to evolve, however, as technology costs come down, WTP for low carbon alternative products increases, and the policy landscape shifts to incentivize carbon removal.

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Objective and Methodology

The objectives of this research were to identify carbon dioxide removal (CDR) approaches with associated products beyond carbon credits, referred to as "CDR-based products," and explore whether they have the potential to be a significant additional demand center for CDR.

This research was conducted via an extensive literature review of CDR, interviews with experts buying and selling CDR-based products, and original analysis. Research on current market conditions utilized a database of CDR credit transactions from 2019-2024 collected by CDR.fyi, a non-profit with a mission to accelerate deployment of CDR worldwide.[1]

Introduction to Carbon Dioxide Removal (CDR)

The Role of CDR

CDR refers to human activities that remove and durably store CO2 from the atmosphere. Due to limited emissions abatement to date, the Intergovernmental Panel on Climate Change (IPCC) has found that capping global warming to 1.5°C with limited to no overshoot will require some degree of CDR. Exactly how much CDR will be required will depend on the speed and degree to which emissions are abated, however, the need for billions of tons of CDR by 2050 is the consensus view of major climate-science focused groups including the IPCC, National Academies of Sciences, Engineering, and Medicine (NAS), and the International Energy Agency (IEA).[2] To stay below 1.5°C of warming, IPCC modeling estimates between 10.8-13.4 GtCO2/y of CDR will be required by 2050 and 17.6-27.0 GtCO2/y by 2100.[3]

CDR cannot take the place of required emissions reductions, but does serve three critical functions in climate regulation:

1. Reducing net emissions during the transition to becoming net zero.
2. Counteracting residual emissions from industries that are hard-to-abate, to fully achieve net zero annual emissions.[i]
3. Removing historical emissions once net zero annual emissions have been achieved, to counteract any overshoot that may have occurred.[4]

It is important to distinguish CDR from projects that avoid greenhouse gas (GHG) emissions and may generate associated carbon credits. To qualify as CDR, a project must remove carbon from the atmosphere, rather than avoid or capture emissions from a point source of emissions. A CDR project must also be in addition to passive or existing carbon removal processes, meaning the associated carbon would not have been removed from the atmosphere without the involvement of intentional human activity. CDR must also result in durable storage, which should be at least over 100 years of storage, but ideally providing 1000+ years of storage with minimal risk of reversal.

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[i] Hard to abate industries may include those with high thermal heat requirements, associated process emissions not related to fuel use, or other fields with technical barriers to decarbonization (e.g. cement, steel, aviation).

CDR Pathways

Existing CDR pathways can be categorized into three types based on primary inputs: biogenic, geochemical, and synthetic.[5] Within these pathways, there are many various approaches, each with varying costs, durability of storage, and risk of reversal.

1) Biogenic CDR leverages naturally occurring biogenic processes to capture carbon, the most common being photosynthesis. The scale of this pathway is often bound by available supplies of sustainable biomass. Today's most conventional forms of CDR are biogenic nature-based solutions, such as afforestation, reforestation, or improved land management.
2) Geochemical CDR leverages naturally occurring geochemical reactions that convert CO2 from the atmosphere into solid carbonate minerals or dissolved bicarbonates. Carbon converted to minerals offers some of the most permanent storage durability of CDR techniques currently available (1000+ years). Geochemical approaches are bound by availability of alkaline materials, which are key inputs to mineralization reactions.
3) Synthetic CDR approaches require energy inputs to directly separate CO2 from the air, or to alter water chemistry such that CO2 is indirectly absorbed from the air. Synthetic pathways are likely to be bound by availability of low carbon energy. Direct air capture (DAC) is a common synthetic CDR approach.

The CDR Demand Gap

Conventional biogenic CDR from country-level land management activities represents almost all the 2 GtCO2 removed in 2023.[ii] This figure comes from analysis of government greenhouse gas (GHG) accounting submissions to the United Nations Framework Convention on Climate Change (UNFCC). Based on long-term strategies reported to the UNFCC, country-level CDR via managed lands is expected to increase to 2.9 GtCO2/y by 2050.[6]

An extremely small amount of CDR has also been deployed via a voluntary carbon market (VCM) for CDR credits that emerged in 2019, driven by private sector buyers who recognized the need for CDR and were willing to pay high prices to help catalyze the market. In the VCM, suppliers of CDR generate a financial instrument, which will be referred to here as a CDR credit, for every ton of CO2 they remove. In exchange for purchasing CDR credits, a buyer gets the right to claim ownership of the removed CO2 and reduce its own carbon footprint by the amount of CO2 associated with the CDR credits purchased. Total tons of CDR credits sold in this market from 2019-April 2024 are only .007 GtCO2, and while VCM demand is expected to see strong growth over the next decade, even outstripping supply in the near term, it is only estimated to reach 0.08-0.87 GtCO2 by 2040.[7]

Combining estimated country-level CDR in 2050 (2.9 GtCO2) with the upper end estimate of 2040 carbon market demand as a stand in for a moderate demand scenario in 2050 (0.87 GtCO2),

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[ii] The often-highlighted flaw of CDR from managed lands is its limited storage durability and high risk of reversal (e.g. land management changes, forest fire, etc.).

total demand for CDR in 2050 may be approximately 3.8 $GtCO_2$/y.[iii] This represents only 30% of CDR required by 2050 to stay below 1.5°C of warming according to IPCC modeling, leaving the world with a demand gap of at least 7 $GtCO_2$/y. CDR is a waste management product operating in markets where there is most often no requirement to manage CO_2 waste. As such, a lack of demand for CDR compared to required levels of deployment to stay below 1.5°C is unsurprising, yet still an incredible challenge for achieving climate goals. (See Figure 1.)

CDR-based Products Beyond Carbon Credits

Given demand for CDR as a waste management product is insufficient, this research sought to characterize the potential for CDR demand via products that offer value beyond carbon credits. This research explored four CDR approaches that generate one or more CDR-based products, which refers to any product or service that is not a CDR credit. These approaches include: 1) bioenergy with carbon capture and storage (BECCS), which generates either electricity or fuel; 2) mineralized concrete, which provides products and services to building material markets; 3) biochar, which produces a charcoal like substance primarily used in agriculture; and 4) enhanced rock weathering (ERW), a mineralization processes that could provide various services to agricultural markets. While there are products beyond these four that utilize captured or stabilized carbon in products, many do not result in a net reduction of atmospheric CO_2 with permanent storage, which is required to classify as CDR.[iv] Other emerging CDR approaches may result in CDR-based products but were not studied in detail for this research. (See Table 1.)

Bioenergy with Carbon Capture and Storage (BECCS)

Electricity from BECCS is generated through the combustion or gasification of biomass, which generates steam that turns a turbine and produces electricity. Fuel from BECCS is generated through the fermentation of biomass, which produces bioethanol. Both processes of electricity and fuel generation result in associated CO_2 emissions that must be captured. To qualify as CDR, BECCS projects must use sustainably sourced biomass, have accurate accounting of life cycle emissions, and permanent storage of captured carbon. While there are various potential options for carbon storage, the most common is geologic storage, where CO_2 is injected in underground formations where it is expected to remain for 1000+ years with minimal risk of reversal. For both BECCS bioethanol and electricity facilities, capturing CO_2 is an additional cost to production, ensuring products cannot compete in the market on cost, and are likely unfinanceable without some combination of government incentives, such as direct energy contracts for differences (CFD) or tax credits, and revenue from CDR credits.

[iii] While not ideal, the upper end of 2040 estimates are used for potential carbon market demand in 2050, which was not included in the BCG modeling referenced in this research. This would be a pattern consistent with BCG's modeling of 2030 to 2040 demand, where the upper end of 2030 estimated demand (200 $MtCO_2$) falls between the estimated low (80 $MtCO_2$) and moderate (230 $MtCO_2$) demand estimates for 2040. BCG estimates include growth in voluntary markets, compliance markets, and direct government procurement.

[iv] Examples of products that did not qualify as CDR include synfuels, chemicals, and oil produced via enhanced oil recovery (EOR). Stabilized biomass in the form of building materials (e.g., mass timber) was initially identified as a CDR-based product, however, due to a lack of clarity on durability of CO_2 storage (e.g., end of product life treatment) and lack of CDR carbon credit transactions for related products, this category was not studied in detail.

For example, 2021 analysis estimated the unsubsidized levelized cost of energy (LCOE) for BECCS via pulverized biomass are as high as $168/MWh.[8] In comparison, utility scale solar PV had an unsubsidized LCOE between $24/MWh- $96/MWh in 2023.[9] Unlike variable renewable generation, however, a BECCS plant can provide dispatchable zero carbon power.

Carbon capture and storage (CSS) technology installed on bioethanol plants is the most mature BECCS technology. It is also one of the lowest cost BECCS applications due to the high concentration of its process CO2 emissions. Currently 90% of carbon captured from biomass sources is from bioethanol facilities. BECCS bioethanol plants also tend to have shorter lead times than power facilities due to less capital-intensive infrastructure requirements.[10] BECCS via bioethanol also benefits from existing regulatory paradigms, such as the Renewable Fuel Standard in the United States, which incentivizes bioethanol production to support renewable fuels.

Given current trends, experts predict a significant shortage of sustainable biomass by 2050. The top four priority applications for biomass (i.e. wood materials, pulp and paper, plastic feedstock, and aviation) have an estimated demand of 65 EJ/y. in 2050, while estimated available sustainable supply is only 40-60 EJ/y. Modeling suggests sustainable supplies could shift up to 120 EJ/y., however, this outcome is dependent on the release of agricultural land due to a dramatic reduction of animal meat consumption.[11] As such, it is likely BECCS, in addition to many biogenic pathways, will face significant headwinds to scale due to raw material sourcing.

Mineralized Concrete

Suppliers of carbon negative concrete have developed processes that speed up and/or enhance naturally occurring geochemical reactions that result in the rapid mineralization of atmospheric CO2 into concrete. Mineralization is often induced by exposing concrete materials to high concentrations of CO2 gas under specific conditions during the production process or the recycling of demolished concrete. Some suppliers are also introducing non-traditional and sometimes proprietary materials into the production of cement or aggregates that accelerate the mineralization process without the use of high concentrations of CO2 gas. (See Table 2.)

For suppliers exposing concrete to high concentrations of CO2 to induce mineralization, the source of CO2 for application must be considered. To qualify as CDR, CO2 must be directly removed from the atmosphere, rather than the result of an avoided emissions project (e.g., CCS on a fossil fuel power plant). As such, the two primary sources of qualifying CO2 for concrete mineralization are DAC and biogenic CO2 from sustainable biomass (this is essentially a BECCS project, but instead of sequestering CO2 geologically, it is sequestered in concrete). While mineralized concrete utilizes a geochemical process, a partial dependence on a supply of biogenic CO2 exposes it to some of the same risk of sustainable biomass supply shortages as biogenic CDR approaches such as BECCS and biochar.

Concrete is a mixture of cement, water, and aggregates that represents approximately 8% of global emissions. While representing only 10% of concrete by mass, cement accounts for most emissions associated with concrete. Fuel used to power kilns that heat limestone in a process required for cement production represent 40% of cement-related emissions. The other 60% of emissions are considered process emissions, as they are the by-product of the chemical reaction that occurs when limestone is heated in the kiln. While shifting to zero carbon fuels or electricity can reduce the 40% of emissions associated with energy use, the remaining 60% of process emissions make cement a particularly hard industry to decarbonize.

This dynamic has made CDR via concrete mineralization a particularly attractive option for real estate developers and concrete manufacturers facing pressure to decarbonize. In 2023, concrete CDR suppliers received $110 million in early-stage funding, the most invested in any CDR approach except DAC.[12] One risk to mineralized concrete providers are cheaper alternatives to decarbonize concrete production. Presently, expensive carbon capture units are required to prevent cement process emissions from entering the atmosphere, however, emerging technology developed by Sublime Systems redesigns concrete production and promises to deliver extremely low to zero carbon emissions without the need for carbon capture units.[13] If this technology is successful and economically viable, it is likely to be prioritized over mineralized concrete approaches.

Biochar

Biochar is a charcoal like substance created through the thermal decomposition of sustainable biomass in a low oxygen environment, a process called pyrolysis. This process locks up carbon in the biomass, preventing the release of CO2 that would have immediately occurred from natural decomposition. While the exact duration of CO2 storage in biochar is an active topic of scientific study, it is the consensus view that storage durations are at least 100 years, qualifying it as a durable CDR method. Duration variance can depend on a variety of factors, including the temperature of both the pyrolysis process and the soil type biochar is applied too. Low temperatures of pyrolysis and high temperatures of soil have the highest rates of carbon storage loss.[14]

The primary use of biochar is as an agricultural soil amendment, however, it also has potential applications in animal feed, fertilizer, and construction markets. These markets range in maturity and customer WTP for biochar products. When comparing potential revenues from biochar on a dollar per ton of CO2 sequestered basis, carbon credits are estimated to provide between $100-$200/tCO2 compared to $100-$500/tCO2 from fertilizer and soil amendment markets. While early in market maturity, biochar revenue from animal feed applications may be $1000/tCO2 or more and applications as a filler for construction materials (e.g., asphalt, concrete) up to $100/tCO2.[15] The production of biochar also results in the release of energy, which is often captured and utilized in energy products. In some circumstances, biochar projects may be economical without the sale of carbon credits. As such, the additionally of projects should be critically considered when verifying projects for carbon credits.

Biochar can be generated in units with a range of technological sophistication, both at a small scale directly on a farmer's property, or at a large-scale via processing plants. Common feedstocks for biochar include forestry and agriculture residues, waste biomass, and manure. While there are biochar projects on almost every continent, most registered production is occurring in North America and Europe.[16]

Demand for biochar carbon credits has doubled in the last two years and some modeling suggests demand could increase 20-fold over the next ten years.[17] In addition to its carbon removal properties, demand for biochar is also driven by its agricultural benefits to address a global trend of increasing soil degradation. Meta-analysis studies of biochar's effect on crop yields shows significant benefits but also large variation, with an increase of between 5-51%. The greatest benefits to crop yields are seen on arid soils.[18] Biochar also reduces fertilizer use by 10-30% and increases nutrient and water retention of soils by up to 15%.[19]

Despite increasing demand, biochar's scale is likely to be constrained by sustainable biomass supply in the medium to long term. This a serious constraint for most biogenic based CDR-approaches, including BECCS, a topic discussed above. Working in its favor, though, are the low costs associated with production of biochar as compared to alternative CDR approaches, with sustainable biomass feedstocks being the largest source of cost variability. Comparatively low capital expenses and short issuance time are likely to help supply of biochar scale quickly to meet rising demand.

Enhanced Rock Weathering (ERW)

As rocks are worn down over time, they release elements such as calcium and magnesium. When these elements interact with carbonic acid (naturally found in air and rain) or bicarbonate (naturally found in oceans), they join in a chemical reaction to form calcium carbonate, also known as limestone. This natural process occurs over millions of years and effectively removes carbon from the atmosphere and transports it to the geologic carbon cycle where it is stored as a mineral for 1000+ years. Natural weathering processes currently remove 1.1 Gt/CO2 annually.[20] Enhanced rock weathering (ERW) speeds up the weathering process by grinding alkaline rocks into a fine gravel or dust-like consistency and physically spreading it out on crop lands, increasing formation of limestone via more contact between the rain, air, and rock.

Rock type, particle size, and local climatic conditions all contribute to the carbon removal efficiency of an ERW project. Basalt, a type of alkaline rock formed by the cooling of lava, is often used for ERW because it is the most common type of rock found in earth's crust, has a high reactivity, and is an abundant and cheap waste product of the mining industry.[21] Scientists at ERW start-up, UNDO, have estimated approximately 4 tons of basalt rock are needed to capture 1 ton of carbon.[22] While research is ongoing, increased mining to supply the energy transition and other factors have led some experts to believe ERW could be deployed at scale without the need of additional mining.[23]

In addition to sequestering carbon, EWR on agricultural land has multiple benefits for farmers. ERW is an effective soil pH management strategy and a potential substitute for agricultural lime, a carbon intensive product, which is commonly used to manage soil acidity. Soil pH regulation with limestone is estimated to emit millions of tons of CO2 annually in the U.S. alone.[24] Additionally, ERW field studies have observed a 14-41% decrease in nitrous oxide (N2O), a GHG with a 20-year global warming potential 273 times higher than CO2. The United States' Corn Belt is responsible for up to a third of the country's N20 emissions, and a suite of products are available to farmers to reduce these emissions. Perhaps most importantly, ERW has also demonstrated substantial benefits to annual crop yields. In the United States' Corn Belt, a ERW study observed improved crop yields of 12% for corn and 16% for soybeans over a 4-year period of annual rock dust applications.[25] In Wisconsin, one farmer participating in ERW services reported a crop yield increase of 36%.[26]

These benefits of ERW suggest the service has a high potential for at least partially replacing the need for alternative fertilizer, agricultural lime, and N20 mitigating products. While farmers recognize the benefits of ERW services, wiliness to pay (WTP) for such services today is non-existent. Leading start-ups deploying ERW, such as Lithos Carbon and UNDO, are currently paying farmers to participate or providing ERW services for free.

Beyond the inability to compete with many substitute products on cost, one significant barrier to unlocking WTP from farmers for ERW is the lack of time-tested data and precise models that illustrate the exact benefits a farmer could expect from ERW, which the traditional fertilizer and soil management industry can provide. While farmers may not currently pay for ERW services, Lithos Carbon reports a waitlist of willing partners that would represent 2.1 MtCO2/y of removal if their operations and carbon credit demand could meet the interest.[27] Lithos CEO Mary Yap stated that to reach a goal of $100 per ton of CO2, farmers will likely need to be willing to pay for basalt deliveries.[v]

Ability to Compete

Reliance on CDR Credit Revenue and Green Premiums

None of the four CDR-based products evaluated were found to be able to compete with substitute products on costs alone, however, all pathways except for ERW can currently compete with a "green premium," defined here as a customer's WTP more for a product with a low carbon footprint or other environmental attributes.

Even with green premiums, however, suppliers of CDR-based products are still selling carbon credits to finance projects. This indicates demand for carbon credits, rather than demand for the CDR-based product, will remain a bottleneck for suppliers selling CDR-based products. Until CDR-based products can reduce costs to compete with substitute products without the support of revenue from carbon credits, they are unlikely to represent a significant new demand center for deployment of CDR. This paradigm is likely to evolve, however, as technology costs come down, WTP for low carbon alternative products increases, and the policy landscape shifts to incentivize carbon removal.

While it does not free suppliers from reliance on carbon credit revenue, selling CDR-based products provides suppliers increased revenue and pricing flexibility. For example, a biochar supplier could lower its carbon credit prices to compete against alternative CDR approaches in carbon markets because it is able to make up the lost revenue via the sale of its biochar as a soil amendment to farmers. Alternatively, a mineralized concrete provider may be able to share carbon credit revenues with concrete buyers to reach an acceptable price for its concrete. In both cases, the supplier is reliant on CDR credit revenue to finance the project, but secondary revenue from selling its CDR-based product provides increase flexibility and revenue generation that could help accelerate CDR deployment. As markets mature, the degree of competitive advantage gained by CDR suppliers generating secondary revenues from CDR-based products will become more apparent.

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[v] ERW provider Lithos was reported as paying farmers $50 per acre in 2023.

Positive Climate Impacts from Product Substitution

Another important finding of this research is the ability of CDR-based products to not only remove carbon from the atmosphere, but also reduce the carbon footprint within industries that have been characterized as hard-to-abate (e.g., concrete, agriculture, fuels). For example, some CDR-based products have the potential to replace or reduce the use of carbon-intensive products within industries, in addition to directly removing CO2 from the atmosphere. As such, deployment of CDR-based products that also result in the avoidance of carbon emissions via product substitution would provide more climate value than CDR approaches that only generate a carbon credit.

Product substitution is likely to be driven by the concept of "insetting," or the corporate practice of directing climate investments to activities that reduce emissions within the value chain, rather than outside. An alternative to this practice would be "offsetting," where a company finances climate projects outside its value chain, generating a credit that can be applied during carbon accounting to reduce corporate emissions. For example, a large food brand replacing carbon intensive fertilizers with biochar on their own crop lands would be insetting. If that same company had purchased CDR credits from a DAC project outside its value chain, it would be considered offsetting. Insetting is often viewed as more favorable than offsetting by stakeholders concerned with corporate emissions, as projects address emissions associated with the company financing the project, rather than simply being applied on paper to offset unabated corporate emissions.

Unique Product Features

CDR-based products have unique features, which provide a competitive edge over some substitute products for certain customer segments. For example, BECCS is more expensive than variable energy generation technologies but provides 24/7 zero-carbon power. Mineralized concrete is stronger after the mineralization process, according to suppliers, and reduces the amount of cement required to produce the same amount of concrete. Biochar is attractive to many customer segments as an effective organic soil amendment (an alternative to chemical fertilizers), and some studies suggest that ERW may improve crop yields more effectively in some circumstances than a common substitute product.[28]

CDR-based products also experience varying degrees of headwinds and tailwinds from a range of trends impacting their ability to scale. While a non-exhaustive list, some of these trends include: supply of key inputs; capital cost; industry awareness and education; measurement, reporting and verification (MRV); as well as regulatory and policy support. (See Table 3.)

Market Dynamics

As suppliers of CDR-based products are most often still selling CDR credits, analysis of CDR credit market transactions is informative to understand their performance. For this research, data of CDR credit transactions from 2019-April 2024 collected by CDR.fyi was used to evaluate the size of current markets, level of competition among suppliers, and pricing dynamics.[29]

Market Size

From 2019-April 2024, only 7 MtCO2 have been sold on the CDR VCM. BECCS represent 55% of total tons sold to date, however, no CDR credits from BECCS have been delivered yet. This is indicative of the lag time between contracting for CDR credits and actual time it takes to execute CDR projects. Biochar holds the third highest share of total tons sold at 12% and represents 87% of total tons delivered. Unlike BECCS projects, biochar is a mature technology with comparatively less complexity that can operate in smaller project sizes and more quickly deliver on sales contracts. Concrete represents most mineralization tons sold to date, however, it is one of the smallest CDR types in the market, along with ERW. Both mineralization and ERW represent only 2% each of total tons sold and 1% of total tons delivered. (See Figure 3 and Table 4.)

Suppliers

Figure 4 shows the number of suppliers with recorded CDR credit transaction between 2019-April 2024 by CDR approach, including approaches without CDR-based products. Across all CDR approaches, there are a limited number of suppliers. Apart from biochar, CDR-based product approaches are also characterized by a concentration of sales by only one or two individual suppliers. For example, ERW has 14 suppliers over the studied period, however, just one supplier is responsible for 77% of ERW credit tons sold (Lithos). For mineralized concrete, there are 5 suppliers over the period, but 68% of tons sold in this category were also from just one supplier (Neustark).

The BECCS market is also concentrated. Despite representing 55% of total tons sold across all CDR types, BECCS only has 8 recorded suppliers. Of these 8, two dominate, representing 32% (Drax) and 42% (Orsted) of total BECCS credits sold respectively. The large project size, capital intensity, technology complexity, and specific locational conditions required for BECCS projects are likely barriers to entry that limit the number of suppliers in the BECCS market.

Biochar has the most recorded suppliers of all CDR types (66), almost 3 times the number of DAC (23), the CDR approach with the second highest count of suppliers. Unlike BECCS, concrete, and ERW, biochar tons sold are spread more evenly among suppliers, with the greatest share of any one supplier at 21% (Exomad Green). This may be attributable to lower barriers to entry in biochar such as smaller project sizes, flexibility of project locations, maturity of technology, and established sales channels, as compared to other CDR approaches. (See Figure 2.)

Weighted Average Price per Ton

CDR approaches with CDR-based products all had a weighted average CDR credit price per ton below the whole market average in 2023 ($488). In some cases, this could indicate a competitive advantage, however, there is a significant amount of noise in price markets. Having a price lower than the average in 2023 is not necessarily a strong indicator of having the lowest-cost products now or into the future. For example, two suppliers with the same price per ton could have very different margins. One maybe overpricing its product because the market demand will bare it, while another may be taking a loss to maintain a pricing position that sends a certain signal to the market or potential investors. (See Figure 4.)

Conclusion

Evaluating the impact of CDR-based products on scaling CDR is challenging in today's early stages of both technology and market development. Access to data is limited, as there are often very few suppliers in any given market, and new business models are being tested for the first time. The potential development of both industry specific and general climate policy is also unpredictable but will play a critical role in the eventual success or demise of CDR-based products. While recognizing that these factors ensure there is likely to be significant evolution in CDR markets in the coming decades, analyzing current market conditions can provide insights into CDR-based product strengths and weakness.

This research found a primary weakness of CDR-based products are their cost. Until CDR-based products are cost competitive with substitute products, they will likely continue to be reliant on carbon credit revenue. This reliance prevents CDR-based products from becoming a significant new demand center for CDR. Despite this, selling CDR-based products can provide increased pricing flexibility and revenue generation, factors that can help suppliers scale more quickly to meet existing CDR credit demand. An important strength of some CDR-based products is their potential to replace or reduce the use of carbon-intensive products within industries, in addition to directly removing CO2 from the atmosphere. As such, deployment of CDR-based products that also result in the avoidance of carbon emissions via product substitution would provide more climate value than CDR approaches that only generate a carbon credit.

While voluntary private sector action is largely to thank for the enormous growth in CDR markets from 2019-2024, private markets are not currently incentivized to generate the required demand for CDR by 2050. As such, scaling CDR will likely require a combination of direct government procurement and regulatory action to catalyze private sector investment and engagement in CDR markets and products beyond current estimations.

Tables and Figures

Table 1: CDR Approaches with Products Beyond Carbon Credits

CDR-based Product End Market	CDR Approach	Storage Mechanism	Storage Durability	Pathway
Energy (fuel, electricity)	Bioenergy with Carbon Capture and Storage (BECCS)	Geologic Storage	High	Biogenic
	Biochar	Product-based	Medium	Biogenic
Building Materials	Mineralization (concrete)	Product-based	High	Geochemical
	Biochar	Product-based	Medium	Biogenic
Agriculture	Biochar	Product- based	Medium	Biogenic
	Enhanced Rock Weathering (ERW)	Product-based	High	Geochemical

Table 2: Suppliers of Concrete-based CDR Credits and Process Types

Company Name	Process Type
CarbonBuilt	• Proprietary portland cement alternative • Mineralization via gas injection
CarbonCure	• Mineralization via gas injection during traditional mixing process
Carbon Limit	• Mineralization via proprietary material additives
Neustark	• Mineralization via gas injection with demolished concrete, which can be used in recycled concrete, roads, or other building materials
O.C.O Technology	• Mineralization using thermal waste materials via gas injection to produce aggregate products

Table 3: Headwinds and Tailwinds for CDR-based Products

Legend	Headwind	Tailwind	Neutral

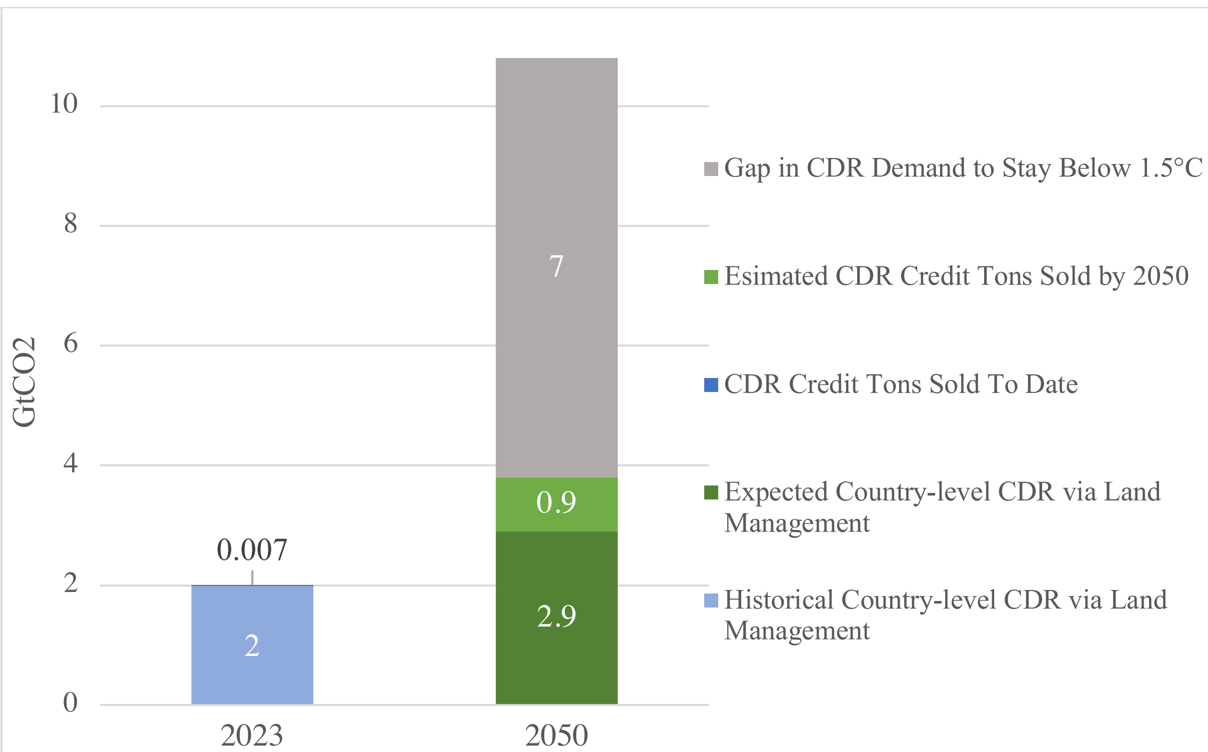
Trends	BECCS	Concrete	Biochar	ERW
Long-term supply of key inputs	Headwind	Headwind	Headwind	Headwind
Industry awareness and education	Neutral	Headwind	Headwind	Headwind
Measurement, reporting, and verification	Tailwind	Tailwind	Headwind	Headwind
Regulatory or policy support	Tailwind	Tailwind	Neutral	Neutral
Growth in CDR VCM demand	Tailwind	Tailwind	Tailwind	Tailwind

Table 4: Percent of Total Tons Sold and Delivered by CDR Approach (2019-April 2024)

CDR Approach	% Tons Sold of Total	% Tons Delivered of Total
BECCS	55%	0%
Biochar	12%	87%
Biomass Removal	1%	8%
Biooil	2%	3%
DAC	19%	0%
ERW	2%	1%
Mineralization	2%	1%
Unspecified	5%	0%

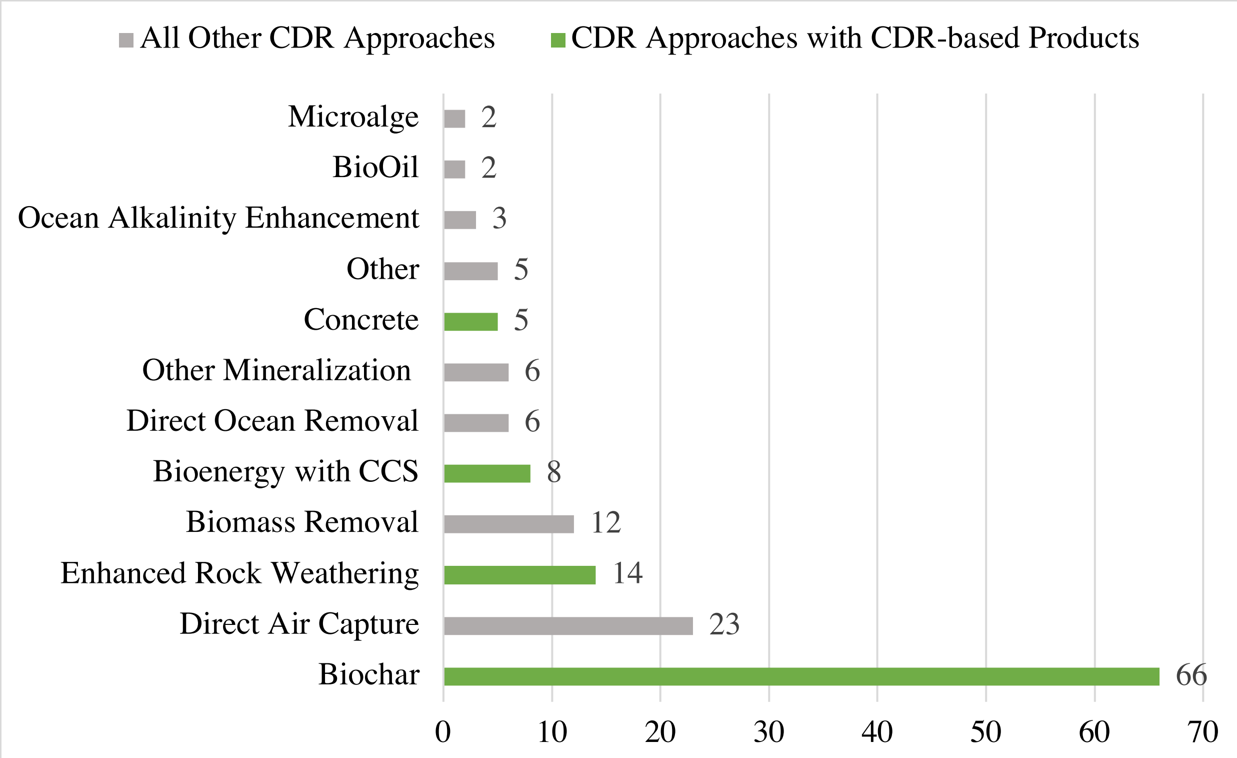
Note: Data accessed from CDR.fyi on April 18th, 2024. CDR types contributing less than 1% were excluded.

Figure 1: Shortfall of Estimated Demand for CDR by 2050



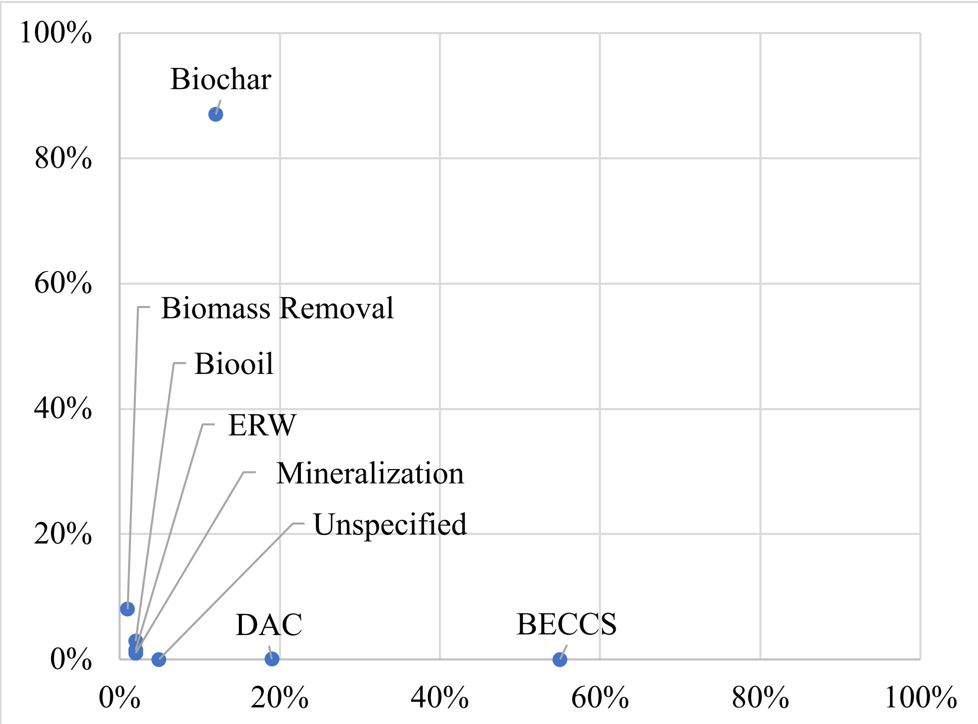
Note: Assumed "Estimated CDR Credit Tons Sold by 2050" is the rounded high end of BCG estimates for 2040 demand, which spans a range of 0.08-0.87 GtCO2. See Footnote 3 for additional context. "CDR Credit Tons Sold To Date" was sourced from CDR.fyi's database. Both historical and expected "Country-level CDR via Land Management" data points were sourced from Carbon Brief, which utilized country level submissions to the United Nations Framework Convention on Climate Change (UNFCC).

Figure 2: Count of Suppliers in CDR Credit Market by CDR Approach (2019-April 2024)



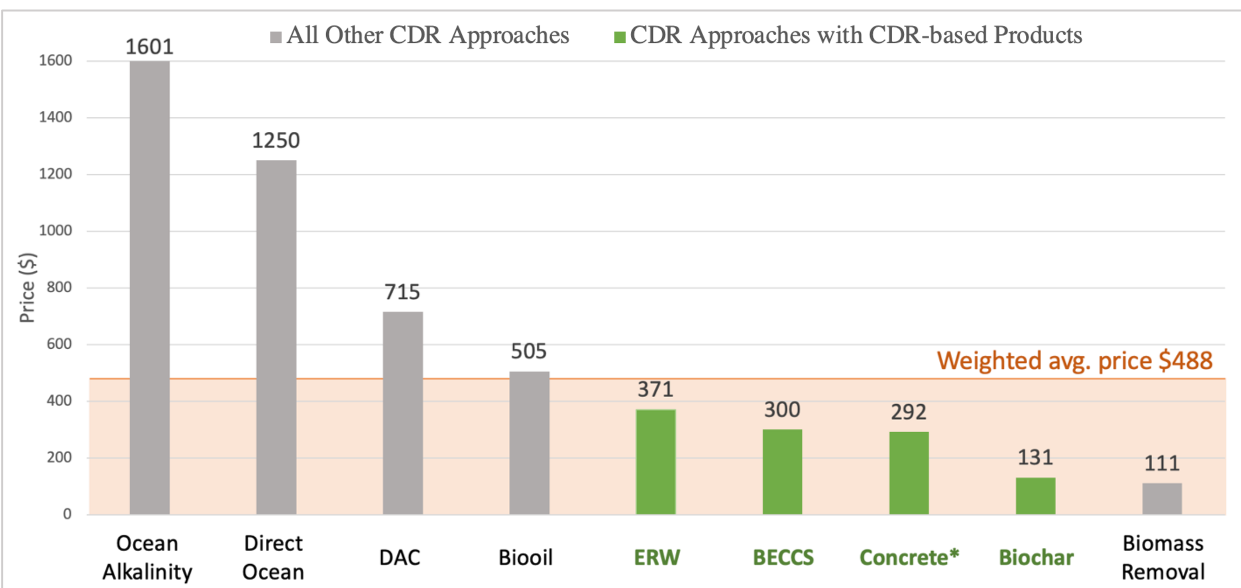
Note: Data accessed from CDR.fyi on April 18th, 2024. CDR approaches with less than 2 suppliers excluded.

Figure 3: Percent of Total Tons Sold and Delivered by CDR Approach (2019-April 2024)



Note: Data accessed from CDR.fyi on April 18th, 2024. CDR approaches with less than 2 suppliers excluded.

Figure 4: Weighted Average Price Per Ton of CDR Credits in 2023 by Approach



Note: *Concrete data from 2021-2022 due to lack of price data from 2023. Approaches with less than 3 data points were omitted. Data from CDR.fyi.

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