McKinsey Sustainability

Carbon removals: How to scale a new gigaton industry

CO_2 removal (CDR) capacity is far from the gigaton scale needed to round out net-zero efforts by 2050. We explore a mature CDR market's potential and possible first-mover advantages.

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Foreword

Halting climate change should be everyone's business. That means putting an end to planet-warming emissions at a pace and scale far greater than seen so far. It also means scaling up CO_2 removal (CDR).

Limiting warming to 1.5°C is an incredibly ambitious goal—and yet a vital one. To achieve the goal would require halving emissions globally before this decade is out. By the time two more decades are out, we must get to net-zero CO_2, using CDR to balance out any remaining emissions. We can ill afford to reach net zero too late. But if we do, CDR becomes an even more important tool in the survival kit for our descendants.

In January 2023, I helped author the first edition of *The state of carbon dioxide removal*, an independent scientific assessment of global progress on CDR. We quantified the challenge: novel CDR methods, in particular, should increase by 2030 by a factor of 30—or even 540 in some scenarios—on a path to meeting our global climate goal.

CDR is moving from research labs into the real world. Good data and practical guidance are needed in the push to scale these solutions rapidly and wisely. That is why I am pleased to see this report by McKinsey. It speaks to the business community about the importance of early action on CDR while putting forward clear data around engaging with CDR.

The CDR industry faces challenges common to many other emerging industries, including high costs and regulatory hurdles. But it is also an industry with economic potential. This report outlines that potential by estimating the value pools across CDR segments and CDR projects in development, assessing the investment gap in CDR, projecting cost trends, and providing potential solutions to close the gap.

I hope that this report enables a much wider community of people across the value chain—investors, entrepreneurs, CEOs, and regulators—to find new opportunities and greater ambition in climate action. A holistic strategy involves both urgent emission reductions and strategic support for CDR. The time is short but full of potential.

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Executive summary

The Intergovernmental Panel on Climate Change (IPCC) has made it clear that CO_2 removal (CDR) is a critical tool for achieving net zero by 2050,[1] because it could enable businesses to neutralize residual carbon emissions once all emission reductions efforts have been exhausted. Thus, by 2050, CDR competency could be a core part of management responsibilities across all sectors.

This report provides an analysis of the market potential for CDR, the investment requirements, and market trends. It also identifies which actions are the most likely to lower barriers to scaling CDR and delineates potential advantages for first movers in different stakeholder groups.

[1] "Summary for policymakers," in *Climate change 2022: Mitigation of climate change*, IPCC, 2022.

CDR's role in reaching net zero

Reducing emissions remains the primary, most effective, and preferred response to climate change. But decarbonization alone could prove insufficient to reduce the residual "hard to abate" emissions that may persist in the medium term. Once decarbonization options have been expended, CDR could play a vital role in neutralizing residual emissions; therefore, most scenarios aligned with the Paris Agreement project substantial CDR capacities. Estimates from the Smith School of Enterprise and the Environment's *The state of carbon dioxide removal* report, for example, show that six to ten metric gigatons of CO_2 in annual CDR capacity would likely be needed by 2050 for most Paris-aligned net-zero pathways.[2] This capacity could not be delivered quickly, however, so efforts would need to begin as soon as possible to ensure 2050 scenarios are achievable.[3] Some estimates require an additional 0.8 to 2.9 metric gigatons of CO_2 per year of removals capacity by 2030—three to ten times more than the volumes currently estimated to be onstream by that date.[4] Biotic feedback loops could also further accelerate the most severe effects of climate change, consequently increasing the speed at which CDR would need to be scaled.

Given CDR's potential importance to achieving net-zero commitments, removals could become a routine consideration for businesses across sectors. For companies to claim they have reached net zero under the Science Based Targets initiative's (SBTi's) Corporate Net-Zero Standard, for example, after they have exhausted decarbonization actions, they must neutralize any residual emissions.[5] CDR can be especially pertinent for sectors with hard-to-abate emissions—those emissions that are technologically or economically prohibitive to reduce.

Closing the removals gap to achieve net zero would require a range of CDR solutions comprising both nature-based removals (NBR) and technology-based removals (TBR). NBR remove carbon by restoring, enhancing, or actively managing ecosystems. Because they tend to cost less per metric ton of CO_2 removed than emergent TBR, NBR could offer a more cost-effective path to increasing near-term CDR capacity. NBR could also play a role in removals over the long term to ensure flexibility and balance in removals capacity. However, TBR generally deliver more "durable" removals by storing CO_2 permanently with minimal risk of re-release into the atmosphere.[6] And durable solutions are generally preferable to ensure removals efforts remain effective in the long term, so increasing volumes of such solutions would be needed. Accelerating the scale-up of durable TBR would require near-term investment and innovation to reduce their relatively higher cost.

2 Climatic need estimates drawn from Stephen M. Smith et al., *The state of carbon dioxide removal*, Smith School of Enterprise and the Environment, 2023.
3 For more, see Oliver Geden et al., "Near-term deployment of novel carbon removal to facilitate longer-term deployment," *Joule*, November 15, 2023.
4 Estimated volumes reflect direct air capture and storage (DACS) and bioenergy with carbon capture and storage (BECCS) announced projects from public announcements. DACS includes an assumption of 30 metric megatons of CO_2 ($MtCO_2$) annual capacity phased in by 2030 from 1PointFive's 75 Mt target, while BECCS includes all projects announced as net negative. Projected removals capacities from other CDR solutions were modeled using McKinsey's Global Carbon Credits Model under a business-as-usual scenario.
5 "SBTi Corporate Net-Zero Standard," SBTi, April 2023.
6 Kaya Axelsson et al., "The meaning of net zero and how to get it right," *Nature Climate Change*, 2022, Volume 15.

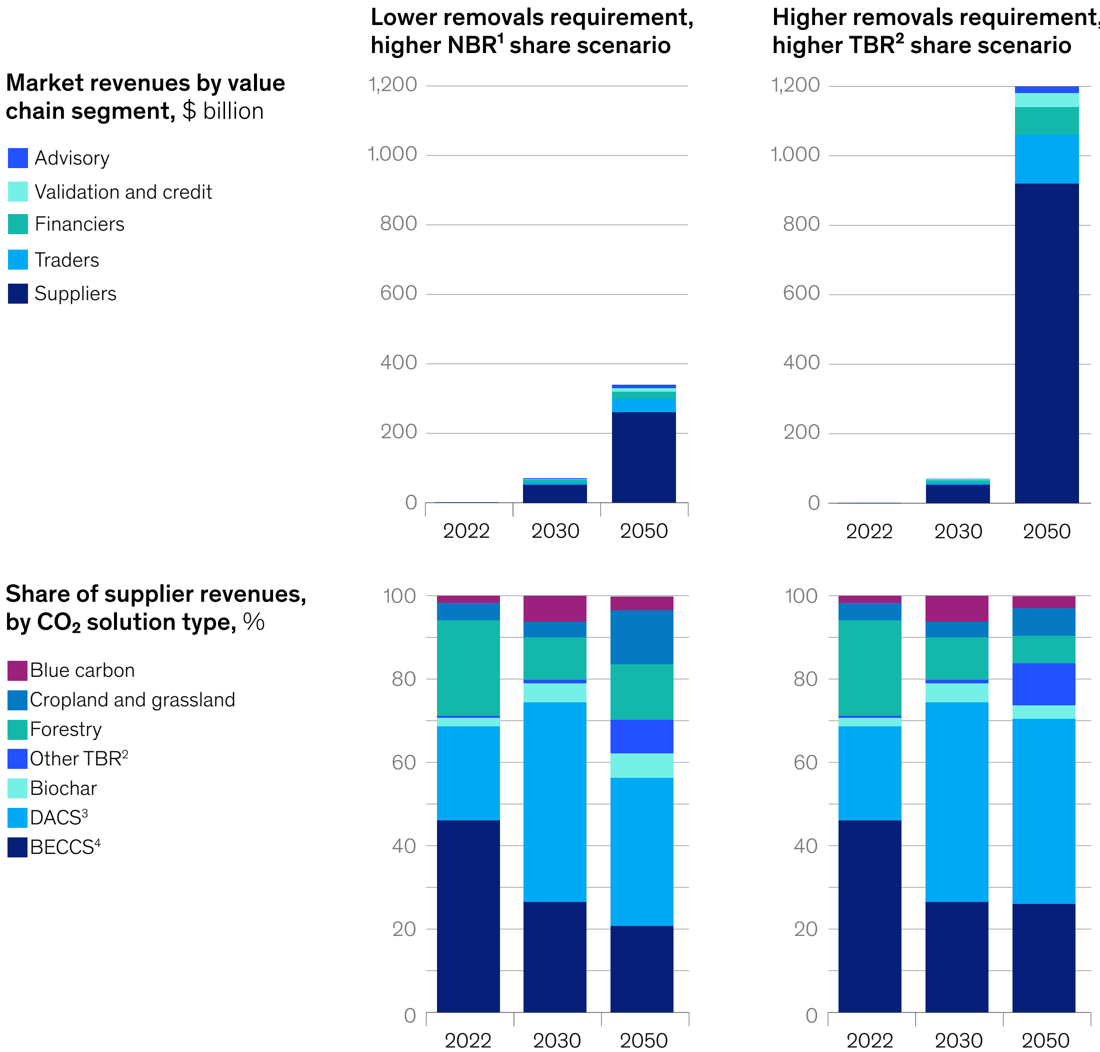
The CDR market: Trillion-dollar potential

A CDR industry capable of delivering gigaton-scale removals at net-zero levels could be worth up to $1.2 trillion by 2050. This industry would require input and support from a range of players—including investors, suppliers, buyers, traders, and other intermediaries—with substantial potential value pools estimated for each (Exhibit E1). These are long-term business opportunities that would require early action to build removal volumes to scale by 2050.

Exhibit E1

Suppliers will likely capture 70 to 80 percent of value in this industry, with traders likely capturing more value over time as the market matures.

Market revenues by value chain segment, $ billion



[1]Nature-based removals. [2]Technology-based removals. [3]Direct air capture and storage. [4]Bioenergy with carbon capture and storage.
Source: McKinsey value pools analysis is indicative and is based on calculations of expected margins from CO_2 removal (CDR) credit sales with the following variables: estimates of 2030 removals volumes by solution informed by capacities of publicly announced projects; estimates of 2050 removals volumes based on McKinsey Global Carbon Credits Model, TRAILS, and Nature Analytics models, and McKinsey expert insight; and estimates of price by solution informed by McKinsey Global Carbon Credits Model; revenue ranges are based on two different 2050 climatic-need pathways and two removal solution pathways (higher technology-based-removal and higher nature-based-removal scenarios); trader margins based on estimates of sales platform usage from cdr.fyi, and margins per sales platform based on McKinsey expert insight; financing revenues estimated through McKinsey Carbon Management Service Line solution-specific cost models, McKinsey Global Carbon Credits Model, and McKinsey expert insight; verification costs based on estimated monitoring, reporting, and verification costs per project from CarbonX; advisory spend based on industry benchmarks of supplier advisory spend

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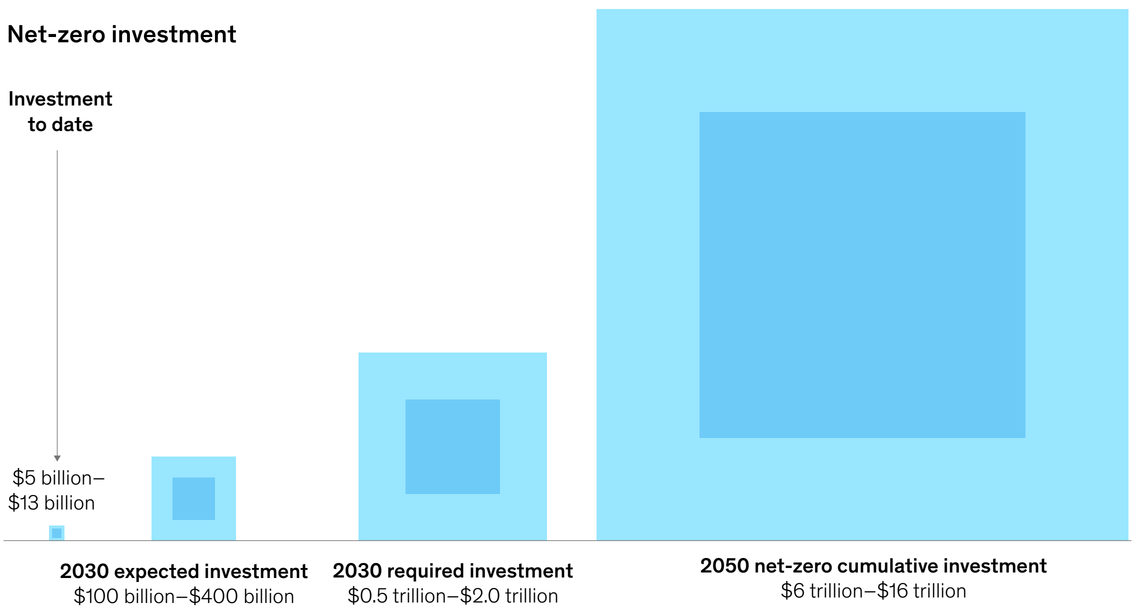
Investment would be needed to support innovation to drive down costs and to support project development. Analysis in this report estimates the cumulative investment in CDR required to deliver net zero in 2050 at $6 trillion to $16 trillion (Exhibit E2). The investment need would depend on the volume of removals needed as well as the range of available CDR solutions. Estimates based on the current trajectory for investment, however, suggest investment could fall considerably short of these levels. In fact, the gap between estimated investment and what is estimated to be needed by 2030 to put CDR on track to meet 2050 targets is between $400 billion and $1.6 trillion.

Exhibit E2

Delivering CO_2 removal capacities for net zero will likely require $6 trillion to $16 trillion of cumulative investment by 2050, far below expected levels.



Note: Ranges reflect uncertainty over costs and volumes, including whether climatic-need scenarios are likely to be more dependent on technology-based removals or nature-based removals. Investments to date reflect actual investment to 2022, with upper bound reflecting estimate of unannounced investments. Assumptions are that investment will be required ahead of capacity: up to three years for bioenergy with carbon capture and storage and direct air carbon capture and storage, two years for biochar and other technology-based solutions, and one year for nature-based solutions.
Source: McKinsey analysis using method-specific costs from McKinsey's Carbon Management Service Line models, climatic-need volumes from the Intergovernmental Panel on Climate Change, and expected investments estimated based on publicly announced CO_2 removal projects

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Market trends: Reducing costs through CDR innovation

The CDR market is currently trading at high prices and small volumes, particularly for emerging TBR. High prices for more durable CDR solutions are likely driven by small capacities and high costs of production. Innovation is key to fostering the higher volumes and lower prices needed to deliver CDR at scale. With continued demand, investment, and innovation, TBR costs are estimated to decline by at least 30 percent and up to 60 percent through 2035 and continue to drop through 2050, albeit more slowly as the industry scales (Exhibit E3). Costs for solutions that currently carry higher costs are estimated to decline fastest, though this scenario relies on the assumption that the required levels of investment and innovation can be achieved. NBR costs, on the other hand, may rise over time as land resources become constrained. NBR costs could rise by 20 to 60 percent through 2035, and 15 to 40 percent between 2035 and 2050.[7]

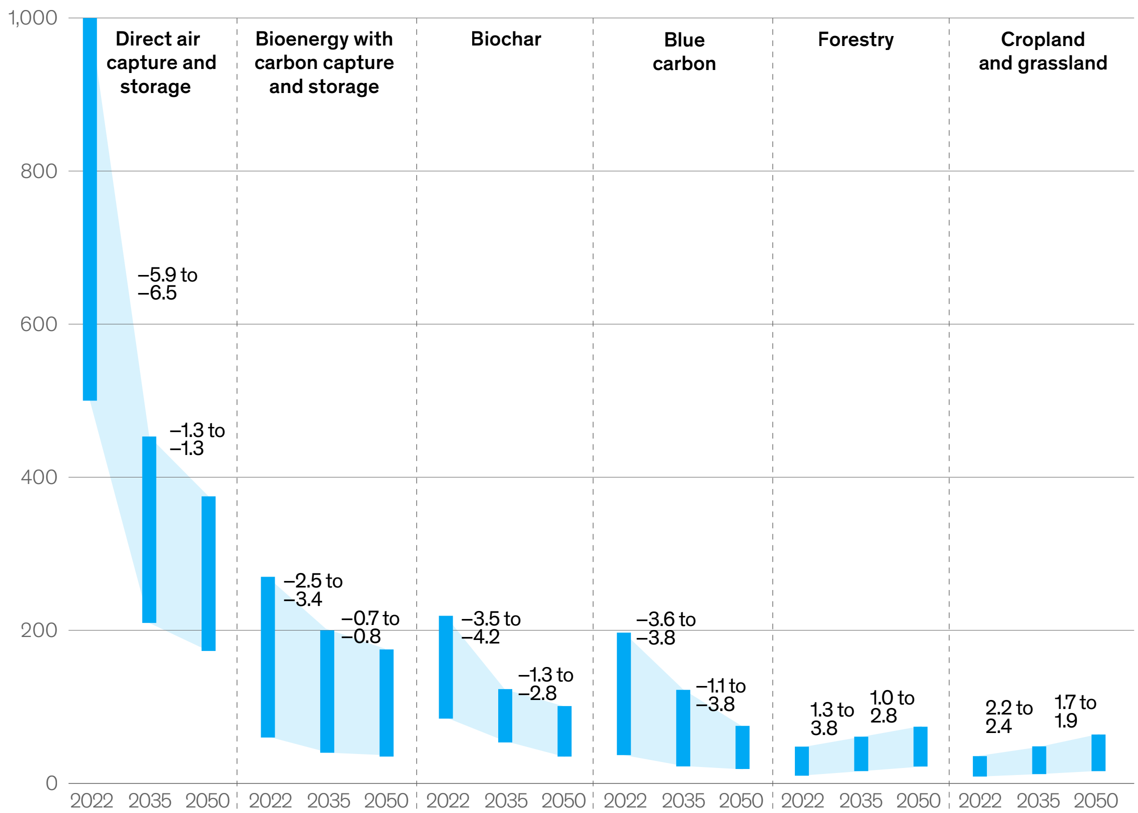
[7] Cost estimates derived from McKinsey TRAILS and Nature Analytics models for nature-based removals, and technology-specific cost models developed through literature review and McKinsey expert insights.

Exhibit E3

Technology-based removals costs are expected to decline over time, while costs for nature-based removals will likely increase.

Levelized cost, \$ per metric ton of CO_2

x.x to x.x = Estimated CAGR across time period, %



Source: McKinsey analysis based on TRAILS and Nature Analytics land-use modeling and technology-specific carbon management service line cost models

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Lowering barriers to scaling CDR

Scaling CDR to deliver net-zero removal volumes is a challenging endeavor, fraught with complexity and nuance. Indeed, the risks and challenges facing the industry have been documented at length,[8] and they include a need for stronger buyer incentives; improved transparency of standards, practices, and services; clear public-sector signals; innovation to unlock lower-cost solutions; and, of course, increased removals capacity. This report explores actions stakeholders across the CDR value chain could take to fulfill these needs.

Existing and developing policy measures and public funding have the potential to accelerate investment, along with enhanced project-level economics that reduce costs and improve future revenue streams. Governments, philanthropists, and nongovernmental organizations could work with the private sector to spur innovation—for example by addressing how CDR is incorporated into environmental, social, and governance (ESG) and carbon-accounting frameworks as well as how CDR could be integrated into cap-and-trade or carbon tax systems. Governments and philanthropists could also consider directly funding early-stage technology development or designing innovative financing arrangements that may help catalyze further private investment.

Early-mover advantages in the CDR industry

Although the challenges for scaling investment and innovation are not inconsiderable, tangible, long-term benefits are potentially available to those who engage in critical near-term efforts to scale the CDR industry. Indeed, the analysis in this report indicates that there may be strategic and competitive advantages available to early movers prepared to address these challenges together with other stakeholders.

Investors
Investors that engage early could gain valuable experience in spotting new opportunities and assessing their potential ahead of investors who wait for the market to grow before they engage. And CDR projects can have long lead times to start delivering removals—some TBR can take up to eight years to begin removing their first volumes of CO_2.[9] Early alliances and support for growth enterprises could help investors reserve the right to play as the industry matures and scales. Early investors could also fortify their reputations as climate leaders by being at the forefront of creating an essential net-zero industry, potentially realizing $20 billion to $80 billion in CDR market revenues by 2050 according to the value pools analysis in this report.

Suppliers
Suppliers (CDR project developers that generate carbon credits based on capture and storage activities) could earn 73 to 82 percent of estimated CDR market revenues—$250 billion to $900 billion—by 2050. Because they carry out physical removal activities (such as carbon capture, transport, and storage) while other market players enable their efforts, suppliers could capture the largest share of industry revenues. When demand scales—for example, if CDR is recognized in carbon trading systems—suppliers will need to be able to respond rapidly to meet it. Because of what could be largely unrivaled access to technology, talent, and capital resources, established suppliers could have a significant advantage in expanding programs quickly and

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[8] Several sources have documented CDR market risks and challenges, including *Pathways to commercial liftoff: Carbon management*, US Department of Energy, April 2023; Freya Chay et al., *Barriers to scaling the long-duration carbon dioxide removal industry*, CarbonPlan, July 2022; *The case for negative emissions*, Coalition for Negative Emissions, June 2021; “Barriers to negative-emissions technologies,” *One Earth*, August 21, 2020, Volume 3, Number 2; Danny Cullenward et al., “Addressing critical challenges in carbon dioxide removal,” ClimateWorks Foundation, December 10, 2020.

[9] Angus Gillespie and Alex Townsend, “Scaling up the CCS market to deliver net-zero emissions,” Global CCS Institute, April 2020.

successfully. Early movers could be positioned to develop approaches to move down the learning curve sooner than those who engage later, thereby reducing early movers' costs.

Buyers

Early buyers that sign future offtake agreements with suppliers could gain confidence that they will have a reliable future removals supply, even in the event of increased demand. If companies were required to purchase CDR to offset emissions—for example, following changes to regulations or guidelines on carbon offsets—then demand for CDR credits could rise sharply. Companies that made public net-zero commitments may require access to CDR urgently as they approach their stated deadlines. Early buyers may be more likely to secure a supply of reliable, high-quality CDR credits that could prove essential for hard-to-abate sectors to neutralize residual emissions and meet net-zero targets. In addition, a well-considered ESG strategy underpinned by CDR could support business aims such as talent recruitment and green premiums.

Marketplaces and intermediaries

As seen in other markets, as volumes grow for CDR, trading for removal volumes could coalesce around a small number of major marketplaces in a "winner takes all" dynamic. This dynamic would result from reduced intermediation costs and increased liquidity of the industry operating through a small number of marketplaces. Market intermediaries could earn 9 to 14 percent of estimated CDR market revenues—$40 billion to $140 billion—by 2050, according to the value pools analysis in this report. Marketplaces could aim to attract new and future buyers by moving early to establish a solid reputation for technical expertise, quality assurance, pricing knowledge, and the ability to diversify. Meanwhile, early-moving standards setters that develop high-integrity methodologies for the major CDR technologies could inform the core standard around which the voluntary carbon market for removals operates.

Governments

Governments that move early to support the CDR industry could shore up their domestic removal capacity to align their nationally determined contribution commitments with the Paris Agreement, satisfy other green commitments, and secure national supplies. CDR could be a global opportunity. A variety of CDR solutions means countries could utilize those solutions best suited to their particular geographies: for example, countries with access to low-cost renewable energy could enjoy cost advantages using energy-intensive CDR such as direct air capture. Likewise, countries with significant land-based natural assets could potentially benefit from expanded NBR; and coastal and island states could find emerging blue-carbon solutions afford them advantages. In addition, supporting CDR could provide governments with opportunities to promote skill development and job creation, thereby helping to facilitate a just transition to a net-zero economy.

Based on our analysis, CDR capabilities may become a core strategic concern for governments, investors, and businesses alike. This report offers analysis of the market potential for CDR, potential actions to scale CDR rapidly, and opportunities for near- and long-term advantages for early-moving CDR stakeholders. By reflecting on the analysis and data presented here, business leaders can gain a foundational understanding of CDR and how it may factor into their organizations' net-zero strategies and overall goals. Bold actions taken today can scale CDR capacity to meet global net-zero requirements.

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01 CDR's role in reaching net zero

The Intergovernmental Panel on Climate Change (IPCC) has made it clear that net-zero emissions need to be realized as quickly as possible to mitigate the effects of rising global temperatures.[10] Net zero means achieving a balance between the amount of human-caused (or anthropogenic) emissions released into the atmosphere and the volume of emissions removed. To strike this critical balance, rapid and large-scale emission reductions will need to be coupled with concerted efforts to remove residual emissions from the atmosphere and store them durably.

Unlike emissions-reducing climate solutions, which limit the amount of CO_2 released into the atmosphere, CO_2 removal (CDR) is defined by the IPCC as "activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products." The IPCC qualifies its definition, stating that CDR "includes existing and potential [human] enhancement of [natural removal processes], but excludes natural CO_2 uptake not directly caused by human activities."[11]

10 "Summary for policymakers," in *Climate Change 2022,* 2022.
11 "Summary for policymakers," in *Global warming of 1.5°C*, IPCC, 2019.

Understanding CDR solutions

A range of CDR solutions are being explored to capture and store CO_2 in a variety of ways. Exhibit 1 describes a number of CDR solutions, along with some of the benefits and challenges of each. Nature-based removals (NBR) typically involve natural processes that remove carbon by protecting, restoring, or managing ecosystems, while technology-based removals typically employ man-made technologies to remove CO_2 from the air and store it permanently (see sidebar "Clarifying commonly used CDR terminology").[12]

Clarifying commonly used CDR terminology

Durable solution. A CO_2 removal (CDR) solution that stores CO_2 with relative permanence and carries minimal risks for reversals is considered durable.

Reversal. Used to describe the unintentional release of previously captured and stored CO_2 back into the atmosphere.

Permanence. The length of time a solution is expected to store CO_2 before it is released back into the atmosphere determines its permanence.

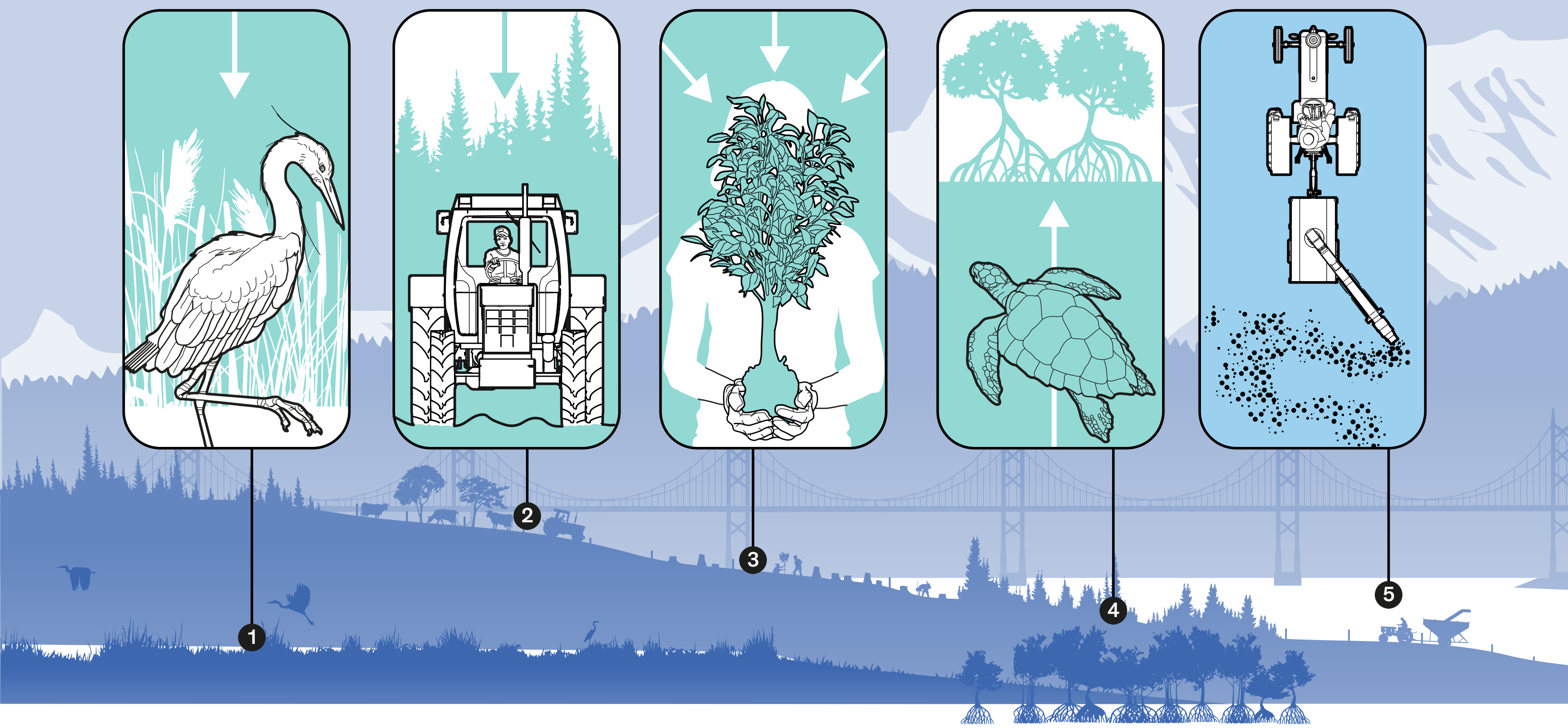
Additionality. A CDR solution is considered additional if the emissions removals it provides would not have taken place without carbon credit revenue incentives.[1]

[1] For more, see "The Core Carbon Principles," The Integrity Council for the Voluntary Carbon Market, accessed November 22, 2023.

Rapid and large-scale emission reductions will need to be coupled with concerted efforts to remove residual emissions from the atmosphere and store them durably.

[12] *The emissions gap report 2017*, UN Environment Programme, November 2017.

Exhibit 1



Understanding carbon dioxide removal solutions

1. Wetland and peatland restoration

Restoring terrestrial wetlands and peatlands to absorb and store more CO_2

Permanence, years

< 100

Cost 2023, \$ per ton CO_2

15–40

Potential benefits
Increase biodiversity; improve water quality; reduce flood risks; eco-tourism

Potential challenges
Release of some greenhouse gases via restoration; uncertain permanence level; long-term monitoring and management

2. Cropland, grassland, and agroforestry

Improving cropland- and grassland-management practices to enhance CO_2 uptake from soils, and improving agroforestry to remove CO_2 from the atmosphere

< 100

10–30

Potential benefits
Increase biodiversity; enhance soil fertility and water retention; agricultural productivity

Potential challenge
Quantifying and monitoring carbon sequestration

3. Reforestation and afforestation

Tree planting in deforested or never-forested land to remove atmospheric CO_2

< 100

10–40

Potential benefits
Increase biodiversity and ecosystem resilience; eco-tourism

Potential challenges
Increased demand for land; release of sequestered CO_2[1]; risks of monoculture tree planting[2]

4. Blue-carbon management

Enhancing carbon uptake and storage of CO_2 in ocean and coastal ecosystems (eg, restoring mangroves, seagrasses, and tidal marshes; cultivating micro- and macroalgae)

< 1,000

25–250

Potential benefits
Improve marine ecosystems; enhance coastal resilience

Potential challenges
Monitoring, reporting, and verification (MRV) for coastal and ocean ecosystems; regulatory uncertainty in international waters

5. Biochar and bio-oil

Produced from biomass, biochar is spread to improve soil quality, and bio-oil is injected underground

< 1,000

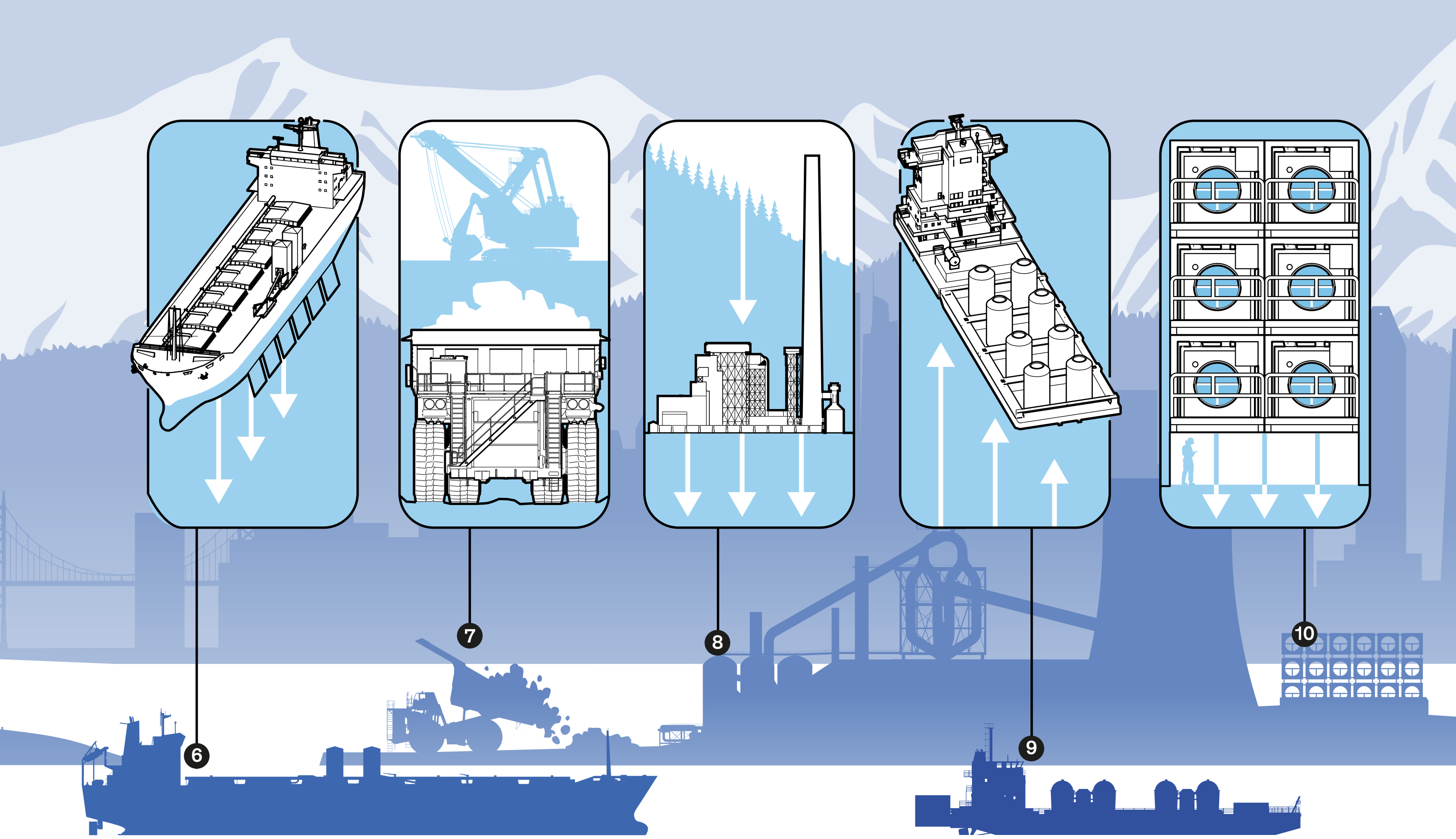
90–220

Potential benefits
Enhanced soil fertility and water retention; uses for biomass residues from agricultural processes

Potential challenges
Increased demand for biomass feedstock and land; uncertain degree of soil permanence

NATURE-BASED REMOVALS

Note: The scalability for each CO_2 removal solution can vary depending on the availability of renewable energy, biomass, land, as well as potential technological, regulatory, and integrity challenges.
[1]The release of carbon back into the atmosphere (also known as reversal) can be caused by factors affecting tree growth, including pests and diseases, and weather events.



6. Ocean alkalinity enhancement	7. Enhanced weathering	8. Bioenergy with carbon capture and storage	9. Direct ocean capture	10. Direct air capture and storage
Adding alkaline substances to the ocean enhances its ability to absorb CO_2 from the atmosphere, accelerating the natural process	Rocks and minerals are broken down to increase surface area, speeding up processes that enable them to store carbon from the atmosphere	Sustainably sourced biomass to produce biofuels, electricity, heat, pulp; CO_2 emissions from these processes are captured and stored	Acid derived from ocean electrodialysis is used to chemically extract CO_2 from surface water; CO_2 then placed in long-term storage	Air passes through solid or liquid chemical filter that binds to CO_2, removing it from the air; concentrated CO_2 from filter is stored in underground geological formations
Permanence, years: >1,000	>1,000	>1,000	>1,000	>1,000
Cost 2023, \$ per ton CO_2: Uncertain	120–800	60–270	Uncertain	500–1,000
Potential benefit Counter ocean acidification	**Potential benefit** Improve agricultural productivity	**Potential benefits** Additional revenue streams from generating coproducts (eg, electricity); retrofit to power plants	**Potential benefits** Counter ocean acidification; use in coproducts (eg, sustainable aviation fuels)	**Potential benefits** Use in coproducts (eg, sustainable aviation fuels); deploy across diverse geographies
Potential challenges Effects on marine ecosystems from alkaline; MRV for ocean ecosystems; regulatory uncertainty in international waters	**Potential challenges** Environmental and social effects; effects of trace metals in local ecosystem	**Potential challenge** Increased demand for biomass feedstock and land	**Potential challenges** Low technological readiness level at scale; MRV for open ocean ecosystems; high energy usage	**Potential challenge** High water and energy usage

TECHNOLOGY-BASED REMOVALS

[2]Compared with natural forests, monoculture tree planting can increase the vulnerability of forests to, for example, pests and diseases and natural disasters.
Source: Intergovernmental Panel on Climate Change; McKinsey analysis, drawing on data from expert interviews

Scaling CDR: What is needed for net zero

The IPCC projects that between six and ten metric gigatons of CO_2 ($GtCO_2$) would need to be removed annually by 2050 to supplement emission reductions to meet Paris Agreement commitments.[13] The world has an existing CDR capacity of around two $GtCO_2$ per year, mostly from NBR,[14] which leaves a gap of four to eight $GtCO_2$ per year between current CDR capacity and net-zero requirements.

A diverse portfolio of CDR solutions would be required to deliver six to ten $GtCO_2$ of removals annually by 2050. As Exhibit 2 shows, no single solution would be sufficient to achieve targeted removals. Each CDR solution has a sustainable potential, which defines the maximum annual volume of CO_2 that the solution could expect to capture and durably store, given constraints and trade-offs with other climate actions. Each solution's sustainable potential could be constrained by various external factors, likely including the availability of biomass (particularly for biochar and bioenergy with carbon capture and storage [BECCS]), renewable energy (particularly for direct air capture and storage [DACS]), and land (particularly for land-based NBR).

Lower-durability solutions (including many NBR, such as afforestation[15] and grassland management[16]) can currently deliver less-expensive removals volumes than higher-durability alternatives. NBR could continue to play a central role in the long term because these solutions can deliver important cobenefits, such as protecting biodiversity. A gradual move toward TBR (and at least one NBR solution—blue-carbon management[17]) that provide greater durability is possible. Both NBR and TBR could continue to contribute sizable portions of total removals through 2050 and beyond.

A diversified approach to removal solutions may help to distribute early-mover risks among more stakeholders and open participation opportunities to a wider range of businesses and governments. Diversity among solutions could also allow for the use of lower-cost solutions while the eventual costs and input demands for solutions currently at an early stage of technological readiness become apparent.

CDR implementation, too, could be distributed globally rather than limited to industrialized countries.[18] For example, carbon sinks[19] are globally distributed, and many are located in emerging economies. Making use of these diverse sites and regional characteristics could help spread economic benefits of the CDR industry more broadly, allowing multiple regions to participate and reducing the risk of concentrating supply in any one region.

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13 The report's climatic need ranges are based on the interquartile range of the IPCC's C1-C3 net-zero pathways, compatible with the Paris Agreement to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." The Smith School *State of carbon dioxide removal* report shows the interquartile range of these scenarios of between six and ten metric gigatons of CDR per year by 2050. Not all these pathways deliver net zero by 2050; some scenarios overshoot emissions and achieve net zero later, bringing 2100 temperatures under the Paris Agreement targets. This range should therefore be regarded as a conservative estimate for the CDR volumes required to limit warming to well below 2°C above preindustrial levels.

14 *The state of carbon dioxide removal*, 2023, estimates that there are about two $GtCO_2$ per year of existing anthropogenic CDR (average between 2000 and 2020) from "land-based removals"—mostly from managed forestry.

15 Afforestation is defined by tree planting in never-forested land to remove atmospheric CO_2 through tree growth.

16 Cropland and grassland management, including agroforestry, includes cropland and grassland management practices that enhance carbon uptake in soils; agroforestry practices additionally remove CO_2 from the atmosphere through tree growth.

17 Blue-carbon management involves restoring mangroves, seagrasses, and tidal marshes to enhance uptake and storage of CO_2 in soils and vegetation. Directly cultivating micro- and macroalgae is also an emerging field within blue carbon.

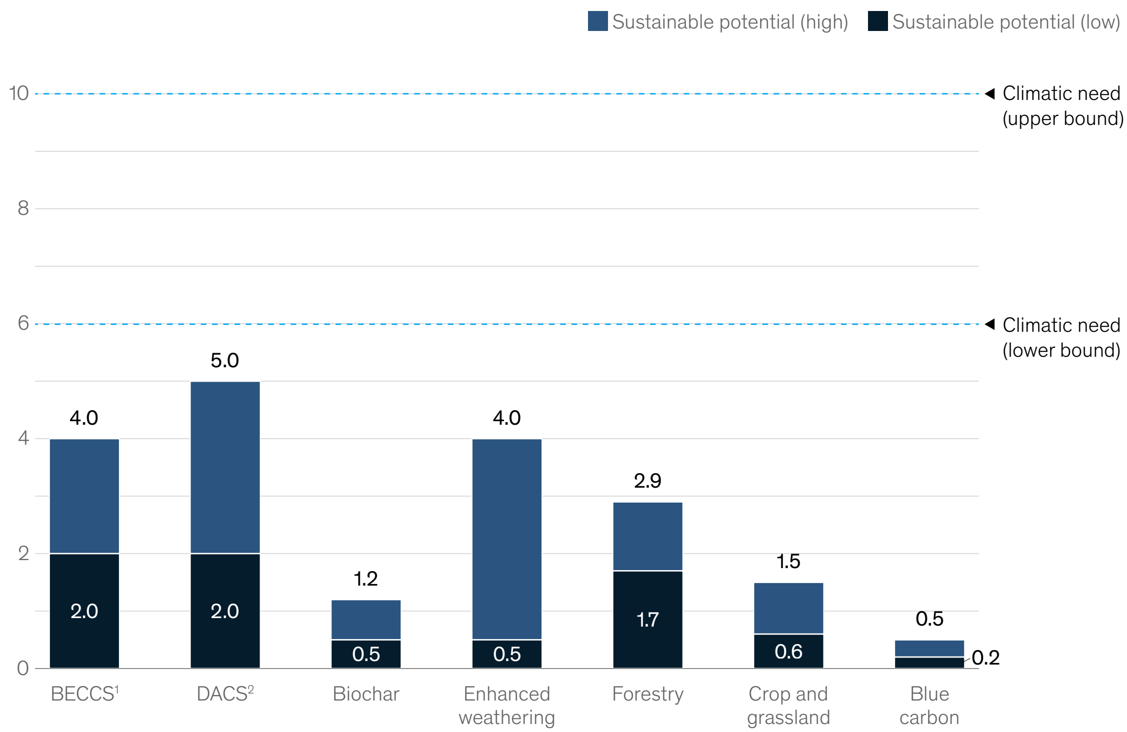
18 "The world needs to capture, use, and store gigatons of CO_2: Where and how?," McKinsey, April 5, 2023.

19 Anything that absorbs more carbon from the atmosphere than it releases, such as plant life, oceans, or soil, is a carbon sink.

Exhibit 2

A portfolio of CO_2 removal solutions could be required to meet climatic needs for net zero.

Sustainable potential of CO_2 removal (CDR) solutions by 2050, metric gigatons (Gt) of CO_2 per annum



Note: Sustainable potentials are conservative estimates based on land-use modeling by McKinsey's TRAILS and Nature Analytics solutions, energy, food, and biodiversity constraints. Capacities should not be summed for total potential: solutions have competing inputs, and potentials are not mutually exclusive. BECCS and biochar, for example, will be limited by the same feedstock constraints. Only net-removal methods are included. The climatic-need ranges are based on the interquartile range of the Intergovernmental Panel on Climate Change's C1-C3 net-zero pathways, while 2 $GtCO_2$ of existing land-based anthropogenic CDR is not included here.

[1]Bioenergy with carbon capture and storage.

[2]Direct air capture and storage.

Source: *Global warming of 1.5°C*, Intergovernmental Panel on Climate Change, 2018; McKinsey TRAILS; McKinsey analysis

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CDR’s potential for businesses, especially in hard-to-abate sectors

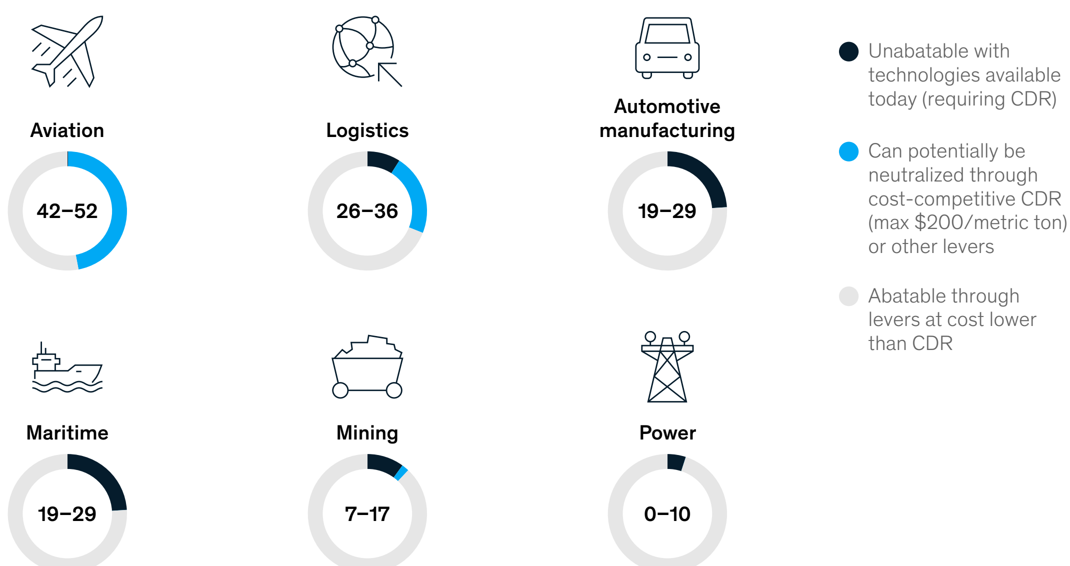
While participation in the CDR industry is currently discretionary, removals could become a routine consideration for businesses seeking to abate residual emissions across sectors. Business leaders could be well served by gaining a foundational understanding of CDR to inform their assessment of the potential role of removals in advancing their organizations’ sustainability objectives and individual paths to net zero.

For organizations in hard-to-abate sectors—those with emissions that are technologically or economically prohibitive to reduce—CDR could prove essential to achieving net-zero ambitions. Exhibit 3 looks at six hard-to-abate sectors to show what percentage of emissions would be currently unabatable with available technologies and would thus require the use of CDR to deliver net-zero emissions.[20] Sectors with the highest percentages of currently unabatable emissions may have a higher incentive to invest early in cutting-edge solutions to ensure further emissions abatement or secure a trusted supply of CDR credits.

Exhibit 3

CO_2 removal cannot substitute for reducing emissions but could help sectors in which abating emissions may be expensive or technically prohibitive by 2030.

Range of emissions that could be neutralized by CO_2 removal (CDR), %



Source: McKinsey Catalyst Zero Decarbonization Lever Library, which uses high-variable and assumption-based forecasts for decarbonization levers for hard-to-abate sectors and residual emissions that non-CDR levers are not expected to be able to address by 2030; decarbonization prices can vary based on geographic, technological, and other factors

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[20] This analysis is based on McKinsey’s Catalyst Zero Decarbonization Lever Library. Technically unabatable emissions are estimated based on Scope 1 and 2 residuals. This analysis models costs for a range of existing or emerging decarbonization levers (in view of 2030), estimated prices, and volumes of emissions that would be mitigated by those levers. Residual emissions are those that are not mitigated either because of levers not being able to be used at necessary volumes or because of technical limitations of the levers themselves.

Business leaders could be well served by gaining a foundational understanding of CDR to inform their assessment of the potential role of removals in advancing their organizations' sustainability objectives and individual paths to net zero.

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02 The CDR market has trillion-dollar potential

Delivering six to ten metric gigatons (Gt) of removals by 2050 could sustain a trillion-dollar industry, though the estimated market size varies considerably depending on the volumes of CO_2 removal deployed and the balance of solutions used to deliver these volumes (see sidebar "Understanding the CDR credit market"). And unlocking six to ten $GtCO_2$ in annual removals would require sizable capital investment. Consequently, the modeling in this report presents ranges of outputs based on several feasible scenarios that vary in two ways:

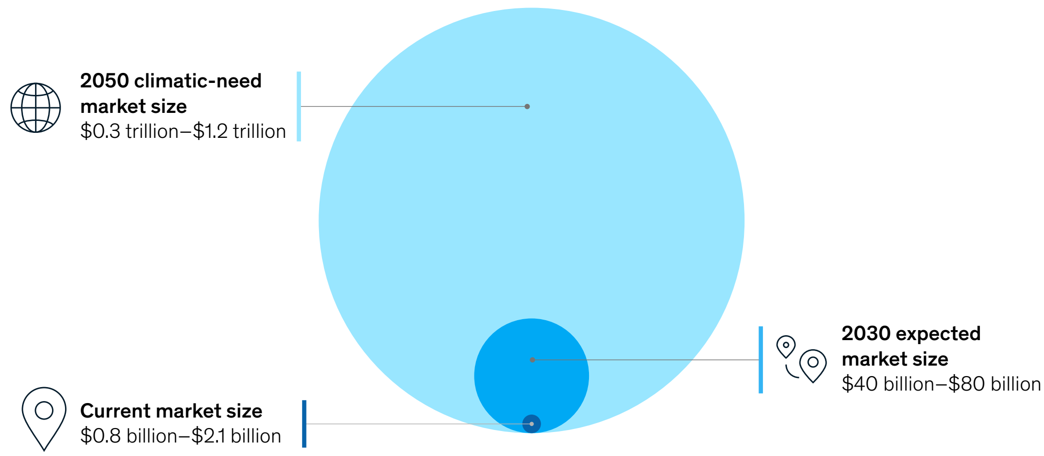
1. CDR volumes needed for climate goals (six to ten $GtCO_2$ per year)
2. the balance of nature-based removals and technology-based removals solutions needed to deliver needed volumes[21]

[21] This report models scenarios with higher NBR and scenarios with a more ambitious pace of TBR scale-up.

Based on expected delivery of announced CDR projects, we estimate a market size of $40 billion to $80 billion by 2030. If demand for CDR credits is scaled up to sufficiently deliver the volumes of CDR needed to meet net-zero-compatible climatic needs by 2050, we estimate annual revenues from the CDR industry would reach $0.3 trillion to $1.2 trillion (Exhibit 4).

Exhibit 4

Delivering six to ten metric gigatons of carbon removals could create an industry worth $0.3 trillion to $1.2 trillion annually by 2050.



Note: Ranges reflect uncertainty over pricing and volumes, including whether climatic-need scenarios are likely to be more dependent on technology-based removals or nature-based removals. Current market size reflects actual purchases in 2022, with the upper bound reflecting estimate of unannounced purchases or where prices were not disclosed. Net-zero market size assumes voluntary market prices.
Source: McKinsey market size analysis, using method-specific prices from the McKinsey Global Carbon Credits Model, climatic-need volumes from the Intergovernmental Panel on Climate Change for net-zero market size, and current and 2030 expected CO_2 removal (CDR) volumes are based on the assessment of publicly announced CDR projects

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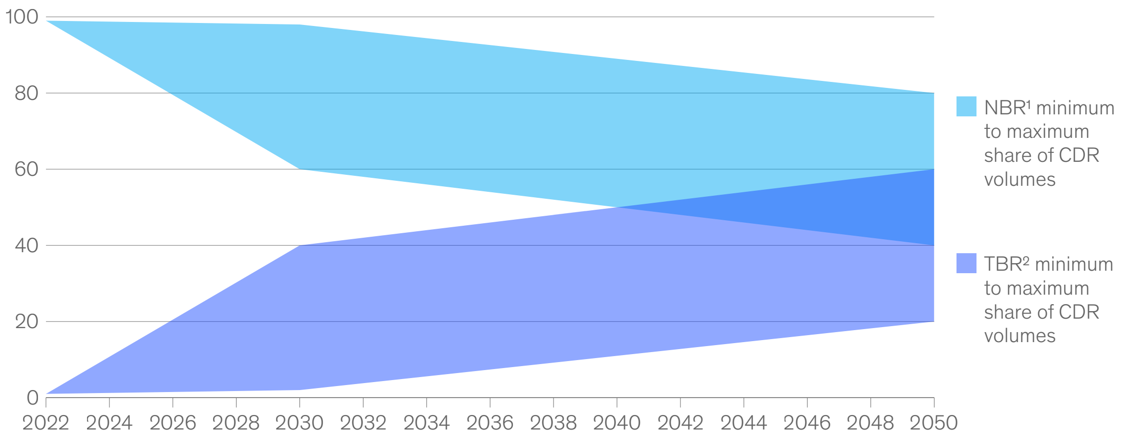
Based on expected delivery of announced CDR projects, we estimate a market size of $40 billion to $80 billion by 2030.

Exhibit 5 shows the share of removals volumes estimated to be delivered by NBR and TBR in all scenarios modeled in this report. These scenarios are indicative of and based on potential growth paths for different solutions while balancing the competing needs of multiple solutions, such as land use for BECCS and biochar. Broadly, NBR may scale up more quickly in the short term, while the use of solutions could shift toward more durable solutions as costs decrease.

Exhibit 5

Approaching 2050, the share of technology-based removals is estimated to ramp up, while the share of nature-based removals falls but remains substantial.

Share of removals volumes in modeled scenarios, by solution type, %



Note: Figures may not sum to 100%, because of rounding. All scenarios assume that 2 metric gigatons of CO_2e per year of existing, land-based NBR volumes are maintained successfully. All other NBR and TBR volumes shown are in addition to these existing removals.
[1]Nature-based removals.
[2]Technology-based removals.

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Understanding the CDR credit market

A CO_2 removal (CDR) carbon credit is a token representing a metric ton of CO_2 removed from the atmosphere. This token can be sold in a carbon market, in which buyers can retire credits to neutralize those emissions they cannot reduce in their own operations. CDR suppliers can generate a credit based on each metric ton of CO_2 they remove and sell these credits on the carbon market to fund capital and operational costs. In most carbon markets, net removal volumes must be verified by a recognized methodology before any credits can be issued; this also increases trust and market integrity.

Carbon markets come in a variety of forms but are generally either carbon markets used for compliance purposes or voluntary carbon markets (VCM). Nearly all CDR today is purchased through VCM. Compliance markets, on the other hand, provide a direct price incentive to encourage companies to reduce their own emissions and emissions in their supply chains, often through a cap-and-trade system that issues allowances to emitting companies. Those allowances then must be traded to stay within an overall emissions cap. Some compliance markets allow carbon credits to be used in lieu of allowances up to a certain threshold, usually around 10 percent. About 23 percent of global emissions are currently covered by a carbon price.[1] Both voluntary and compliance markets are likely to coexist as the market for CDR grows.

[1] *State and trends of carbon pricing 2023*, World Bank Group, 2023.

The McKinsey analysis presented in this report assumes that the CDR industry will generate revenues from buying and selling carbon credits and be powered by a value chain comprising finance, supply, intermediation, and demand (see sidebar “The CDR value chain”).

The CDR value chain

Delivering CO_2 removal (CDR) at net-zero volumes would require an efficient value chain with actors working together to create inputs and outputs for stakeholders across the chain. Policy, regulatory, and governance structures could support the efficient operation of multiple actors across this value chain, comprising the following segments:

Finance

CDR suppliers would need investment to fund capital expenditures for project development and R&D. Investors could provide finance across the spectrum of CDR solutions. Investors with higher risk appetites, such as venture capitalists, currently provide the greatest investment into emerging CDR solutions, especially for higher-durability solutions. In these early stages of CDR market development, funding also comes from philanthropic, government, and academic sources.

Supply

The development and operation of CDR projects, including capture, transport, and storage, make up CDR supply. There are two primary business models: suppliers can either capture and store carbon and then sell credits to buyers (the removals-as-a-service approach) or provide clients with the hardware required to capture their emitted carbon and operation and maintenance support (the hardware supplier approach).[1] Suppliers could also organize themselves somewhere along the spectrum between these two business models.

Demand

The purchase of CDR credits occurs via a marketplace and brokers or on a bilateral basis between a supplier and buyer. Buyers of CDR are also organizing demand through future offtake agreements, including advance market commitments (AMC),[2] which purchase removal credits for future delivery at a fixed price, providing a guaranteed revenue stream for early-stage suppliers to gain financing.

Intermediation

Market intermediaries are the actors that help the carbon market operate efficiently between buyers and suppliers. This includes the facilitation of carbon credit trading on a market platform, associated services such as validation of credits, standard setting, trading, data, registry, and settlement. Suppliers would also need associated services such as insurance, legal, and risk management to operate efficiently.

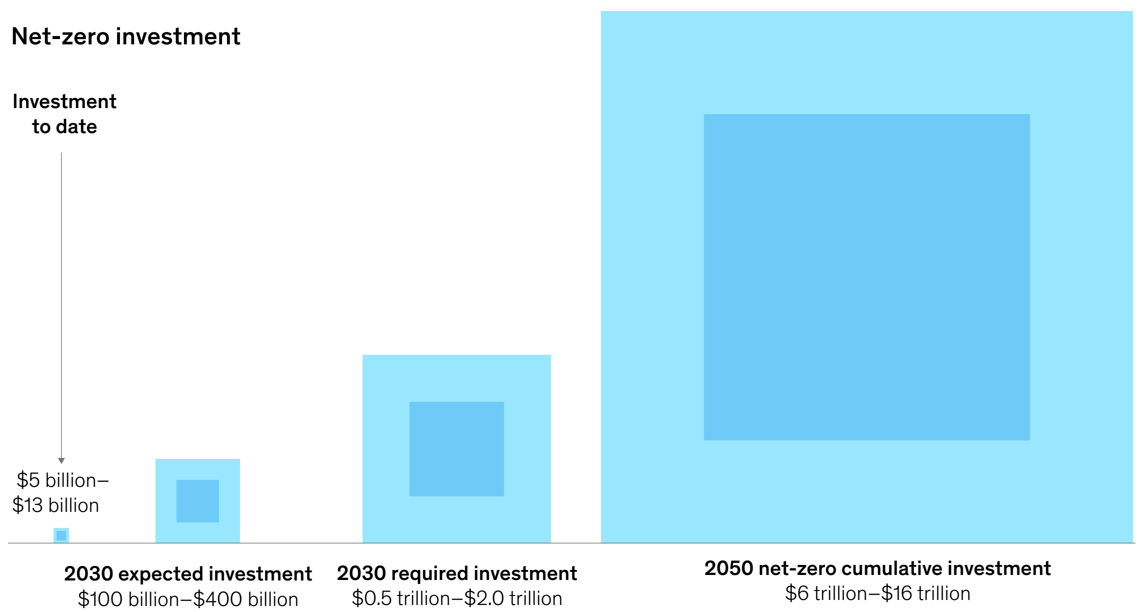
1 Global Thermostat is one example of this. For more, see Maria Gallucci, “A buzzy new carbon removal plant is catching and releasing CO_2,” Canary Media, April 4, 2023.
2 An AMC is a CDR buying mechanism in which organizations commit to prepurchase agreements with suppliers to fund project development; upon the delivery of removals, the AMC pays suppliers and issues carbon credits back to buyers.

A significant investment gap holds back CDR market potential

As noted, to unlock six to ten $GtCO_2$ in annual removals would require sizable capital investment. And removals funding to date is estimated to total between $5 billion and $13 billion (Exhibit 6). Based on announced CDR projects in development, McKinsey estimates that investment could reach between $100 billion and $400 billion by 2030.[22] Although these are large amounts, this estimated investment is roughly five times lower than what would be needed by 2030 to be on track for net zero. Indeed, our estimates show $0.5 trillion to $2.0 trillion in cumulative investment would be needed by 2030 to provide the early traction necessary to put the industry on track to deliver the $6.0 trillion to $16.0 trillion of investment required by 2050.

Exhibit 6

Delivering CO_2 removal capacities for net zero will likely require $6 trillion to $16 trillion of cumulative investment by 2050, far below expected levels.



Note: Ranges reflect uncertainty over costs and volumes, including whether climatic-need scenarios are likely to be more dependent on technology-based removals or nature-based removals. Investments to date reflect actual investment to 2022, with upper bound reflecting estimate of unannounced investments. Assumptions are that investment will be required ahead of capacity: up to three years for bioenergy with carbon capture and storage and direct air carbon capture and storage, two years for biochar and other technology-based solutions, and one year for nature-based solutions.
Source: McKinsey analysis using method-specific costs from McKinsey's Carbon Management Service Line models, climatic-need volumes from the Intergovernmental Panel on Climate Change, and expected investments estimated based on publicly announced CO_2 removal projects

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Even if the investment gap were to be closed immediately, project development timelines would still need to be compressed to meet 2030 requirements and stay on track for 2050. This is particularly true for TBR projects, which require significant lead time for permitting, technical talent recruitment, supply chain organization, and—given how new these methods are—experimental learning before full capacities could be realized.

[22] McKinsey analysis of CDR supplier plans, offsetting commitments, estimated investor activity, and nationally determined contributions.

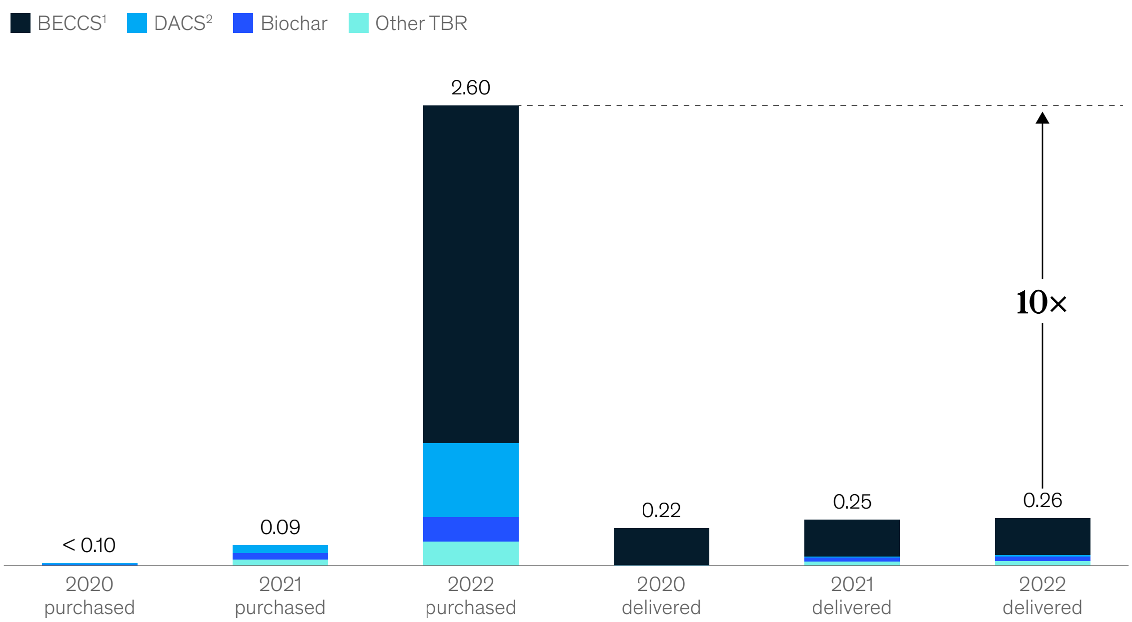
Why most tech-based CDR purchases today are for future capacity yet to be delivered

There are currently numerous TBR suppliers aiming to deliver on TBR's long-term potential, and some high-profile corporate buyers have added TBR to their carbon credit portfolios. Between 2020 and 2022, publicly recorded novel TBR purchases grew by a factor of 2,000, with purchases for offtake capacity exceeding delivered supply by ten times (Exhibit 7).[23] However, the market has yet to achieve mainstream adoption. Early TBR buyers have generally paid high prices for relatively small volumes with high delivery risk—sometimes citing an expressed desire to stimulate wider funding for TBR investment and research. It appears unlikely that the market will have appetite to pay high prices for volumes at the gigaton scale in the medium term.

Exhibit 7

Technology-based-removal credit purchases exceeded delivered volumes by ten times in 2022.

Comparison of volumes of technology-based-removal (TBR) credit purchases and in-year CO_2 removal (CDR) delivery, metric megatons CO_2



[1]Bioenergy with carbon capture and storage.
[2]Direct air capture and storage.
Source: McKinsey analysis of publicly announced CDR purchases and recorded projects being traded as CDR credits

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[23] The year 2022 was dominated by two major TBR purchases: Drax sold up to two metric megatons of CO_2 ($MtCO_2$) of bioenergy with carbon capture and storage (BECCS) credits to Respira, and Airbus purchased 400 metric kilotons of CO_2 ($ktCO_2$) direct air capture and storage credits from 1PointFive. While the exhibit does not include purchases from the first half of 2023, this momentum has continued, with Microsoft purchasing 2.76 $MtCO_2$ of BECCS from Ørsted and JP Morgan committing to 800 $ktCO_2$ projects across a range of suppliers.

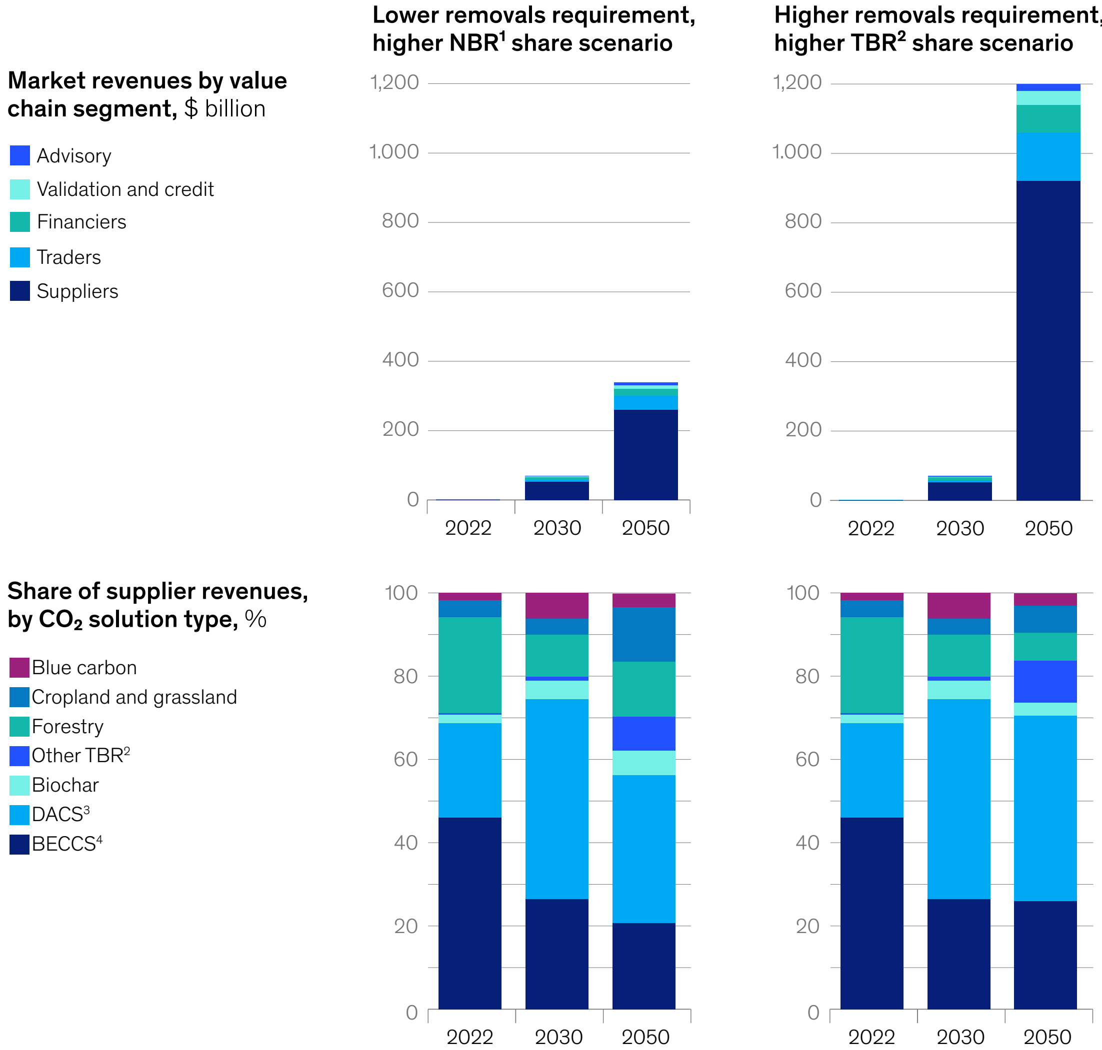
Value pools analysis

To understand how the potential trillion-dollar market could deliver revenue opportunities for stakeholders across the value chain, we conducted a value pools analysis for this report (see sidebar "Value pools analysis: Methodology"). The results of this analysis are shown in Exhibit 8.

Exhibit 8

Suppliers will likely capture 70 to 80 percent of value in this industry, with traders likely capturing more value over time as the market matures.

Market revenues by value chain segment,
$ billion



[1]Nature-based removals. [2]Technology-based removals. [3]Direct air capture and storage. [4]Bioenergy with carbon capture and storage.
Source: McKinsey value pools analysis is indicative and is based on calculations of expected margins from CO_2 removal (CDR) credit sales with the following variables: estimates of 2030 removals volumes by solution informed by capacities of publicly announced projects; estimates of 2050 removals volumes based on McKinsey Global Carbon Credits Model, TRAILS, and Nature Analytics models, and McKinsey expert insight; and estimates of price by solution informed by McKinsey Global Carbon Credits Model; revenue ranges are based on two different 2050 climatic-need pathways and two removal solution pathways (higher technology-based-removal and higher nature-based-removal scenarios); trader margins based on estimates of sales platform usage from cdr.fyi, and margins per sales platform based on McKinsey expert insight; financing revenues estimated through McKinsey Carbon Management Service Line solution-specific cost models, McKinsey Global Carbon Credits Model, and McKinsey expert insight; verification costs based on estimated monitoring, reporting, and verification costs per project from CarbonX; advisory spend based on industry benchmarks of supplier advisory spend

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Value pools analysis: Methodology

McKinsey value pools analysis estimates the distribution of annual revenues from CO_2 removal (CDR) credit sales across value chain stakeholders. The distribution of value today is based on an average of market activity from 2020 to 2022. Estimated revenues are based on announced projects that may be online by 2030, and modeled CDR volumes for 2050 are based on multiple potential scenarios that consider varying volumes of emissions that may be required for net zero and the balance of solutions that could be used to deliver this requirement. This analysis is indicative and is based on calculations of estimated margins from CDR credit sales with the following variables:

— Estimates of 2030 removals volumes by solution are informed by capacities of publicly announced projects. Estimates of 2050 removals volumes are based on McKinsey Global Carbon Credits Model, TRAILS, and Nature Analytics models and on McKinsey expert insight.

— Estimates of price by solution are informed by McKinsey Global Carbon Credits Model.

— Revenue ranges are based on two different 2050 climatic-need pathways and two removal-solution pathways (higher technology-based removals and higher nature-based removals scenarios).

— Trader margins are based on estimates of sales platform usage from cdr.fyi, and margins per sales platform are based on McKinsey expert insight.

— Financing revenues are estimated through McKinsey Carbon Management Service Line solution-specific cost models, McKinsey Global Carbon Credits Model, and McKinsey expert insight.

— Verification costs are based on estimated measurement, reporting, and verification costs per project from CarbonX.

— Advisory spend is based on industry benchmarks of supplier advisory spend.

The supplier revenue pool represents revenues from all activities surrounding the capture, transport, and storage of CO_2. Based on this analysis, suppliers could gain the greatest share of annual revenues: up to 80 percent by 2050. This high share reflects the complex and costly delivery models for suppliers that would require greater spend on operation and maintenance, both of built infrastructure and of natural assets such as forests.

For investors, we estimate investment returns to soften over time as technologies mature, dropping from 12 to 16 percent today to 9 to 13 percent in 2030 and 4 to 8 percent in 2050. Note that these returns are average ranges based on a portfolio of different solution types, including both NBR and TBR. In parallel, risk profiles could lower and open investment opportunities to a greater number of investors. Current financing margins are largely driven by the higher margins on financing for riskier TBR investments; significantly lower returns are estimated from more-mature NBR. The decrease in financing margins over time reflects an increase in the technological maturity of TBR.

Commodity traders and marketplaces are estimated in this analysis to increase their share of market revenues from 4 to 6 percent today to 6 to 9 percent in 2030 and 8 to 14 percent by 2050. Many early buyers are making bilateral purchases directly from suppliers, rather than facilitating trades through brokers or other intermediaries. This may change over time because intermediary services could be able to offer advantages including diversifying risk through portfolios of CDR credits, industry experience, and price transparency. As the market matures, a move away from bilateral purchases could increase the value pool for traders.

An increase in the share of TBR relative to NBR within the global portfolio of CDR capacity could cause validation revenues to narrow from 2.8 to 3.2 percent today to an estimated 2.1 to 2.5 percent by 2030. TBR tend to have lower monitoring, reporting, and verification (MRV)[24] costs than many NBR. If, as estimated, the balance of TBR increases toward 2030, the comparative share of MRV revenues may decline. A slight uptick is estimated in MRV revenue shares through 2050, reflecting estimated increases in stringency of standards and further reporting requirements.

The value pools for advisory services are estimated to decrease over time as well, reflecting more-mature removal processes and less need for advisory services on innovation, CDR purchasing strategies, and integrating CDR into ESG frameworks.

Suppliers could gain the greatest share of annual revenues: up to 80 percent by 2050. This high share reflects the complex and costly delivery models for suppliers that would require greater spend on operation and maintenance . . .

[24] The net climate impact of a carbon removal project is determined by monitoring and verifying its total emissions, energy consumption, and environmental and public health impacts. Then, a report can be compiled on the project's safety and effectiveness.

Cost estimates: Economies of scale and innovation produce declines

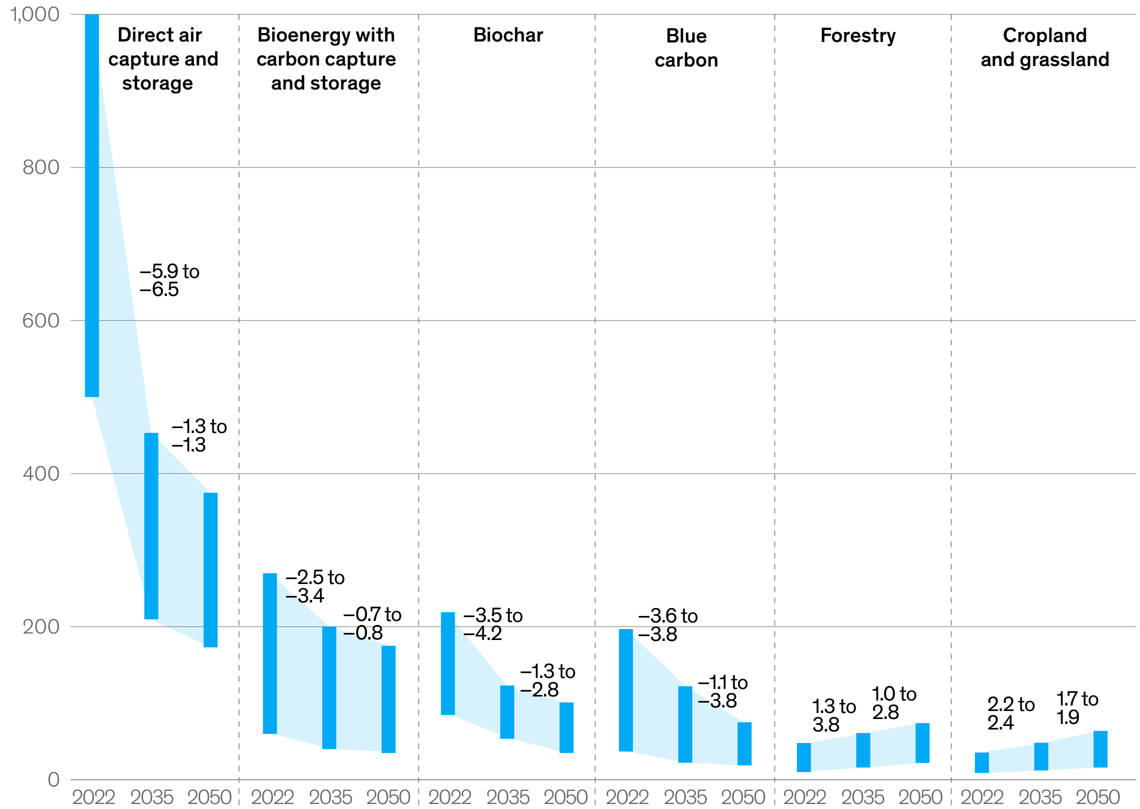
A successful CDR market operating at scale would require costs to decline considerably, especially for durable TBR such as direct air capture and storage. And indeed, our CDR cost[25] estimates show costs declining for most technologies at scale (Exhibit 9), provided the levels of investment and innovation are sufficient to accelerate scale-up and deployment. There is potential for a positive feedback loop in which cost declines lead to further uptake of removals.

Exhibit 9

Technology-based removals costs are expected to decline over time, while costs for nature-based removals will likely increase.

Levelized cost, \$ per metric ton of CO_2

x.x to x.x = Estimated CAGR across time period, %



Source: McKinsey analysis based on TRAILS and Nature Analytics land-use modeling and technology-specific carbon management service line cost models

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[25] We define "cost" as the net levelized cost of removal (LCOR), considered as the total lifetime cost divided by net lifetime CO_2 emissions (with net lifetime emissions defined as gross removal volumes minus all relevant operational emissions). We do not consider noncarbon impacts in our cost calculations. Net LCOR also removes all noncarbon credit revenues generated through removals processes, with these revenues apportioned to reduce the unit cost of one metric ton of carbon removal.

DACS costs may decline the most, largely because they start from the highest baseline. The cost estimates in the exhibit represent costs associated with currently available DACS facilities, including solid and liquid sorbent approaches. Anecdotal evidence from innovative DACS suppliers suggests that future DACS technologies may reduce costs more than is currently possible. At present, realizing DACS cost reductions would largely depend on achieving product innovation for capture efficiency, supply chain efficiency and maturity, and economies of scale and transport. The cost per metric ton of CO_2 removal for DACS could also drop as the emissions intensity of DACS energy inputs falls—for example, through grid decarbonization. Consequently, net removal costs for DACS could decrease.

BECCS is currently a more technologically mature TBR solution than DACS and can deliver durable CDR volumes today at significantly lower cost[26]; thus, BECCS cost declines may be less dramatic. New approaches using biogenic sources of CO_2 such as those from pulp and paper mills may carry opportunities for lower costs than power BECCS because of lower capital expenditures associated with retrofitting pulp and paper plants, lower biomass processing costs, and the existing integration of biomass sources into pulp and paper production.[27] However, costs may increase in later years due to heightened competition for land driven by increasing demand for food, livestock, bio-based feedstock, and fuel.[28] A similar risk exists for biochar,[29] although additional non-carbon-capture revenue—from use as fertilizer, for example—may be able to offset higher feedstock costs.

Although potentially remaining lower than TBR costs, terrestrial NBR costs are estimated to rise, also driven by increasing competition for land. The lowest-cost NBR could be quickly exhausted. Additionally, the rise of new durability and MRV standards may remove less costly, less durable NBR from the market supply in the long term, increasing costs per metric ton while adding to project development times.[30] However, some MRV costs could also fall with scale, digitalization, and standardization.

Because it is exempt from competition for land, blue carbon is a notable exception among NBR. Overall, average costs for blue carbon are estimated to fall only slightly and the range to remain relatively fixed. While the lowest-cost blue-carbon NBR (mostly mangroves) could exhaust quickly, more-novel, higher-durability examples (such as macroalgae and microalgae) are estimated to decline in cost. While the cost profile for mangroves is similar to that of other NBR, mangroves are constrained by suitable coastline; there are no land constraints for noncoastal blue carbon. MRV costs for blue carbon could, however, be relatively high because of challenges inherent in monitoring and reporting on open ocean systems. This could hinder cost reductions.

[26] Thorben Amann et al., “Negative emissions—part 2: Costs, potentials and side effects,” *Environmental Research Letters*, 2018, Volume 13, Number 6.
[27] Chao Fu et al., “Integration of carbon capture in a pulp mill—effect of strategic development towards better biomass resource utilization,” *Frontiers in Thermal Engineering*, 2023, Volume 3.
[28] “Striking the balance: Catalyzing a sustainable land-use transition,” McKinsey, November 7, 2023.
[29] Biochar is a stable, carbon-rich material created by heating sustainably sourced biomass in the absence of oxygen; biochar can be used as a soil amendment and as a means of long-term carbon storage.
[30] For more, see Grayson Badgley et al., “Unpacking ton-year accounting,” CarbonPlan, January 31, 2022.

Rising government commitments

Grants and subsidies are CDR's main supply-side support mechanisms from the public sector. In the United States, the Inflation Reduction Act of 2022 increased the 45Q tax credit to $85 per metric ton (t) of CO_2 for CO_2 captured from industrial and power generation facilities and stored geologically and the credit for geological storage from DACS to $180 per tCO_2.[31] The US Department of Energy has also launched the Carbon Negative Shot, whose objective is to capture and store CO_2 at gigaton scale for less than $100 per metric ton of CO_2 equivalent by 2050.[32]

An increasing number of other governments have begun giving grants to CDR start-ups and supporting technological development of pilot facilities. Removr, a Norwegian DACS company, received around $3.5 million in government backing from Norwegian state enterprise Enova for its industrial-scale pilot.[33] The provisional agreement on the revision of the European Union's Renewable Energy Directive considers the role of financial support for BECCS projects, noting that using biomass for power qualifies for financial support because it is one of the most economical and environmentally beneficial applications for woody biomass.[34]

Some governments are buying or investing in CDR directly. Procurement initiatives aim to build CDR capacity by providing predictable, long-term revenue for suppliers. Sweden has launched an annual $200 million BECCS reverse-auction process, enough to buy at least one Mt of removals, with intended delivery beginning in 2026.[35] This system acts as a price floor procurement model that provides a backup offtake guarantee: the Swedish government will buy credits if suppliers cannot get a better voluntary carbon market (VCM) price. Other governments are investing through sovereign wealth funds. Saudi Arabia's Public Investment Fund recently launched a domestic VCM, while the Nigeria Sovereign Investment Authority will invest in removals as part of a $50 million joint carbon credit venture with Vitol, an energy and commodities company.[36]

Industrial clusters are another means by which governments could consider supporting the CDR market, helping to develop the shared infrastructure needed to reduce CDR supply costs and help mitigate residual industrial emissions.[37] Examples include $1.2 billion in funding for the US Department of Energy's Four Regional Direct Air Capture Hubs,[38] Norway's Northern Lights industrial carbon capture and storage[39] hub's integration of Climeworks' DACS technology, and the United Kingdom's East Coast Cluster, which includes the Drax BECCS plant.

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31 For a summary of these changes, see "Carbon capture and the Inflation Reduction Act," Clean Air Task Force, February 16, 2023.
32 "Carbon Negative Shot," Office of Fossil Energy and Carbon Management, accessed November 22, 2023.
33 "Norway backing Removr's efforts to industrialise Direct Air Capture, finances pilot at world-leading technology test center," Removr, February 28, 2023.
34 "European Green Deal: EU agrees stronger legislation to accelerate the rollout of renewable energy," European Commission, March 30, 2023.
35 "Expenditure area 20 general environmental and nature conservation" ("Utgiftsområde 20 Allmän miljö- och naturvård"), Riksdag of Sweden, October 10, 2021.
36 "Nigerian sovereign fund, Vitol launch venture to invest in carbon removal projects," Reuters, April 5, 2023.
37 Sometimes referred to as hubs, industrial clusters are made up of emissions facilities in the same geographic areas that share the same CO_2 transportation and storage or utilization infrastructure.
38 "Regional Direct Air Capture Hubs," Office of Clean Energy Demonstrations, accessed November 22, 2023.
39 A process that captures CO_2 emissions from industrial processes, power plants, or the atmosphere and stores them underground or in other long-term storage facilities.

03 Lowering barriers to scaling CDR

Scaling CO_2 removal to deliver net-zero removal volumes is a challenging endeavor, fraught with complexity and nuance. Indeed, the risks and challenges facing the industry have been documented at length.[40] This chapter considers those challenges broadly, framing them in terms of the industry's need for the following:

— stronger buyer incentives

— improved transparency of standards, practices, and services

— clear public-sector signals

— lower-cost approaches

— greater capacity to deliver at scale

[40] Several sources have documented CDR market risks and challenges, including *Pathways to commercial liftoff*, April 2023; *Barriers to scaling the long-duration carbon dioxide removal industry*, July 2022; *The case for negative emissions*, June 2021; "Barriers to negative-emissions technologies," 2020; "Addressing critical challenges in carbon dioxide removal," December 10, 2020.

We will outline each of the above briefly and then explore actions that could be undertaken to lower barriers and address these issues, including illustrative examples of efforts under way. The right combination of resources, skills, planning, and regulatory oversight could foster the growth needed to scale CDR, but collaboration and exigent action from all stakeholders are imperative.

Stronger buyer incentives

CDR demand is currently at the megaton scale—three orders of magnitude smaller than the six to ten $GtCO_2$ annual CDR capacity needed by 2050. And demand is central to increasing CDR capacities: encouraging demand signals could provide incentives for suppliers to innovate and increase capacities in the near term. Market price and buyers' perceived need for CDR credits determine their willingness to pay. Actions stakeholders could take to strengthen buyer incentives are detailed below.

Increased public recognition of CDR purchases

Although purchasing removals is voluntary, some companies have already begun integrating CDR into their sustainability plans. Several corporate buyers have set and publicized their own removals-purchasing goals, many of which can be tracked on open-source resources such as cdr.fyi. Microsoft has, for example, provided extensive project-by-project reviews of its CDR purchases, including cobenefits and side effects.[41] And Stripe retains an open request-for-proposal GitHub repository to provide market transparency into its CDR purchases.[42]

Recognition of near-term purchases

Voluntary net-zero schemes such as the Science Based Targets initiative (SBTi) provide guidance and support for organizations to set robust climate goals. However, most existing voluntary net-zero schemes do not include removals in frameworks for recognizing near-term mitigation efforts. This is largely to encourage focus on efforts to decarbonize operations and supply chains, before encouraging the use of removals. Voluntary bodies could consider approaches to phasing in targets for purchases of CDR credits in the near term—potentially as a supplementary opt-in for those with targets compliant with net zero. Signatories to voluntary schemes could also influence the net-zero targets for stakeholders within their supply chains. SBTi has acknowledged the importance of CDR and is developing carbon removal purchase guidance that, once available, could play a role in spurring near-term demand.[43]

Improved transparency of standards, practices, and services

Because many CDR solutions are novel approaches, there are reasonable concerns over their effectiveness and integrity. Demand could be dampened by the perception that the quality of CDR is unreliable or if opaque reporting were to undermine trust in wider uptake of CDR. As demonstrated by existing standards and guidelines for emissions reduction and avoidance credits, establishing high-integrity and feasible methodologies for measuring CDR would be paramount to establishing a well-functioning CDR market. Integrity could be evidenced by high-quality CDR credits, verification of additionality, and enforcement of accounting guidelines. Feasibility could be demonstrated through standards, methodologies, and guidelines that are readily evidenced as well as clear, practical, cost-effective, and replicable. There are numerous actions that stakeholders across the value chain could take to effect improvements in transparency and thereby demonstrate integrity and feasibility.

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41 "Microsoft carbon removal: Lessons from an early corporate purchase," Microsoft, 2021.
42 "Stripe climate carbon removal purchases - source materials," GitHub, accessed November 30, 2023.
43 "SBTi Public Consultation on Beyond Value Chain Mitigation (BVCM)," SBTi, June 2023.

Global standards for high integrity
Standards setters and voluntary bodies could earn public support and trust with standards that facilitate transparency, promote high-quality removals, and do not compromise on integrity. Stakeholders are taking actions to secure CDR credit integrity. The Integrity Council for Voluntary Carbon Markets (ICVCM) has established the Core Carbon Principles that define a high-integrity carbon credit.[44] Verra and other VCM players are beginning to develop guidelines for technology-based removals accounting.[45] There have likewise been efforts to strengthen guidance and requirements for durability in CDR credits. Climate Action Reserve, an offset registry for global carbon markets, for example, has a 100-year minimum permanence requirement for its nature-based removals.[46]

Some frameworks, such as the international greenhouse-gas standard SOCIALCARBON, are also pursuing robust guidance for assessing noncarbon benefits of CDR solutions.[47] Offset accreditors have begun to develop mechanisms to quantify and monitor performance according to the United Nations' Sustainable Development Goals (SDGs), such as the Sustainable Development Verified Impact Standard (SD VISta) from Verra and SDG Impact Tool from Gold Standard.[48] Increasingly, marketplaces are establishing their own guidelines, such as those for biochar in Carbonfuture's C-Sink certification standards.[49]

Buyer's guides and market integrity tools
The CDR market is complex, and its complexity may only grow in the short term as new solutions are piloted. Intermediaries and other services providers could help buyers to cut through this complexity by, for example, providing carbon footprint simulation tools that could help identify appropriate CDR solutions, accounting for emission scopes, costs, and more. McKinsey has previously shared insights on this topic.[50] Additionally, service providers could reinforce market integrity by providing insurance covering CDR delivery or reversal risks, accessible price benchmarking (including cost breakdowns for transport, storage, and MRV), and wider knowledge about the evolving marketplace.[51]

Clear public-sector signals

It is currently unclear how near-term CDR credit purchases may be regarded within policy frameworks. Over time, policy frameworks could establish a system in which high-quality removals could be sourced and sold globally. Greater clarity on CDR's integration into global markets could strengthen demand signals in areas with cost-effective sites for CDR solutions. Integration of CDR credits into compliance-based market mechanisms could also stimulate broad and reliable demand, creating revenue streams capable of supporting CDR capacity at net-zero scale.

44 "The Core Carbon Principles," ICVCM, access November 22, 2023.
45 "New initiative to boost carbon capture and storage solutions will develop a methodology under the Verified Carbon Standard," Verra, June 24, 2021.
46 Jennifer Weiss, "Keeping it 100—permanence in carbon offset programs," Climate Action Reserve, July 26, 2022.
47 The SOCIALCARBON standard is focused on NBR. For more, see *SOCIALCARBON standard v6.1*, SOCIALCARBON, June 2023.
48 "Sustainable Development Verified Impact Standard," Verra, accessed November 22, 2023; "Gold Standard SDG Impact Tool," Gold Standard, accessed November 22, 2023.
49 Hannes Junginger-Gestrich, "Carbonfuture Sink certification standards," Carbonfuture, March 5, 2021.
50 For more, see "CO_2 removal solutions: A buyer's perspective," McKinsey, February 3, 2023.
51 *The case for negative emissions*, June 2021.

A long-term CDR policy outlook

Policy mechanisms that provide insight into long-term CDR market movements could provide signals to stimulate short-term demand and enable stakeholders to prepare for future market developments. For example, the European Union's Horizon Europe program has included grants to help identify issues and options for MRV and carbon removal account systems broadly as well as for specific CDR solutions.[52]

Integrated carbon-trading schemes

Integrating CDR into carbon-trading schemes could increase suppliers' confidence in revenue streams and boost investments to scale cost-efficient supply. For example, carbon removals guidance currently under public consultation[53] may be integrated into Article 6.4 of the Paris Agreement, allowing removal credits to eventually be purchased through a global carbon market overseen by the United Nations' Article 6.4 Supervisory Body and accounted for under national determined contributions.[54] The European Union's proposed Carbon Removal Certification Framework (CRC-F) attempts to align guidelines, principles, standards, and methodologies around the certification aspects of CDR.[55] Once implemented, CRC-F may address many MRV integrity and accuracy concerns, helping improve market certainty and boost buyer confidence. It would be up to individual jurisdictions to decide how much to integrate their CDR credits in global carbon-trading systems relative to holding CDR credits for their own net-zero goals. A more open global trading system could create more demand offtakes for emerging CDR suppliers.

Direct procurement of CDR credits

In addition to traditional buyers, public entities could act as buyers via procurement programs, either purchasing removals directly or placing net-zero requirements on future public tenders, subcontractors, and partners. The US Department of Energy, for example, has committed to procuring $35 million worth of CDR credits through the Purchase Pilot Prize.[56] Existing instruments could be adapted to other solution types and adopted in other regions. Direct public procurement of CDR could also be funded by a carbon tax.

Guidance for green claims and disclosure

Clear guidance and accounting practices for green claims and sustainability disclosure around CDR is largely lacking. The EU Green Claims Directive is an example of efforts to align environmental claims with scientific evidence. The European Union, through its Corporate Sustainability Reporting Directive and pending European Sustainability Reporting Standards, aims to require a broad set of companies to report on their sustainability targets and disclose CO_2 removal and mitigation projects financed by carbon credits.[57] Future efforts within CDR could include stress-testing and target-planning requirements for environmental claims.

52 *Horizon Europe—Work Programme 2021-2022: 8. Climate, energy and mobility*, European Commission, May 10, 2022.
53 "Call for input 2023—structure public consultation: Removal activities under the Article 6.4 mechanism," UN Framework Convention on Climate Change, June 2023.
54 "Article 6.4 mechanism," UN Framework Convention on Climate Change, accessed November 22, 2023.
55 "Carbon removal certification," European Commission, accessed November 22, 2023.
56 "DOE announces $35 million to accelerate carbon dioxide removal," Office of Fossil Energy and Carbon Management, September 29, 2023.
57 "Corporate sustainability reporting," European Commission, accessed November 22, 2023; note that these would be done separately to overall climate target disclosures.

Public authorities, standard setters, and the scientific community could provide clarity about CDR with regard to the distinctions between CDR and avoidance and reduction credits, which have received criticism about credit integrity, for example,[58] or by defining fact-based and science-driven criteria for what CDR entails and what environmental claims can be made. In addition, ensuring that existing and future certifications and quality criteria are widely understood and accessible would enable investors to perform due diligence. Nongovernmental organizations could serve as watchdogs and work alongside academia and public authorities to establish a transparent, inclusive social dialogue about the place-based impacts of CDR, its effects on local economic development, and intersections with environmental justice.

Cross-industry collaboration

The number of organizations working across the CDR industry has grown rapidly, with organizations operating as brokers, exchanges, marketplaces, registries, standard setters, MRV providers, project developers, AMC initiatives, credit raters, advocacy organizations, and more.[59] This rapid growth leaves room for greater collaboration between actors. Improved collaboration could reduce duplicative efforts and could take many forms. The emerging CDR industry could, for example, issue a purpose statement. This could follow the example of the Business Roundtable's "Purpose of a Corporation"[60]—and include nontraditional CDR actors—to boost the field's visibility and credibility, shore up investor confidence, and encourage more suppliers to enter the market. Coordination at the systems level (such as through industry groups) could help unify the industry and leverage its collective strengths. Global and industry-wide collaboration is an ambitious but achievable action, as evidenced by examples in other industries, such as the Hydrogen Council and the Industrial IoT Consortium.

Lower-cost approaches

Today, the high price of CDR credits remains a significant barrier to mainstream market adoption. Encouraging initiatives that can reduce costs, therefore, could play a key role in increasing the uptake of CDR. Many CDR solutions are constrained by resource availability and trade-offs with other climate technologies, so a wide range of available solution types could support lower average costs over time. Innovations in CDR could also reduce up-front costs and pricing for near- and long-term purchases. Specific stakeholder actions could help accelerate the transition to a lower-cost, higher-volume industry.

Cost innovation initiatives

Public research grants or calls for consortium-based initiatives focused on cost reduction could empower CDR suppliers to take bold and innovative steps to scale. Suppliers of a given solution type could work together to develop capital expenditure reduction efforts across different projects. Funding to develop economical MRV implementation is vital for many NBR and would provide important support for other solutions as well.

[58] "The carbon con," SourceMaterial, January 18, 2023.
[59] For more, see Puro.earth's map of the voluntary carbon market.
[60] "Business Roundtable redefines the purpose of a corporation to promote 'an economy that serves all Americans,'" Business Roundtable, August 19, 2019.

Supplier-led cost reduction innovations

Existing suppliers and developers are innovating to bring down the cost of durable CDR, scale capacity, and provide new market solutions. TBR providers CarbonCapture and Charm Industrial are exploring the benefits of modular approaches that could be rolled out at smaller scales for DACS and bio-oil, respectively. Many other TBR approaches, on the other hand, would require industrial-scale infrastructure to deliver, and so modular approaches could provide greater flexibility and scaling at pace. XPRIZE Milestone Award winner Captura[61] is developing direct ocean capture technology that could provide engineering approaches aiming to deliver lower costs than DACS. And NBR provider Mast Reforestation is using drones to drop seeds, significantly reducing costs and lead times for large-scale forestry projects.

Project financing of first resort

Governments, philanthropic actors, and investors with a higher risk tolerance could improve project economics for emerging CDR providers by financing early-stage and applied-research projects, demonstrator sites, or first-of-a-kind plants, lowering costs as well as the risks for specific projects. Public actors could also leverage blended finance tools to support the supplier business case and hence crowd in private investments.

Greater capacity to deliver at scale

The conundrum faced by supplier start-ups is that without first mounting successful pilot projects, they cannot attract sufficient funding, but start-ups need funding to build pilot installations. Scale-ups face a similar challenge: they need considerable investment to fund their expansion efforts but lack the proof of concept at high volumes that investors seek. But these catch-22 situations could be broken with targeted stakeholder actions.

Many CDR solutions are constrained by resource availability and trade-offs with other climate technologies, so a wide range of available solution types could support lower average costs over time.

[61] Captura was one of 15 teams awarded $1 million each to develop carbon removal solutions. "XPRIZE and the Musk Foundation award $15M to prize milestone winners in $100M Carbon Removal competition," XPRIZE, April 22, 2022.

CDR clusters

Industrial trade associations, public actors, and investors could assist start-up suppliers by supporting the development of CDR industrial clusters or hubs. CDR hubs could help pool resources in shared transport and storage infrastructure and increase suppliers' access and ability to attract talent. Hubs or clusters could also, in turn, play an important role in contributing to the economies surrounding them by leveraging existing supply chains and infrastructure, supporting goals for place-based development.

CDR innovation systems

Scientific and engineering talent is at the core of CDR. Public agencies, universities, accelerators, incubator programs, and private-sector actors could develop and deploy programs such as accelerators to encourage development of CDR talent, products, and services. Creating direct paths to enter and contribute to the CDR industry could include funding basic and applied research, highlighting funding opportunities, and coaching for researchers and entrepreneurs.

Supporting infrastructure for CDR at scale

As CDR grows, collective coordination may be needed to address limitations of accessible renewable energy, biomass, and land. CDR providers would need stable supplies of components and materials as well as talent. Careful planning and collaboration to address issues related to supply chains and national and international climate strategies could circumvent impediments to scaling on the desired timeline.

Guidance on transport and storage

Clear national and international rules, guidelines, and permitting requirements for transporting and storing CO_2 may help to unlock global supply chains necessary for a CDR industry operating at scale. This would also require inclusion of clear requirements for treatment of carbon reversals (physical leakage of CO_2 from storage sites). In the United Kingdom and European Union, for example, there is national and regional regulation in place, respectively, to determine required actions for different parties in reversal events. In the United States, reversal regulation is, to date, determined at the state level. Further legal guidance on reversal liabilities could help to unlock storage supply in broader geographies.

Given the cross-cutting challenges facing the CDR industry, it seems unlikely that focusing on singular initiatives would be enough to create the collaborative environment needed for CDR to scale. Intra-industry collaborations that acknowledge and build upon existing work could avoid costly duplication and encourage practical actions to scale CDR capacity to meet climatic needs. Credibility and market confidence could unlock demand, foster vital research and innovation of CDR solutions and infrastructure, and bolster the CDR talent pool. In short, bold, collective action in the near term can help deliver CDR's promise in the long term.

Given the cross-cutting challenges facing the CDR industry, it seems unlikely that focusing on singular initiatives would be enough to create the collaborative environment needed for CDR to scale. Bold, collective action in the near term can help deliver CDR's promise in the long term.

04 Potential early-mover advantages in the CDR industry

There may be tangible, long-term benefits (including strategic and competitive advantages) available to those who engage in critical near-term efforts to scale the CO_2 removal industry. This chapter explores these potential benefits by stakeholder group.

Investors could build market-leading capabilities

The value pools assessment in this report shows that investors could realize $20 billion to $100 billion in CDR market revenues by 2050. Investors that engage early could build their reputation and relationships to position themselves as market leaders in the future industry. Proactive investors could, for example, build CDR-focused business units to build relationships with early suppliers, standards setters, regulators, and associated services such as insurance. Building these relationships and helping to fund early players could establish an investor as a go-to funder of CDR initiatives, positioning them ahead of competitors and helping them unlock significant revenue opportunities once the market matures.

Early investors in CDR suppliers could develop market insights that give them an edge over the competition in identifying high-potential opportunities and accelerating growth, including a deep understanding of CDR supply chains, optimal business models, and which financing mechanisms are most appropriate for different CDR solutions. And, by acting alongside climate venture capitalists and others seeking catalytic climate impacts, early investors could fortify their reputations as climate leaders by being at the forefront of creating an essential net-zero industry.

A range of investment returns is available

CDR investments remain largely early stage, with a range of investment risks available: from lower-risk investments in nature-based removals to higher-risk investments in novel technology-based removals. This variety of returns profile may prove helpful for interested investors, who could tailor portfolios of CDR investments to balance risks.

For investors with higher risk appetites, CDR could be an opportunity to achieve higher internal rates of return (IRR); for example, Credit Suisse estimated potential IRRs of 12 to 20 percent for carbon capture and storage projects.[62] Investors with higher risk appetites may benefit from early involvement because current IRRs may decline as technologies mature and the market scales.

Investing in more-mature NBR may present a more attractive opportunity for investors with lower risk appetites. Finance Earth estimates that nature-based climate solutions could earn IRRs between 2 and 12 percent.[63] For many investors, engaging in a range of different CDR solutions could help diversify risks and avoid overcommitting to specific generations of technologies.

Suppliers could establish foundations for future success

Our value pools analysis shows that suppliers could earn 73 to 82 percent of estimated CDR market revenues—$250 billion to $900 billion—by 2050. If demand scales, suppliers would need to rapidly respond to meet it. Suppliers with established physical infrastructure, supply chains, and skilled workforces could have a significant advantage in expanding programs quickly and successfully. TBR suppliers that move down the learning curve earlier and faster could deliver lower-cost solutions—which are essential for a market operating at scale. Early movers could be especially relevant to NBR, for which relationships with local landowners and local ecosystem expertise could make or break implementation.

Future innovation and growth funding

Suppliers scaling early could complement their business case with numerous available funding sources, such as grants, subsidies, and philanthropic funding that could become less accessible as the market matures. Financial incentives such as those offered through the Inflation Reduction Act in the United States, the European Union's Innovation Fund, or XPRIZE[64] and similar organizations could help early suppliers invest in innovation with time to test and develop proprietary technologies affording long-term competitive cost advantages.

62 *Treeprint: Carbon markets—the beginning of the big carbon age*, Credit Suisse, April 8, 2022. This report assumes a carbon price of $50 to $100 per metric ton.
63 *A market review of nature-based solutions: An emerging institutional asset class*, Finance Earth, May 2021.
64 XPRIZE Carbon Removal, funded by Elon Musk and the Musk Foundation, is a $100 million, four-year prize to develop CDR solutions.

Retrofitting of existing assets
For some suppliers, CDR capacity could be added to existing assets via relatively cost-effective retrofitting. For example, coal-fired power plants could be converted to BECCS, potentially helping to mitigate the transition risk of decommissioning under net-zero pathways. Decommissioning assets and bringing them back online later could be cost prohibitive or even infeasible if assets are not maintained. Oil and gas companies could use much of their existing infrastructure, talent, and physical sites for storage.[65] Gas and oil provider Equinor, for example, has been creating development vehicles for BECCS projects to take CO_2 into depleted wells.[66] Some opportunities may be less apparent: forestry companies may have underground storage for direct air capture; agriculture companies could encourage landowners in their supply chain to participate in carbon capture through improved soil management or utilizing biochar on fields; and shipping and marine companies could think about how they might use removal technologies in waterways.

Buyers could secure sufficient removals and signal long-term commitment

Early buyers that sign future offtake agreements with suppliers could gain confidence that they will have a reliable supply of future removals even if demand rises sharply because of new expectations for companies to purchase CDR to neutralize emissions or tighter standards on other carbon credits such as avoidance credits, for example. Early buyers may be more likely to secure a reliable, high-quality CDR supply required to neutralize residual emissions to meet net-zero targets. If demand were to outstrip supply, the lead time for delivering additional capacity could be long. Additionally, buyers that agree to long-term deals with suppliers (including future offtake agreements) may lock in prices that could hedge against risks of potential price increases (for scenarios in which demand increases faster than delivered capacity).

As a pledge to neutralize residual emissions once decarbonization efforts have been exhausted, CDR purchase commitments can be a valuable addition to ESG strategies. Beyond the sustainability gains, a well-considered ESG strategy underpinned by CDR could support business aims such as talent recruitment and revenue growth from potential green premiums[67] on products associated with environmentally conscious products. Respondents to McKinsey's carbon buyer survey rated their marketability to employees and ability to realize green premiums as 7.0 and 7.5 out of 10.0, respectively, in terms of their importance as factors driving interest in carbon credits.[68]

Marketplaces and intermediaries could set the bar on integrity and industry expertise

As volumes grow for CDR, trading for these volumes could coalesce around a small number of major marketplaces in a "winner takes all" dynamic. This dynamic can be seen in other markets; for example, there is a high concentration of crude oil price benchmarks around a small number

65 Carbon injection and sequestration into aquifers and reservoirs is, for example, analogous to the reverse process of extracting hydrocarbons.
66 Matthew B.H. Bright and Patricia Loria, "Lessons captured from 50 years of CCS projects," *The Electricity Journal*, August–September 2021, Volume 34, Number 7.
67 A green premium is an increase in price that consumers are willing to pay for products that fulfill certain environmental criteria.
68 The survey was conducted online in 2022 (sample size of 72). Respondents were asked, "What are the motivating factors for your company to purchase carbon removals? On a scale of one to five, please score the following factors on importance for motivating your company in selecting a platform (one = not an important factor, five = extremely important factor)." Responses were averaged and rescaled to be out of ten.

of players, including Brent and West Texas Intermediate. Our value pools analysis shows that marketplaces and other intermediaries and service providers could earn 9 to 14 percent of estimated CDR market revenues—$40 billion to $140 billion—by 2050. As the ecosystem of CDR intermediaries takes shape, standards setters, market service providers, exchanges, commodity traders, and MRV providers could inform and develop superior industry benchmarks for quality, transparency, and integrity. The first-mover advantages realized by intermediaries depends on the role they play in the market, as outlined below.

Standards setters and guideline bodies

Early-moving standards setters and guideline bodies that develop high-integrity methodologies for the major CDR technologies could inform the core standard around which the voluntary carbon market removals market operates. Moving early also gives standards setters and guideline bodies a greater chance to test approaches in a lower-volume market, helping test and strengthen methodologies.

MRV providers

MRV providers that trial methods early could build a solid and trusted track record, taking advantage of the smaller market to innovate cost-effective methods to measure and report at scale. A trusted reputation, developed in early stages in a smaller market, may also persist and unlock greater revenue opportunities in the future market.

Marketplaces

Currently, marketplaces have relatively low barriers to entry and face lower costs to establish themselves. Building a solid reputation with early buyers could help attract new buyers that enter the CDR market later and seek out established marketplaces with technical expertise, quality assurance, pricing knowledge, and the ability to diversify investments.

Commodity traders

Commodity traders could integrate CDR into their existing supply chains, working with agricultural suppliers to integrate biochar or bio-oil solutions, for example. Early insight into the future of carbon trading gleaned from such integrations could support upstream commodity suppliers with additional revenue streams from carbon credits.

Governments could support social and economic growth

CDR could facilitate opportunities for governments to support regions where jobs could be affected by the transition to renewable energy. Estimates from a 2021 Coalition for Negative Emissions report, for example, demonstrated the potential for skills transfers from legacy industries to CDR: STEM professionals in oil and gas have a 70 to 90 percent skills match with their peers in BECCS and DACS.[69] There is also an opportunity for governments to explore overlaps in location between companies in the fossil-fuel industry and novel CDR such as DACS and BECCS. Industrial clusters could also work with governments to embed CDR as part of their long-term commercial strategies, which could help keep productive industrial assets in regions. There may also be opportunities for governments to support the use of cobeneficial environmental and production CDR solutions in the agricultural sector.

Governments may also move early to support the CDR industry to help deliver national climate commitments and secure national supplies.

69 *The case for negative emissions*, June 2021.

Globally, multiple regions could realize comparative advantages to delivering CDR volumes at scale. In the near term, regions with natural-capital resources for NBR could target a scale-up in CDR supply that could include afforestation, improving the carbon capture potential of cropland and grassland or improving coastal carbon capture through mangrove restoration. One example of this is the Great Green Wall initiative, which spans 11 African countries and has restored nearly 18 million hectares of degraded land with green landscapes, bringing food and water security to residents and restoring plant and animal habitats.[70] Regions with access to affordable renewable energy sources such as geothermal and solar may realize advantages in supplying TBR, such as DACS, that depend on ready sources of renewables to scale. Storage may also be a key area of advantage for regions to explore. Major oil-producing regions, for example, may be able to store carbon in exhausted wells; peridotite-rich regions such as the Arabian Peninsula could sequester carbon via mineralization.[71]

While CDR is not a substitute for concerted commitments to decarbonization, the IPCC has made it clear that carbon removals are an essential component of long-term net-zero pathways. The analysis and wide-ranging potential action steps discussed in this report set out a path for scaling the CDR industry in the near term while potentially affording compelling near- and long-term advantages to early movers across the value chain. Business leaders (especially in hard-to-abate sectors) who develop CDR literacy now can help ensure their organizations have access to the removals they need to hit their net-zero targets in 2050 and beyond.

[70] "A green wall to promote peace and restore nature in Africa's Sahel region," UN Environment Programme, February 22, 2023.
[71] Douglas Fox, "Rare mantle rocks in Oman could sequester massive amounts of CO_2," *Scientific American*, July 1, 2021.

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