PCO2R Partnership

Plains CO_2 Reduction (PCOR) Partnership

Energy & Environmental Research Center (EERC)

PATHWAYS FOR THE GROWTH OF THE COMMERCIAL CCUS INDUSTRY IN THE PCOR PARTNERSHIP REGION THROUGH 2034

Plains CO_2 Reduction (PCOR) Partnership
Deliverable 17

Prepared for:

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EXECUTIVE SUMMARY

The commercial development of carbon, capture, utilization, and storage (CCUS) is already underway in the Plains CO_2 Reduction (PCOR) Partnership region. To date, there are 17 commercial CCUS projects that are injecting CO_2 within the region. Also in the region are four partially permitted commercial CCUS projects that have secured storage facility permits (North Dakota) or permits to construct (Wyoming); CO_2 injection at these projects can commence following approval of a permit to inject. This commercial landscape is dominated (11 of the 17 projects) by CCUS projects that store CO_2 concurrently with the production of oil during CO_2 enhanced oil recovery (CO_2 EOR), i.e., associated storage; however, these early projects were not optimized to maximize the storage of CO_2. Rather, they focused on minimizing the amount of purchased CO_2 and maximizing the revenues from the sale of the produced oil. The remainder of the commercial CCUS activity in the United States was focused on the dedicated storage of CO_2 captured from ethanol production plants, coal gasification plants, and coal-fired power plants; commercial CCUS activity in Canada was also focused on coal-fired power plants as well as other industrial sources such as oil and bitumen refineries and ammonia production using a combination of associated and dedicated CO_2 storage.

However, looking forward to the next 10-year period (2024–2034), several of the more recent road maps that present pathways for the commercial deployment of CCUS in both the United States and Canada note that more rapid growth of the commercial CCUS industry is necessary to achieve the CO_2 emission reduction targets established by the 2015 international treaty on climate change. In addition, more commercial CCUS projects will be needed 1) to meet the net-zero emission goals set by many state, provincial, and federal governments and 2) to comply with the U.S. Environmental Protection Agency (EPA) final rule that establishes carbon pollution standards for existing coal-fired and new gas-fired power plants. This New Source Performance Standard, which was published May 9, 2024, and scheduled to go into effect July 8, 2024, recognizes CCUS as the "best system of emission reduction (BSER), taking into account costs, energy requirements, and other statutory requirements." EPA proposes that these standards and the installation of the necessary controls be phased in over time, during the period of 2030–2032.

The PCOR Partnership region has the potential to increase the rate of growth of the CCUS industry through 2034, given that 35 commercial CCUS projects comprising 25 projects in Canada and ten projects in the United States have been announced in the PCOR Partnership

region,[1] with many of these slated to begin construction or injection operations by 2034. Unlike the past commercial development, this next generation of commercial CCUS projects in the PCOR Partnership region is likely to be dominated by the dedicated storage of CO_2. This shift in commercial activity to dedicated storage is occurring in the U.S. portion of the region largely because of the investments of the federal government (i.e., CarbonSAFE [Carbon Storage Assurance Facility Enterprise] projects funded by the U.S. Department of Energy [DOE] and the funding provided by the Infrastructure Investment and Jobs Act, otherwise known as Bipartisan Infrastructure Law) and the 2022 enhancements to the 45Q tax credits, which are greater for dedicated storage. In Canada, a driving force toward dedicated storage is the Canadian initiative to develop a hydrogen economy, which requires a rapid scale-up of the production of blue hydrogen from its natural gas reserves in Alberta.

It is anticipated that moving forward in the PCOR Partnership region, CCUS commercial deployment at coal- and natural gas-fired power plants is likely to increase across the U.S. portion of the region as the recent EPA regulations are enacted. An increase in commercial CCUS activity at gas-processing facilities is also anticipated as these facilities continue to expand in tandem with CO_2 EOR but with more attention on process optimization that considers a combination of CO_2 utilization, oil production, and CO_2 storage. Lastly, CO_2 capture and storage at ethanol facilities is expected to increase, given the combined incentives associated with meeting the Low-Carbon Fuel Standard markets coupled with the current 45Q tax credits. At the same time, Canada will also be focusing on the decarbonization of a variety of industrial emitters.

The PCOR Partnership proposes to build upon the significant commercial CCUS activity that has already occurred in the region to create a path forward through 2034 for the basinwide growth of a commercial CCUS industry in the region. This will be done by 1) facilitating the deployment of several of the 35 commercial CCUS projects that have been announced in the region and 2) more thoroughly investigating and addressing the regional knowledge gaps in several areas, including the capture of CO_2, advanced geologic characterization of onshore carbon storage, targeted characterization of associated storage from conventional and unconventional CO_2 EOR, active reservoir management, regional pipeline infrastructure, and risk assessment and management tools. These efforts will be integrated with the recent DOE initiative to foster the commercial deployment of CCUS at the basin scale, with particular attention given to 1) build-out of critical infrastructure, e.g., CO_2 pipelines; 2) development of CCUS hubs and clusters; 3) streamlining of the commercial permitting process across the entire region; 4) demonstration of the effectiveness of the business cases for commercial projects, including the identification of the key variables or factors that are impacting the project economics; and 5) improving the acceptance of a commercial CCUS industry by the general public and landowners.

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[1] The authors recognize that they may not have captured every commercial CCUS project in the region that has been announced because of the rapid changes in daily announcements and permit application filings that are occurring, which are not always publicly available in a timely manner.

PATHWAYS FOR THE GROWTH OF THE COMMERCIAL CCUS INDUSTRY IN THE PCOR PARTNERSHIP REGION THROUGH 2034

1.0 BACKGROUND AND OBJECTIVES

Over the last 5 years, several road maps have been published that present pathways for the commercial deployment of carbon capture, utilization, and storage (CCUS) in the United States and Canada (National Petroleum Council, 2019; Global CCS Institute, 2019; Carbon Sequestration Leadership Forum, 2021; and International CCS Knowledge Centre and RSM Canada LLP, 2020).[1] Each of these road maps cites 1) the importance of the rapid deployment of commercial CCUS projects across the globe in achieving the CO_2 emission reduction targets established by the 2015 international treaty on climate change as well as the more recent net-zero emission goals established by many governments; 2) the availability of proven technologies along the entire CCUS supply chain and the need to improve the economics of their commercial deployment; and 3) the challenges associated with the development of effective policy, regulatory, and legal frameworks that will incentivize the implementation of regional and national strategies for growing the CCUS industry. In addition, lessons learned to date have highlighted several barriers to the commercial deployment of the CCUS industry that must be addressed, particularly the build-out of critical infrastructure, e.g., CO_2 pipelines, and the availability of financial incentives such as tax credits and direct government grants.

Major contributions to the technical groundwork that were relied upon for these national and international CCUS road maps were the product of investments that have been made by the U.S. Department of Energy (DOE) over the past 20 plus years, beginning with the formation and continued funding of the Regional Carbon Sequestration Partnerships (RCSPs) from 2003 through 2019 and, more recently, the funding of the Regional Initiatives (a.k.a., the continuation of the RCSPs) in 2019, 2020, and 2021 and the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative, an ongoing multiphase effort focused project development that began in 2016. The large-scale demonstration projects sponsored by the CarbonSAFE Initiative, combined with industry-funded commercial projects, have increased the confidence that CCUS projects with the potential to store 50+ million metric tons (MMt) of CO_2 can be deployed technically and economically. This has been accomplished by improving the understanding of project

[1] The terms "commercial deployment" and "at-scale" deployment have been used somewhat interchangeably in the various road maps. As used by the National Petroleum Council (NPC) (2019), the term "at-scale" deployment refers to achieving the capture and storage of "approximately 500 Mtpa" across the entire United States within the next 25 years; the Global CCS Institute defines large-scale carbon capture and storage (CCS) development as having an annual capture capacity of more than 400,000 metric tons of CO_2 for industrial applications and more than 800,000 metric tons for power generation applications. For the purpose of this report, the term "commercial deployment" is used and refers to the ability of commercial enterprises, such as coal- and natural gas-fired power plants, gas-processing plants, ethanol production plants, etc., to profitably deploy CCUS in the PCOR Partnership region.

screening; site selection and characterization; baseline monitoring, verification, and accounting (MVA) procedures; and facility permitting. As of May 2024, 15 Class VI CO_2 injection wells have been permitted by a combination of the U.S. Environmental Protection Agency (EPA, four) and individual states that have Class VI primacy (11)[2] and 130 Class VI permit applications are pending for 44 projects in 12 states and one tribal reservation[3] (Congressional Research Service, 2024). Over the next 5 years, through the Office of Fossil Energy and Carbon Management (FECM), DOE plans to continue to catalyze the growth and expansion of the CCUS industry within targeted geologic basins in the United States. Substantial additional investments in the CarbonSAFE Initiative are planned to ensure that basinwide storage resources are efficiently and safely utilized during the expansion of the CCUS industry.

Concurrent with these recent national and international initiatives, the Energy & Environmental Research Center (EERC), manager of one of DOE's four ongoing regional initiatives—the Plains CO_2 Reduction (PCOR) Partnership Initiative—has been assisting the commercial growth and expansion of the CCUS industry in the PCOR Partnership region. Beginning in 2022, the EERC has identified and examined business models for the commercial deployment of CCUS in the region; most recently, these investigations are focusing on approaches where multiple facilities/industries collectively pursue commercial CCUS projects through hubs and clusters that integrate shared infrastructure. The results of these efforts are presented in the following three PCOR Partnership reports:

1. CCUS Business Models in the PCOR Region (Peck and others, 2022)
2. Simulation of CCUS Hub Build-Out Scenarios (Beddoe and others, 2023)
3. Regional Business Model Assessment: Part II (Peck and Connors, 2023)

These reports build upon previous examinations of CCUS business models in the PCOR Partnership region to create a path forward through 2034 for the basinwide growth of a commercial CCUS industry. The remainder of this regional road map 1) briefly describes the common themes of the recommendations of the national and international commercial CCUS road maps that have been recently developed for the United States and Canada as well as the 5-year, basin-scale CCUS initiative that is pursued by DOE; 2) provides an overview of the business models that have led to the existing commercial CCUS industry in the region; and 3) presents a path forward for the PCOR Partnership that integrates its regional, basin-specific efforts with the developing national and international initiatives to increase the commercial growth of the CCUS industry in the region through 2034.

2.0 COMMON THEMES OF NATIONAL AND INTERNATIONAL CCUS COMMERCIAL ROAD MAPS

In general, the previously cited national and internationals road maps recognized CCUS as a proven commercial technology, the rapid deployment of which is critical to meeting the CO_2

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[2] To date, three states currently have Class VI primacy, two of which (North Dakota and Wyoming) are in the PCOR Partnership region.
[3] All the permits under review by EPA are in the preconstruction phase at this time.

emission reduction targets and deadlines currently in place for many international and national governments. While these road maps acknowledged that substantial progress has been made over the last one or two decades regarding CCUS and its capabilities, the development of supportive regulatory frameworks, the establishment of financial incentives, and an increased emphasis on stakeholder engagement, they all offered additional recommendations in each of these areas, with the goal of accelerating the growth of the commercial deployment of CCUS. The common themes represented by these recommendations are as follows:

- Perform additional research, development, and demonstration that targets CO_2 capture technology, CO_2 storage technology, nonconventional CO_2 storage (including enhanced oil recovery [EOR]) technology, and CO_2 use technology.

- Rapidly identify, plan, and build out strategic power and industrial CO_2 capture clusters with common CO_2 transportation and storage infrastructure (hubs) to ensure the necessary increase in the application of CCUS to industrial production facilities and power and heat plants, including waste-to-energy plants.

- Increase efforts to build stakeholder confidence by conducting meaningful engagement, simplifying and clarifying outreach messaging, more clearly articulating and demonstrating societal benefits, and increasing the funding of engagement research and education opportunities.

- Develop incentive frameworks, business models, and risk-sharing mechanisms that will enable CCUS projects to be financeable, including placing a value on CO_2 emissions reductions and differentiating between business and financial risks.

- Implement legal, regulatory, and accounting frameworks to ensure the safety and environmental integrity of CO_2 capture, storage, utilization, and transport operations while ensuring regulatory pathways to support the operational aspects of projects.

The road maps also recognized the importance of the continuous transfer of knowledge from existing large-scale projects to new projects, the concept of "learning by doing," and the sharing of best practices as the means to foster cost reduction and help countries and industries grow and expand investments in CCUS.

Consistent with these common themes of the national and international road maps, DOE has initiated efforts to foster the commercial deployment of CCUS at the basin scale. These efforts reflect the fact that the deployment of multiple commercial CCUS projects in a single basin will introduce new challenges to ensure that storage resources at the basin and national scale are efficiently and safely utilized during the anticipated rapid deployment of these commercial projects. To that end, DOE and the U.S. Department of the Interior convened a meeting in Washington, D.C., in February 2024 to identify the challenges facing the growth and expansion of commercial CCUS projects at the basin scale. A summary of these challenges, in the context of the U.S. portion of the PCOR Partnership region, is provided in Figure 1. As shown in this figure, the basin-scale challenges fall into five broad categories: 1) basin-wide modeling, 2) orderly

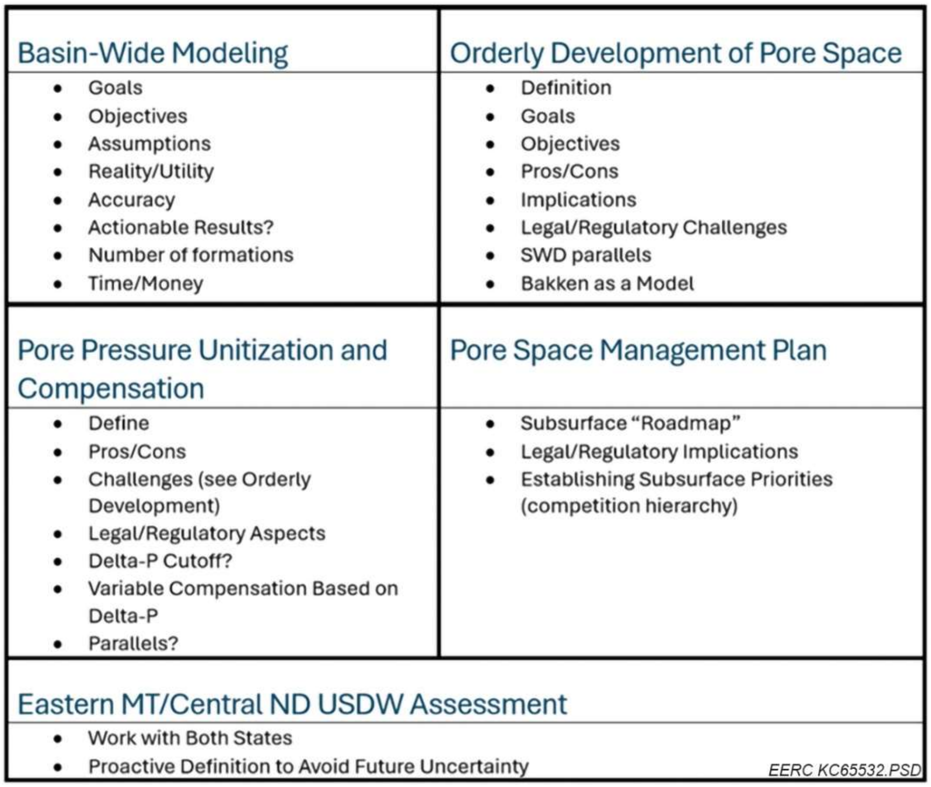

Figure 1. Challenges facing basin-scale deployment of multiple CCUS projects.

development of pore space, 3) pore pressure unitization and compensation, 4) pore space management, and 5) underground source of drinking water (USDW) assessments. It is clear from this summary that pore space management at the basin scale represents a critical area of interest regarding the commercial deployment of multiple CCUS projects within a specific basin.

More specifically, the broad technical basin-scale topics of interest that are being targeted by DOE were articulated in a recent request for information ([RFI] No. DE-FOA-0003262), "Carbon Basin Assessment and Storage Evaluation (CarbonBASE)." These topics included, but were not limited to, the following:

- Models and monitoring systems designed for assessing, forecasting, and predicting basin-scale resource performance and impacts.
- Tools, data, and technologies that stakeholders (e.g., industry, regulators, investors, insurers, federal/state land managers) can use to assess and/or confirm isolation of influences between independent projects or to detect interferences.
- Studies aimed at enhancing the current understanding of basin-scale geomechanical influences.
- Best practices for efficient and safe CO_2 storage resource management at the basin scale.

With the goal of identifying the spectrum of needs regarding the basin-scale effects of CCUS during commercial deployment, the RFI requested responses to the six questions listed in Table 1. Basin-scale considerations have already begun to surface and be addressed in the PCOR Partnership region because of the level of commercial deployment that has occurred and is planned to date within specific geologic basins (see Section 4.0). The EERC responded to this RFI and proposed several specific research topics for incorporation into this road map moving forward. The execution of these research efforts will provide CCUS stakeholders with the data and tools needed to help derisk future government- and industry-sponsored commercial CCUS projects in the region.

Table 1. RFI Questions Regarding Basin-Scale Deployment of Commercial CCUS Projects

Question No.	Question
1	To enhance current understanding and characterization of basin-scale effects, which processes and effects need to be better characterized and at what scale?
2	To facilitate effective and rapid site screening and selection: what type of data and level of data resolution (space and time) would be sufficient?
3	To ensure economical and efficient use of storage resources, what information would be most important as inputs to a tool that could optimize storage efficiency and resource utilization as well as manage/reduce risks?
3.a	What state/federal/regulatory factors or policies need to be considered?
3.b	What outputs would you like such tools to provide?
4	When multiple projects are developed within a basin, what challenges would exist regarding competition for resource utilization?
4.a	What basin management paradigms should be considered?
5	To effectively manage multiple projects in a basin, what would be an adequate basinwide monitoring strategy including for storage in multiple horizons?
5.a	What monitoring parameters would be the highest priority?
5.b	Would monitoring strategies need to consider other activities in multiuse basins (e.g., geothermal, subsurface mining, water disposal, oil and gas operations, etc.)?
6	To facilitate development of the nation's CO_2 storage resources, which basins/regions, including unconventional and offshore, should be targeted for additional characterization to fill data gaps?
6.b	What specific data, geologic or other, should be high priority?

3.0 CURRENT BUSINESS MODELS FOR COMMERCIAL CCUS IN THE PCOR PARTNERSHIP REGION

The PCOR Partnership has identified and discussed several business model frameworks for the CCUS industry (Peck and others, 2022; Beddoe and others, 2023; and Peck and Connors, 2023). These frameworks contain common threads that organize and connect the transactions of an entity seeking to reduce its CO_2 emissions with external parties. With only minor differences, the models define the contractual relationships and drivers between the three main components of the CCUS value chain, i.e., capture, transport, and storage, that will yield acceptable shared risks and returns for all parties (Peck and others, 2022).

The business models fall into one of three frameworks:

- Resource recovery: which focuses on the management of carbon in the production of hydrocarbons, e.g., CO_2 EOR.

- Green growth: which prioritizes CO_2 reductions in support of climate action using CCUS to reduce the carbon footprint of economic activity.

- Low-carbon grid: which emphasizes the value of CCUS as an alternative (or complement) to grid-scale energy storage to enable a lower-cost and more stable grid with high renewables penetration.

Within these frameworks, the contractual relationships across the CCUS value chain include vertically integrated arrangements (integration of the entire value chain within a single company); joint venture arrangements (multiple companies pool their resources to manage the CCUS value chain); or collaboration arrangements involving a capture entity and external service providers, i.e., 1) the CCUS operator model, where a capture entity partners with a third party to handle the CO_2 after it has been captured; transportation of the CO_2 can be associated with either the capture entity or the third-party end user or 2) the CCUS transporter model, where separate entities are responsible for the operating and maintenance costs of each of the three main components of the CCUS value chain. The contractual relationship of choice will vary depending on the characteristics of the commercial project and the various federal and/or state policies that are in place to incentivize the projects. For example, in those instances where the source of CO_2 is close to a CO_2 storage opportunity, the vertically integrated arrangement, where the generator of the CO_2 will likely be the owner of all three of the primary components of the CCUS value chain, will likely be used. However, if the CO_2 must be transported long distances for storage, a collaboration arrangement, where each of the components of the CCUS value chain will be owned by individual entities, might be the preferred arrangement. Other contractual relationships may also be of interest if the 45Q tax credits are to be transferred to another party by the CO_2 generator. In this instance, a different entity may build and own the CO_2 capture facilities in return for both the tax credits as well as any revenues associated with the sales of CO_2 for associated storage during CO_2 EOR. This arrangement could permit the CO_2 generator to reduce, or perhaps even eliminate, the cost penalty associated with the parasitic energy load of the CO_2 capture by selling both steam and electricity to the owner of the CO_2 capture facilities.

Regardless of the business model and contractual relationships that are place, the primary drivers for commercial CCUS projects within the PCOR Partnership region have been tax incentives, e.g., Section 45Q tax credits, investment tax credits, and/or tax penalty avoidance, and product sales, e.g., CO_2 sales, hydrocarbon sales, or sales of lower-carbon-intensity fuels in the LCFS (Low Carbon Fuel Standard) markets of the West Coast. Other potentially significant drivers influencing the business model and contractual relationships in the region, when paired with these tax and sales incentives, are policies that address the management of long-term liability, the UIC (underground injection control) Class VI primacy status of the states, and the increasing impact of ESG (environmental, social, and governance) ratings on the availability of capital for the funding of the projects.

Ultimately, the commercial deployment of CCUS in the PCOR Partnership region from 2024 through 2034 will be based on the revenue potential of the individual projects around which the elements of funding sources, capital sourcing and ownership, and risk management will be structured accordingly.

4.0 COMMERCIAL DEPLOYMENT OF CCUS IN THE PCOR PARTNERSHIP REGION THROUGH 2034

The PCOR Partnership, one of the four ongoing DOE regional initiatives, covers a region comprising over 3.8 million square miles from Missouri to Alaska, including ten states and four Canadian provinces (Figure 2).

Figure 2. Geographic extent of the PCOR Partnership region comprising ten states and four Canadian provinces.

The region is home to abundant and diverse sources of anthropogenic CO_2 (e.g., coal- and gas-fired power plants, gas-processing plants, ethanol plants), excellent geology for CO_2 storage and utilization, a history of CO_2 transport and an expanding pipeline infrastructure, and an established industrial/energy commercial base. The primary targets for CO_2 storage include oil and gas reservoirs and deep saline formations found within several sedimentary basins; the most prominent of these are shown in Figure 3 and briefly described below:

- The Alberta Basin, which is located on the eastern side of the Rocky Mountains in western Canada, extends from British Columbia through Alberta and Saskatchewan into Manitoba.

- The Cook Inlet Sedimentary Basin, which is located from the Gulf of Alaska into Southcentral Alaska, just east of the Matanuska Valley.

- The Denver–Julesberg Basin, which is located in northeastern Colorado, southeastern Wyoming, and parts of Nebraska, South Dakota, and Kansas.

- The Greater Green River Basin, which occupies the Central Rocky Mountains in southwest Wyoming, northeast Utah, and northwest Colorado.

- The North Slope Basin, which is bounded on the north by the Beaufort Sea and runs from the Canadian border to the maritime boundary with Russia in the west.

- The Williston Basin, which lies along the eastern edge of the Rocky Mountains in western North Dakota, eastern Montana, and southern Saskatchewan, Canada.

- The Power River Basin, which is in southeast Montana and northeast Wyoming.

For over a decade, working with over 250 industry and government partners, the focus of the PCOR Partnership has been the integration of CCUS into the existing commercial industries within the region. These PCOR partners represent key industrial sectors with a stake in CCUS deployment; numerous state, regional, and federal governmental research entities; and several state and federal regulatory agencies. Over this same period, multiple outreach initiatives have also been implemented by the PCOR Partnership and its public and private sector stakeholders to foster the public acceptance of commercial CCUS.

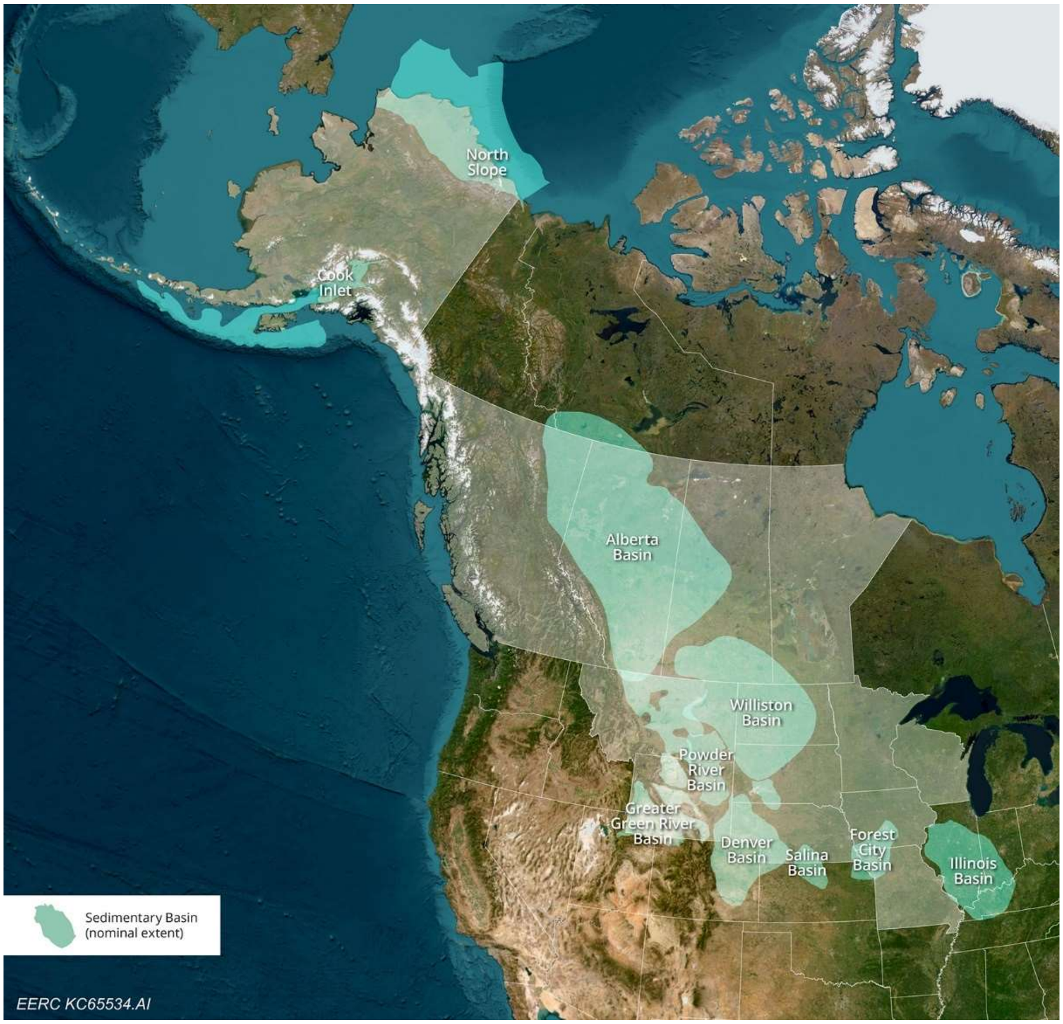

Figure 3. Major regional sedimentary basins in the PCOR Partnership region.

Additionally, federal/state policies and regulations have evolved which have provided a clearer path and timeline for advancing commercial CCUS projects. Specific examples include the 45Q federal tax credits, which have improved the potential economics of many CCUS projects, as well as EPA approval of Class VI primacy applications for two states within the region, i.e., North Dakota and Wyoming, to permit and regulate the Class VI injection wells used for the geologic storage of CO_2.[4] Equally important, as of April 24, 2024, the urgency for commercially deploying CCUS in the region, and across the entire United States, increased as EPA published its final carbon pollution standards for existing coal-fired and new gas-fired power plants.[5] The rule, which

[4] The state if Louisiana is the third state in the United States to receive primacy; however, it does not lie within the PCOR Partnership region.
[5] New Source Performance Standards for Greenhouse Gas Emissions from New, Modified, and Reconstructed Fossil Fuel-Fired Electric Generating Units; Emission Guidelines for Greenhouse Gas Emissions from Existing Fossil Fuel-Fired Electric Generating Units; and Repeal of the Affordable Clean Energy Rule: 89 Federal Register, p. 39798–40064 (to be codified at 40 Code of Federal Regulations [CFR] 60), May 9, 2024.

becomes effective on July 8, 2024, requires all coal-fired plants intending to operate past 2039 and all new baseload gas-fired plants to employ the best system of emissions reduction (BSER) to control 90% of their carbon emissions based on CCS. With the release of these standards, EPA characterized CCS as an "available and cost-effective control technology that can be directly applied to power plants," recognizing it as a "proven add-on control technology" that represents the "best system of emission reduction (BSER), taking into account costs, energy requirements, and other statutory requirements." EPA proposes that these standards and the installation of the necessary controls be phased in over time during the period of 2030–2032. Additional pressure on the commercial deployment of CCUS in the region is also being applied by some of the individual states within the region as the governors of both North Dakota and Wyoming have proclaimed that their states will achieve "net-zero" carbon emissions within a similar time frame. In addition, the Canadian Zero Accountability Act of 2021 enshrines in legislation a commitment to achieve a 40% reduction in greenhouse gas emissions below the 2005 emission levels by 2030 and net-zero emissions by 2050.[6] The commercial deployment of CCUS is a critical component of meeting these state and federal government proclamations.

Future commercial deployment of CCUS in the PCOR Partnership region will build upon the existing commercial project base that has evolved over the past 20 plus years by facilitating the deployment of the commercial CCUS projects that have been announced and are currently in the planning stages in the region and by further exploring the more nascent commercial opportunities that are evolving over time. Figure 4 provides an overview of the currently active/operating and partially permitted commercial CCUS projects in the region along with the commercial projects that have been announced at this time.[7] In total, 56 projects, comprising 17 active/operating projects, four partially permitted projects, and 35 announced projects, are identified in Figure 4. The remainder of this section provides an overview of the status of commercial development in the region to date and the commercial projects that have been announced and are currently in the planning stage; some of the more speculative future commercial opportunities that are possible in the foreseeable future are also briefly noted.

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[6] www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html (accessed May 2024).

[7] "Partially permitted" projects refer to the fact that CCUS projects in North Dakota and Wyoming require both a storage facility permit (SFP) or permit to construct, respectively, as well as a permit to inject before CO_2 injection can begin. To operate a commercial project, both permits must have been approved; projects that only have the first-phase permit in-hand have been designated as "partially permitted" projects. Additionally, "announced" projects are in varying stages of planning, ranging from conceptual plans to completion of front-end engineering and design (FEED) studies to filing Class VI permits.

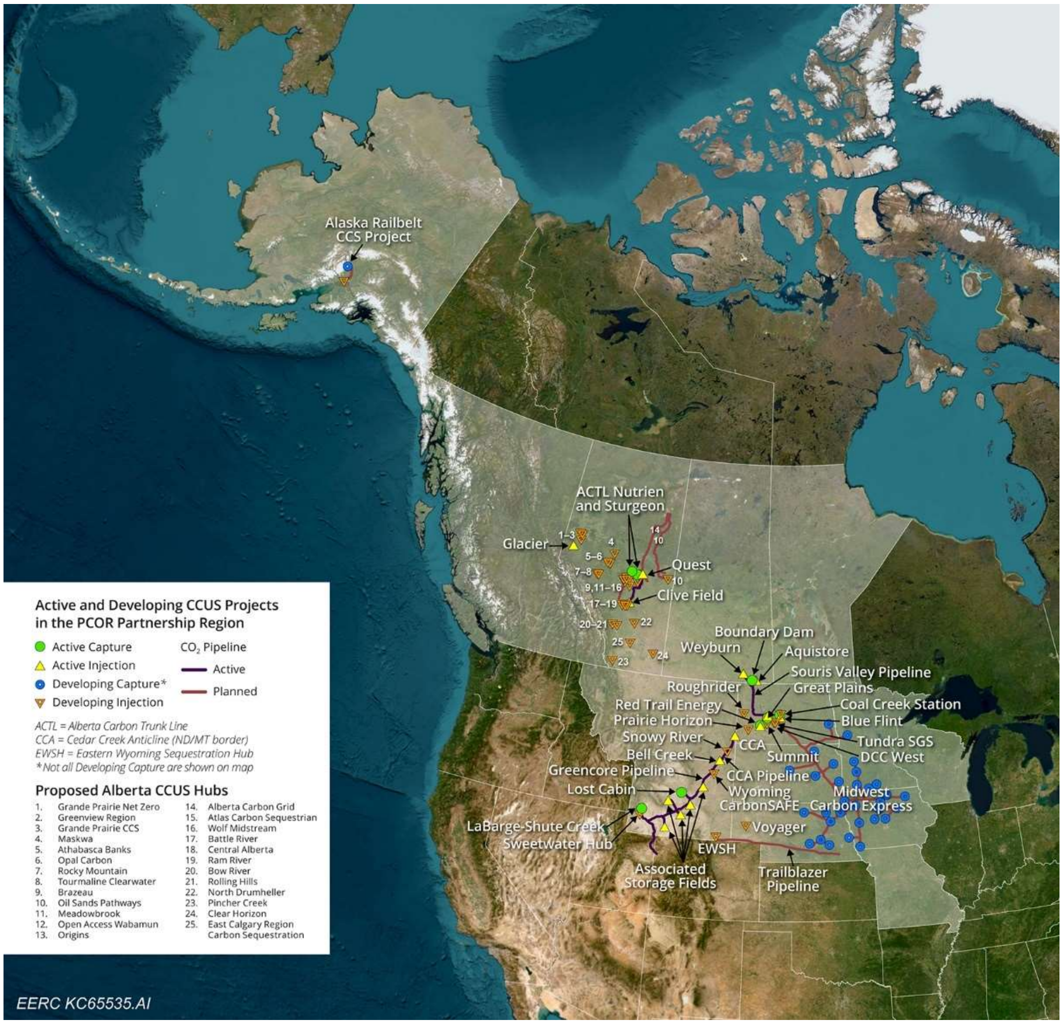

Figure 4. Active/operating, partially permitted, and announced commercial CCUS projects in the PCOR Partnership region.

4.1 Active/Operating and Partially Permitted Commercial CCUS Projects in the PCOR Partnership Region

The 17 active and four partially permitted commercial CCUS projects in the PCOR Partnership region to date are shown in Figure 5. The basic characteristics of these projects are summarized in Table 2; more detailed descriptions of these projects are provided in Appendix A.

Figure 5. Active/operating and partially permitted CCUS projects in the PCOR Partnership region.

Table 2. Basic Characteristics of Active/Operating and Partially Permitted Commercial CCUS Projects in the PCOR Partnership Region

No.	State/ Province	Project Name	Owner/ Operator	CO_2 Source	CO_2 Source Type	Storage Type	Injection Rate	Storage Capacity	Operating	Partially Permitted	Announced
OPERATING/ACTIVE PROJECTS											
CANADA											
1	AB	Alberta Carbon Trunk Line (ACTL)[8] Clive CCUS[9]	Enhance Energy, Wolf Midstream	NWR Sturgeon Refinery and Nutrien Redwater Fertilizer[10]/other	Bitumen refinery and ammonia (fertilizer)/ other	Associated/ storage hub	14.6 MMta	TBD	X		
2	AB	Glacier Project	Entropy	Advantage Glacier Gas Plant	Natural gas processing	Dedicated storage	~0.2 MMta[11] (combined phases)	TBD	X		
3	AB	Quest CCS Project	Shell Canada Energy	Shell Scotford Upgrader	Oil refinery	Dedicated storage	~1.0 MMta[12] (2022: 7.7 MMt captured)	>27 MMt[13] (25 years)	X		
4	SK	Aquistore Deep Saline CO_2 Storage Project	Petroleum Technology Research Centre	Boundary Dam Power Station	Lignite-fired	Dedicated storage	Varies	~585 MMt (02/2024)	X		
5	SK	Boundary Dam CCS Facility and Associated CO_2 Storage at Weyburn[14]	Whitecap Resources	Boundary Dam Power Station	Lignite-fired	Associated storage	~1.7 MMta	TBD	X		

Continued . . .

[8] https://wolfmidstream.com/carbon/ (accessed May 2024).
[9] https://enhanceenergy.com/our-operations/ (accessed May 2024).
[10] www.nutrien.com/what-we-do/stories/advancing-carbon-solutions-and-reducing-emissions-redwater (accessed May 2024).
[11] www.carbonexpocanada.com/media/9933/entropy-presentation.pdf (accessed May 2024).
[12] https://open.alberta.ca/dataset/356aeeda-134c-4779-971c-931573400ddf/resource/8a1b4350-9634-4e66-a983-8c16199fa2e7/download/quest-annual-summary-report-2022-alberta-department-of-energy.pdf (accessed May 2024) (0.974 Mt in 2002).
[13] Quest | Global Carbon Capture and Storage Institute. www.globalccsinstitute.com (accessed May 2024).
[14] www.wcap.ca/sustainability/co2-sequestration (accessed May 2024).

Table 2. Basic Characteristics of Active/Operating and Partially Permitted Commercial CCUS Projects in the PCOR Partnership Region (continued)

No.	State/ Province	Project Name	Owner/ Operator	CO_2 Source	CO_2 Source Type	Storage Type	Injection Rate	Storage Capacity	Operating	Partially Permitted	Announced
OPERATING/ACTIVE PROJECTS (continued)											
CANADA (continued)											
6	SK// ND	Great Plains Synfuels Plant and Associated CO_2 Storage at Weyburn–Midale	Dakota Gasification Company	Great Plains Synfuels Plant	Lignite	Associated storage	~ 2.0 MMta	TBD	X		
UNITED STATES											
7	MT	Bell Creek EOR Project	Denbury Inc.	Shute Creek/ Lost Cabin (WY)	Gas processing	Associated storage	0.94 MMta	TBD	X		
8	ND	Blue Flint CO_2 Storage Project	Blue Flint Sequester Company, LLC	Blue Flint Ethanol	Ethanol production	Dedicated storage	0.2 MMta	4.0 MMt (20 years)	X		
9	ND	Cedar Creek Anticline, North Dakota	Denbury Inc.	Shute Creek/ Lost Cabin (WY)	Gas processing	Associated storage	> 1 MMta	TBD	X		
10	ND	Great Plains Sequestration Project	Dakota Gasification Company	Great Plains Synfuels Plant	Lignite	Dedicated storage	1.0 MMta to 2.7 MMta	26 MMt[15] (~12 years)	X		
11	ND	Red Trail Energy Project	Red Trail Energy LLC	Red Trail Energy	Ethanol production	Dedicated storage	0.18 MMta	3.6 MMt (20 years)	X		
12–17	WY	Greencore Pipeline Associated Storage Fields	Various	Lost Cabin and Shute Creek	Gas processing	Associated storage	Various	TBD	X (6)		

Continued . . .

[15] www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/DGC/C29450.pdf (accessed May 2024).

Table 2. Basic Characteristics of Active/Operating and Partially Permitted Commercial CCUS Projects in the PCOR Partnership Region (continued)

No.	State/ Province	Project Name	Owner/ Operator	CO_2 Source	CO_2 Source Type	Storage Type	Injection Rate	Storage Capacity	Operating	Partially Permitted	Announced
PARTIALLY PERMITTED PROJECTS											
UNITED STATES											
18	ND	Dakota Carbon Center West SGS (Secure Geologic Storage) Project	DCC West Project LLC	Milton R. Young Station, other	Lignite, other	Dedicated storage	6.11 MMta	122.9 MMt (20 years)		X	
19	ND	Tundra SGS /North Dakota CarbonSAFE (Broom Creek Formation)	DCC East Project LLC	Milton R. Young Station	Lignite	Dedicated storage	4.3 MMta	86 MMt (20 years)		X	
20	ND	Tundra SGS/North Dakota CarbonSAFE (Deadwood Formation)	DCC East Project LLC	Milton R. Young Station	Lignite	Dedicated storage	1.17 MMta	23.4 MMt (20 years)		X	
21	WY	Sweetwater Carbon Storage Hub	Frontier Carbon Solutions	Multiple	Industrial, direct air capture (DAC)	Dedicated/ storage hub	5 MMta	100 MMt (20 years)		X	

As shown in Table 2:

- Eleven of the active CCUS commercial projects store CO_2 concurrently with the production of oil, i.e., associated storage, during CO_2 EOR, with eight of the associated storage sites located in the United States and three located in Canada.[16] The remaining six active commercial projects use dedicated storage sites, three of which are located in the United States and three in Canada.

- The four partially permitted commercial CCUS projects are located in the United States and are targeting the dedicated storage of CO_2. Three of these dedicated storage projects are in North Dakota and are capturing CO_2 from a coal-fired power plant; the remaining dedicated storage project, which is located in Wyoming, is part of a carbon storage hub that will provide carbon storage for key industrial emitters across the Mountain West and direct air capture (DAC) partners.

The first of these active commercial CCUS projects was initiated in the late 1980s by gas-processing plants that captured CO_2 for transport and use in CO_2 EOR; however, these operations were not optimized to maximize the storage of CO_2. Moving forward in time, the capture of CO_2 from these and similar facilities continued to increase but with more attention on process optimization, which focused on a combination of CO_2 utilization, oil production, and CO_2 storage. Other sources of captured CO_2 that appeared in the region over this time included coal gasification plants, ethanol production plants, oil and bitumen refineries, and coal-fired power plants. Ethanol production plants and coal-fired power plants have dominated the recent landscape in the United States, whereas Canada has emphasized both coal-fired power plants and other industrial sources such as oil and bitumen refineries and ammonia production.

To support these commercial projects, there is approximately 6000 miles (>9600 km) of existing pipelines in the region with a primary focus on delivering CO_2 for CO_2 EOR, e.g., the Souris Valley Pipeline delivering CO_2 from North Dakota to the Weyburn–Midale oil fields in southern Saskatchewan; the Salt Creek/Greencore pipeline in Wyoming delivering CO_2 to CO_2 EOR fields in Wyoming, southeastern Montana, and southwestern North Dakota; and Alberta Carbon Trunk Line (ACTL) near Edmonton, Alberta, delivering CO_2 from North West Redwater Partnership (NWR) Sturgeon Refinery and Nutrien Redwater Fertilizer to CO_2 EOR fields near Clive, Alberta.

4.2 Announced Commercial CCUS Projects in the PCOR Partnership Region: 2024–2034

To date, 35 commercial CCUS projects comprising 25 projects in Canada and 10 projects in the United States have been announced in the PCOR Partnership region (Figure 6), with many of these slated to begin construction or injection operations by 2034. Unlike the commercial development to date, this next generation of commercial CCUS projects in the PCOR Partnership

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[16] One of the Canadian storage sites is part of a cross-border project where the CO_2 is captured at the Great Plains Synfuels Plant in the United States and transported via pipeline to Canada for CO_2 EOR in the Weyburn–Midale oil fields.

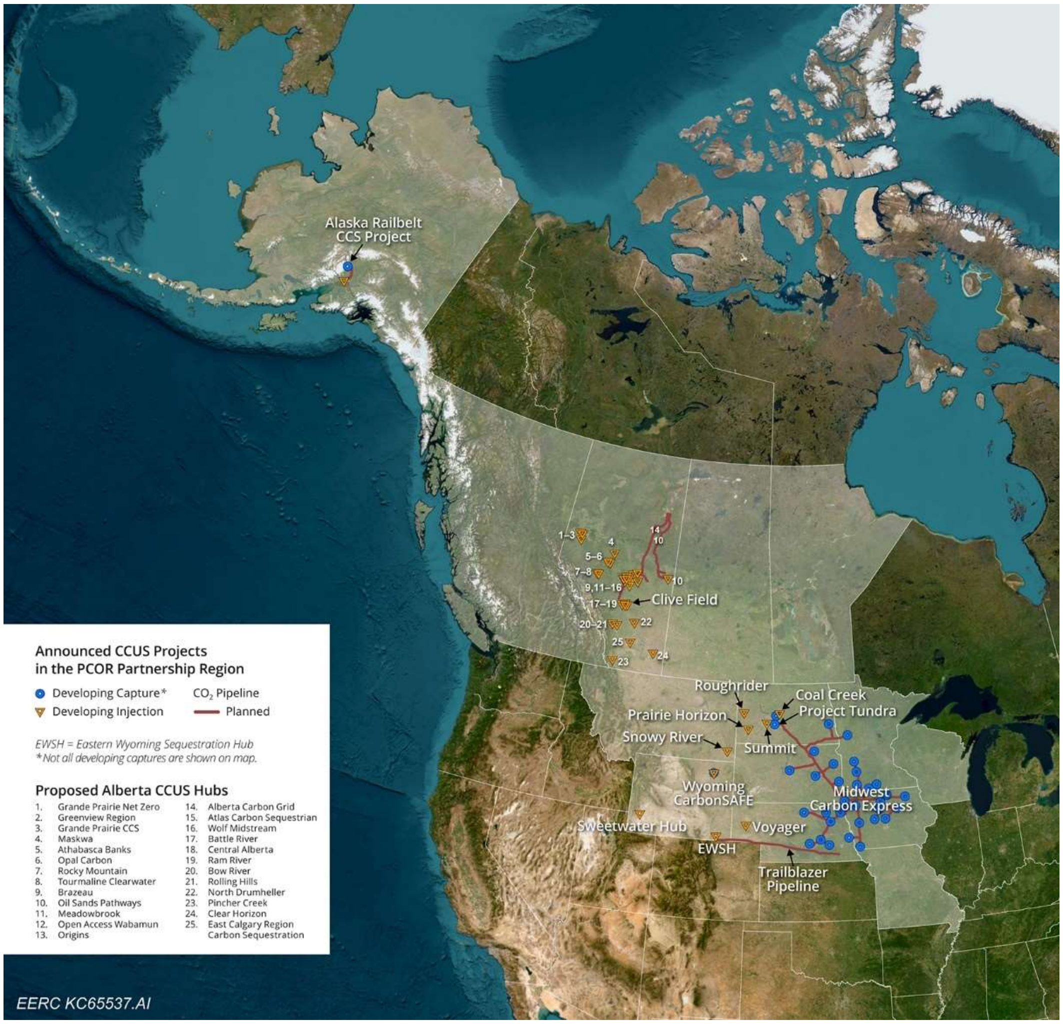

Figure 6. Announced commercial CCUS projects in the PCOR Partnership region.

region is dominated by the dedicated storage of CO_2. This shift in commercial activity to dedicated storage has been occurring in the U.S. portion of the region largely because of the investments of the federal government (i.e., the DOE CarbonSAFE projects and the funding provided by the Infrastructure Investment and Jobs Act, otherwise known as Bipartisan Infrastructure Law) and the 2022 enhancements to the 45Q tax credits, which are greater for dedicated storage (Connors and others, 2023). Another driving force in the region is the movement in Canada to develop a hydrogen economy which requires a rapid scale-up of the production of blue hydrogen. The basic characteristics of these announced projects are summarized in Table 3; more detailed descriptions of these projects are provided in Appendix B.

The shift toward dedicated storage over associated storage is evident in Table 3, where all the announced projects are focused on dedicated storage. At the same time, there is also a significant emphasis on the development of CO_2 "storage hubs" across the entire region.[17]

[17] CO_2 storage hubs are designated pore space areas managed by an operator that can effectively plan and enable CO_2 sequestration of captured CO_2 from various emissions sources.

Table 3. Basic Characteristics of Announced Commercial CCUS Projects in the PCOR Partnership Region

No.	State/ Province	Project Name	Owner/ Operator	CO_2 Source	CO_2 Source Type	Storage Type	Injection Rate	Storage Capacity	Operating	Partially Permitted	Announced
ANNOUNCED PROJECTS – CANADA											
1–23	AB	Alberta Development of Carbon Storage Hubs: Rounds 1 and 2	Various	Various	Various	Various	Various	Various			X (23)
24	AB	Alberta Carbon Grid[18]	TC Energy Corporation, Pembina Pipeline Corporation	Multiple		Dedicated/ storage hub	~20.0 MMta	TBD			X
25	AB	Oil Sands Pathways to Net Zero aka Pathways CO_2 Transportation Network and Storage Hub Project[19]	Pathways Alliance[20]	Multiple	Oil sands	Dedicated/ storage hub	~10–12 MMta	TBD			X
ANNOUNCED PROJECTS – UNITED STATES											
26	AK	Alaska Railbelt CCS Project	State of Alaska	Chugach Electric Association: George Sullivan Plant 1, Southcentral Power Project/ new build[21]	Natural gas	Dedicated storage	TBD	≥50 MMt (≤30 years)			X
27	MT	Snowy River CO_2 Sequestration Project[22]	Denbury Carbon Solutions, LLC	Shute Creek/ Lost Cabin (WY)	Gas processing	Dedicated storage	TBD	136 MMt			X

Continued . . .

[18] www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2022/market-snapshot-new-projects-alberta-could-add-significant-carbon-storage-capacity-2030.html (accessed May 2024).
[19] https://pathwaysalliance.ca/foundational-project/regulatory/ (accessed May 2024).
[20] www.rbccm.com/en/insights/story.page?dcr=templatedata/article/insights/data/2023/02/meet_the_pathways_alliance#:~:text=Pathways%20will%20be%20executed%20via,finishing%20the%20job%20by%202050 (accessed May 2024).
[21] https://static1.squarespace.com/static/59f229bd2aeba5312c87df44/t/65ef6eceb9b27d3c6118433e/1710190289944/doe-proposal.pdf (accessed May 2024).
[22] https://eplanning.blm.gov/public_projects/2026556/200564713/20086275/250092457/1_Snowy%20River%20CO2%20Sequestration%20Plan%20of%20Development_508.pdf (accessed May 2024) (150 million tons = 136 MMt).

Table 3. Basic Characteristics of Announced Commercial CCUS Projects in the PCOR Partnership Region (continued)

No.	State/ Province	Project Name	Owner/ Operator	CO_2 Source	CO_2 Source Type	Storage Type	Injection Rate	Storage Capacity	Operating	Partially Permitted	Announced
ANNOUNCED PROJECTS – UNITED STATES (continued)											
28	NE	Voyager[23]	Carbon America, Voyager Sequestration LLC, Bridgeport Ethanol LLC	Bridgeport Ethanol	Ethanol production	Dedicated storage	0.175 MMta	TBD			X
29	ND	Coal Creek Capture Project: Site Characterization and Permitting	Rainbow Energy Center	Coal Creek Station	Lignite	Dedicated storage	~9 MMta	~200 MMt (22 years)			X
30	ND	Midwest Carbon Express (MCE) Project	Summit Carbon Storage #1, LLC	Multiple (ND, SD, IA, MN, NE)	Ethanol production/ Other	Dedicated/ storage hub	~6.22 MMta	~124.4 MMt (20 years)			X
31	ND	MCE Project	Summit Carbon Storage #2, LLC	Multiple (ND, SD, IA, MN, NE)	Ethanol production/ Other	Dedicated/ storage hub	~4.92 MMta	~98.3 MMt (20 years)			X
32	ND	MCE Project	Summit Carbon Storage #3, LLC	Multiple (ND, SD, IA, MN, NE)	Ethanol production/ Other	Dedicated/ storage hub	~6.49 MMta	~129.7 MMt (20 years)			X
33	ND	Prairie Horizon Hydrogen Hub FEED & Design	Prairie Horizon Energy Solutions	Dickinson Renewable Diesel Facility	Renewable diesel processing	Dedicated/ storage hub	TBD	~100 MMt			X
34	ND	Roughrider Carbon Storage Hub	ONEOK, Inc.	Lonesome Creek, Cerilon/ multiple (ND)	Gas processing/ gas to liquids	Dedicated/ storage hub	TBD	≥50 MMt (≤30 years)			X
35	WY	Wyoming CarbonSAFE	Basin Electric Power Cooperative	Dry Fork Station	Coal	Dedicated storage	TBD	≥50 MMt (≤30 years)			X

[23] https://ccusmap.com/markers/project-detail/voyager (accessed May 2024).

As shown in Table 3, this development is driven in the United States by ethanol production facilities. These facilities, which are relatively small emitters of CO_2, are moving toward the sharing of critical infrastructure, such as CO_2 pipelines and storage operations, as a means of cost-effectively storing CO_2 and producing ethanol that meets the LCFSs of the West Coast. In Canada, the province of Alberta is leading the way on the development of CO_2 storage hubs as part of its hydrogen road map. Alberta has introduced the concept of CO_2 storage hubs and put a process in place where companies can apply to the government for the right to inject CO_2 while ensuring open and affordable access is provided for use of the hub. Alberta is allocating carbon sequestration rights through a competitive process. To date, as part of this carbon sequestration tenure management process, six evaluation agreements were awarded by the provincial government in March 2022, with a focus on the decarbonization of the Industrial Heartland emitters around Edmonton; an additional 19 evaluation agreements were awarded in October 2022 to address the areas outside of the Industrial Heartland area. While there is no guarantee that all these agreements will move forward, the use of this approach has many advantages including the collaboration that it fosters for the decarbonization of industrial hubs as well as the increased efficiency and lowering of the costs of pore space use. These benefits have the potential to facilitate the growth of CCUS commercial deployment at the basin scale and throughout the PCOR Partnership region.

Pipeline development efforts are a critical component of infrastructure required to support carbon storage hubs such as those proposed in PCOR Partnership region (Figure 6). Efforts in the region are in place to investigate this potential barrier to commercial deployment at both an individual project level and on a more regional scale, including the potential to extend the efforts of the state of Wyoming, which has designated CO_2 pipeline corridors under the Wyoming Pipeline Corridor Initiative, to lay the groundwork for CCUS project expansion across the entire region.

In summary, this next round of commercial CCUS deployment in the PCOR Partnership region will focus on the development of carbon storage hubs and the deployment of CO_2 pipelines as a critical component of the infrastructure required for this approach to commercial growth and expansion. Storage hubs also have the advantage of facilitating pore space management at the basin scale, a major concern of DOE, as more and more projects begin to compete for pore space within those basins that offer the best geologic opportunities for CO_2 storage. A mixture of dedicated and associated storage will continue to be developed, although the current tax policies are clearly contributing to an increase in interest in dedicated storage over associated storage in contrast to the past commercial activity in the region (Section 4.1).

Moving forward, CO_2 capture at coal- and natural gas-fired power plants is likely to increase across the region as the recent EPA regulations are implemented. At the same time, CO_2 capture at gas-processing facilities will likely continue to grow as these facilities expand, as will CO_2 capture and storage at ethanol facilities, given the combined incentives associated with meeting the LCFSs of the West Coast and the current 45Q tax credits. The driving force in Canada is likely to be its shift to a hydrogen economy, which will focus on the production of blue hydrogen from the natural gas reserves of Alberta.

4.3 Potential Future Commercial CCUS Opportunities in the PCOR Partnership Region

Other potential, but more speculative, commercial CCUS opportunities have been identified for the region over the time horizon of this road map. To date, the following types of commercial CCUS projects are deemed possible and are being explored for commercial deployment:

- Direct ambient air capture of CO_2 followed by its conversion into synthetic fuels in Canada.
- CO_2 capture from gas-processing plants in Alaska followed by pipeline transport for associated storage during CO_2 EOR on the North Slope.
- CO_2 capture from multiple ethanol plants in Iowa, Minnesota, Nebraska, North Dakota, and South Dakota followed by pipeline transport for utilization and/or dedicated geologic storage in saline aquifers (including stacked storage) in the Williston and Denver–Julesberg Basins.
- Installation of key commercial CO_2 pipelines to facilitate the anticipated growth and expansion of a commercial CCUS industry.

Other than DAC, these potential future commercial CCUS projects include the use of known capture and storage technologies; however, their application in challenging environments, i.e., Alaska, and the viability of the business model for combining the CO_2 captured from multiple ethanol plants for transport through a common pipeline to a CO_2 storage hub require further investigation. In addition, the full implementation of the recently promulgated New Source Performance Standards for Greenhouse Gas Emissions from New, Modified, and Reconstructed Fossil-Fuel Fired Electric Generating Units, combined with any new policy and/or financing incentives that are put in place, may result in the evolution of other viable business models to advance the commercialization of CCUS in the region.

5.0 CHALLENGES/OPPORTUNITIES ASSOCIATED WITH THE CONTINUATION OF THE COMMERCIAL GROWTH OF CCUS IN THE PCOR PARTNERSHIP REGION

It is evident from Section 4.1, the commercial deployment of CCUS has been in progress for many years. The first 30 years of this deployment was largely organic, predominantly relying on a resource recovery business model with collaboration arrangements for either the transportation or storage operators or both. Toward the end of that period, the green growth and low-carbon grid business models began to materialize. The former evolved as a market and began to develop on the West Coast for low-carbon fuels, such as ethanol produced from plants outfitted with CCUS, and blue hydrogen was produced to convert Canadian oil sands bitumen into synthetic crude for refining into fuels and other products. Other blue hydrogen projects involving a refinery and fertilizer plant were also spawned in Canada, serving as anchor projects for the ACTL system that transports the captured CO_2 to CO_2 EOR operations. Lastly, Unit 3 of SaskPower's Boundary Dam coal-fired power plant installed a fully integrated postcombustion CCUS facility, making it the only CCUS facility operating on a coal-fired power plant at that time. The CCUS operation projected a 90% capture rate of CO_2 emissions, extending the life of the plant by 30 years.[24]

Another indication of the current commercial CCUS activity in the region is the number of approved Class VI permits. For example, in addition to the three operating dedicated storage projects identified in the U.S. portion of the PCOR Partnership region, an additional four commercial dedicated storage projects have been permitted to store CO_2 (three in North Dakota and one in Wyoming). These approved projects range from single-source with nearby single injector (Red Trail Energy) to large-volume sources with multiple injection wells (Dakota Gasification Company). At the time of this report, Summit Carbon Solutions has three pending storage permits in North Dakota and multiple pending CO_2 pipeline routing permits for a project targeting the aggregation of multiple sources, transporting CO_2 via multistate pipeline network, and utilizing multiple Class VI injection wells. In addition, North Dakota and Wyoming both require storage units and pore space access to be addressed at the time of permitting. To date, the seven approved projects consist of 11 Class VI injection well permits; eight Class VI permits have been issued in North Dakota and are actively injecting, and three Class VI well permits have been approved in Wyoming.

This pattern of commercial deployment of CCUS projects demonstrates the technical readiness of CCUS technology as well as the ability to secure permits for its construction and operation in the PCOR Partnership region. However, the recent urgency of the trend toward deep decarbonization to meet power sector regulations and net-zero emission targets as early as 2035 requires a more rapid commercial growth and expansion of CCUS.

5.1 Commercial Roadblocks and Hurdles to the Growth of CCUS

Based on a review of the barriers to the commercial deployment of CCUS presented in the road maps identified in Section 2.0 of this document, the primary roadblocks and hurdles for achieving the commercial growth and expansion of CCUS that is required for the deep decarbonization of the PCOR Partnership region can generally be grouped into the following four categories: 1) government/regulatory, 2) technical, 3) financial/market, and 4) public perception. These four categories are interconnected. For example, removing roadblocks/hurdles to reduce permitting costs and timelines will improve the financial viability of projects which, in turn, would lead to further commercial deployment. Additional commercial applications would improve the understanding of the technology through the process of "learning by doing" and result in even further reductions of cost. Successful commercial operations would also increase the confidence of the public in the use of CCUS. The previous success of the commercial deployment of emissions control technologies for sulfur and nitrogen oxides provides evidence that such learning-by-doing cost reductions are possible for CCS technologies as well (Rodes and others, 2023).

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[24] It should be noted that SaskPower's Boundary Dam project listed in Table 2 had the ability to store CO_2 in either dedicated or associated storage to provide operating flexibility, e.g., periods when the offtake of the CO_2 by the oil field does not require all the CO_2 that is captured.

Some examples of solutions to overcoming the roadblocks/hurdles in each of the above categories have been identified as follows (U.S. Department of Energy and U.S. Energy Association, 2020):

Technical

- Expand the funding of research and development of advanced CCUS technologies such as catalysts, chemical looping, membranes, and solvents.

Government/Regulatory

- Make legislative and regulatory changes that accelerate the build-out of CO_2 pipelines, e.g., expediting CO_2 pipeline permitting and development.

- Address Class VI permitting cost and timeline challenges by:

    1. Developing an expedited process for delegating primacy to states given that EPA may not have the resources to manage an influx of Class VI applicants.

    2. Allowing area permits for multiple CO_2 injection wells instead of requiring permits for individual wells.

    3. Moving to site-specific, risk-based assessments of Class VI wells similar to the statutory standards imposed by the Safe Drinking Water Act (SDWA).

    4. Basing closure of a carbon storage facility on a demonstration of a stable CO_2 plume and modifying or eliminating the 50-year postinjection site care period.

    5. Allowing monitoring flexibility by emphasizing indirect monitoring over direct monitoring (i.e., dedicated monitoring well[s]), which would drive technology innovation, minimize the potential for creating possible leakage pathways, and potentially reduce project costs.

    6. Allowing UIC Class V permits for CCUS demonstration projects.

    7. Allowing for new aquifer exemptions and the use of existing aquifer exemptions for Class VI injection.

Financial/Market

- Establish a means of assigning the tax credits for those that capture the CO_2 to those parties that store or utilize the CO_2 in permitted applications.

- Provide loan guarantees to project investors and cost-sharing of FEED studies.

Public Perception

- Focus efforts on strategies to gain public acceptance for the full CCUS value chain (e.g., CO_2 pipeline infrastructure).

- Show economic benefits and value (e.g., job creation and retention, new economic opportunities, the development and sale of low-carbon marketable products) of CCUS at the local, state, and regional levels.

- Provide fact-based, science-based information on safe transport and storage, how CCUS can contribute to local and state economies, as well as the potential benefit for monetizing pore space resources.

The investigation of various aspects of these solutions is already in progress within the PCOR Partnership region. For example, both North Dakota and Wyoming have already been granted Class VI primacy by EPA, and efforts to create a well-defined permitting process and reporting templates for CCUS projects based on the permits which have been submitted and approved to date and are under consideration. As part of the current permits, North Dakota has permitted projects by addressing pore space property rights through unitization (for associated storage through CO_2 EOR) and amalgamation (for dedicated storage) and has established provisions for the transfer of regulatory responsibility for long-term caretaker and monitoring of a closed site starting at 10 years postinjection. In addition, the PCOR Partnership has performed life cycle analyses of selected CCUS commercial operations using state-of-the-art conventions established by the DOE National Energy Technology Laboratory (NETL); is advancing the use of risk-based approaches for establishing the area of review (AOR) for Class VI permitting; and, through the Wyoming Pipeline Corridor Initiative, is investigating strategies associated with expanding the rights of way (ROWs) for CO_2 pipelines on private, state, and Bureau of Land Management (BLM)-managed lands in the state of Wyoming.

At the same time, three of the states within the PCOR Partnership region (North Dakota, Wyoming, and Montana) also have in place tax incentive programs to complement the federal 45Q tax credits. These incentives include state tax credits as well as exemptions for an array of taxes, such as property taxes, severance taxes, gross receipt taxes, and sales taxes (U.S. Department of Energy and U.S. Energy Association, 2020).

5.2 Continuation of the Growth of the Commercial Deployment of CCUS in the PCOR Partnership Region

An "all of the above" approach is needed to tackle the rapid decarbonization of the world's economy. Given the goal of decarbonization, high reliability, and low cost, CCUS-mitigated fossil fuels are an existing solution that must be supported both nationally and within the PCOR Partnership region to address the gap that remains between projected CO_2 reductions and the publicly stated goals of political leaders (Rodes and others, 2023).

Building on the current commercial efforts (Section 4.1), the pace of the growth and expansion of the commercial deployment of CCUS in the PCOR Partnership region will be increased, to the extent possible, to maximize its contribution to achieving the current decarbonization objectives of the region over the 10-year period from 2024 through 2034. This will be done by 1) facilitating the deployment of the current commercial CCUS projects that are in the planning stages (Section 4.2) and 2) more thoroughly investigating and addressing the regional knowledge gaps in several areas, including the capture of CO_2, advanced geologic characterization of onshore carbon storage, targeted characterization of associated storage from conventional and unconventional CO_2 EOR, active reservoir management, regional pipeline infrastructure, and risk assessment and management tools. These efforts will be implemented keeping in mind the following guiding principles provided by Rodes and others (2023) for large-scale CCS development: 1) adopting a portfolio approach to development, 2) encouraging development of a supporting infrastructure, 3) recognizing the value of information and mitigating uncertainty, 4) acknowledging the absence of firm legislative guidance, 5) affirming the roles of multiple stakeholders, and 6) ensuring that basic research can maintain a concurrent track with commercial development.

5.2.1 Facilitating the Deployment of Announced Commercial CCUS Projects

The announced commercial CCUS projects for the PCOR Partnership region (Section 4.2) represent several targeted opportunities for advancing the commercial operations within the region. As discussed, these opportunities are driven by a variety of business models that focus on different objectives such as the production of hydrocarbons (resource recovery), the desire to reduce the carbon footprint of economic activity (green growth), or the ability to create a lower-cost, resilient, and reliable electric grid with high renewables penetration (low-carbon grid). Targeting the deployment of the announced commercial projects through 2034 has the potential to significantly expand the current commercial CCUS base in the region as well as increase its commercial deployment of the industry beyond that time frame by:

- Further demonstrating that the CCUS value chain of carbon capture, transportation, and storage has achieved the technology readiness level required for commercial deployment at the basin scale and beyond.

- Demonstrating that the entire CCUS value chain can safely capture and store CO_2 while also protecting human health and the environment.

- Providing templates for developing the construction and operating permits for commercial geologic storage projects, which will identify the permit data needs, data-processing algorithms, and supporting technical submittals regarding site characterization, geologic modeling and computational simulation (i.e., CO_2 plume modeling), and robust monitoring of sites as well as typical schedules and timelines for the preparation and approval of these permits. These templates as well as the Class VI regulations of North Dakota and Wyoming (the Class VI primacy states in the region) will provide the foundation for the remainder of the states in region.

- Documenting the actual capital and operating costs of deploying and operating commercial CCUS projects that comply with applicable (federal and/or state) Class VI regulations.

- Demonstrating that favorable economics can be achieved for several commercial CCUS projects in the region given the available CCUS technology, characteristics and logistics of possible source–sink combinations, and recent implementation of federal/state policies and regulations.

Of equal importance, the above actions, when taken together, will improve acceptance of a commercial CCUS industry by the general public and landowners, which is key to its widespread deployment throughout the region. However, a major outstanding challenge will be the ability to adequately extend these project- and regional-specific outreach programs and messages to the region as a whole.

Lastly, details regarding the effectiveness of the business cases of each of the commercial projects in the region will be mined as a means of identifying key variables or factors that are impacting the project economics. This information will be compiled and analyzed to inform and, if possible, expedite the deployment of future commercial CCUS projects in the region.

5.2.2 Investigation of Knowledge Gaps

5.2.2.1 Capture of CO_2

The ability to capture CO_2 effectively and economically from a variety of industrial sources is critical for any CCUS project. As such, continued innovation in capture technology is crucial to continuing to grow the commercial CCUS industry in the PCOR Partnership region.

Knowledge Gaps. The high cost of CO_2 capture is the primary challenge facing this component of the CCUS value chain. Processes for the capture of CO_2 comprise chemical and physical absorption, membrane separation, or the use of solid adsorbents. For all these processes, the capital and annual maintenance costs are directly affected by their ability to selectively remove CO_2, their overall CO_2 removal capacity and efficiency, and their overall commercial footprint. The primary knowledge gaps associated with these processes are briefly discussed below.

Chemical/Physical Absorption Systems. The performance of chemical/physical absorption solvents is primarily dependent upon the properties of the solvent, the design of the physical system, and the propensity for the loss of solvent and subsequent environmental impacts. Specific knowledge gaps which have been identified for these systems are as follows:

- Chemical/Physical Absorption Solvents
  - Development of solvents that 1) reduce the energy required for regeneration (i.e., water-lean solvents), 2) reduce or eliminate solvent degradation (i.e., solvents with a high tolerance for trace contaminants), or 3) require smaller, less expensive absorption towers (i.e., solvents with faster CO_2 absorption/reaction kinetics).

- Physical System Design
  - Improvement of gas–liquid contacting through more innovative packing structures, thereby increasing mass transfer and reducing physical column heights.

- Improvement CO_2-stripping processes to reduce residence time and increase heat transfer.
- Improved heat exchangers to increase heat transfer and overall capture efficiency.

- Solvent Loss Mitigation and Environmental Impacts
  - Development of an understanding of the formation solvent degradation products (e.g., nitrosamine), which is directly related to the degree of gas preconditioning available prior to CO_2 separation.
  - Development of an understanding of the formation and impact of aerosols coming in and out of capture technologies.

Specifically, with regard to aerosols, it is known that the combustion of many fuels, and especially low-rank coals, produces aerosols that consist mainly of alkali and alkaline-earth sulfates as well as some minor and trace elements. These aerosols and trace elements have the potential to penetrate air pollution control devices and impact the performance of solvent-based CO_2 capture systems. In addition to the impact of these aerosols on solvent emissions, they also have the potential to catalyze solvent degradation should they be permitted to accumulate in the solvent. The main knowledge gaps concerning aerosols are summarized below:

- Which species cause the most aerosol formation and how can they be removed?

- At what level will these fine particulates in the solvent cause significant degradation of products?

- Which species are the most reactive with the solvent, causing the most degradation to occur?

- What methods of removal of the metals are most economical to prevent solvent degradation?

- Can the products of degradation be transformed to yield a viable CO_2 capture solvent?

- What are the potential costs of disposal of any degradation products that are removed?

Membrane Systems. In general, membrane systems need to become more robust and capable of withstanding higher levels of contamination in the raw gas stream, which will both lengthen their lifespan and reduce their susceptibility to poisoning. The effectiveness of membrane technologies is highly dependent upon the application, with some of the primary knowledge gaps as follows:

- Ability to manufacture large-scale membranes.

- Ability to develop membranes with increased permeability.

- Ability to develop new membrane materials for extended life in harsh operating conditions with impurities present.

Solid Adsorbents. The use of solid adsorbents in chemical looping has the potential to reduce the energy penalty of CO_2 capture and reduce equipment costs. Specific knowledge gaps associated with these include the following:

- The cost for tailor-made materials and the added complexity of solids handling must also be addressed.
- The ability to develop low-cost, tailor-made adsorbents for specific capture applications.
- The ability to enhance the reactivity and recyclability of solid adsorbents.
- An improved understanding of heat and mass transfer within these solids-based systems is needed.

PCOR Partnership Activities to Address Gaps. Efforts to address these knowledge gaps are ongoing in the region and will provide additional insights into this key component of a commercial CCUS operation. Specifically, the EERC has completed two engineering studies (one FEED and one pre-FEED) investigating the technical and economic considerations for adding postcombustion CO_2 capture to two different coal-fired power plants in North Dakota. In addition, it is anticipated that key information regarding many of the above knowledge gaps will be obtained through the operation of the Wyoming Integrated Test Center at the Dry Fork power plant near Gillette, Wyoming, where testing of CO_2 capture systems will be performed over the next 5 years. Lastly, the PCOR Partnership will coordinate with operators of the commercial CCUS operations in the region to collect and analyze data from the operating plants in the region to conduct an engineering analysis of the performance of the capture technologies that are deployed. The data from the FEED studies, the Wyoming Integrated Test Center, and the operating commercial plants will be compiled and analyzed to provide a commercial-scale assessment of this component of the CCUS value chain and to reevaluate and prioritize the knowledge gaps for further investigation.

5.2.2.2 Advanced Geologic Characterization of Onshore Carbon Storage

The distribution of the major industrial sources of CO_2 emissions that exist within the region is presented in Figure 7. This figure shows:

- An abundance of electrical utility sources of CO_2 throughout the region but with a concentration of facilities in the eastern/southeastern portion of the region, i.e., states of Minnesota, Wisconsin, Iowa, and Missouri. At the same time, the closures of five large coal-fired electric utilities have been announced, three in Wyoming and one each in Montana and North Dakota.
- Several agricultural processing and ethanol plants in eastern North Dakota and South Dakota, Minnesota, and Iowa.
- A large number of petroleum and natural gas sources of CO_2 in Canada, largely concentrated in Alberta, along with coal-fired electric power plants in both Alberta and along the U.S. border in Saskatchewan.

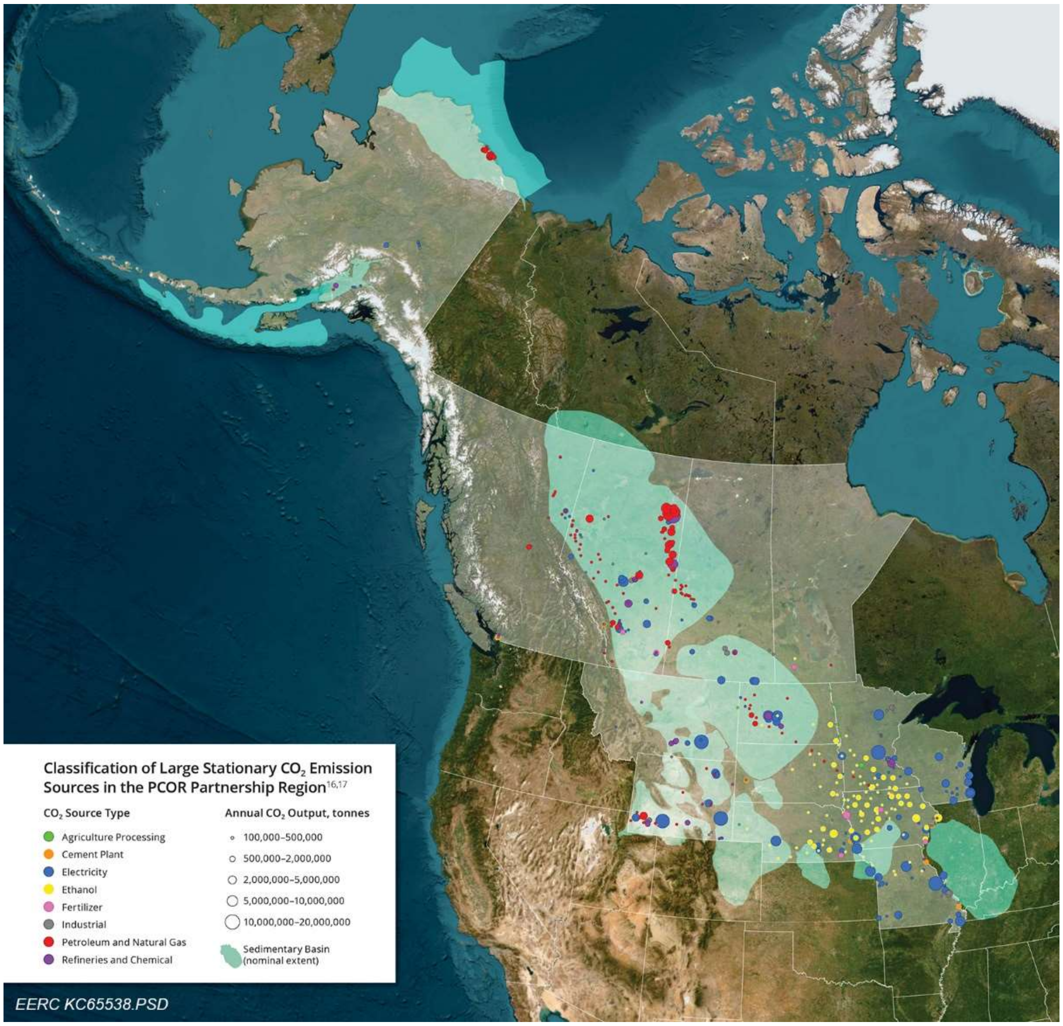

Figure 7. Major stationary sources of CO_2 in the PCOR Partnership region relative to sedimentary basins.

A significant challenge for growing and expanding the commercial deployment of CCUS in the PCOR Partnership region is finding a storage location for the CO_2 generated at these sources. More specifically, given that the geology in Minnesota, Wisconsin, Iowa, and Missouri does not offer any primary targets for geologic storage, where and how can these CO_2 emissions be captured and stored within the region?

There are several knowledge gaps that have the potential to limit the number and location of available geologic storage sites within the PCOR Partnership region. These knowledge gaps and the activities that the partnership has in progress to address them are listed below:

- **Public perception and acceptance**. The social license to conduct CCUS on a commercial scale is critical to its widespread commercial implementation in the region. The PCOR Partnership is conducting several public outreach activities to disseminate simplified scientific information in a clear and concise manner while also emphasizing the societal benefits of CCUS. These activities include creating and maintaining a public website, supporting PCOR Partnership members by providing them ready access to technical reports and other products, updating the PCOR Partnership Regional Atlas with current information, and informing and educating a variety of stakeholders of the business model challenges and opportunities associated with CCUS.

- **Rapid, accurate storage resource appraisal**. The growth and expansion of CCUS projects will require a cost-effective and agile approach to storage resource appraisal. The PCOR Partnership developed the adaptive management approach (AMA) to assist project developers in rapid and accurate evaluation to reduce project risk and manage project uncertainty. The first stage of the AMA begins with site screening to identify one or more candidate storage sites that 1) are economically accessible to a source(s) of CO_2, 2) have sufficient capacity and injectivity to store the total projected volume of CO_2 that will be captured and at the required rate, and 3) have the geologic structure or stratigraphy necessary to securely contain the CO_2 in the storage reservoir. If site-screening criteria are met, the feasibility assessment stage will determine the technical and economic viability of storing CO_2 at the candidate geologic storage site, including storage resource potential. Using this staged approach for CO_2 storage project development and storage resource appraisal will inform and lead to go/no-go decision points that allow the project developer to determine if advancement of the project to the next phase is warranted. (Livers-Douglas and others, 2023). The PCOR Partnership will continue to build off the AMA and develop advanced characterization methods to reduce uncertainty and accelerate project timelines.

- **Improved storage efficiency**. To maximize storage in the region, it will be necessary to optimize the allocation of the available resources. Optimization strategies will be explored for this purpose. A key component of these strategies will be improved storage efficiency, which will both reduce the amalgamated pore space area as well as the risks associated with a larger CO_2 plume. Efforts through the PCOR Partnership will quantify potential improvements to storage efficiency and balance those improvements with expected costs and/or savings.

- **Understanding the current stress state and potential for basement faulting**. Basal formations within the PCOR Partnership region have been identified as potential CO_2 storage targets; however, there is a lack of knowledge related to stresses and the location of any existing fractures or faults within these formations. An understanding of the current stress states and the presence of faults/fractures is key to permitting and utilizing these formations for commercial-scale CO_2 storage. The PCOR Partnership will investigate stress regimes in basal storage formations in the region using new data being collected through ongoing CCUS commercial activity to evaluate stresses and identify fractures or faults. Geomechanical modeling and simulation will be used to assess potential basement fault reactivation to reduce technical uncertainties related to CO_2 storage in potential basal storage reservoirs.

- **Alternatives to large-scale 4D seismic surveys to monitor plume growth**. Time-lapse seismic surveys are the most frequently used indirect monitoring method for tracking the extent of injected CO_2. Although this technique has proven to be effective for monitoring CO_2 in the subsurface, it does not provide real-time data and traditional implementation of these techniques can be challenging (e.g., disruptive to operations; expensive; require substantial technical effort to interpret and integrate results with operations and modeling). The PCOR Partnership will explore the next generation of indirect monitoring techniques that are conducive to informing site operability and allow management of project risk in a timely and cost-efficient manner.

- **MVA in CO_2 stacked storage scenarios**. The use of a stacked storage strategy will ultimately allow for maximum CO_2 storage in a minimum geographic extent. This strategy will also improve the project risk profile because of the smaller extent of the CO_2 plume. However, with the use of stacked storage comes the challenge of accurately delineating the plume through multiple layers of CO_2. The PCOR Partnership will investigate this potential challenge through modeling and simulation of site-specific geology.

- **Pragmatic approach to AOR delineation**. The availability of some storage reservoirs may be precluded by the subsurface pressure profile that exists prior to CO_2 injection. This limitation is the result of the methods described in the EPA Class VI rule for estimating the AOR of a CO_2 storage facility (U.S. Environmental Protection Agency, 2013), which were developed assuming that the storage reservoirs would be in hydrostatic equilibrium with overlying aquifers. However, within the PCOR Partnership region and elsewhere around the United States, many candidate storage reservoirs are already overpressurized relative to overlying freshwater aquifers and thus subject to potential vertical formation fluid migration from the storage reservoir to the lowermost USDW even prior to the planned storage project. Consequently, applying EPA (2013) methods to these geological situations essentially results in an infinite AOR, making regulatory compliance infeasible. As an alternative, the PCOR Partnership developed a site-specific, risk-based methodology that allows for a reduction in the AOR while ensuring protection of drinking water resources, which would make these storage reservoirs possible candidates for storage. This effort is discussed further under another topic area of this document, Risk Assessment and Management Tools (Section 5.2.2.6).

5.2.2.3 Targeted Characterization of Associated Storage in Conventional and Unconventional Reservoirs

There are outstanding knowledge gaps related to the continued commercial deployment of the associated storage of CO_2 during CO_2 EOR in conventional reservoirs as well as its future application to unconventional reservoirs within the PCOR Partnership region, e.g., the Bakken petroleum system. The knowledge gaps and the PCOR Partnership activities that will address them are presented for both applications in the remainder of this section.

Associated Storage in Conventional Reservoirs

Knowledge Gaps. There is a need for an improved understanding of the technical strategies and techno-economic assessments for transitioning waterflood EOR operations in conventional reservoirs in the Williston Basin into CO_2 EOR operations. The boom in production from the unconventional Bakken petroleum system has had unintended consequences for the advancement of EOR opportunities in conventional oil fields in the Williston Basin. Specifically, over the past decade, operators have largely focused their resources and capital investments in developing the Bakken oil play, with an unintended consequence being that many of the conventional oil fields that were previously identified by PCOR Partnership regional characterization activities as being prime candidates for CO_2 EOR have not been operated or maintained for this future transition. There is a need to explore operational strategies that address technical challenges associated with bringing suspended or inconsistently operated conventional water injection and oil production wells back online, optimizing the current facilities, and systematically evaluating necessary new facilities.

PCOR Partnership Activities to Address Gaps. As part of the regional characterization activities under the PCOR Partnership, the top conventional oil fields that were identified as prime CO_2 EOR candidates will be revisited. Specific areas of research will include investigations of the roles that advanced SCADA (supervisory control and data acquisition) systems, machine learning, and artificial intelligence may play in evaluating these existing conventional waterflood EOR operations and guiding their transition to CO_2 EOR operations. This, in turn, will contribute to an enhanced understanding of how CO_2 storage efficiency and associated CO_2 storage potential will be affected by designing waterfloods to optimize EOR potential.

Associated Storage in Unconventional Reservoirs

Knowledge Gaps. The primary knowledge gaps associated with the commercialization of the CO_2 storage resource potential of the Bakken petroleum system and other unconventional reservoirs that represent potential CO_2 EOR targets are:

- The need for more knowledge and data regarding the key factors affecting CO_2 storage in these types of reservoirs, including CO_2 permeation rates, free-phase storage volumes in pores and fracture networks, and adsorption/absorption potential with clay minerals and organic matter.

- The ability to manage conformance of CO_2 injection.

- The need for information regarding the geomechanical properties of the unconventional reservoirs for input into local scale, drilling spacing unit scale, and fieldwide scale to define the parameters for controlling the AOR.

PCOR Partnership Activities to Address Gaps. State- and DOE-funded projects occurring within the PCOR Partnership region are focused on CO_2 storage in unconventional reservoirs such as the Bakken and are examining the application of machine learning and artificial intelligence to improve modeling and simulation of Bakken EOR schemes, including CO_2 EOR approaches. Other DOE-funded projects in the PCOR Partnership region are also conducting laboratory- and modeling-based efforts to support the design and implementation of future CO_2 EOR pilot tests in the Bakken petroleum system that would address knowledge gaps related to injection conformance.

To complement the current ongoing data-gathering efforts of DOE and further address these knowledge gaps, the PCOR Partnership recommends the following:

1. The conduct of a laboratory-based analysis of various types of unconventional reservoir samples, including petrophysical, geochemical, and petrographic analysis coupled with adsorption testing and advanced imaging-based analysis of sample matrices, to increase the knowledge of the fundamental factors that affect associated CO_2 storage and migration in unconventional reservoirs undergoing CO_2 EOR. Specifically:

   a) Laboratory-based work is needed to better understand the CO_2 adsorption potential within organic-rich shales as a function of organic content and type as well as CO_2 adsorption within tight, nonshale reservoirs as a function of porosity, clay type, and content.

   b) Additional petrophysical and advanced petrographic testing of unconventional rock samples is needed to better understand and quantify pore space connectivity, native fracture versus induced fracture occurrence and characteristics, and CO_2 permeation rates as a function of mineralogy and geochemistry. This information will provide a better understanding of the key factors that affect CO_2 permeation, migration, and free-phase storage within shales and tight nonshale reservoirs.

2. The conduct of field trials of innovative approaches to injection, reservoir surveillance, and reservoir management are needed to better manage conformance of CO_2 injection in unconventional reservoirs.

3. The conduct of laboratory tests, combined with modeling and simulation, to attain the desired geomechanical properties of the unconventional reservoirs, including Young's modulus, bulk modulus, shear modulus, formation density, and Poisson's ratio. Additional datasets to be incorporated and interpreted as part of this effort include wireline logs, such as dipole sonic and formation microimaging (FMI), to understand local wellbore-scale elastic and fracture properties.

5.2.2.4 Active Reservoir Management

The extraction of formation brines is one means to increase the CO_2 storage capacity of a reservoir. The outstanding knowledge gaps associated with implementing this strategy and the activities of the PCOR Partnership to address these data gaps are provided below.

Knowledge Gaps. The key knowledge gap associated with active reservoir management using brine extraction is the lack of understanding of the ability of this technique to 1) improve storage capacity, injectivity, and storage efficiency associated with geologic CO_2 storage systems; 2) provide a means to "steer" injected fluids or pressure away from areas of concern (e.g., trespass on offset pore space, potential leakage pathways, etc.); and 3) significantly reduce the AOR associated with geologic CO_2 storage projects and the accompanying permitting, monitoring, and leasing requirements. Consequently, the techno-economics of this means of reservoir management are not well understood, especially when the need for treating and disposing of the extracted brine is incorporated into the analysis.

PCOR Partnership Activities to Address Gaps. The PCOR Partnership is currently conducting a study on optimizing CO_2 storage, which will consider brine extraction. Other relevant work is also in progress, although not funded as part of the regional partnership. Specifically, the PCOR Partnership region is home to the DOE-funded Brine Extraction and Storage Test (BEST) field project. The BEST project is working to validate the potential efficacy and cost of active reservoir management involving brine extraction at a CO_2 geologic storage site. This first-of-a-kind industrial-scale field test is also investigating the efficacy and cost of treating extracted formation brines of various total dissolved solids (TDS) concentrations to meet a variety of disposal options using the water treatment test bed facility which was constructed at the field demonstration test site.

5.2.2.5 Regional Pipeline Infrastructure

Knowledge Gaps. Fully understanding the pipeline infrastructure needs of the PCOR Partnership region and developing an optimal, cost-effective pipeline infrastructure that links the CO_2 sources with potential storage locations represent a knowledge gap facing the commercial deployment of CCUS in the PCOR Partnership region.

PCOR Partnership Activities to Address Gaps. PCOR Partnership activities to address this knowledge gap include the following:

- An analytical template was created by the PCOR Partnership to identify scale-up challenges and assess site readiness factors for CO_2 pipelines in North Dakota (Peck and others, 2019a, b). This template developed CO_2 pipeline options using AspenPlus software, with inputs such as optimal ROW corridors, pipe schedule and grade, pressure/compression/temperature requirements, and other factors that impact costs. Of particular importance was a review of ROW corridors, which examined preliminary pipeline routes that took full advantage of existing ROWs, e.g., those for electric transmission or pipeline transport of other fluids.

- The PCOR Partnership is examining the viability of recommendations generated by national groups for addressing policy, legal, regulatory, and economic challenges for deploying CO_2 pipelines (National Petroleum Council, 2019; Interstate Oil and Gas Compact Commission, 2010; State CO_2 EOR Deployment Work Group, 2017; Great Plains Institute, 2020), with the goal of facilitating the potential build-out of pipelines in the region. Of particular interest is the strategic involvement of federal and/or state governments to mitigate challenges associated with pipeline permitting and/or siting. Recommendations already deployed in one state within the PCOR Partnership region include predetermined acceptable routes to expedite CO_2 pipelines in the state of Wyoming. The viability of implementing this strategy in the remainder of the PCOR Partnership region will be explored through consultation with state and federal regulatory agencies along with other strategies for schedule and cost management. The PCOR Partnership's Regulatory Round-Up meetings will serve as a venue for discussions on this topic with the "governmental corporations" or "pipeline authorities" which currently exist in North Dakota, Alaska, and Wyoming.

- The learnings associated with the commercial CO_2 pipelines that are present in the PCOR Partnership region, i.e., the Dakota Gasification Souris Valley pipeline, the Greencore pipeline, and the ACTL, will be compiled through interviews with regulatory and industry representatives. Collectively, these pipelines have transported tens of millions of tons of CO_2 over a combined distance exceeding 500 miles and with a combined operational history of nearly three decades. Information of interest will include the primary steps that were implemented for commercial deployment of the pipelines with associated timelines and costs; the results of a retrospective assessment of the critical challenges to deployment, how they were overcome, and potential opportunities for cost savings and/or reduced timelines for future pipeline projects; and the safety performance of these pipelines over their lifetime of operations.

- Lastly, the use of the open-source tool for optimizing CO_2 capture, transport, and storage infrastructure, SimsCCS, which was developed by Los Alamos National Laboratory, will be evaluated for use in the region.

Generally, given the location of the CO_2 sources and the potential storage areas, consideration will be given to the construction of trunk lines to move the CO_2 from the eastern portions of the region to the west and north. The construction of these trunk lines could be expedited by the involvement of the federal government and the implementation of strategies such as those put in place by the Wyoming Pipeline Corridor Initiative, e.g., expansion of ROWs on private, state, and BLM-managed lands. Based on recent history within the PCOR Partnership region, outreach and public education will also be a critical component of this effort.

5.2.2.6 Risk Assessment and Management Tools

The PCOR Partnership has performed several risk assessments involving the geologic storage of CO_2. In the process of performing these assessments, several knowledge gaps have been identified and are summarized in this section along with those efforts of the PCOR Partnership that are in place to address them.

Knowledge Gaps. The following knowledge gaps have been identified based on the performance of several risk assessments within the PCOR Partnership region:

- In general, there is a lack of unified commercial tools for quantifying uncertainty in the storage complex (storage reservoir, primary seal [cap rock], and overlying units including secondary seals, USDW, and overburden) given the limited (and sometimes sparse) site characterization data from wells or the technological/physical limitations of geophysical methods like 3D seismic surveys. The underlying uncertainty in the storage complex affects estimates of potential impacts of CO_2 injection to groundwater and surface receptors which, in turn, affects the ability to design monitoring programs that can detect potential environmental impacts.

- For the risk assessment process applied to storage projects, there are limited methods for quantitatively assessing the risk likelihood (probability) and/or risk severity (impact) beyond expert judgment. Consequently, risk assessments for storage projects heavily rely on subject matter experts. While relying on subject matter experts represents an acceptable approach, the process requires human risk judgments and is therefore susceptible to human bias and error, making the process less quantitative than many engineering-type construction projects.

- Current monitoring technologies using wells or geophysical methods have limited ability to observe impacts in the deep subsurface, which creates challenges for the early detection of potential risks to groundwater or surface receptors. Optimal monitoring designs that use systematic planning (data quality objectives [DQO] process) are needed.

- Delineating the AOR for a geologic storage project is a critical component of a technical risk assessment. The methods outlined by EPA (2013) for this delineation were developed assuming that the storage reservoirs would be in hydrostatic equilibrium with overlying aquifers. However, in the state of North Dakota and elsewhere around the United States, many candidate storage reservoirs are already overpressurized relative to overlying aquifers and thus subject to potential vertical formation fluid migration from the storage reservoir to the lowermost USDW, even prior to the planned storage project. Consequently, applying EPA (2013) methods to these geological situations essentially results in an infinite AOR, which makes regulatory compliance infeasible.

PCOR Partnership Activities to Address Gaps. As part of its risk assessment efforts, the PCOR Partnership has initiated efforts to begin to address the knowledge gaps described above:

- The PCOR Partnership is testing several National Risk Assessment Partnership (NRAP) tools, including NRAP-Open-IAM (Vasylkivska and others, 2020) and DREAM (Yonkofski and others, 2020), to understand their ability to quantify uncertainty in the storage complex and the potential impacts to USDWs. The PCOR Partnership is testing these tools using site characterization, modeling, and simulation data for storage projects located within the PCOR Partnership region. The site-specific stratigraphy, petrophysical properties, wellbore surveys, and high-fidelity, physics-based reservoir simulations provide unique input datasets for testing the NRAP tools and better quantifying the effects of uncertainty of the inputs on the NRAP-modeled outputs. The focus of this testing is on two risk proxies: brine (TDS) and CO_2 concentrations in USDWs.

- The PCOR Partnership has expanded, in Burton-Kelly and others (2021), a FORTRAN-based model developed by Cihan and others (2011, 2012) and a risk-based AOR framework proposed by Birkholzer and others (2013) and Oldenburg and others (2014, 2016) to develop a recommended workflow and set of tools for delineating a risk-based AOR that complies with SDWA requirements and provisions for the UIC program, which fall under the Class VI rule of the UIC program – wells used for geologic sequestration of CO_2. The use of this approach has the potential to expand the storage capacity of the region by permitting the use of those formations which would have previously been rejected for storage because of their preinjection, subsurface pressure profile.

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APPENDIX A

ACTIVE/OPERATING AND PARTIALLY PERMITTED COMMERCIAL CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS) PROJECTS IN THE PLAINS CO_2 REDUCTION (PCOR) PARTNERNSHIP REGION

Table A-1. Basic Characteristics of Active/Operating and Partially Permitted Commercial Carbon Capture, Utilization, and Storage (CCUS) Projects in the Plains CO_2 Reduction (PCOR) Partnership Region

No.	State/ Province	Project Name	Owner/ Operator	CO_2 Source	CO_2 Source Type	Storage Type	Injection Rate	Storage Capacity	Operating	Partially Permitted	Announced
					OPERATING/ACTIVE PROJECTS						
					CANADA						
1	AB	Alberta Carbon Trunk Line (ACTL)[25] Clive CCUS[26]	Enhance Energy, Wolf Midstream	NWR Sturgeon Refinery and Nutrien Redwater Fertilizer[27]/other	Bitumen refinery and ammonia (fertilizer)/ other	Associated/ storage hub	14.6 MMta	TBD	X		
2	AB	Glacier Project	Entropy	Advantage Glacier Gas Plant	Natural gas processing	Dedicated storage	~0.2 MMta[28] (combined phases)	TBD	X		
3	AB	Quest CCS Project	Shell Canada Energy	Shell Scotford Upgrader	Oil refinery	Dedicated storage	~1.0 MMta[29] (2022: 7.7 MMt captured)	>27 MMt[30] (25 years)	X		
4	SK	Aquistore Deep Saline CO_2 Storage Project	Petroleum Technology Research Centre	Boundary Dam Power Station	Lignite-fired	Dedicated storage	Varies	~585 MMt (02/2024)	X		
5	SK	Boundary Dam CCS Facility and Associated CO_2 Storage at Weyburn[31]	Whitecap Resources	Boundary Dam Power Station	Lignite-fired	Associated storage	~1.7 MMta	TBD	X		

Continued . . .

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Table A-1. Basic Characteristics of Active/Operating and Partially Permitted Commercial Carbon Capture, Utilization, and Storage (CCUS) Projects in the Plains CO_2 Reduction (PCOR) Partnership Region (continued)

No.	State/ Province	Project Name	Owner/ Operator	CO_2 Source	CO_2 Source Type	Storage Type	Injection Rate	Storage Capacity	Operating	Partially Permitted	Announced
OPERATING/ACTIVE PROJECTS (continued)											
CANADA (continued)											
6	SK	Great Plains Synfuels Plant and Associated CO_2 Storage at Weyburn–Midale	Dakota Gasification Company	Great Plains Synfuels Plant	Lignite	Associated storage	~2.0 MMta	TBD	X		
UNITED STATES											
7	MT	Bell Creek EOR Project	Denbury Inc.	Shute Creek/ Lost Cabin (WY)	Gas processing	Associated storage	0.94 MMta	TBD	X		
8	ND	Blue Flint CO_2 Storage Project	Blue Flint Sequester Company, LLC	Blue Flint Ethanol	Ethanol production	Dedicated Storage	0.2 MMta	4.0 MMt (20 years)	X		
9	ND	Cedar Creek Anticline, North Dakota	Denbury Inc.	Shute Creek/ Lost Cabin (WY)	Gas processing	Associated storage	>1 MMta	TBD	X		
10	ND	Great Plains Sequestration Project	Dakota Gasification Company	Great Plains Synfuels Plant	Lignite	Dedicated storage	1.0 MMta to 2.7 MMta	26 MMt[32] (~12 years)	X		
11	ND	Red Trail Energy Project	Red Trail Energy LLC	Red Trail Energy	Ethanol production	Dedicated storage	0.18 MMta	3.6 MMt (20 years)	X		

Continued . . .

[32] https://www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/DGC/C29450.pdf (accessed May 2024).

Table A-1. Basic Characteristics of Active/Operating and Partially Permitted Commercial Carbon Capture, Utilization, and Storage (CCUS) Projects in the Plains CO_2 Reduction (PCOR) Partnership Region (continued)

No.	State/ Province	Project Name	Owner/ Operator	CO_2 Source	CO_2 Source Type	Storage Type	Injection Rate	Storage Capacity	Operating	Partially Permitted	Announced
PARTIALLY PERMITTED PROJECTS (continued)											
UNITED STATES (continued)											
12–17	WY	Greencore Pipeline Associated Storage Fields	Various	Lost Cabin and Shute Creek	Gas processing	Associated storage	Various	TBD	X (6)		
18	ND	Dakota Carbon Center West SGS (Secure Geologic Storage) Project	DCC West Project LLC	Milton R. Young Station/ other	Lignite/ other	Dedicated storage	6.11 MMta	122.9 MMt (20 years)		X	
19	ND	Tundra SGS/North Dakota CarbonSAFE (Carbon Storage Assurance Facility Enterprise) (Broom Creek Formation)	DCC East Project LLC	Milton R. Young Station	Lignite	Dedicated storage	4.3 MMta	86 MMt (20 years)		X	
20	ND	Tundra SGS/North Dakota CarbonSAFE (Deadwood Formation)	DCC East Project LLC	Milton R. Young Station	Lignite	Dedicated Storage	1.17 MMta	23.4 MMt (20 years)		X	
21	WY	Sweetwater Carbon Storage Hub	Frontier Carbon Solutions	Multiple	Industrial/ direct air capture (DAC)	Dedicated /storage hub	5 MMta	100 MMt (20 years)		X	

DESCRIPTION OF ACTIVE/OPERATING AND PARTIALLY PERMITTED COMMERCIAL CCUS PROJECTS IN THE PCOR PARTNERSHIP REGION

ACTIVE/OPERATING COMMERCIAL CCUS PROJECTS

CANADA

ALBERTA

1

Alberta Carbon Trunk Line (ACTL)

The ACTL is a multiparty, open access pipeline designed to connect CO_2 sources with different end-use opportunities. Owned and operated by Wolf Midstream, the line currently gathers 1.6 MMt of CO_2 per year from the North West Redwater Partnership (NWR) Sturgeon Refinery and Nutrien Redwater Fertilizer facility and transports it 150 miles to an Enhance Energy field near Clive, Alberta, for associated storage. The pipeline can transport 14.6 MMt of CO_2 per year.[33] Since its first injection in 2020, the Clive project has captured and stored more than 4 MMt of CO_2.[34] In September 2023, Wolf announced a decision to extend the existing ACTL into the Edmonton region to support existing and new industrial facilities. The extension is called the ACTL Edmonton Connector.[35] Funding support for the ACTL has been provided by the Government of Alberta (through its Carbon Capture and Storage Fund) and the Government of Canada (through its ecoEnergy Technology Initiative and the Clean Energy Fund).[36]

2

Glacier CCS Project

The Glacier CCS project, a postcombustion capture and storage project at the Glacier Gas Plant in Saddle Hills County, Alberta, is operated by Entropy Inc., a subsidiary of Advantage Energy Ltd. The project is using a phased approach with increasing capture rates, including a demonstration of Entropy's Modular Carbon Capture™ equipment. Injection began in August 2022, with a reduction of 0.047 MMt per year from one engine. Phase 1b will involve an increase of CCS capacity to 0.063 MMt per year and involve deployment of Entropy's Integrated Carbon Capture and Storage™ equipment. With funding received in December 2023 from the Canada Growth Fund (a public investment fund backing Canadian cleantech), the project is moving on to Phase 2, the engineering phase, designed to capture an additional 0.185 MMt per year.[37]

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[33] https://wolfmidstream.com/carbon/(accessed May 2024).
[34] https://enhanceenergy.com/our-operations/ (accessed May 2024).
[35] https://wolfmidstream.com/wolf-midstream-to-extend-alberta-carbon-trunk-line-into-the-edmonton-region-enabling-large-scale-emissions-reduction/ (accessed May 2024).
[36] https://enhanceenergy.com/new-carbon-solution-in-alberta-delivers-use-for-industrial-emissions/ (accessed May 2024).
[37] https://sustainablebiz.ca/first-of-its-kind-carbon-credit-deal-to-support-entropys-ccs (accessed May 2024).

3

Quest CCS Project

The Quest CCS facility is operated by Shell Canada Energy on behalf of the Athabasca Oil Sands Project. Located at the Scotford Upgrader near Edmonton, Alberta, operations commenced in November 2015. In 2022, nearly 1.0 MMt (0.97 MMt) was transported about 37 miles via pipeline and injected for permanent storage in a saline formation near Thorhild, Alberta. As of December 2022, over 7.7 MMt of CO_2 has been injected toward the expected goal of 27 MMt. Based on reservoir performance and injectivity assessments, no additional injection well development is anticipated. Monitoring, measurement, and verification activities indicate that there has been no CO_2 migration outside of the Basal Cambrian Sands (BCS). Revenue streams are generated through offset credits for net CO_2 stored and additional offset credit for CO_2 captured, plus operational funding available from the Government of Alberta (for first 10 years of operation).[38]

SASKATCHEWAN

4

Aquistore Deep Saline CO_2 Storage Project

Aquistore is located near Estevan, Saskatchewan, and is operated by the Petroleum Technology Research Centre (PTRC). With its location approximately 2.0 miles from SaskPower's Boundary Dam CCS Facility, Aquistore provides a dedicated storage option for unsold CO_2 from Unit 3 of the coal-fired power plant and receives a steady stream of 200–500 metric tons per day. Injection operations started in April 2015, via a single vertical well at a depth of about 2.0 miles underground. As of February 2023, over 0.5 MMt of CO_2 has been stored. Known for leading research, Aquistore learnings include injection operations studies, pressure and geochemical change monitoring, deep subsurface seismic imaging, and CO_2 movement modeling.[39] In fact, the PCOR Partnership Program supported Aquistore through early geologic modeling and simulation activities.

5

Boundary Dam CCS Facility and Associated CO_2 Storage at Weyburn

In 2014, Boundary Dam Power Station near Estevan, Saskatchewan, became the first power station to successfully use CCS technology. Unit 3 produces 115 MW of power and using postcombustion technology captured nearly 0.8 MMt of CO_2 in 2023. As of the end of 2023, 5.8 MMt of CO_2 has been captured.[40] The CO_2 is transported 46 miles via the Whitecap Resources Boundary Dam CO_2 pipeline to the Weyburn oil field at a rate of 1.0 MMt per year.[41] Any CO_2 not used for enhanced oil recovery (EOR)/associated storage at Weyburn is stored deep underground at Aquistore (see above).

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[38] https://open.alberta.ca/dataset/356aeeda-134c-4779-971c-931573400ddf/resource/8a1b4350-9634-4e66-a983-8c16199fa2e7/download/quest-annual-summary-report-2022-alberta-department-of-energy.pdf (accessed May 2024).

[39] https://ptrc.ca/media/whats-new/aquistore-co2-storage-project-reached-+500000-tonnes-stored (accessed May 2024).

[40] https://www.saskpower.com/about-us/our-company/blog/2024/bd3-status-update-q4-2023 (accessed May 2024).

[41] https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2024/market-snapshot-canada-is-expanding-its-co2-pipeline-network.html (accessed May 2024).

6

Great Plains Synfuels Plant and Associated CO_2 Storage at Weyburn–Midale

Beginning in 2000, Dakota Gasification Company (DGC) has captured more than 40.0 MMt of CO_2 at its Beulah, North Dakota, Great Plains Synfuels Plant for associated storage at oil fields in Saskatchewan. DGC can capture up to 3.0 MMt of CO_2 per year and transports it 205 miles[42] across the Canadian border via the Souris Valley Pipeline. The synfuels plant also participates in the world's largest carbon storage project (see the Great Plains Sequestration Project below).

Injection of CO_2 began in the Weyburn oil field in 2000 and in the Midale oil field in 2005. In 2017, Whitecap Resources assumed ownership of Weyburn from Cenovus and since inception, injection in the field averages 1.7 MMt per year. The Midale Field was operated by Apache Canada until it was sold to Cardinal Energy Ltd. in 2017.[43] In 2020, approximately 0.19 MMt of CO_2 was injected in the Midale unit, with nearly 5 MMt of CO_2 injected.[44]

<u>UNITED STATES</u>

MONTANA

7

Bell Creek EOR Project

Located in southeast corner of Montana, the Bell Creek oil field is connected to the ConocoPhillips Lost Cabin Gas Plant and the ExxonMobil Shute Creek Gas Plant via the 232-mile Greencore pipeline at a target rate of 0.35 MMt[45] CO_2 per year. Beginning in 2010, the PCOR Partnership, in coordination with Denbury Resources (now ExxonMobil), began characterization efforts to better understand the associated storage at the field. Injection began in 2013, and the PCOR Partnership conducted an extensive monitoring, verification, and accounting program featuring over 16 monitoring techniques. As of July 31, 2018, the end of the Phase III demonstration project, over 5.3 MMt of CO_2 was stored. Estimates predict that at the end of commercial operations at the field over 11.5 MMt of CO_2 will be stored.[46]

NORTH DAKOTA

8

Blue Flint CO_2 Storage Project

The Blue Flint ethanol facility, located near Underwood, North Dakota, began ethanol production in 2007 and is owned and operated by Harvestone Low Carbon Partners. During ethanol production, an annual average of 0.20 MMt of CO_2 with a stream composition greater than 99.98%

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[42] https://www.dakotagas.com/about-us/CO2-capture-and-storage/index (accessed May 2024).

[43] www.pipelinenews.ca/news/local-news/weyburn-unit-up-for-salemidale-unit-sold-1.20684078 (accessed May 2024).

[44] https://cardinalenergy.ca/wp-content/uploads/2021/03/March-9-2021- 2020-ESG-Report-Final.pdf (accessed May 2024).

[45] 50 million cubic feet per day (1000 MMscfd = 6.972 MMta) http://www.bobby-strain-group.com/BSG_LNG.htm (accessed May 2024).

[46] https://pcor.undeerc.org/assets/PDFs/PCOR-Phase-III-Final-Report.pdf (accessed May 2024), where 1 ton = 0.907185 metric tons.

is produced. The storage facility was permitted in 2023, and injection operations into the Broom Creek Formation began in October 2023, with the CO_2 transported 3 miles to the injection wellsite. As of March 2024, 0.071 MMt of CO_2 has been stored deep underground.[47] Funding for the project was provided by the North Dakota Lignite Research Program and the North Dakota Clean Sustainable Energy Authority.[48]

9

Cedar Creek Anticline, North Dakota

The Cedar Creek Anticline (CCA) is located in eastern Montana and into southwest North Dakota. The CCA is considered one of the larger U.S. oil-bearing structures, with an estimated 5 billion barrels of original oil in place (OOIP) spanning nearly 100 miles in length, yet only a few miles in width. Drilling for oil began in 1935 near the Bowman County, North Dakota–Montana border.[49] In late 2021, Denbury (now ExxonMobil) completed its 105-mile pipeline extension from the Bell Creek Field (see Bell Creek EOR Project above) to Fallon County, near Baker, Montana. Also added was a 17-mile lateral CO_2 line to Bowman County, North Dakota. Injection operations commenced in early 2022 in the Cedar Hills South Unit (North Dakota), using an estimated annual average greater than 1.0 MMt of CO_2 for associated storage. The CO_2 is sourced from the Wyoming-based ConocoPhillips Lost Cabin and ExxonMobil Shute Creek Gas Plants.

10

Great Plains Sequestration Project

DGC's Great Plains Synfuels Plant (see also Great Plains Synfuels Plant and Associated CO_2 Storage at Weyburn–Midale above) produces CO_2 as one of the by-products from the gasification process from lignite coal to natural gas. Injection operations in the Broom Creek Formation began in 2024, with CO_2 transported 6.8 miles from the plant to the individual injection sites. There exists excess compressor capacity that makes capture of an additional 1.0 MMt per year possible (beyond what is sent to Canada for associated storage). Expectations are that additional compressed volumes of CO_2 will become available over the next 4 years, resulting in on-site storage of 2.7 MMt annually. Project life is anticipated at 12 years, with stored volumes of CO_2 estimated at 26 MMt. Four injection wells are anticipated initially, with two additional wells planned in 2026 or when increased volumes are warranted.[50] As of March 2024, 0.25 MMt of CO_2 has been stored.[51]

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[47] www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/CO2%20Reporting/Website%20CO2%20Volume%20Reporting_Blue%20Flint.pdf (accessed May 2024).

[48] https://www.ccus-expo.com/industry-news/harvestone-blue-flint-facility-north-dakota-begins-co2-injection#:~:text=In%20October%20of%202023%20the,Resources%20to%20start%20this%20process.(accessed May 2024).

[49] https://archives.datapages.com/data/ndgs/data/011/051/051.html (accessed May 2024).

[50] www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/DGC/C29450.pdf (accessed May 2024).

[51] www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/CO2%20Reporting/Website%20CO2%20Volume%20Reporting_DGC.pdf (accessed May 2024).

11
Red Trail Energy (RTE) Project
RTE is operating a CO_2 capture facility adjacent to its ethanol production plant near Richardton, North Dakota. The plant began operating in 2007, and an average 0.18 MMt of CO_2 is emitted per year from the fermentation process during ethanol production. The stream composition is projected to be 99.9% CO_2. The storage facility was permitted in 2021, and injection operations into the Broom Creek Formation began in June 2022, with the CO_2 transported 2 miles to the injection wellsite. RTE was the first active Class VI project in North Dakota. As of the March 2024, RTE injected nearly 0.29 MMt of CO_2, essentially meeting the goals of the system.[52]

WYOMING

12–17
Greencore Pipeline Associated Storage Fields
There are six current CO_2 associated storage projects active in Wyoming. These projects are located along the Greencore Pipeline in Carbon, Fremont, Nutrona, and Sweetwater Counties. The CO_2 is sourced from the Wyoming-based ConocoPhillips Lost Cabin and ExxonMobil Shute Creek Gas Plants. The first CO_2 flood in Wyoming, beginning in 1986, continues today in the Lost Soldier–Wertz Fields. Since 1986, oil production using CO_2 is approximately 150 million barrels (bbl), with severance tax revenue to the state of over $400 million ($50/bbl oil price). The six fields and their associated operators are listed as follows:[53]

- Monnel Unit (Patrick Draw) – Contango
- Lost Soldier/Wertz Fields – Amplify
- Beaver Creek Field – Denbury/ExxonMobil
- Big Sand Draw Field – Denbury/ExxonMobil
- Grieve Field – Denbury/ExxonMobil
- Salt Creek Field – Contango

PARTIALLY PERMITTED COMMERCIAL CCUS PROJECTS

UNITED STATES

NORTH DAKOTA

18
Dakota Carbon Center West SGS Project
The Dakota Carbon Center West SGS Project will be operated by DCC West Project LLC (DCC West), a subsidiary of Minnkota Power Cooperative, Inc. (Minnkota). The two-unit Milton R. Young Station (MRYS), located approximately 6 miles from Center, North Dakota, is a minemouth lignite coal-fired power plant and Minnkota's primary generating resource. The lignite

[52] www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/CO2%20Reporting/Website%20CO2%20Volume%20Reporting_Red%20Trail.pdf (accessed May 2024).
[53] https://www.eoriwyoming.org/projects-resources/publications/eori-co2-eor-fact-sheets-2024/viewdocument/344 (accessed May 2024).

used as fuel for electrical generation is the primary source of CO_2. The stream composition is anticipated to be at least 98% CO_2 and will be transported approximately 7 miles to the injection wellsite. The storage facility was permitted in 2023 for injection operations into the Broom Creek Formation. The storage facility is designed to receive a maximum operating rate of 6.11 MMt per year, with a maximum of 122.9 MMt over a 20-year injection period. In addition to providing storage services to MRYS, to the extent there is additional storage capacity, DCC West may decide to market CO_2 storage services to third-party entities, provided the stream meets the prescribed composition terms.[54]

19–20

Tundra SGS Project (North Dakota CarbonSAFE)

Project Tundra, which comprises two separate but connected scopes, Tundra Capture and Tundra SGS (secure geologic storage), is an initiative to install postcombustion CO_2 capture and geologic storage at MRYS and associated property. MRYS is operated by, and the associated property is owned by, Minnkota (see also Dakota Carbon Center West SGS Project above). The two storage facilities (stacked storage) were permitted in 2021, and the CO_2 is planned to be transported 0.25 miles to the injection wellsite. The projected stream composition is at least 99% CO_2, with Minnkota permitted to capture up to an annual average of 4.3 MMt per year for injection into the Broom Creek Formation and 1.17 MMt per year for injection into the Deadwood Formation, if needed.[55] Minnkota transferred its interest in Tundra SGS to DCC East Project LLC and was awarded $350 million from the DOE Office of Clean Energy Demonstrations in December 2023 to pursue capture facilities under the Bipartisan Infrastructure Law.[56]

WYOMING

21

Sweetwater Carbon Storage Hub

Frontier Carbon Solutions, LLC (Frontier) is developing the Sweetwater Carbon Storage Hub (SCS Hub), spanning more than 100,000 acres in southwestern Wyoming. The SCS Hub will provide carbon storage for key industrial emitters across the Mountain West. At full capacity, the SCS Hub is anticipated to store up to 5 MMt of CO_2 annually from neighboring industrial emitters and DAC partners. In December 2023, Frontier received three Class VI permits to construct under Wyoming's underground injection control (UIC) program. These were the first permits received in Wyoming. The SCS Hub will be constructed in phases and operational for over a 20-year injection period. The first phase of the project with three wells has a combined permitted injection rate of 1.274 MMt of CO_2 per year.[57] Frontier plans to complete construction of the three Class VI

[54] https://www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/DCC%20West/C30122.pdf (accessed May 2024).

[55] https://www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/Minnkota/BC/C29029.pdf and https://www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/Minnkota/DW/C29032.pdf (accessed May 2024).

[56] https://www.energy.gov/oced/carbon-capture-demonstration-projects-selections-award-negotiations (accessed May 2024).

[57] https://ccusmap.com/markers/project-detail/sweetwater-carbon-storage-hub (accessed May 2024).

wells in 2024 and begin injection shortly thereafter. Frontier is also preparing six additional Class VI UIC permits to file with the Wyoming Department of Environmental Quality.[58]

[58] https://www.worldoil.com/news/2023/12/19/frontier-carbon-solutions-secures-first-permits-for-sweetwater-carbon-storage-hub-in-wyoming/ (accessed May 2024).

APPENDIX B

ANNOUNCED COMMERCIAL CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS) PROJECTS IN THE PLAINS CO_2 REDUCTION (PCOR) PARTNERNSHIP REGION

Table B-1. Basic Characteristics of Announced Commercial Carbon Capture, Utilization, and Storage (CCUS) Projects in the Plains CO_2 Reduction (PCOR) Partnership Region

No.	State/ Province	Project Name	Owner/ Operator	CO_2 Source	CO_2 Source Type	Storage Type	Injection Rate	Storage Capacity	Operating	Partially Permitted	Announced
				ANNOUNCED PROJECTS – CANADA							
1–23	AB	Alberta Development of Carbon Storage Hubs: Rounds 1 and 2	Various	Various	Various	Various	Various	Various			X (23)
36	AB	Alberta Carbon Grid[59]	TC Energy Corporation, Pembina Pipeline Corporation	Multiple		Dedicated/ storage hub	~20.0 MMta	TBD			X
37	AB	Oil Sands Pathways to Net Zero aka Pathways CO_2 Transportation Network and Storage Hub Project[60]	Pathways Alliance[61]	Multiple	Oil sands	Dedicated/ storage hub	~10–12 MMta	TBD			X
				ANNOUNCED PROJECTS – UNITED STATES							
38	AK	Alaska Railbelt CCS Project	State of Alaska	Chugach Electric Association: George Sullivan Plant 1, Southcentral Power Project/ new build[62]	Natural gas	Dedicated storage	TBD	≥50 MMt (≤30 years)			X
39	MT	Snowy River CO_2 Sequestration Project[63]	Denbury Carbon Solutions, LLC	Shute Creek/ Lost Cabin (WY)	Gas processing	Dedicated storage	TBD	136 MMt			X

Continued . . .

59 https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2022/market-snapshot-new-projects-alberta-could-add-significant-carbon-storage-capacity-2030.html (accessed May 2024).
60 https://pathwaysalliance.ca/foundational-project/regulatory/ (accessed May 2024).
61 www.rbccm.com/en/insights/story.page?dcr=templatedata/article/insights/data/2023/02/meet_the_pathways_alliance#:~:text=Pathways%20will%20be%20executed%20via,finishing%20the%20job%20by%202050 (accessed May 2024).
62 https://static1.squarespace.com/static/59f229bd2aeba5312c87df44/t/65ef6eceb9b27d3c6118433e/1710190289944/doe-proposal.pdf (accessed May 2024).
63 https://eplanning.blm.gov/public_projects/2026556/200564713/20086275/250092457/1_Snowy%20River%20CO2%20Sequestration%20Plan%20of%20Development_508.pdf (accessed May 2024) (150 million tons = 136 MMt).

Table B-1. Basic Characteristics of Announced Commercial Carbon Capture, Utilization, and Storage (CCUS) Projects in the Plains CO_2 Reduction (PCOR) Partnership Region (continued)

No.	State/ Province	Project Name	Owner/ Operator	CO_2 Source	CO_2 Source Type	Storage Type	Injection Rate	Storage Capacity	Operating	Partially Permitted	Announced
				ANNOUNCED PROJECTS – UNITED STATES (continued)							
40	NE	Voyager[64]	Carbon America, Voyager Sequestration LLC, Bridgeport Ethanol LLC	Bridgeport Ethanol	Ethanol production	Dedicated storage	0.175 MMta	TBD			X
41	ND	Coal Creek Capture Project: Site Characterization and Permitting	Rainbow Energy Center	Coal Creek Station	Lignite	Dedicated storage	~9 MMta	~200 MMt (22 years)			X
42	ND	Midwest Carbon Express (MCE) Project	Summit Carbon Storage #1, LLC	Multiple (ND, SD, IA, MN, NE)	Ethanol production/ other	Dedicated storage hub	~6.22 MMta	~124.4 MMt (20 years)			X
43	ND	MCE Project	Summit Carbon Storage #2, LLC	Multiple (ND, SD, IA, MN, NE)	Ethanol production/ other	Dedicated storage hub	~4.92 MMta	~98.3 MMt (20 years)			X
44	ND	MCE Project	Summit Carbon Storage #3, LLC	Multiple (ND, SD, IA, MN, NE)	Ethanol production/ other	Dedicated storage hub	~6.49 MMta	~129.7 MMt (20 years)			X
45	ND	Prairie Horizon Hydrogen Hub FEED & Design	Prairie Horizon Energy Solutions	Dickinson Renewable Diesel Facility	Renewable diesel processing	Dedicated storage hub	TBD	~100 MMt			X
46	ND	Roughrider Carbon Storage Hub	ONEOK, Inc.	Lonesome Creek, Cerilon, multiple (ND)	Gas processing/ gas to liquids	Dedicated storage hub	TBD	≥50 MMt (≤30 years)			X
47	WY	Wyoming CarbonSAFE	Basin Electric Power Cooperative	Dry Fork Station	Coal	Dedicated storage	TBD	≥50 MMt (≤30 years)			X

[64] https://ccusmap.com/markers/project-detail/voyager (accessed May 2024).

DESCRIPTION OF ANNOUNCED COMMERCIAL CCUS PROJECTS IN THE PCOR PARTNERSHIP REGION

CANADA

ALBERTA

1–23
Alberta Development of Carbon Storage Hubs: Rounds 1 and 2
The Government of Alberta (Alberta) received many inquiries and significant interest from entities looking to obtain carbon sequestration tenure, also known as pore space. In response, Alberta decided in 2021 to seek through a competitive process "Expressions of Interest" for a strategic hub concept. Successful proponents are expected to have the technical, financial, and operational capacity to manage the hub, i.e., an area of pore space overseen by a private company that can undertake carbon sequestration of captured CO_2 from various emissions sources. Successful proponents are expected to obtain all necessary regulatory approvals and ensure the safe and effective operation and closure of the hub, enabling access to pore space and sequestration of emissions from Alberta's industrial sector at fair rates.[65] In March and October 2022, the province selected a total of 25 new carbon capture and storage (CCS) projects for further evaluation.[66] Two of these proposed projects are described in more detail below, namely, the Alberta Carbon Grid and the Oil Sands Pathways to Net Zero (also known as the Pathways CO_2 Transportation Network and Storage Hub Project). A final investment decision is anticipated in 2025, with a targeted project completion date set for 2028.[67]

24
Alberta Carbon Grid
TC Energy and Pembina Pipeline entered into a carbon sequestration evaluation agreement with Alberta to evaluate Alberta Carbon Grid (ACG) – a storage hub for safely storing carbon from industrial emissions in Alberta. ACG secured the rights to evaluate over 2 million acres of land north of Fort Saskatchewan. ACG would be an open-access system and developed in phases. The first phase is in the Alberta Industrial Heartland project, with the potential of storing up to 10 MMt of CO_2 annually. The long-term vision of ACG is to annually transport and store up to 20 MMt of CO_2 through several hubs across Alberta.

25
Pathways CO_2 Transportation Network and Storage Hub Project
The Pathways Alliance consists of Canada's six largest oil sands producers, namely Canadian Natural Resources Limited, Cenovus Energy, ConocoPhillips Canada, Imperial, MEG Energy, and Suncor Energy, working collectively to achieve net-zero greenhouse gas emissions from oil sands

[65] https://www.alberta.ca/system/files/custom_downloaded_images/energy-request-for-full-project-proposals-rfpp-guidelines.pdf (accessed May 2024).
[66] https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2022/market-snapshot-new-projects-alberta-could-add-significant-carbon-storage-capacity-2030.html (accessed May 2024).
[67] https://albertacarbongrid.ca/wp-content/uploads/2024/03/AlbertaCarbonGrid_Factsheet.pdf (accessed May 2024).

operations by 2050.[68] The Pathways Alliance's first project is building a CCS network connecting more than 20 facilities in the Fort McMurray, Christina Lake, and Cold Lake regions of northeast Alberta to a carbon storage hub near the Cold Lake region for storage deep underground.[69] The 250-mile Pathways CO_2 Transportation Network will move approximately 10–12 MMt of CO_2 equivalents annually from oil sands facilities.[70] The CO_2 will move via the network to associated hub piping (tie-ins) where it will be transferred to the Pathways CO_2 injection wells within the Pathways CO_2 Storage Hub. Each Pathways CO_2 injection well will be drilled and completed to inject CO_2 into the Basal Cambrian Sands. Construction is anticipated to begin as early as Quarter 4, 2025.[71]

UNITED STATES

ALASKA

26

Alaska Railbelt CCS Project

This proposed project aims to address the pending shortage of natural gas and electricity supply in the Railbelt of Alaska, including major urban centers of Anchorage, Fairbanks, and the Matanuska–Susitna Valley.[72] As part of the U.S. Department of Energy (DOE) CarbonSAFE (Carbon Storage Assurance Facility Enterprise) Phase II effort, the project will assess the feasibility of using a storage complex in the Beluga River gas field on the northern shore of Cook Inlet Basin for commercial-scale storage (≥50 MMt CO_2 within 30 years). Based on gas volumes produced to date and using CO_2 density at reservoir conditions, the prospective CO_2 storage resource for the Beluga River Field is estimated at 157 MMt. The CO_2 would be captured from a proposed new 400-MW-gross, dual-fuel-capable power generation plant plus two existing facilities in southcentral Alaska at a rate of 2.6 MMt per year. Additional depleted regional fields may also be explored for storage resources.[73]

MONTANA

27

Snowy River CO_2 Sequestration Project

The Snowy River CO_2 Sequestration Project is proposed in Carter County, situated in the lower southeast corner of Montana, on a combination of federal, state, and privately owned land. In 2021, Denbury (ExxonMobil) submitted an application for transportation and utility systems and facilities on federal lands to the Bureau of Land Management (BLM). This right-of-way application for a 30-year term requested use of approximately 100,200 acres of BLM pore space

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[68] https://pathwaysalliance.ca/wp-content/uploads/2024/03/Pathways-Project-Overview-Final-PRINT-sep20.pdf (accessed May 2024).
[69] https://pathwaysalliance.ca/wp-content/uploads/2023/10/PA-fact-sheet-FOUNDATIONAL-RGB-F1.1-MAL.pdf (accessed May 2024).
[70] https://pathwaysalliance.ca/foundational-project/regulatory/ (accessed May 2024).
[71] https://pathwaysalliance.ca/foundational-project/regulatory/ (accessed May 2024).
[72] https://omb.alaska.gov/ombfiles/25_budget/UA/Proposed/2025proj65319.pdf (accessed May 2024).
[73] https://static1.squarespace.com/static/59f229bd2aeba5312c87df44/t/65ef6eceb9b27d3c6118433e/1710190289944/doe-proposal.pdf (accessed May 2024).

to store CO_2 underground.[74] Although specific capture facilities were not specified, the existing 105-mile Cedar Creek Anticline pipeline (see Cedar Creek Anticline, North Dakota, above) would be used to transport approximately 136 MMt of CO_2 over the course of 20 years for dedicated storage. There are 15 proposed well pads (12 on federal land and three on state land). In September 2023, Denbury submitted a plan of development (POD) and to support its previous application.[75] In February 2024, Denbury submitted an updated POD and environmental assessment (EA), with public comments due by May 17, 2024. Because Montana does not have Class VI primacy, application(s) to the U.S. Environmental Protection Agency (EPA) are required for Class VI injection permits.

NEBRASKA

28
Voyager
Carbon America announced in 2022 that it was working with Bridgeport Ethanol, LLC, to develop a CCS project in eastern Nebraska. The plant began operating in 2007, and an average of 0.159 MMt of CO_2 is emitted per year from the fermentation process during ethanol production. In March 2024, Class VI permit application —the first in Nebraska, was submitted to EPA.[76] Nebraska does not have Class VI primacy. The proposed storage site is located about 10 miles west of the ethanol plant. Carbon America's website provides a goal to begin commercial operations in 2025;[77] however, EPA aims to review complete Class VI applications and issue permits, when appropriate, within approximately 24 months.[78]

NORTH DAKOTA

29
Coal Creek Capture Project
As part of a DOE CarbonSAFE Phase III: Site Characterization and Permitting effort, the Coal Creek Capture Project is looking to advance a large-scale commercial CO_2 storage hub at the plant located near Underwood, North Dakota. The proposed hub would store up to 8.9 MMt of CO_2 per year captured from the Coal Creek Station and up to 0.20 MMt of CO_2 per year from the colocated Blue Flint Ethanol plant. Primary project activities are to acquire 3D seismic data, drill a geologic characterization (stratigraphic test) well, conduct a pipeline front-end engineering and design (FEED) study, prepare North Dakota Class VI permit applications, and generate National Environmental Policy Act (NEPA) documentation such as an environmental information volume

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[74] https://eplanning.blm.gov/eplanning-ui/project/2026556/510 (accessed May 2024).
[75]https://eplanning.blm.gov/public_projects/2026556/200564713/20087640/250093822/Denbury%20Snowy%20River%20CO2%20Sequestration%20Project_Information%20Sheet.pdf (accessed May 2024).
[76] https://carbonherald.com/carbon-america-submits-first-class-vi-permit-application-in-nebraska/ (accessed May 2024) (175,000 tons = .159 MMt).
[77] https://www.carbonamerica.com/bridgeport (accessed May 2024).
[78] https://www.epa.gov/uic/current-class-vi-projects-under-review-epa#:~:text=Please%20see%20the%20links%20below,projects%20in%20states%20with%20primacy.&text=For%20more%20information%20on%20Class%20VI%20primacy%2C%20please%20see%20EPA's,appropriate%20within%20approximately%2024%20months (accessed May 2024).

(EIV) and subsequent EA or environmental impact statement (EIS). The Phase III project is anticipated to run through September 2026.[79]

30–32

Midwest Carbon Express (MCE) Project

Summit Carbon Solutions, LLC (SCS) proposes to construct the MCE Project, which will capture or receive CO_2 from over 30 anthropogenic sources (biofuel and other industrial facilities) across the Midwest and transport the CO_2 via pipeline to North Dakota to be permanently stored within deep underground formations. The commingled stream composition in the MCE pipeline from all sources is anticipated to average ≥98.25% CO_2, with less than 1.75% trace quantities of other constituents. The MCE Project is conservatively designed with a 95% CO_2, 2% O_2, and 3% N_2 specification; therefore, the three operating entities (Summit Carbon Storage #1, LLC; Summit Carbon Storage #2, LLC; and Summit Carbon Storage #3, LLC) requested a CO_2 stream that will range from 95% CO_2 to ≤99.9% CO_2 in its commercial permit applications to receive CO_2 from a variety of industrial sources. The MCE Project is designed to transport up to 18 MMt of CO_2 per year via a 2000-mile Greenfield pipeline. The pipeline will receive CO_2 from over 30 anthropogenic sources, including biofuels from ethanol facilities and other industries across the Midwest, including Iowa, Minnesota, Nebraska, South Dakota, and North Dakota. Each site will also have associated surface facility infrastructure that will accept CO_2 transported via a CO_2 flowline. Combined maximum modeled storage volume across all three storage facilities is 352 MMt over 20 years. The captured CO_2 will be injected into the Broom Creek Formation.[80] On February 6, 2024, SCS filed three storage facility permit applications with the North Dakota Department of Mineral Resources Division of Oil & Gas.[81] A public hearing is scheduled for June 11 and 12, 2024.[82]

33

Prairie Horizon Hydrogen Hub FEED and Design

Prairie Horizon Energy Solutions, a collaboration between Marathon Petroleum Corporation and TC Energy, is exploring the feasibility of a potential low-carbon energy project in Stark County, North Dakota. The project includes a production of low-carbon hydrogen and ammonia at a facility near Dickinson, North Dakota, for industrial and agricultural use. CO_2 from the production facility would be captured, transported, and stored deep underground at a site in the region.[83]

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[79] https://www.netl.doe.gov/project-information?p=FE0032331 (accessed May 2024).

[80] https://www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/Summit/SCS%20%231/C30869.pdf (accessed May 2024).

[81] https://www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/Summit/SCS%20%231/C30869.pdf; https://www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/Summit/SCS%20%232/C30873.pdf; https://www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/Class%20VI/Summit/SCS%20%233/C30877.pdf (accessed May 2024).

[82] https://www.dmr.nd.gov/oilgas/dockets/2024/docket061124.pdf (accessed May 2024).

[83] https://www.tcenergy.com/operations/energy-solutions/prairie-horizon-energy-solutions/ (accessed May 2024).

Roughrider Carbon Storage Hub
As part of a DOE CarbonSAFE Phase II effort, the Roughrider Carbon Storage Hub project is determining the feasibility of developing a commercial-scale (≥50 MMt CO_2 within 30 years) stacked storage complex in northwestern North Dakota. The CO_2 will be captured from several gas-processing plants in the area owned and operated by ONEOK and a planned gas-to-liquids (GTL) plant in the project area. This 2-year effort is scheduled to run through September 2025.

WYOMING

35
Wyoming CarbonSAFE
The University of Wyoming School of Energy Resources (UWY SER) leads the Wyoming CarbonSAFE Phase III: Site Characterization and Permitting project at Basin Electric Power Cooperative's Dry Fork Station (DFS) in the Powder River Basin. DFS is a coal-based electric generation station proposed as the project's CO_2 source. The project goal is to finalize surface and subsurface site characterization and certify the safety and security of eventual commercial-scale storage at DFS. Applications for Class VI permits to construct will be submitted to the Wyoming Department of Environmental Quality, the state agency with primary regulatory authority for Class VI. In addition, a NEPA EIV and potential EA will be prepared. This project will incorporate Membrane Technology and Research's FEED and CO_2 capture analysis into the project's commercialization assessments. The project is currently scheduled to run through September 2024.[84]

[84] https://www.netl.doe.gov/project-information?p=FE0031891 (accessed May 2024).