United States Energy Association:

Life Cycle Assessment of Carbon Dioxide Removal Methods Summary Report

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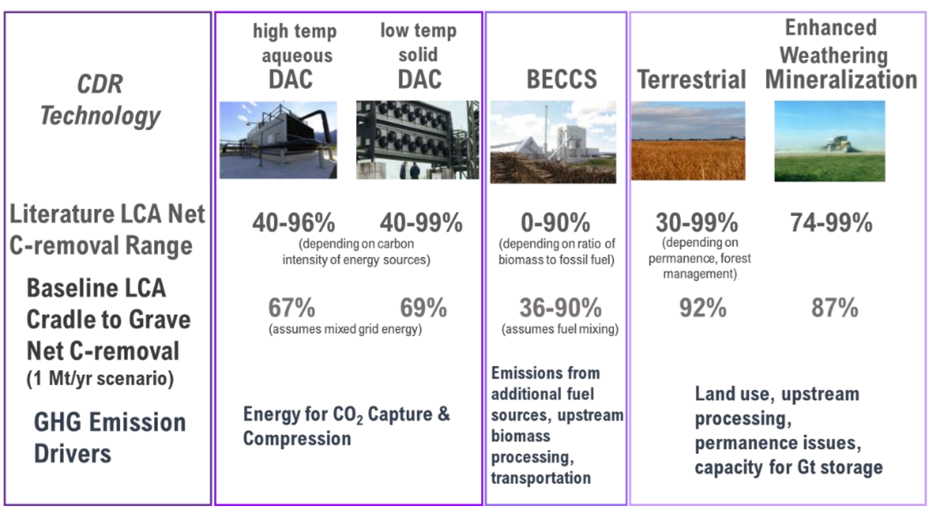
Executive Summary

This report describes the status of carbon dioxide (CO_2) removal (CDR) technologies, life cycle greenhouse gas emissions for real-world CDR applications, and recommendations for CDR development in the US. Key conclusions of the study are presented below:

- Over 50 CDR technologies are in existence, with additional technologies being proposed on a regular basis. This study focused on low and high temperature direct air capture (DAC), bioenergy with carbon capture and storage (BECCS), reforestation, and mineralization, as these technologies have the most realistic potential for widespread application at scales of 100,000s-1,000,000s metric tons (mt) CO_2 removal per year.
- CDR technologies are being scaled up from kgs CO_2/year experiments and pilot-scale tests (1,000s mt CO_2/year) to industrial scale projects (>100,000 mt CO_2/year).
- It is important to consider the “cradle to grave” life cycle for greenhouse gases, including upstream, gate-to-gate, and downstream activities. Many CDR LCAs only address individual components of the CDR process like the CO_2 capture process for DAC.
- Literature values range from 0-99% for CDR LCAs’ net negative carbon removal values.
- A streamlined energy and emissions LCA of aqueous solution DAC, solid DAC, BECCS, reforestation, and mineralization suggests that CDR operations at industrial scale of ~1 million metric tons per year CO_2 capture may have net carbon removal of 65-95%.
- The energy source for DAC and BECCS is a key driver for greenhouse gas emissions. Integrating renewable energy as energy sources for all technological CDR applications will increase net carbon removal.
- DAC and BECCS will require large industrial facilities that have significant construction, embodied emissions, land use changes, and operating emissions.
- Reforestation and mineralization will rely on natural systems and require land use changes. The long-term effectiveness of these natural processes in terms of the carbon cycle is more difficult to assess than engineered systems like DAC and BECCS.



Overall, this greenhouse gas emissions-based LCA suggested that CDR technologies have the potential to produce effective cradle-to-grave net carbon removal rates of 65-95%. All CDR technologies would generate greenhouse gas emissions in some way that need to be accounted for with an LCA (given the current reliance on fossil fuel energy in the US). It will be important to monitor technology emissions over 5-20 years to understand how operations balance out after initial construction and “shake down” deployment periods. In addition, these technologies will likely optimize their operations to increase net carbon removal.

1.0 Introduction and Scope of Assessment

Battelle is pleased to submit this summary report to the United States Energy Association on "Greenhouse Gas Life Cycle Assessment (LCA) of Carbon Dioxide Removal (CDR) Technology Applications in the U.S." This report was prepared under United States Energy Association Subagreement No. USEA/633-2022-004-01 Task 1.0 (Battelle Contract # CON00048).

In recent years, there has been a rapid expansion of interest in carbon dioxide (CO_2) removal (CDR) technologies. While the large-scale deployment of such technologies has yet to occur, it is important to develop tools alongside the technology to guide the development and deployment of these technologies. Life cycle assessment (LCA) is one such tool. This study utilizes an abbreviated LCA methodology intended to provide comparative results in an expeditious format for the purposes of assisting deployment decision makers.

As of summer 2022, there is a large amount of research, investment, and development in CDR technologies. Therefore, it is important to understand the greenhouse gas (GHG) emissions that may be generated during the entire life cycle of the technology application, especially in terms of large-scale deployment. Items such as construction, embodied emissions, energy use for capture, compression, transport, fugitive emissions, and injection/storage may generate emissions. CO_2 removal permanence may also affect the net negative emissions, especially for CDR technologies that rely on natural systems like reforestation and mineralization.

This report presents a review of current CDR technology status, process overview, a review of CDR LCA research, baseline "cradle to grave" LCA for several different CDR technologies, and guidance on integrating LCA into deployment. The main drivers for GHG emission LCA are identified in relation to opportunities to optimize and deploy CDR in the US. Net negative emission values were used to compare the GHG emission LCA. While the net negative emissions LCA is a very simple calculation (Figure 1-1), the input and assumptions involved in the LCA are much more complicated.

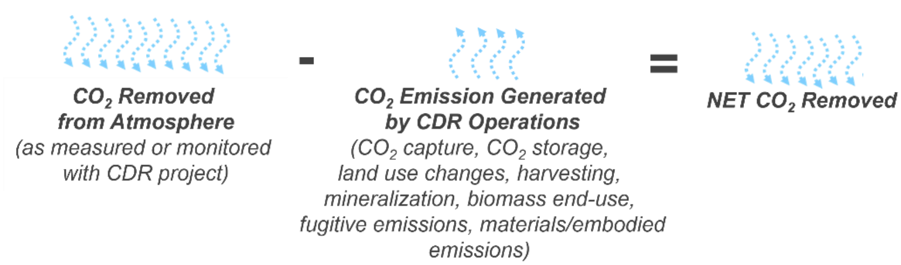


Figure 1-1. Net negative emissions concept.

1.1 Objectives

The objective of the Task 1 effort is to evaluate the life cycle greenhouse gas (GHG) emissions generated by CDR technologies and provide recommendations for technology development in the US. Under this task, products were developed to facilitate understanding of CDR technologies of life cycle GHG emissions, including the following:

- A review of CDR technologies,
- Analysis of life cycle GHG emissions generated by the technologies,

- Evaluation of geographic factors for CDR development in the US, and
- Recommendations for CDR development in the US to optimize net removal of carbon from the atmosphere.

1.2 Technical Approach

The technical approach was broken down into three subtasks:

1. CDR Technology Review
2. Life Cycle Assessment of GHG Emissions and Carbon Reduction Balance for CDR Technologies
3. CDR Technology Development Recommendations and Reporting.

The analysis focused on energy and emission based GHG LCA of CDR technologies as they may be deployed in the US. The GHG LCA approach utilized a combination of internal Battelle models for GHG LCA, US Department of Energy National Energy Technology Laboratory (US DOE NETL) LCA libraries, research, international experience with CDR demonstrations, technology vendor information, and technical literature. Some key aspects of the technical approach include the following items:

- The approach was a “cradle to grave” LCA for GHGs, including upstream (energy production, embodied emissions, mining, capture materials), midstream (CO_2 capture, dehydration, compression, storage/injection, land use, land preparation, transportation [CO_2, minerals, biomass]), and downstream activities (harvesting, end products, energy transmission). Many CDR LCAs only address individual components of the CDR process like the CO_2 capture process for DAC.
- CDR technologies are in the early stages of deployment, with no long-term operational data of 5-10+ years that are necessary to understand practical aspects of operations, natural cycles, and energy sources. All large-scale CDR LCA results are essentially projections at this stage because no projects have been deployed at scales greater than 100,000 metric tons per year.
- Many research studies have been completed for CDR LCAs, including a few articles released during the development of this paper. Literature values for net negative emissions may reflect a different scope or purpose of the particular LCA conducted.

The study used a streamlined energy and emissions LCA model, with the objective of comparing net negative emissions of several different CDR technologies. The ultimate goal of this study is to provide guidance on deploying CDR technologies in the US to maximize CO_2 removed from the atmosphere and minimize emissions generated by the construction, land use, materials, and operations necessary for the technologies.

A full reference list for the CDR technology review is provided in Appendix A. The objective of this study was to compare high-level LCA results for the different CDR technologies rather than an in-depth evaluation of all aspects of implementing each approach. As such, only key references are listed in the report.

2.0 CDR Technology Review

This section provides a brief review of select CDR methodologies (the list is not exhaustive), the key benefits and disadvantages for each selected methodology, and a review of carbon intensity data to provide a description of CDR status. Numerous CDR projects are currently proposed around the world. The Carbonplan.org database lists more than 200 CDR projects proposals with various locations, processes, and scales. Current CDR approaches include bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), terrestrial, mineralization, ocean, and other/experimental technologies. CDR technologies were reviewed in terms of overall CDR process, equipment, deployment scales, costs, status, and technology readiness levels.

2.1 BECCS

Bioenergy with carbon capture and storage takes biomass and burns it usually in combination with coal or other fossil fuels to create energy (Figure 2-1). The resulting emissions are then sequestered and stored. For bioenergy to have net negative CO_2 emissions it must be paired with carbon capture and storage. BECCS takes biomass and converts it into a product that can be cofired in a power plant, where a carbon capture system separates CO_2 from the emissions and stores it in geologic sinks. BECCS requires access to suitable geological carbon sequestration sites. The technology also requires significant land use that varies with the desired percent of biomass in the plant feedstock. Many BECCS plants are fuel switching, burning primarily fossil fuels and 10-40% biomass to reach carbon neutral status(K. Buchheit 2021). The BECCS facility location must be chosen based on local biomass growth potential and land availability to avoid transportation requirements. A BECCS facility must also address supply issues due to harvest and storage times. As of 2020 only six BECCS plants were in operation worldwide with four of the facilities located in the US, Archer Daniels Midland Ethanol (USA), Kansas Arkalon Ethanol (USA), Bonanza CCS Ethanol (USA), Husky Energy CO2 Injection (Canada), and Farnsworth CCS Ethanol (USA). (Consoli 2019). Cost ranges from \$60 to \$160 per ton of CO_2 removed (Cameron Hepburn 2019).

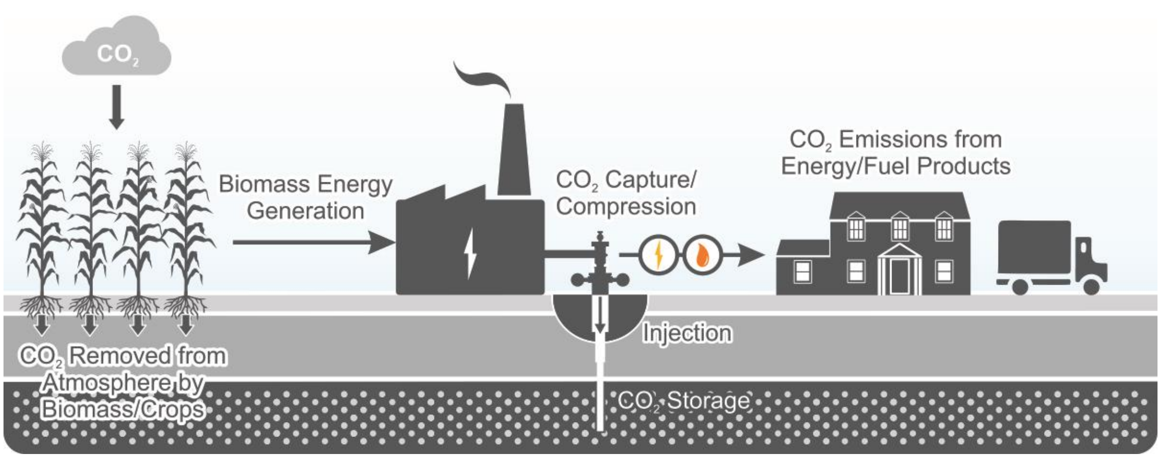


Figure 2-1. BECCS Process Diagram.

The major components of BECCS facilities that may generate GHG emissions include the following:

- Facility construction
- Transportation

- Land use
- Fuel switching emissions (if coal, gas, other hydrocarbons are burned in conjunction with biomass)
- Biomass production/transportation
- Energy production

2.2 Direct Air Capture (Aqueous or Solid)

DAC systems take in surrounding air and remove and concentrate CO_2 and use geologic sequestration to store the concentrated CO_2 stream. There are two primary DAC system types with many sub-variants. One uses a liquid solvent and the other a solid sorbent. Each type has it's own process and economic hurdles and benefits. One primary difference is the temperature of the regeneration which can complicate the power selection process. The liquid systems utilizing a calciner typically require regeneration temperatures of 900°C (National Academies of Sciences 2019). The solid sorbent typically requires approximately 100°C (National Academies of Sciences 2019). Additionally, there is also a growing field of using captured carbon and converting it into useful products such as chemicals, fuels, and building materials which can help recover costs. Since CO_2 is low concentration within ambient air (~418 parts per million [ppm]), DAC technologies must process a large volume of air with fans/blowers or other collection methods to capture meaningful amounts of CO_2. Combining DAC with sequestration technology leads to the requirement of being located near a suitable geological sink. To maximize carbon capture, DAC technology needs access to low carbon footprint energy sources. Current cost ranges from $100 to $1000 per ton CO_2 removed (Yuki Ishimoto 2017), although there is a great deal of ongoing research to decrease costs of CO_2 capture and some have claimed current costs as low as $94/ton (David W. Keith 2018).

CDR processes that may generate GHG emissions in DAC systems include the following components:

- Construction (capture facilities)
- Chemical production (sorbent materials)
- Energy production (thermal and electrical power, CO_2 compression)
- Land use (DAC facilities)
- Materials (sorbents)
- CO_2 storage (pipeline transport, injection wells)

The major new technology for DAC is the capture system. Carbon Engineering's DAC system utilizes some unit operations that have been in use for decades. The Carbon Engineering system uses potassium hydroxide to capture the CO_2 from the air. The solution then travels to a pellet reactor forming solid pellets, and then on to a calciner to release the CO_2 for compression and transport. The capture solution is then regenerated in the slaker for reuse in the capture system. The calciner requires a large thermal power load during continuous operations. Likewise, compression of the CO_2 to supercritical conditions requires continuous operations of multi-stage compression.

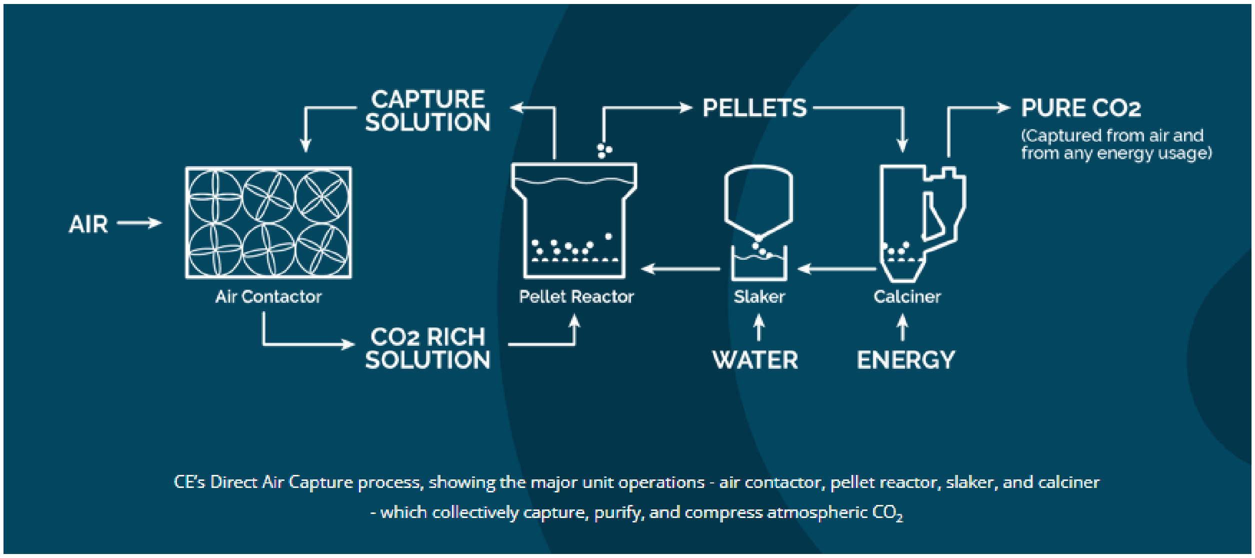


Figure 2-2. Carbon Engineering's DAC system diagram
(https://carbonengineering.com/our-technology/).

Climeworks, Carbon Engineering, and Global Thermostat have DAC plants in use, and other development projects have received significant funding from DOE to research sorbents, materials, and processes to more efficiently capture small amounts of CO_2 from airstreams (Figure 2-2). Most DAC technologies are reliant on improving the performance of these sorbents, materials, and/or processes for capture (Table 2-1).

Company	Project	DOE Funding
Electricore	DAC using novel structured adsorbents	$2,500,000
GE Research	Advanced Integrated Reticular Sorbent-Coated System to Capture CO_2 from the Atmosphere	$799,981
Georgia Tech Research Corporation	MIL-101(Cr)-Amine Sorbents Evaluation Under Realistic Direct Air Capture Conditions	$755,166
Global Thermostat Operations, LLC	Demonstration of a Continuous-Motion Direct Air Capture System	$2,499,996
Harvard University	Experimental Demonstration of Alkalinity Concentration Swing for Direct Air Capture of Carbon Dioxide	$720,048
InnoSense, LLC	High-Performance, Hybrid Polymer Membrane for Carbon Dioxide Separation from Ambient Air	$799,998
IWVC, LLC	A Combined Water and CO Direct Air Capture System	$2,500,000
Palo Alto Research Center	Tunable, Rapid-uptake, AminoPolymer Aerogel Sorbent for Direct Air Capture of CO_2	$799,998
Rensselaer Polytechnic Institute	Direct Air Capture Using Trapped Small Amines in Hierarchical Nanoporous Capsules on Porous Electrospun Hollow Fibers	$800,000
RTI International	Development of Advanced Solid Sorbents for Direct Air Capture	$800,000
Southern States Energy Board	Direct Air Capture Recovery of Energy for CCUS Partnership	$2,500,000
SUNY, in collaboration with University at Buffalo and Trimeric Corporation	Membrane Adsorbents Comprising Self-Assembled Inorganic Nanocages (SINCs) for Super-fast Direct Air Capture Enabled by Passive Cooling	$800,000
The Trustees of Columbia University in the City of New York	Next Generation Fiber-Encapsulated Nanoscale Hybrid Materials for Direct Air Capture with Selective Water Rejection	$800,000
The University of Akron in collaboration with Aspen Aerogels, Inc	Gradient Amine Sorbents for Low Vacuum Swing CO Capture at Ambient Temperature	$800,000
University of Delaware	Electrochemically-Driven Carbon Dioxide Separation	$800,000
University of Kentucky Research Foundation	Development of Novel Materials for Direct Air Capture of CO_2	$699,509
InnoSepra, LLC	Transformational Sorbent Materials for a Substantial Reduction in the Energy Requirement for Direct Air Capture of CO_2	$800,000
Susteon Inc	Low Regeneration Temperature Sorbents for Direct Air Capture of CO_2	$799,687

Table 2-1. Summary of DAC Technologies Funded by U.S. DOE
(https://www.energy.gov/fecm/articles/foa-2187-and-foa-2188-project-selections).

Solid DAC sorbents are based on utilizing solid sorbents with different thermodynamic properties, which results in different energy usage and GHG emissions. These systems usually have screens or monoliths that capture the CO_2 and are heated to 80-120°C once they are saturated with CO_2 in a two-step process that is cycled during operations. As of this writing the three companies with the most advanced DAC technologies are Carbon Engineering, with its liquid solvent approach, and Climeworks and Global Thermostat, with solid sorbent systems.

Figure 2-3 summarizes aqueous/liquid DAC technologies for CO_2 capture. These approaches have different energy requirements, CO_2 generated, net CO_2 reduction, and capture costs. Aqueous CO_2 solvents are an established technology, and they have been used for gas processing for many decades. However, liquid CO_2 solvents are typically used for higher CO_2 concentrations (5-25% CO_2), such as in industrial applications, as opposed to the concentrations typically found in ambient air.

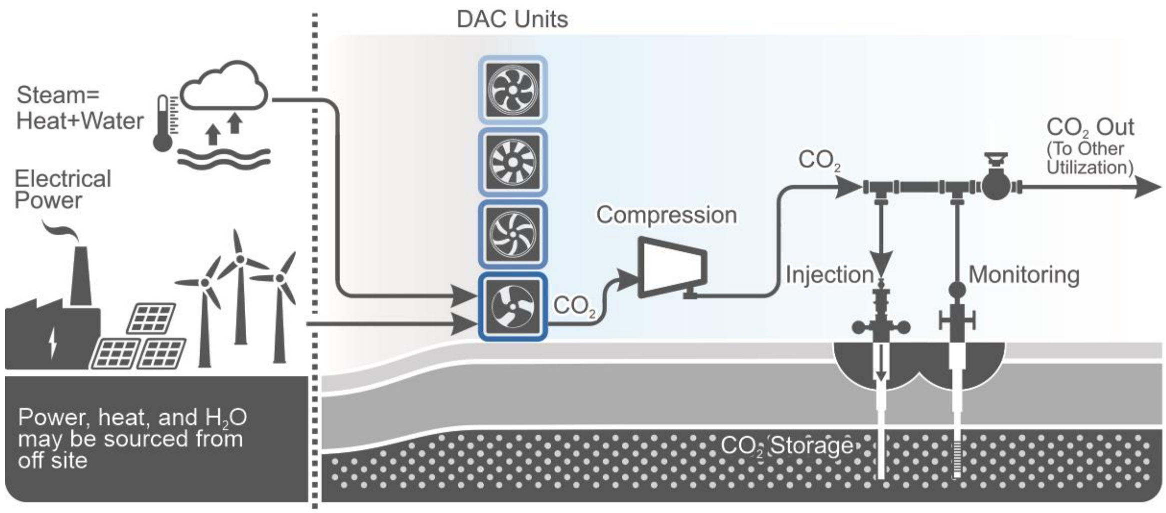


Figure 2-3. Liquid Solvent DAC Process Components

Figures 2-4 and 2-5 represent solid sorbent systems that utilize substrates with specific chemistry to allow for the selective removal of CO_2 from the air. The substrates are then heated, typically directly with steam, to regenerate the sorbent. The electrical power consumption is primarily from the use of fans to drive the optimal amount of air through the sorbent at the adequate velocities. The heat used is typically in the form of low-grade (~100 degree centigrade) steam. The total energy consumed is roughly 10-20% electrical power and the remaining is in thermal energy.

Figure 2-4. Global Thermostat Solid Sorbent DAC Process Components

Source: https://globalthermostat.com/

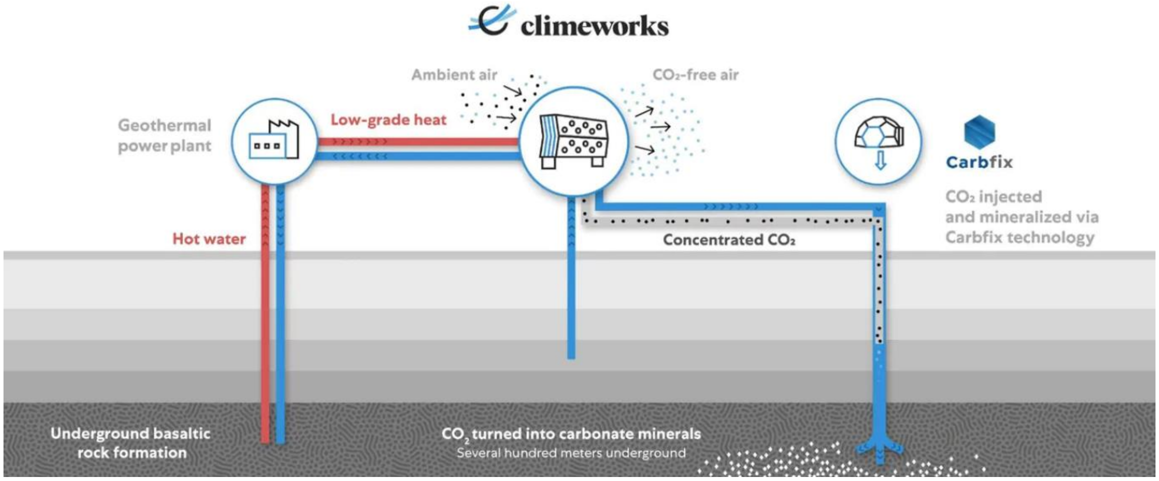


Figure 2-5. Climeworks Solid Sorbent DAC Process Components

Source: https://climeworks.com/what-is-direct-air-capture-and-storage

Table 2-1 summarizes the resultant effect of utilizing capture numbers from the National Academies report (National Academies of Sciences 2019) and incorporating them into a streamlined LCA analysis tool that adds in other factors such as compression and transport for of the DAC system. These net removal numbers are provided in Table 2-2. The carbon intensity of the heat and power source used to run the DAC system has a large impact on the over net removal numbers. Pairing DAC with solar, wind, and nuclear sources tends to provide the best overall net reduction (National Academies of Sciences 2019).

Table 2-2. Summary of liquid vs solid DAC factors

	Net Removal	
	Low	High
Liquid Solvent	33%	45%
Solid Sorbent	47%	92%

2.3 Terrestrial Carbon Removal

Terrestrial land use for carbon sequestration is defined as increasing the amount of organic carbon stored in soil or biomass (Figure 2-6) by biological removal of CO_2 from the atmosphere. Terrestrial carbon removal reforests an area or creates a new forested area and uses forestry management practices to sequester atmospheric carbon in biomass and the soil. Current commercial status of carbon removal via terrestrial land use is active. Land-use based offsets currently play a minor role in current cap-and-trade markets. Afforestation/reforestation refers to planting trees on land that has been in non-forest use to increase the amount of organic carbon stored. Reforestation has been extensively studied and considered immediately deployable, with more than 100 projects (Carbonplan.org 2021).

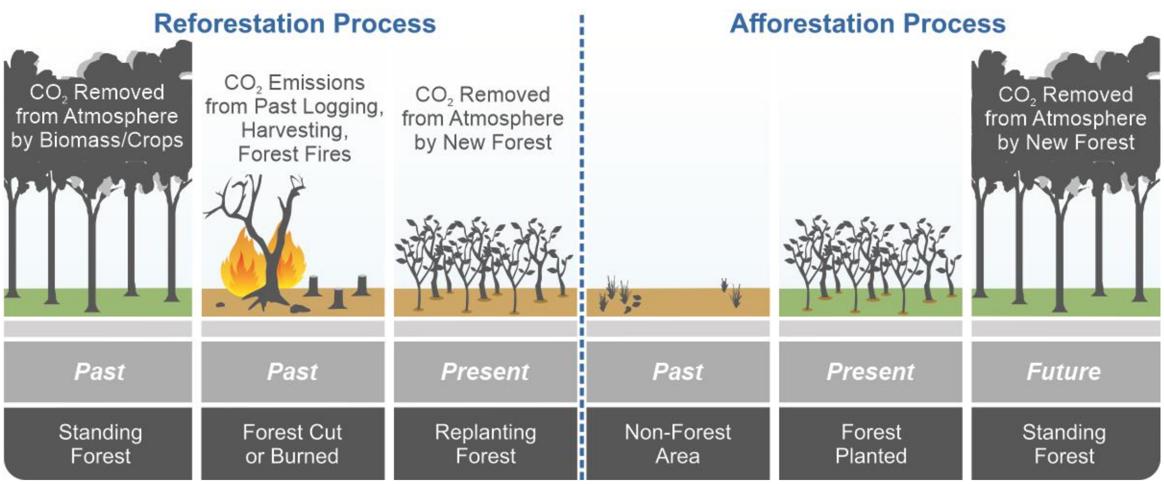


Figure 2-6. Terrestrial Carbon Dioxide Removal Process Diagram

The major components of terrestrial CO_2 removal that may generate LCA GHG emissions include the following:

- Land use
- Transportation
- Maintenance
- Biomass decomposition/forest fires
- Road access/maintenance
- Sampling production/transportation

2.4 Mineralization/Enhanced Weathering

Mineralization/enhanced weathering CDR is based on the concept that CO_2 can be stored in the form of carbonate minerals produced from reactions with common silicate rocks. Enhanced rock weathering is done by crushing and grinding minerals that absorb CO_2 and spreading them over fields where they will react with atmospheric CO_2 to sequester it as stable carbonate minerals (Figure 2-7). This method can be deployed via croplands to provide soil and crop production benefits. Deployment is recommended to be limited to croplands to aid in the economics and reduce the associated cost of carbon removal. Uncertainties still exist on mineralization/enhanced weathering because the method is based on extrapolation of lab-scale weathering rates to field scale. The technology must also be proven against natural weathering. Average cost in US ranges from less than $50 to $200 per ton of CO_2 removed. (Institute for Carbon Removal Law and Policy 2020)

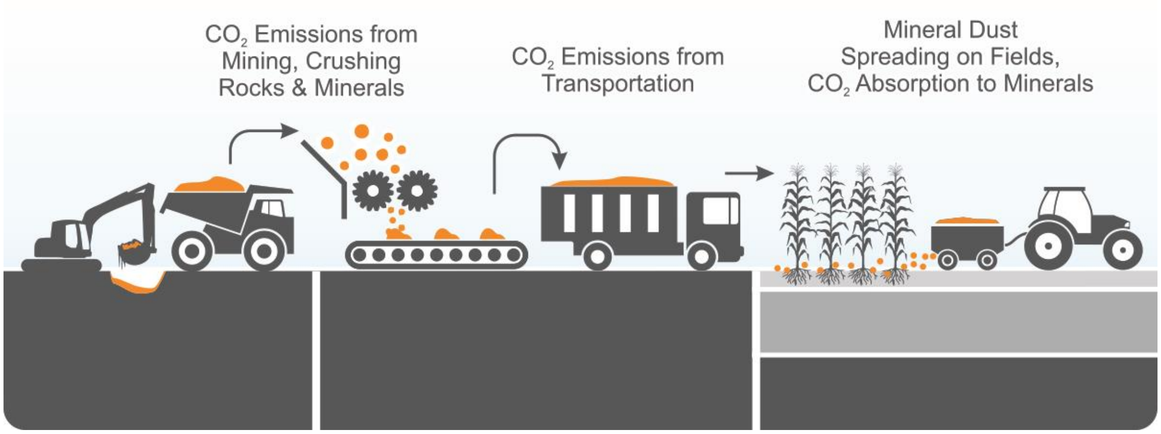


Figure 2-7. Mineralization DAC Diagram

The major components of terrestrial DAC that may generate LCA GHG emissions include the following:

- Land use
- Transportation
- Maintenance
- Biomass decomposition
- Rock mining
- Powder production/transportation

2.5 Biochar

Biochar is the method of producing biomass, having it undergo pyrolysis, and using the resulting biochar as a method of increasing crop yields. Several biochar projects are in operations at smaller scales. Cost ranges from $30 to $120 per ton of CO_2 removed.

The major components of biochar CDR that may generate LCA GHG emissions include the following:

- Land use

- Transportation
- Maintenance
- Biomass pyrolysis
- Biomass decomposition
- Road access/maintenance
- Sampling production/transportation

2.6 Coastal Blue Carbon/Ocean CDR

Coastal blue carbon is the method of sequestering CO_2 in the ocean using plant growth and the burial of the resulting organic carbon. This approach can help restore and create coastal wetlands as an added benefit. Additional research is required to provide accurate future predictions of CO_2 removal capability.

2.7 Other/Experimental CDR Technologies

Many other experimental CDR technologies have been proposed. In general, these technologies are early stage technologies with niche applications:

- CDR with synthetic fuel production
- Using captured carbon to create synthetic fuels
- Removing CO_2 by turning it into carbonate minerals
- Direct burial- growing biomatter to turn CO_2 into organic carbon, and burying to prevent release of GHGs
- CDR to building materials (cement, bricks, etc).

2.8 Key Literature on CDR Greenhouse Gas Life Cycle Assessments

Several research studies examine life cycle emissions for CDR technologies, as the carbon balance is a key factor for these applications. Studies have progressed from feasibility assessments based on unit process estimates, to lab tests based on experiments, to pilot tests based on field data, to larger scale projects based on operational performance. Research on CDR life cycle emissions is an active area of research, with several studies released within 2021-2022. As more CDR projects are developed at scales greater than 100,000 mt/year, quantitative data will be available to determine net negative emissions more accurately. Key CDR LCA efforts are summarized as follows.

Negative Emissions Technologies and Carbon Capture and Storage to Achieve the Paris Agreement Commitments (Haszeldine et al., 2018)
https://doi.org/10.1098/rsta.2016.0447

- Examines policy and drivers for CDR at global scales.
- Considers timelines, costs, and status of CDR technologies.

Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (National Academies of Sciences and Medicine, 2019)
https://www.ncbi.nlm.nih.gov/books/NBK541453/

- Analyzes costs, barriers, and scaling factors for CDR technologies on a global scale.

- Concludes that CDR technologies can supplement other efforts to reduce existing emissions as the world transitions to low-carbon industry.
- Lays out research agenda for CDR development.

Carbon Dioxide Removal Primer (Wilcox, Kolosz, and Freeman, 2021) https://cdrprimer.org/read

- Summarizes CDR technologies, opportunities, and benefits.
- Provides framework for analysis and quantification of negative emissions.

Life Cycle Assessment of Carbon Dioxide Removal Technologies: A Critical Review (Terlouw et al., 2021) https://doi.org/10.1039/D0EE03757E

- Reviews status of CDR technologies in relation to quality of life cycle assessment calculations.
- Concludes that tracking temporal changes to carbon balance and transparent LCA calculations are important for developing CDR technologies.
- Suggests that current LCA results should be interpreted with caution.

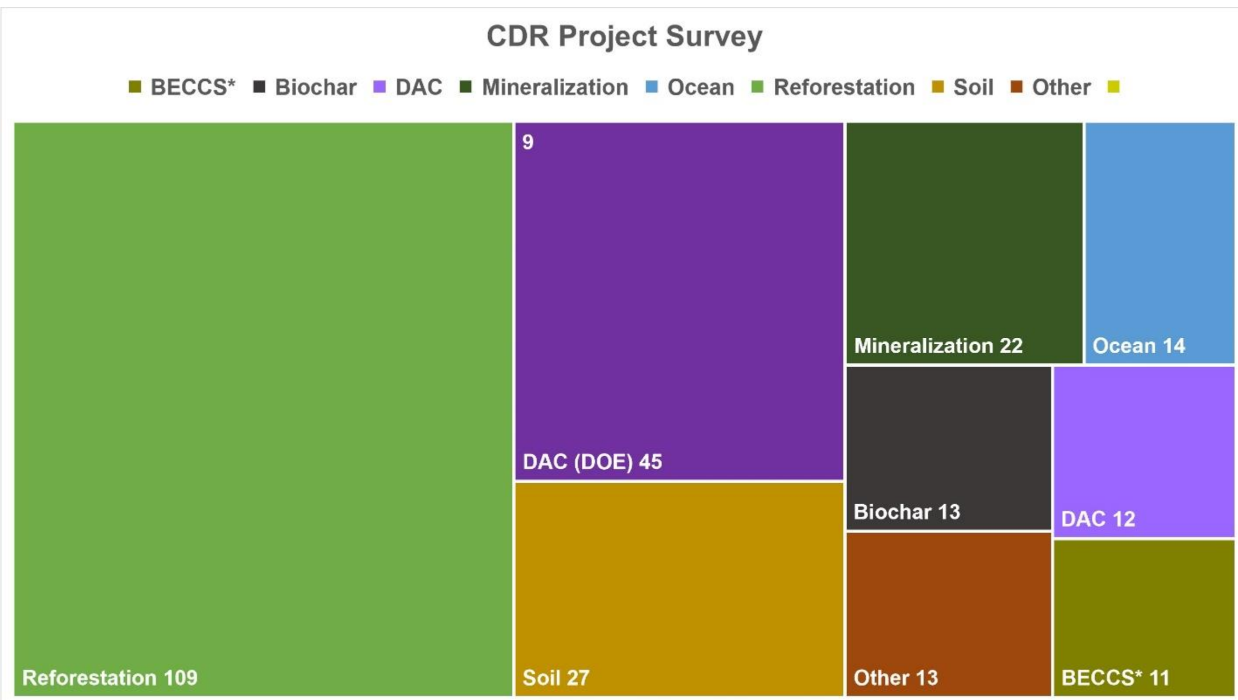
The Life Cycle Environmental Impacts of Negative Emission Technologies in North America (Jasmin et al., 2022) https://doi.org/10.1016/j.spc.2022.06.010

- Compares lifespans, scales, environmental impacts, and net carbon removal for CDR technologies based on life cycle assessment.
- Suggests that terrestrial/forestation and mineralization have the highest net negativity and lowest environmental impacts while having time and scalability limitations.

3.0 Status of CDR facilities in U.S. and International Locations

The status of CDR technologies was surveyed based on public information and databases. Figure 3-1 summarizes the status of CDR technologies as of summer 2022. CDR technologies are emerging, with new technologies being proposed frequently. Categorizing CDR projects is increasingly difficult, because projects involve many different processes, energy sources, embodied emissions, land use changes, and end products (these items also affect ability to compare GHG LCA results for CDR projects). CDR survey results are listed as follows.

- CarbonPlan.org lists 219 CDR projects proposals in its database, which are associated with Stripe and Microsoft corporate efforts. CarbonPlan indicates that most of the projects in this database are in early stages with inconsistent LCA information.
- The International Energy Agency (2021) stated "There are currently 19 direct air capture (DAC) plants operating worldwide, capturing more than 0.01 Mt CO_2/year."
- Global Carbon Capture and Storage Institute lists two BECCS projects and 39 ethanol carbon capture and storage projects in its database.
- The DOE is currently funding 18 projects on novel DAC technologies under FOA2188, 12 projects on DAC materials under FOA2402, nine projects on materials/chemicals for DAC under FOA2481, and five CDR FEED projects under FOA2560. The DOE has also announced intent to support several DAC Hubs on FOA2735, CDR deployment and demonstration projects under FOA2660, and mineralization projects under FOA2614.



*Not including 39 Bioethanol plants with CCS that may be considered CDR.

Figure 3-1. CDR Project Count Survey

In terms of scale, CDR technologies are under development at varying scales. DAC, BECCS, and mineralization are in the lab/experimental scale (kilograms) to pilot scale (1,000s metric tons/year).

- Reforestation projects are being developed at the industrial scale but will require time to produce meaningful LCA results. These results must also be verified with monitoring.
- Ethanol/corn oil plants with carbon capture and storage which may be considered CDR, depending on the downstream emission factors of the ethanol used in fuel products.
- DAC projects range from laboratory studies on the gram scale up to thousands of metric tons per year. No industrial scale DAC projects are currently operating (not counting ethanol carbon capture and storage projects that are not commonly included as CDR). A Carbon Engineering ~1,000,000 metric tons per year DAC plant is under construction in Texas with operations expected in 2024-2025.
- BECCS projects are currently being constructed at pilot scale (1,000s metric tons/year).
- Numerous reforestation and soil CDR projects are operating at scales of 1,000s to 1,000,000s metric tons CO_2.
- Mineralization projects appear to be mostly in the laboratory (100s metric tons) to pilot scale (1,000s metric tons) with a wide range of application scales.
- Biochar, biomass, ocean CDR, direct burial, and other CDR technologies are generally on the scale of kilograms to 1,000s metric tons CO_2.

3.1 CDR Technology Selection for LCA

As described, numerous CDR technologies are in development. As such, few GHG LCA studies are based on real-world operational data. To down-select key CDR technologies, a review of technology deployment feasibility was completed based on costs, carbon removal potential, and deployment factors. Figure 3-2 summarizes deployment feasibility review. There are limiting factors for all CDR technologies in terms of scale and costs.

Based on the CDR technology review, the project team identified five key CDR technologies for analysis:

- DAC aqueous solution
- DAC solid capture
- BECCS, biomass, ethanol
- Reforestation
- Mineralization

These technologies were selected because they have the greatest potential to be scaled up to industrial scales of 100,000s to 1,000,000s metric tons CO_2 per year in the near term. In addition, there are LCA research studies, pilot scale tests, and real-world operational data on the five technologies that were selected. It is also important to consider the total project lifespan application of the CDR technologies. A large DAC plant may be able to operate for 25 years at 400,000 metric tons net carbon removal per year for total project lifespan carbon removal of 10 Mt CO_2. A 400,000 metric ton reforestation or surface mineralization project may be constrained by land area and natural CDR rates and have total project lifespan carbon removal of 400,000 mt CO_2.

CDR Technology	Estimated Cost	US Carbon Removal Potential at (Gt/y CO2)	Limiting Deployment Factors
Direct Air Capture	Medium-High	0.5-5	Access to geologic carbon sequestration sites, and low carbon energy sources
Bioenergy with Carbon Capture	Medium	0.5-5	Access to land availability, biomass growth potential, and geologic sequestration sites
Terrestrial Carbon Removal	Low	0.04-0.34 (0.7-6.4Mg/ha yr C)*	Requires land availability
Enhanced Rock Weathering	Medium-High	0.5-5	Limited to croplands to aid economics
Biochar	Low-Medium	0.3-2	Unknown
Coastal Blue Carbon	Low		Requires further research

Deployment Feasibility
Moderate
Favorable
Prospective/Unknown

*Terrestrial 0.7-6.4(Mg/(ha y) C) Birdsey, 1996

133 million acres of reforestable land Reforestation Hub - Reforestation Opportunities for Climate Change Mitigation 37.53 Mt/yr-343.7Mt/yr

Figure 3-2. CDR Technology Review

4.0 Life Cycle Assessment of CDR Technologies

For the five CDR technologies, a GHG life cycle assessment of the technologies was completed to evaluate net CO_2 storage, accounting for emissions generated from CDR processes such as CO_2 capture, pipeline transport, construction, CO_2 injection, and embodied emissions. The first step was to define boundaries for “cradle to grave” and “gate-to-gate” LCA for CDR technologies. An energy and emissions-based analysis of the CDR scenarios was then completed using a streamlined energy and emissions based LCA model for CCS operations. The GHG LCA was used to evaluate net carbon removal given emissions and materials related to CDR operations.

Based on the CDR technology review, the project team developed one-page LCA summaries of five key CDR technologies as follows. The streamlined energy and emissions LCA input and calculations for the analysis are provided in Appendix B.

Direct Air Capture (Low Temp Solid Sorbent)

Technology Process Description

DAC technology captures carbon directly from the air, concentrates, and compresses it and stores it in a geologic sink.

Upstream
Chemical Production

Land Use
DAC plant, CO_2 storage, pipelines

Construction
DAC plant, injection wells, pipelines

DAC CO_2 Capture
Fuel/electricity, fugitive emissions

CO_2 transport
Pipeline to CO_2 storage site

CO_2 storage
Injection, boosting, monitoring

Downstream Losses
Leakage, fugitive emissions

Technology Maturity
Mix of development and Pilot Scale

Current Scale
7 projects 50-4,000 t/yr

Negativity
0.40-0.99

GHG LCA Components and Emission Factors

LCA Component	Description	Direct Air Capture Low Temp Solid Sorbent (Climeworks, etc) ton CO_2 emitted / ton CO_2 stored
Construction/Site Prep	Emissions from energy required to construct facility	0.033
CO_2 Capture	Capture Process	0.050
CO_2 Transportation/Storage	Emissions from compressing and sending CO_2 to storage	0.050
Other	Energy Production	0.014

Benefit Analysis

Advantages
Can use waste heat for energy, can be constructed in many locations

Disadvantages
Construction, 24-7 operations, matching CO_2 sinks, large footprint

Deployment Potential
DAC plants will require scaling up from 1000s tons per year to 100,000s tons per year. DAC plants will require 10s of acres land use for each DAC facility and large areas for large scale application. DAC will also need to be integrated with CO_2 pipeline transport and injection for CO_2 storage. DAC efficiency may be affected by climate factors like humidity and temperature.

Risks
Significant Energy requirement for operations, energy source may reduce net CO_2 storage

[1]Tom Terlouw, Karin Treyer, Christian Bauer, and Marco Mazzotti, Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources Environmental Science & Technology 2021 55 (16), 11397-11411

Direct Air Capture (High Temp Aqueous)

Technology Process Description

DAC technology captures carbon directly from the air, concentrates, and compresses it and stores it in a geologic sink.

Upstream
Fuel/Electricity production for DAC plant

Land Use
DAC plant, CO_2 storage, pipelines

Construction
DAC plant, injection wells, pipelines

DAC CO_2 Capture
Fuel/electricity, fugitive emissions

CO_2 Compression
Compression to SC CO_2

CO_2 transport
Pipeline to CO_2 storage site

CO_2 storage
Injection, boosting, monitoring

Downstream Losses
leakage, fugitive emissions

Technology Maturity
Mix of development and Pilot Scale

Current Scale
3-5 projects <1 Mt/yr

Negativity
0.4-0.96

GHG LCA Components and Emission Factors

LCA Component	Description	Literature Range $\frac{\text{ton } CO_2 \text{ emitted}}{\text{ton } CO_2 \text{ stored}}$
Upstream	Energy Production	0.25
Construction	Emissions from energy required to construct facility	0.025
CO_2 Capture	Capture Process	0.4
CO_2 Transportation/Storage	Emissions from compressing and sending CO_2 to storage	0.05

Benefit Analysis

Advantages
Scalable, can be constructed in many locations, provides direct removal, allows rapid carbon removal, allow direct metering of LCA during operations.

Disadvantages
Construction, 24-7 operations, matching CO_2 sinks, large footprint

Deployment Potential
DAC plants will require scaling up from 1000s tons per year to 100,000s tons per year. DAC plants will require 10s of acres land use for each DAC facility and large areas for large scale application. DAC will also need to be integrated with CO_2 pipeline transport and injection for CO_2 storage. DAC efficiency may be affected by climate factors like humidity and temperature.

Risks
Significant energy required for CO_2 capture, energy source may reduce net CO_2 storage

[1]Ringrose, P., Furre, A. K., Bakke, R., Dehghan Niri, R., Paasch, B., Mispel, J., ... & Hermansen, A. (2018, October). Developing Optimised and Cost-Effective Solutions for Monitoring CO_2 Injection from Subsea Wells. In 14th Greenhouse Gas Control Technologies Conference Melbourne (pp. 21-26).

[2]Chadwick, R.A.; Eiken, O.. 2013 Offshore CO_2 storage: Sleipner natural gas field beneath the North Sea. In: Gluyas, Jon; Mathias, Simon, (eds.) Geological Storage of Carbon Dioxide (CO_2): geoscience, technologies, environmental aspects and legal frameworks. Cambridge, UK, Woodhead Publishing, 227-253.

[3]Melinda M.J. de Jonge, Juul Daemen, Jessica M. Loriaux, Zoran J.N. Steinmann, Mark A.J. Huijbregts, Life cycle carbon efficiency of Direct Air Capture systems with strong hydroxide sorbents, International Journal of Greenhouse Gas Control, Volume 80, 2019, Pages 25-31.

BECCS

Technology Process Description

BECCS uses harvested biomatter and converts it into a product that can be burned with coal in a power plant, then captures and stores the CO_2 in a geologic sink.

Upstream
Cropland, forest, fertilizer

Land Use
BECCS plant, CO_2 storage, pipelines

Construction
BECCS plant, harvesting, transport

DAC CO_2 Capture Process
Fuel/electricity, fugitive emissions

CO_2 Compression
Compression to SC

CO_2 transport
Pipeline to CO_2 storage site

CO_2 storage
Injection, boosting, monitoring

Downstream Losses
leakage, fugitive emissions

Technology Maturity
Mix of development and Pilot Scale

Current Scale
11 projects <1 – 9 Mt/yr

Negativity
0-0.90

GHG LCA Components and Emission Factors

LCA Component	Description	Literature Value $\frac{\text{ton } CO_2 \text{ emitted}}{\text{ton } CO_2 \text{ stored}}$
Upstream	Emissions associated with biomass production	0.282
Construction/Site Prep	Emissions from energy required to construct facility	0.026
Transportation	Emissions from biomass transportation	0.15
CO_2 Capture	Capture process	0.1
CO_2 Transportation/Storage	Emissions from compressing and sending CO_2 to storage	0.059

Benefit Analysis

Advantages
Produces Electricity

Disadvantages
Construction, 24-7 operations, matching CO_2 sinks, large footprint, requires significant biomatter supply chain, could be net positive depending on percent of co-firing.

Deployment Potential
Can be retrofitted onto existing power plants, needs to have easily accessible supply of biomass

Risks
Significant energy required for CO_2 capture, energy source may reduce net CO_2 storage

*after Mathieson, A., Midgelya, J., Wright, I., Saoula, N., and Ringose, P., 2011. In Salah CO_2 Storage JIP: CO_2 sequestration monitoring and verification technologies applied at Krechba, Algeria. Energy Procedia 4 (2011), 2596-3603.

[5]Fajardy, M., Mac Dowell N., Can BECCS deliver sustainable and resource efficient negative emissions?, Energy Environ. Sci., 2017,10, 1389-1426

Terrestrial Carbon Sequestration

Technology Process Description

Reforestation and afforestation are the primary method of terrestrial carbon sequestration. Trees are grown to capture atmospheric CO_2 and then harvested for lumber products.

Upstream
Seed production/transportation

Land Use
Converted land for forest growth

Construction
Road Access, Forest monitoring stations

Technology Maturity
Mix of development and Pilot Scale

Current Scale
100+ projects <1 - 15 Mt/yr

Negativity
0.30-0.99

GHG LCA Components and Emission Factors

LCA Component	Description	Literature Value $\frac{\text{kg } CO_2 \text{ emitted}}{\text{Hectare}}$
Upstream	Emissions associated with biomass production	0.282
Land Use	Requires significant changes in land footprint	0.58
Construction/Site Prep	Emissions from energy required to construct facility	0.026
Transportation	Emissions from biomass transportation	0.15
CO_2 Transportation/ Storage	Emissions from compressing and sending CO_2 to storage	0.059

Benefit Analysis

Advantages
Few Direct Energy Costs

Disadvantages
large footprint, limited to areas appropriate for forest growth

Deployment Potential
Relatively high sequestration potential at the cost of significant land needs

Risks
Studies should be done on a variety of tree species to determine effectiveness; Temporal analysis of carbon stocks need to be further evaluated. Risks of forest fires changing sequestration effectiveness.

[1]Simon Gaboury, Jean-François Boucher, Claude Villeneuve, Daniel Lord, Réjean Gagnon, Estimating the net carbon balance of boreal open woodland afforestation: A case-study in Québec's closed-crown boreal forest, Forest Ecology and Management, Volume 257, Issue 2, 2009, Pages 483-494

Enhanced Weathering

Technology Process Description

Enhanced weathering is the crushing and milling of basalt rocks and transporting the resulting product to spread onto agricultural land. The crushed rock takes up atmospheric CO_2 and increases crop yield.

Upstream
Rock milling/production and transportation

Land Use
Creation of new mining sites/use of existing sites

Construction
Road Access

Technology Maturity
Mix of development and Pilot Scale

Current Scale
22 projects 100-30,000 t/yr

Negativity
0.74-0.99

GHG LCA Components and Emission Factors

LCA Component	Description	Enhanced Rock Weathering $\frac{\text{ton } CO_2 \text{ emitted}}{\text{ton } CO_2 \text{ stored}}$
Upstream	Emissions associated with rock mining	0.13
	Emissions associated with rock grinding	0.113
Transportation	Emissions from rock transportation	0.015

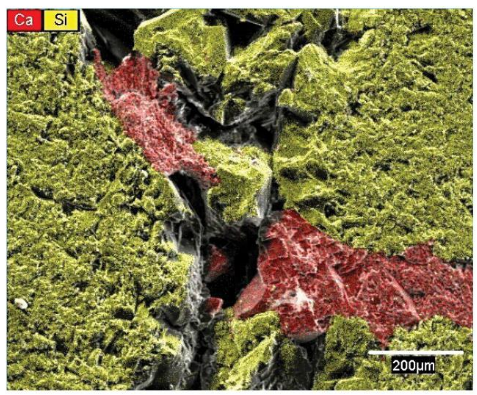
Benefit Analysis

Advantages
Increases crop yield leading to possible hidden increased sequestration benefits

Disadvantages
Requires close access to rock supply chain/low carbon transportation

Deployment Potential
Deployment currently limited to relatively small sequestration projects

Risks
Few comprehensive LCA studies



Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil - ScienceDirect

[1]David Lefebvre, Pietro Goglio, Adrian Williams, David A.C. Manning, Antonio Carlos de Azevedo, Magda Bergmann, Jeroen Meersmans, Pete Smith, Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil, Journal of Cleaner Production, Volume 233, 2019, Pages 468-481

4.1 Comparison of CDRs

Figure 4-1 summarizes the LCA results for the five CDR technologies evaluated in this study. As shown, there is a large (0-99%) range of net negativity results for cradle-to-grave LCAs in the literature. In fact, articles suggest some CDR technologies may have net positive emissions. This speaks to the variability of CDR projections at this early development stage. The main contributors to GHG emissions for DAC and BECCS include emissions related to capture and compression, construction, and operations. The energy source also affects net negativity of DAC applications. BECSS is also impacted by the proportion of biomass used for energy production. Terrestrial carbon removal and mineralization have large land use emission factors. These CDR technologies also require verification of CO_2 storage, accounting for growth cycles, decomposition, and forest fires.

Due to the highly variable nature of the existing LCAs for CDR technology it is hard to draw a direct comparison between the different technologies. Based on the analysis of existing LCAs it is recommended to compare possible projects on a site-by-site basis where data on local electric production portfolios can be more closely examined, as well as other key aspects to the other CDR technologies such as access to geologic carbon sinks, biomass, or low carbon transportation methods. Current research, field pilot, and commercial scale CDR projects include a GHG LCA component. The DOE has a LCA toolbox, LCA unit process library, and DAC LCA calculation methodology. Other options for completing LCAs include GREET, OpenLCA, and ISO standards.

DAC plants are one of the more flexible CDR options, especially if paired with green energy development in the project area. The DAC energy source should be evaluated to ensure use of excess green energy rather than displacing green energy from residential or industrial use. DAC plants themselves only need to take proximity to geologic sinks in mind. BECCS operations are similar, however there are significant GHG emissions associated with transportation and indirect land use changes for producing and transporting the biomass needed to sustain the operation. Forestation techniques are great in theory, however, there seems to be significant issues with monitoring carbon storage associated with these products that need to be rectified for a more robust accounting procedure of carbon removal. Lastly, enhanced rock weathering shows some promise, but is the least studied of these technologies and more information needs to be gathered to verify its usefulness. A flexible approach to CDR technology seems to be the best solution at present. This approach should consider the resources local areas can provide in terms of energy, land, water, infrastructure, and CO_2 storage.

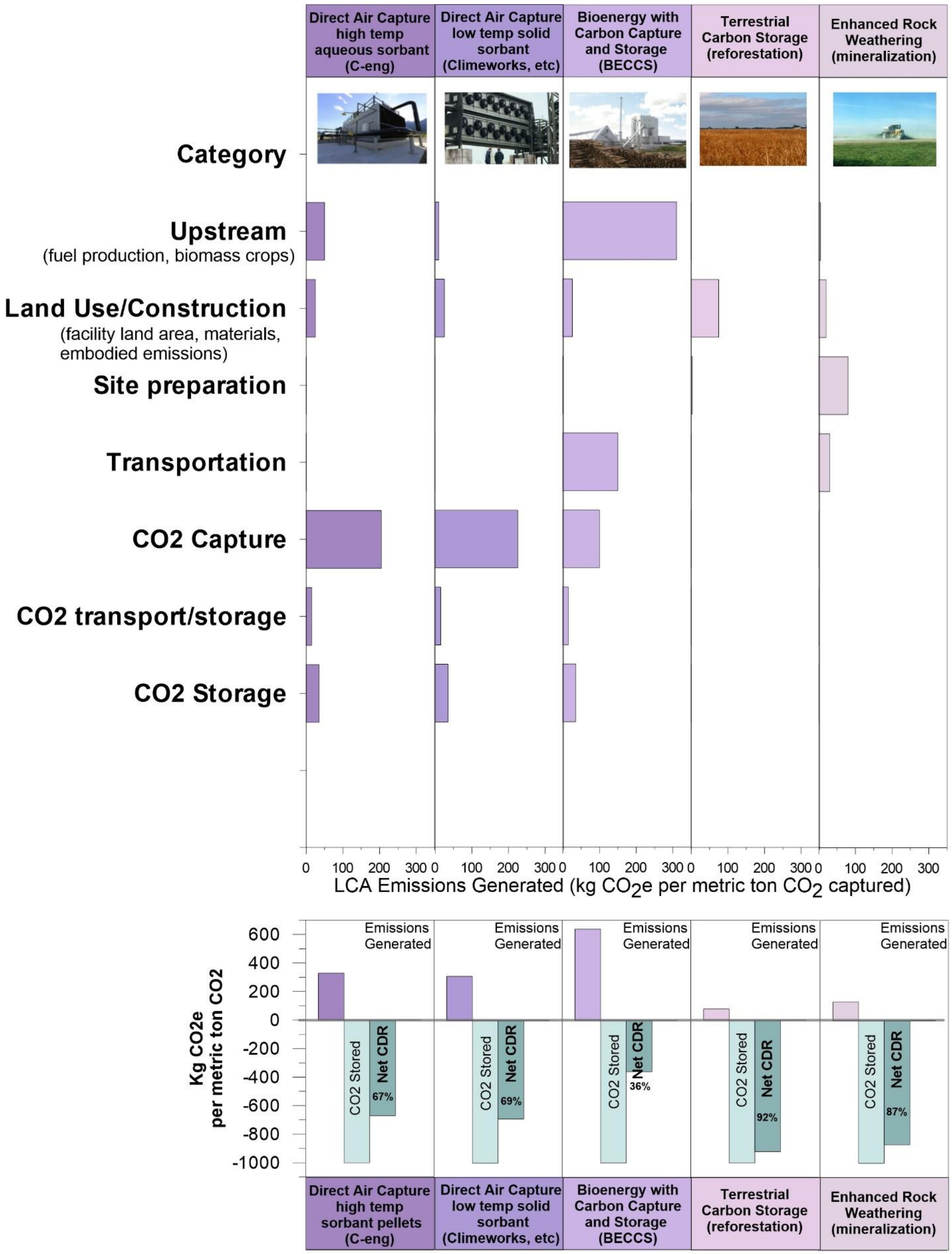


Figure 4-1. Comparison of CDR LCA Results and Net Negativity

4.2 Operational GHG LCA for CDR Applications

Many of the current LCAs on CDR technologies are based on preliminary engineering studies of unit processes, laboratory-, bench-, or pilot-scale testing. Long-term metering and monitoring of CDR operations is recommended for more accurate depiction of net negative emissions. These calculations should be based on facility operations. Over the facility operational lifetime (20-30 years), emissions related to operations will have the largest contribution to GHG emissions in comparison to initial construction and embodied emissions.

For example, DAC facilities would need to monitor energy usage for CO_2 capture, compression, dehydration, injection, fugitive emissions, and sorbent materials. Monitoring equipment may include a supervisory control and data acquisition system to record energy usage and CO_2 flow meter data for the DAC operations from the capture facility to the injection wells. Together, these meters provide a comprehensive account of the CO_2 moving through system operations (Pasumarti et al., 2016).

Figure 4-2 shows example data from CO_2 capture and compression operations from 1997-2017 for a natural gas processing facility (Sminchak et al., 2020). This provides a practical example of long-term CO_2 capture operations, albeit from a more concentrated CO_2 gas stream (~15%). During this 22-year period, the facility captured 2,233,269 metric tons CO_2. Emissions from the capture system were derived from operational records on the natural gas used to power the capture system, materials, and construction. Emissions from the capture operations were estimated at 478,476 metric tons CO_2equivalent. Emissions for CO_2 compression, pipeline transport, and injection operations were estimated as 374,147 metric tons CO_2e. Consequently, net negative emissions would be 1,380,646 metric tons CO_2, or 62% of the total 2.23 million metric tons CO_2 captured by the system. This illustrates the substantial energy/emission penalty from CO_2 capture and compression.

Year	CO_2 Captured (metric tonnes)	Total Emissions (metric tonnes)	
		Upstream CO_2 Capture	Gate to Gate Compression, Transport, Injection
1996	110,238	22,872	7166
1997	68,162	14,142	10511
1998	98,763	38,543	19554
1999	5,941	1,289	12025
2000	15,259	2,061	9786
2001	0	0	8759
2002	665	72	8237
2003	11,585	1,174	9397
2004	4,728	528	9521
2005	1,500	175	4697
2006	95,992	19,916	13308
2007	26,867	5,574	10042
2008	149,346	30,986	18472
2009	112,862	23,417	17449
2010	157,520	32,682	18740
2011	174,449	36,195	24530
2012	172,926	35,879	26342
2013	196,448	40,759	26118
2014	157,796	32,740	26908
2015	165,223	34,280	27971
2016	196,448	40,759	26118
2017	310,549	64,433	38495
Total	2,233,269	478,476	374,147

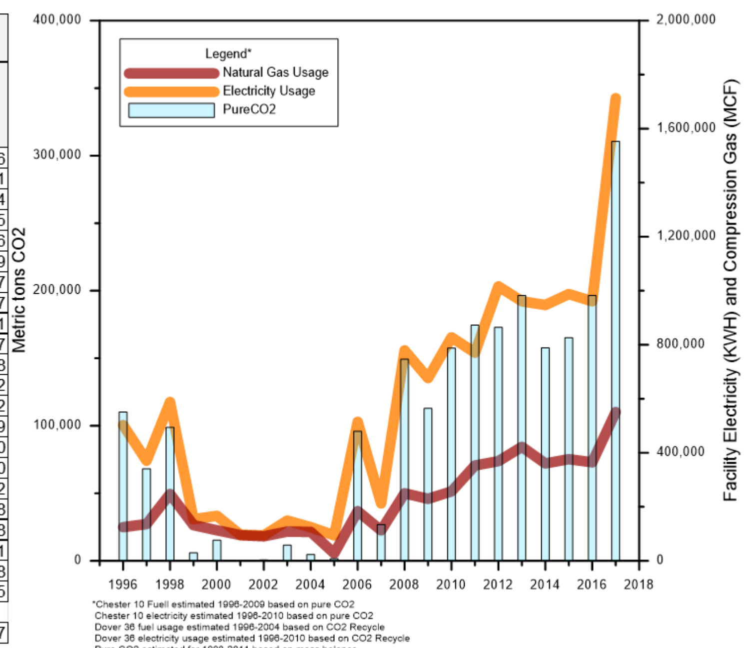


Figure 4-2. Example Long-term Energy Usage from a Natural Gas CO_2 Capture and Compression System Illustrating Performance Monitoring of CO_2 Capture, Energy, and Fuel

This example illustrates the substantial energy/emission penalty from CO_2 capture and compression that may be incurred in DAC systems and other CDR technologies. In this case, the energy for capture and compression was provided by natural gas. Emissions would likely be less for green energy sources. However, it may be difficult to find readily available green energy sources of this magnitude that would not displace energy from the grid. The example also illustrates the value of metering long-term operational data and metering a facility. DAC and BECCS facilities are better equipped to meter and monitor energy, emissions, and CO_2 flows. Reforestation and mineralization efforts are more difficult to track since they do not directly meter CO_2.

Large DAC installations will be new net users of thermal and electrical energy as opposed to utilizing slack in the grid. Current estimates from the National Academies report on Negative Emissions estimates requirements of 0.55-1.1 GJ/tCO_2 for power and 3.4-4.8GJ/tCO_2 (from NASEM, 2018) for thermal energy for solid adsorbent systems and considerably higher for liquid solvent systems. To deploy DAC at scale, additional power and heat sources will have to be built out to satisfy the thermal and power requirements. A number of Front-End Engineering and Design (FEED) studies for DAC systems are being funded by the DOE. As these projects progress, the heat, power, and water requirements will be refined and added to the collective understanding required for at-scale deployment.

5.0 Regional Factors for CDR Development in the US

Regional factors for CDR technology deployment in the US include items such as proximity to geologic CO_2 storage resources, transportation corridors (CO_2 pipelines, biomass transport), energy mix, GHG policies, incentives for carbon removal, climate conditions, economics, and land use. Regional factor analysis focused on the following issues for CDR development in the US:

- Timeline and technology readiness level assessment
- Economic factors for CDR
- Options for optimizing net carbon removal for CDR technologies

5.1 DAC Plants

DAC plants are relatively flexible in geographic flexibility. They can be placed nearly anywhere, but performance may be affected by climate and access to energy, water, pipeline, and CO_2 storage resources. Depending upon the technology, there are additional factors to consider when locating DAC facilities:

Altitude: One common issue for most technologies is a high-altitude location typically reduces the capture efficiency and can require additional or equipment changes from a sea-level or moderate altitude facility.

Humidity: The humidity level can be a factor for capture efficiency depending on the DAC technology.

Spacing: Some types of DAC systems will require a careful assessment of spacing to ensure dilute air streams from upwind modules do not affect the capture efficiency.

Low-Carbon Heat and Power: At-scale DAC utilizes significant amounts of heat and electrical power. As the carbon intensity drives the DAC system net reduction, it is important to locate these systems within areas that can provide low-carbon energy.

Water: Some types of DAC can use large amounts of water. The ability to recycle this water or have ample supply is important.

Distance to sink: The further from suitable geology the installation is the lower the overall reduction. Additionally, long runs of pipelines will add additional cost and complexity of the overall system.

5.2 BECCS Plants

Most discussion around BECCS is about retrofitting already existing coal-fired power plants. Any retrofit projects or new projects will have to examine the accessibility of biomass in relation to the plant. An ideal situation would have all of the supplied biomass geographically near the project, or access to efficient transportation methods such as train or barge. The further a project must source biomass, the less likely that the project will have a net negative impact on atmospheric carbon. BECCS plants also need to keep in mind access to geologic sinks to transport the supercritical CO_2.

5.3 Terrestrial Carbon Removal

The major regional factor for terrestrial carbon removal projects is the ability for planted forests to thrive in the local climate. Regions should be paired with native plant species that are able to grow and thrive to maximize carbon reduction of the project. In addition, forestry management practices should be followed to keep the health of the forestry project high.

5.4 Enhanced Rock Weathering

Rock weathering projects should also be selected based on geographic closeness to the supply of crushed rocks being used. These rocks should be transported via low carbon transportation methods if possible. If the project is trying to maximize additional side benefits, the location should also be close to farms to take advantage of fertilizing side effects of enhanced weathering.

5.5 Timeline and Technology Readiness for CDR Deployment

Figure 5-1 illustrates the conceptual relationship between timing and technology readiness levels for CDR technology deployment. All CDR options would likely require 5-10 years to reach meaningful scales of gigatons (Gt) CO_2 removal. DAC and BECCS require substantial construction and connection to geologic storage projects. BECCS and reforestation require natural growth cycles to establish biomass. Most of the components for CDR are at high technology readiness levels, but they often require concurrent development to reach scale. For example, a BECCS plant would require development of suitable biomass resources, transport to the plant, biomass boiler, capture plant, compression plant, CO_2 transport pipelines, and CO_2 storage complex. DAC technology appears to have the most uncertainty in technology readiness level because it has not been demonstrated at industrial scale (> 100,000 metric tons per year).

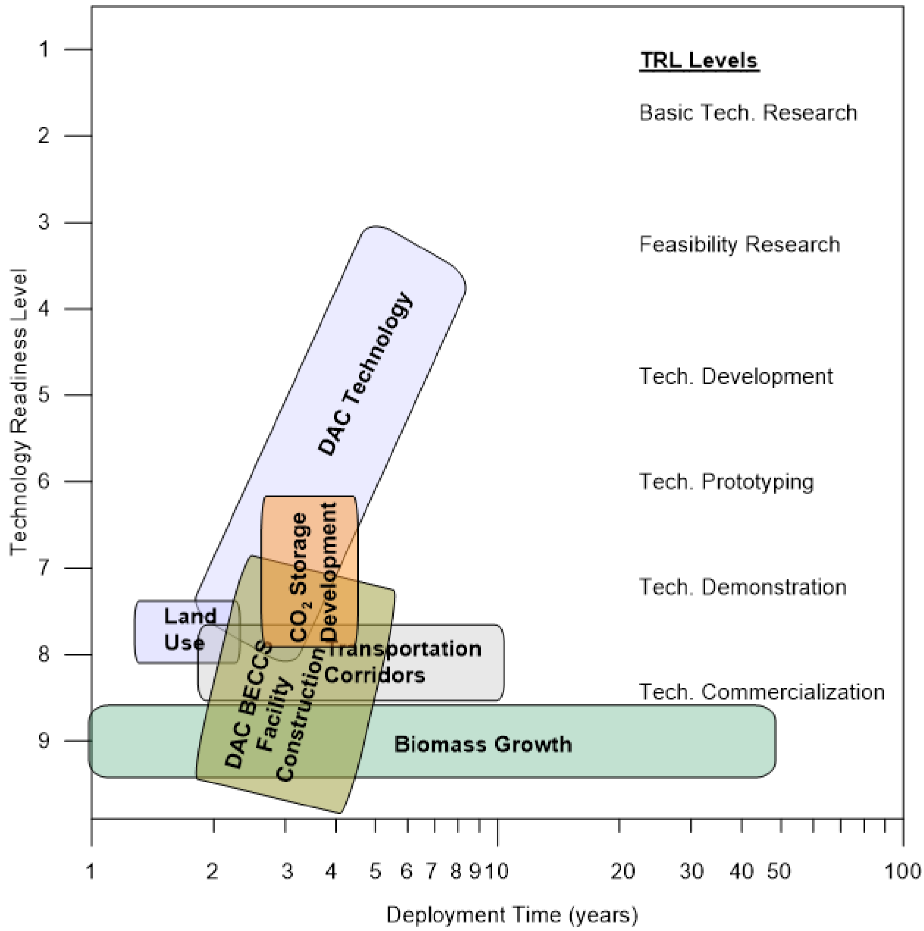


Figure 5-1. Conceptual Relationship between Technology Readiness and Deployment Time for CDR Technologies

5.6 Geographic Factors for CDR Deployment

Geographic factors related to land use, climate, transportation corridors (pipeline, rail, barge, roads), energy, and vicinity to CO_2 storage resources may also affect CDR deployment. DAC facilities will need to be located near CO_2 storage resources, available low carbon energy, and/or land access. Figure 5-2 shows a map of green energy generation and carbon storage basins in the US illustrating areas with both features. Terrestrial and BECCS will require access to biomass summarized in Figure 5-3 and evaluated extensively in numerous research efforts. BECCS will also need to have access to land use, transportation corridors, and CO_2 storage. DAC may also be more efficient in areas with lower humidity and precipitation (Figure 5-4). Reforestation and mineralization will have land use, climate, and transportation factors to consider for deployment (Figure 5-4).

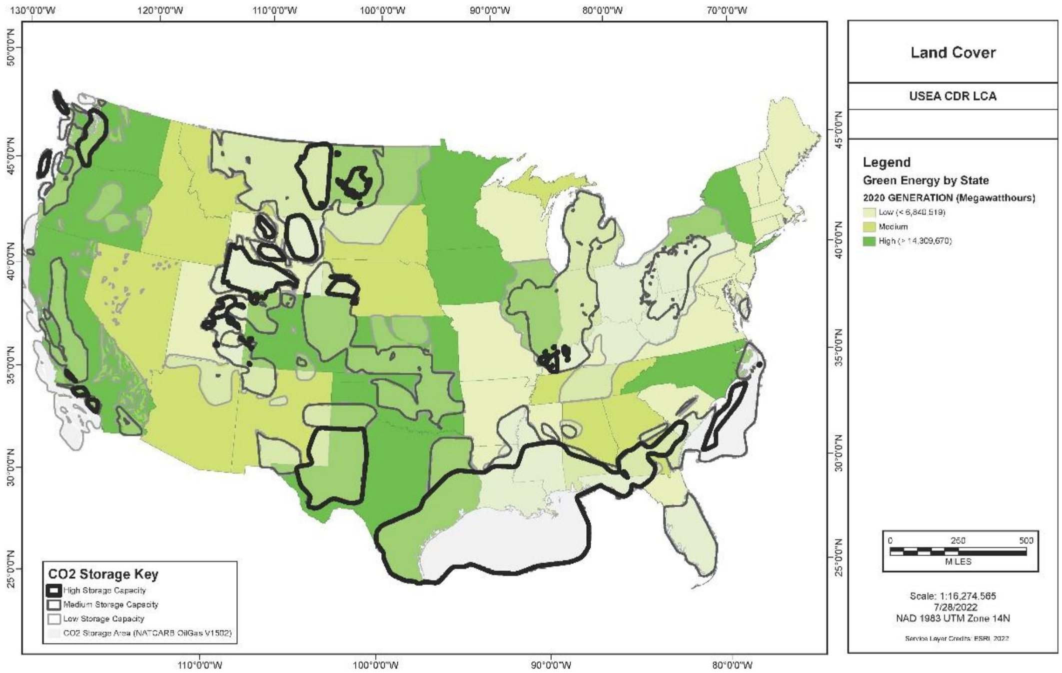


Figure 5-2. Map of Green Energy Generation and CO_2 Storage Basins

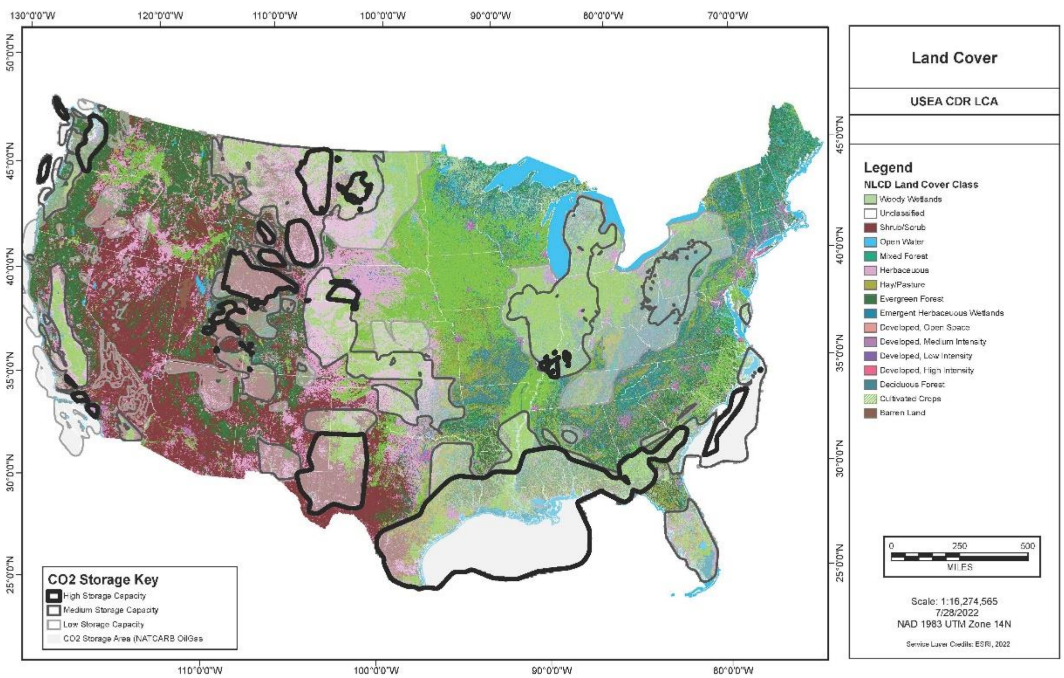


Figure 5-3. Map of Land Use and CO2 Storage Basins

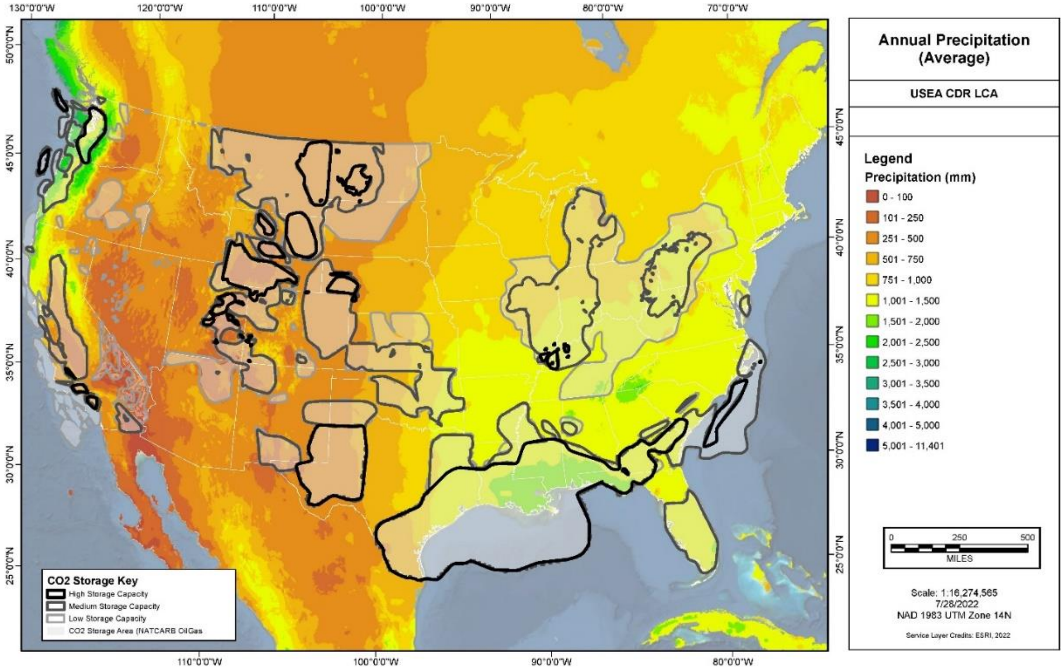


Figure 5-4. Map of Precipitation and CO2 Storage Basins

5.7 Criteria for CDR Deployment

Criteria for demonstrating CDR effectiveness are likewise important for CDR GHG LCA net negativity. These criteria are often used to validate CDR technologies, but they also apply to LCA methods:

- **Verifiability**- CO_2 volumes substantiated with monitoring, metering, measurements, and reporting from field operations are necessary for LCA models/methods.
- **Permanence**- The potential for CO_2 leakage during geological carbon storage, decomposition/harvesting of biomass from reforestation, fugitive emissions are used to calculate net carbon removal.
- **Physical footprint**- The size of the CDR projects is used for LCA land use emission factors.
- **Capacity**- Technology scalability is a consideration to ensure meaningful CO_2 removal volumes.
- **Additionality**- LCA must ensure that CDR technology results in additional removal of carbon that does not displace existing naturally occurring processes in carbon cycle or low-carbon energy.

In terms of CDR LCA results, verifiability is a key criterion to incorporate with CDR project plans. Real operational data provide a level of confidence to the GHG LCA results, especially with uncertainty regarding scale up of many of the CDR technologies. CDR technologies are in the early stages of development with little operational data to verify cradle to grave life cycle emissions balances.

5.8 Market Factors for CDR Development

Given the diversity of CDR applications, many different market factors may affect CDR development. These include decremental factors such as expenses for construction/operations as well as beneficial factors like 45Q tax credits and returns from selling power generated by a BECCS plant. Table 5-1 summarizes market factors for CDR development.

Table 5-1. Market Factors for CDR Development

	Impact to Deployment				
Market Factor	DAC (Solid)	DAC (Aqueous)	BECCS	Reforestation	Mineralization
Energy Cost/ Availability	High	High	Low	Low	Low
Land Use/Access	Med	Med	High	High	High
Operating Costs	High	High	High	Low	Low
Construction/ Capital Costs	High	High	High	Low	Low
45Q Credits	High	High	Med	Low	Low
Revenue	NA	NA	High	NA	Low

5.9 Technology Gaps in Commercialization of CDR Technologies

Table 5-2 summarizes technology gaps for CDR technologies. DAC and BECCS applications build upon existing technologies like gas processing, power generation, and compression. Reforestation and mineralization applications are not technology dependent, but there are gaps related to permanence and verifiability.

Table 5-2. Potential Gaps for CDR Technology Commercialization

Commercialization Gap	DAC (Solid)	DAC (Aqueous)	BECCS	Reforestation	Mineralization
Energy	X	X			
CO_2 Capture	X	X			
CO_2 Transport					
Biomass Transport			X	X	
CO_2 Removal Permanence				X	X
Scalability	X	X	X	X	X
Verifiability				X	X

6.0 Summary

The assessment of CDR technologies identifies key contributing factors that drive each of the emissions generated by the specific technologies. These key factors can be used to assist in the effective deployment of these technologies. Based on the GHG emissions LCA review, the five CDR technologies reviewed have the potential to be 65-95% net negative in 1 Mt/yr deployment scenarios. Literature values for net negative emissions range from 0 to 99%. However, most unbiased CDR LCA research suggests net negativity within the range of 65-95%, providing consensus on the potential for carbon removal.

An evaluation of regional factors for CDR technology deployment in the US (geographic factors, infrastructure, energy mix, market factors, climate, economics) suggests that locating CDR projects near low carbon energy, biomass, land for terrestrial, source rock for mineralization, and/or CO_2 transport, and storage resources is key to minimizing life cycle emissions. Overall, this is the direction that CDR project development is moving toward.

Various aspects will benefit the deployment of these methods at-scale. The recommendations included the following items:

- Timeline and technology readiness level assessment for CDR technology deployment in the US
- Economic factors for CDR
- Options for optimizing net carbon removal for CDR technologies
    - DAC
        - Access to green energy
        - Close access to geologic sinks
        - Development and validation of effective CO_2 sorbents
        - Addressing climate factors on sorbent performance
    - BECCS
        - Close access/low carbon transportation for biomass
        - Close access to geologic sinks
        - Evaluation of fuel mixing effects on net negativity
    - Terrestrial
        - Appropriate climate for trees being planted
        - Proper forestry management
        - Validation of CO_2 removal rates
        - Verification of permanence for natural systems carbon cycles
        - Scaling and timing factors for climate change goals
    - Enhanced weathering
        - Close access/low carbon transportation for crushed rock

- Validation of CO_2 removal rates
- Verification of permanence for natural systems carbon cycles

Current CDR projects include GHG emissions LCA to verify net negative emissions. These early-stage projects are often based on unit processes and small-scale lab/pilot tests. As projects progress, operational data should be used to perform more accurate LCAs using actual land use, construction, energy, materials, and CO_2 monitoring data.

7.0 References

Cameron Hepburn, E. A., John Beddington, Emily A. Carter, Sabine Fuss, Niall Mac Dowell, Jan C. Minx, Pete Smith, Charlotte K. Williams (2019). "The technological and economic prospects for CO2 utilization and removal." Nature.

Carbonplan (2021). "CDR Database." Retrieved 11/4/2022, from https://carbonplan.org/research/cdr-database.

Consoli, C. (2019). 2019 Perspective Bioenergy and Carbon Capture and Storage, Global CCS Institute.

David Lefebvre, P. G., Adrian Williams, David A.C. Manning, Antonio Carlos de Azevedo, Magda Bergmann, Jeroen Meersmans, Pete Smith (2019). "Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil." Journal of Cleaner Production **233**: 468-481.

David W. Keith, G. H., David St. Angelo, Kenton Heidel (2018). "A Process for Capturing CO2 from the Atmosphere." Joule **2**(8).

Fajardy, M., Mac Dowell Niall (2017). "Can BECCS deliver sustainable and resource efficient negative emissions? ." Energy Environ. Sci.

IEA (2022). Direct Air Capture. Paris, IEA.

Institute for Carbon Removal Law and Policy, A. U. (2020). "Fact Sheet: Enhanced Mineralization." Retrieved November 11, 2022, 2022, from https://www.american.edu/sis/centers/carbon-removal/fact-sheet-enhanced-mineralization.cfm.

K. Buchheit, E. L., K. Mahbubani, and D. Carlson (2021). Technoeconomic and Life Cycle Analysis of Bio-Energy with Carbon Capture and Storage (BECCS) Baseline, National Energy Technology Laboratory.

Melinda M.J. de Jonge, J. D., Jessica M. Loriaux, Zoran J.N. Steinmann, Mark A.J. Huijbregts (2019). "Life cycle carbon efficiency of Direct Air Capture systems with strong hydroxide sorbents." International Journal of Greenhouse Gas Control **80**: 25-31.

National Academies of Sciences, E., and Medicine (2019). Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press.

Pasumarti, A., Mishra, S., Ganesh, P. R., Mawalkar, S., Burchwell, A., Gupta, N., Razi, S., and Pardini, R. (2016). Practical Metrics for Monitoring and Assessing the Performance of CO2-EOR Floods and CO2 Storage in Mature Reservoirs. Society of Petroleum Engineers.

Remi Chauvy, L. D. (2022). "Life cycle and techno-economic assessments of direct air capture processes: An integrated review." International Journal of Energy Research.

Simon Gaboury, J.-F. B., Claude Villeneuve, Daniel Lord, Réjean Gagnon (2009). "Estimating the net carbon balance of boreal open woodland afforestation: A case-study in Québec's closed-crown boreal forest." Forest Ecology and Management **257**(2): 483-494.

Sminchak, J. R., Mawalkar, S., and Gupta, N. (2020). "Large CO2 Storage Volumes Result in Net Negative Emissions for Greenhouse Gas Life Cycle Analysis Based on Records from 22 Years of CO2-Enhanced Oil Recovery Operations." Energy & Fuels.

Terlouw, T. C. B., Lorenzo Rosa and Marco Mazzotti (2021). "Life cycle assessment of carbon dioxide removal technologies: a critical review." Energy Environ. Sci.

Tom Terlouw, K. T., Christian Bauer, and Marco Mazzotti (2021). "Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources." Environ. Sci. Technol.

Yuki Ishimoto, M. S., Etsushi Kato, Ryo Moriyama, Kazuhiro Tsuzuki and Atsushi Kurosawa (2017). "Putting Costs of Direct Air Capture in Context." Forum for Climate Engineering Assessment.