



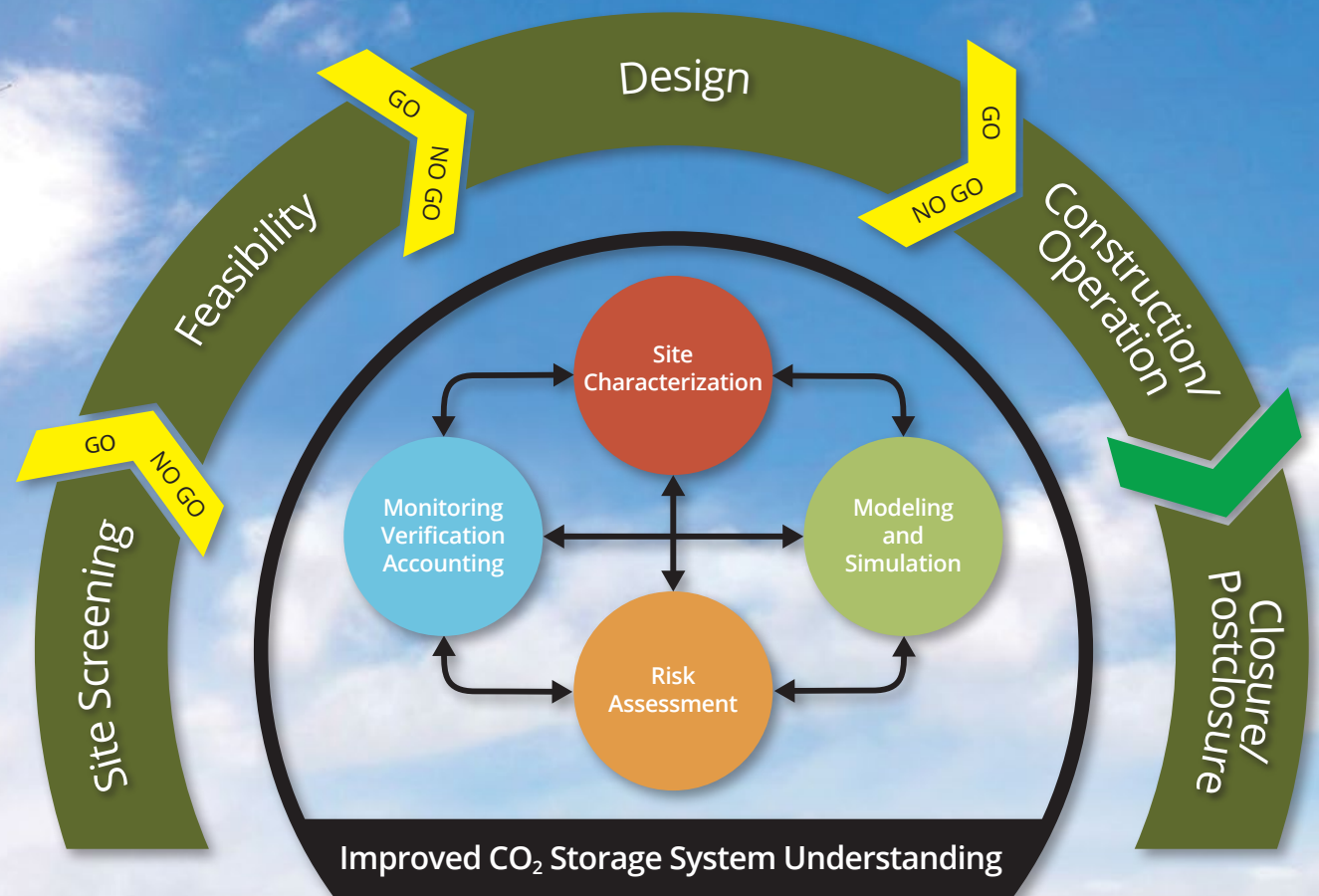
TAKING ACTION

The pathway to developing a commercial CCUS project includes an iterative assessment of a prospective CO₂ storage location and moving efficiently through the permitting process. Several commercial CCUS projects are active in the PCOR Partnership region, with these projects containing combinations of CO₂ capture, transportation, dedicated and associated storage, EOR, and production of low-carbon fuels. The lessons learned from these projects at all stages of development are a catalyst to support future commercial CCUS development in the region.

PHILOSOPHY OF APPROACH

The PCOR Partnership employs a philosophy that integrates site characterization, modeling and simulation, risk assessment, and MVA strategies into an iterative process to produce meaningful results for large-scale CO₂ storage projects. Elements of any of these activities are crucial for understanding or developing the other activities. For example, new knowledge gained from site characterization reduces uncertainty in

geologic reservoir properties. This reduced uncertainty can then propagate through modeling, risk assessment, and MVA efforts. Because of this process, the PCOR Partnership Program is in a strong position to refine characterization, modeling, risk assessment, or MVA efforts based on the results of any of these activities and has produced a best practices manual for this adaptive management approach.

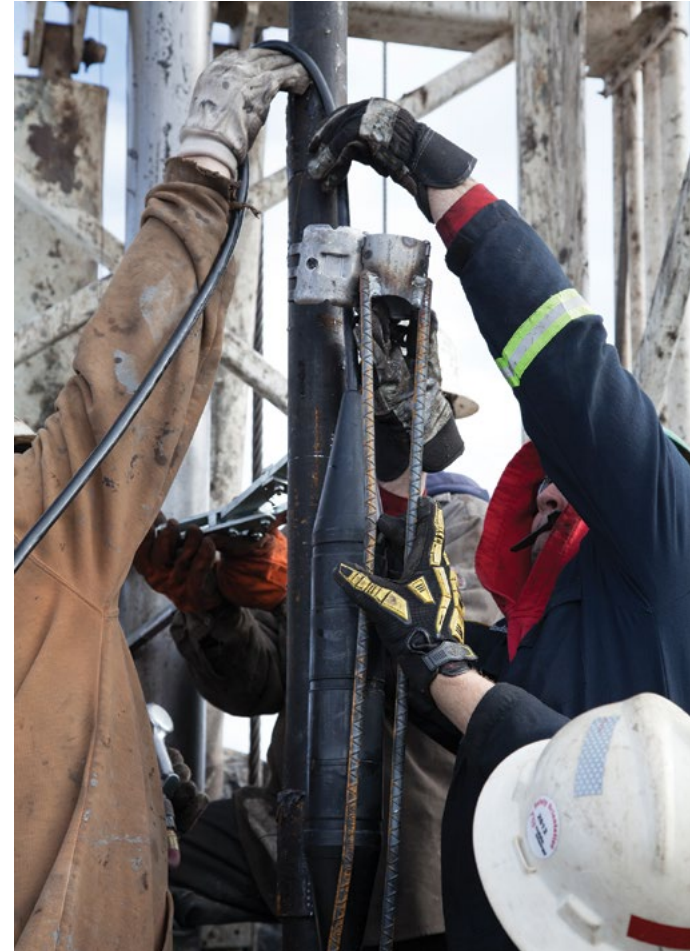


SITE CHARACTERIZATION

Site characterization comprises collection, analysis, interpretation, and application of data to understand CO₂ storage potential and assessment of factors that could impact CO₂ storage project performance. Data collection methods range from accessing existing reports and documentation available from public and private sources to using a wide array of field technologies for determining or measuring various geologic/physical/chemical properties of subsurface and surface environments.

Site characterization activities serve as direct inputs into the various modeling and simulation activities to better predict CO₂ migration pathways, assess technical subsurface risks, and aid in the monitoring of CO₂ migration in the subsurface. These elements of the project help evaluate expected and actual performance during commercial-scale CO₂ injection, storage, and EOR.

Site characterization objectives and associated activities are largely driven by project- and site-specific risk and uncertainty and the need to inform site design and operation. Depending on the project phase, several different types of data may be collected, including petrophysical, mineralogical, geomechanical, and geochemical. Data acquisition occurs throughout the entire project, although the intensity of the effort and the characterization techniques employed vary with the different phases of the project.

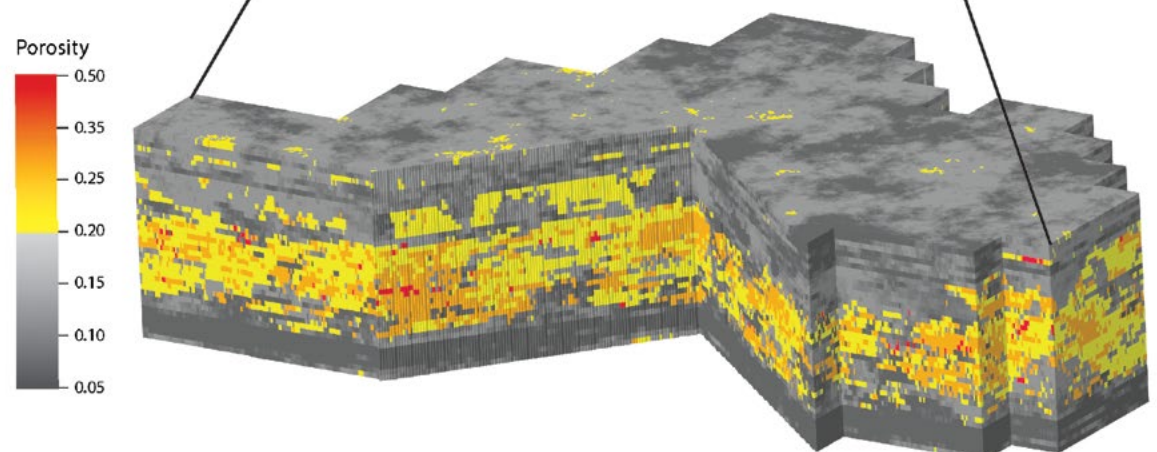
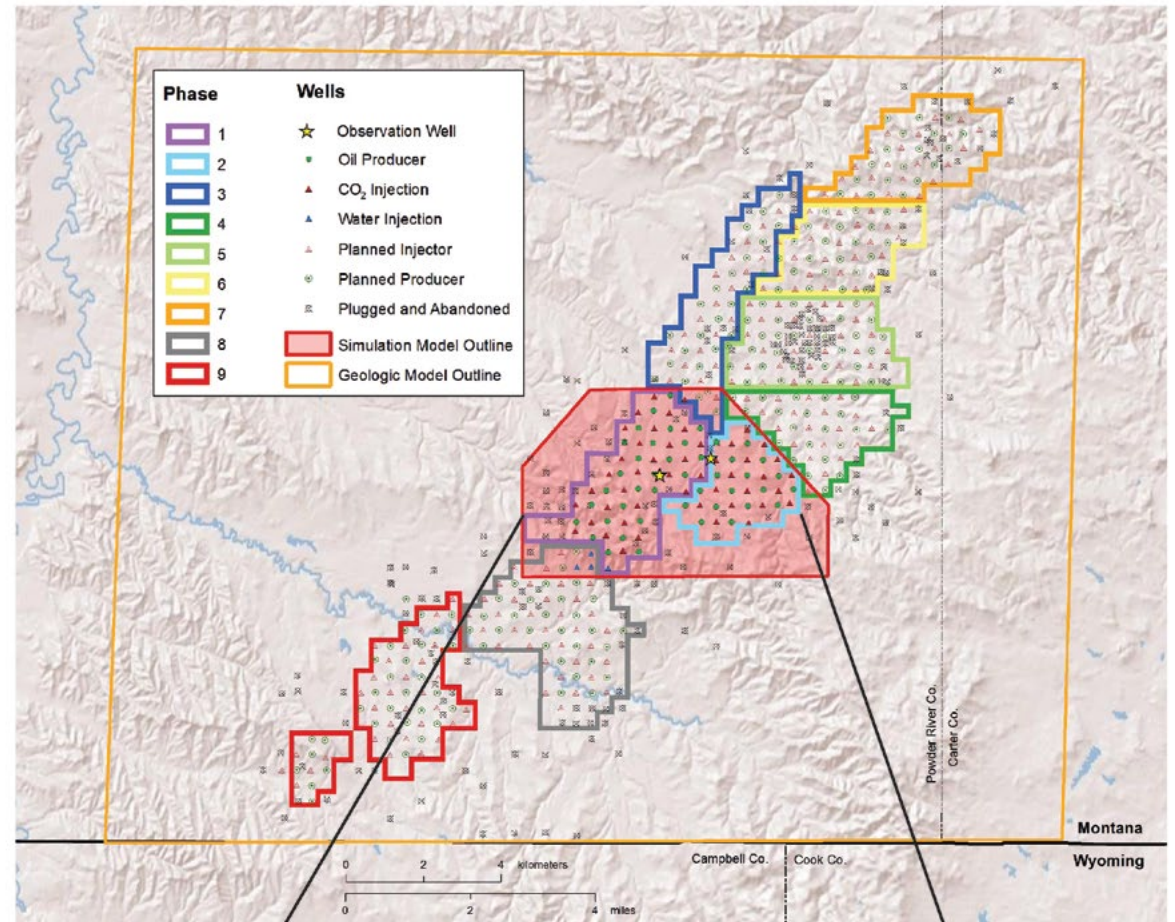


SIMULATION AND MODELING

A geologic model is a computerized 3D rendering of the subsurface that provides a digital framework of CO₂ reservoir complexities, critical to understanding CO₂ storage. The model provides a 3D understanding of the storage horizon and associated cap rock to allow design and implementation of a CO₂ injection project. Common components of geologic models include information generated from site characterization activities, with estimates of rock properties (e.g., rock type, porosity, permeability) and structural framework (i.e., geologic surfaces, geologic layers, faults).

Predictive multiphase fluid flow simulations, geomechanical modeling, and geochemical simulation are used to interpret and analyze the geologic, reservoir, and fluid data and conduct predictive multiphase flow, geomechanical, and geochemical simulations to identify data gaps, identify potential risks, and guide the MVA program.

Geologic models serve as the basis for the fluid flow simulations to predict the subsurface extent of the injected CO₂ and the potential pressure effects associated with storing CO₂. These predictions are important for the design of a CO₂ storage system, assessment of project risks, and design and interpretation of the results of a monitoring and accounting program. Geomechanical and geochemical simulations are also conducted to identify potential risks and guide monitoring programs.



Muddy Sandstone (Bell Creek Field reservoir)

RISK ASSESSMENT

Risk assessment is a vital component of the adaptive management approach for CO₂ storage project development.

“Risk” is the severity of consequences (negative impacts) of an event weighed against how likely those consequences are to occur. In the context of a CO₂ storage project, risks can affect operational performance and long-term permanence of CO₂ storage. “Risk assessment” is the iterative process of identifying, analyzing, and evaluating potential project risks.

For over a decade, the PCOR Partnership has conducted risk assessments for CO₂ storage projects consistent with international standard protocols.³⁹⁻⁴² These best practices provide reliable methods for identifying project-related risks, including analyzing probability and potential impacts and evaluating risk treatment and priority.

Identifying and assessing potential risks for a CO₂ storage project start early in the development of a project when the project team identifies and evaluates potential risks grouped into broad categories (e.g., capacity, injectivity, and lateral and vertical migration).⁴³ These risks are refined over time as more data become available.

Risk assessment outcomes inform CO₂ storage project development through every phase. Additionally, the risk assessment informs the monitoring, reporting, and verification (MRV) plan for a CO₂ storage project, ensuring higher-ranking risks are being monitored by one or more measurements.

ESTABLISH THE CONTEXT

- Define the storage project.
- Define the storage facility and storage unit(s).
- Define the risk criteria that will be used to evaluate the identified risks.

RISK IDENTIFICATION

- Use an independent risk management expert to facilitate the process.
- Elicit input from project stakeholders and subject matter experts.
- Generate a functional model of the storage complex.
- Identify potential risks that would negatively impact the storage project.
- Ensure that the following four technical risk categories are considered:
 - Storage capacity
 - Injectivity
 - Lateral and vertical containment of CO₂ and formation fluids
 - Induced seismicity
- Thoroughly document each potential risk, and generate a risk register.

RISK ANALYSIS

- Develop a set of quantifiable physical consequences and a means to link these to project impacts.
- Consult the available site characterization, geologic modeling, and reservoir simulation results.
- Evaluate predictive simulations to forecast storage project performance during CO₂ injection.
- Capture risk probability and impact scores from subject matter experts.
- Quantify uncertainty in the risk scores.

RISK EVALUATION

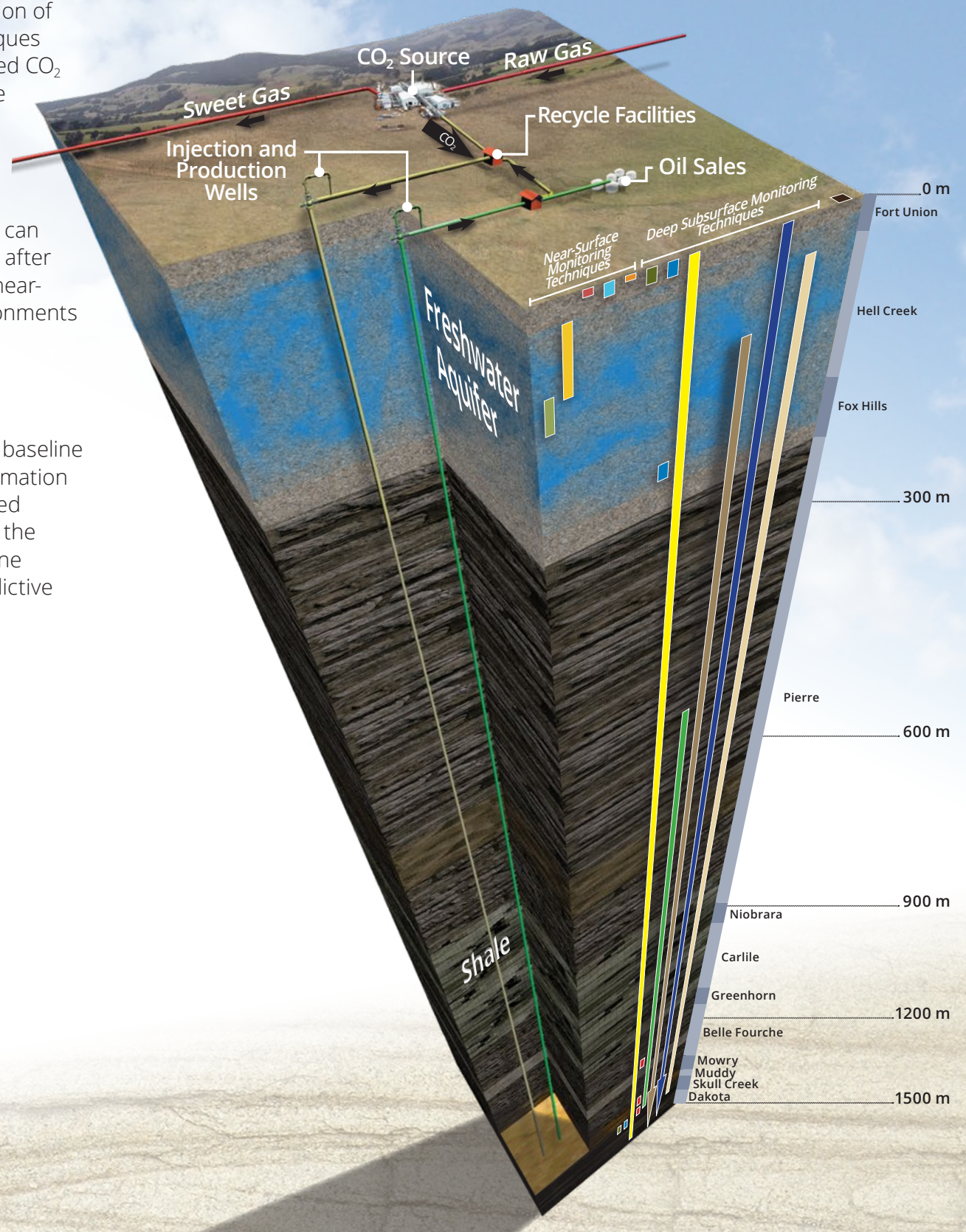
- Plot each individual risk onto a risk map, and evaluate uncertainty in the risk scores.
- Identify moderate and high-ranking risks that plot in the orange and red fields.
- If a more quantitative evaluation is needed, then employ a probabilistic method such as Monte Carlo simulation or Bayesian methods.

MONITORING, VERIFICATION, AND ACCOUNTING

Monitoring, verification, and accounting, known as MVA, is the combination of monitoring technologies and techniques used to track the migration of injected CO₂ as well as to confirm that the surface and subsurface environments are not negatively impacted by injection activities.

A variety of monitoring technologies can be implemented before, during, and after injection operations in the surface, near-surface, and deep subsurface environments at a CO₂ storage site.

MVA data collected before injection operations (often as part of the site characterization process) serve as a baseline framework for the storage site. Information collected after injection begins is used to monitor the dynamic response of the system and provide feedback to refine the geologic model and update predictive simulations.



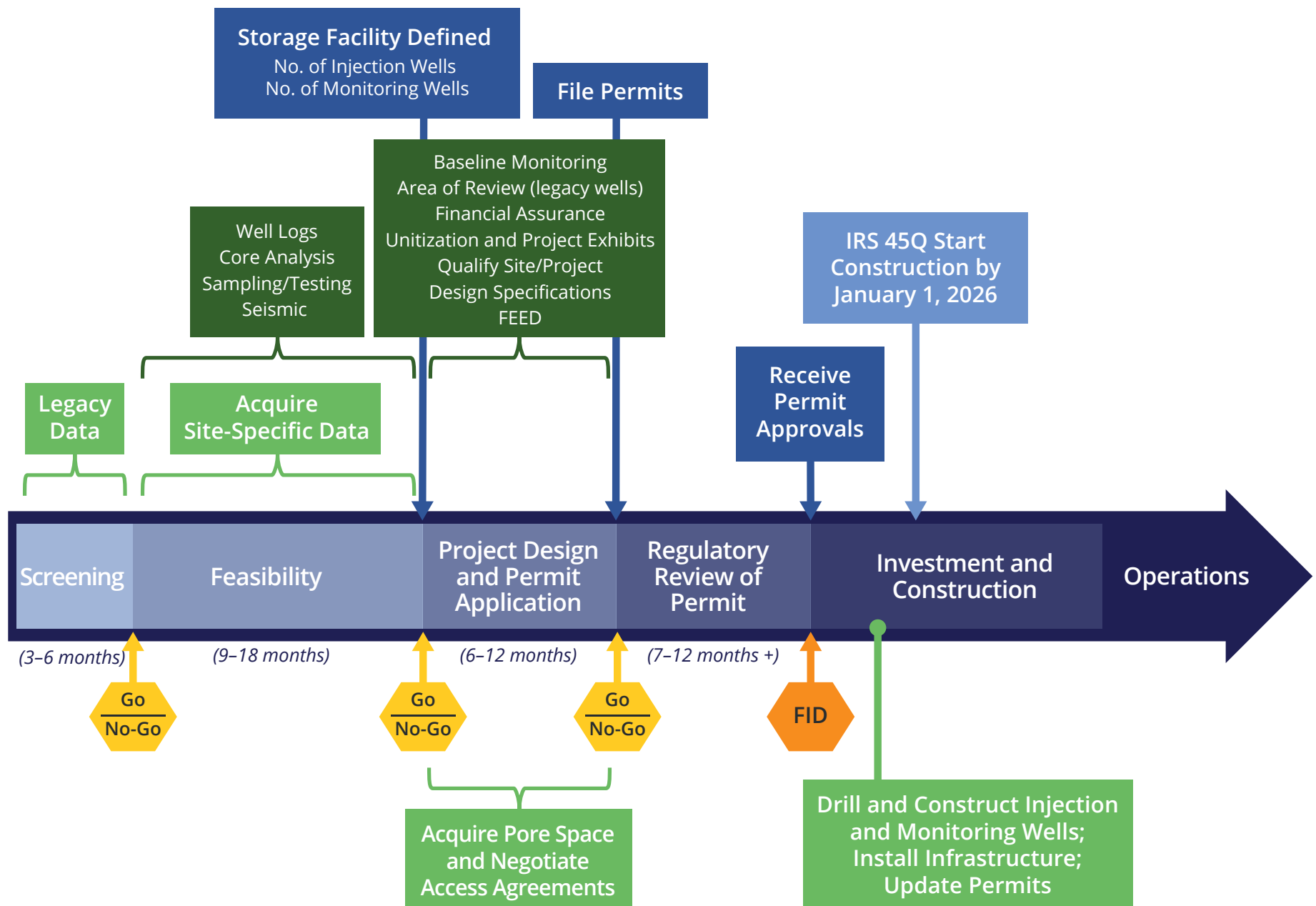
- Fox Hills Groundwater Wells
- Groundwater Wells
- Surface Water
- Soil Gas Profile Stations
- Soil Gas Probes
- Production and Injection Rates
- Wellhead Pressure Monitoring
- Temperature PDM*
- Pressure PDM
- 3D Time-Lapse VSP**
- 3D Time-Lapse Seismic
- Passive Seismic Monitoring
- Neutron Logging
- InSAR***

* Permanent downhole monitoring.
 ** Vertical seismic profile.
 *** Interferometric synthetic aperture radar.

A PERMITTING PROCESS

Permitting considerations for a CO₂ storage project are important even at the earliest stages of project development. Data and information about project feasibility and geologic suitability of the potential storage site(s) will eventually be used to support the permits needed to store CO₂. The figure shows the CCUS project development and permitting process for the state of North Dakota, which begins by the gathering of any existing data in or near the site(s) of interest.

Although this figure is specific to North Dakota, the general progression of the process, as well as the geologic and project data required, is commensurate with other jurisdictions. Reducing the time to develop CCUS permit applications, the length of time for regulatory review, and issuance of a final decision will help accelerate commercial deployment of CCUS. The PCOR Partnership is engaging with regulators and project developers throughout the region to support the permitting process and find ways to promote permit application consistency where possible.



ACTIVE AND DEVELOPING CCUS PROJECTS






Alberta Carbon Trunk Line (ACTL)
This pipeline is capable of transporting up to 14.6 Mt/yr from multiple capture facilities. The CO₂ is transported for EOR operations.

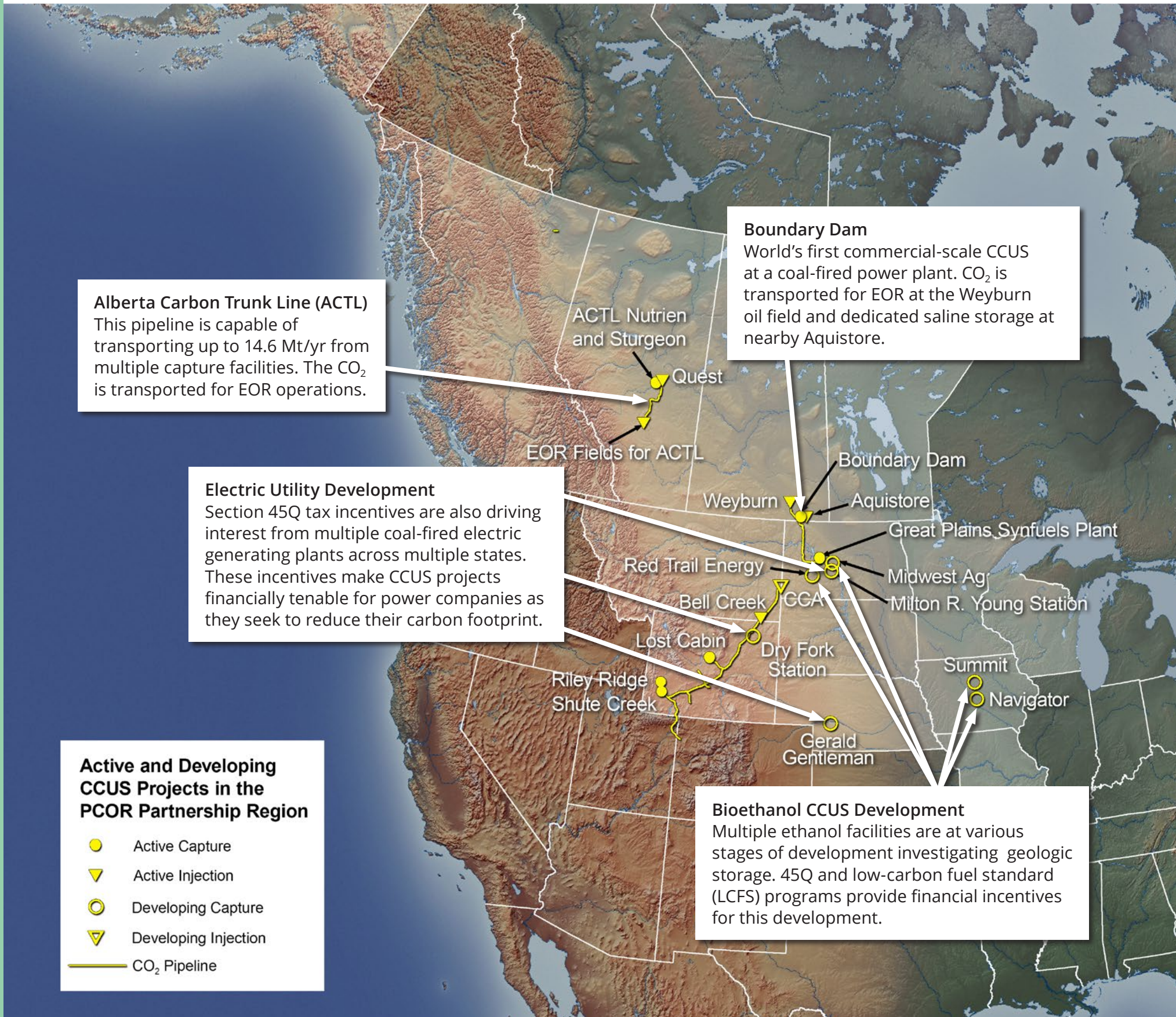
Electric Utility Development
Section 45Q tax incentives are also driving interest from multiple coal-fired electric generating plants across multiple states. These incentives make CCUS projects financially tenable for power companies as they seek to reduce their carbon footprint.

Boundary Dam
World's first commercial-scale CCUS at a coal-fired power plant. CO₂ is transported for EOR at the Weyburn oil field and dedicated saline storage at nearby Aquistore.

Bioethanol CCUS Development
Multiple ethanol facilities are at various stages of development investigating geologic storage. 45Q and low-carbon fuel standard (LCFS) programs provide financial incentives for this development.

Active and Developing CCUS Projects in the PCOR Partnership Region

-  Active Capture
-  Active Injection
-  Developing Capture
-  Developing Injection
-  CO₂ Pipeline



CCUS EFFORTS OUTSIDE OF NORTH AMERICA

Although significant activity is happening across the PCOR Partnership, successful development and operation of full-scale commercial CCUS projects across the world will be required to seriously abate CO₂ emissions from electric generation and industrial sources.

Across North America, numerous CCUS projects are in operation, with the earliest projects dating back to the 1970s

and 1980s. While most of those projects have targeted EOR, many of the projects under development are targeting dedicated storage.

Outside of North America, multiple CCUS projects are active across Europe, the Middle East, Asia, and Australia. The projects represent significant steps forward in advancing our knowledge about how CCUS systems operate under real-world conditions.

The Illinois Industrial CCS Project captures CO₂ from a corn-to-ethanol plant in Decatur, Illinois. One million metric tons per year is transported to a nearby injection well for dedicated storage.

The Langskip CCS – Brevik Norcem is under construction to capture CO₂ from a cement production plant by 2024. The offshore Aurora area is the ideal target, and transport will include a combined ship and pipeline system.

The Karamay Dunhua EOR Project capture systems were retrofitted to a methanol plant in 2015. Captured CO₂ is transported by tanker truck to the Xinjiang oil field for EOR.

The Terrell gas-processing facility has been capturing CO₂ since the early 1970s. The CO₂ is transported and distributed to mature oil fields for EOR.

The Abu Dhabi project is the world's first commercial CCS facility in the iron and steel industry.

Commercial CCUS Projects by Status

- Operational (31)
- Under Construction (3)
- Advanced Development (20)

The Gorgon project, Australia's first CCS project, captures and stores between 3.5 million to 4 million metric tons of CO₂ per year.

Project information from the Global CCS Institute's CO2RE Facilities Database (co2re.co/FacilityData) accessed July 2021. Projects shown are either operational or at advanced stages of development and do not include projects in the early stages of planning.

CO₂ CAPTURE AT GREAT PLAINS SYNFUELS PLANT

The majority of the CO₂ used in the Weyburn–Midale EOR project comes from the Dakota Gasification Company's Great Plains Synfuels Plant, the only commercial-scale coal-to-natural gas facility in the United States. In November 2020, the Great Plains Synfuels Plant reached a milestone: capturing 40 million metric tons of CO₂ since 2000. Approximately 2 million metric tons of CO₂ is captured each year, making it one of the largest carbon capture facilities in the world.⁴⁴

Dakota Gas and its Canadian subsidiary, Souris Valley Pipeline Ltd., operate a 205-mile pipeline to transport the CO₂ from the synfuels plant in Beulah, North Dakota, United States, to the Weyburn and Midale oil fields in Saskatchewan, Canada, for

EOR. CO₂ EOR at Weyburn has generated 104 million barrels of incremental production to date.⁴⁵

In July 2020, during the COVID-19 pandemic, Dakota Gas had its first shipment of beverage-grade CO₂ captured from the Great Plains Synfuels Plant's ammonia production facility and shipped to be sold in the commercial food and beverage industry. The first load was used to help balance pH levels in the water at water treatment plants in North Dakota. In December 2020, Dakota Gas worked with the North Dakota Department of Health to provide beverage-grade liquefied CO₂ to aid in keeping the COVID-19 vaccine at the recommended storage temperature.⁴⁴

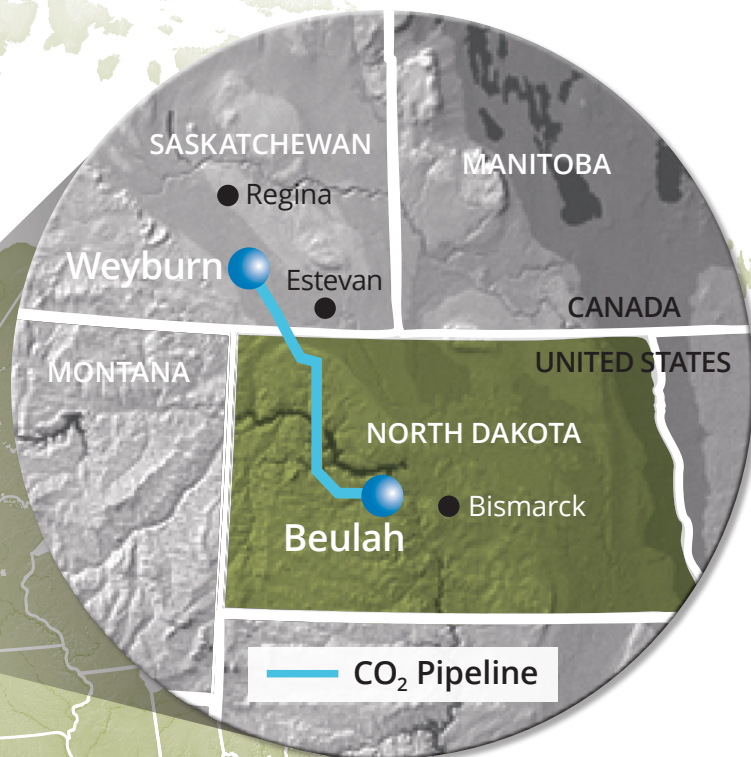


Photo courtesy of Basin Electric Power Cooperative.

CO₂ is captured from the Dakota Gasification Company's Great Plains Synfuels Plant in Beulah, North Dakota, United States, and piped 330 km into the Weyburn and Midale oil fields in Saskatchewan, Canada, for EOR. The injection location covers an area of 21,000 hectares and produces 20,000 barrels of oil a day.

CO₂ MONITORING AND STORAGE PROJECT

THE WEYBURN AND MIDALE OIL FIELDS AND ASSOCIATED IEAGHG WEYBURN-MIDALE CO₂ MONITORING AND STORAGE PROJECT

Injection of CO₂ for EOR purposes began in the Weyburn oil field in 2000 and at the Midale oil field in 2005. The Weyburn Field was operated by Cenovus Energy until 2017 when it sold its majority stake in the project to Whitecap Resources.⁴⁶ In 2020, 2 million tonnes of CO₂ was stored, with more than 34 million tonnes of CO₂ stored since 2000, mainly sourced from the Great Plains Syfuels Plant but with an additional supply of CO₂ from Boundary Dam since 2014.⁴⁷

The Midale Field was operated by Apache Canada until it was sold to Cardinal Energy Ltd. in 2017.⁴⁸ In 2020, approximately 188,000 tonnes of CO₂ was injected in the Midale unit. Since 2005, nearly 5 million tonnes of CO₂ has been injected.⁴⁹ To date, the sale of CO₂ from the Dakota Gasification Company to Whitecap Resources and Cardinal Energy Ltd. represents the only instances of large quantities of captured CO₂ being traded across an international border.

Supplies from Great Plains to Weyburn and Midale represent the first case of CO₂ being traded between two countries.



CO₂ CAPTURE AT BOUNDARY DAM

THE BOUNDARY DAM CARBON CAPTURE PROJECT

The Boundary Dam Carbon Capture Project is the world's first commercial-scale, fully integrated CCS project at a coal-fired power station, with postcombustion capture of CO₂ from the rebuilt Unit 3. The capital cost of Can\$1.2 billion was supported by funding from the provincial government of Saskatchewan and the federal government of Canada. Operated by the government-owned utility SaskPower, the project is designed to capture up to 1 Mt of CO₂ per year; between the commencement of operations in October 2014 and May 2021, SaskPower reports that 4.14 Mt of CO₂ has been captured.⁵⁰

Unit 3 provides 115 MW of power. In addition to reducing CO₂ emissions from Unit 3 by up to 90%, the capture process removes 100% of SO₂ emissions which are converted to sulfuric acid for industrial use.

The main destination for captured CO₂ is the Weyburn oil field, with Whitecap Resources transporting the purchased CO₂ via a 66-km pipeline. A branch of the pipeline in close proximity to the power station feeds the Aquistore Project, which is designed to provide dedicated storage for unsold CO₂.

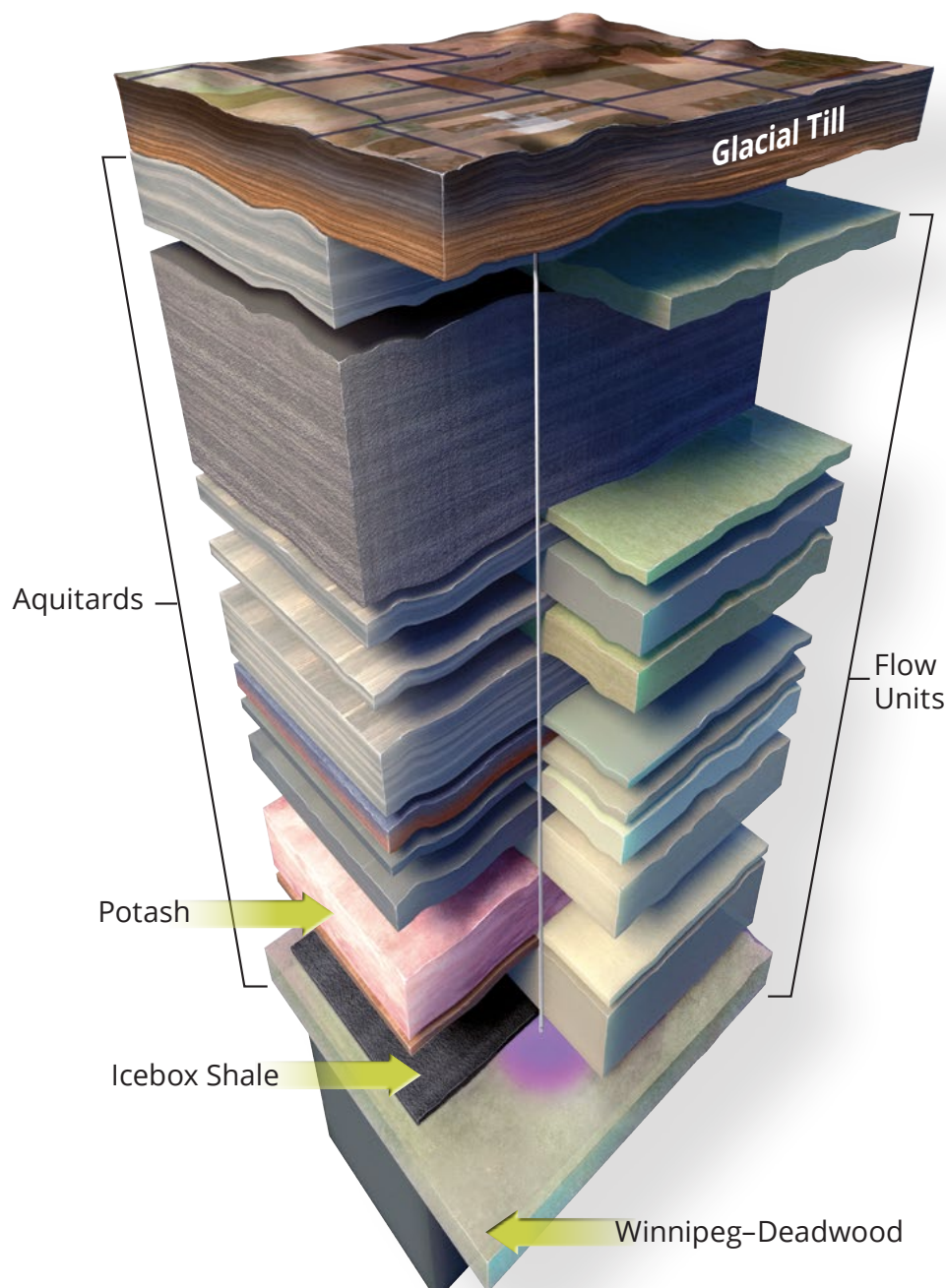


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THE AQUISTORE PROJECT

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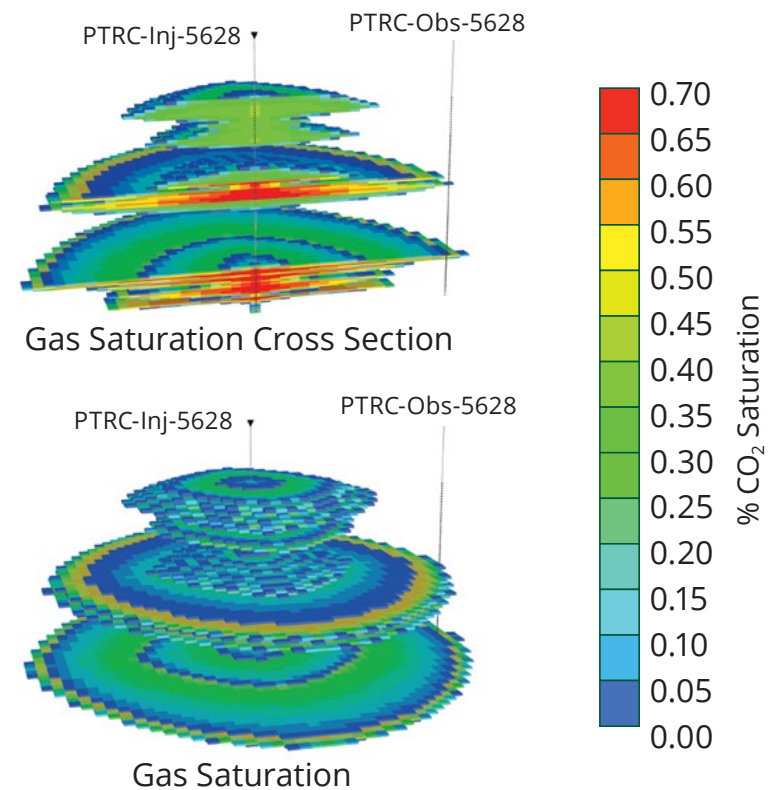
Aquistore is a dual-purpose project.⁵¹ From a commercial perspective, Aquistore provides a dedicated storage option for unsold CO₂ from Boundary Dam—in effect providing buffer storage so as to prevent any need for SaskPower to vent CO₂ from capture operations. Injection operations commenced in April 2015, making Aquistore the first dedicated storage project to be operating in Canada. As of April 2021, over 370,000 tonnes of CO₂ has been injected.⁵²



Injection of CO₂ at Aquistore is via a single vertical well into the Winnipeg and Deadwood Formations at a depth of approximately 3.4 km below ground level.⁵¹

Monitoring of the Aquistore site is managed by Petroleum Technology Research Centre (PTRC), which installed the injection well plus an observation well and other monitoring infrastructure through funding by federal and provincial government agencies and private industry. In addition to providing monitoring data for the regulator in accordance with permitting of the storage site, Aquistore is run as a collaborative PTRC research project which aims to demonstrate that dedicated storage in a DSF is a safe and workable solution to reduce GHG emissions.

Established and novel technologies are under evaluation at Aquistore. These include cost-effective repeat 3D seismic surveys facilitated by a permanent array of 650 surface geophones, passive seismic monitoring, and downhole monitoring, including fiber optic cables.⁵³



Carbon dioxide saturation within the injection plume resulting from a simulated 50-year injection scenario (37 Mt) at the PTRC Aquistore site. The model grid is nearly square, with sides approximately 5.6 km in length.

QUEST CCS PROJECT

Shell Canada Energy commenced operations at Quest, a fully integrated CCS project located northeast of Edmonton, in November 2015. As of July 2020, the Quest CCS facility has captured and stored 5 million tonnes of CO₂. The cost to operate Quest is about 35% lower than what was forecast in 2015, and if Quest were to be built today, it would cost about 30% less thanks to capital efficiency improvements.⁵⁴

The capture plant, located at the Scotford Refinery, was built as a modification to an existing steam methane reformer that produces hydrogen for upgrading oil sands bitumen into synthetic crude oil. Licensed Shell amine technology is used in the capture process, which reduces CO₂ emissions from the upgrading operations by approximately one-third.

Captured CO₂ is transported via a 60-km pipeline to a dedicated storage site and injected into the Basal Cambrian sandstone, a DSF, at a depth of around 2 km below the surface. Infrastructure at the site includes three injection wells and a host of monitoring technologies that provide opportunities for international research collaborations. The project is expected to store at least 27 Mt of CO₂ over the anticipated 25-year life of the upgrader, although the storage reservoir has a much greater storage potential.



ALBERTA CARBON TRUNK LINE

The ACTL system is the world's newest integrated, large-scale CCUS system.⁵⁵ Located in central Alberta, CO₂ captured from the NWR (North West Redwater Partnership) Sturgeon Refinery and the Nutrien Fertilizer facility is transported down a 40-cm-diameter, 240-km-long pipeline to mature oil fields near Clive, Alberta. Designed as the backbone infrastructure needed to support a lower carbon economy in Alberta, the ACTL system captures industrial emissions and delivers the CO₂ to mature oil and gas reservoirs for use in EOR and permanent storage. The ACTL can transport up to 14.6 Mt of CO₂ per year, and as of March 2021, 1 Mt of CO₂ has been injected and stored in the Clive oil field.

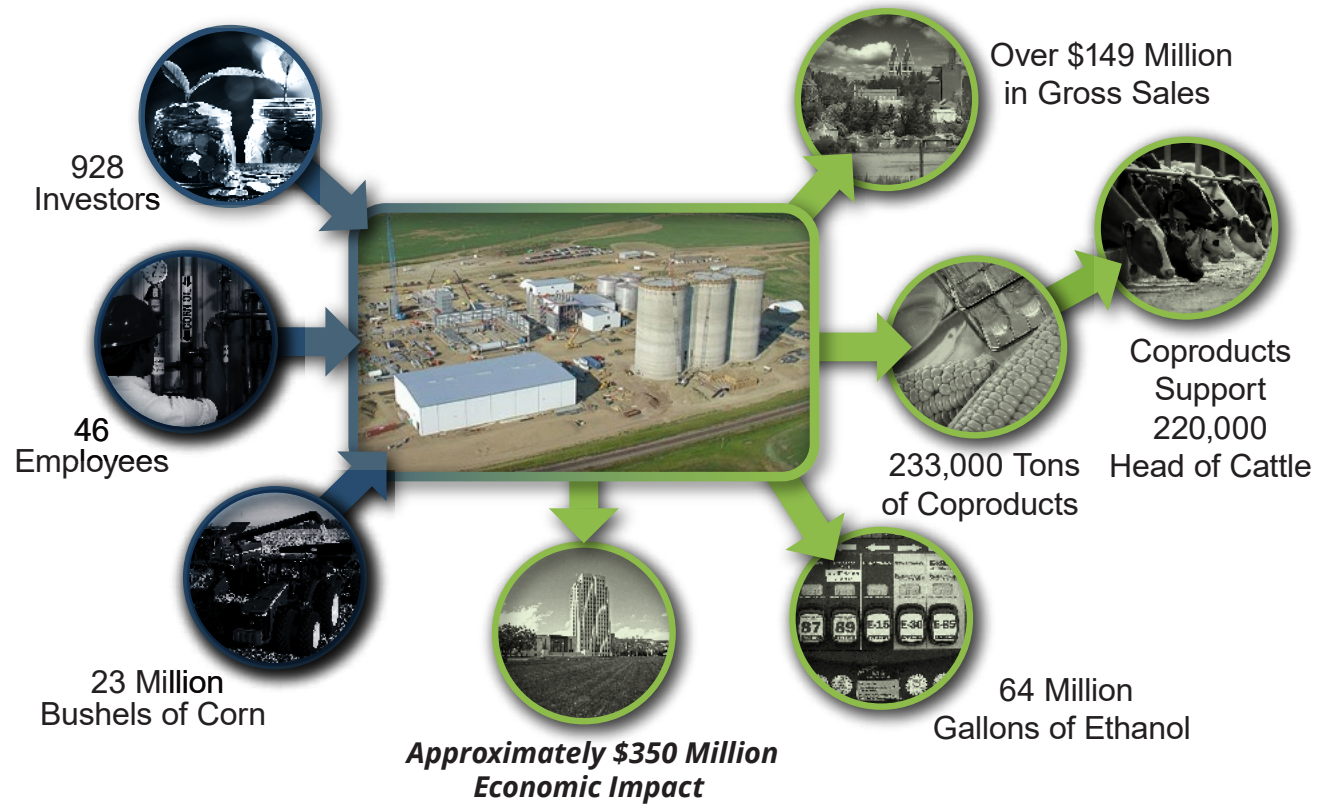


RED TRAIL ENERGY

Red Trail Energy, LLC (RTE) is pursuing a commercial-scale CCUS project at its ethanol manufacturing facility near Richardton, North Dakota. The goal of this effort is to make a CCUS fuel that qualifies for low-carbon fuel programs and capitalize on the Section 45Q tax credit program. Through this project, an average of 180,000 metric tons of CO₂ will be captured annually from RTE's 64-million-gallon dry mill ethanol facility.

RTE partnered with the EERC, NDIC, and DOE to conduct a feasibility and implementation study for the CCUS project. Fieldwork that included drilling two wells and collecting 3D seismic data confirmed that the Broom Creek Formation at a depth of approximately 6400 feet is a safe and viable storage horizon for the captured CO₂.

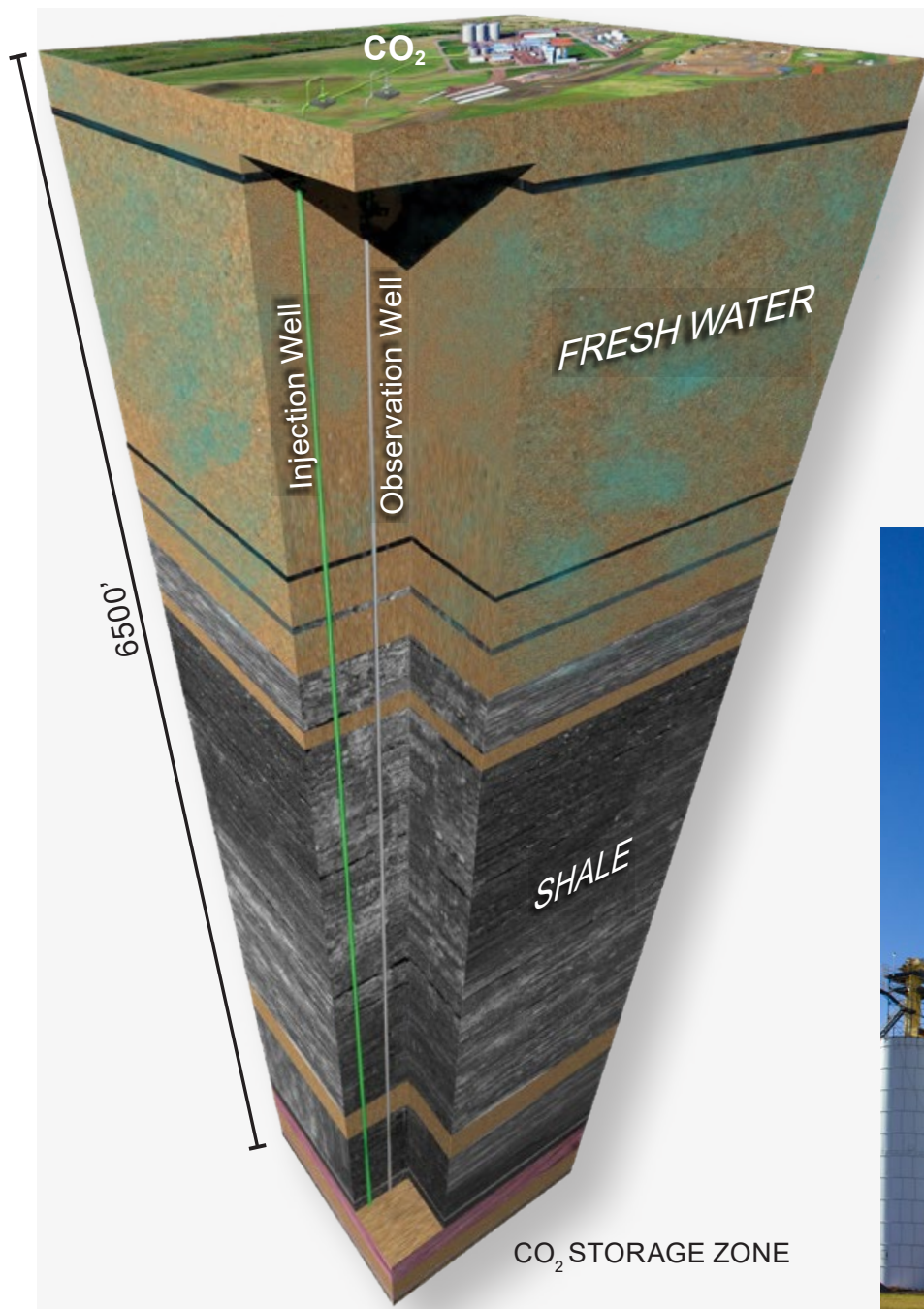
A North Dakota carbon storage permit application was developed and formally submitted in February 2021. The Department of Mineral Resources (DMR), in consultation with the North Dakota Department of Environmental Quality, evaluated the permit application to determine whether approval should be granted. This first-time regulatory process has taken about 8 months, including a public comment period and hearing. Approval was granted in October 2021 and brings RTE one step closer to becoming the first facility in North Dakota to commercially capture and permanently store CO₂ in the deep subsurface.





“We’re excited to submit the first application in the state for safe, permanent geologic storage of CO₂. Using CCS to reduce the CO₂ emissions of our ethanol ensures the long-term viability of Red Trail Energy in a highly competitive global market.”

Red Trail Energy CEO Gerald Bachmeier



PROJECT TUNDRA (CARBONSAFE NORTH DAKOTA)

Project Tundra is a bold initiative to build the world's largest carbon capture facility in North Dakota. Innovative technologies are being designed to capture 90% of the CO₂ produced at the Milton R. Young Station (about 4 million metric tons per year). This capture rate is the equivalent to taking 800,000 gasoline-fueled vehicles off the road. North Dakota-based Minnkota Power Cooperative is leading the project, along with research support from the EERC through DOE's CarbonSAFE initiative.

In the fall of 2020, the North Dakota CarbonSAFE project began Phase III of the DOE initiative, a 3-year effort building off of the success of Phase II and covering site characterization and permitting. Field activities over the past few years include drilling three stratigraphic test wells and collecting nearly 20 square miles of 3D seismic data in the area around the Milton R. Young Station.

The field activities gathered various geologic data on three potential injection targets about 1 to 2 miles below the surface to demonstrate their suitability to permanently store CO₂. These data were used to prepare two North Dakota CO₂ storage facility permit applications that were submitted in May of 2021. Those storage permit applications represent the second and third CO₂ storage facility applications submitted in North Dakota.



North Dakota CarbonSAFE is part of ongoing regional efforts to ensure reliable, affordable energy, the wise use of North Dakota's resources, and wide-scale commercial deployment of CCUS.



Industrial Commission of North Dakota
Lignite Research, Development and
Marketing Program



- May 2021 | Storage Facility Permit Applications Submitted
- Summer 2021 | Front-End Engineering and Design (FEED) Study Complete
- 2022 | Construction Started
- 2025 | First CO₂ Captured



DRY FORK STATION (CARBONSAFE WYOMING)

The University of Wyoming School of Energy Resources (UWY SER) leads the Wyoming CarbonSAFE project at Dry Fork Station in the Powder River Basin. Funded by DOE, Wyoming CarbonSAFE investigates the practical, secure, and permanent geologic storage of CO₂ emissions from coal-based electricity generation facilities near Gillette, Wyoming. The Wyoming CarbonSAFE team is characterizing the subsurface geology for suitability of CO₂ storage, preparing permitting documents, working to integrate CO₂ capture technologies, assessing regulatory and business issues, and helping to advance the project toward commercialization. Along with many committed industry, academic, and government partners, UWY SER has drilled a stratigraphic test well, conducted downhole petrophysical tests, analyzed core, collected and analyzed seismic data, and been committed to developing robust monitoring plans and communicating project details to the public.



THE INTEGRATED TEST CENTER

Located outside of Gillette, Wyoming, and opened in May of 2018, the Integrated Test Center (ITC) is a facility designed for applied testing of CCUS technologies using the coal-based flue gas from Dry Fork Station. Only the second such facility in the country, the ITC is a public-private partnership that provides an opportunity for research and development of CO₂ capture technologies as well as technologies to turn flue gas into marketable commodities.

Wyoming's Carbon Valley: a trifecta of private, state, and federal interests leveraged off of each other toward one common goal: CCS.



