CARBON CAPTURE AND CARBON REMOVAL

STATE OF THE SCIENCE FOR RESPONSIBLE DEPLOYMENT

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MEETING CLIMATE GOALS REQUIRES CAPTURE AND STORAGE OF CARBON DIOXIDE EMISSIONS AND REMOVAL FROM THE ATMOSPHERE

The Intergovernmental Panel on Climate Change (IPCC) released its newest report on the state of climate change in August 2021, which warned again that humanity has to limit global warming levels to 1.5 or 2 degrees Celsius in the coming years to minimize severe impacts on society.[1] While this statement has been a finding of the IPCC's Physical Science reports for the last 30 years, new information reveals that impacts as the world nears the 1.5 degree limit have become more severe and are now experienced in every region in the United States.[1] Predictive models that integrate a variety of components into their computing to determine best- and worst-case scenarios all show that to meet the 1.5 degree target set in the 2016 Paris Agreement and stabilize the global climate, reaching net-zero carbon dioxide (CO_2) emissions is a requirement.[1] A net-zero goal means that a combination of drastic emissions cuts from polluting sources like cars and power plants must be combined with strategies to pull existing CO_2 out of the atmosphere for storage in nature, underground, or by other means. To reduce the more than 40 gigatons of anthropogenic CO_2 released annually into the atmosphere, new negative emissions technologies have emerged.[2] Therefore, it is critical for the public and policy makers to better understand the basics and potential implications of these technologies and how they fit into a cleaner, more just future.

Swiss carbon capture company Climeworks first tested their modular technology on the industrial scale at the Capricorn plant in Hinwil, Switzerland in 2017. The direct air capture plant sits atop a local waste incineration plant and uses the waste heat to power the process, capturing hundreds of tons of CO_2 per year. Credit: Getty.

WHAT IS THE DIFFERENCE BETWEEN CARBON CAPTURE AND CARBON REMOVAL?

In conversations about reducing the amount of CO_2 in the atmosphere, two pathways are often discussed in association with storage of the CO_2: (1) capture, and (2) removal. It should be noted that not all strategies are listed here, and this brief serves to focus on technological decarbonization strategies. More information on natural climate solutions, including natural carbon removal strategies, can be found at www.nwf.org/naturalsolutions.

1. CAPTURE

Climate mitigation strategies like carbon capture are often demonstrated in the context of carbon capture, utilization, and storage techniques, as a way to prevent heavy-emitter industries like cement and steel manufacturing, or the energy sector, from continuing to emit more CO_2 as the U.S. works to transition to a green economy. With the help of carbon capture technology, CO_2 can be largely captured at the source either pre- or post-combustion.[3]

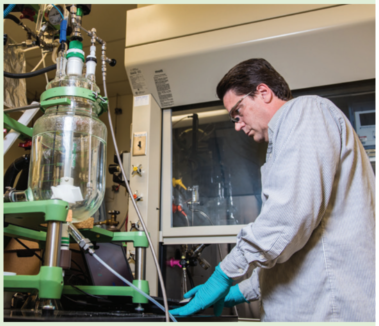
In industry manufacturing, flue gases from cement and lime kilns contain concentrations of CO_2, which can be captured and separated from other gases.[4] In iron and steel manufacturing, CO_2 can be captured during the processes used to turn iron ore into the elemental iron used for steelmaking.[4]

The electricity and heat production sector is responsible for the greatest amount of CO_2 emissions out of all global sectors, with the United States electricity sector producing nearly 2 gigatons of CO_2 alone in 2018.[2] By retrofitting coal- and gas-operated power plants with carbon capture technology, this sector can also reduce emissions at facilities (especially natural gas) that may be unlikely to be retired or replaced in the near-term by zero-carbon energy sources like wind and solar power.[4] Thus far, however, retrofitting already uneconomical coal-fired power plants in the U.S. has not proven financially worthwhile.[5] That said, in rapidly developing nations like China, coal carbon capture retrofits may be an essential climate strategy given the nearly 30 gigawatt rise in coal capacity approved since 2020, alongside continued advocating for new plants, which has raised China's total coal power capacity to 247 gigawatts—enough to power all of Germany.[6]

2. REMOVAL

Additional climate mitigation strategies referred to as carbon dioxide removal, absorb CO_2 directly from the ambient air. There exist a variety of nature-based solutions for this strategy, including reforestation and native prairie restoration, enhanced weathering, ocean fertilization, and mineralization. More recently, technological strategies have also gained attention, for example direct air capture (DAC). This technology is a beneficial backstop for CO_2-emitting sectors where capturing carbon at the source may be more difficult, like agriculture and transportation.[7]

Since DAC removes CO_2 from the ambient air, the technology can be located anywhere, but due to the dilute nature of CO_2 in the air, DAC requires more energy to capture CO_2 than point-source carbon capture. This energy is often derived from various electricity mixes today.[4] In order for deployed DAC to be a true negative emissions technology, the amount of removed greenhouse gases must be greater than the amount of greenhouse gases emitted during the entire life cycle process of the technology, which will require a combination of low-carbon manufacturing resources and clean power supplies.[7] The DAC process usually consists of two phases: (1) where the ambient CO_2 chemically binds to sorbents, and (2) where the CO_2 is separated. The second step is the most energy intensive part of the process.[7]



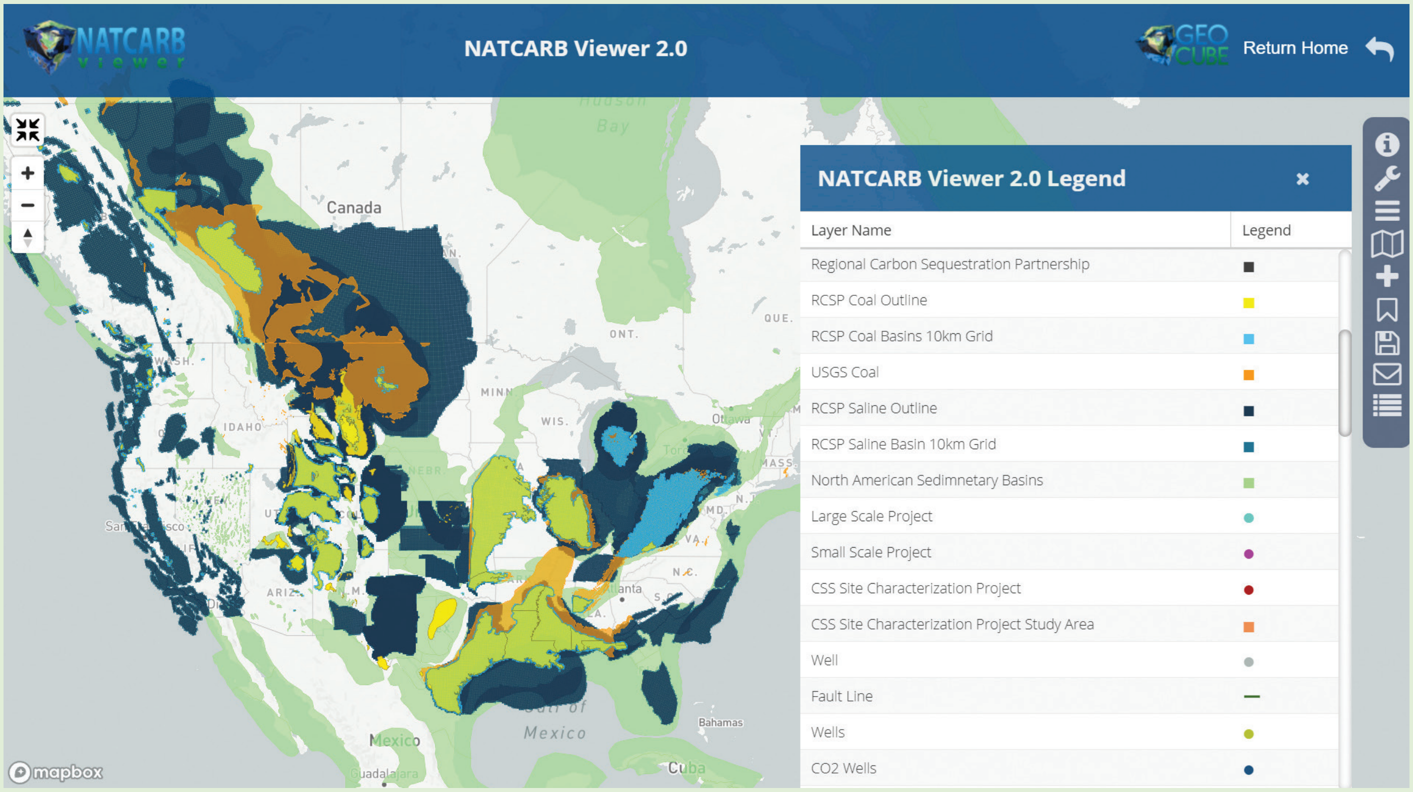
At the Pacific Northwest Laboratory in Washington State, a scientist works to develop novel solvents for better capturing CO_2 from a coal power plant. Credit: Department of Energy: Energy Technology Visuals Collection.

WHAT HAPPENS TO CO_2 ONCE IT IS CAPTURED?

Right now, there are two major pathways captured CO_2 can take: (1) injection into geological formations for permanent storage, and (2) utilization.

1. INJECTION/STORAGE

One of the most common pathways for captured CO_2 is injection deep underground where it is stored geologically in porous rocks, saline aquifers, or depleted oil and gas wells.[3] To prevent leakage of CO_2 stored in this manner, a layer of impenetrable rock must cover the storage site.[3] These permanent storage techniques are usually successful because CO_2 naturally accumulates in underground reservoirs.[8] Other storage techniques include injecting the CO_2 into the ground and chemically reacting it to form mineral rock (a technique called mineralization), or storing the CO_2 below the ocean floor, since at depths greater than 3,000 meters CO_2 is denser than water. The environmental impacts of the latter, however, are not well understood at the moment.[3] Another use for injection of CO_2 is in enhanced oil recovery processes, where CO_2 is injected into oil fields to increase oil production from a particular field.[3] While this process does result in lower life cycle emissions in oil production, it is less preferable from a climate standpoint than storage or measures that will not lead to further combustion and emissions.[9] Enhanced oil recovery has been the primary pathway for captured CO_2 in the U.S. thus far, largely because, in the absence of a value or price on carbon emissions, it has provided the primary economic use for CO_2. But because saline formations are common and are being continually identified, with capacity into the thousands of millions of tons in North America alone—far outweighing what is available for enhanced oil recovery—and with the help of tax credits like 45Q and related policy incentivizing saline storage, this is steadily set to change.[4]



NATCARB Viewer 2.0 Legend

Layer Name	Legend
Regional Carbon Sequestration Partnership	⬛
RCSP Coal Outline	🟨
RCSP Coal Basins 10km Grid	🟦
USGS Coal	🟧
RCSP Saline Outline	⬛
RCSP Saline Basin 10km Grid	🟦
North American Sedimnetary Basins	🟩
Large Scale Project	●
Small Scale Project	🟣
CSS Site Characterization Project	🔴
CSS Site Characterization Project Study Area	🟧
Well	●
Fault Line	—
Wells	●
CO2 Wells	🔵

The Department of Energy (DOE) developed the Carbon Storage Atlas to estimate the potential CO_2 storage resources based on data collected by DOE field projects and information gathered by the National Carbon Sequestration Database and Geographic Information System (NATCARB). The highlighted areas on the map represent a variety of geological permanent storage solutions available in North America. Credit: Department of Energy Carbon Storage Atlas.

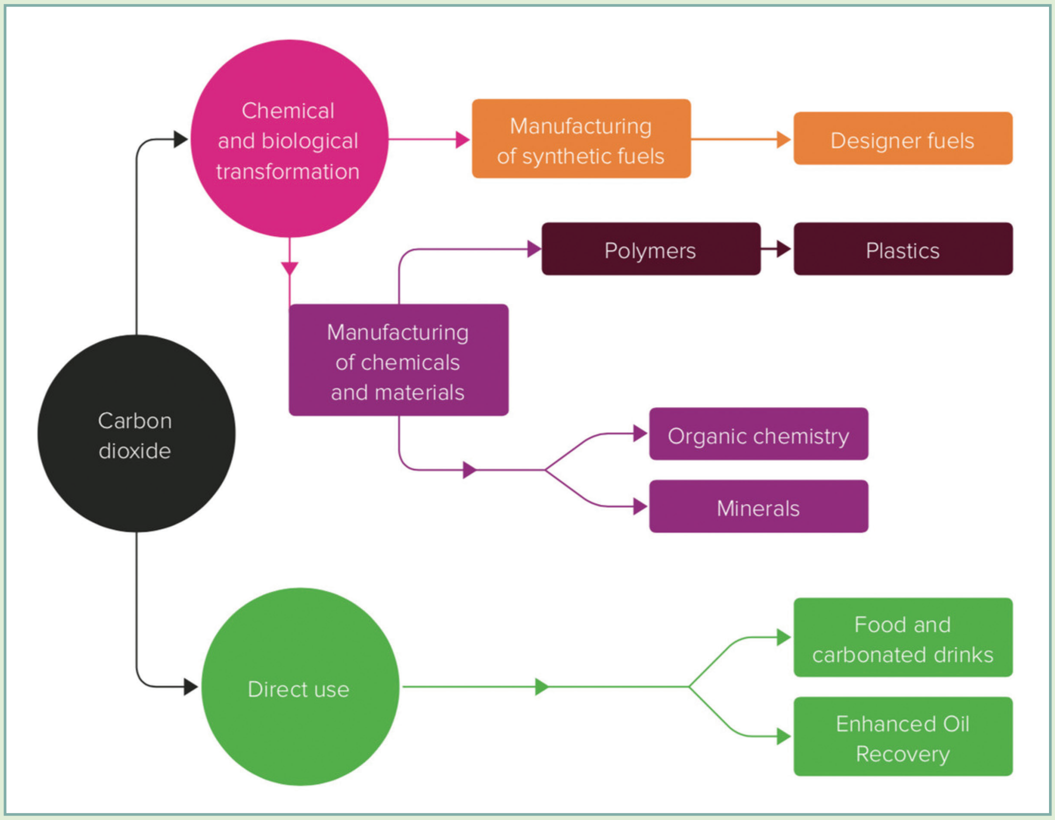
2. UTILIZATION

An alternative to injection/storage is for the captured CO_2 to undergo other processes to be transformed into a product. Though products made from captured CO_2 are still very new, several emerging markets have been identified, including:[10]

- **Building Materials.** Global industry produces around 8 billion tons of CO_2 emissions annually, of which somewhere around 2 billion tons comes from cement manufacturing.[4] CO_2 can be chemically reacted to make minerals, which can then be used as aggregates (e.g., gravel or crushed stones), and captured CO_2 can be used in the concrete curing process. This leads to higher-performing concrete with lower costs, and the potential to reduce the CO_2 emissions from concrete manufacturing by an estimated 80 percent.[11]

- **Chemical Intermediates and Polymers.** Often mentioned with regard to alternative fuels, CO_2 can replace fossil fuels in the process of developing chemical byproducts like methanol and methane.[11] Similarly, CO_2 can replace fossil fuels typically utilized in the process of creating polymers, which then go on to be used in a variety of different materials such as plastics, foams, and resins.[11] The life cycle reduction of CO_2 emissions depends on the product and the percentage of CO_2 present in the final product, but could be up to 15 percent reduction for a product containing 20 percent CO_2.[11] Some examples of consumer products include sunglasses made from polycarbonate manufactured with recycled CO_2 and sneakers made with bio-material combining oxygen and CO_2 as a replacement for synthetic plastics.

- **Alternative Fuels.** The transportation sector right now is in the top three of heavy CO_2 emitters alongside industry and power due to heavy reliance on fossil fuels. Low-carbon fuel represents one of the largest markets for CO_2 utilization.[10] Creating fuels like methanol, methane, and gasoline from CO_2 may be particularly useful for difficult to decarbonize transportation industries like aviation and shipping where electrification is less feasible. This process can be done by combining CO_2 with other chemicals like hydrogen and subsequent chemical processes, bringing down the process-induced emissions for alternative fuels.[11]



Research continues to discover pathways for captured CO_2 which includes the manufacturing of low carbon chemicals and materials that can then be transformed into consumer products, in addition to the already common direct uses. Credit: Kleij A, North M, & Urakawa A, The Royal Society.

From 2016-2019 the Tomakomai CCS demonstration project on Hokkaido Island captured CO_2 from the offgas resulting from the hydrogen production unit of a coastal oil refinery, sequestering it in offshore saline aquifers. While the project is no longer active, the storage of the captured CO_2 is still being monitored and documented for research purposes. Credit: International Energy Agency.

WHAT ARE THE ENVIRONMENTAL IMPACTS OF CARBON CAPTURE AND CARBON REMOVAL?

As the technology often involved in carbon capture and carbon dioxide removal strategies have yet to be scaled up and widely implemented, it is difficult to anticipate all of the environmental impacts of the technologies and required infrastructure. This has contributed to an increasing number of questions and concerns among environmental justice and conservation groups, as well as the public. Further, few publicly available full life cycle assessments have been completed. These are tools to evaluate the CO_2 emissions from the cradle-to-grave of each piece of the capture process, from the creation and manufacturing of the plant (including necessary chemicals), transport and storage of the CO_2, energy supply needs, and product pathways. Each piece of this picture will have unique considerations that are often site- and energy-dependent, and will result in a variety of environmental impacts that should be taken into consideration.[7] Those that have been completed have identified these categories as potential areas of major impact—both positive and negative:

- **Air Quality.** Considerations regarding air quality or potential CO_2 emissions related to infrastructure development, construction, and increased power generation during build out are important.[12] In the context of industrial and energy carbon capture and retrofits, there is encouraging potential for the co-benefit of removal of criteria air pollutants during the pretreatment of flue gas.[13] Pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter, often byproducts of fossil fuel combustion, pose significant harm to public health and risk contaminating carbon capture systems, and must therefore be removed if carbon dioxide is to be captured from that same system.[13]

- **Chemical Use.** Both carbon capture and carbon dioxide removal use chemical compounds (i.e., adsorbents and solvents) that attach to the CO_2 in their capture processes, which results in a carbon footprint from the production of the chemical as well as at the end-of-life.[14] For six commonly used adsorbents, 60-91 percent of their carbon footprint comes from the production of the chemical before being used in carbon capture, but overall the footprint is low.[14] The European Commission's Joint Research Center, an independent research body that advises European Union policymakers, categorized these same adsorbents

Canadian company CarbonCure injects captured CO_2 into fresh concrete where it undergoes a mineralization process and remains permanently embedded, thus reducing the overall carbon footprint of the product. In April 2021 CarbonCure won the NRG COSIA Carbon XPRIZE, a global competition where competitors develop breakthrough technologies to convert CO_2 into usable products. Credit: Carbon Cure Low Carbon Concrete.

according to environmental impact and quality level, as well as evaluated their impacts on eutrophication, human toxicity, and land use.[14] For methods using solvent-based absorption, the use of potassium-hydroxide has been well studied in industrial uses, and has been shown to produce minimal wastewater.[15] Most degraded solvent waste can be incinerated or disposed of using established processes, though the environmental implications of these processes should be considered.[16]

- **Transportation and Storage.** For captured CO_2 that will not be stored on-site, which is often the case with both point-source capture and DAC, transportation to the final storage site is necessary. Captured CO_2 can be transported via several methods including pipelines, ship, barge, rail, and by truck, and each method will have its own implications that are highly localized.[12] Comprehensive life cycle analysis also shows that emissions from storage and transport of CO_2 can be one of the largest contributors to total project emissions.[7] There are a variety of permanent storage mechanisms that vary based on geological conditions, but many are well understood due to years of research on oil and gas wells. One of the primary concerns for communities is the potential for CO_2 leakage from underground storage sites. Risks of CO_2 leakage include human health and safety risks, as well as risks to nearby flora and fauna, due to direct effects of elevated gas CO_2 concentrations in the near surface environment; effects of dissolved CO_2 on groundwater chemistry; and effects of the displacement of fluids by injected CO_2.[8] Leakage from an underground storage site is typically not a risk unless the permeability of the site is questionable or the site is in a location prone to seismic phenomenon, both of which should disqualify a site from receiving a permit.[17] Rapid releases of CO_2 typical of environmental concerns is unlikely, as CO_2, like oil and gas deposits, remains trapped in geological formations for millions of years.[17] While unlikely when sited and stored properly, leakage from pipelines transporting CO_2 is always a possibility, though the existing pipelines utilize robust technology to track CO_2 in the subsurface and alert operations of any issues.[12,17]

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- **Land Usage.** As with any energy or industrial operation, every phase of carbon capture and carbon dioxide removal requires some form of land usage. While the estimates vary depending on scenario, it is still an important consideration. Though most DAC plants are still in their pilot phase, research shows that the direct land transformation required will depend on the capacity of the plant and its energy configuration. In the most land-intensive case study, this could result in the transformation of up to 4.7 square kilometers for a plant removing 100,000 tons of CO_2 per year, requiring an area as large as 59,000 square kilometers (~1.5x the total land surface area of Switzerland) when scaled to the gigaton level.[7]

  When it comes to energy supplies, the necessary land surface can be reduced by utilizing grid electricity sources—although in order for carbon capture and carbon dioxide removal to be true negative emissions strategies, this power would need to come from renewable or zero-carbon sources, and the carbon permanently stored.[7]

  The number and location of oil and gas fields for geological storage are limited and often distant from carbon capture projects, thus requiring enhanced pipeline or highway infrastructure for CO_2 transportation. Saline formations, on the other hand, are more widespread with U.S. capacities in the thousands of millions of tons, making CO_2 transport over long distances less necessary.[4] Comprehensive mapping of these storage sites has been completed by the Department of Energy as a part of their "Carbon Storage Atlas."

- **Energy Supply Needs.** Carbon capture retrofits on power projects have the benefit of built-in power supplies, but in order for carbon dioxide removal technologies to help achieve net-zero or negative emissions, most scenarios rely on renewable energy as the main source of power supply. DAC, if land use restrictions allow, can be developed near renewable energy sources, which is necessary due to the high thermal and electricity needs of the technology.[12] Energy supply is a key factor in the deployment of DAC, and while renewables are an option to meet this need, they each come with their own set of environmental impacts, including the development of energy storage for intermittent technologies.[7] Comprehensive life cycle research shows that based on life cycle greenhouse gases emitted per ton of gross CO_2 removed[7]: (1) sites using low greenhouse gas-intensive electricity mixes (e.g. renewables) result in the lowest greenhouse gas emissions, and (2) battery storage for energy supply needs can be a large contributor to total project emissions due to the CO_2 intensive nature of developing battery storage.

CONCLUSION

As the effects of climate change grow to be more hazardous and widespread, it is imperative that carbon capture and carbon dioxide removal technologies be deployed alongside a suite of renewable and zero-carbon energy sources to power them. It has become clearer with each climate change study that negative emissions technologies are necessary for meeting climate goals, and this opportunity to build out new industry, policy,

The Climeworks Orca direct air capture facility in Hellisheidi, Iceland launched September of 2021 with a capture capacity of 4,000 tons making it the largest operational direct air capture project to date. Credit: Climeworks.

and infrastructure should be done in such a way that environmental and social concerns are framed within the groundwork, so as not to repeat the negative effects of fossil fuel production and combustion. The Biden Administration, Congress, and private industry each have a vital role to play in fostering responsible buildout, including detailed planning involving community members and local stakeholders, as well as continuing to develop regulatory frameworks regarding infrastructure and transport, safety, and environmental monitoring, while pursuing transparent research to fill data gaps and improve understanding and confidence in these technologies.

Additional contributors to this issue brief include ***NWF Senior Director of Climate and Energy Policy Shannon Heyck-Williams and Clean Air Task Force International Director Lee Beck, Technology and Markets Director John Thompson, Staff Geoscientist Ben Grove, and Policy Specialist Marc Jaruzel,*** *and was made possible with the support of the Linden Trust for Conservation, the Mike Schroepfer and Erin Hoffmann Family Fund, the William and Flora Hewlett Foundation, and the John D. and Catherine T. MacArthur Foundation, as well as the many individual supporters of the National Wildlife Federation.*

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