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EMERGING TECH RESEARCH

Postcombustion Carbon Removal

Incentives and interest in a developing industry

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Key takeaways

- Carbon capture technologies are experiencing high global interest and investment, and the regulatory environment has created pressures and incentives that will support their continued growth in the future.

- Q2 2022 saw the highest-ever VC investment in carbon capture startups, with $841.5 million invested across 11 deals, a significant increase over prior quarters.

- While carbon removal technology is not new, the landscape for modern carbon removal technologies (both point source carbon capture and direct air capture) is relatively young and extremely broad, encompassing various approaches with a focus on decreasing energy requirements.

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Contents

Approaches to carbon removal

Climate change reduction and management has finally become a core global interest. While there are many avenues and approaches to it—and success will require a combination of these—possibly the most obvious is to remove greenhouse gases so that they cannot contribute to climate change. Carbon removal is often considered a single process, but in reality, there is a wide landscape of technologies and approaches, including

- **Precombustion capture,** in which high-carbon fuels are converted to low-carbon fuels + carbon (often as carbon dioxide [CO_2], or solid carbon). An example of this is the creation of syngas: natural gas (CH_4) + water (H_2O) -> hydrogen ($3H_2$) + carbon monoxide (CO). The carbon monoxide can then be converted to CO_2 for storage and the hydrogen used as a fuel.
- **Oxy-fuel combustion,** in which fuels are burned in pure oxygen. This gives more complete combustion and produces a stream of essentially pure CO_2, though it requires pure oxygen as an input.
- **Postcombustion capture,** which uses carbon-scrubbing technologies to remove carbon released after fuel is burned (or released through other chemical processes). This is generally more efficient to do at the source of the emissions, which create relatively CO_2-rich exhaust gases (3%-20% CO_2),[1] but can also be applied to atmospheric carbon (419 ppm, or 0.04%).[2]

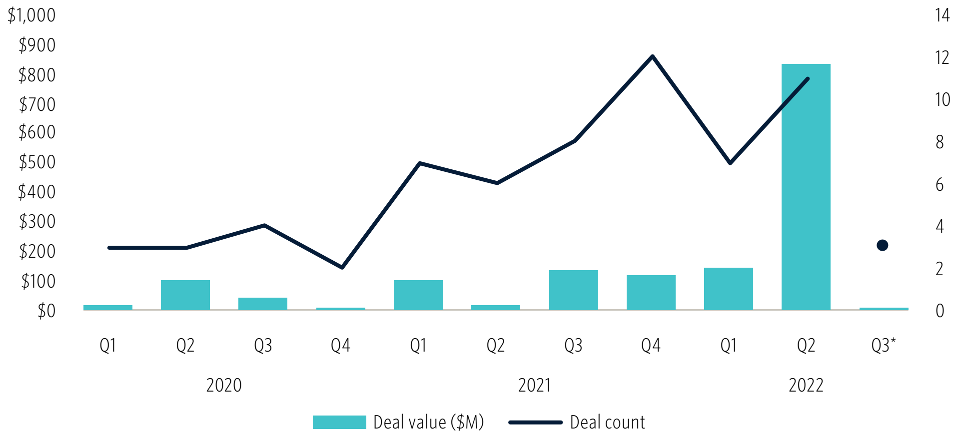
All three of these technology areas are valuable tools in reducing carbon emissions, but **postcombustion carbon capture** has strong benefits because it can readily integrate with (and capture carbon from) existing infrastructure. This integration makes it a very appealing investment to those looking to extend the life of their carbon-intensive assets (such as power stations and industrial facilities) during the pivot to a low-carbon paradigm, essentially allowing decarbonization without the immediate upfront costs of building new facilities. With postcombustion carbon capture, CO_2 can be removed at the point of emission (known as point source carbon capture) or removed from the air after emission (known as direct air capture, or DAC).

1: Feron, P. H. M. and Hendriks, C. A. 2005. "CO_2 capture process principles and costs." *Oil & Gas Science and Technology* 60 (3): 451-459.
2: "Trends in Atmospheric Carbon Dioxide," Global Monitoring Laboratory, n.d., accessed September 7, 2022.

VC activity in the postcombustion carbon capture space

In Q2 2022, venture capital (VC) investment in carbon capture tech skyrocketed, with $841.5 million raised over 11 deals. This far surpasses any prior quarter, with the total invested over the previous four quarters totaling only $432.1 million, though much of this can be attributed to two particularly large deals: DAC company Climeworks' $634.4 million Series F and point source carbon capture company Carbon Clean's $150 million Series C. Activity in the first two months of Q3 seems muted, but we expect the pace for VC deals to continue to grow (though likely fall short of Q2 2022), driven by the recent improvements to tax credits for carbon capture in the US and the general tightening of carbon allowances in Europe.

Postcombustion carbon capture VC deal activity since 2020



Source: PitchBook | Geography: Global
*As of August 29, 2022

Drivers of interest and investment

The regulatory landscape

In the last few years, national and private sector carbon reduction pledges of various kinds have increased dramatically, usually with a 2040-2050 target and an interim target in 2030 to ensure action is not overly postponed. Though fossil fuel alternatives are available for some of the largest carbon-emitting sectors (such as power generation and transportation), other sectors (industry and construction, for example) aren't as well covered. Even in the power sector, immediately replacing fossil fuel power stations with renewable power is not practical and will take many years. To facilitate this transition, carbon capture projects are attracting high levels of investment, and carbon capture startups are using this investment to develop more-advanced approaches to carbon capture.

Carbon reduction pledges have also spurred more governmental support. The EU's emissions trading system (ETS) issues a certain number of carbon emissions allowances (allocated depending on a company's industry and size, or via auction, depending on the industry in question). This number is gradually being reduced as additional industries are added to the ETS's coverage. As total allocations decrease, the cost of obtaining them increases, incentivizing emitters to reduce their emissions through other, cheaper means, such as carbon capture technologies (though at present, DAC-derived carbon is not factored into the ETS).

Russia's invasion of Ukraine and the resulting sanctions and energy crisis have driven much of Europe to seek alternative sources of power. However, with new decarbonized power sources unable to meet rising near-term demand, Europe is turning to readily available high-carbon power sources, such as coal. Existing climate pledges will require a combination of responses to mitigate higher carbon emissions, with carbon capture chief among them. This is likely to drive European investment in point source carbon capture, at least until the current energy situation begins to resolve.

The US environment for postcombustion carbon capture differs considerably from that of Europe. Some smaller regions have cap-and-trade systems for carbon emissions (similar in concept to the EU's ETS), but at a federal level, the most significant driver of carbon dioxide removal is the 45Q tax credit, which companies can claim for each ton of CO_2 they capture and store (or utilize as a feedstock for manufacturing). The following table shows the changes to the 45Q tax credit brought on by the Inflation Reduction Act of 2022. In particular, the value per ton of carbon captured increased by about 70% for point source carbon capture and enhanced oil recovery (in which CO_2 is used as a fracking fluid to extract oil) and increased more than 250% for DAC.

The distinction made between DAC and point source carbon capture is highly relevant considering the relative immaturity of the DAC space. This is because much of the industry consists of newer firms building relatively small-scale facilities (compared with carbon sequestered from some point source carbon capture installations) that previously did not meet tax credit eligibility requirements. The changes to the tax credit's eligibility thresholds (the minimum mass of CO_2 that must be captured per year for the company to be eligible to receive the credit) will make it easier for newer providers and startups to benefit. At present, the largest

Changes to the US 45Q tax credit made by the Inflation Reduction Act of 2022*

	Before	After
Categorization	Types of carbon capture are differentiated through source and use of carbon only.	Direct air capture is considered differently from other carbon capture activity, for both tax credit value and minimum threshold for eligibility.
Value	Standard carbon capture and storage: $50 per ton Carbon capture and use for EOR: $35 per ton Direct air capture (considered the same as point source carbon capture and storage): $50 per ton	Standard carbon capture and storage: $85 per ton Carbon capture and use for EOR: $50 per ton Direct air capture: $180 per ton
Eligibility thresholds	Power generation: 500,000 MTPA Industrial facilities: 100,000 MTPA Direct air capture (considered the same as industrial facilities): 100,000 MTPA	Power generation: 18,750 MTPA Industrial emissions: 12,500 MTPA Direct air capture: 1,000 MTPA
Claiming tax credits	Available as a standard tax credit, which is used against tax liabilities. Tax credits above liabilities do not provide additional value.	Payable through direct payment, in which the 45Q credit is essentially considered tax overpayment. Additional 45Q credits above tax liabilities result in a tax refund equal to their value.

Source: PitchBook | Geography: Global
*As of September 12, 2022

DAC facility can capture 4,000 MTPA of CO_2, well below the previous threshold of 100,000 MTPA. The switch to direct pay also allows small DAC companies with relatively low tax liabilities to receive the maximum benefit from the 45Q tax credit.

Aside from the regulatory landscape, support for carbon capture technologies is also coming from organizations with a large number of high-carbon assets (such as petrochemical infrastructure and fossil fuel-powered manufacturing facilities). Carbon capture tech can extend the lifetimes of high-carbon assets beyond what is economically possible. Similarly, high-carbon processes that do not currently have low-carbon alternatives can continue without increasing atmospheric carbon levels.

Varied technological approaches

Postcombustion carbon capture includes both point source carbon capture and DAC, with the underlying technologies often remarkably similar. Both methods consist of a chemical, material, or device that can remove carbon. The material is then exposed to a stream of carbon-bearing gas (i.e., air or exhaust gas). The core difference between point source carbon capture and DAC is the concentration of CO_2 in the gas. In point source carbon capture, exhaust gases often have CO_2 concentrations two orders of magnitude higher than the atmosphere, enabling much faster CO_2 capture rates (increasing the significance of the Inflation Reduction Act's distinction between point source carbon capture and DAC). On the other hand, DAC facilities often require significant airflow augmentation capabilities to ensure that they expose their carbon capture technologies to the maximum possible volume of air. Point source carbon capture can connect to the exhaust streams from various sources, including power generation, industrial applications, and large vehicles. Additionally, point source carbon capture can be retrofitted to existing assets, with providers often building flexibility into the installation and integration capabilities to maximize potential use cases.

While integration and connectivity are important, the core of carbon removal technologies is the removal mechanism itself. The most mature approaches to carbon capture (using a monoethanolamine solvent) originated commercially in the oil & gas industry to remove carbon dioxide (plus sulfur-bearing molecules) from natural gas streams to reduce acidity.[3] Over the years, the technologies have diversified greatly to include a wide range of chemical and physical approaches. Newer chemical approaches build on the processes involved in amine gas scrubbing and aim to improve capacity for CO_2, reduce the energy needed to regenerate the capture chemical, or reduce costs. However, there are many ways to approach these challenges, as described in the following chart.

3: This process is called "sweetening." It reduces damage to infrastructure and reduces sulfur-based pollution.

Developing technologies in the postcombustion carbon removal space*

Conventional chemical approaches

Alkanolamine solvents

This involves exposing an aqueous solution of alkanolamines to carbon-bearing gas, which binds to the amine and is released under heating. This heating step increases the total energy requirements dramatically and is a core focus for startups. Use of alkanolamines is currently mature and is often considered the most viable technology available.[4] Aside from the energy costs, solvent degradation and corrosivity over time are potential problems.

Novel solvents

These are alternatives to alkanolamines and generally provide different balances of energy requirements, fiscal cost, emissions cost of production, and operational characteristics (e.g., stability and toxicity).[5]

Solid sorbents

Rather than using liquid solvents, some companies have recently begun developing technologies to commercialize the use of solid sorbents (which bind CO_2 to the surface of the solid). In many cases they consist of a high-surface-area material that is coated in carbon-capturing chemistry (often the same chemistry used in solvent technologies). Solid sorbents have strong potential for use in DAC facilities, working well with highly dilute gas streams and varied humidity levels that DAC handles.[6] Depending on the specific chemistries involved, solid sorbents can have lower regeneration energy requirements than solvent-based approaches.

climeworks

Improved substrates

Solid sorbents are bound to an underlying material, and this substrate benefits from having very high surface area, plus mechanical strength and heat and chemical resistance. Approaches in development use alternative substrates to improve performance, including polymer-impregnated resins, metal-organic frameworks, ion exchange resins, and cellulose derivatives. Impregnating CO_2 removal chemistry onto novel substrates can reduce the energy and time requirements of regeneration.[7]

Regeneration approaches

Regeneration is critical to chemical CO_2 capture, allowing CO_2 to be released from the capture technology so that it can then be reused. This usually represents the most energy-intensive stage in the overall CO_2 capture cycle. Improving the energy efficiency of this stage is therefore a key step to reducing overall costs. Conventional methods use "temperature-swing" regeneration, which uses heat to regenerate the chemistry, but alternative approaches allow "pressure-swing" and "moisture-swing" regeneration, potentially at lower energy costs. Furthermore, new technologies based on electrochemical CO_2 capture are core components of several recent startups and allow chemical regeneration using the application of electricity.

MISSION ZERO TECHNOLOGIES, TRAVERTINE, VERDOX

Alternative approaches

Membrane approaches

Using chemical means to separate the CO_2 from gas streams is not the only option available, and R&D focused on use of semipermeable membranes has increased. Though still a young concept, membranes offer potential benefits of simplicity and size footprint.[8] Energy usage also tends to be lower for membrane technologies due to a lack of requirement for regeneration. Some potential weaknesses of membrane approaches are low gas permeance and low selectivity for just CO_2 (i.e., membranes are selective for CO_2, but also for other molecules).

Cryogenic carbon removal

Due to energy costs and carbon concentrations, cryogenic CO_2 removal is viable only for point source carbon capture. The technology involves cooling CO_2-laden exhaust gases below the sublimation temperature, such that solid CO_2 (dry ice) forms and can be removed for storage. This can also capture other pollutants from the gas stream at the same time.

Revcoo Global cooling

Molten salt

While molten salt capture is derived from calcium looping—a chemical approach using calcium oxide to capture carbon that is regenerated by very high temperatures—it is unique in that it uses a molten salt to absorb CO_2 at a very high operating temperature. Though this high temperature is energy-intensive, it can be used as process heat for other applications that require high temperatures, reducing the costs directly associated with molten salt capture. We currently see limited numbers of startups using this technology.

Mantel

Source: PitchBook | Geography: Global
*As of September 12, 2022

4: Castel, C., Bounaceur, R., and Favre, E. 2021. "Membrane processes for direct carbon dioxide capture from air: possibilities and limitations." *Frontiers in Chemical Engineering* 3, 668867.
5: Luis, P. 2016. "Use of monoethanolamine (MEA) for CO_2 capture in a global scenario: Consequences and alternatives." *Desalination* 380: 93-99.
6: Sanz-Pérez, E. S., et al. 2016. "Direct capture of CO_2 from ambient air." *Chemical Reviews* 116 (19): 11840-11876.
7: Parvazinia, M., Garcia, S., and Maroto-Valer, M. 2018. "CO_2 capture by ion exchange resins as amine functionalised adsorbents." *Chemical Engineering Journal* 331: 335-342.
8: Fujikawa, S., Selyanchyn, R., and Kunitake, T. 2021. "A new strategy for membrane-based direct air capture." *Polymer Journal* 53 (1): 111-119.

The abundance of carbon removal approaches, as well as the possibility that slight adjustments can have outsize impacts, is a key feature of this complex industry. As a result, there is no single cost for captured CO_2, but rather an ever-changing range as CO_2 capture costs steadily decrease with technological advancement and fluctuate with the costs of energy and raw materials.

In 2020, the average CO_2 emissions per US power facility (based on 11,070 utility scale power plants and 1.55 billion metric tons of CO_2)[9,10] was 140,000 tons per year. Under the Inflation Reduction Act, each ton is eligible for $85 in tax credits if captured and stored, which would give a yearly value of $11.9 million. Given capture and storage costs of $52-$90 per ton (differing depending on the emissions source and based on domestic onshore storage),[11] the increase in value of the 45Q tax credit will mean that carbon capture and storage is now a net positive (financially speaking) for a large proportion of this range rather than an overall expense. The initial cost of installation, though (which varies greatly with technology approach, size of facility, geographic location, etc.), means that there may be a considerable delay before the break-even point.

Rather than focusing on a few approaches, startups have embraced a wide range of capture technologies, a reflection of the nascency of the industry. It is likely that certain carbon removal technologies will become more dominant, though there are a few mature approaches today (particularly ethanolamine solvent approaches) that offer strong performance for relatively low costs. Even when the space has matured, different applications of carbon capture technology (with point source carbon capture and DAC being the most prominent) will be dependent on certain factors, as illustrated by the following table.

Drivers of differences between point source carbon capture technologies and DAC technologies*

	Point source carbon capture	DAC
Carbon concentration	Point source carbon capture applications favor technologies that operate well at high CO_2 concentrations. This is very much the standard for approaches—those that operate well at low concentrations often also work well at higher concentrations.	The comparatively low percentage of CO_2 in the atmosphere prohibits technologies that are not effective at low concentrations.
Location and size	These technologies must often integrate with existing facilities that were not designed to integrate carbon capture, which can constrain installation size. Similarly, locations are exclusively chosen based on the location of the point source itself.	DAC facilities have much more flexibility regarding both size and location, as they are independent of carbon sources. This allows their construction in areas without strong size constraints, in areas with access to low-cost clean energy, and areas close to carbon storage locations.
Gas stream purity	Gas streams from point sources often include some level of contaminants from the fuel combustion itself (some of these contaminants can be scrubbed from exhaust streams, but this is not always possible or complete). This favors technologies that are not overly affected by contaminants.	DAC gas streams are less likely to contain combustion-linked contaminants, but humidity levels can fluctuate significantly, which requires either technologies that are less affected by this or additional process stages to reduce gas stream humidity.

Source: PitchBook | Geography: Global
*As of September 12, 2022

9: "How many power plants are there in the United States?" U.S. Energy Information Administration, November 2, 2021.
10: "How much carbon dioxide is produced per kilowatthour of U.S. electricity generation?" U.S. Energy Information Administration, November 4, 2021.
11: Schmelz, W. J., Hochman, G., and Miller, K. G. 2020. "Total cost of carbon capture and storage implemented at a regional scale: northeastern and midwestern United States." *Interface Focus* 10 (5): 20190065.

Additionally, differences in gas stream temperature can affect the choice of technology, as can the availability of process heat (excess heat that can be used to replenish chemistry, reducing overall energy needs) from other processes.

Recent deal and investment trends

Interest in reducing carbon emissions has increased dramatically in recent years, and postcombustion carbon capture technologies are one of the core approaches to this. While the space is young, its industrial roots have resulted in a mix of mature, commercially available technologies; newly developed approaches; and methods that show promise but are still in the trial phase of development. In addition to novel approaches, startups are also focused on ways to improve or increase the applications of existing technologies (such as transport emissions sources). Many of the technological advancements occurring in the DAC space are driven by the need to lower the energy cost of carbon removal to improve the cost-benefits profile of carbon capture and make DAC implementations more economically viable.

Climeworks

Climeworks
Founded: 2009
Employees: 200
Total VC raised: $786.7 million
Last financing: $634.4 million in Series F funding
Last financing valuation: $1.9 billion
Lead investors: Partners Group, GIC

After its Series F funding, with a post-money valuation of $1.9 billion, Climeworks is one of the largest privately owned carbon removal companies. Headquartered in Switzerland, it develops and operates DAC facilities in Iceland, which offers a location with relatively cheap low-carbon energy due to Iceland's hydropower- and geothermal-driven power grid. Climeworks' first large-scale DAC facility (named "Orca") is capable of capturing 4,000 MTPA of CO_2, and construction began in Q2 2022 for the much larger "Mammoth" facility—also in Iceland—which will be able to capture 36,000 MTPA of CO_2. Climeworks partners with Carbfix for carbon storage, which pumps captured carbon underground, where it mineralizes and is sequestered permanently as carbonate rock. Climeworks holds a number of patents pertaining to the DAC space, including those for physical DAC devices, chemical regeneration methods, and chemisorbent carbon capture media (including the amine-functionalized cellulose sorbent used in their current facilities).[12] Climeworks is currently aiming for gigaton-scale carbon removal by 2050.

Mantel

Mantel
Founded: 2020
Employees: 3
Total VC raised: $2.0 million
Last financing: $2.0 million in Seed funding
Last financing valuation: N/A
Lead investors: The Engine

A relatively recent startup, Mantel uses a somewhat novel approach to point source carbon capture, using molten borate salts as a medium to capture carbon. This approach operates at very high temperatures (around 600 degrees Celsius), which would require large amounts of energy under regular conditions, but Mantel's technology is designed to operate inside boilers, kilns, and furnaces, and the heat required can be further used as process heat for other applications. The use of molten salts is relatively uncommon in the carbon capture space, and Mantel is one of the few firms we have seen that is developing this approach.

12: "Comparison of direct air capture technology to point source CO_2 capture in Iceland," Anna Ingvarsdóttir, 2020.

Mission Zero
Founded: 2020
Employees: 15
Total VC raised: $5.1 million
Last financing: $5.0 million in Seed funding
Last financing valuation: N/A
Lead investors: N/A

Mission Zero

Mission Zero develops and provides DAC technology based on an electrochemical regeneration process, allowing chemical capture with regeneration at much lower temperatures than conventional approaches. In Mission Zero's case, this means regeneration at room temperature, and regeneration (release of the captured carbon or storage/utilization) is triggered by the application of electricity. Though only founded in the last two years, Mission Zero uses off-the-shelf components to construct modular technology, allowing varied installation sizes. Currently, London-based Mission Zero is collaborating with Oman-based 44.01 (which provides permanent carbon sequestration technology through mineralization) to plan a DAC facility in Oman named "Project Hajar." Their first pilot facility will launch in 2023 in Thetford, UK.

Revcoo
Founded: 2018
Employees: 5
Total VC raised: $4.0 million
Last financing: $3.7 million in early-stage VC funding
Last financing valuation: N/A
Lead investors: N/A

Revcoo

France-based Revcoo uses a nonchemical approach to carbon capture, instead using low-temperature technologies (sometimes referred to as "cryogenic carbon removal") to cool exhaust gases from industrial facilities, which causes the CO_2 to solidify (this occurs at higher temperatures than other atmospheric components of exhaust gas). This approach has the additional benefit of also capturing other atmospheric pollutants such as NOx, SOx, and volatile organic compounds. After capture, Revcoo transports the CO_2 to be utilized in other industries, including construction materials, carbonated drinks, and fuels. Due to CO_2 concentration, low-temperature approaches are not viable for DAC, but they have potential in the point source carbon capture space. These approaches are young, however, and it is not yet clear how these technologies will compare with conventional approaches. Revcoo's approach holds some additional advantages over chemical approaches, in that there is no chemical degradation to manage (which essentially requires chemicals to be replaced when they become too contaminated/degraded). The physical footprint of low-temperature carbon removal systems also tends to be quite small, potentially allowing the use of this technology in space-limited applications, such as large transport vehicles.

Travertine
Founded: 2022
Employees: 5
Total VC raised: $3.0 million
Last financing: $3.0 million in Seed funding
Last financing valuation: $12.0 million
Lead investors: N/A

Travertine

Founded in 2022, Travertine uses renewable electrical power to power its DAC technology. Using an electrochemical approach, Travertine converts CO_2 in the atmosphere into carbonate rock for permanent sequestration. Unlike other DAC firms, Travertine also simultaneously converts sulfate waste from industrial applications into sulfuric acid for use in applications such as mining and metal extraction. This approach of creating a coproduct during carbon capture is uncommon and differs from carbon utilization approaches in that carbon is not used to create the coproduct and can still be sequestered.

Verdox
Founded: 2019
Employees: 31
Total VC raised: $150.1 million
Last financing: $80.0 million in early-stage VC funding
Last financing valuation: N/A
Lead investors: Breakthrough Energy Ventures

Verdox

Founded in 2019, Verdox provides carbon capture technology that can be used for both DAC and point source carbon capture. The company is one of a group of recent startups to develop an electrochemical approach that allows regeneration of carbon capture mechanisms through the application of electricity. This in turn provides lower energy requirements for regeneration, reducing the overall costs of carbon capture. Verdox's technology is modular and consists of stacks of electrochemical carbon capture cells. The number of modules per stack can be varied to suit the carbon capture requirements of the installation.

Differentiation through add-on capabilities

In addition to a focus on energy efficiency for DAC technologies, we are also seeing some carbon capture startups integrating add-on carbon utilization functionality into their carbon removal. This can be applicable to both point source carbon capture and DAC technologies and provides an alternative to carbon storage requirements. Essentially, it allows companies to use their captured carbon as a feedstock for manufacturing other products, such as construction materials or carbon fiber. This can provide more varied revenue streams to carbon capture facilities/installations and reduce potential issues with transporting captured carbon to storage sites. Using captured carbon to produce carbon-neutral fuels is becoming more popular, given the need for carbon-neutral fuels; however, the clean energy requirements of this form of carbon utilization are usually very high, further increasing postcombustion carbon capture's need for low-cost clean energy.