A Survey of Active U.S. Carbon Capture Projects

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Date: August 28th, 2021

SUMMARY

The objective of this report is to provide a comprehensive survey of active carbon capture and sequestration ("CCS") projects in the continental United States. The scale, stage of development, variety and uses of CCS facilities will be detailed to understand the current state of CCS projects and their future potential to contribute greenhouse gas emissions reductions. The report includes CCS projects which are either in development, active or suspended.

The materials collected to develop this report were sourced from several primary types of data, all of which were retrieved from online sources including governmental agencies, state regulatory agencies, private CCS consortiums, private & public company disclosures, news reports, and academic literature. Data was first collected from aggregated lists of U.S.-based projects which could be compared and used to validate the existence of each project. The primary sources for this phase of the project were Scottish Carbon Capture & Storage project (via the University of Edinburgh), the Global Carbon Capture & Storage Institute, the CCS Project Database at the Massachusetts Institute of Technology, and the National Energy Technology Laboratory (U.S. Department of Energy). Once all projects aggregated, the remainder of the data sources were pursued to verify details of each operation. Detail for certain pre-operational projects was limited by lack of disclosure. In those cases, company press releases were relied upon to estimate operational parameters to the extent possible.

A key learning in this project is that there are three classes of CCS projects which are most common: 1) early pilot projects funded with federal research grants, 2) projects focused on carbon capture for industrial emissions and 3) projects seeking to minimize the cost of CCS at commercial scale. Another key finding is that past site developments have been economically challenged. CCS is likely to be influenced positively by planned enhancements to tax subsidies (e.g. 45Q). Today, there are 11 operational projects domestically injecting a total of 40 million tonnes per annum (Mtpa) of CO_2 into underground geologic storage or enhanced oil recovery (EOR) projects. Notable facilities include the Century Plant operated by Occidental in Pecos, Texas which injects at a rate of 8.4 Mtpa (largest facility by rate). The Exxon Mobil Schute Creek Plant in Wyoming is second largest, injecting at a rate of 7 Mtpa. Together, the two facilities comprise >35% of all CO_2 sequestration taking place in the U.S. today and appear the most effective at successful sequestration. The longest-lived project began in Val Verde County, Texas (Terrell) in 1972, nearly 49 years ago, to source CO_2 for local oilfields.

This report does not present novel conclusions as it is a survey of active U.S. Carbon Capture projects; however, it does seek to summarize CCS site development in a way that is more coherent than existing literature, especially as it relates to groupings of projects in each phase identified above. The report provides a framework through which to discuss CCS projects and to understand the motivation of site developers.

INTRODUCTION

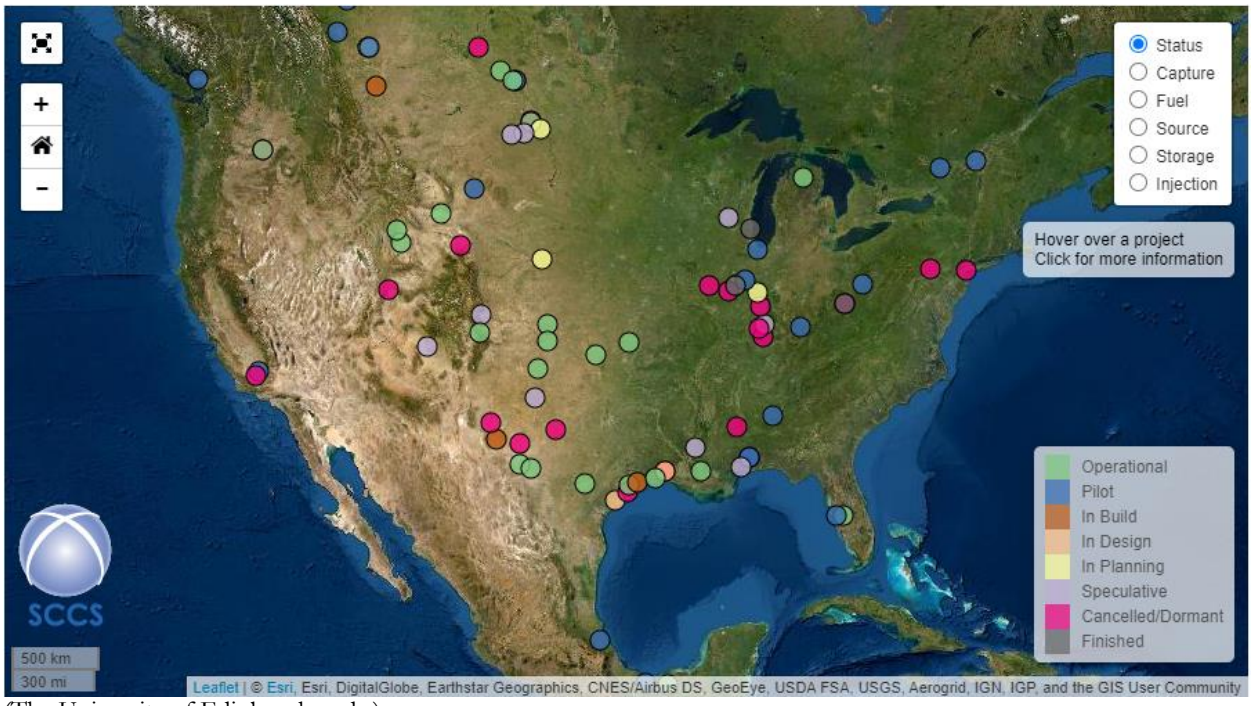
The last few decades have seen an increased societal focus on climate change initiatives. Scientists have coalesced around the view that increasingly high levels of CO_2 in our atmosphere have contributed to global climate change and threaten to imperil the Earth's ecosystems through a disruption of the carbon cycle. Recent changes in atmospheric CO_2 concertation as high as 80 ppm / 50 years are significantly higher than the fastest observed historical pace of introduction (0.007ppm / 50 years). Although CO_2 is not the only greenhouse gas with major impact to the atmosphere (e.g., methane, nitrous oxide, etc.) it is one of the most controllable and longest-lived molecules that impact the changing climate.

Domestic efforts have been underway for roughly the last five decades to begin controlling the level of emissions of CO_2, particularly from stationary point sources like power plants which produce about ¼ of all atmospheric CO_2 emissions. Other sources are more dispersed or mobile, making them difficult to control in the near term. Of particular concern are the carbon dioxide emissions resulting from combustion of fossil fuels, which together produce ~84.3% of all CO_2 emissions (2019). The recent transition from coal-fired power to natural gas and renewable generation in the U.S. have contributed significantly to the arrest of further emissions growth in this county; however, other less developed nations have continued a rapid and alarming buildout of coal-fired power plants as their populations grow. This fact and the continued growth of energy use in general threaten the global climate balance and create a need for solutions to address growing levels of atmospheric CO_2 without depriving the world of energy.

Carbon Capture and Sequestration (CCS) projects have been proposed as one tool to help mitigate the impacts of increasing levels of atmospheric CO_2. A 2007 study of European CO_2 sources found that 47% of emitted volumes were

addressable through CCS project, while 53% would remain addressable owing to their dispersion or mobile nature. Of those addressable sources, roughly half were coal-fired power plants. Typical technologies deployed to address the capture of CO_2 from industrial processes are referred to as adsorption, absorption, and membrane processes. Each technology comes with benefits and drawbacks based on variables such as concentration of the gas stream, relative throughput volumes, cost of deployment and limitations of the technology itself.

A map of all current (and many planned) U.S.-based facilities can be found below, designated by their status:



(The University of Edinburgh, n.d.a)

In total, existing U.S.-based projects constitute total injection capacity today of roughly ~40 million tonnes per annum (Mtpa). New projects are being announced almost daily due to improvement in U.S. federal and selected state fiscal regimes which allow for companies to claim credits for captured CO_2 through both permanent sequestration and enhanced oil recovery (EOR) pathways. Even though some announced projects may not ultimately be sanctioned for a variety of reasons, it seems likely that the total annual volume of sequestered CO_2 in the U.S is likely to double or triple over the coming five to ten-year time horizon.

This survey provides a comprehensive review of legacy, active and in-development CCS projects located in the continental United States. The projects will be broken into the following categories according to the maturity of the projects: 1) Facilities in Operation, 2) Facilities Under Construction, 3) Facilities in Advanced Development, 4) Facilities with Suspended Operations, 5) Facilities in Early Development and 6) Past Pilot Projects.

Terrell Natural Gas Processing Plant

Terrell Natural Gas Plant is one of five Val Verde gas plants in Fort Stockton, TX (30.37, -101.85) operated by the Occidental Petroleum Corporation (The University of Edinburgh, n.d.zzz). The Val Verde plants include Mitchell, Gray Ranch, Puckett, Pikes Peak, and Terrell, with Terrell being the only plant still thoroughly in operation currently (The University of Edinburgh, n.d.zzz). The plants combined emit over 2 Mtpa of CO_2. Capture from these plants initially started in the mid-1970s for EOR, which was the first of its kind (Bluesource, n.d.). CO_2 is captured by the Selexol absorption method at 0.4 Mtpa per year and then pipelined for EOR by Kinder Morgan via 132 km onshore Val Verde and CRC pipelines to Sharon Ridge in the West Texas Carbonate Permian Basin for injection at 2,300 - 3,100 feet depth (MIT, 2016r). When the Val Verde pipeline connecting to the Permian Basin was completed in 1998, injections began at an initial rate of 1.3 Mtpa (MIT, 2016r). However, in 2014, the Mitchell and Puckett plant shut down while Gray Ranch and Pikes Peak were shutting down (The University of Edinburgh, n.d.zzz). Terrel is the oldest operating industrial CCS project. (MIT, 2016r).

(Dewing, n.d.)

Core Energy CO_2 – EOR

Core Energy operates a carbon sequestration project as part of the Midwest Regional Carbon Sequestration Partnership (MRCSP). The project is spearheaded by a group that includes DTE Energy, Core Energy, and Battelle and was initiated to study the feasibility of industrial carbon sequestration in the depleted oilfields of northern Michigan. The project has had numerous rounds of sponsorship, totaling around $23 million, primarily from the Department of Energy ("DOE") (The University of Edinburgh, n.d.l). For this project, CO_2 is extracted from Core Energy's Atrium Shale gas processing plant through Amine absorption and then connected via a 15-mile pipeline to be injected 6,000 feet in a series of previously depleted carbonate reservoirs located in Michigan's Northern Niagaran Pinnacle Reef Trend (44.91, -84.54). The properties utilized for sequestration are owned and operated by Core Energy LLC (MIT, 2016m). The project started in 2013 and planned to store 1 Mtpa of CO_2 up to 13 km in-depth in the next three to five years under a UIC Class II permit (The University of Edinburgh, n.d.l). Injections stopped in 2018 while monitoring continued, and as of 2021, the study was concluded to be successful in carbon capture, utilization, and storage, paving the way for potential commercial projects in the trend (Battelle, 2021).


(Core Energy, LLC, n.d.b)

Shute Creek Gas Processing Plant

Shute Creek plant is a natural gas processing plant owned by Exxon Mobil, which composes 16 sour gas wells, drawing natural gas from LaBarge field in Wyoming (41.89, -110.09) (The University of Edinburgh, n.d.y). Initially started in 1986 for EOR in the surrounding locations, the project has expanded, notably to 4 Mtpa rate of injection in 2008 and 7 Mtpa rate of injection in 2010 to curb CO_2 emissions (MIT, 2016l). Exxon Mobil's Single Step Cryogenic absorption based Selexol process separates natural gas from the field, which freezes out and melts the CO_2, separating the impurities (MIT, 2016l). Carbon is transported for EOR up to 460 km in the same field and surrounding locations operated by Exxon, Chevron, and Anadarko (The University of Edinburgh, n.d.y). Using current technologies, Exxon can capture and monitor up to 75% of the CO_2 excess from LaBarge Field operations (Parker, Northrop, Valencia, Foglesong & Duncan, 2011). As of January 2020, Exxon has filed for a permit in Wyoming to expand CCS operations for dedicated storage and sale of CO_2, which is scheduled to operate in 2023 (Wyoming Department of Environmental Quality, n.d.).


(Exxon Mobil, n.d.)

Century Plant

CO_2 is captured from high content CO_2 gas produced in the Permian Basin by Sandridge Energy and then processed at Occidental's $1.1 billion Century Gas processing plant in Pecos, Texas (30.61, -102.58) through the Selexol absorption process (The University of Edinburgh, n.d.c). It began operations in 2010 and is projected to inject for 30 years. 100% of the methane gas from captured CO_2 is owned by Sandridge Energy, and all CO_2 is owned by Occidental and is transported to Denver City where it is injected in the Kinder Morgan Permian delivery system. This transmits the gas 160 km via pipeline for use in Occidental's EOR operations in the Permian Basin (Zero Emission Resource Organization, n.d.). This is the largest capture facility globally, with a capacity of 8.4 Mtpa after an expansion in 2012 (MIT, 2016d). However, only 5 Mtpa is being stored due to lower shale gas prices and demand (Zero Emission Resource Organization, n.d.).

(Control Insulation Services, n.d.)

Enid Fertilizer

At the Enid Fertilizer facility, CO_2 is captured through the Benefield process, a solvent-based absorption method, as a byproduct of fertilizer production from the Koch Nitrogen Plant in Enid, Oklahoma (36.39, -97.76) (The University of Edinburgh, n.d.f). The plant was built in 1974 for ammonia, urea, and liquid fertilizer production and purchased by Koch in 2003 (MIT, 2016g). The captured CO_2 is injected through a 225 km onshore pipeline for operations in the depleted Golden Trend Field and Sho-Vel-Tum fields, using the Muddy Formation Sandstone as a sequestration storage target (MIT, 2016g). These fields are owned respectively, by Chaparral Energy and Merit Energy, and CO_2 is stored at about 0.68 Mtpa (MIT, 2016g). Since 1982 there have been EOR operations in these fields; CO_2 usage from the Koch Nitrogen Plant began in 2003 (The University of Edinburgh, n.d.f). The plant saw an expansion in 2017 and another expansion is planned for 2022 to more than double the original urea production, while CCS capture technology remains constant (KochFertillizer, 2021).


(KochFertilizer, 2021)

Great Plains Synfuels Plant and Weyburn-Midale

The Great Plains Synfuels Project was originally an eight-year project costing around $80 million and funded by the DOE and Canadian government to study and monitor CCS storage to store up to 20 Mtpa of CO_2 (National Energy Technology Laboratory, n.d.a). Using the Rectisol Process, a solvent-based absorption technique, very pure (96%) CO_2 is captured from the $2.1 billion Great Plains Synfuels Plant in Beulah, North Dakota (47.36, -101.84) and transported via a 316 km pipeline to the Weyburn field owned by Cenovus Energy and Midale Field owned by Apache Corporation for respective EOR operations (The University of Edinburgh, n.d.h). Injection began in 2000 at a rate of 3 Mtpa, with about 50% of CO_2 being captured when the plant is at full capacity (The University of Edinburgh, n.d.h). As of 2020, a total of 40 Mt has been captured by the plant, and CO_2 storage is still in operation, paving the way for future CCS projects (K.X. Net, 2020).


(Holdman, 2018)

PCS Nitrogen

PCS Nitrogen is a project that captures CO_2 through anime scrubbing from fertilizer production by the PCS plant in Geismar, Louisiana (30.23, -91.06) (The University of Edinburgh, n.d.r). Starting in 2013, CO_2 is used for EOR, with around 0.3 Mtpa of CO_2 injected by Denbury Resources in the South Texas Fields (The University of Edinburgh, n.d.r).

As of 2021, the plant operations are pending a state permit to discharge highly contaminated wastewater into the Mississippi River (USNews, 2021).

(Feig, 2021)

Coffeyville Gasification Plant

At the Coffeyville Gasification Plant, CO_2 is captured using Chaparral Energy technology from a petroleum-coke-based nitrogen fertilizer facility owned by CVR partners in Coffeyville, Kansas (37.05, -95.60) and is the only of its type in North America (The University of Edinburgh, n.d.). CO_2 is captured using the Selexol absorption process and then pipelined via 112 km to the North Burbank Unit (Fluvial Sandstone) used for Chaparral's EOR operations (The University of Edinburgh, n.d.d). An oil refinery utilizes a gasification process to supply hydrogen for the Coffeyville plant, which the Coffeyville plant uses for ammonia production, venting about 0.85 Mtpa of CO_2 in the atmosphere before capture technology. (National Energy Technology Laboratory, n.d.b). Cost of the CCS infrastructure (including the pipeline and the CO_2 compression facility) are partially offset by EOR revenue (MIT, 2016e). Injection for EOR began in 2013 at 3,000 feet depth. Approximately 0.65 Mtpa of CO_2 is currently being injected (MIT, 2016e). In October 2020, Coffeyville was reported to earn its first CO_2 tax credits for helping to offset emissions (CVR Partners, LP., 2020).


(Associated Press, 2004)

Bonanza Bioenergy CCUS EOR

The Bonanza Bioenergy CCUS EOR facility captures CO_2 from an ethanol production (corn/sorghum) plant in Garden City, Kansas (37.96, -100.84), which is owned by Conestoga Energy. It is used for EOR in the Stewart Field. Beginning in 2012, PetroSantander began to manage the transport of CO_2 through a 15-mile pipeline for storage of the CO_2 (The University of Edinburgh, n.d.b). The project is currently in the pilot phase with carbon storage at a rate of 0.1 Mtpa along with active monitoring. (The University of Edinburgh, n.d.b).

(Schroeder, 2012)

Illinois Industrial Carbon Capture and Storage

Illinois Industrial Carbon Capture and Storage is an extension of the previously completed Decatur project, which lasted from 2011-2014 (MIT, 2016j). The project is primarily funded by the DOE, Archer Daniels Midland, Schlumberger Carbon Services, Illinois State Geological Survey, and Richland Community College, with contributions of about $141 million and about $66 through private funding (MIT, 2016j). This project aims to capture 6 Mt of CO_2 from Archer Daniel Midlands's ethanol plant located in Decatur, Illinois (39.87, -88.89) at a rate of 1.1 Mtpa through the Alstom process of amine separation (The University of Edinburgh, n.d.k). Schlumberger Carbon Services transport captured CO_2 for dedicated geological storage 6,500+ feet in the Mount Simon Sandstone, a saline formation overlaying the Eau Claire shale seal (The University of Edinburgh, n.d.k). CO_2 injections began in 2017 after being granted a Class VI injection well permit from the EPA, notably one of the first permits of this type to be issued (United States Environmental Protection Agency, n.d.).


(McDonald, 2017)

Air Products Steam Methane Reformer

CO_2 capture is conducted from hydrogen production in Air Product's two steam methane reformers in Port Arthur, Texas (29.87, -93.97) (The University of Edinburgh, n.d.a). Steam methane reformers produce hydrogen through heating methane gas with steam and a catalyst, while CO_2 remains a byproduct (National Energy Technology Laboratory, 2017). The project is funded primarily through the DOE's American Recovery and Reinvestment Act, constituting $284 out of the $431 million, with the rest being private investments (The University of Edinburgh, n.d.a). CO_2 is captured using post-combustion vacuum swing adsorption technology and then transported by a 150 km pipeline and stored in the West Hastings / Oyster Bayou Fields for use in EOR, with both the pipeline and fields owned and operated by Denbury Resources (MIT, 2016q). Injection into the Frio Sandstone at a depth of ~1,700 m began in 2013 with CO_2 stored at a rate of 1 Mtpa (The University of Edinburgh, n.d.a).


(Bailey, 2020)

The Zeros Project

The 'Zeros 'Project', also known as Zero-emission Energy Recycling Oxidation System, seeks to produce energy from sources such as municipal waste and agricultural waste through System International's ZEROS technology, which utilizes oxy-fuel combustion while containing CO_2 emissions ("Systems International Announces," 2019). The planned project is significant in that it produces no byproduct emissions such as water, carbon, nor smokestack while also managing to capture 1.5 Mtpa of CO_2 ("Systems International Announces," 2019). The plant is based in Chambers/Liberty County, Texas (29.87, -93.97) and is owned by Systems International absorption (Global Carbon Capture and Storage Institute, 2020b). Captured CO_2 is used for EOR and storage to produce net negative carbon emissions and obtain 45Q tax credits. (Global Carbon Capture and Storage Institute, 2020b).

(ZEROS, n.d.)

Wabash CO_2 Sequestration

Wabash CO_2 is a project in Terre Haute, IN (39.53, -87.43) operated by Wabash Valley Resources (owned by Morgan Stanley) and supported by OCGI Investments to capture CO_2 from gasification and repurpose to fertilizer production using a solvent (The University of Edinburgh, n.d.zzzzz). Captured CO_2 is stored in the Mt. Simon sandstone, a saline formation, at 1 Mtpa with additional EOR potential in the Illinois East Basin (The University of Edinburgh, n.d.zzzzz). Ultimately, around 50 Mt of carbon will be stored 7000 feet deep during the entirety of the project, addressing the feasibility of large saline storage projects (United States Department of Energy, n.d.d). As of 2019, the project has applied for and has a pending class EPA class IV permit (The University of Edinburgh, n.d.zzzzz). Potential could lead to project demonstrate feasibility of anhydrous ammonia plants and green ammonia if successful (Saenz, 2019).

(Jasi, 2019)

Lake Charles Methanol

Lake Charles Methanol is a project operated by Lake Charles Methanol LLC in Lake Charles, LA (30.19, -93.30) that takes petroleum waste, which produces harmful emissions if burned, and converts it to carbon-free blue methanol through General Electric's Selexol process of solvent-based adsorption (The University of Edinburgh, n.d.m). Fluor will build the facility with loans amounts exceeding $2 billion from the DOE, with a total cost of $5 billion (The University of Edinburgh, n.d.m). Up to 90% of the plant's CO_2 will begin to be stored in 2025 at 4 Mtpa for EOR with MRV operation in Texas operated by Denbury Resources (The University of Edinburgh, n.d.m).


(Lake Charles Methanol, n.d.)

Project Tundra

Project Tundra is in Nelson Lakes, North Dakota (47.07, -101.21) and is owned and operated by the Minnkota Power Cooperative (The University of Edinburgh, n,d.w). CO_2 from the Milton R. Young station coal plant will be captured through Amine solvent, which aims for up to 90% CO_2 capture (The University of Edinburgh, n.d.s). The project aims to use the abundant coal supply in North Dakota and draw evaluations from the Petra Nova project to provide clean and cheap energy (Brick, n.d). Currently, the project is in the pilot stage, and potential costs could be upwards of $1.3 billion (The University of Edinburgh, n.d.w). Numerous rounds of grants sponsored by the DOE have been granted, with the project applying for a storage permit in June 2021 (The University of Edinburgh, n.d.w). In the mid-2020s, the captured CO_2 is planned to be injected at 2,000km into a saline aquifer for storage at a rate of 3.6 Mtpa (Global Carbon Capture and Storage Institute, 2020b).


(Brick, n.d.)

San Juan Generating Station Carbon Capture

The San Juan Generation Station is a coal generation plant located in Waterflow, NM (36.80, -108.44) and is owned by Enchant Energy in cooperation with PNM and the city of Farmington (The University of Edinburgh, n.d.x). Due to

emission regulations, ownership of the project was transferred to Enchant Energy and Tucson Electric Power, which seek to use tax credits based on a report in 2010 which concluded the cost for 6 Mtpa capture to be around $1.2 billion; however, Enchant is partnering with the architects of Petra Nova to ensure feasibility (The University of Edinburgh, n.d.x). If successfully operating, the plant would be the largest CCS project globally, costing $1.4 billion, magnifying the existing Petra Nova project that it takes from (Bryan, 2020). Amine solvents are used to capture 90% of the CO_2, which will be pipelined 20km in Kinder Morgan's Cortez Pipeline for EOR and research (The University of Edinburgh, n.d.x). Around 6 Mtpa of CO_2 will begin to be injected in 2024 once the project is operational, aiming to make most of the revenue through 45Q tax credits. (Global Carbon Capture and Storage Institute, 2020b).


(Bryan, 2020)

Gerald Gentleman

Gerald Gentleman is a coal plant owned and operated by Nebraska Public Power District located in Sutherland, NE (41.08, -101.14). CO_2 capture technology will be added using ION engineering's advanced solvents (The University of Edinburgh, n.d.g). Current funding is mainly through the DOE, and the design of the project includes a 600 MW capture facility in Unit 2 after a successful pilot project in 2017 in Unit 1 of the power station (The University of Edinburgh, n.d.g). Capture and storage of the project are still in question, with ION engineering overseeing the operations which will begin in the mid-2020s with a capture capacity of 3.8 Mtpa (Global Carbon Capture and Storage Institute, 2020b).

(Nebraska Public Power District, n.d.)

Prairie State Generating Station Carbon Capture

Prairie State Generating Station, located in Urbana, IL (38.28, -89.67), is a project conducted by the University of Illinois, Kiewit Corporation, Mitsubishi Heavy Industries America, and Sargent & Lundy to capture CO_2 coal generation through post-combustion capture at one of two power units (United States Department of Energy, n.d.b). Prairie State is one of the biggest emitters of carbon in the United States; having emitted 12.7 Mt of carbon in 2019 makes it the most significant source of carbon emission in Illinois (Chase & Gearino, 2021). Captured CO_2 by Mitsubishi is to be stored for dedicated geological storage at a rate of 6 Mtpa in the mid-2020s (Global Carbon Capture and Storage Institute, 2020b). Currently, the project's future is uncertain as Illinois legislation seeks to transition away from fossil fuels and meet climate goals (Chase & Gearino, 2021).

(Srenco, n.d.)

Plant Daniel Carbon Capture

Initially, a phase II project, Plant Daniel is in Escatawpa, Mississippi (30.53, -88.56) and is operated by Mississippi Power and Gulf Power (United States Department of Energy, n.d.c). Plant Daniel is the largest power plant in Mississippi, and due to efforts to curb carbon emissions, a CCS study in 2008 was conducted to address safe storage with 2,772 metric tons stored (United States Department of Energy, n.d.c). Plant Daniel is a half coal, half natural gas plant. Future development includes the use of q Linde-BASF absorption technology for CO_2 capture to inject captured CO_2 into the Lower Tuscaloosa saline reservoir at a rate of 1.8 Mtpa for storage (Global Carbon Capture and Storage Institute, 2020b). In April 2021, Mississippi Power announced that the gas-powered units would be decommissioned in the next five years to climate excess power reverses and meet climate goals (Clarion Energy Content Directors, 2021).

(Mississippi Power Co., 2019)

Cal Capture

Carbon capture from the Elk Hills natural gas plant located in Kern County, CA (35.23, -119.47) was initially proposed and rejected in 2016; however, it is being reinstated to meet climate goals (The University of Edinburgh, n.d.j). The new project captures CO_2 through Fluor's Econamine PG and will be used for EOR with MRV in the Elk Fields oilfield operated by Occidental (CRC, Carbon Capture & Sequestration). In 2013, for the original project, funding came from the DOE through the Clean Coal Power initiative, which amounted to $408 million (The University of Edinburgh, n.d.j). Injections will start in 2024 at 1.4 Mtpa (Global Carbon Capture and Storage Institute, 2020b).


(California Air Corp., 2019)

Mustang Station of Golden Spread Electric Cooperative Carbon Capture

Mustang Station of Golden Spread Electric Cooperative Carbon Capture is a project by GSEC and the University of Texas at Austin that aims to add CCS to the Mustang Station's 450 MWe gas-powered plant located in Denver City, TX (32.972172, -102.741636) (Global Carbon Capture and Storage Institute, 2020a). CO_2 is captured through the Piperazine Advanced Stripper process, a form of amine scrubbing. Plans include injecting 1.5 Mtpa (Global Carbon Capture and Storage Institute, 2020a); however, the storage method is still undecided (Global Carbon Capture and Storage Institute, 2020a).


(Golden Spread Electric Cooperative Inc., 2018)

SUSPENDED OPERATIONS

Lost Cabin Gas Plant

Lost Cabin Gas Plant is a natural gas processing plant located in Lost Cabin, Wyoming (43.28, -107.61) and is owned by ConocoPhillips (The University of Edinburgh, n,d.k). CO_2 from the plant is captured through the Selexol absorption process and then transported for EOR by Denbury Resources via a 370 km, $400 million pipeline to Bell Creek Field, a

muddy formation sandstone (The University of Edinburgh, n,d.k). CO_2 started to be injected in 2013 at a rate of 0.9 Mtpa (Global Carbon Capture and Storage Institute, 2020b). The CCS project stopped in 2020 when Denbury went bankrupt due to low oil and natural prices induced by the COVID-19 pandemic (Erickson, 2020).


(Coren, 2016)

Petra Nova Carbon Capture

Petra Nova Carbon capture is a project by NRG and J.X. Nippon to capture 90% of CO_2 produced by one of four of NRG's coal plants located at the WA Parish facility in Thompsons, TX (29.48, -95.63) (The University of Edinburgh, n.d.s). Fluor constructed capture technology and the costs for this project equate to $1 billion (The University of Edinburgh, n.d.s). Using Econamine FG plus amine scrubbing as the separation method, CO_2 is captured and then pipelined 130km to the West Ranch Oilfield for injection at 1.4 Mtpa for EOR, with MRV starting in 2017 (The University of Edinburgh, n.d.s). Petra Nova has experienced operational challenges due to a decline in the price of crude oil from the time the project was sanctioned until today; this commodity price decline directly impacts the price operators are willing to pay for CO_2 in EOR projects. Despite being the only CCS coal plant in North America and capturing a total of 3.8 Mt, the combination of COVID-19 pandemic-induced low oil prices and costly mechanical failures resulting in missed carbon capture targets led to an indefinite shutdown of the plant (Groom, 2020).


(Golden Spread Electric Cooperative Inc., 2018)

Arkalon CO_2 Compression Facility

Arkalon CO_2 Compression Facility is a $79 million partnership between South West Partnership (SWP), New Mexico Institute of Mining and Technology, Chapparal Energy (storage/transport), LLC Los Alamos National Laboratory, Oklahoma Geological Survey, Pacific Northwest National Laboratory, Utah Geological Survey, University of Missouri, University of Utah, Sandia National Laboratories and Schlumberger Carbon Services, funded mainly by the DOE primarily as a feasibility study for CCS deployment (MIT, 2016i). CO_2 is captured primarily from the Arkalon plant in Liberal, Kansas (37.11, -100.80) and the Agrium Fertilizer Plant in Borger, Texas, and used for EOR operations at the Farnsworth Unit in the Anadarko Basin, which is comprised of an upper morrow sandstone formation (The University of Edinburgh, n.d.z). The project aims to capture 1 Mt total of CO_2 with a current rate of 0.2 Mtpa injected at 7,000 feet, starting in 2013. (The University of Edinburgh, n.d.z). As of 2018, the project was deemed successful in seismic monitoring and CCS (United States Department of Energy, n.d.a).


(Wilmoth, 2012)

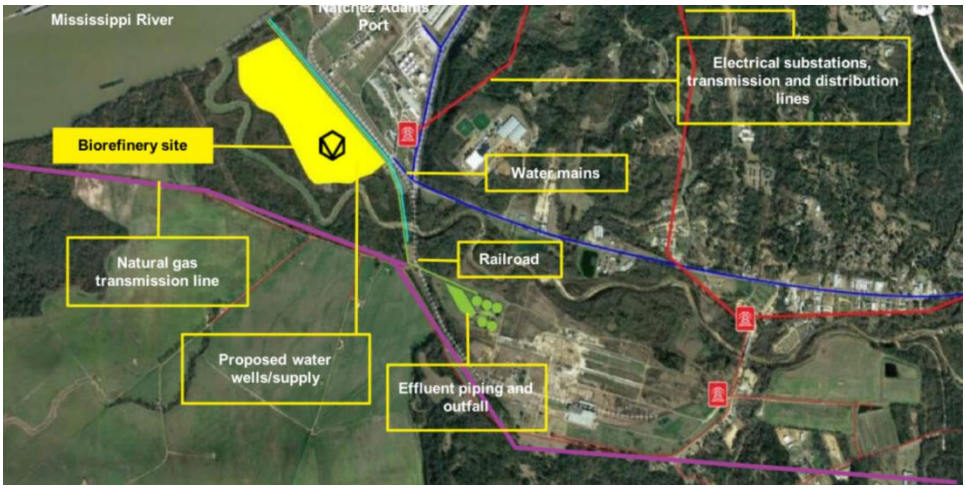
Project Interseqt - Hereford Ethanol Plant / Project Interseqt - Plainview Ethanol Plant

Hereford Ethanol Plant and Planview Ethanol Plant located in Hereford and Plainview are ethanol production plants owned by White Energy (Global Carbon Capture and Storage Institute, 2020b). The ethanol plants utilize railcar systems that can deliver most of the produced ethanol at the plant, primarily targeting California and Texas markets. To capture CO_2, there is a partnership with Occidental and LCFS for EOR using Occidental's West Seminole field at 0.30 Mtpa for the Hereford plant and 0.33 Mtpa for the Plainview plant (OXY Low Carbon Ventures, n,d.). The objective of the projects is to receive 45Q tax credits and California's Low Carbon Fuel credits, which Occidental received approval from the EPA for its Permian Basin EOR with MRV operations in 2018, being the first to do so (White Energy, 2018).

(Bundy, n.d; Boll, n.d.)

Velcoys Bayou Fuels Negative Emission Project

The project aims to add CO_2 capture technology to the Bayou Fuels facility, a municipal-waste-to-ethanol facility located in Natchez, MS (31.53, -91.44) and owned by Velcoys. Occidental will conduct CO_2 capture and storage, with injections planned to start in 2024 for EOR with MRV use at the Cranfield Field at 0.33 Mtpa (The University of Edinburgh, n.d.zzzz).



(Velcoys, 2021)

OXY and Carbon Engineering Direct Air Capture and EOR Facility

OXY and Carbon Engineering Direct Air Capture and EOR Facility located in Permian Basin, TX (31.53, -91.44) is a project by Occidental and Carbon Engineering to directly capture CO_2 from the air using Carbon Engineering technology (Carbon Engineering, 2019b). Once completed, this will be the largest DAC capture facility globally, a considerable scale up from active facilities that can only capture thousands of tons of CO_2 a year (Carbon Engineering, 2019b). Captured CO_2 will be used for EOR operations in the Permian Basin starting in the mid-2020s at a rate of 1 Mtpa and as feedstock (Global Carbon Capture and Storage Institute, 2020b). Oxy is likely to take advantage of credits from both the California Low Carbon Fuels program and the federal 45Q tax credit program.


(Carbon Engineering, 2020)

LafargeHolcim Cement Carbon Capture

The project includes adding CCS to the Holcim Portland Cement plant in Florence, CO (38.39, -105.02), owned by LafargeHolcim (The University of Edinburgh, n.d.q). The cement plant is a dry process cement plant that uses alternative fuel sources, such as used tires, to produce 1.8 Mtpa for Colorado, New Mexico, Kansas, Wyoming, Idaho, Texas, Utah, and Nebraska markets (LafargeHolcim, n.d.) To meet capture neutrality goals by 2050, capture technology has been supplied by Svante, which will use the captured CO_2 for EOR with MRV in the Permian Basin at a rate of 0.72 Mtpa beginning mid-2020 (The University of Edinburgh, n.d.q).


(LafargeHolcim., n.d.)

Dry Fork Integrated CCS

The Dry Fork Integrated CCS project is a planned CO_2 capture project by Basin Electric Power Cooperative and Wyoming Municipal Power Agency (National Energy Technology Laboratory, n.d.d). It will gather CO_2 from emissions of the Dry Fork coal station located in Gillette, WY (44.39, -105.47) for storage in underground saline aquifers in the nearby Powder River Basin (National Energy Technology Laboratory. (n.d.d). The injection is planned to commence in 2025 at a rate of 3 Mtpa to store a total of 50 Mt for 30 years (Global Carbon Capture and Storage Institute, 2020b).


(Patal, 2018)

Red Trail Energy BECCS Project

Red Trail Energy CCS project seeks to add CCS to the Red Trails Ethanol Plant in Richardton, ND, which traditionally uses corn and distiller grains as its fuel source (46.88,-102.30) (Global Carbon Capture and Storage Institute, 2020b). In 2025, captured CO_2 is planned to be stored at a rate of 0.18 Mtpa in the Broom Creek Formation (a saline formation) at 6,400 feet (University of North Dakota Energy & Environmental Research Center, 2021a). Red Trail has submitted a provisional pathway through the California Air Resources Board to accommodate CO_2 from ethanol facilities (California Air Resources Board, 2020). This region is also the focus of industrial projects targeting interstate transfer and sequestration of CO_2 from ethanol facilities throughout the Midwest.

(University of North Dakota Energy & Environmental Research Center, 2021a)

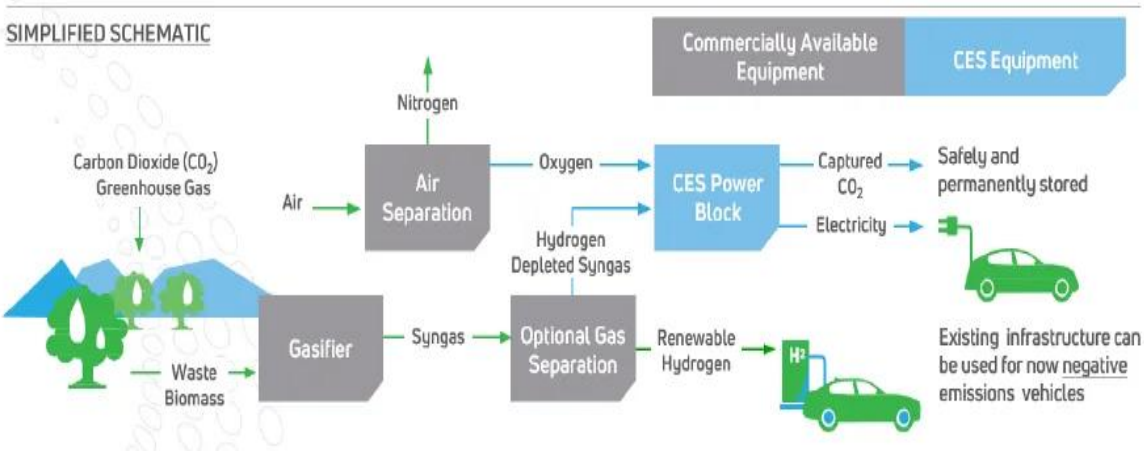
The Illinois Clean Fuels Project

The Illinois Clean Fuels Project is a municipal waste to energy plant located near Mattoon, IL (46.88, -102.30) that will capture CO_2 and sequester it (Global Carbon Capture and Storage Institute, 2020b). The plant mainly aims to produce synthetic fuel geared towards creating clean, sustainable aviation fuels and operates without additional subsidies (Illinois Clean Fuels, 2021). Injection of CO_2 is slated to begin in 2025 and will occur at a rate of 2.7 Mtpa (Global Carbon Capture and Storage Institute, 2020b).

(Illinois Clean Fuels, 2021)

Clean Energy Systems Carbon Negative Energy Plant - Central Valley

This negative carbon project located in Central Valley, CA (36.75, -120.37) seeks to capture CO_2 from an ethanol fuel source and store it at a rate of 0.32 Mtpa in a to be determined location, which will start in 2025 (Global Carbon Capture and Storage Institute, 2020b). A previous feasibility study conducted in 2016 by CES successfully utilized biofuel to power turbines and capture more than 99% of CO_2 emissions (Clean Energy Systems, 2021a). Net negative emissions result from the use of waste biomass to produce synthesis gas, which can be utilized to produce hydrogen or power, and the carbon byproduct is sequestered (Clean Energy Systems, 2021a).



(Clean Energy Systems, 2021a)

Alberta Carbon Trunk Line

Alberta Carbon Trunk Line is a CCS project based in Redwater, Alberta (53.83,-113.1) owned by Wolf Carbon Solutions and Enhance Energy. It is funded primarily by the Alberta Government, costing CAD $495 million starting in 2009 (The University of Edinburgh, n.daa). CO_2 is captured from Nutrien's Agrum fertilizer plant and then pipelined 240km by Wolf for EOR operations (Wolfmidstream, n.d.). Wolf operates and owns the pipeline, which was completed in 2019 and has the capacity to delivery 14.6 Mtpa (The University of Edinburgh, n.d.aa). EOR is conducted by Enchant Energy in Clive, Alberta and as of January 2021, there has been 1 Mt of CO_2 stored (Wolfmidstream, n.d.).


(Hydrocarbons Technology, n.d.)

Plant Barry

Plant Barry is a pilot CCS project aimed at a 25 MW power generating station sponsored by Southern Energy, Mitsubishi Heavy Industries (MHI), Southern Company, SECARB (US DOE's Southeast Regional Carbon Sequestration Partnership), and Electric Power Research Institute with $70 million in funding from the DOE and a total budget of $150 million (MIT, 2016n). Plant Barry also received $ 295 million from the DOE in 2009 but was canceled in 2010 due to concerns about total project costs meeting DOE demands (MIT, 2016n). CO_2 is captured above 90% using the KM CDR amine-based solvent process by Mitsubishi from the Plant Barry coal Power Station located in Mobile, Alabama (31.01, -88.01). It is then pipelined 19 km to the saline Citronelle Dome to be injected at 2,900m (University of Edinburgh, n.d.t). CO_2 injections began in 2012 at a rate of 0.1 to 0.15 Mtpa, and in January 2014, the goal of 0.15 Mt was injected (University of Edinburgh, n.d.t). In 2015, FuelCell Energy and Exxon demonstrated interest in fuel cell technology at the plant (University of Edinburgh, n.d.t).

(AZCO, n.d.)

Kevin Dome

Kevin Dome is a research project funded mainly by the DOE and in conjunction with Big Sky Partnership (lead by Montana State University-Bozeman), Schlumberger Carbon Services, Vecta Oil & Gas Ltd, Lawrence Berkeley National Lab, Los Alamos National Lab to evaluate CO_2 storage at Kevin Dome (MIT, 2016k). Kevin Dome is in Sunburst, Montana (48.87, -111.73) and is a saline formation with natural CO_2 reserves (The University of Edinburg, n.d.l). The project aims to extract CO_2 from the reserves and inject it into The Duperow Formation, which does not contain CO_2 (MIT, 2016k). Kevin Dome holds significance because it resembles many nearby formations and has successfully naturally stored and secured CO_2 for millions of years (MIT, 2016). Injections began in 2015 and ended in 2019 when 1 Mt was injected (The University of Edinburgh, n.d.l).

(Big Sky Carbon Sequestration Partnership, n.d.)

Polk Station

Polk Station is a pilot project by Tampa Electric and Siemens to test carbon capture along with Warm Gas Cleanup technology at the Polk Power Station in Bradley, Florida (27.73,-81,99). It is funded primarily by the DOE through the American Recovery and Reinvestment Act costing, at around $169 million (The University of Edinburgh, n.d.v). Starting in 2014, CO_2 was captured at 0.3 Mtpa using BASF's aMDEA aqueous amine-based technology. CO_2 would be injected in the saline Cedar Keys Lawson formation for study and monitoring (The University of Edinburgh, n.d.v). As of projection completion in 2014 with 1,000 operational hours, no plans for storage are in sight (MIT, 2016p).


(Hornick, 2007)

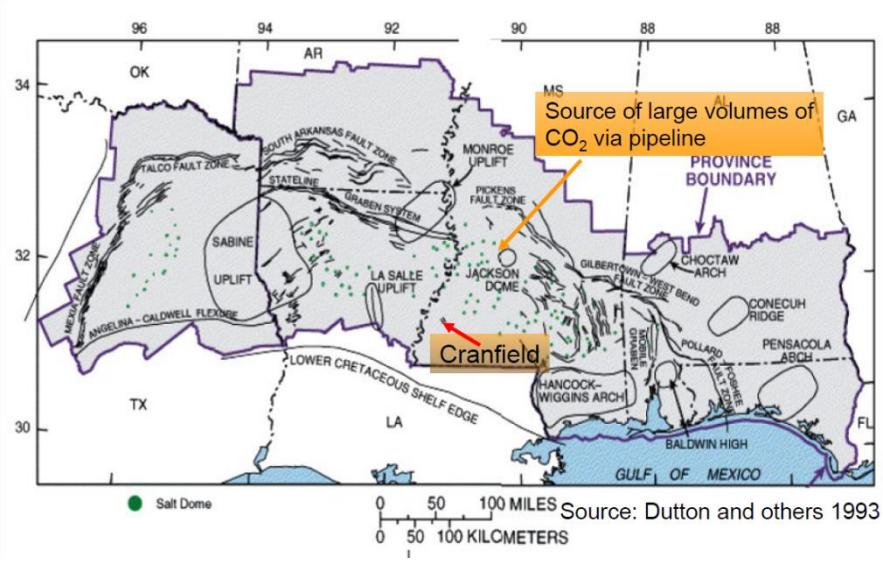
Net Power

Net power is a pilot project by NET Power, CB&I, and 8 Rivers Capital to capture CO_2 from a 50MW unit in the NET power plant in La Porte, Texas (29.05, -95.05) that totals around $140 million and may eventually scale up to capture 295MW units (The University of Edinburgh, n.d.q). The plant demonstrates NET Power's Allam Cycle technology to produce clean energy (Netpower, n.d.). Allam Cycle technology includes burning natural gas with pure oxygen to result with CO_2 that is recycled to spin the turbines; the CO_2 byproduct is sold or sequestered (Netpower, n.d.). The demonstration project is booming as of 2021 and there are plans for more facilities (Netpower, n.d.).

(Ryan, n.d)

Cranfield

The Cranfield project is a pilot project by SECARB, Denbury Resources, ARI, EPRI, University of Alabama, and NETL, and is funded primarily by the DOE for $65 million and $94 million total (MIT, 2016f). The project lasted from 2009 to 2015 with 5.37 Mt CO_2 sequestered (National Energy Technology Laboratory, n.d.e). CO_2 was captured from the Jackson Dome formation, which naturally contains CO_2 and is transported via pipeline by Denbury to the saline Tuscaloosa Sandstone Formation for monitoring (MIT, 2016f).



(National Energy Technology Laboratory, n.d.ee)

SUMMARY OF FINDINGS & CONCLUSION

The projects presented in this report demonstrate that companies in the U.S. have made significant progress in confirming the technical viability of carbon sequestration. It also introduces uncertainty as to the development potential for new projects without further subsidy improvements given that many projects appear to have been suspended for economic reasons. A table including all projects, their location, rate, sources, and CO_2 fates are included in the table below.

Project	Status	Start Date	Location	Operator	Rate (Mtpa)	CO2 Source	Capture Method	CO2 Fate
Terrell Natural Gas Processing Plant	1 - In Operation	1972	Fort Stockton, TX	Occidental Petroleum Corporation	0.400	Natural Gas Processing	Industrial Separation	Enhanced Oil Recovery
Core Energy CO2 - EOR	1 - In Operation	2003	Michigan Basin, MI	MRCSP, DTE Energy, Core Energy and Batelle	0.350	Natural Gas Processing	Industrial Separation	Enhanced Oil Recovery
Shute Creek Gas Processing Plant	1 - In Operation	1986	LaBarge, Wyoming	Exxon Mobil	7.000	Natural Gas Processing	Industrial Separation	Enhanced Oil Recovery
Century Plant	1 - In Operation	2010	Pecos County, TX	Occidental Petroleum, Sandridge Energy	5.000	Natural Gas Processing	Industrial Separation	Enhanced Oil Recovery / Geo Storage
Enid Fertilizer	1 - In Operation	1982	Enid, Oklahoma	Koch Nitrogen Company, Chaparral Energy	0.200	Fertisliser Production	Industrial Separation	Enhanced Oil Recovery
Great Plains Synfuels Plant and Weyburn-Midale	1 - In Operation	2000	Beulah, North Dakota	Cenovus Energy, Apache Energy	3.000	Chemical Production (Others)	Industrial Separation	Enhanced Oil Recovery
PCS Nitrogen	1 - In Operation	2013	Giesmar, Louisiana	PCS Nitrogen (Potash Corp)	0.300	Fertisliser Production	Industrial Separation	Enhanced Oil Recovery
Coffeeyville Gasification Plant	1 - In Operation	2013	Coffeeville, Kansas	CVR Partners, LC	1.000	Fertisliser Production	Industrial Separation	Enhanced Oil Recovery
Bonanza Bioenergy CCUS EOR	1 - In Operation	2012	Garden City, Kansas	Conestoga Energy Partners LLC	0.100	Ethanol Production	Industrial Separation	Enhanced Oil Recovery
Illinois Industrial Carbon Capture and Storage	1 - In Operation	2017	Decatur, Illinois	Archer Daniels Midland	1.000	Ethanol Production	Industrial Separation	Dedicated Geological Storage
Air Products Steam Methane Reformer	1 - In Operation	2013	Port Arthur, TX	Air Products	1.000	Hydrogen Production in Refinery	Post-Combustion Capture	Enhanced Oil Recovery
The Zeros Project	2 - In Construction	Late 2020s	Chambers County, Texas	Systems International	1.500	Waste to Energy	Oxy-fuel Combustion Capture	Enhanced Oil Recovery
Wabash CO2 Sequestration	3 - Advanced Development	2022	Terre Haute, IN	Wabash Valley Resources (WVR), OCGI Investments(supported)	1.750	Fertisliser Production	Industrial Separation	Dedicated Geological Storage
Lake Charles Methanol	3 - Advanced Development	2025	Lake Charles, LA	Lake Charles Methanol LLC	4.000	Chemical Production (Others)	Industrial Sepeartion	Dedicated Geological Storage
Project Tundra	3 - Advanced Development	2025-2026	Nelson Lake, North Dakota	Minnkota Power Cooperative	3.600	Power Generation Coal	Post-Combustion Capture	Dedicated Geological Storage
San Juan Generating Station Carbon Capture	3 - Advanced Development	2023	Waterflow, NM	PNM, Tucson Electric Power, Farmington, Los Alamos County, NM, Utah Associated Munipial	6.000	Power Generation Coal	Post-Combustion Capture	Enhanced Oil Recovery
Gerald Gentleman	3 - Advanced Development	Mid 2020s	Sutherland, NE	Nebraska Public Power District	3.800	Power Generation Coal	Post-Combustion Capture	Under Evaluation
Prarie State Generating Station Carbon Capture	3 - Advanced Development	Mid 2020s	Urbana, IL	University of Illinois, Kiewit Corporation, Mitsubishi Heavy Industries America, Inc., Sargent &	6.000	Power Generation Coal	Post-Combustion Capture	Dedicated Geological Storage
Plant Daniel Carbon Capture	3 - Advanced Development	Mid 2020s	Escatawpa, Mississippi	Mississippi Power, Gulf Power	1.800	Power Generation Natural Gas	Post-Combustion Capture	Dedicated Geological Storage
Cal Capture	3 - Advanced Development	2024	Kern County, CA	EPRI, CRC, Fluor	1.400	Power Generation Natural Gas	Post-combustion Capture	Enhanced Oil Recovery
Mustang Station of Golden Spread	3 - Advanced Development	Mid 2020s	Denver City, TX	Golden Spread Electric Cooperative, Inc, University of Texas at Austin	15.000	Power Generation Natural Gas	Post-combustion Capture	Under Evaluation
Arkalon CO2 Compression Facility	4 - Operation Suspended	2009	Liberal, Kansas	Chaparral Energy, Southwest Partnership	0.290	Natural Gas Processing	Industrial Separation	Enhanced Oil Recovery
Kevin Dome	4 - Operation Suspended	2016	Tool County, MT	Big Sky Partnership, Schlumberger Carbon Services, Veeta Oil & Gas Ltd, LBNL, LANL	0.125	Geologic CO2 Reservoir	Source from pipeline	Dedicated Geological Storage
Lost Cabin Gas Plant	4 - Operation Suspended	2013	Lost Cabin, Wyoming	ConocoPhillips, Denbury Resources	0.900	Natural Gas Processing	Industrial Separation	Enhanced Oil Recovery
Petra Nova Carbon Capture	4 - Operation Suspended	2017	Thompsons, TX	NRG	1.400	Power Generation Coal	Post-combustion Capture	Enhanced Oil Recovery
Project Interseqt - Hereford Ethanol Plant	5 - Early Development	2021	Hereford, TX	White Energy, Low Carbon Ventures, Occidental	0.300	Ethanol Production	Industrial Separation	Dedicated Geological Storage
Project Interseqt - Plainview Ethanol Plant	5 - Early Development	2021	Plainview TX	White Energy, Low Carbon Ventures, Occidental	0.330	Ethanol Production	Industrial Separation	Dedicated Geological Storage
Veloys' Bayou Fuels Negative Emission Project	5 - Early Development	2024	Natchez, MS	Veloys,Occidental	0.500	Chemical Production	Industrial Separation	Dedicated Geological Storage
OXY / Carbon Engineering DAC and EOR Facility	5 - Early Development	Mid 2020s	Permian Basin, TX	Oxy Low Carbon Ventures, Carbon Engineering Ltd.	1.000	Air	Industrial Separation	Enhanced Oil Recovery
LafargeHolcim Cement Carbon Capture	5 - Early Development	Mid 2020s	Florence, CO	Svante, LafargeHolcim, Oxy Low Carbon Ventures LLC, Total	0.720	Cement Production	Industrial Separation	Under Evaluation
Dry Fork Integrated CCS	5 - Early Development	2025	Gillette, WY	Basin Electric Power Cooperative, Wyoming Municipal Power Agency	3.000	Power Generation	Post-combustion Capture	Dedicated Geological Storage
Red Trail Energy BECCS Project	5 - Early Development	2025	Richardton, ND	RED Trail Energy	0.180	Ethanol Production	Industrial Separation	Dedicated Geological Storage
The Illinois Clean Fuels Project	5 - Early Development	2025	Near Mattoon, IL	Illinois Clean Fuels	2.700	Chemical Production	Industrial Separation	Dedicated Geological Storage
Clean Energy Systems Carbon Negative Energy Plant	5 - Early Development	2025	Central Valley, CA	Clean Energy Systems	0.320	Power Generation	Oxy-Combustion Capture	Under Evaluation
Polk Station	6 - Pilot Project	2014	Ruskin,Fl	Tampa Electric, Siemens	0.300	Power Generation Coal	Pre-Combustion Capture	Dedicated Geological Storage
Net Power	6 - Pilot Project	2017	La Porte, Texas	NET Power	0.804	Natural Gas Processing	Industrial Separation (NGCC)	Enhanced Oil Recovery
Cranfield	6 - Pilot Project	2009	Natchez, Mississippi	Denbury Onshore	0.100	Geologic CO2 Reservoir	Source from pipeline	Enhanced Oil Recovery
Plant Barry	6 - Pilot Project	2012	Mobile, AL	SECARB Consortium	1.000	Power Generation Coal	Industrial Seperation	Dedicated Geological Storage

A key observation in this project is that there are three classes of CCS projects which are most common (pilot projects, early carbon capture for industrial emissions, and new commercial scale projects). Another key finding is that CCS sites have struggled to maintain commercial viability. The fact that there have been no major projects move to operating status since 2017, when the Illinois Carbon Capture project began injection, is evidence of this conclusion. The mothballing of the Petra Nova CCS site is another example of the difficulty in operating large CCS facilities in a profitable manner. These examples serve as indicators that CCS is a technology that is challenged in the current economic environment.

In the future, much work is required to ensure CCS site development projects can reach commercial viability through an enhanced ability to recover the cost of investment. At this stage, there are two main sources for this income: the federal government via the 45Q tax credit program and certain states (e.g., California) which have implemented Low Carbon Fuels Standards and issue tradeable credits for emissions reductions for transportation fuels. As voluntary carbon credit markets develop further, it could encourage continued investment in this space. For the planned projects to proceed as announced, firms which plan to underwrite the investment in each project must gain surety of cost recovery. It is clear from a review of the numerous sources for this project that developing a stable credit trading paradigm will be essential to this goal. Moreover, federal legislation currently being considered would significantly bolster the federal programs (e.g. 45Q) which reward CCS projects for their impact on reducing anthropogenic emissions through associated and permeant storage. With an improvement in these incentives, CCS projects should flourish in the U.S., with the potential to multiply our sequestered emissions to date over the coming decade.

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