Rhodium Group

The Benefits of Innovation: An Assessment of the Economic Opportunities of Highly Durable Carbon Dioxide Removal

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Executive summary

The emerging industry of carbon dioxide removal (CDR) encompasses an array of innovative solutions that are ready for takeoff. The US has an opportunity to maintain and enhance its position as a global leader in this space thanks to its high geologic carbon dioxide (CO_2) storage potential, varied landscapes, skilled workforce, and advanced research capabilities. While climate change mitigation may be a primary motivation for CDR support, a host of additional benefits will accompany a scaling of this industry. These include economic, social, and environmental benefits. Given the diversity of CDR approaches, these opportunities will be distributed over a range of workers, communities, and ecosystems in the US.

Job opportunities associated with scaling CDR

In this analysis, we focus on leading highly durable forms of CDR—those that remove CO_2 and keep it out of the atmosphere for at least 1,000 years—included in our recent report The Landscape of Carbon Dioxide Removal and US Policies to Scale Solutions. The five CDR approaches we explore are enhanced rock weathering (ERW), biomass with carbon removal and storage (BiCRS), direct ocean capture (DOC), ocean alkalinity enhancement (OAE), and direct air capture (DAC). As CDR continues to gain momentum, companies with new and compelling methods to remove CO_2 will keep popping up. The rapidly evolving nature of this field underscores the importance of tech neutrality when developing CDR policies.

Each CDR project type is unique in process, location, and capture capacity. To provide an idea of CDR employment opportunities once the industry has reached commercialization in the US, we conducted an analysis exploring cumulative CDR jobs associated with scaling each approach to capture 20 MMT of CO_2 annually—totaling 100 MMT of CO_2 removal across our five in-scope solutions (Figure ES1). Policies that support carbon removal at this scale can unlock significant job creation. With adequate support, each of these CDR approaches could achieve at least 20 MMT of annual capacity between 2030 and 2040.

Employment associated with highly durable CDR will total between 95,000 and 130,000 jobs per year once the industry reaches 100 MMT of annual capture capacity.

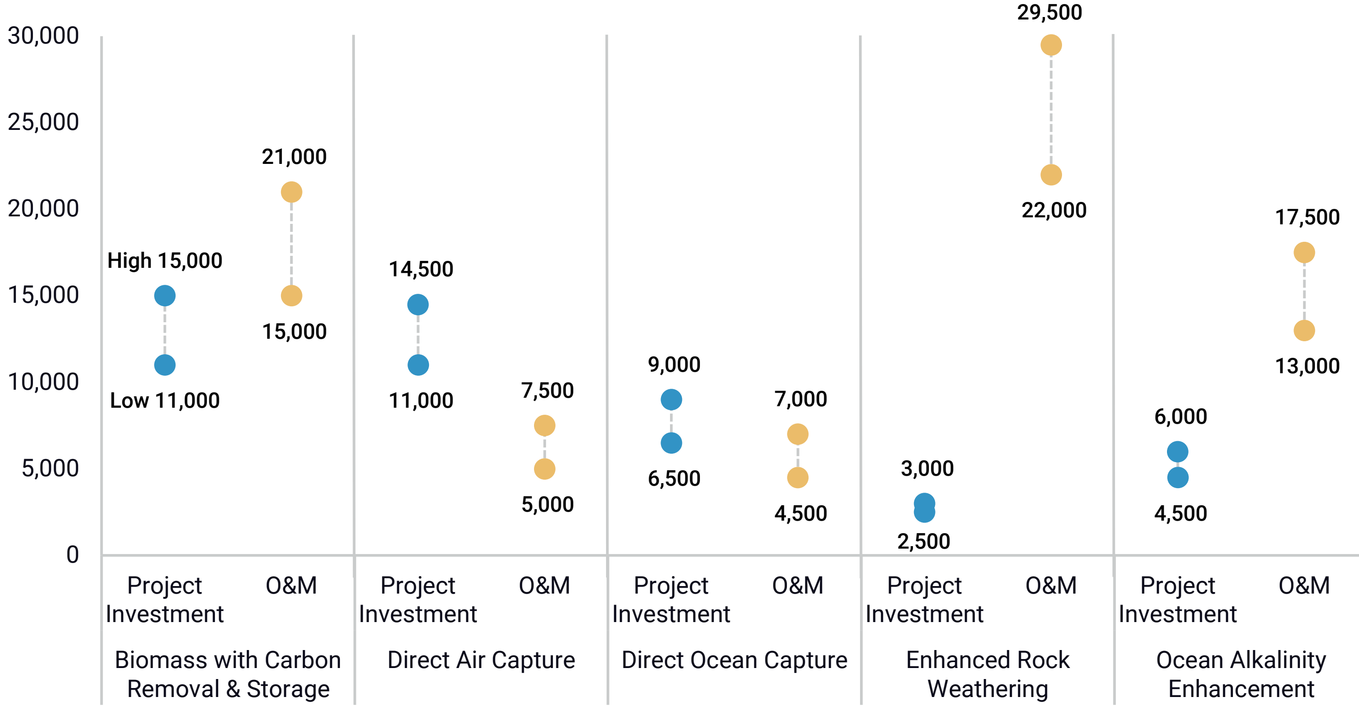
These job numbers include project level and upstream supply chain jobs; they do not include induced jobs.[1] Across approaches, just over one-third of the employment opportunities come from project investment jobs, which are associated with the construction, engineering, materials, equipment, and supply chains required to establish a project, and the remaining two-thirds come from ongoing jobs to operate the projects. The exact distribution is dependent upon the type of CDR.

[1] Induced jobs are those resulting from increased spending by workers (e.g., an increase in restaurant workers due to project workers dining out).

FIGURE ES1

Jobs associated with 100 MMT of annual CDR deployment

Average annual project investment jobs and ongoing operations and maintenance (O&M) jobs



Source: Rhodium Group

Notes: We assume the 100 MMT of annual CDR deployment is split evenly at 20 MMT across each of these highly durable approaches. Our job numbers reflect the expected cost learning associated with deployment. Project investment job values above are averaged over an 8-year scaling period. The actual jobs associated with capital investment in any given year will depend on the pace of project development. Employment per industrial output is assumed to stay constant over time. BiCRS deployment is comprised of BECCS, bio-oil, and biowaste injection. BECCS, DAC, and DOC jobs include jobs associated with CO_2 injection and storage.

Supporting a diverse array of CDR approaches will support a diverse variety of workers

The breadth of CDR approaches is reflected in the wide variety of occupations that these projects will support. For this analysis, we explored the top occupations associated with each highly durable CDR approach (Table ES1).

Certain skill sets will be important across CDR approaches—this includes metal workers and assemblers (such as welders); engineers; machinery installation, maintenance, and repair technicians; and project developers. In contrast, some CDR approaches will support unique occupations that cater to their process. For instance, ERW and OAE will support mining and quarry workers. BiCRS approaches will support biomass waste transportation occupations due to their use of agricultural and livestock waste. Moreover, CDR approaches that require geologic storage of CO_2 and biomass (DAC, DOC, and BiCRS) can open job opportunities for oil and gas workers who have easily transferable skill sets.

TABLE ES1

Top occupations associated with each highly durable CDR approach

Direct Ocean Capture	**Enhanced Rock Weathering**
Metal workers and assemblers	Transportation occupations
Operators and production occupations	Mining and quarry workers
Engineers	Construction trades
Direct Air Capture	**BiCRS: Bioenergy with Carbon Capture & Storage**
Construction trades	Metal workers and assemblers
Metal workers and assemblers	Construction trades
Engineers	Engineers
BiCRS: Bio-oil / Biowaste Injection	**Ocean Alkalinity Enhancement**
Machinery installation, maintenance, and repair technicians	Transportation workers
Transportation occupations	Machinery installation, maintenance, and repair technicians
Project developers and site managers	Operators and production occupations

Source: Rhodium Group.
Notes: This is a synthesized table; an expanded version can be found in Chapter 7.

Co-benefits beyond employment opportunities

Each CDR approach has a unique set of environmental and social benefits, in addition to employment opportunities. In this report, we describe some of the top co-benefits associated with each CDR approach, including the handful of highlights listed below.

- **ERW:** agricultural ERW can improve soil health, increase crop productivity, and enhance resilience to heat and pests. Wastewater ERW can improve water quality by removing dissolved CO_2 and reducing nitrogen pollution.
- **BiCRS:** biomass-based solutions can help reduce excess woody biomass from forest residues in fire prone areas, reducing wildfire risks.
- **OAE & DOC:** these approaches can help reduce ocean acidity by introducing an alkaline water stream into the ocean. In turn, this can have positive impacts on marine life, especially those with carbonate shells such as mussels, oysters, and corals.

CHAPTER 1

Highly durable carbon dioxide removal

Carbon dioxide removal (CDR) is a group of climate change mitigation solutions that result in a net removal of CO_2 from the atmosphere. As the complexity of curbing greenhouse gas emissions has become more evident, carbon dioxide removal (CDR) has come into focus as a key component of achieving economy-wide decarbonization. The emerging CDR industry encompasses an array of innovative solutions ready for takeoff. The US has an opportunity to maintain and enhance its position as a global leader in this space thanks to its high geologic CO_2 storage potential, varied landscapes, skilled workforce, and advanced research capabilities. CDR can play three primary roles in decarbonizing the US economy:

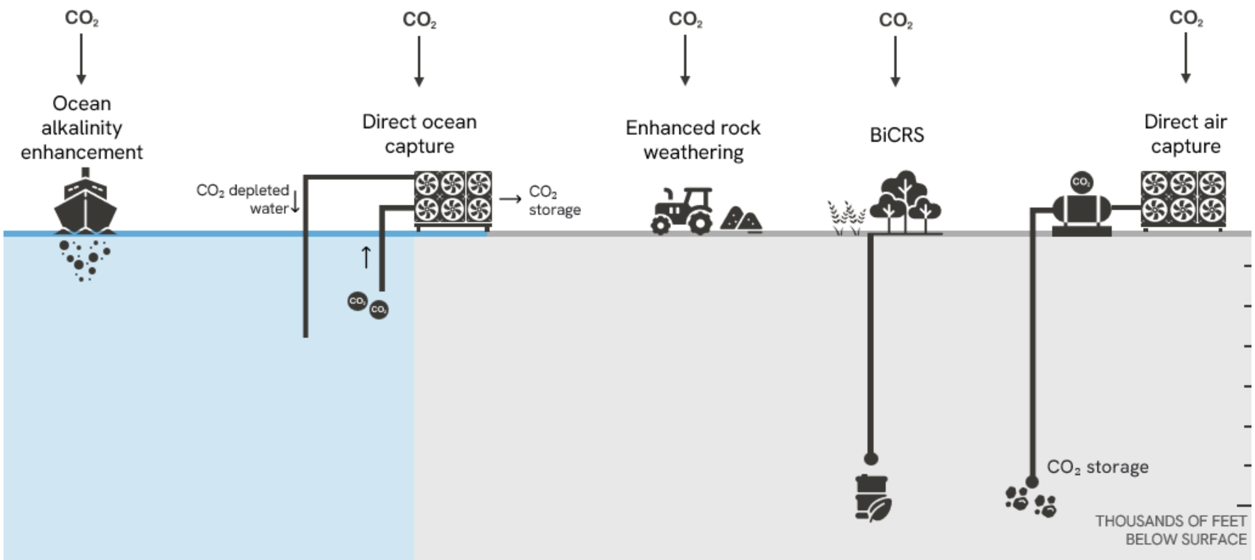
1. It can help achieve net-zero emissions by offsetting greenhouse gas emissions from particularly hard-to-abate sectors, such as aviation and industry,
2. Certain CDR solutions produce a pure stream of CO_2 which can be used as a feedstock for low-emission fuels to help reduce emissions from sectors such as transport, and
3. CDR can remove anthropogenic emissions that already exist in the atmosphere, often referred to as legacy emissions, to limit global temperature rise.

Moreover, assuming successful decarbonization globally, CDR is the only strategy that can continue to reduce atmospheric concentrations of CO_2 in the long run.

Our recent report The Landscape of Carbon Dioxide Removal and US Policies to Scale Solutions provides a comprehensive overview of the variety of CDR approaches and policy options to boost CDR deployment. We find that achieving decarbonization by midcentury will require the US to scale CDR capacity to at least one gigaton per year.

Dozens of CDR approaches exist, each of which vary across key factors, including cost, scalability, maturity, and durability. Durability, or permanence, refers to how long a CDR method keeps CO_2 out of the atmosphere. Depending on the type of CDR, this can range from decades to millions of years. In this report, we focus on leading highly durable forms of CDR—those that have at least 1,000 years of permanence—included in our Landscape of CDR report. The five CDR approaches we explore are enhanced rock weathering (ERW), biomass with carbon removal and storage (BiCRS), direct ocean capture (DOC), ocean alkalinity enhancement (OAE), and direct air capture (DAC) (Figure 1).

FIGURE 1
Illustration of highly durable CDR solutions in scope



Source: Rhodium Group

While climate change mitigation may be the primary motivation for CDR deployment, a host of additional benefits will accompany a scaling of this industry. These include the economic benefits associated with CDR projects. In this report, we explore the diverse array of jobs and occupations associated with highly durable CDR projects. In addition to economic benefits, each CDR approach has a unique set of environmental and social benefits. We highlight key co-benefits associated with each CDR approach in their dedicated chapters below.

This report will first outline the methodology and assumptions underpinning our economic impact analysis. Next, a section will be dedicated to each of the highly durable CDR approaches where we explore the jobs associated with a first-of-a-kind (FOAK) project. To provide a better picture of what the economic benefits of a CDR industry at scale might provide, the final chapter will explore the total jobs associated with 100 million metric tons (MMT) of CO_2 removal per year distributed evenly across the five approaches.

Economic impact methodology

Each highly durable CDR category is an umbrella of sub-technologies or processes. Our jobs results represent a blend of at least two sub-approaches for each CDR approach. We used our analytical judgment based on current cost and performance data availability, stage of development, process scalability, and access to industry experts to determine which sub-approaches to include in the analysis. Therefore, it does not represent all highly durable CDR sub-approaches comprehensively. Moreover, this is a rapidly evolving field. As CDR continues to gain momentum, companies with new and compelling methods to remove CO_2 will keep popping up.

Since these are emerging climate solutions, many of these projects are still in the early stages of deployment. Therefore, empirical job data is unavailable, and uncertainty remains regarding the precise job profiles that will be associated with these projects. Our economic impact analysis provides a directional estimate of the amount and types of jobs we expect to accompany CDR deployment. To do this, we determined each CDR method's capital and operating costs for a first-of-a-kind facility based on expert interviews, literature, cost models, and Rhodium analysis. The costs are informed by the size of the projects, technology maturity, and any associated costs such as transportation, monitoring, reporting, and verification (MRV), and CO_2 storage. For CDR approaches that produce pure streams of CO_2, we model carbon storage rather than utilization. To estimate employment numbers, we input Rhodium's CDR cost data into the economic input-output model IMPLAN using its national-level tools. We distinguish job types into two categories:

1. project investment jobs, which are associated with the construction, engineering, materials, equipment, and supply chains required to establish a project and

2. operations and maintenance (O&M) jobs, which are ongoing jobs over the lifetime of a project.

Our employment numbers capture both on-site and off-site jobs supporting the installation and maintenance of CDR projects. Project-level jobs are associated with direct inputs, including construction, engineering, equipment, materials, and operating expenses. Supply chain jobs refer to upstream jobs that feed into these expenses. To better understand the skilled labor needed to fill these positions, we analyzed the underlying occupations that make up CDR project investment and O&M jobs. We pulled occupational results from IMPLAN and supplemented these outputs with Bureau of Labor Statistics data and industry insights. We do not consider supplier jobs in our occupational analysis.

For our first-of-a-kind (FOAK) analyses, we evaluated the various CDR processes, assuming they were at an initial commercial-scale size. Given that the CDR approaches range from relatively small modular projects to massive industrial buildings, it is important to note that the FOAK analyses vary in size and project construction times across the CDR approaches. The methodology and assumptions used for our removal industry at 100 MMT scale scenario are outlined in the chapter titled *CDR's Collective Impact*.

CHAPTER 2

Biomass with carbon removal and storage

As the name suggests, biomass with carbon removal and storage (BiCRS) refers to CDR methods that capture CO_2 using biomass. The biomass feedstock used for these CDR processes absorbs CO_2 via photosynthesis while growing. That carbon is subsequently isolated and stored in some form—for instance, in CO_2 injection wells or locked away in a material. Several forms of BiCRS exist in the CDR space, from oceanic to terrestrial applications. In this report, we narrow our focus on two BiCRS categories that have a high certainty of achieving at least 1,000 years of permanence: (1) bio-oil and biowaste injection and (2) bioenergy with carbon capture and storage (BECCS). Since these two categories vary greatly in terms of project size, processes, and costs, we provide separate economic impact analyses for each.

Bio-oil and biowaste injection

Like the other CDR categories we explore in this report, the sub-approaches bio-oil and biowaste injection have distinct processes; however, they are similar in terms of project size, given their modular nature and overall strategy for removing CO_2 from the atmosphere. Bio-oil is a CDR method that heats biomass (likely agricultural or forestry waste) to high temperatures to produce a bio-oil, which is then stored deep in the subsurface using injection wells. Bio-waste injection takes organic waste, including but not limited to agricultural waste and paper sludge, and injects the substance into geologic formations to sequester the carbon. For this report, we will occasionally refer to the umbrella of these approaches as biomass injection methods.

BIO-OIL AND BIOWASTE INJECTION JOB OPPORTUNITIES FOR AN INITIAL COMMERCIAL-SCALE PROJECT

For this analysis, we assume a FOAK project size of 30,000 tons of CO_2 capture per year for individual bio-oil and biowaste projects. We estimate that a capital investment of $3 to $9 million will be required to support building a FOAK project of this size. As you will see in later sections, this is a relatively small project size compared to some of the other CDR approaches explored in this report. The size of a FOAK project is not indicative of biomass injection methods' cumulative capture potential nor their scalability; it simply reflects the modular nature of these processes. Unlike large, centralized projects, bio-oil and biowaste injection projects plan to remain modular as they scale. This allows developers to optimize for opportunities where the local supply of biomass can sustain individual projects, ideally located close to areas with conducive geologic injection potential.

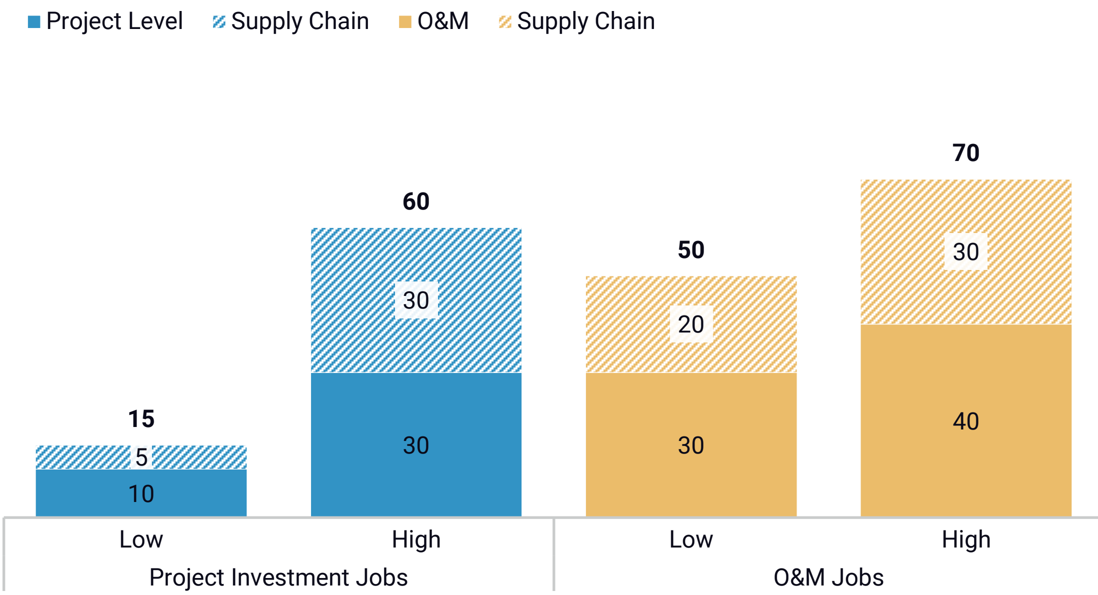
We find that a first-of-a-kind 30-kiloton biomass injection CDR project generates between 15 and 60 jobs over a 1-year construction period. Additionally, we see 50 to 70 ongoing jobs over the project's lifetime associated with operations and maintenance.

These job estimates include project investment jobs and those associated with the required supply chain (Figure 2).

FIGURE 2

Jobs associated with an initial 30-kiloton per year biomass injection project

Average annual project investment and ongoing O&M jobs



Source: Rhodium Group

Notes: These job estimates reflect employment estimates for bio-oil sequestration and biowaste injection. We assume a project construction period of one year. These projects are expected to be operational for 20-30 years. Results will vary by biomass injection approach and project configuration.

BIO-OIL AND BIOWASTE INJECTION OCCUPATIONS

The top occupations associated with FOAK biomass injection projects include: (1) machinery installation, maintenance, and repair technicians, (2) transportation occupations, (3) project developers and site managers, (4) operators and production occupations, and (5) metal workers and assemblers.

Top biomass injection occupations

- Machinery installation, maintenance, and repair technicians
- Transportation occupations
- Project developers and site managers
- Operators and production occupations
- Metal workers and assemblers

Transportation occupations primarily include truck drivers associated with moving biomass to the injection site. Operators and production occupations include computer-controlled tool operators. Inspectors, and testers needed for facility construction and operation. Metal workers and assemblers encompass welders and solderers, machinists, machine tool cutting operators and tenders, and structural metal fabricators and fitters needed to construct a biomass injection project.

BIO-OIL AND BIOWASTE INJECTION CO-BENEFITS

Bio-oil and biowaste injection offer several co-benefits beyond job creation. One advantage is the potential to use abandoned oil and gas wells for biomass injection, which can lower investment costs while enabling verification that the wells aren't leaking pollutants or greenhouse gases. Furthermore, given the need for geologic injection expertise, these projects can help create job opportunities for fossil fuel workers due to their transferable skill sets. These processes can also produce small amounts of biochar, increasing carbon removal potential and enhancing soil health when applied. Moreover, bio-oil and biowaste injection can help reduce excess woody biomass from forest residues in fire-prone areas, reducing wildfire risks. They can also make use of unwanted biomass, such as municipal solid waste, that would otherwise be sent to landfills. Additionally, utilizing waste biomass that would otherwise be left to decompose helps prevent methane emissions resulting from the decomposition process.

Bioenergy with carbon capture and storage

BECCS is a sub-category of BiCRS that converts biomass into an energy product while capturing the CO_2 emissions using carbon capture and storage technology. Like any CDR process, whether a BECCS project qualifies as CDR depends on the life-cycle emissions of the entire process. In practice, BECCS qualifying as carbon negative means that the biomass feedstock and transport has a low-carbon intensity, the energy source is low-emitting, and most or all the process and combustion emissions are captured and stored. A biomass feedstock with low-carbon intensity will most likely be sourced from biomass waste or residues. It's unlikely that a BECCS process that uses dedicated energy crops as a feedstock would qualify as CDR. For this report, we are only referring to BECCS processes that achieve carbon negativity.

There are numerous BECCS processes that result in a variety of energy products or feedstocks. The BECCS sub-approaches included in this analysis are biomass combustion for electricity generation and biomass gasification for hydrogen production.

BECCS JOB OPPORTUNITIES FOR AN INITIAL COMMERCIAL-SCALE PROJECT

For our jobs analysis, we assume a FOAK project size of 500,000 tons of CO_2 capture per year for an initial commercial-scale BECCS project. This sizing aligns with planned BECCS for electricity generation and hydrogen production projects in the US, such as:

- The Filer City BECCS electricity project which is projected to capture about 500 kilotons of CO_2 per year and scheduled to begin construction in 2025, and
- Mote's Sacramento BECCS for hydrogen production project which plans to sequester more than 450 kilotons of CO_2 per year.

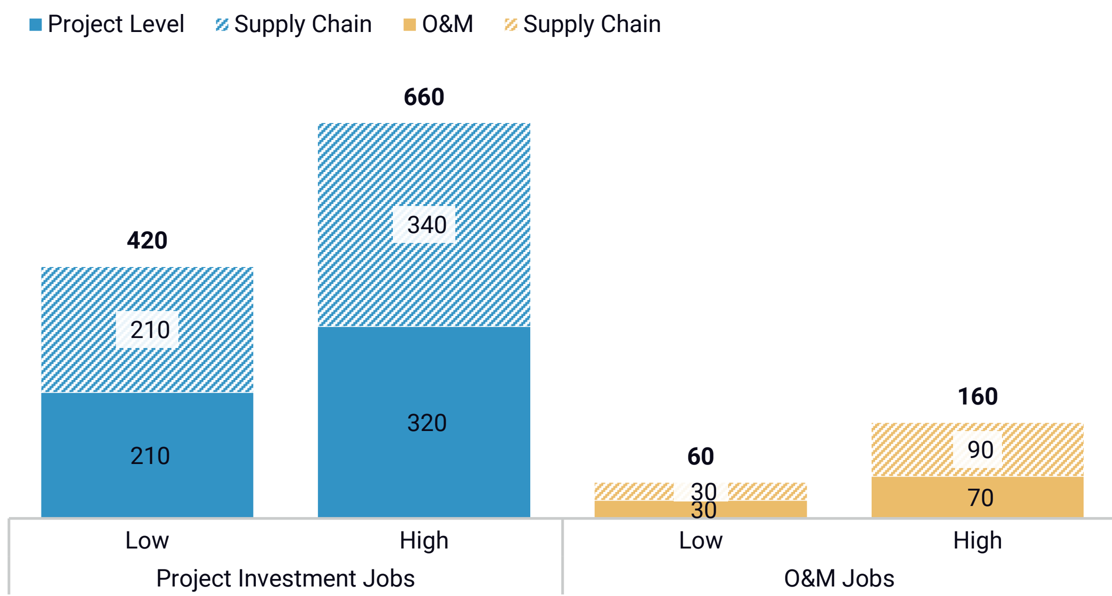
We find an initial 500-kiloton BECCS project generates between 420 and 660 average annual jobs over the 4-year construction period, including project investment and supply chain jobs (Figure 3). Additionally, we see 60 to 160 ongoing jobs associated with operating and maintaining the project and related supplier activities over the facility's lifetime.

Rhodium estimates that a capital investment of $260 to $350 million will be required to support building a 500-kiloton FOAK BECCS project.

FIGURE 3

Jobs associated with an initial 500-kiloton per year BECCS project

Average annual project investment and ongoing O&M jobs



Source: Rhodium Group

Notes: These job estimates reflect employment estimates for BECCS for electricity production and BECCS for hydrogen production. We assume a project construction period of four years. These projects are expected to be operational for 20-30 years. Results will vary by BECCS approach and project configuration.

These employment estimates include the jobs associated with CO_2 injection and storage via geologic saline storage or in-situ mineralization. In-situ mineralization is an emerging CO_2 storage process that accelerates CO_2 mineralization compared to natural processes and conventional geologic storage methods. This is usually accomplished through injecting CO_2 into basalt rock or injecting pre-dissolved CO_2 into a geologic reservoir. Of the total BECCS jobs, 15 to 25 project investment jobs are associated with establishing CO_2 injection wells. Additionally, 5 to 20 ongoing jobs are associated with 500 kilotons of annual CO_2 storage.

BECCS OCCUPATIONS

The top occupations associated with FOAK BECCS projects include: (1) metal workers and assemblers, (2) construction trades, (3) engineers, (4) project developers and site managers, and (5) transportation occupations. Construction trades primarily include electricians, pipefitters, pipelayers, and plumbers needed for the buildout of BECCS facilities. Engineering roles involve mechanical, industrial, and civil engineers, as well as drafters and engineering technicians, to design and build a BECCS facility. Transportation occupations include truck drivers needed to move biomass to the BECCS facility.

Top BECCS occupations

- Metal workers and assemblers
- Construction trades
- Engineers
- Project developers and site managers
- Transportation occupations

BECCS also requires jobs for CO_2 storage. These roles include engineers, like those previously listed, as well as petroleum engineers. Additionally, CO_2 storage operations require workers such as derrick and rotary drill operators and roustabouts.

BECCS CO-BENEFITS

In addition to capturing carbon, BECCS facilities create useful products such as hydrogen, electricity, and fuels. Like bio-oil and biowaste injection, BECCS projects can use unwanted biomass, such as municipal solid waste, that would otherwise be sent to landfills. BECCS facilities can also utilize woody biomass sourced from forest residues in fire prone areas, reducing wildfire risks. Furthermore, by utilizing biomass that otherwise would be left to decompose, BECCS can help to prevent methane emissions typically produced by the decomposition process. Since carbon-negative BECCS projects will likely utilize injection and storage for CO_2 sequestration, they can help create employment opportunities for oil and gas industry workers with easily transferrable skill sets.

BiCRS at scale

By the time the BiCRS solutions in this chapter reach 20 MMT of deployment in the US, we expect 11,000 to 15,000 average annual project investment jobs and 15,000 to 21,000 ongoing jobs.

For our at-scale analysis, the 20 MMT is divided evenly between biomass injection methods and BECCS deployment. More information can be found about our Nth of a kind (NOAK) analysis in the final chapter titled *CDR's Collective Impact*.

CHAPTER 3

Direct air capture

Direct air capture (DAC) is a form of CDR that removes CO_2 directly from ambient air and stores the captured carbon.

Thus far, DAC has received the most policy support of the CDR approaches. The Inflation Reduction Act increased 45Q tax credits for DAC to $180 per ton when paired with storage. Additionally, the Infrastructure Investment and Jobs Act includes $3.5 billion for the Regional Direct Air Capture Hubs program to develop four commercial-scale DAC hubs. In a previous analysis, we explored the economic benefits of the Direct Air Capture Hubs. The 45Q tax credit and the DAC Hubs program are exemplary models of demand-side and demonstration-and-deployment policies that can help accelerate the commercialization of CDR solutions.

Our job estimates capture the economic impacts associated with multiple DAC processes currently under construction beyond the pilot scale in the US: solid sorbent, liquid solvent, and mineralization DAC. Below, we provide a brief description of each process:

- Solid sorbent DAC uses solid filters to chemically and/or physically bind with CO_2 from the atmosphere. Once saturated, these filters are heated to around 100°C, allowing concentrated CO_2 to be released for storage or utilization.
- Liquid solvent DAC captures CO_2 using an aqueous solution to dissolve CO_2 and currently requires much higher temperatures, around 900 °C, to release the captured CO_2 for storage or utilization.
- Mineralization DAC uses solvents like sodium hydroxide or calcium oxide to capture and dissolve CO_2 from ambient air. The CO_2 is then removed from this material by heating or other methods so that it can be stored or utilized. The leftover solvents are then re-exposed to ambient air to restart the CO_2 capture process.

DAC job opportunities for an initial commercial-scale project

In this section, we estimate the jobs associated with the construction and operation of a FOAK DAC project that captures 500,000 tons of CO_2 per year. This capacity aligns with the first large-scale commercial DAC projects in the US. Occidental's Stratos Project is expected to be operational later this year and capture 500 kilotons of CO_2 annually. Similarly, Project Cypress in Louisiana is expected to capture a total of 1 MMT of CO_2 per year across two facilities. As DAC continues to scale, the capture rate per facility will likely increase. For instance, the South Texas DAC Hub is designed to initially capture 500 kilotons of CO_2 per year with plans to double its capacity to 1 MMT over time, eventually reaching twice the size of this illustrative 500-kiloton FOAK facility.

Rhodium estimates that building a 500-kiloton FOAK DAC project will require a capital investment of $380 to $980 million, depending on the technology used.

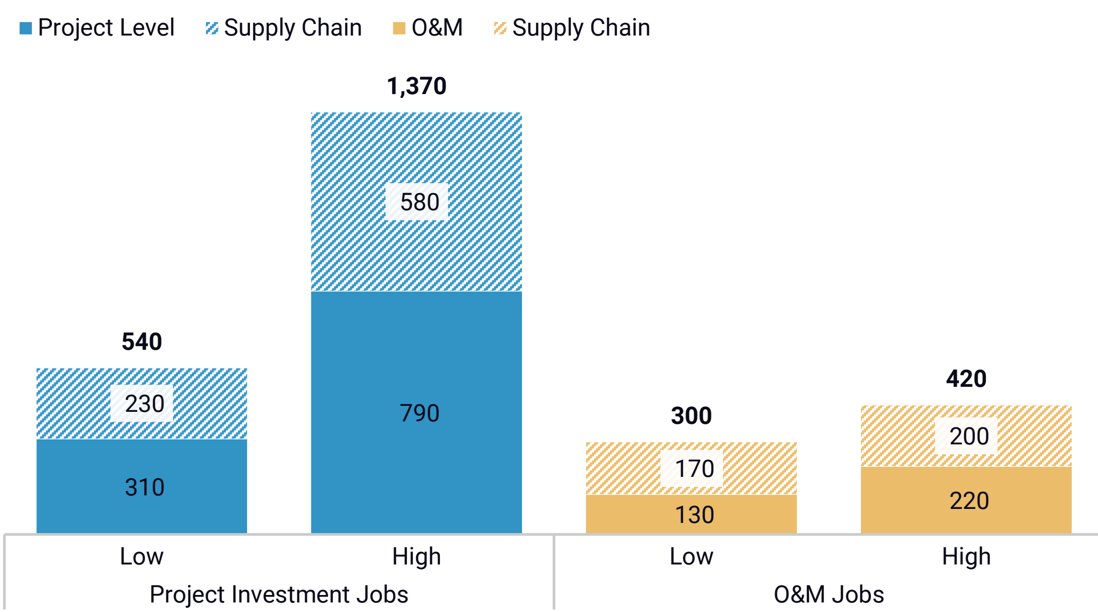
We find an initial 500-kiloton DAC project generates between 540 and 1,370 average annual jobs over the 5-year construction period, including project investment and supply chain jobs (Figure 4). Additionally, we see 300 to 420 ongoing jobs associated with operating and maintaining the project and related supplier activities over the facility's lifetime.

These employment estimates include the jobs associated with CO_2 injection and storage via geologic saline storage or in-situ mineralization. See the section *BECCS job opportunities for an initial commercial-scale project* in the previous chapter for more information on in-situ mineralization and the job estimates associated with 500 kilotons of CO_2 storage.

FIGURE 4

Jobs associated with an initial 500-kiloton per year DAC project

Average annual project investment and ongoing O&M jobs



Source: Rhodium Group

Notes: These job estimates reflect employment estimates for solid sorbent, liquid solvent, and mineralization DAC. We assume a project construction period of five years. These projects are expected to be operational for 20-30 years. Results will vary by DAC approach and project configuration.

DAC occupations

The top occupations associated with FOAK DAC projects are: (1) construction trades, (2) metal workers and assemblers, (3) engineers, (4) machinery installation, maintenance, and repair technicians, and (5) project developers and site managers. Construction trades include construction laborers, managers, carpenters, electricians, pipelayers, plumbers, and construction equipment operators associated with DAC facility construction. Metal workers and assemblers include welders, solderers, machinists, and various assemblers and fabricators, needed during both the facility construction and operations phases. Engineering roles include mechanical, civil, industrial, and electrical engineers, drafters, and engineering technologists.

Top DAC occupations

- Construction trades
- Metal workers and assemblers
- Engineers
- Machinery installation, maintenance, and repair technicians
- Project developers and site managers

DAC projects will also require skill sets associated with CO_2 injection and storage. These roles include engineers, like those previously listed, and petroleum engineers. CO_2 storage workers such as derrick and rotary drill operators and roustabouts will also be needed.

DAC co-benefits

One benefit of DAC facilities is their flexibility in siting, as demonstrated in our state-by-state DAC interactive dashboard. This flexibility enables communities across the US to benefit from the economic impacts of DAC deployment. DAC also requires injection and storage workers, who could come from the oil and gas industry as they often have skill sets that are easily transferrable. In addition to employment opportunities, some solid sorbent DAC technologies can generate freshwater, which can be utilized in various ways.

DAC at scale

NOAK DAC facilities will have similar occupational profiles to initial DAC facilities. However, we expect a slightly lower percentage of machinery installation, maintenance, and repair technicians due to increased energy efficiency at facilities.

Once DAC has reached 20 MMT of capture capacity in the US, we expect between 11,000 to 14,500 average annual project investment jobs and 5,000 to 7,500 ongoing jobs.

More information can be found about our NOAK analysis in the chapter titled *CDR's Collective Impact*.

CHAPTER 4

Direct ocean capture

Direct ocean capture (DOC) is another promising CDR method that removes CO_2 from ocean waters and the atmosphere by changing the pH, pressure, or temperature of ocean water in a facility. This CO_2 is stored or utilized, and the CO_2-depleted water is returned to the ocean to recapture CO_2 from the atmosphere. Our jobs estimates reflect a variety of DOC processes. Certain approaches simply accomplish carbon removal, while others also result in the formation of byproducts such as electrolytic hydrogen.

DOC job opportunities for an initial commercial-scale project

Based on insights from developers in this space, our FOAK jobs analysis assumes a capture capacity of 100 kilotons of CO_2 per year. This capacity also aligns with the DOC company Equatic's first commercial plant in Quebec which is set to be operational in the next few years. Rhodium estimates that a capital investment of $70 to $150 million will be required to support building a 100-kiloton initial commercial-scale project.

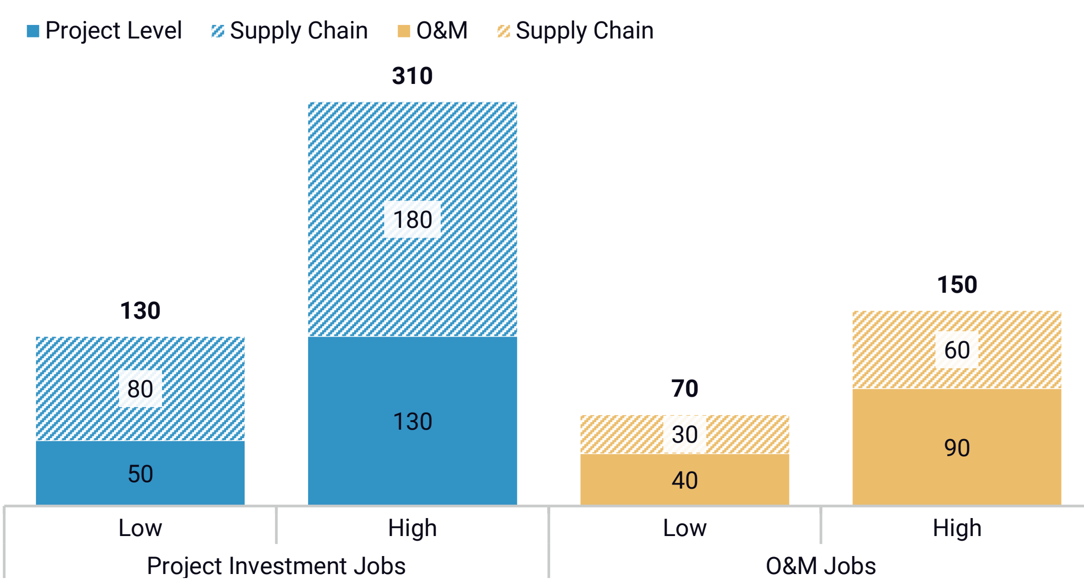
We find an initial 100-kiloton DOC plant generates between 130 and 310 average annual jobs over the 3-year construction period (Figure 5). Additionally, we see 70 to 150 ongoing jobs over the lifetime of the project associated with operations and maintenance.

These estimates include project investment jobs and the required supply chain jobs.

FIGURE 5

Jobs associated with an initial 100-kiloton per year DOC project

Average annual project investment and ongoing O&M jobs



Source: Rhodium Group.

Notes: These job estimates reflect employment estimates for DOC processes that may or may not produce additional byproducts. We assume a project construction period of three years. These projects are expected to be operational for 20-30 years. Results will vary by DOC approach and project configuration.

Notably, these employment estimates are not directly comparable to those of a DAC facility. This illustrative project represents one-fifth the capacity of our assumed DAC plant, involves distinct processes, and assumes a shorter construction period.

DOC occupations

The top occupations associated with FOAK DOC projects are: (1) metal workers and assemblers, (2) operators and production occupations, (3) engineers, (4) project developers and site managers, and (5) machinery installation, maintenance, and repair technicians. Metal workers and assemblers, the largest category, includes welders, machinists, various tool operators, assemblers, and fabricators associated with the construction of the DOC facility. Operators and production occupations include computer-controlled tool operators, inspectors, testers, and chemical equipment operators and tenders, all of which are crucial for both facility construction and ongoing operations. The primary engineering occupations include mechanical, industrial, and electrical engineers, drafters, and engineering technicians. These occupations are particularly needed during the design and construction of a DOC facility.

Top DOC occupations

- Metal workers and assemblers
- Operators and production occupations
- Engineers
- Project developers and site managers
- Machinery installation, maintenance, and repair technicians

Additionally, DOC will require occupations related to the storage of CO_2. This will involve various engineering occupations, including petroleum engineers. These projects will also need various CO_2 storage workers, which could include derrick and rotary drill operators, roustabouts, mining machine operators, and rock splitters.

DOC co-benefits

The DOC process offers several co-benefits. One of these outcomes is an alkaline stream of water, which, when released into the oceans, helps to reduce ocean acidity. This can have positive impacts on marine life, especially species with carbonate shells such as muscles, oysters, and corals. The released stream of water is also of high quality, as impurities are filtered out before the electrolytic process begins. Moreover, DOC requires jobs associated with injection and storage of CO_2, which utilize skill sets often found in the oil and gas industry. As DOC scales, it could provide new job opportunities for oil and gas workers, supporting their transition as our economy becomes less fossil fuel dependent.

DOC at scale

Once DOC reaches commercialization, Rhodium foresees NOAK projects will have similar occupational profiles as the initial projects outlined above. We expect that most individual onshore DOC projects to maintain a capacity of roughly 100 kilotons per year, while offshore projects could deploy at the megaton scale.

By the time DOC has reached 20 MMT of deployment in the US, we expect 6,500 to 9,000 average annual project investment jobs and 4,500 to 7,000 ongoing jobs.

More information can be found about our NOAK analysis in the chapter titled *CDR's Collective Impact*.

CHAPTER 5

Enhanced rock weathering

Enhanced rock weathering (ERW), also known as enhanced weathering (EW), is a CDR approach that expedites natural weathering processes. This is usually accomplished by grinding or crushing alkaline minerals or rocks to increase surface area and allow for more CO_2 capture potential. Through interaction with water and CO_2, ERW converts CO_2 into bicarbonate ions, which can eventually move into streams, rivers, and the ocean. This bicarbonate can be safely sequestered for geologic timescales.

The two sub-approaches of ERW we include in our analysis are agricultural ERW and wastewater ERW. As the name suggests, agricultural ERW involves applying crushed calcium and magnesium rich rocks, typically silicate rock, to farmland. This practice is similar to the common US agricultural method of applying limestone to manage the pH balance of the soil, which is most commonly viewed as a carbon source. By switching to silicate rocks, such as basalt, this practice has the added benefit of becoming a carbon-negative solution in addition to maintaining soil health. Wastewater ERW achieves carbon removal by contacting crushed rock with CO_2-rich municipal and industrial wastewater streams. Both forms of ERW transform CO_2 from a greenhouse gas into bicarbonate, which stays in oceans for geologic timescales.

ERW job opportunities for an initial commercial-scale project

Since ERW projects occur on individual farms and in conjunction with wastewater facilities, the size of an initial commercial-scale project is much smaller than that of the other CDR approaches explored in this report. For our FOAK analysis, we assume 5,000 tons of CO_2 capture per year. To contextualize these numbers, our assumed FOAK DAC and BECCS facilities capture 100 times the amount of CO_2 of our sample ERW project. Similar to bio-oil and biowaste injection, the size of a ERW FOAK project is not indicative of the solution's cumulative capture potential or scalability but instead reflects the modular nature of these processes.

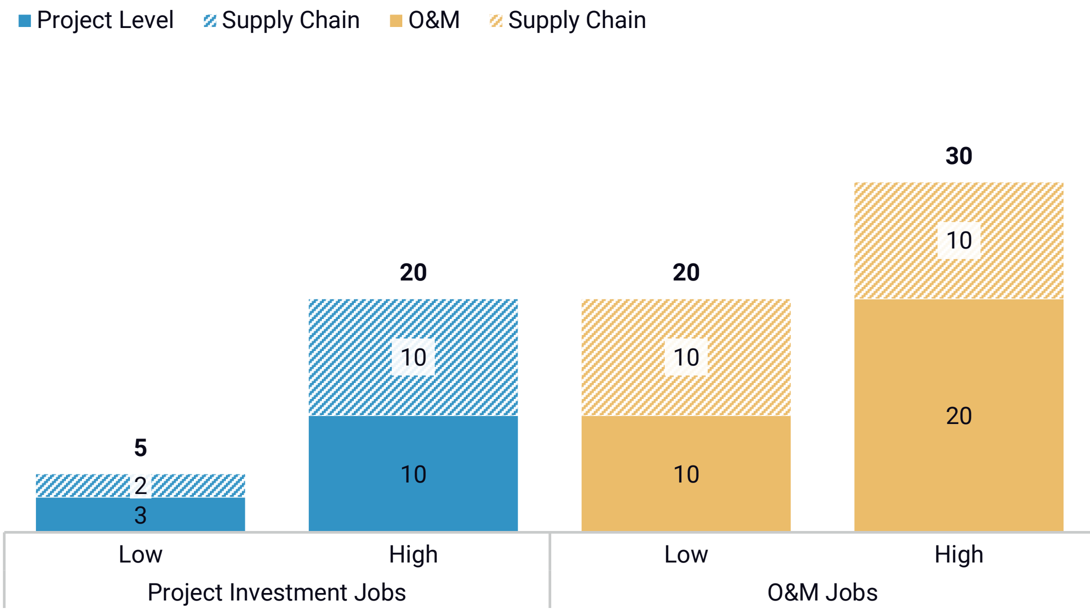
In the context of agricultural ERW, the farm size needed to achieve this level of capture is highly dependent on project-specific factors, including the region and soil quality. As a rough estimate, 5 kilotons of annual capture may correspond to farms ranging from 2,000 to 8,000 acres, depending on the assumed capture rate per acre and the annual removal rate. US agricultural ERW developers report projects with farms as small as 15 acres and as large as 20,000 acres. Assuming 5 kilotons of annual capture for agricultural EWR aligns with our expectations for a FOAK wastewater ERW facility with ideal organic material concentrations.

We find that a 5-kiloton ERW project generates 5 to 20 average annual jobs over the 1-year construction period (Figure 6). Half of these jobs are at the project level and the other half come from supply chain requirements. In addition, we see 20 to 30 ongoing jobs over the lifetime of these projects.

FIGURE 6

Jobs associated with an initial 5-kiloton per year ERW project

Average annual project investment and ongoing O&M jobs



Source: Rhodium Group

Notes: These job estimates reflect employment estimates for agricultural and wastewater ERW. We assume a project construction period of one year. These projects are expected to be operational for 5-30 years depending on the ERW approach. Results will vary by ERW approach and project configuration.

Unlike other forms of CDR, agricultural ERW projects do not require the build-out of large industrial-sized facilities or much upfront equipment. Therefore, most jobs are associated with the ongoing operations of these carbon removal projects.

ERW occupations

The top occupations associated with a FOAK ERW project include: (1) transportation occupations, (2) mining and quarry workers, (3) construction trades, (4) project developers and site managers, and (5) machinery installation, maintenance, and repair technicians. Transportation occupations will be key to delivering basalt to agricultural fields and distributing it across the farmland. Construction trades, such as construction equipment operators, electricians, pipelayers, and plumbers, are necessary for wastewater ERW facility construction, as well as operating and maintaining equipment for agricultural and wastewater ERW projects.

Top ERW occupations

- Transportation occupations
- Mining and quarry workers
- Construction trades
- Project developers and site managers
- Machinery installation, maintenance, and repair technicians

ERW co-benefits

ERW processes offer numerous co-benefits in addition to job opportunities. Agricultural ERW can improve soil health, increase crop productivity, and enhance resilience to heat and pests. Alkaline rocks such as basalt can reduce the need for chemical fertilizers that can release powerful greenhouse gases such as nitrous oxide. Basalt can directly substitute for limestone, which releases CO_2 when broken down. Additionally, basalt can reduce topsoil loss by forming secondary clays that help to stabilize the soil. Using basalt can also extend the life of quarries and eliminate excess basalt dust, which is often a waste material at these sites. Furthermore, wastewater ERW can improve water quality by removing dissolved CO_2 and reducing nitrogen pollution.

ERW at scale

As ERW deployment increases, we expect there will likely be a higher share of mining and quarry occupations due to technological breakthroughs in data collection methods.

At 20 MMT per year of ERW deployment in the US, we expect 2,500 to 3,000 average annual project investment jobs and 22,000 to 29,500 ongoing jobs.

For ERW, particularly agricultural ERW, a very small percentage of overall costs goes towards capital investment since it does not require the build-out of a facility or much upfront equipment. Most of the effort and project costs are associated with the ongoing operations of transporting, applying, and monitoring basalt application. As a result, ERW has the lowest project investment jobs of those we explore but has the highest amount of ongoing jobs. More details are provided in the final chapter titled *CDR's Collective Impact*.

CHAPTER 6

Ocean alkalinity enhancement

Ocean alkalinity enhancement (OAE) is CDR approach that transforms CO_2 in the oceans into carbonate and bicarbonate ions through the introduction of alkaline material. This reduces the CO_2 concentration of ocean waters, allowing them to re-absorb more CO_2 from ambient air. There are two primary types of OAE:

1. Mineral-based OAE, which includes adding minerals such as olivine, rocks like basalt, or other alkaline material to ocean water, coastlines, or rivers and
2. Electrochemical-based OAE, which involves facilities capturing acidic seawater from the oceans and returning the more alkaline portion of the seawater back to the ocean.

In this analysis, our job estimates reflect mineral-based OAE processes occurring in the ocean and on coastlines and electrochemical-based OAE.

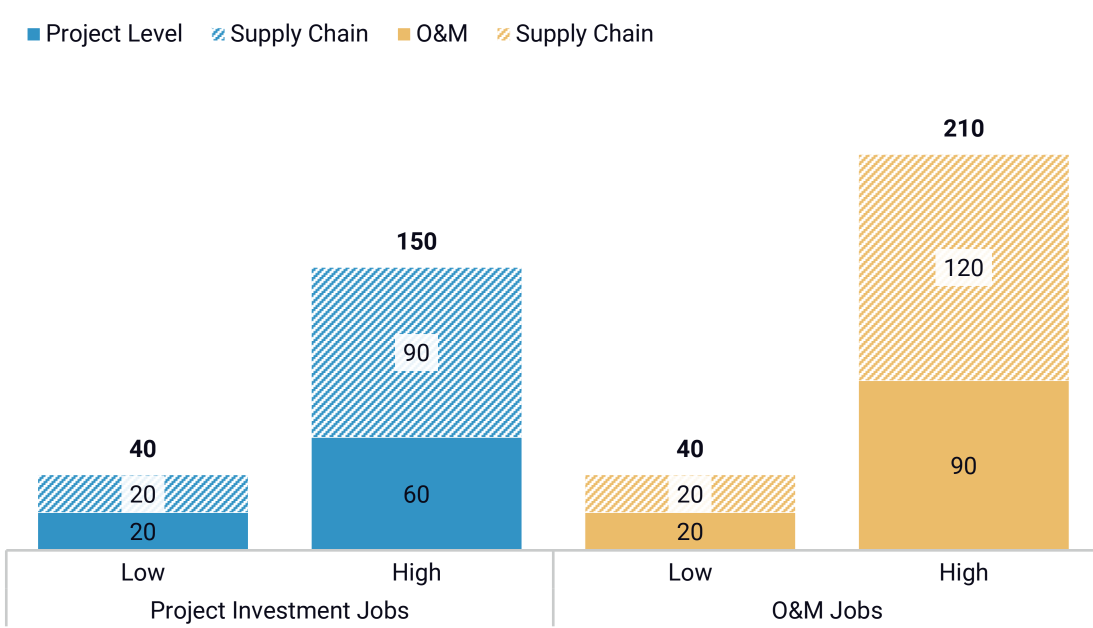
OAE job opportunities for an initial commercial-scale project

For our FOAK jobs analysis, we assume an OAE project capacity of 100 kilotons of CO_2 removal per year. We believe this size is realistic, however, it is likely on the larger side of initial projects. We estimate a capital investment between $12 to $68 million will be required to support establishing a 100-kiloton initial commercial-scale project.

FIGURE 7

Jobs associated with an initial 100-kiloton per year OAE project

Average annual project investment and ongoing O&M jobs



Source: Rhodium Group

Notes: These job estimates reflect employment estimates for mineral-based and electrochemical-based OAE. We assume a project construction period of two years. These projects are expected to be operational for 5-30 years depending on the OAE approach. Results will vary by OAE approach and project configuration.

We find that a first-of-a-kind OAE project generates between 40 and 150 average annual jobs over the 2-year construction period (Figure 7). Additionally, we see 40 to 210 ongoing jobs over the project's lifetime to support operations, maintenance, and related supplier activities.

OAE occupations

The top occupations associated with FOAK OAE projects are: (1) transportation occupations, (2) machinery installation, maintenance, and repair technicians, (3) operators and production occupations, (4) mining and quarry workers, and (5) engineers. Transportation occupations include truck drivers and ship operators associated with the movement of alkaline material needed for these projects. Operators and production occupations include computer-controlled tool operators, inspectors, testers, and chemical processing machine operators and tenders associated with the construction and operation of an OAE project. Engineering roles include mechanical, electrical, and industrial engineers, as well as engineering technologists needed to establish and operate an OAE project.

Top OAE occupations

- Transportation occupations
- Machinery installation, maintenance, and repair technicians
- Operators and production occupations
- Mining and quarry workers
- Engineers

OAE co-benefits

OAE offers several co-benefits. By producing an alkaline water stream, OAE can help reduce ocean acidity, benefitting marine life, especially species with carbonate shells such as muscles, oysters, and corals. Some OAE methods repurpose waste products, like steel slags, to create a high-purity alkalinity for the process, with the added potential for critical mineral extraction. Electrochemical OAE can also generate valuable products such as hydrogen and other chemicals with industrial applications. The outflow of high-purity water from these facilities can improve water quality when released.

OAE at scale

Rhodium expects OAE projects at scale to have similar occupational requirements as the FOAK project detailed above.

By the time OAE has reached 20 MMT of deployment in the US, we expect 4,500 to 6,000 average annual project investment jobs and 13,000 to 17,500 ongoing jobs.

More information can be found about our NOAK analysis in the next chapter.

CHAPTER 7

CDR's collective impact

As the previous chapters showcased, each CDR approach is unique in terms of its processes and occupational profiles. This diversity is reflected in the wide variety of occupations supported by these projects (Table 1).

TABLE 1

Top occupations associated with each highly durable CDR approach

Direct Ocean Capture	**Enhanced Rock Weathering**
Metal workers and assemblers	Transportation occupations
Operators and production occupations	Mining and quarry workers
Engineers	Construction trades
Project developers and site managers	Project developers and site managers
Machinery installation, maintenance, and repair technicians	Machinery installation, maintenance, and repair technicians
Direct Air Capture	**Bioenergy with Carbon Capture & Storage**
Construction trades	Metal workers and assemblers
Metal workers and assemblers	Construction trades
Engineers	Engineers
Machinery installation, maintenance, and repair technicians	Project developers and site managers
Project developers and site managers	Transportation occupations
Bio-oil / Biowaste Injection	**Ocean Alkalinity Enhancement**
Machinery installation, maintenance, and repair technicians	Transportation workers
Transportation occupations	Machinery installation, maintenance, and repair technicians
Project developers and site managers	Operators and production occupations
Operators and production occupations	Mining and quarry workers
Metal workers and assemblers	Engineers

Source: Rhodium Group

Certain skill sets will be important across CDR approaches, including metal workers and assemblers (such as welders); engineers; machinery installation, maintenance, and repair technicians; and project developers. In contrast, some CDR approaches will support unique occupations that cater to their process. For instance, ERW and OAE will require mining and quarry workers to source silicate rocks and minerals. BiCRS approaches will support biomass waste transportation occupations due to their use of agricultural and livestock waste.

CDR at scale

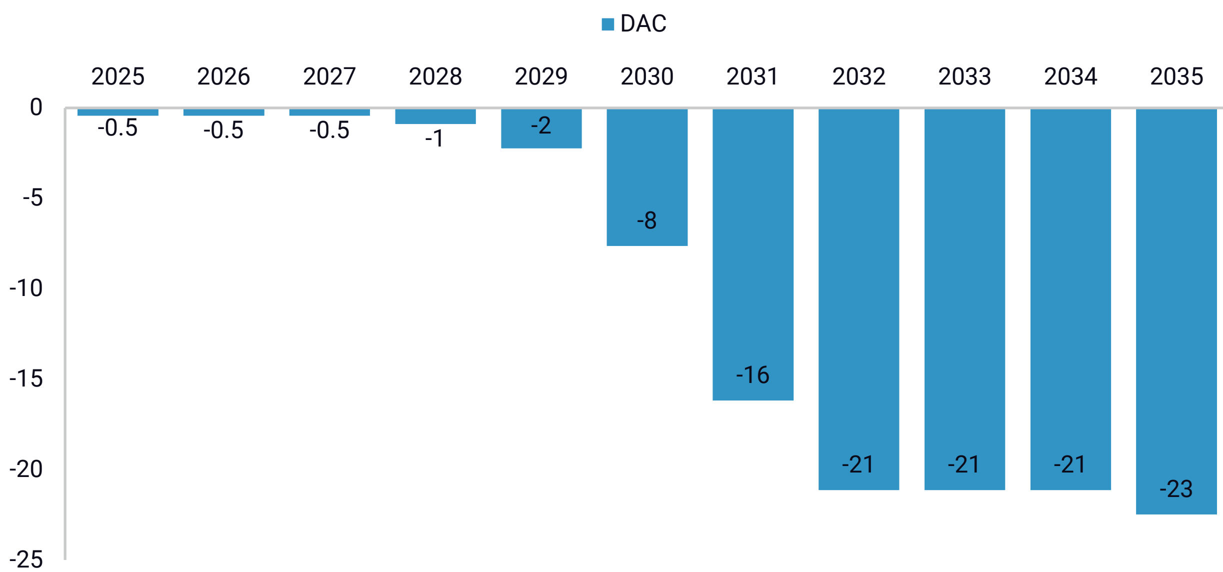
Our FOAK analyses show that each CDR project type is extremely unique in terms of process, location, and capture capacity, making it hard to envision their cumulative impact. To illustrate potential CDR employment opportunities once the industry has reached commercialization in the US, we conducted an analysis exploring the economic benefits associated with achieving 100 MMT of CO_2 removal per year, evenly distributed across the five highly durable CDR approaches in our scope.

This level of deployment—though only 10% of the gigaton-scale CDR deployment needed in the US by midcentury to achieve economy-wide decarbonization—still far exceeds what we see occurring with current policy support. While this amount may seem inconsequential, 100 MMT of CDR capacity represents more than 4x the amount of highly durable CDR deployment Rhodium anticipates occurring in the US under current policy by 2035 (Figure 8).

FIGURE 8

Policy-driven highly durable CDR deployment in the US

Net million metric tons (MMT) of CO_2e removal from the atmosphere



Source: Rhodium Group's Taking Stock 2024, under our mid-emissions scenario.
Notes: This chart only displays policy-driven CDR deployment of highly durable solutions; it does not include policy-driven natural CDR deployment for carbon sinks associated with natural and working lands.

Assuming no policy rollbacks, our projections show only one highly durable CDR approach, DAC, achieving 20 MMT of CDR by 2032 under current policy. This level of DAC deployment may be achieved sooner thanks to the help of voluntary markets. The International Energy Agency's CCUS Project Database reports 26 MMT of planned DAC projects in the US by 2030, including 16.3 MMT of deployment attributable to Oxy Low Carbon Venture's expansion plans.

Many factors will influence CDR's pace and ability to scale, including policy support and economic conditions. Our report, The Landscape of Carbon Dioxide Removal and US Policies to Scale Solutions, provides a comprehensive overview of policy options to boost

CDR deployment. With adequate policy support, the rest of the CDR approaches in our scope have the potential to reach at least 20 MMT of annual capacity between 2030 and 2040.

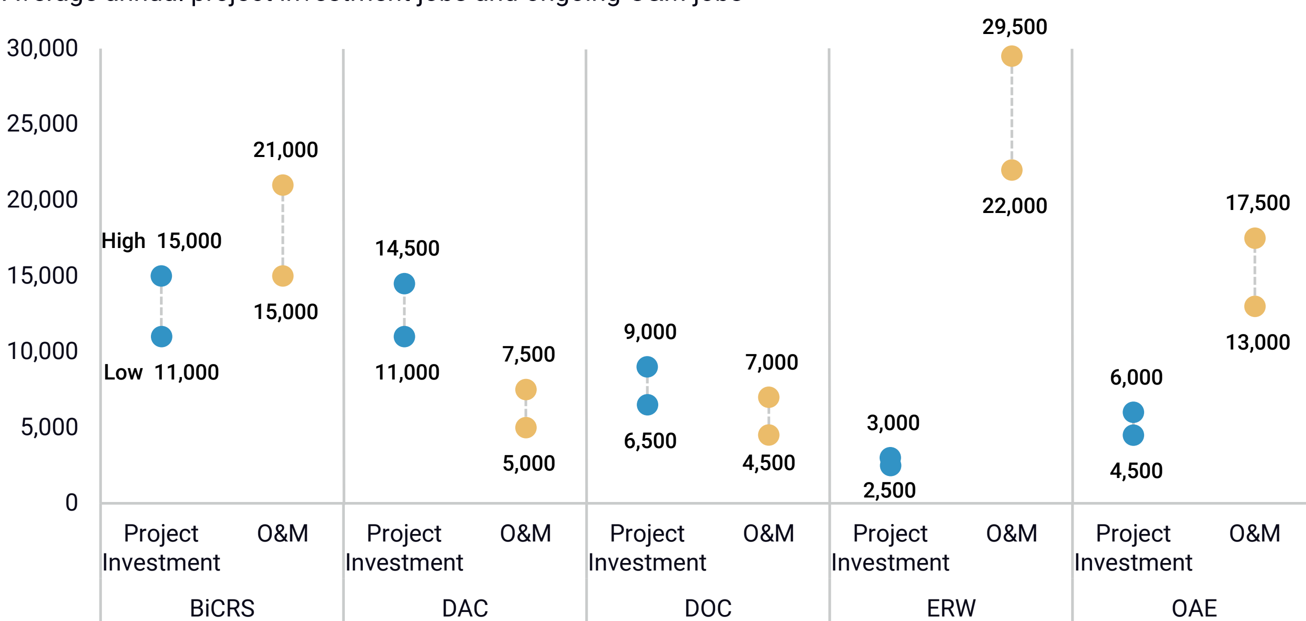
Employment associated with highly durable CDR will total between 95,000 and 130,000 jobs per year once the industry reaches 100 MMT of annual capture capacity.

These job numbers include both project level and upstream supply chain jobs, but they do not include induced jobs[2] (Figure 9). For each CDR approach, we conducted separate cost learning analyses to incorporate the economies of scale and efficiency gains that Rhodium anticipates will accompany deployment. To annualize the project investment job numbers across a consistent timeframe, we average these numbers over an assumed 8-year scaling period. As noted, certain CDR approaches are likely to begin scaling at the megaton level sooner than others so the exact years this ramp up occurs will vary by approach.

FIGURE 9

Jobs associated with 100 MMT of annual CDR deployment

Average annual project investment jobs and ongoing O&M jobs



Source: Rhodium Group.

Notes: We assume the 100 MMT of annual CDR deployment is split evenly at 20 MMT across each of these highly durable approaches. Our job numbers reflect expected cost learning associated with deployment. Project investment job values above are averaged over an 8-year scaling period. The actual jobs associated with capital investment in any given year will depend on the pace of project development. Employment per industrial output is assumed to stay constant over time. BiCRS deployment is comprised of BECCS, bio-oil, and biowaste injection. BECCS, DAC, and DOC jobs include jobs associated with CO_2 injection and storage.

Across approaches, almost two-thirds of the employment opportunities will come from ongoing jobs to operate these CDR projects. The remaining third will come from project investment jobs, though the exact distribution is dependent upon the type of CDR. Certain

[2] Induced jobs are those resulting from increased spending by workers (e.g. an increase in restaurant workers due to project workers dining out).

approaches, such as BECCS, DAC, and DOC require the construction of large facilities to capture CO_2. This leads to a greater share of jobs being associated with the project investment to get these projects up and running. For others, such as ERW and OAE, a smaller percentage of their overall costs goes towards upfront capital investment and equipment. The bulk of the effort and project costs are associated with maintaining the projects. As a result, these projects have a smaller share of project investment jobs and larger share of operating jobs.

It is critical to note that a relatively lower job profile does not mean a CDR method is less worthwhile. In fact, this could correlate to lower overhead costs or process efficiencies that require less labor per ton of CO_2 removed, which also has benefits in terms of scaling potential.

Since each CDR approach has unique processes, feedstocks, and capture capacities, our analysis highlighted that it can prove difficult to draw comparisons across CDR solutions. Even when narrowed down to highly durable approaches, developers in this category don't always speak the same language in terms of how they think about project size. For processes that produce pure CO_2 streams like DAC, DOC, and BECCS, project size is thought of in terms of tons of carbon captured—which is how our report is framed. For processes like ERW, OAE, and bio-oil injection, projects are often framed around the amount of wastewater processed, basalt applied, or biomass used. While standardizing calculations is possible, as evidenced by our analysis, these challenges make us sympathetic to policy makers in the CDR space.

Supporting a diverse array of CDR approaches in the US will support a robust workforce

The emerging industry of carbon dioxide removal (CDR) encompasses an array of innovative solutions that are ready for takeoff. The US has an opportunity to continue to position itself as a global leader in this space thanks to its high geologic CO_2 storage potential, varied landscapes, skilled workforce, and advanced research capabilities.

Given the diversity of CDR approaches, as CDR projects scale in the US, the opportunities will be distributed over a range of workers, communities, and ecosystems. This allows for a rare opportunity for stakeholders to explore CDR pathways that are most beneficial to their communities. For instance, those interested in supporting agricultural workers and crop yields may have a keen interest in ERW. Communities that would like to see a continuation of job opportunities for oil and gas workers in a decarbonizing world may see value in investing in bio-injection methods or CDR approaches that utilize CO_2 injection methods for storage such as DAC, DOC, and BECCS. While a diverse portfolio of CDR solutions will ultimately help the US achieve decarbonization goals, it will also support a robust workforce as the industry scales.

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