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IEA Bioenergy: Task 40

Contribution of IEA Bioenergy Task 40 to the IEA Bioenergy inter-task project
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A case study of sequestering CO_2 from ethanol production

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Preface

Substantial amounts of negative emissions will be required if global climate change and the ensuing increase in temperature is to be limited to well-below 2°C above pre-industrial levels, as is the ambition of the 2015 Paris Climate Agreement. Among the different negative emissions options available, bioenergy with carbon capture and storage, also referred to as Bio-CCS, or BECCS where E is for energy, is arguably one of the most commonly discussed in climate policy debates.

Up until recently, Bio-CCS was primarily discussed in terms of its potential and drawbacks over very long timeframes, e.g., 2050 and beyond, but there is now growing focus on more near-term aspects. The IEA Bioenergy inter-task project Deployment of BECCS/U Value Chains, where U is for utilization, runs between 2019-2021 and strives to provide insights about the opportunities and challenges pertaining to take BECCS/U from pilots to full-scale projects. To this end, the project puts focus not only on technological aspects but also on how BECCS/U business models could be set up and the role that public policy could play in enabling sustainable deployment of BECCS. The project focuses on the CO_2 capture, transportation, and storage phases of the supply chain. Upstream biomass feedstock supply systems are only touched upon very briefly, as these issues are analyzed in great detail in other IEA Bioenergy work.

An important characteristic of BECCS is that it can be implemented in a broad range of sectors - basically any setting where there are biogenic emissions of CO_2 available in sizeable quantities. This includes generation of heat and power in various contexts, but also industrial facilities like cement production, pulp & paper mills or ethanol plants. The specifics related to BECCS implementation can however vary quite substantially from sector to sector. This is partly because of differences in technological factors like CO_2 concentrations, but also a result of how different sectors operate under widely varying commercial and regulatory conditions.

This case study is part of a series of studies carried out under the Deployment of BECCS/U Value Chains project with the aim to highlight these sector-specific characteristics. The case studies provide deeper insights into the key aspects that come into play for companies that are in the process of setting up value chains for capture, transportation and sequestration or utilization of biogenic CO_2.

Acknowledgements

We thank Archer Daniel Midland (ADM) for providing valuable information for this case study. Special thanks go to Scott McDonald and Rishi Shukla at ADM who provided valuable insights on the current state of technology at ADM and contributed to reviewing this case study.

The Industrial Carbon Capture and Storage (ICCS) project is administered by the U.S. Department of Energy's Office of Fossil Energy and managed by the National Energy Technology Laboratory (award number DE-FE-0001547) and by a cost share agreement with the ADM, U of I (ISGS), SLB, & RCC.

The Intelligent Monitoring System (IMS) Project is administered by the U.S. Department of Energy's Office of Fossil Energy and managed by the National Energy Technology Laboratory (award number DE-FE-0026517) and by a cost share agreement with the ADM, LBNL, Silixa, SLB, U of I (ISGS), & RCC.

The Midwest Geological Sequestration Consortium (MGSC) is funded by the U.S. Department of Energy through the National Energy Technology Laboratory via the Regional Carbon Sequestration Partnership Program (contract number DE-FC26-05NT42588) and by a cost share agreement with the Illinois Department of Commerce and Economic Opportunity (DCEO).

The MGSC is a collaboration led by the geological surveys of Illinois, Indiana, and Kentucky.

Executive summary

The Archer Daniels Midland Company (ADM), in collaboration with a consortium of academic, industry, and national laboratory partners, have studied the potential for sequestering CO_2 generated from an ethanol production plant at multiple sites in the Illinois Basin. The two projects represented in this case study include the Illinois Basin Decatur Project (IBDP) which represents a large-scale geologic test to inject one million metric tons (mt) of CO_2 over a three-year period (1,000 mt/day) and the Illinois Industrial CCS project (IL-ICCS) targeted to demonstrate advanced CCS technologies at industrial scale facilities and inject and store one million mt of CO_2 per year (3,000 mt/day). The demonstrations were coupled with development of the Intelligent Monitoring System (IMS) program to develop and validate software tools.

The project demonstrated a range of environmental and economic benefits ranging from lower emissions to lower capital costs. On-site CO_2 emissions were lower, and the process demonstrated a GHG reduction efficiency of 94% based on using Midwest electricity grid average CO_2 intensity. Reduction in the carbon footprint of fuel ethanol was accompanied with lower operational expenses compared to other forms of CO_2 capture. Additional applications can also include development of CO_2 based chemicals and products including carbonates, biochar, fertilizers, alcohols, fuels, acids as well as the potential for use in enhanced oil recovery from subsurface rock formations between wells.

1. Introduction

1.1 BACKGROUND

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement sets a target of limiting the global temperature increase to "well below 2°C" and to implement efforts to limit the temperature increase to 1.5°C. The global fight against climate change is raising concerns more than ever before as we are failing to decarbonize the global economy fast enough and the global temperature rise is already 1ºC compared to the pre-industrial level and is increasing 0.2°C per decade (NCEI, 2020). Limiting the temperature increase to 1.5°C implies reaching net zero CO_2 emission approximately by 2050. CO_2 emissions continue to remain high and scientists as well as policymakers are looking for solution pathways to meet the Paris Agreement temperature target. The pathways that aim to keep the global temperature rise within the limit rely on energy-demand improvement, decarbonizing the power and fuel industry, reducing the agricultural emissions and large-scale deployment of carbon dioxide removal (CDR) technologies with carbon storage on land or sequestrated in geological reservoirs. According to the most recent report of UN's Intergovernmental Panel on Climate Change (IPCC), bioenergy with carbon capture and storage (BECCS) or Utilization (BECCUS) is emerging to be one of the most effective negative emission technology (NET) pathways (IPCC, 2018). BECCS has an estimated potential to remove between 0.5-5 gigatones (Gt) of CO_2 per year by 2050 (ICRLP, 2020).

In light of the Paris agreement, the United States of America (US) has set the ambitious goal to reach net-zero emission by 2050, which will require reducing annual CO_2 emissions by 5.7 Gt within the next 30 years. In the pathways to achieve deep decarbonization in the US, BECCS is referred to as the most mature and well understood technology to implement CDR. However, the deployment of BECCS has been slow for the last two decades since its introduction in 2001. There are uncertainties yet to be overcome for the technology in terms of biomass availability, CO_2 storage capacity, conflicts with biodiversity and food security, competition for land, water and fertilizer as well as financial security (Fridal & Lehtveer, 2018). Hence, BECCS is still under the development phase and there are only a few operating facilities around the world. The US Department of Energy (USDOE) introduced the Carbon Negative Shot as the first major incentive for innovation in technologies that will facilitate Gt-scale CO_2 removal and durable storage for less than \$100/net metric ton of CO_2-equivalent in the next decade. Achieving the Carbon Negative Shot will help the US overcome the most crucial uncertainties towards implementing BECCS while reaching the net-zero target and creating a sustainable economy.

Being the leading biofuel producer in the world, the US is currently investing heavily in establishing CCS facilities with biofuel production plants due to the mature supply chain network of biomass feedstocks as well as lower capture cost for the almost pure CO_2 coming from the fermentation gas stream of ethanol plants. The largest BECCS facility in the US is located in Decatur, Illinois at the Archer Daniels Midland (ADM) ethanol plant with a capacity to capture one million tons of CO_2 per year (Mt pa). ADM, in collaboration with a consortium of academic, industry, and national laboratory partners, have studied the potential for sequestering CO_2 generated from an ethanol production plant at multiple sites in the Illinois Basin. ADM's research initiatives include biomass conversion to fuel additives, integrated biorefinery, carbon capture and storage, membrane solvent extraction, hydrothermal liquefaction (HTL), chemical platform development, catalytic pyrolysis and hydrogen research, among other areas.

1.2 OBJECTIVES

The objective of this study is to present the case study of a BECCS application by ADM and conduct a review of literature to identify the technological, economic, and policy aspects of sustainable deployment of BECCS projects in the US. The specific tasks include:

I. Synthesize current knowledge on the deployment of bio-based carbon capture and storage technologies and potential future directions in the US.
II. Collate case studies demonstrating the evolution of bioenergy with carbon capture and storage (BECCS) projects from pilot scale to full scale in the US.
III. Describe in detail BECCS projects, namely the Illinois Basin Decatur Project (IBDP) and Illinois Industrial CCS (IL-ICCS) Project (the ADM case)
IV. Identify opportunities and challenges pertaining to BECCS projects.

2. BECCS and BECCU Technologies in the USA

Deployment of BECCS incorporates different stages including biomass harvesting and conversion of biomass feedstocks into bioenergy as well as capture, transport, storage, or use of CO_2 produced during biomass conversion. Technologies can vary widely depending on different conversion pathways (e.g., biochemical vs. thermochemical conversion) from variable biomass feedstock (e.g., conventional food-based, ag. residues, forest residues and dedicated energy crops), types of carbon capture pathways (e.g., post combustion, pre-combustion and oxy-combustion) and storing or using carbon in different forms.

The US is the leading global biofuel producer, generating around 16.9 billion gallons of conventional ethanol from corn grain. According to the Billion-Ton report by the Department of Energy (DOE), the US has the potential to produce approximately 775 million dry tons of agricultural residues, and dedicated energy crops (USDOE, 2016). Alongside with the potential supply of feedstocks, two-thirds of the US has deep saline formations beneath it which has an estimated CO_2 storage capacity of 2,000 Gt (Baik et al., 2018). Many of these storage sites are near bioenergy feedstock locations creating an opportunity for lower transportation cost of CO_2 from the bioenergy facilities. The large underground storage capacity of CO_2 combined with the biomass feedstock availability in the US has facilitated the deployment of BECCS. Alongside the ADM BECCS plant, there are currently four other operational BECCS/BECCUS facilities located in Kansas and California (Appendices Table 1). These plants have different end-uses for captured carbon. The facilities in Kansas are using captured carbon for enhanced oil recovery (EOR) while the Calgren Recovery plant in California utilizes the captured carbon in the food, beverage, and manufacturing industry. The Charm Industry waste to bio-oil pilot plant is also utilizing carbon sequestration on a pilot-scale, making Illinois Decatur plant the only commercial-scale project that is sequestering carbon into geological reservoirs (e.g., deep saline formations).

While both EOR and saline reservoir storage is considered as carbon sequestration, there is debate regarding the extent to which the EOR method is carbon negative. In the EOR process, CO_2 is injected into oil fields to increase the pressure in an oil reservoir and produce more oil. Around 90-95% of the CO_2 ends up staying underground, taking the place of oil in the reservoir. However, the oil that is recovered has a GHG emission factor of its own when combusted. The emission footprint varies greatly depending on the field location and the lifetime of the project (Overton, 2016; McGlade, 2019). From an environmental perspective, long term sequestration into saline aquifers and reactive mineral formations is considered the reliable solution since each ton of injected carbon will be stored underground for the next 100 to 1,000 years.

3. Challenges of BECCS Deployment

Not all BECCS projects are considered carbon negative. Whether BECCS is carbon-negative or carbon-positive depends on factors such as land-use management, feedstock characteristics, energy conversion technology, and carbon capture approach. For example, emissions from transport, preprocessing and using CCS technology represents 64% of the captured carbon for dedicated energy crops (Fern, 2022). Considering the ADM scenario, the total carbon emission from the ADM Decatur complex was 4.5 million t CO_2 in 2020 (EPA, 2020). The company is currently using carbon capture and sequestration technology in their alcohol plant at the Decatur complex where ethanol alcohol is produced from corn by wet-mill processing. The alcohol plant contributes only about 14% of the total CO_2 emissions from the Decatur complex. ADM captures 95% of the available CO_2 coming off the anaerobic fermentation unit of the alcohol plant. However, around 6% of the CO_2 produced during fermentation has about 25% air dilution and ADM does not collect this CO_2. Adding up the aforementioned complexities, ADM was able to capture and sequester around 521,000 t CO_2 in 2020 which is half of the annual designed capacity (EPA, 2020).

ADM processes corn grain to produce a variety of end products such as sweeteners, starches, animal feed, bioproducts and ethanol. Since ADM operates both as a bioenergy company and food/feed processing company, the corn that comes from the field not only serves as a carbon source for bioenergy but also supplies food/feed for human and animal use. However, this may not be the case for future implementation of BECCS to achieve atmospheric carbon removal. Biomass will be treated solely as a carbon source rather than a food/feed source. Large-scale deployment of BECCS introduces potential concerns regarding food security, biodiversity loss, water resources, increased fertilizers usage, soil carbon loss, and limited geologic storage (Babin et al., 2021).

Moreover, large scale BECCS deployment faces the challenge of overcoming financial barriers. The US DOE has provided more than $5 billion in funding to carbon capture and storage projects (Hettinger, 2020). ADM's Decatur facility is one of the few successful ones. Most of the other projects were cancelled due to their high cost and performance issues. Since BECCS include several stages of the supply chain for biomass harvesting, transporting and conversion as well as carbon capture, compression, transportation and storage, the total cost per ton of CO_2 rises with each of these variables. Current estimates for BECCS carbon removal costs vary widely from $20 per mt of CO_2 (tCO_2) to $400 per mt of CO_2. Studies also estimated that adding carbon capture to a bioenergy plant would double the capital cost of the facility (Quin, 2018) while adding the complexity of building CO_2 transport pipelines. The environmental impacts of BECCS on air, water and land quality as well as risks of carbon leakage are subject to further scientific research and debate.

4. Illinois Basin Decatur Project (IBDP) and Illinois Industrial CCS (IL-ICCS) Project – the ADM case

The Illinois Basin Decatur Project (IBDP) represents a large-scale geologic test to inject one million mt of CO_2 over a three-year period (1,000 mt/day). The project team comprised ADM, Illinois State Geological Survey, Schlumberger Carbon Services, and the National Energy Technology Laboratory (NETL). The IBDP project received $66.7 million of federal funding from the US Department of Energy (USDOE) and another $17.6 million from the private sector to successfully store 1 million ton over the three-year period (CCST MIT, 2022). The goal of injecting and storing one million ton of CO_2 was achieved in November 2014. After the successful completion of the IBDP project, the Illinois Industrial CCS project (IL-ICCS) targeted to demonstrate advanced CCS technologies at industrial scale facilities and inject and store one million mt of CO_2 per year (3,000 mt/day). In this effort, Richland Community College joined the project team.

The IL-ICCS project cost was $207 million of which $141 million (68%) came from federal funding (Office of Fossil Energy and Carbon Management, 2017). ADM also receives tax credits for the IL-ICCS project which was one of the biggest financial motivations behind the project formation. According to the Sequestration Tax Credit – often referred to using the IRC section, 45Q - ADM receives around $23.82 per mt of geologically sequestered CO_2 (CRS, 2021a). If ADM can capture 1 million t of CO_2 for the next five years, it can receive around $24 million per year totalling $120 million in tax credits which surpasses the initial investment of ADM. The tax claim is available until 75 million t of CO_2 have been captured and sequestered (CRS, 2021a). Moreover, the total capital and operational cost of the project were estimated at $28.35/t of CO_2 (McKaskle et al., 2019) which is lower compared to other CCS technologies such as direct air capture, and from power generation plants (Schmelz et al., 2020; Lebling, 2022).

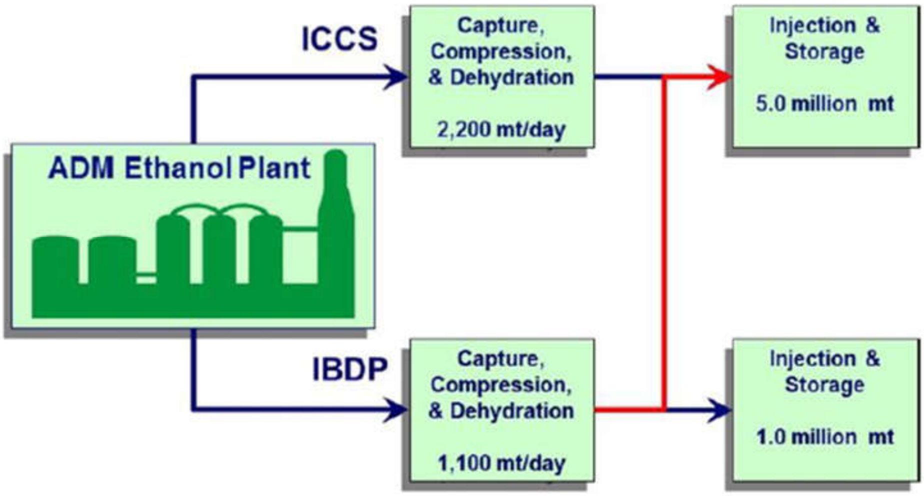

Figure 1: Industrial Carbon Capture and Storage Project (McDonald, 2012). Units are in metric tons

The primary objectives of the Illinois Decatur project can be summarized as:

- Design, construct, and operate a new CO_2 collection, compression, and dehydration facility capable of delivering up to 2,200 mt of CO_2 per day to the injection site.
- Integrate the new facility with an existing 1,000 mt of CO_2 per day compression and dehydration facility to achieve a total CO_2 injection capacity of 3,300 mt per day or one million tons annually.
- Study the interaction between the CO_2 plumes from two injection wells within the same formation.
- Implement deep subsurface and near-surface Monitoring, Verification and Accounting (MVA) of the stored CO_2.
- Develop and conduct an integrated community outreach, training, and education initiative.

Additionally, the Intelligent Monitoring System (IMS) program aimed to:

- Develop and validate software tools that advance CCS-specific IMS by enabling access, integration and analysis of real-time surface and subsurface data for decision-making and automation of process.
- Demonstrate integration of system components to validate feasibility of real-world application to CCS.

4.1 PROJECT PROCESS FLOW

The process relies on wet CO_2 produced from a corn-to-ethanol fermentation process. Using a centrifugal blower, the CO_2 is delivered to 4-stage reciprocating compressors with interstage coolers and water knock out vessels. After the third stage of compression, a glycol dehydration unit is used to reduce the CO_2 water content to less than 480.55 kg of water per million m^3 CO_2. The fourth stage of compression is the transcritical stage where the CO_2 changes from a vapor phase to a supercritical fluid. Further compression of the CO_2 is accomplished using a 45-stage centrifugal pump after which the CO_2 is delivered to the injection wellhead. The CO_2 is injected at a depth of approximately 2,134 meters in Mount Simon sandstone.

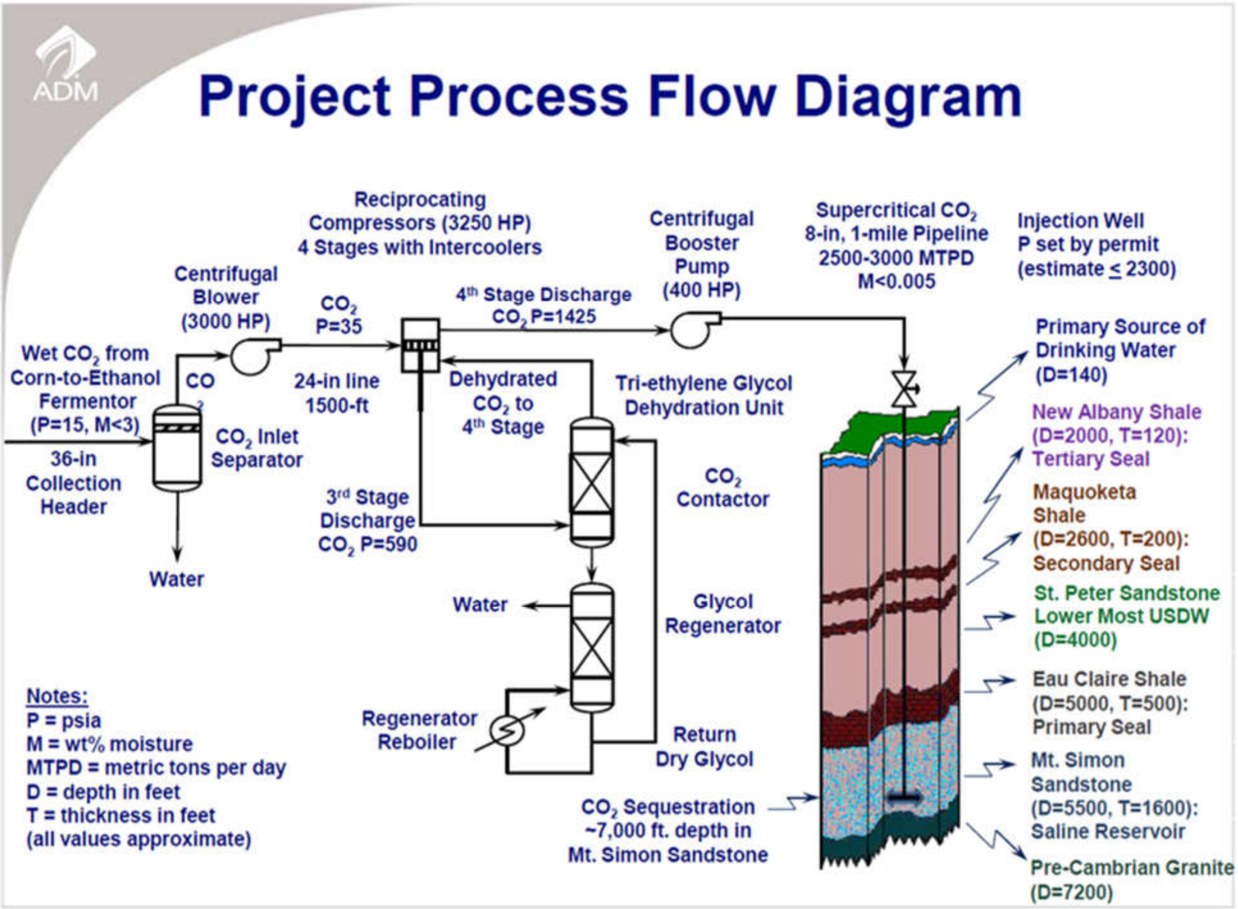

Figure 2: Project Process Flow Diagram (McDonald, 2017)

4.2 SITE CHARACTERIZATION

IL-ICCS project site selection benefited from the information developed through the Regional Carbon Sequestration Partnership. Site selection began with a characterization phase spanning 2 years (2003-2005) during which potential storage locations and CO_2 sources were identified. The validation phase lasted between 2005 and 2010 during which injection tests in saline formations, depleted oil, unmineable coal seams and basalt were evaluated. Finally, in the development phase (2008-2017), 9 large scale injections (over one million tons each) were executed, as well as understanding of commercial scale operations, regulatory, liability and ownership issues was attained.

Some of the objectives for the site selection encompass:

- Engage regional, state, and local governments
- Determine regional sequestration benefits
- Baseline region for sources and sinks

- Establish monitoring and verification protocols
- Address regulatory, environmental, and outreach issues
- Validate sequestration technology and infrastructure

A site in the Cratonic basin, a 60,000 square mile area, is the location for the ADM Decatur facility. The region is structurally complex to the south with faulting and seismicity. The estimated CO_2 storage capacity ranges between 27 to 109 billion mt. In addition, the Decatur site has:

- High purity source of CO_2
- Thick permeable formation for storage. Porosity <20% and permeability 26 mD
- Formation depth and additional seal formations
- Thick seal with no resolvable faulting
- No local penetrations of the primary seal formation
- Low population density

4.3 SITE MODELING

A 2,206 m deep In-Zone monitoring well and a 1,083 m deep geophysical monitoring well were drilled in November 2012. An integrated flow control technology was used to obtain continuous pressure measurements across Mount Simon Sandstone. The site model was calibrated using measurements obtained during the first four months of the IBDP injection period. The IBDP injection rate was input into the simulation to calculate the bottom hole pressures and pressures at five different zones at the monitoring well. Reservoir permeability and skin were the main parameters impacting the injection pressure calibration and were used as fitting parameters. Once the injection bottom hole pressure was calibrated, simulated pressures at five different zones at the monitoring well were fine-tuned, calibrating the kv/kh ratio of the tight sections and compressibility of the reservoir rock. The injection location is at the top of Mt. Simon Sandstone at a depth of 1,677 m below the ground surface and has a thickness of 457 m. Reservoir saturation tool (RST) well logs helped to identify the location, saturation and thickness of the CO_2 column around the injection and monitoring wells. Using the calibrated model, a predictive simulation was run to evaluate plume development and pressure perturbation during the injection period. The simulation was run for the project's 50 years planned injection period.

4.4 SITE MONITORING

4.4.1 CO_2 Injection Monitoring

CO_2 injection was monitored using deep subsurface monitoring. Data obtained from the monitoring of the injected CO_2 between 2013 and 2020 showed containment of the plume within the Lower Mount Simon zone. ADM will monitor the site surrounding the well for the 10-year post injection period to confirm the predicted behavior of the injected CO_2. Alongside the direct methods including fluid sampling, pressure & temperature monitoring, indirect methods such as seismic surveys will be considered as CO_2 storage monitoring programs. Stringing thousands of cables and running thumper trucks every few years can test the limits of good reservoirs. Permanent reservoir monitoring offers a way to obtain higher quality information with minimal intrusion into surrounding lands. Moreover, to check for microseismicity, the site has installed five seismic monitoring stations and three borehole monitoring stations. Microseismic activity refers to minor seismic events that are caused by human activity which alerts the stresses and fluid pressures beneath the earth's surface. Distributed Acoustic Sensing (DAS) provides high spatial and temporal resolution. Excitation of DAS cables can be achieved through permanent fixed rotary sources for continuous monitoring.

4.4.2 Environmental Monitoring

Near-surface monitoring activities were conducted to monitor environmental impacts of the project. Near infrared imagery will be used to evaluate plant stress. Soil CO_2 flux measurements will be observed to identify changes in CO_2 concentrations. Moreover, geochemical sampling of ground water at shallow depths will be done with pressure and temperature monitoring to ensure the safety of these water resources.

5. Future Deployment of BECCS

Several federal policies and programs directly address BECCS including USDOE, USDA and EPA. USDOE has funding of $63.5 million in 2022, $66.2 million in 2023, $69.5 million in 2024, and $72.9 million in 2025 for research and development in the CDR technologies (CRS, 2021b). Moreover, Section 45Q Carbon Dioxide Sequestration credit might be one of the biggest incentives for future BECCS deployment. The amount of carbon credit depends on the type of CO_2 end use. Long-term sequestration could earn up to \$50/tCO_2 by 2026 whereas CO_2 with EOR could earn \$35/tCO_2 by 2026 leading the way for long-term sequestration (CRS, 2021a). Ethanol plants that emit more than 100 ktCO_2/year are also eligible for this tax credit.

Moreover, there are 4,500 miles of existing CO_2 pipelines connecting carbon capture projects with CO_2 sequestration sites in the US. The pipeline network is currently being used almost completely for EOR with coal and gas fired power plants. However, the system can be expanded to incorporate large-scale deployment of BECCS. The industry has recently seen the development of companies like Summit Carbon Solutions to use shared CO_2 pipelines to transport and permanently store CO_2 from over 30 ethanol plants in the Midwest (Fig. 3). Some other notable future projects include the Mendota project in California aiming for geological sequestration and Occidental and White Energy projects in Texas using CO_2 for EOR (Appendices Table 2).

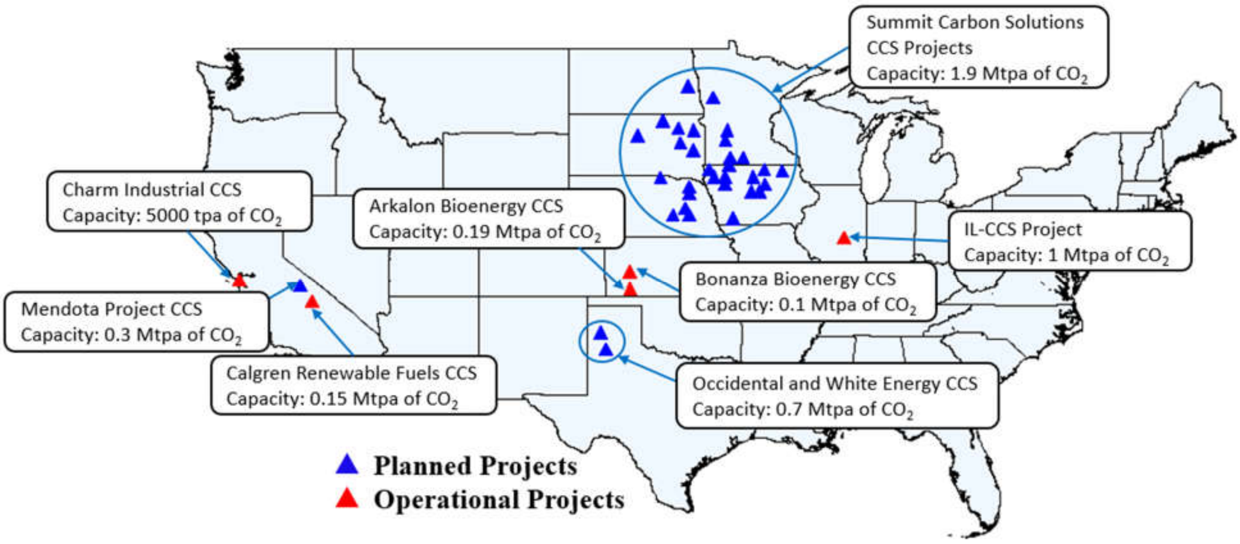

Figure 3. BECCS/BECCUS projects in the US

It is estimated that the US has the potential to sequester 737 million tonnes of CO_2 per year by 2040 (Langholtz et al., 2020). In order to reach the full potential, it is necessary to deploy BECCS in various energy sectors alongside biofuels including the pulp and paper industry, the cement industry, waste to energy plants and bioelectricity. Technologies to implement BECCS with various energy sectors already exist in Europe, Canada and Japan. Drax power station in the UK and Mikawa Post Combustion Capture plant in Japan have demonstrated capabilities to capture 300 tons per year (tpa) and 180,000 tpa of CO_2 respectively from biomass-fired power plants. The Klemetsrud Plant in Oslo, Norway and the ARV Duiven in the Netherlands capture 315,000 and 60,000 tpa of CO_2 respectively from the processing of Municipal Solid Waste (MSW). Moreover, the Saint-Felicien pulp mill in Quebec, Canada has deployed commercial CCS with a capacity of 11,000 tpa of CO_2. The Norcem Cement plant in Brevik, Norway is currently working towards installing a CCS facility with their plant to capture 400,000 tpa of CO_2 by 2024, which will be the first industrial scale CCS plant in the world at a cement production facility.

Combustion power plants in the US have an estimated emission of 1,925 million t of CO_2, which is 37% of the total US energy-related CO_2 emissions (CSLF, 2018). The US already has the feedstock supply capacity to facilitate such BECCS plants as it is supplying approximately 20% of the world's biomass for power production in the form of wood pellets. The pulp and paper mills of the US have emissions of approximately 150 million t of CO_2 each year of which 77% is biogenic and it has significant potential to remove CO_2 from the atmosphere with the implementation of BECCS (Sagues et al., 2020). Moreover, the US cement industry has an estimated production of 114.7 Mt/year which has a total emission of 137 Mt pa of CO_2 (DEG, 2020). USDOE has announced funding of $9 million to design and build CCS facilities with the Eagle Materials/Central Plains Cement Sugar Creek Plant and Holcim's Ste. Genevieve Cement Plant in Missouri (DOE, 2021). Deployment of BECCS with these various industry sectors will have major contributions to reduce the US industry carbon footprint and move forward towards the negative emissions target.

6. Summary and Conclusion

The Illinois Basin region projects have paved the way for deployment of large-scale BECCS facilities in the US. IBDP and IL-CCS projects have demonstrated industrial application of BECCS technology in the Midwest with environmental and economic benefits ranging from lower emissions to lower capital costs compared to other CCS technologies. Onsite CO_2 emissions were lower and the process demonstrated GHG reduction efficiency of 94% based on using Midwest electricity grid average. Reduction in the carbon footprint of fuel ethanol was accompanied with lower operational expenses compared to other forms of CO_2 capture.

As of 2022, there are currently 192 operating ethanol biorefineries in the US (USEIA, 2022). According to Renewable Fuels Association, if every ethanol biorefinery deployed CCS technologies with their facility, around 45 million mt of CO_2 could be removed from the atmosphere every year (Lewis, 2021). Biorefineries can be the most promising sector for BECCS deployment as it is the most mature and technology ready bioenergy industry in the nation. However, only four ethanol plants currently have CCS/U technologies. This is due to the complexities involved with the development and operation of a BECCS facility such as large variation in the CO_2 capture cost depending on the size, location and lifetime of the project and multi-stage long development phase. As evident from the IBDP and IL-CCS projects, it can up to 10 years to complete the development phase and reach the project to its full potential in terms of CO_2 storage. Each of the design and construction stages including site selection and characterization, site modelling, deep subsurface monitoring of injected CO_2 and environmental monitoring can take several years to complete. CO_2 capture cost can vary between $20/mt of CO_2 to $400/mt of $CO_{2,}$ and thus far federal policies and incentives have been vital. As the number of BECCS facilities increases nationwide and technological advancement takes place, the design, construction and monitoring period is expected to become shorter with reduced complexities in future.

Additional CCS applications can include development of CO_2 based chemicals and products including carbonates, fertilizers, biochar, alcohols, fuels, acids as well as the potential for use in enhanced oil production from subsurface rock formations between wells. Biochar is already being produced in the US to use for soil regenerative purposes. Companies like ARTi, Pacific Biochar, and Glanris are producing carbon-rich biochar (44% carbon by weight) from oat hulls, rice hulls and wood residues. Moreover, to scale up the commercial deployment of BECCS by 2050, it would be necessary to cost-effectively utilize biomass resources, which are generally situated in remote locations from CO_2 storage sites. A large integrated regional network for biomass transportation alongside expanded long-distance CO_2 pipelines is imperative for the Gt-scale BECCS deployment within the next decade.

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Glossary

ADM: Archer Daniels Midland Company

CCS: Carbon Capture and Storage

CCUS: Carbon Capture, Utilization and Storage

CCS/U: Carbon Capture and Storage or Utilization

DAS: Distributed Acoustic Sensing

DCEO: Department of Commerce and Economic Opportunity

EOR: Enhanced Oil Recovery

HTL: Hydrothermal Liquefaction

IMS: Intelligent Monitoring System

MGSC: Midwest Geological Sequestration Consortium

MVA: Monitoring, Verification and Accounting

USDOE: United States Department of Energy

USGS: United States Geological Survey

NETL: National Energy Technology Laboratory

USDA: United States Department of Agriculture

EPA: Environmental and Protection Agency

Appendices

Name	Capture Source	Location	Capacity (tpa*)	Operation Year	Industry Type	Carbon Disposition
Illinois Industrial CCS	Archer Daniels Midland (ADM) corn to ethanol plant	Decatur, Illinois, USA	1,000,000	2017	Ethanol production	Geological storage
Arkalon CO2 Compression Facility	Arkalon Energy Ethanol Plant	Liberal, Kansas, USA	190,000	2009	Ethanol production	Enhanced oil recovery (EOR)
Bonanza Bioenergy CCUS EOR	Bonanza Bioenergy Ethanol Plant	Garden City, Kansas, USA	100,000	2012	Ethanol production	Enhanced oil recovery (EOR)
Air Liquide commissions carbon dioxide plant at Calgren facility	Calgren Renewable Fuels ethanol plant	Tulare, California, USA	150,000	2015	Ethanol production	Utilization (Used in food, beverage, manufacturing)
Charm Industrial CO_2 Removal	Charm Industrial	San Francisco, California, USA	5,000	2020	Bio-oil	Geological storage

Table 1 Operational projects in the USA

* tons of CO_2 per year

Name	Capture Source	Location	Capacity (tpa*)	Operation Year	Industry Type	Carbon Disposition
Schlumberger New Energy, Chevron, Clean Energy Systems and Microsoft's Mendota Project	Waste biomass to electricity plant	Mendota, CA, USA	300,000	2025	Syngas, Power	Geological storage
Occidental and White Energy's CCS project	White Energy's ethanol facility	Hereford, TX; Plainview, TX	700,000	2024	Ethanol production	Enhanced oil recovery (EOR)
Summit Carbon Solutions CCS	Biorefinery plants	IA, USA; SD, USA; ND, USA; NE, USA; MN, USA.	1,900,000	2024	Ethanol production	Geological storage

Table 2 Planned projects in the USA

* tons of CO_2 per year

IEA Bioenergy
Technology Collaboration Programme