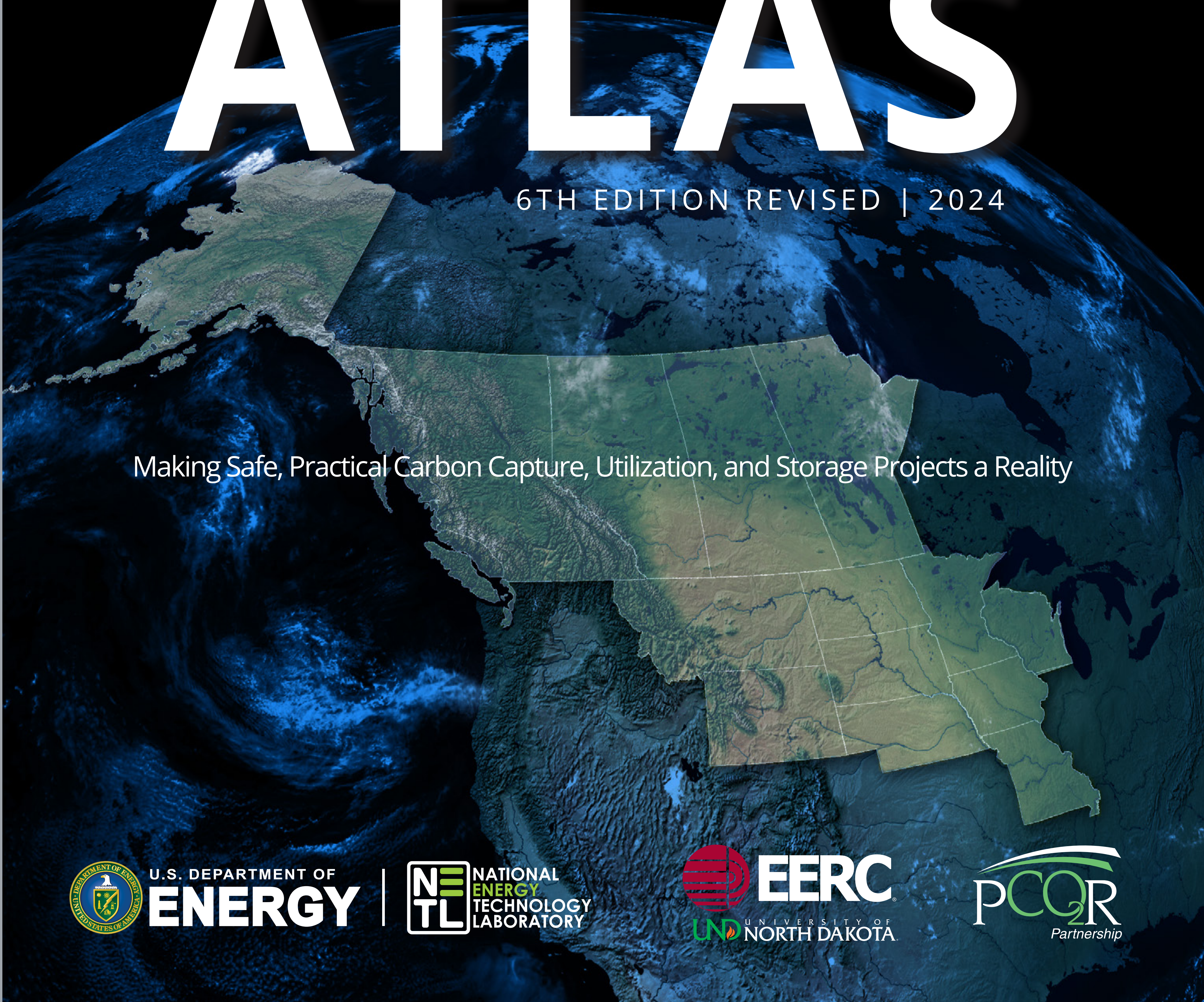
PCOR PARTNERSHIP
ATLAS

6TH EDITION REVISED | 2024



Making Safe, Practical Carbon Capture, Utilization, and Storage Projects a Reality

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

EERC
UNIVERSITY OF NORTH DAKOTA

PCOR Partnership

PCOR Partnership ATLAS

6TH EDITION REVISED | 2024

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The PCOR Partnership is a group of public and private stakeholders working together to enable deployment of carbon capture, utilization, and storage (CCUS) of CO_2 emissions from stationary sources in the upper Great Plains and northwestern regions of North America. The PCOR Partnership is led by the EERC at the University of North Dakota with support from the University of Wyoming and the University of Alaska Fairbanks and is one of four competitive awards by the U.S. Department of Energy National Energy Technology Laboratory under the Regional Initiative to Accelerate CCUS.

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NOTICE

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Several members of the PCOR Partnership research team from the EERC provided valuable input to this effort through the production of technical publications, presentations, and outreach materials. This body of work provided the foundation from which this atlas was created.

The following EERC staff focused on the execution of PCOR Partnership efforts in 2019–2024. This atlas was possible because of their creative energy and collective efforts:

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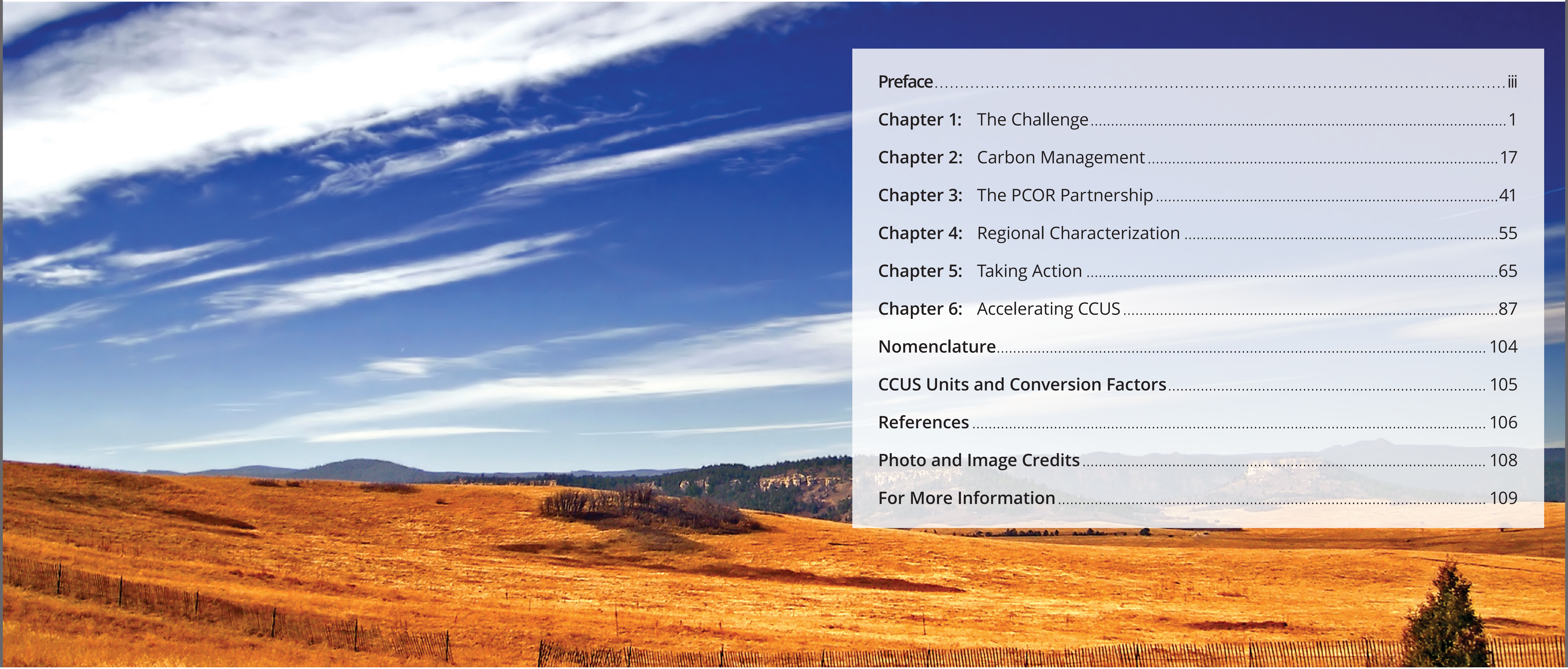


PREFACE

Carbon capture, utilization, and storage (CCUS) are a key set of technologies developed for commercial deployment to significantly reduce anthropogenic (human-made) carbon dioxide (CO_2) emissions. These technologies have been proven to capture large-scale CO_2 emissions from major stationary sources and safely store the CO_2 underground in geologic rock formations. CCUS is a solution for providing a safe, effective, and efficient means of managing CO_2 emissions while producing energy for electricity, fuels, and other industrial processes. The Plains CO_2 Reduction (PCOR) Partnership Initiative is one of four regional initiative projects established in 2019 through the Regional Carbon Sequestration Partnership (RCSP) Program. Under this U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL)-supported initiative, the PCOR Partnership continues to serve its region and broad stakeholder base to advance and accelerate CCUS deployment. The PCOR Partnership Initiative region encompasses ten U.S. states and four Canadian provinces in the upper Great Plains and northwestern regions of North America.

The Energy & Environmental Research Center (EERC), which leads and manages the PCOR Partnership, has been conducting focused research on geologic CO_2 storage since 2003. The goal of this joint government–industry effort is to identify and address regional capture, transport, use, and storage challenges facing commercial deployment of CCUS throughout the PCOR Partnership region.

This atlas provides a profile of CO_2 sources and potential storage locations across the nearly 6.2 million square kilometers of the PCOR Partnership region. Since the founding of the PCOR Partnership in 2003, a wealth of information about CCUS has emerged. This revised sixth edition of the atlas provides an up-to-date look at PCOR Partnership Initiative activities, including additional regional characterization and updates on the growing number of commercial projects in the region. Additional background information to support CCUS is included to give the reader a better understanding of how CCUS addresses concerns about climate change while allowing future energy needs to be met.

CHAPTER 1

THE CHALLENGE

Managing global carbon emissions is one of the most pressing environmental concerns of our time. Many scientists are concerned that anthropogenic (human-made) greenhouse gases (GHGs) are affecting Earth's climate. Although earth-warming gases exist naturally in the atmosphere, human activities are adding more of these GHGs, including carbon dioxide (CO_2). The challenge is to address anthropogenic GHG emissions while providing access to reliable, affordable, resilient energy around the world. Carbon capture, utilization, and storage (CCUS) can address this challenge, and the activities conducted through the Plains CO_2 Reduction (PCOR) Partnership are playing an important role in developing and deploying CCUS technologies.

GREENHOUSE EFFECT

At the heart of this challenge is Earth's natural greenhouse effect, which plays an essential role in our climate patterns. The effect is the result of heat-trapping gases, called GHGs, which absorb heat emitted from Earth's surface and lower atmosphere and then release much of the heat back toward the surface. Without this greenhouse effect, the average surface temperature of Earth would be about 0°F (or −18°C)[1] instead of 59°F (15°C) and life as it is known would not be possible.

GREENHOUSE GASES

Many gaseous chemical compounds in Earth's atmosphere contribute to the greenhouse effect.[2] These gases absorb infrared radiation emitted from Earth's surface and trap the heat in the atmosphere. Some of these gases occur in nature, while others are products of human activity.

WATER VAPOR (H_2O) is the most abundant GHG in the atmosphere. As the temperature of the atmosphere rises, it can hold more water vapor. This higher concentration of water vapor is able to absorb more heat, further warming the atmosphere. This cycle is called a feedback loop. Water molecules have very little heat-trapping capacity compared to other GHGs, and thus changes to the amount of water vapor have the least impact on the greenhouse effect.

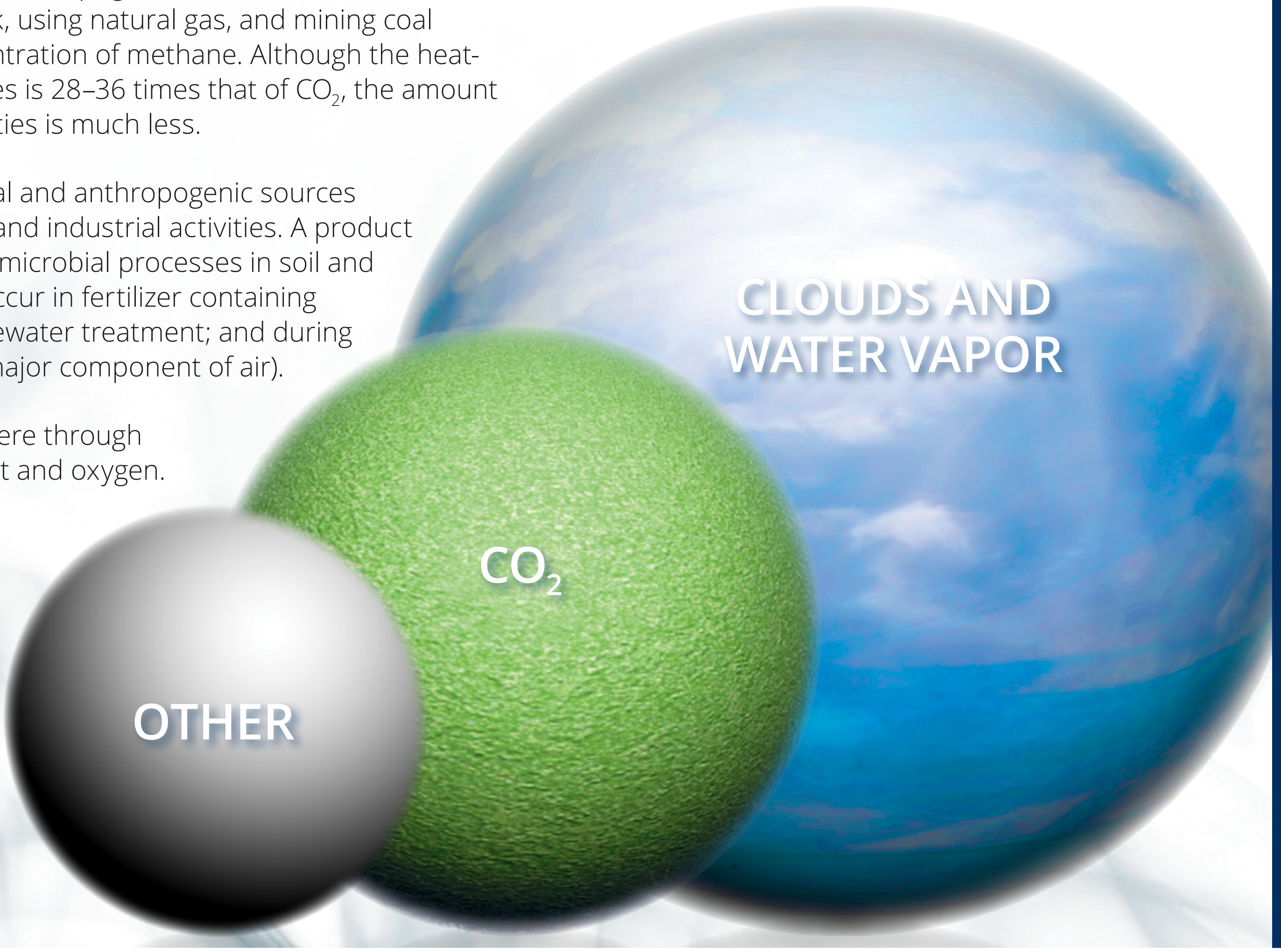
CARBON DIOXIDE has both natural and anthropogenic sources. CO_2 plays a vital role in supporting life on Earth through the global carbon cycle. The heat-trapping capacity of CO_2 molecules is much greater than water vapor. Because its production is so prevalent in human activity, CO_2 is the major focus of GHG reduction efforts.

METHANE (CH_4) has both natural and anthropogenic sources. Human activities such as growing crops, raising livestock, using natural gas, and mining coal have added to the atmospheric concentration of methane. Although the heat-trapping capacity of methane molecules is 28–36 times that of CO_2, the amount of methane produced by human activities is much less.

NITROUS OXIDE (N_2O) has both natural and anthropogenic sources associated with agricultural, land-use, and industrial activities. A product of decomposition, N_2O is produced by microbial processes in soil and water, including those reactions that occur in fertilizer containing nitrogen; in both solid waste and wastewater treatment; and during combustion (because nitrogen is the major component of air).

OZONE (O_3) is formed in the stratosphere through the interaction between ultraviolet light and oxygen. This natural O_3 layer has been supplemented by O_3 created by human processes, such as automobile exhaust and burning vegetation.

> Human contributions of GHGs to the atmosphere may seem minor compared to the large share of water vapor and clouds. The heat-trapping capacity of these molecules is, however, much greater than water vapor, so smaller changes have a greater impact.

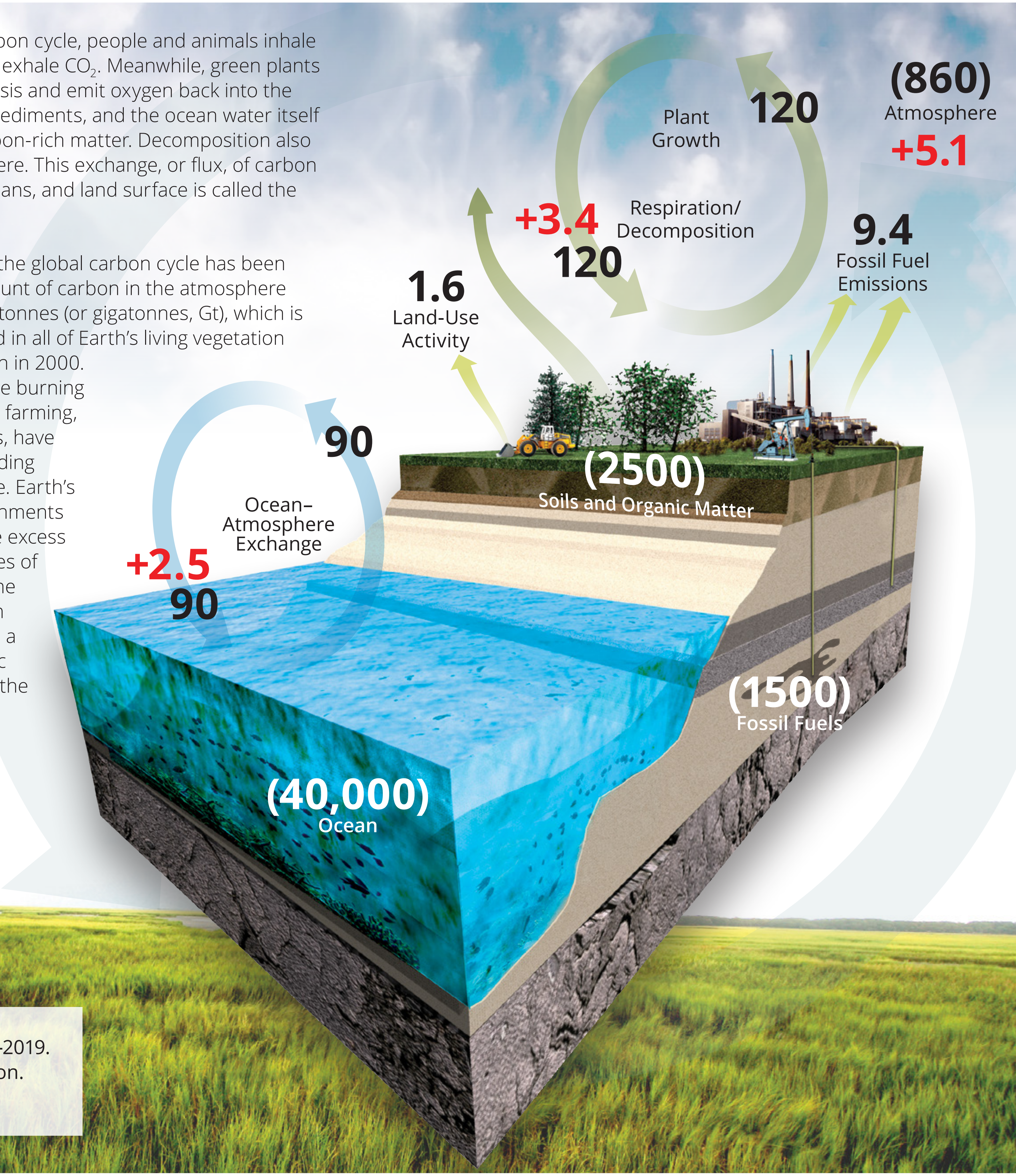


Relative total GHG effect contributions.[3]

GLOBAL CARBON CYCLE

As part of the natural carbon cycle, people and animals inhale oxygen from the air and exhale CO_2. Meanwhile, green plants absorb CO_2 for photosynthesis and emit oxygen back into the atmosphere. Marine biota, sediments, and the ocean water itself also absorb CO_2 and/or carbon-rich matter. Decomposition also returns CO_2 to the atmosphere. This exchange, or flux, of carbon among the atmosphere, oceans, and land surface is called the global carbon cycle.[4]

For most of human history, the global carbon cycle has been roughly in balance. The amount of carbon in the atmosphere is approximately 860 billion tonnes (or gigatonnes, Gt), which is more carbon than contained in all of Earth's living vegetation and roughly 80 Gt more than in 2000. Human activities, namely, the burning of fossil fuels, deforestation, farming, and other land-use activities, have altered the carbon cycle, adding extra CO_2 to the atmosphere. Earth's ocean and terrestrial environments compensate for some of the excess by taking up billions of tonnes of extra CO_2 (shown in red in the figure). Still, much remains in the atmosphere, resulting in a 45% increase in atmospheric concentrations of CO_2 since the Industrial Revolution.



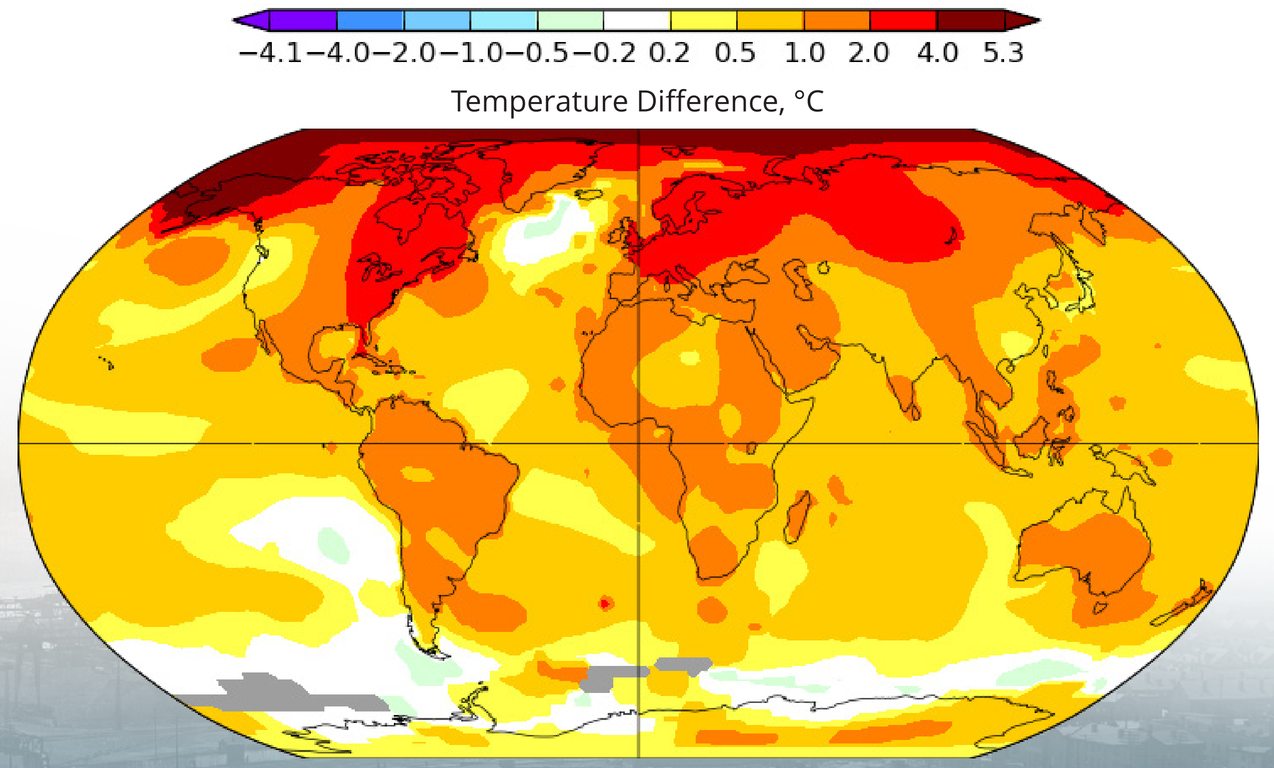
Averaged annual emissions, 2010–2019.
Fluxes and pools are in Gt of carbon.
Pools are noted in parentheses.

CLIMATE CHANGE PATTERNS

> “The slight percentage of carbonic acid in the atmosphere may, by the advances of industry, be changed to a noticeable degree in the course of a few centuries.”
>
> Svante Arrhenius, 1904

Since instrumental records of temperature began in 1880, the overall temperature of Earth has risen by more than 2°F (1.2°C), with 2023 being the warmest year on record according to the National Oceanic and Atmospheric Administration.[5] The world's 10 warmest years have all occurred in the last 10 years. These rising temperatures are causing wide-ranging impacts, such as the loss of sea ice and ice sheet mass, sea level rise, longer and more intense heat waves, and shifts in habitats. Most climate scientists attribute these current changes in climate at least in part to anthropogenic GHG emissions.

The map shows the average surface temperature trends for 2013–2023 relative to the 1991–2020 average. Warming was more pronounced at high latitudes, especially in the Northern Hemisphere and over land.[6]



More than 100 years ago, Swedish scientist and Nobel Prize winner Svante Arrhenius postulated that anthropogenic increases in atmospheric CO_2 as the result of fossil fuel combustion would profoundly affect the heat budget of Earth. In 1904, Arrhenius became concerned with rapid increases in anthropogenic carbon emissions.[7]

MAJOR STATIONARY CO_2 SOURCES

INDUSTRIAL

Cement Plant

PETROLEUM AND NATURAL GAS

Refinery

ELECTRIC UTILITY

Coal-Fired Power Plant

AGRICULTURE-RELATED PROCESSING

Ethanol Plant

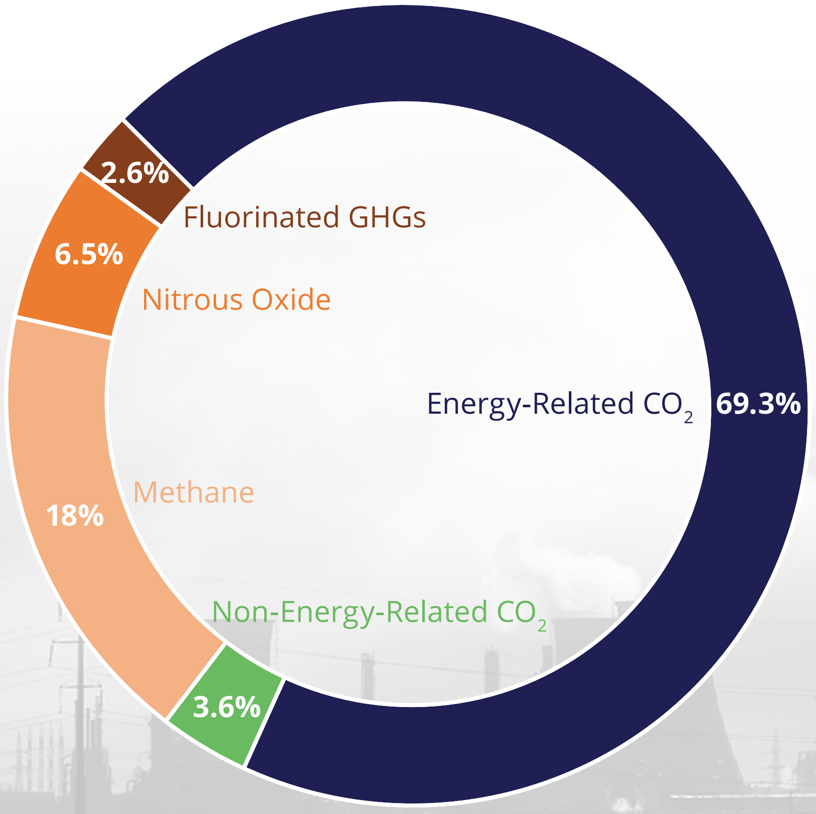
ANTHROPOGENIC CO_2

Carbon dioxide produced through human action is referred to as anthropogenic CO_2. The primary source of anthropogenic CO_2 emissions in North America is the burning of fossil fuels for energy. Industrial activities such as manufacturing cement, producing ethanol, refining petroleum, producing metals, and combusting waste also contribute a significant amount of anthropogenic CO_2. Collectively, these are referred to as large stationary CO_2 point sources. Nonstationary CO_2 emissions include activities such as using gasoline, diesel, and other fuels for transportation.

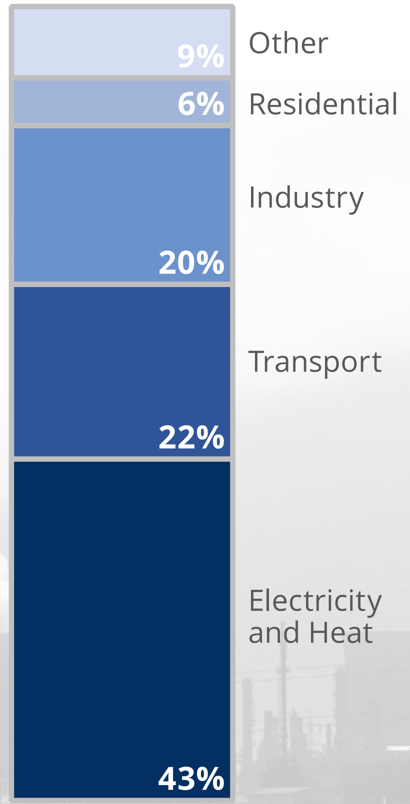
Changes in land use and land conversion also contribute to anthropogenic CO_2 emissions. These include practices like plowing land, which releases exposed carbon in the soil to the atmosphere as CO_2, and deforestation, which reduces plant biomass, thus reducing the plant uptake of airborne CO_2. Deforestation also releases CO_2 if the biomass is burned.

WHAT IS CO_2? Carbon dioxide is a colorless, odorless, naturally occurring gas comprising one atom of carbon and two atoms of oxygen. At temperatures below −76°C, CO_2 condenses into a white solid called dry ice. When warmed, dry ice vaporizes directly from a solid to a CO_2 gas in a process called sublimation. With enough added pressure, liquid CO_2 can be formed. CO_2 has many industrial uses: in fire extinguishers, as a propellant in spray cans, in treatment of drinking water, for cold storage (CO_2 as dry ice), and to make bubbles in soft drinks. CO_2 is also used in large quantities for enhanced oil recovery (EOR) as part of oil production in some oil fields.

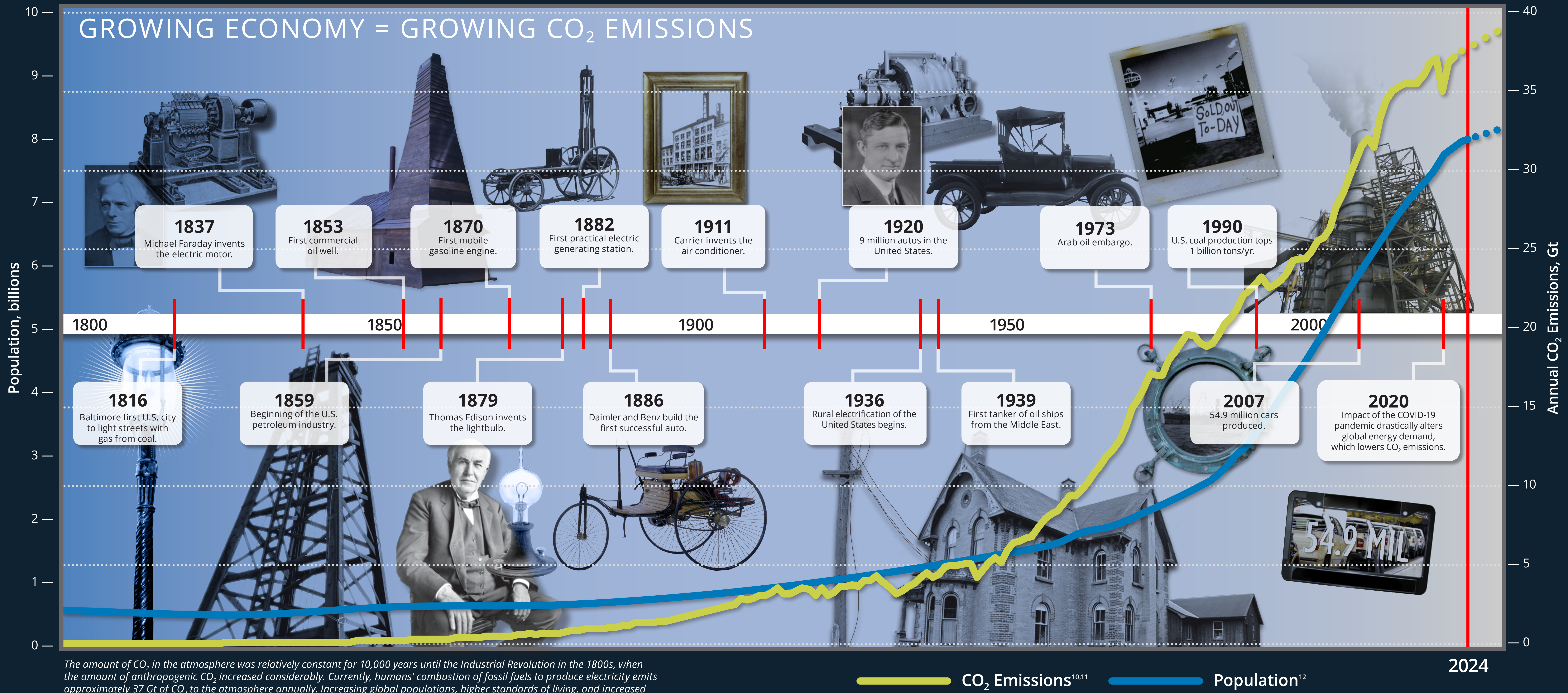
2020 GLOBAL GHG EMISSIONS[8]



2020 GLOBAL CO_2 FROM FUEL COMBUSTION BY SECTOR[9]



GROWING ECONOMY = GROWING CO_2 EMISSIONS



1816 Baltimore first U.S. city to light streets with gas from coal.

1837 Michael Faraday invents the electric motor.

1853 First commercial oil well.

1859 Beginning of the U.S. petroleum industry.

1870 First mobile gasoline engine.

1879 Thomas Edison invents the lightbulb.

1882 First practical electric generating station.

1886 Daimler and Benz build the first successful auto.

1911 Carrier invents the air conditioner.

1920 9 million autos in the United States.

1936 Rural electrification of the United States begins.

1939 First tanker of oil ships from the Middle East.

1973 Arab oil embargo.

1990 U.S. coal production tops 1 billion tons/yr.

2007 54.9 million cars produced.

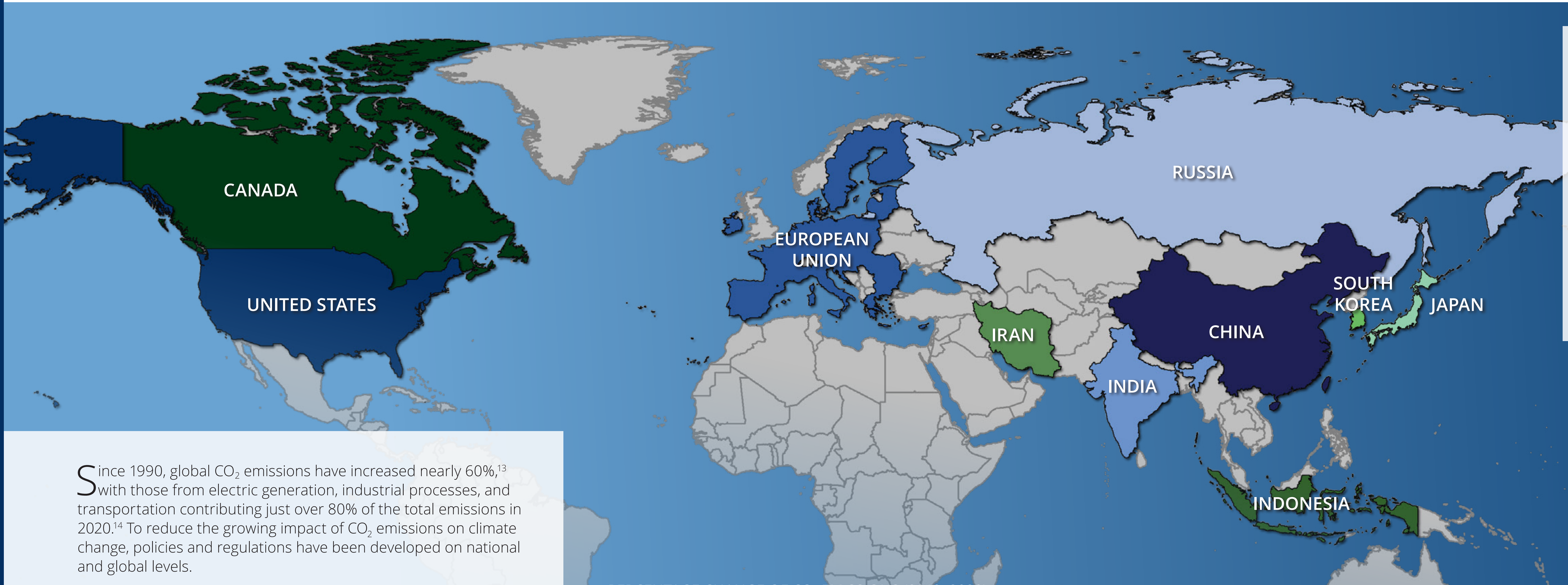
2020 Impact of the COVID-19 pandemic drastically alters global energy demand, which lowers CO_2 emissions.

The amount of CO_2 in the atmosphere was relatively constant for 10,000 years until the Industrial Revolution in the 1800s, when the amount of anthropogenic CO_2 increased considerably. Currently, humans' combustion of fossil fuels to produce electricity emits approximately 37 Gt of CO_2 to the atmosphere annually. Increasing global populations, higher standards of living, and increased demand for energy will likely result in continued increases in global CO_2 emissions.

WORLD CO_2 EMISSIONS

The United Nations Framework Convention on Climate Change held its 28th meeting of the Conference of the Parties climate change conference (COP 28) in Dubai, United Arab Emirates, from November 30 to December 13, 2023. COP 28 was the first global stocktake by nearly 200 parties since the Paris Agreement in 2015. Because of slow progress across all areas of climate action, countries outlined plans to accelerate action by 2030. These plans include a call for governments to speed up the transition away from fossil fuels in their next round of climate commitments.

The global stocktake was considered the central outcome of COP 28 and can be used by countries to develop stronger climate action plans that are due by February 2025. The stocktake aims to cut GHG emissions by 43% by 2030 compared to 2019 levels to limit global temperature increase to 1.5°C.[15]

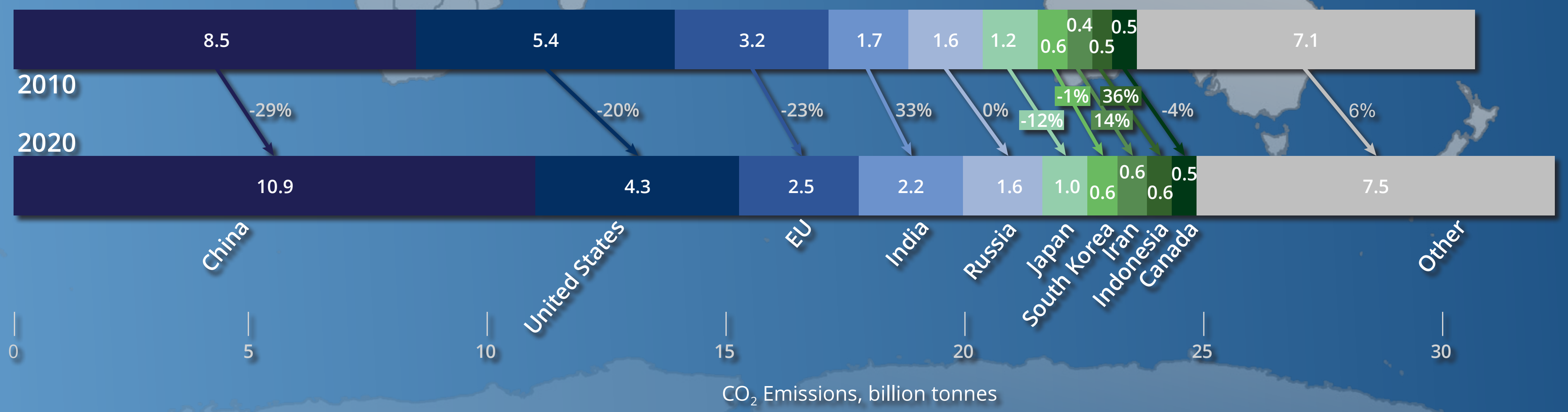


Since 1990, global CO_2 emissions have increased nearly 60%,[13] with those from electric generation, industrial processes, and transportation contributing just over 80% of the total emissions in 2020.[14] To reduce the growing impact of CO_2 emissions on climate change, policies and regulations have been developed on national and global levels.

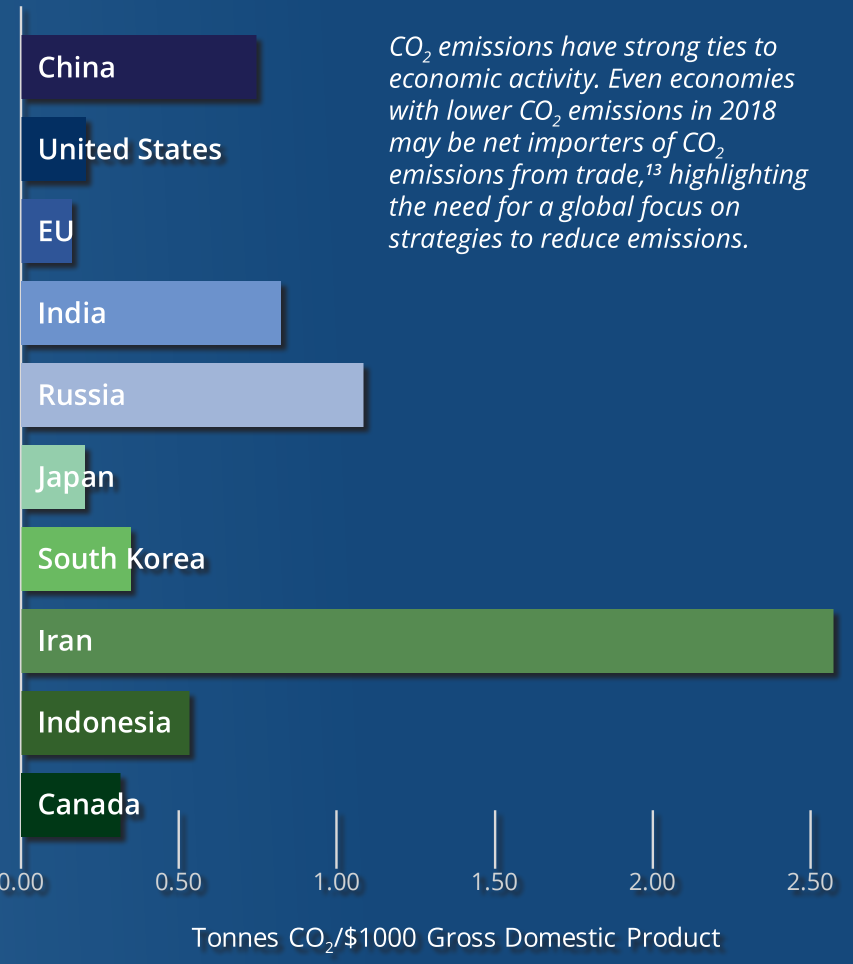
Ten economies account for about 78% of global CO_2 from energy and industrial processes. Illustrated in the bar graph, right, the 1.7-Gt increase in emissions from 2010 to 2020[14] comes mainly from five of these countries, including major increases in emissions in China, India and, to a lesser extent, Indonesia as they work to modernize their economies and provide more economic opportunities for their inhabitants.

Five of the top ten emitting economies had lower CO_2 emissions in 2020 as compared to 2010. The savings from these five economies offset the 5% increase in CO_2 emissions from the rest of the world. The greatest percentages of decrease are 23% and 20% for the European Union (EU, 27 nations) and the United States, respectively.

PERCENTAGE CHANGE OF CO_2 EMISSIONS (2010–2020)

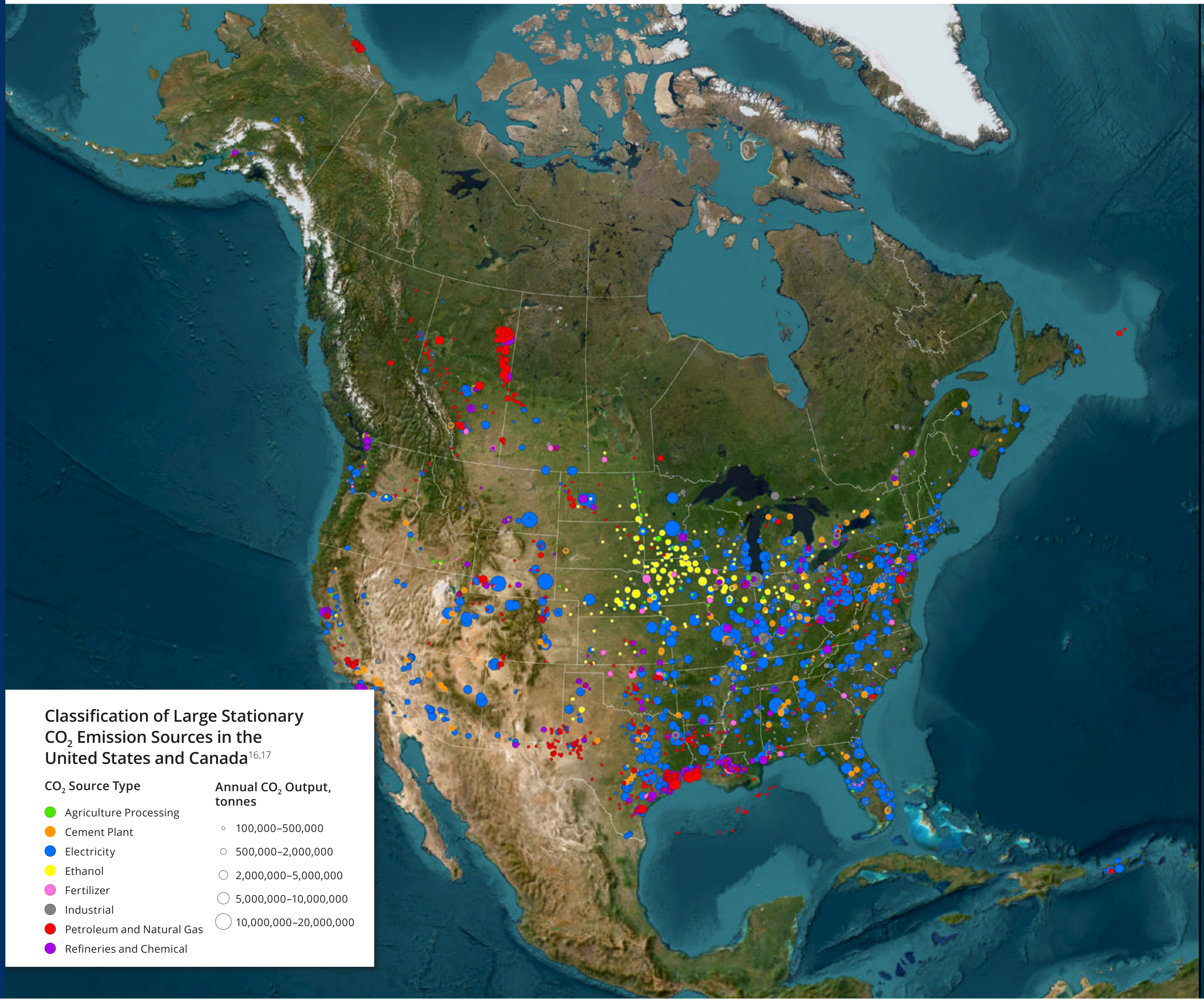


RATIO OF CO_2 EMISSIONS TO GROSS DOMESTIC PRODUCT FOR WORLD ECONOMIES (2018)



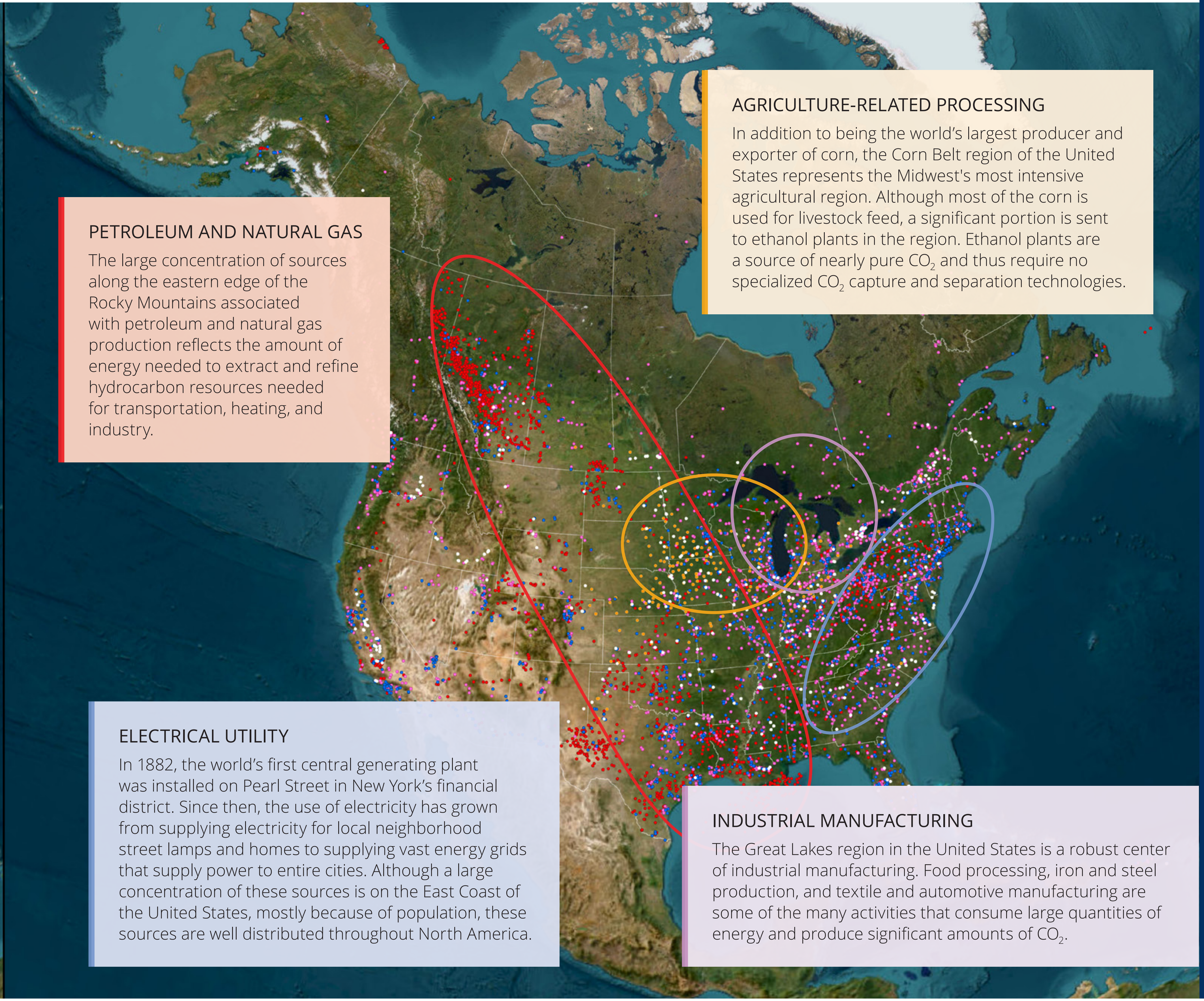
CO_2 emissions have strong ties to economic activity. Even economies with lower CO_2 emissions in 2018 may be net importers of CO_2 emissions from trade,[13] highlighting the need for a global focus on strategies to reduce emissions.

U.S. AND CANADIAN CO_2 SOURCES



Classification of Large Stationary CO_2 Emission Sources in the United States and Canada[16,17]

U.S. AND CANADIAN PROFILE



AGRICULTURE-RELATED PROCESSING

In addition to being the world's largest producer and exporter of corn, the Corn Belt region of the United States represents the Midwest's most intensive agricultural region. Although most of the corn is used for livestock feed, a significant portion is sent to ethanol plants in the region. Ethanol plants are a source of nearly pure CO_2 and thus require no specialized CO_2 capture and separation technologies.

PETROLEUM AND NATURAL GAS

The large concentration of sources along the eastern edge of the Rocky Mountains associated with petroleum and natural gas production reflects the amount of energy needed to extract and refine hydrocarbon resources needed for transportation, heating, and industry.

ELECTRICAL UTILITY

In 1882, the world's first central generating plant was installed on Pearl Street in New York's financial district. Since then, the use of electricity has grown from supplying electricity for local neighborhood street lamps and homes to supplying vast energy grids that supply power to entire cities. Although a large concentration of these sources is on the East Coast of the United States, mostly because of population, these sources are well distributed throughout North America.

INDUSTRIAL MANUFACTURING

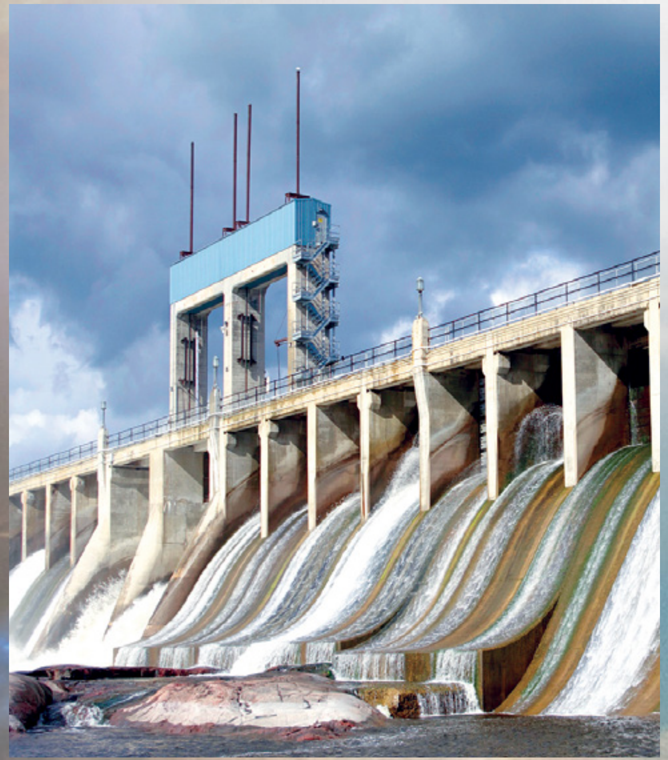
The Great Lakes region in the United States is a robust center of industrial manufacturing. Food processing, iron and steel production, and textile and automotive manufacturing are some of the many activities that consume large quantities of energy and produce significant amounts of CO_2.

FINDING A CO_2 SOLUTION

Addressing climate change is a large-scale, global challenge that is compounded by our growing demand for energy. To reduce the risks associated with climate change, the amount of CO_2 released by human activity must be substantially reduced.

A number of techniques can be employed to reduce CO_2 emissions, including conserving energy, using fossil fuels more efficiently, and increasing the use of renewable (i.e., wind, solar, geothermal, hydropower) and nuclear energy. But in the face of growing world populations and rising worldwide standards of living, CCUS provides an opportunity to combine the continued use of fossil fuels with a significant reduction in GHG emissions. CCUS lies at the intersection of energy, the economy, and the environment, which makes it a critical approach to meet our world's clean energy needs. The PCOR Partnership is working to ensure that CCUS is developed and implemented in a practical and environmentally sound manner.

> 41 CCUS facilities are in operation worldwide, capturing 49 million tonnes of CO_2. An additional 26 projects are in construction, and 325 projects are in development.[18]
>
> Global Status of CCS Report 2023



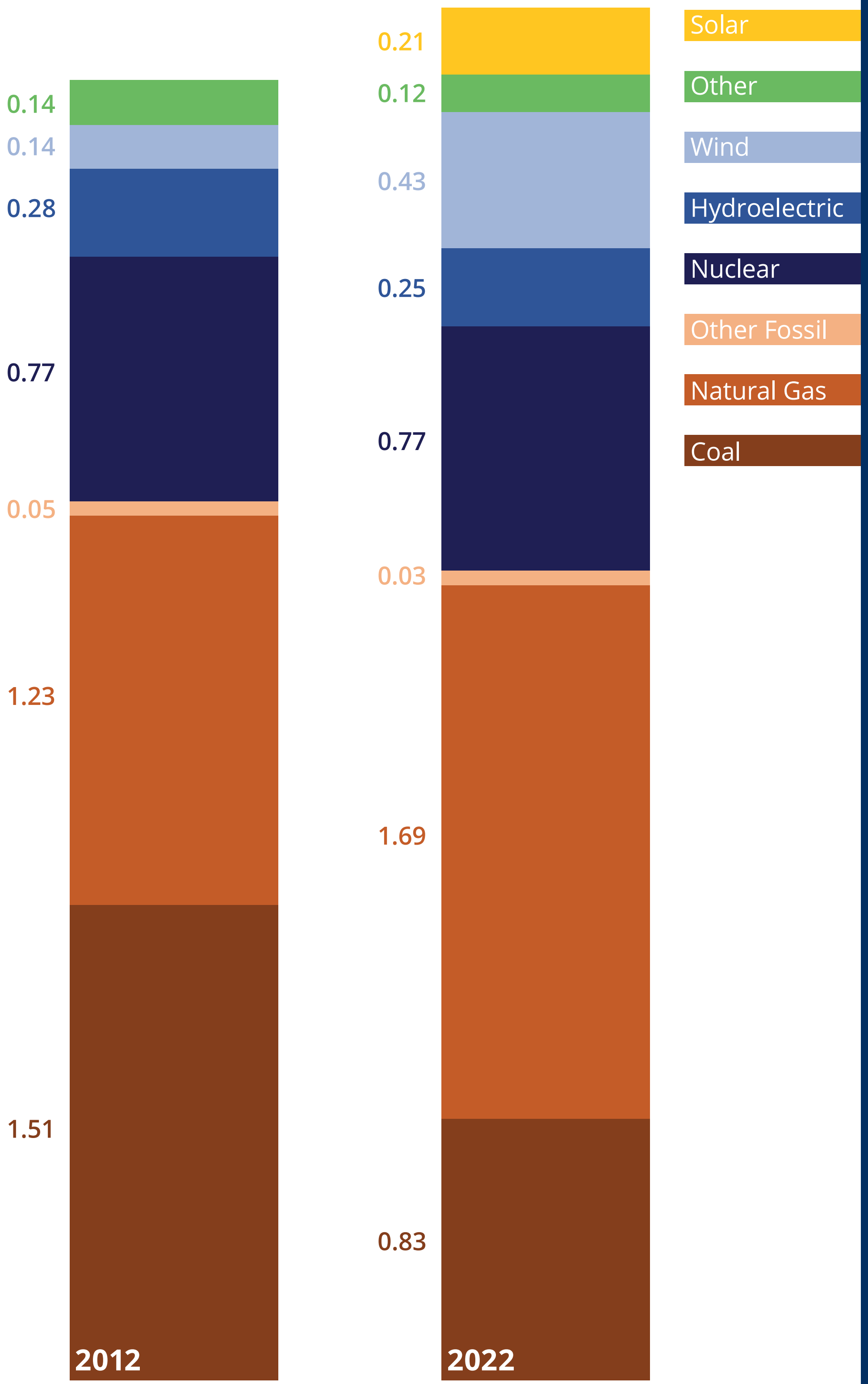
RELIABLE ENERGY MIX

Over the past decade, increasing concerns over the potential impacts of climate change and increasing competition from natural gas and renewable energy sources have caused a significant shift in the U.S. energy production profile. Today coal generates about 20% of the U.S. net power generation—down about 50% from 2012. Although much of that decrease has been offset by natural gas power generation, an increasingly larger portion of power generation is coming from low-carbon renewables, such as wind and solar.

Increasing reliance on low-carbon renewable energy sources may sacrifice grid resilience and reliability. These concerns have been amplified during recent extreme weather events in the United States when much of the country was without power. A significant challenge in reducing the reliance on fossil fuels in the energy sector is to find solutions to the shortcomings of renewable energy in an economically feasible manner.

Traditional power plants equipped with CCUS technology can play an important role to ensure that future low-carbon power generation can evolve without sacrificing resilience and reliability. A study by the International Energy Agency (IEA) concludes that when accounting for system reliability and flexibility, the competitiveness of carbon capture in the power system increases relative to other generation sources.[19] Thus CCUS-enabled power production can contribute to energy security while complementing and facilitating the increased deployment of renewables.

U.S. NET ELECTRICITY GENERATION FOR ALL SECTORS[19]
(billion MWh)



Although the total amount of electricity generated for the U.S. grid has remained relatively constant over the last decade, the primary energy used to generate electricity has changed dramatically. Factors in the change include the price of natural gas, tax incentives for renewables, and pressure to reduce CO_2 emissions from energy production.

CHAPTER 2

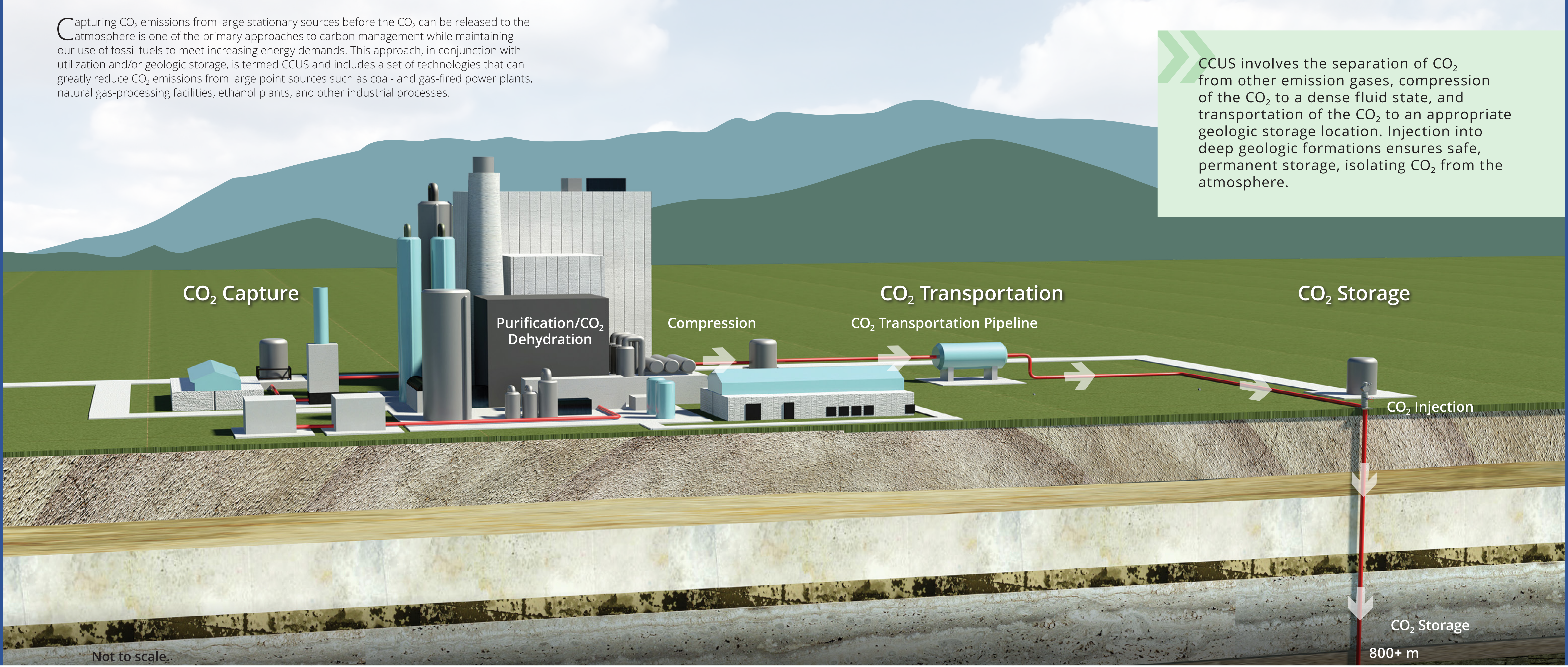
CARBON MANAGEMENT

The need to stabilize atmospheric concentrations of CO_2 requires a suite of carbon management solutions, including energy efficiency, using less carbon-intensive fuels, enhancing natural carbon uptake in the biosphere, and broadening the use of renewable energy. One of the most promising approaches involves capturing CO_2 from the exhaust gas at large stationary sources and placing it underground into permanent storage. This option is referred to as CCUS and is at the forefront for decreasing GHG emissions while retaining our existing energy generation infrastructure. This chapter covers some of the fundamental components of CCUS.

CARBON CAPTURE, UTILIZATION, AND STORAGE

Capturing CO_2 emissions from large stationary sources before the CO_2 can be released to the atmosphere is one of the primary approaches to carbon management while maintaining our use of fossil fuels to meet increasing energy demands. This approach, in conjunction with utilization and/or geologic storage, is termed CCUS and includes a set of technologies that can greatly reduce CO_2 emissions from large point sources such as coal- and gas-fired power plants, natural gas-processing facilities, ethanol plants, and other industrial processes.

CCUS involves the separation of CO_2 from other emission gases, compression of the CO_2 to a dense fluid state, and transportation of the CO_2 to an appropriate geologic storage location. Injection into deep geologic formations ensures safe, permanent storage, isolating CO_2 from the atmosphere.

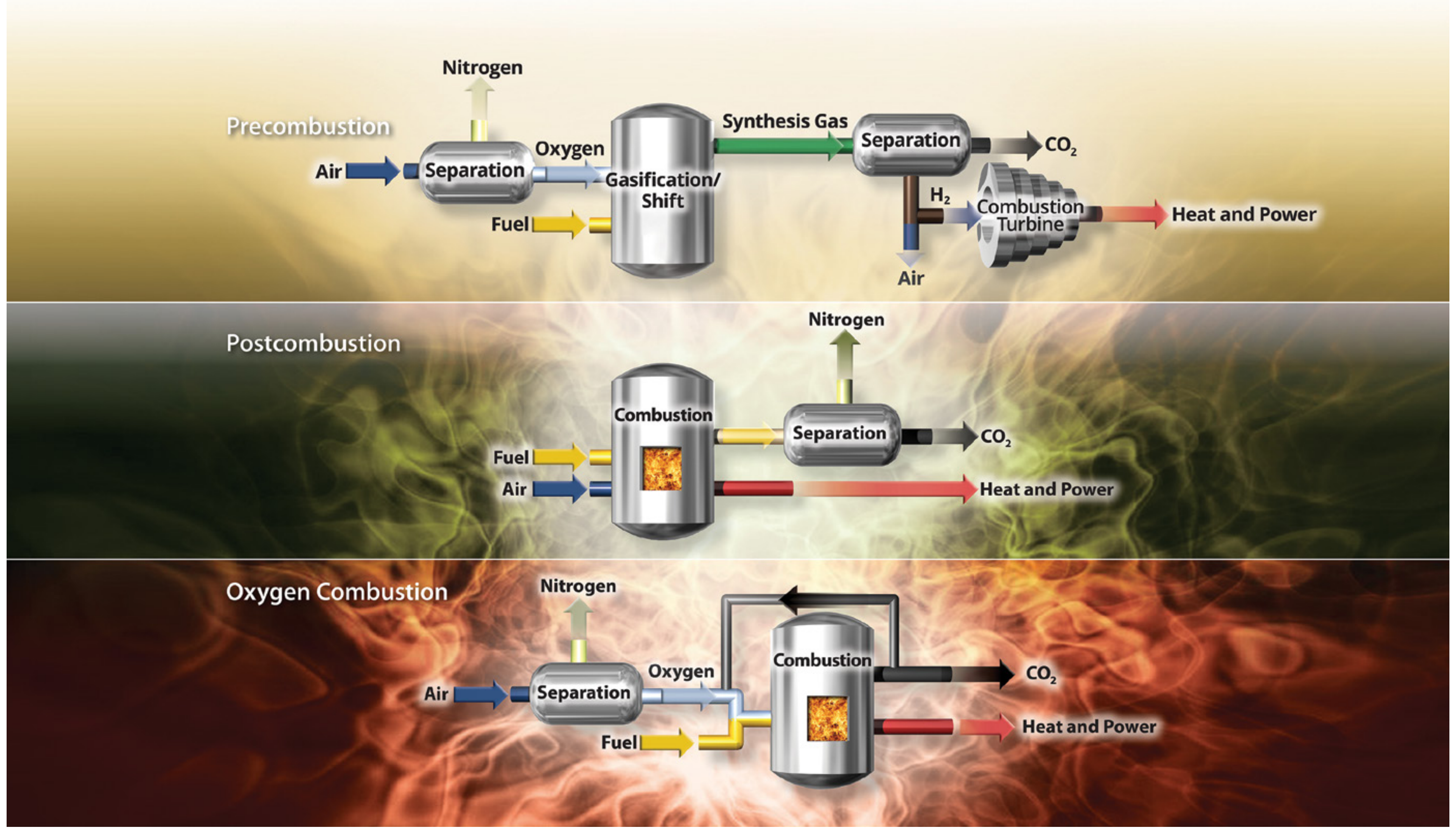


Not to scale.

CO_2 CAPTURE FROM INDUSTRIAL PROCESSES

Capture is the separation of CO_2 from a gas stream to prevent atmospheric release. Capture can be performed before, during, or after the combustion process. Precombustion technologies consist of capturing CO_2 in conjunction with either gasification or methane reforming to produce hydrogen for use in a turbine. Capture during combustion is possible when the oxygen source is pure oxygen rather than air.

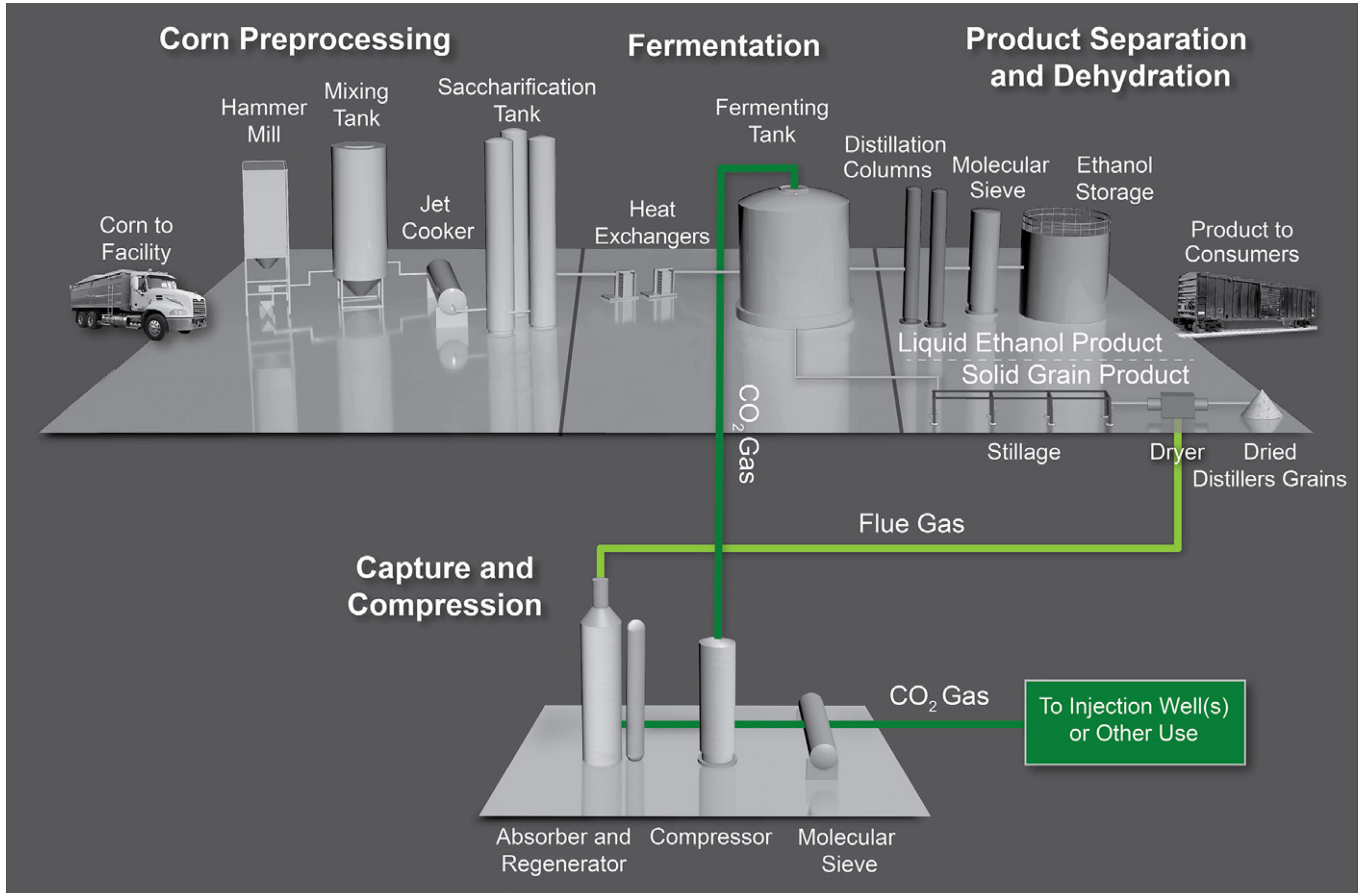
To maintain the correct boiler temperature, some flue gas is recycled to the boiler during oxygen combustion,[20] meaning that the atmosphere in the boiler is not pure oxygen but rather a mixture consisting primarily of oxygen and CO_2. Most capture technologies focus on separating low-concentration CO_2 from the exhaust gas stream after combustion takes place; this is called postcombustion capture. Because the concentration of CO_2 in typical power plant flue gas is low (ranging from 3% by volume for some natural gas-fired plants to about 13% by volume for coal-fired plants),[21] any postcombustion capture process must be sized to handle the entirety of the exhaust gas. The large scale of equipment, quantities of chemicals required, and energy needed to operate the capture system require significant capital investment. The cost of capturing the CO_2 can represent 75% of the total cost of a CCUS operation.[21] Because capture is the costliest portion of a CCUS project, research is being performed to develop more efficient CO_2 capture processes and improve the economics of existing ones. CO_2 capture has been demonstrated at various scales, from pilot to commercial, in some coal- and gas-fired boilers. Natural gas-processing and fertilizer industries are already capturing CO_2 at commercial scale, and the Great Plains Synfuels Plant in Beulah, North Dakota, uses precombustion techniques to separate CO_2 from its lignite-derived synthetic natural gas.



CAPTURE FROM ETHANOL PROCESSES

Ethanol plants typically generate two emission streams containing CO_2. One of these streams comes from the combustion of natural gas or coal used to dry corn ethanol by-products. Capture of CO_2 from this emission stream would require technology like that used to capture CO_2 from power plants.

The second CO_2 emission stream from ethanol plants comes from the fermentation (biogenic) associated with converting corn to fuel. This emission stream contains more than 95% CO_2 and requires little additional capture processing prior to subsurface injection and geologic storage or EOR. Although coal-fired power plants can provide much larger volumes of CO_2 for use in EOR, the nearly capture-ready nature of biogenic CO_2 makes ethanol plants a prime target for early CCUS projects.



DIRECT AIR CAPTURE

Another CO_2 capture technology that is gaining interest is direct air capture (DAC). In this case, CO_2 is removed directly from the atmosphere by using liquid solvents or by flowing air over or through solid sorbents. An advantage of DAC is that the plant can be located near CO_2 sinks such as oil fields for use in EOR or other areas suitable for permanent geologic storage. That proximity eliminates the need to transport the CO_2 over long distances. Additionally, DAC technologies are typically not subjected to the impurities encountered in point-source capture applications. Challenges include the energy required for the process, which can be more energy-intensive compared to CO_2 removal from concentrated sources. Large volumes of air must be circulated over or through the sorbent material because of the small percentage of CO_2 in the atmosphere.

Banks of fans blow air through a CO_2-capturing solution in this rendering of a DAC plant.

CO_2 AND COMPRESSION

Captured CO_2 must be dehydrated and compressed into a supercritical or liquidlike state before transport to the storage site. CO_2 must be compressed to at least 1200–1700 pounds per square inch (psi) for transport in a pipeline to ensure that CO_2 remains a dense liquid.[22] Because compression is energy-intensive, improved compression methods are under development.

CO$_2$ TRANSPORTATION INFRASTRUCTURE

Following capture and compression, CO$_2$ is transported to a storage site. Given the quantities of CO$_2$ that are likely to be captured from industrial sources, pipelines are the most efficient mode for transporting the captured gas to geologic storage sites. Currently, more than 8500 km (5300 miles) of CO$_2$ pipeline is in service in North America, with additional pipeline planned or under construction.[22]

CO$_2$ PIPELINES

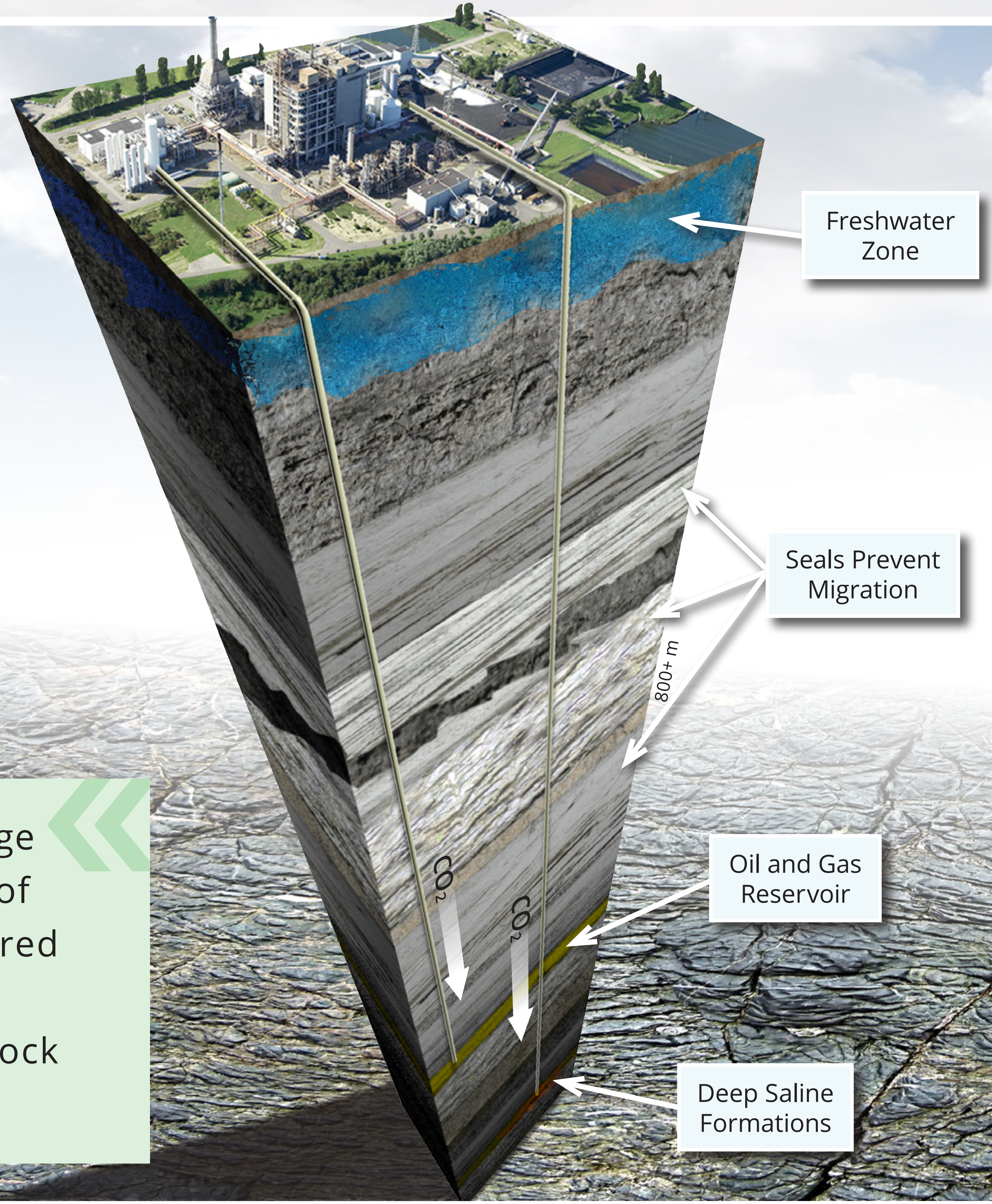
Pipelines are a proven technology and have been used to safely transport industrial quantities of CO$_2$ for over 50 years. CO$_2$ pipelines are similar in design and operation to natural gas pipelines, although the higher pressures needed for CO$_2$ transportation require thicker-walled carbon steel pipe.

Building a regional CO$_2$ pipeline infrastructure for CCUS activities will require thoughtful planning. Pipelines may be built to connect individual CO$_2$ sources and storage sites in a point-to-point fashion; however, pipelines may also be used to connect multiple sources and storage sites in a network. Network options may reduce overall costs, but common carrier issues such as those related to CO$_2$ stream quality may need to be addressed.

Pipelines carrying CO$_2$ have an excellent safety record. Strategies undertaken to manage risks include fracture arresters approximately every 300 m, block valves to isolate pipe sections if they leak, the use of advanced seals, and automatic control systems that monitor volumetric flow rates and pressure.

> NO fatalities have been reported as a result of CO$_2$ transport via pipeline.[23]

SECURE GEOLOGIC STORAGE



Geologic storage is the process of injecting captured CO_2 into deep underground rock formations.

GEOLOGIC STORAGE CRITERIA

Geologic storage involves injecting captured anthropogenic CO_2 into deep underground geologic formations. Typically found in areas with thick accumulations of sedimentary rock known as basins, these formations include porous and permeable layers of rock (reservoirs) that may contain natural fluids, including very salty water (brine), oil, gas, and even CO_2. Scientists have identified many potentially suitable areas across the globe that have the capacity to securely hold hundreds of years of anthropogenic CO_2 emissions deep underground.

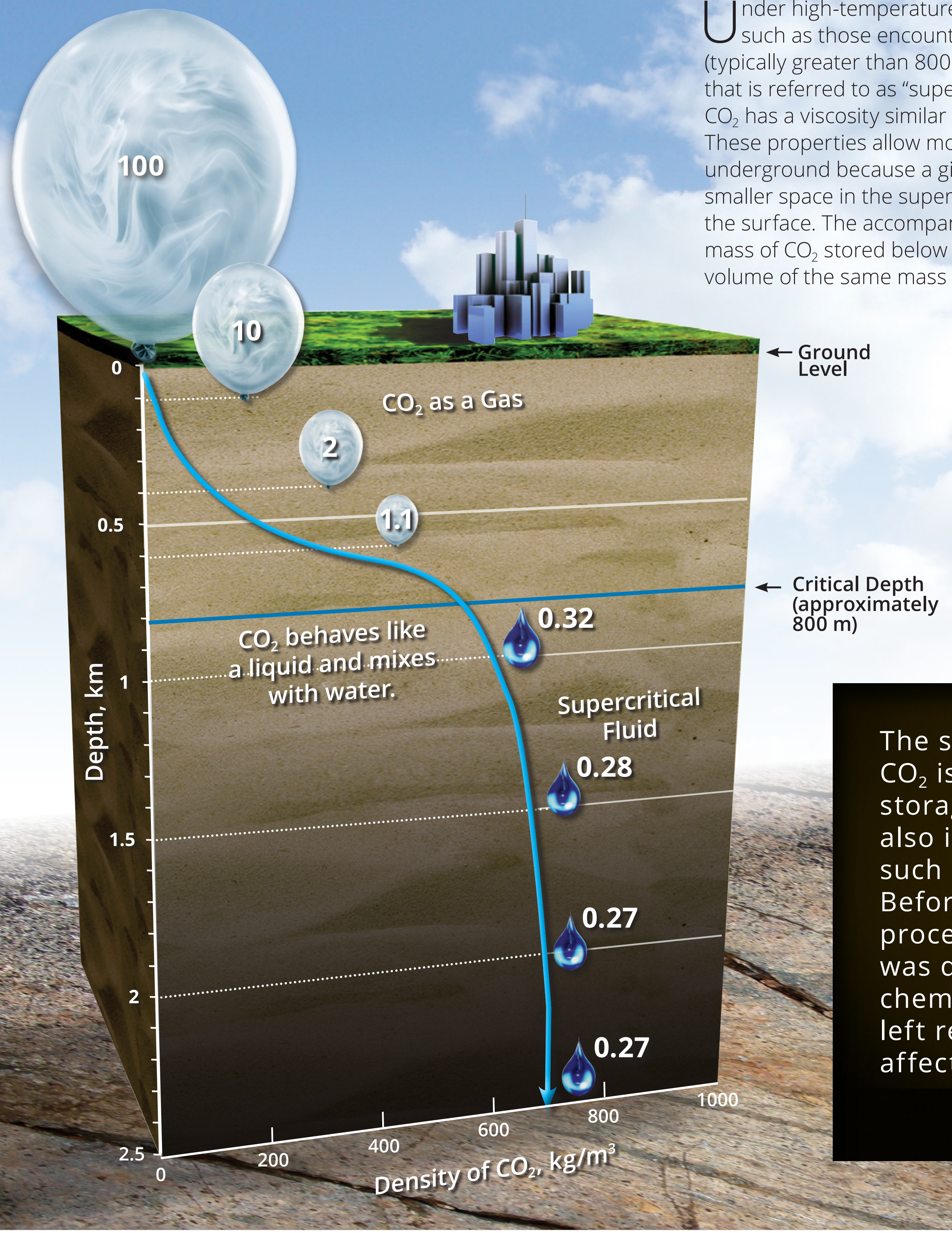
STORAGE RESERVOIR CHARACTERISTICS

Site selection is central to securely storing CO_2 because successful geologic storage requires that CO_2 stay in place and not pose significant risk to human health and the environment. Storage reservoirs should:

- Be capable of storing large quantities of CO_2 permanently.
- Be overlain by thick, laterally continuous seals or cap rocks that prevent upward migration of CO_2.
- Be at depths that take advantage of dense-phase CO_2 (typically >800 m), which allows efficient use of reservoir pore space for storage.
- Not impact underground sources of drinking water (USDWs), defined in the United States as water with salinity values less than 10,000 mg/L.
- Not be located in areas likely to be affected by natural or individual seismic activity.

SUPERCRITICAL CO_2

Under high-temperature and high-pressure conditions, such as those encountered in deep geologic formations (typically greater than 800 m), CO_2 will exist in a dense phase that is referred to as "supercritical." At this supercritical point, CO_2 has a viscosity similar to a gas and the density of a liquid. These properties allow more CO_2 to be efficiently stored deep underground because a given mass of CO_2 occupies a much smaller space in the supercritical state than it does as a gas at the surface. The accompanying illustration shows that any given mass of CO_2 stored below 800 m occupies around 0.3% of the volume of the same mass at the surface.



The supercritical state of liquidlike CO_2 is not only important for efficient storage in the deep subsurface, but also in a host of other applications, such as decaffeinating coffee. Before the supercritical CO_2 process was used, coffee was decaffeinated with chemical solvents that often left residues, negatively affecting the flavor.

TRAPPING CO_2 IN ROCKS

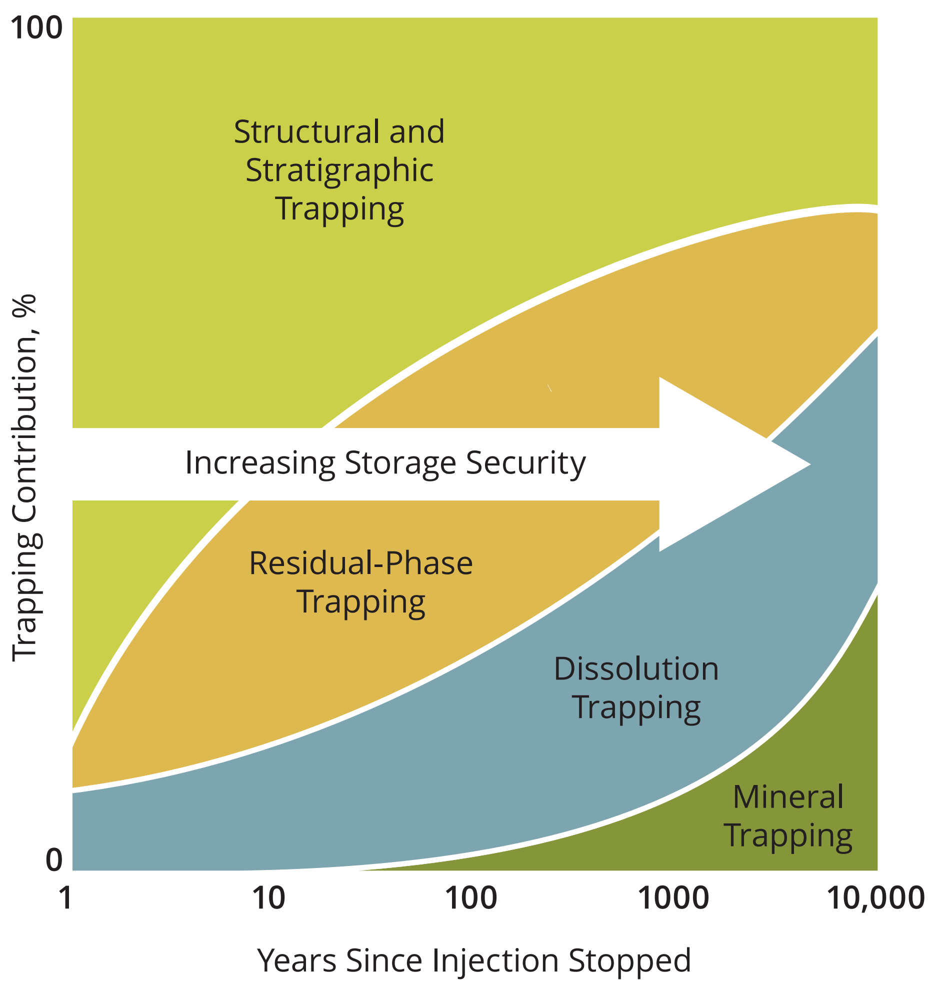
Several mechanisms function to trap and store CO_2 in deep geologic formations.[21]

STRUCTURAL AND STRATIGRAPHIC TRAPPING – Injected CO_2 is typically less dense than native pore fluids, most commonly brine, in deep geologic formations. This lower density causes CO_2 to rise through the storage reservoir. An overlying seal or cap rock, consisting of relatively impermeable rock such as shale or salt, can prevent upward migration out of the reservoir. Various configurations of rocks can lead to this trapping, as depicted in the diagrams at the bottom of this page. This primary trapping mechanism has held natural accumulations of CO_2 for millions of years.

RESIDUAL-PHASE TRAPPING – As injected CO_2 migrates through a reservoir, small droplets may become detached and remain trapped within the center of pore spaces, typically surrounded by brine. These residual droplets are effectively immobilized.

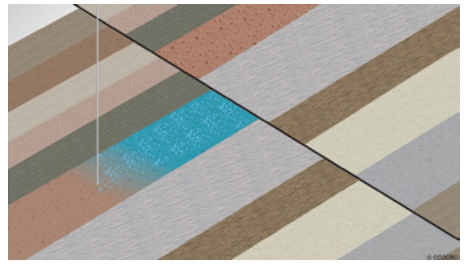
DISSOLUTION TRAPPING – Just as sugar dissolves in water, some of the CO_2 will dissolve into brine in the pore spaces. Brine with dissolved CO_2 becomes denser than the surrounding brine and will sink to the bottom of the reservoir, minimizing the possibility of further migration.

MINERAL TRAPPING – The last stage of CO_2 trapping involves a chemical reaction between the dissolved CO_2 in the formation fluids and the minerals in the target formation and cap rock to form new solid minerals, thus effectively locking the CO_2 in place. Mineral trapping will typically occur over extended timescales and is difficult to predict with accuracy.

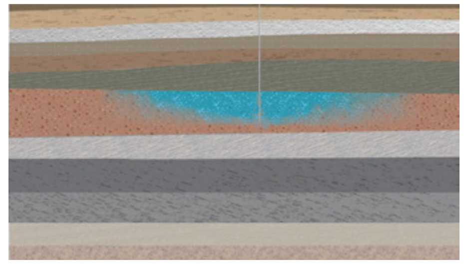


As time passes after the injection of CO_2 into a deep geologic environment, the trapping mechanism becomes more effective. Storage security increases as the trapping mechanism moves from the physical process of structural and stratigraphic trapping toward geochemically based processes.

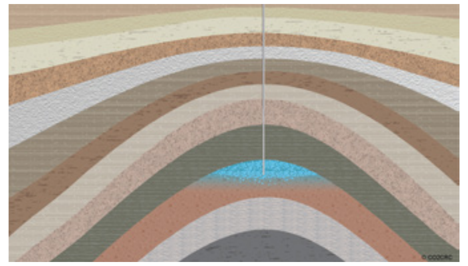
STRUCTURAL AND STRATIGRAPHIC TRAPPING



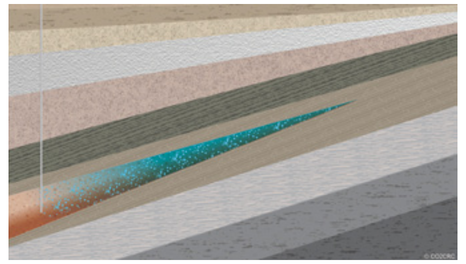
A sealing fault can line up an impervious rock layer with the formation to prevent the CO_2 from moving upward out of the formation.



The CO_2 is trapped when there is a sudden change in the rock formations so that the CO_2 cannot move upward.



The buoyant CO_2 will collect under a curved layer of impermeable rock at the highest point, unable to move out of the formation.



CO_2 can become trapped when the rock type in the formation changes from permeable to impermeable.

OIL FIELDS OF THE UNITED STATES AND CANADA

Distribution of Oil Fields[24]

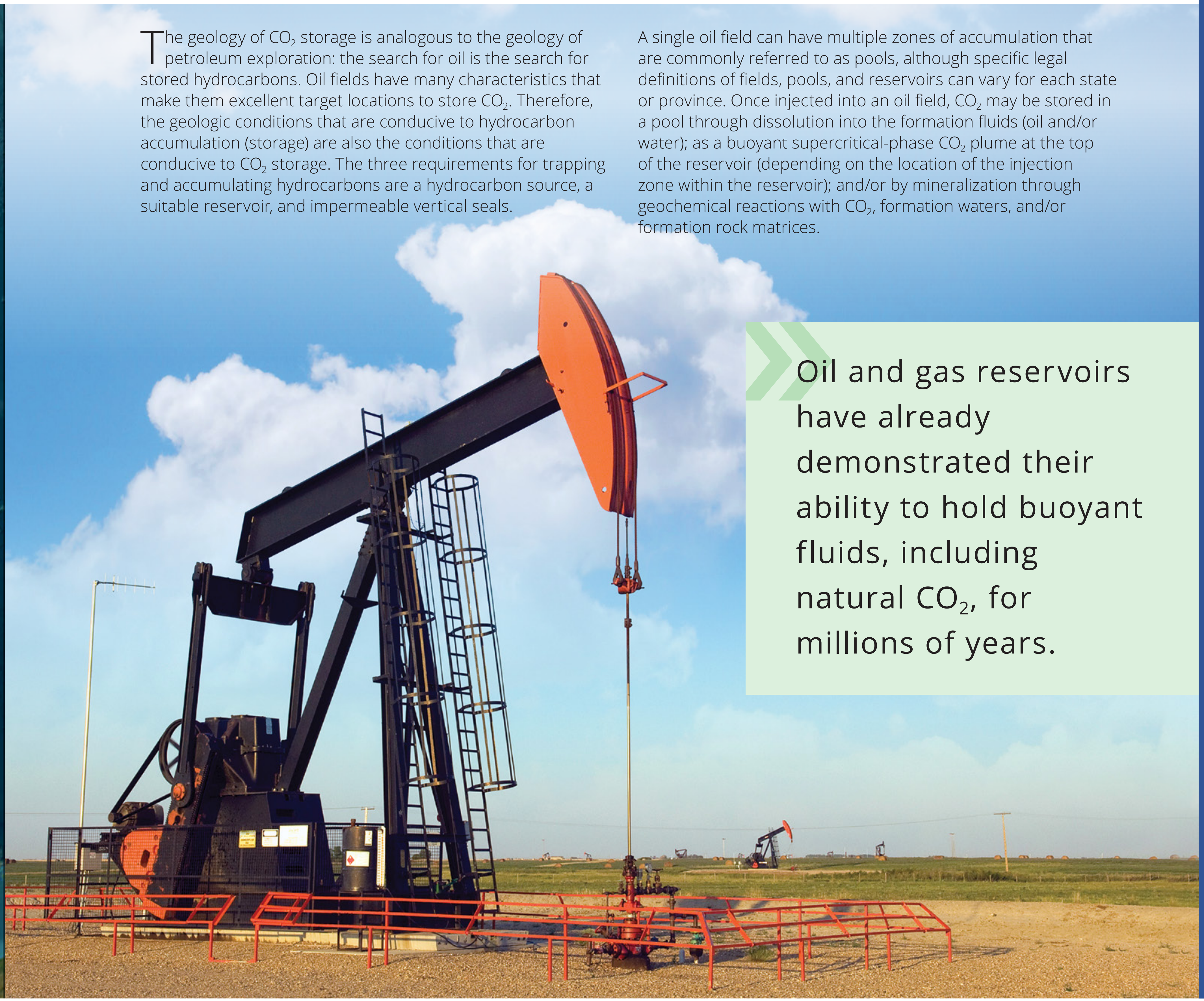
🟨 Oil Field

Note: Mexico has many oil fields; however, they are not pictured because of data limitations.

CO$_2$ IN OIL FIELDS

The geology of CO$_2$ storage is analogous to the geology of petroleum exploration: the search for oil is the search for stored hydrocarbons. Oil fields have many characteristics that make them excellent target locations to store CO$_2$. Therefore, the geologic conditions that are conducive to hydrocarbon accumulation (storage) are also the conditions that are conducive to CO$_2$ storage. The three requirements for trapping and accumulating hydrocarbons are a hydrocarbon source, a suitable reservoir, and impermeable vertical seals.

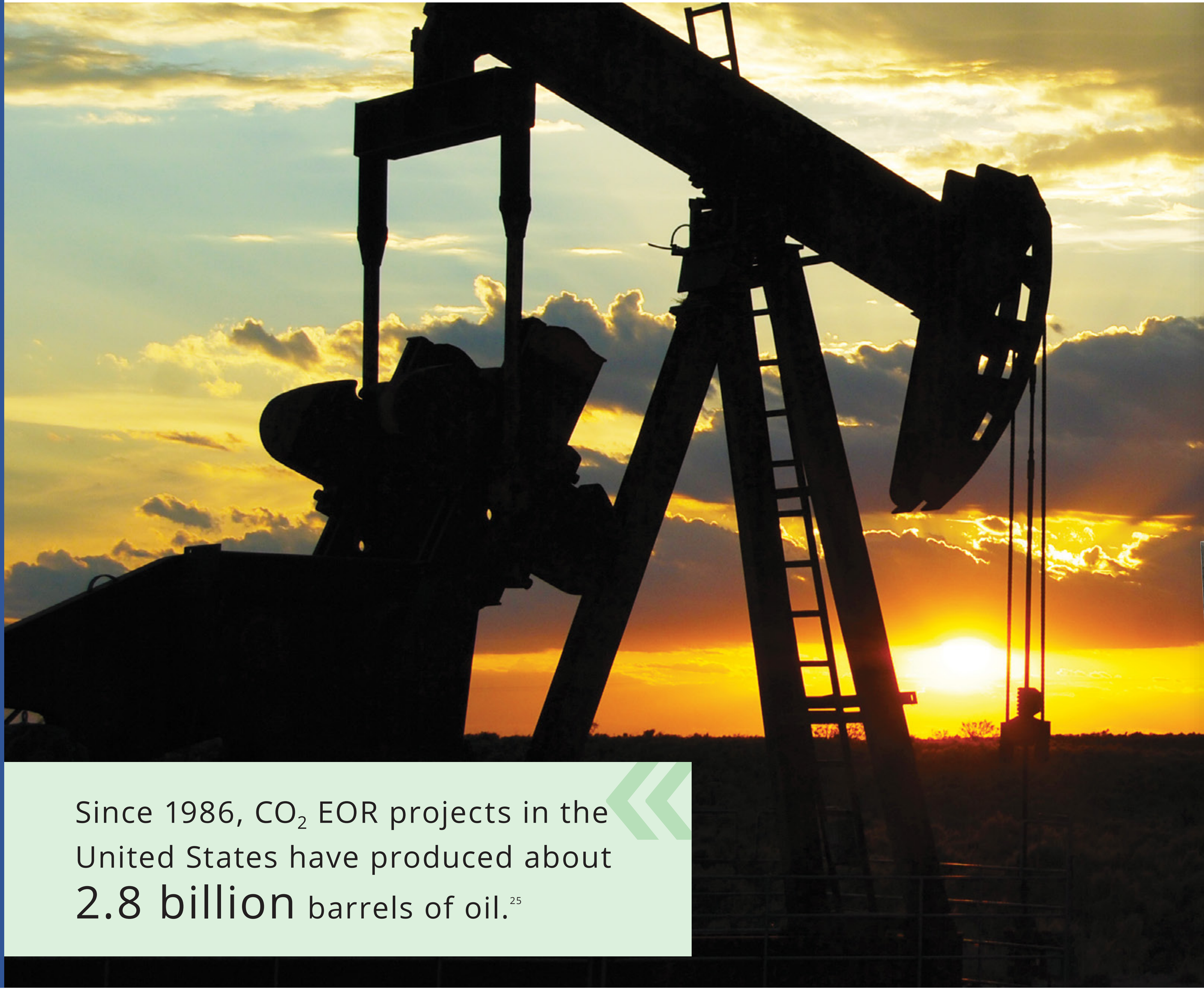
A single oil field can have multiple zones of accumulation that are commonly referred to as pools, although specific legal definitions of fields, pools, and reservoirs can vary for each state or province. Once injected into an oil field, CO$_2$ may be stored in a pool through dissolution into the formation fluids (oil and/or water); as a buoyant supercritical-phase CO$_2$ plume at the top of the reservoir (depending on the location of the injection zone within the reservoir); and/or by mineralization through geochemical reactions with CO$_2$, formation waters, and/or formation rock matrices.



> Oil and gas reservoirs have already demonstrated their ability to hold buoyant fluids, including natural CO$_2$, for millions of years.

ENHANCED OIL RECOVERY

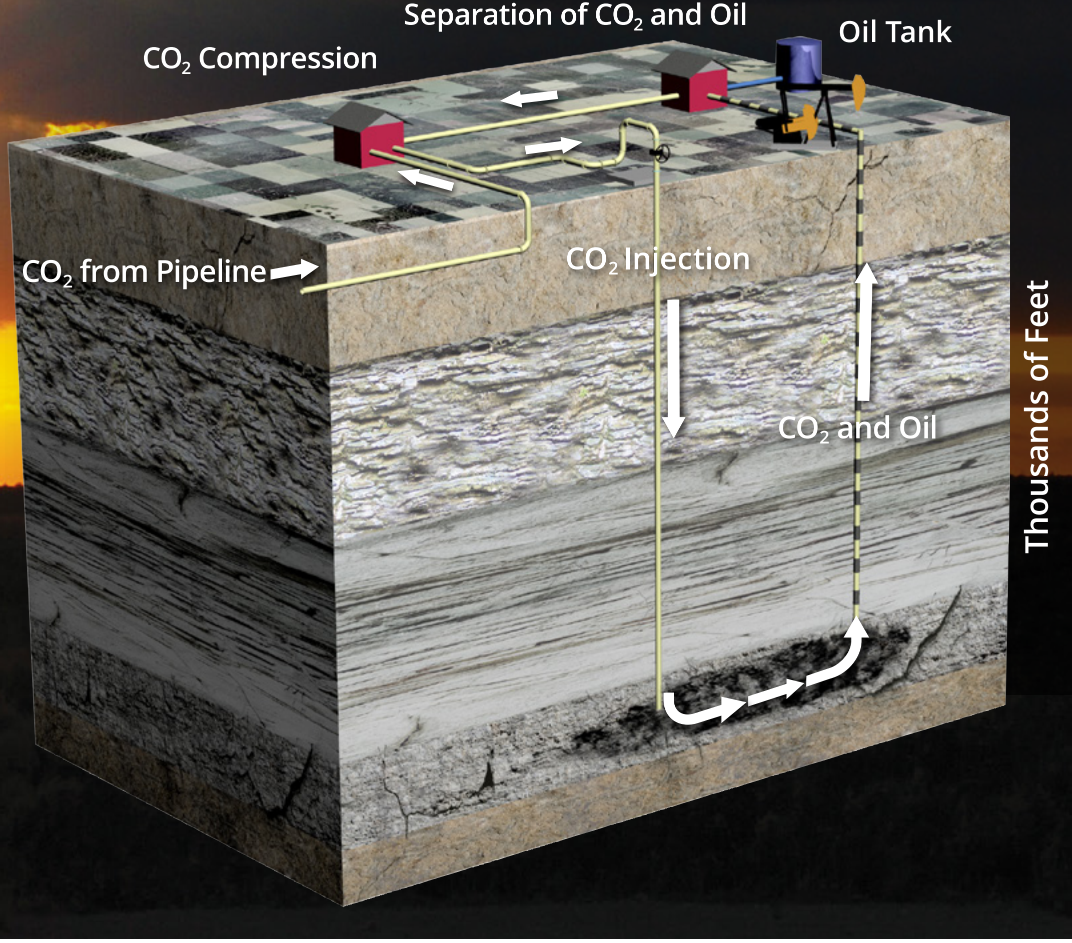
CO_2 GETS THE OIL OUT



Most oil is extracted in three distinct phases: primary, secondary, and tertiary (or enhanced) recovery. Primary and secondary recovery operations often leave more than two-thirds of the oil in the reservoir. Injecting CO_2 into the reservoirs through the EOR process can recover some of that remaining oil.

HOW EOR WORKS:

When CO_2 comes into contact with oil, a significant portion dissolves into the oil, reducing the oil's viscosity and increasing its mobility. This, combined with the increased pressure from injection, can result in increased oil production rates and extend the lifetime of the oil reservoir. While some CO_2 is produced along with the extra oil, a significant portion of the CO_2 remains in the subsurface. When an oilfield operator is finished with EOR operations, nearly all of the CO_2 remains trapped in the subsurface.



Not all reservoirs are good candidates for CO_2-based EOR. Factors such as geology, depth, and the nature of the oil itself will determine the effectiveness of CO_2 for EOR.

Since the 1970s, operators in West Texas have safely pumped millions of tonnes of CO_2 into oil fields for EOR purposes. As of the end of 2022, there were 139 CO_2 EOR projects underway across 12 states. Although a majority of CO_2 used in this process is sourced from natural underground deposits, the proportion of CO_2 derived from the capture of anthropogenic emissions is increasing. CO_2 EOR has also been deployed for two decades or more in Canada, and in recent years, China, Saudi Arabia, Brazil, and Mexico have begun pilot- or full-scale projects.

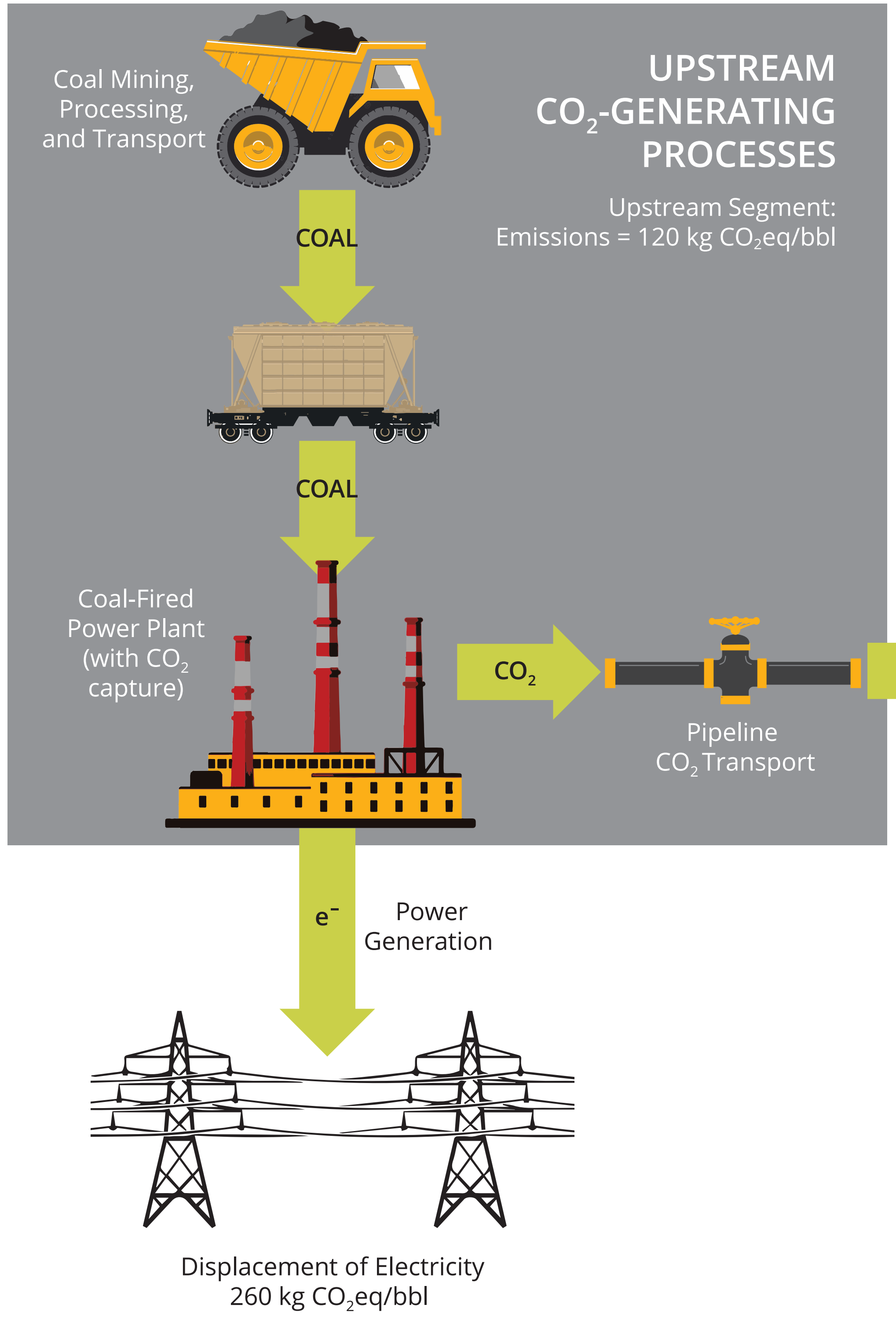
Since 1986, CO_2 EOR projects in the United States have produced about **2.8 billion** barrels of oil.[25]

CO_2 EOR LIFE CYCLE ANALYSIS

Life cycle analysis (LCA) is an approach to account for CO_2 storage at an EOR site and to track CO_2 emissions at all stages of a CO_2 EOR project. The LCA results may then be used to evaluate the life cycle CO_2 emissions per barrel of oil produced via CO_2 EOR as compared to oil produced by other methods.

The Energy & Environmental Research Center (EERC) conducted a detailed LCA of CO_2 emissions associated with a generic CO_2 EOR project where the CO_2 was sourced from a coal-fired power plant.[26] The modeled system included three segments: upstream, gate-to-gate, and downstream CO_2-generating processes. Upstream processes included coal extraction and processing, transport, power generation with CO_2 capture, and CO_2 transport to the CO_2 EOR field. Gate-to-gate processes included CO_2 stored at a reservoir, land use, injection and recovery, bulk separation and storage of fluids and gases, and other supporting processes such as venting and flaring gases. Downstream processes included crude oil transport, refining, fuel transport, and combustion. The average total CO_2 equivalent (CO_2eq) emissions from upstream, gate-to-gate, and downstream segments were 690 kg CO_2eq/bbl.

However, since 85% or more of the required CO_2 was captured at the power plant, emissions associated with electricity generation were significantly reduced. This electricity coproduct displaced alternative sources of electricity from the U.S. electricity grid, i.e., each new MWh produced with CO_2 capture displaced an existing MWh (a one-to-one replacement). Accounting for this displacement resulted in a final emissions factor for the incremental oil produced via CO_2 EOR of 430 kg CO_2eq/bbl.



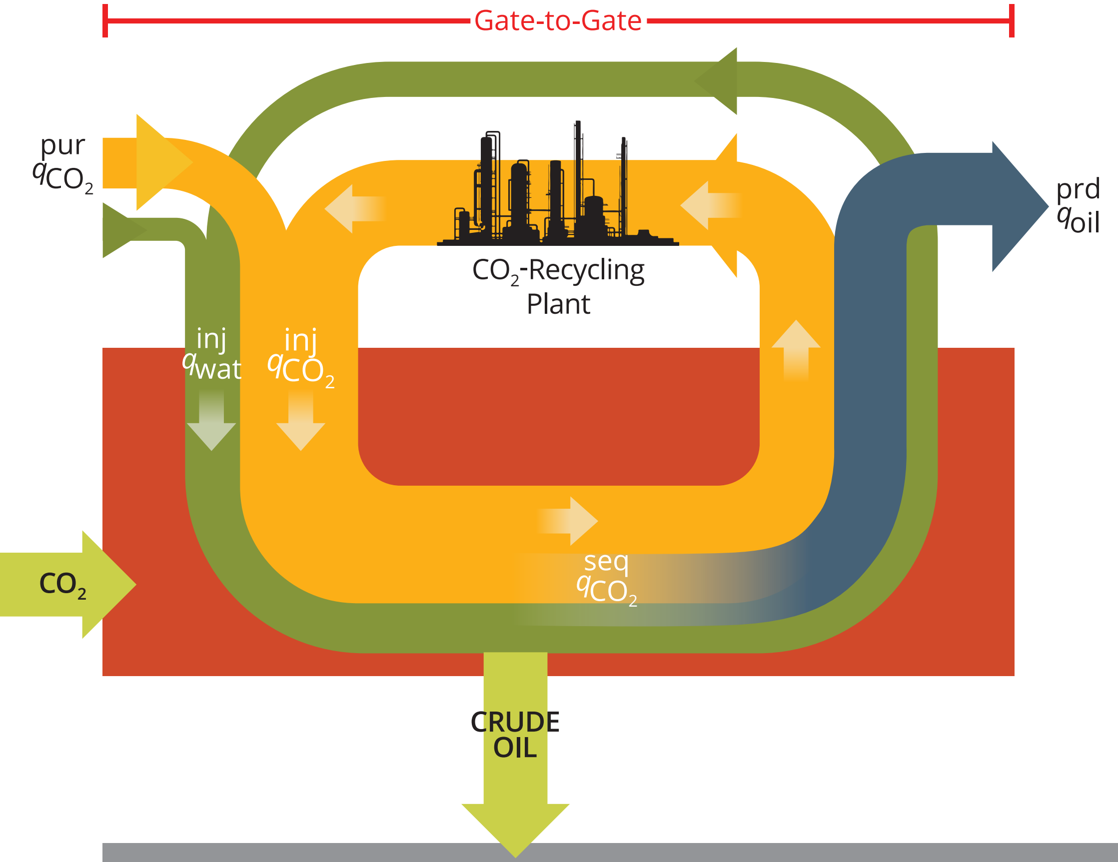
UPSTREAM CO_2-GENERATING PROCESSES

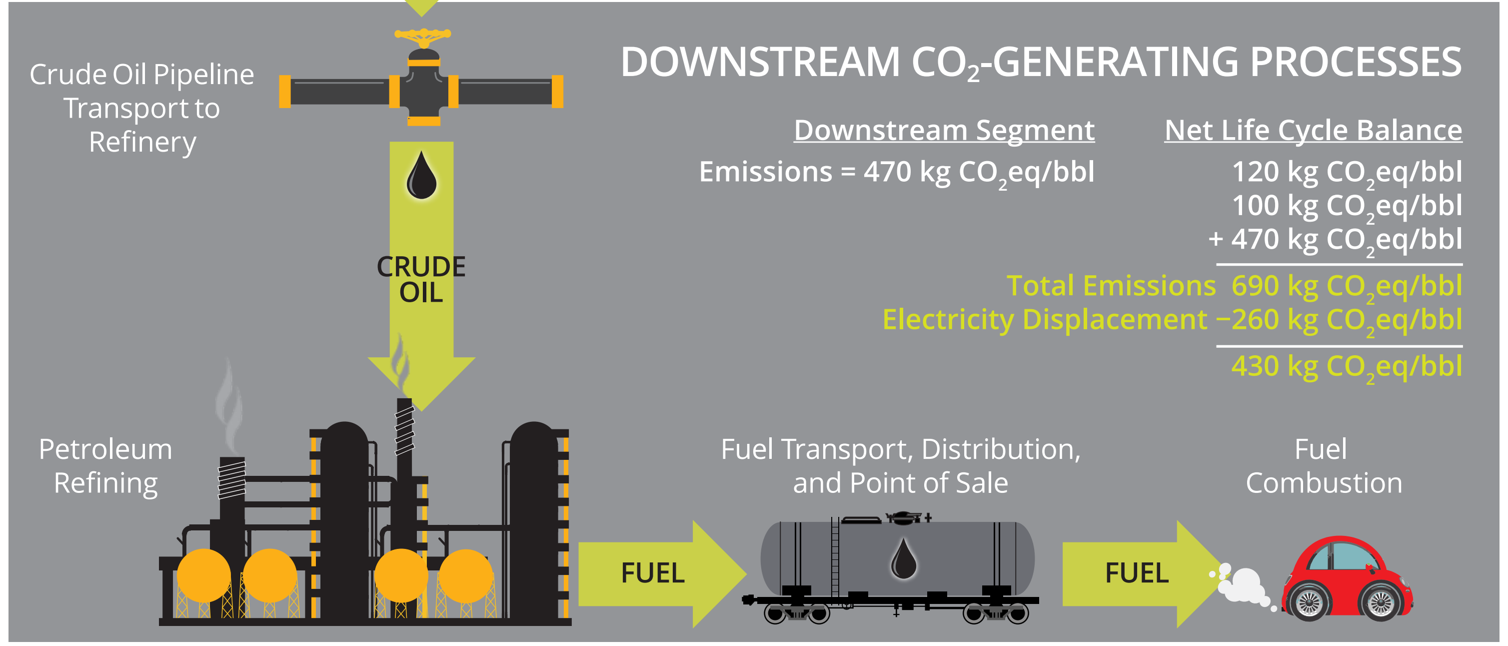
Upstream Segment:
Emissions = 120 kg CO_2eq/bbl

Displacement of Electricity
260 kg CO_2eq/bbl

CO_2 EOR OPERATIONS (gate-to-gate)

Gate-to-Gate Segment: Emissions = 100 kg CO_2eq/bbl



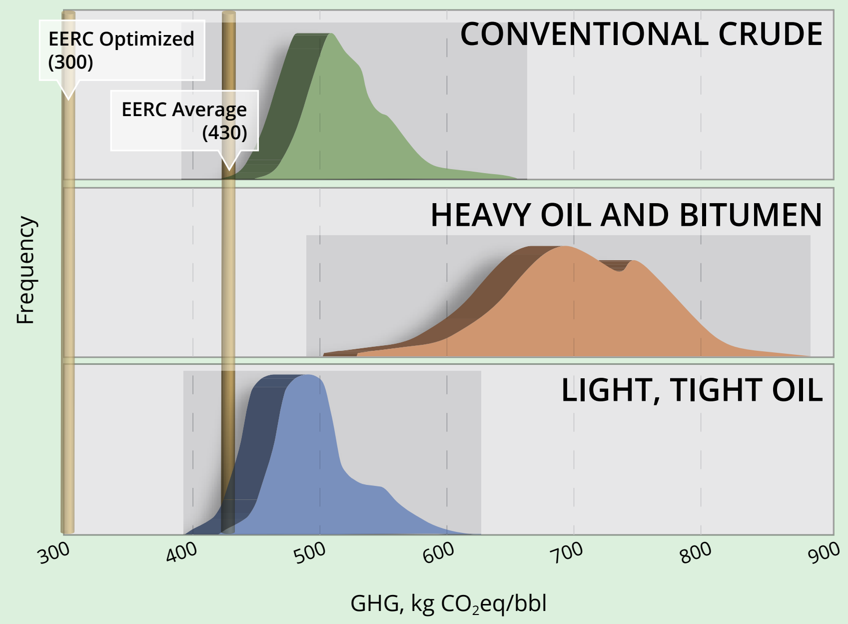


DOWNSTREAM CO_2-GENERATING PROCESSES

Downstream Segment	Net Life Cycle Balance
Emissions = 470 kg CO_2eq/bbl	120 kg CO_2eq/bbl 100 kg CO_2eq/bbl + 470 kg CO_2eq/bbl
Total Emissions	690 kg CO_2eq/bbl
Electricity Displacement	−260 kg CO_2eq/bbl
	430 kg CO_2eq/bbl

pur = purchased
pro = produced
inj = injected
seq = sequestered

Note: Emissions are expressed as CO_2eq, which includes CO_2, CH_4, and N_2O.



Life cycle emission distributions for conventional crude (top); heavy oil and bitumen (middle); and light, tight oil (bottom).[27] Most conventional crude oil contains about 500 kg CO_2eq/bbl. Tan bars indicate EERC estimates from a detailed LCA of GHG emissions associated with CO_2 EOR where the CO_2 is sourced from a coal-fired power plant. The average value (430 kg CO_2eq/bbl) represents the LCA result when all inputs are set to their mean values, and the optimized value (300 kg CO_2eq/bbl) represents the LCA results when all inputs are set to maximize CO_2 storage and minimize the oil GHG emissions.

NORTH AMERICAN SEDIMENTARY BASINS

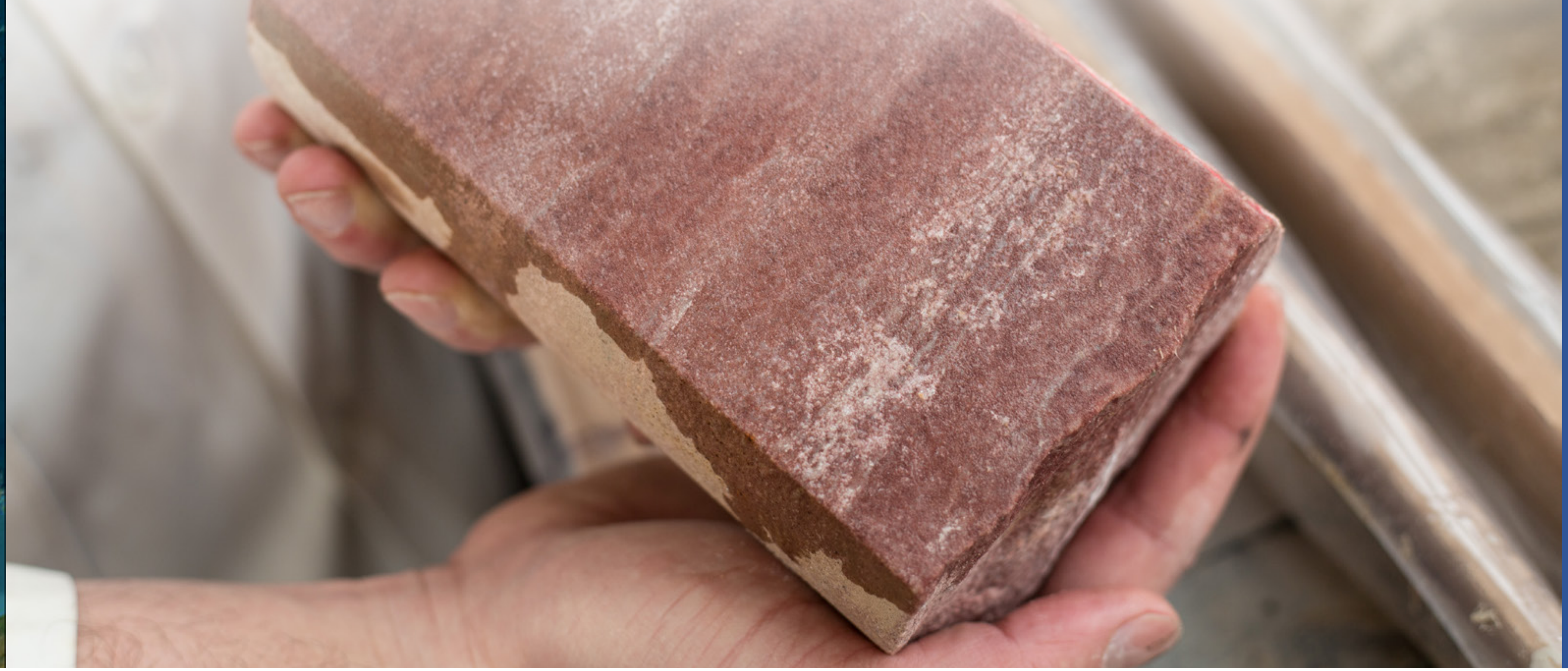
Distribution of Sedimentary Basins Greater than 800 m Deep[28]

CO_2 IN SALINE FORMATIONS

Sedimentary basins are relatively large areas of Earth's surface that, for various reasons, have subsided over long periods of geologic time. This subsidence allowed for the accumulation of sediments that eventually lithified into rock. Areas where the accumulation of sediments is thick enough (>800 m) may have an arrangement of rock layers suitable for CO_2 storage.

Many sedimentary basins are home to hydrocarbon accumulations that are being tapped in the oil and gas fields of the world. In addition to oil and gas, the rocks in sedimentary basins are often saturated with brine. These layers of rock are referred to as saline formations and are widely distributed throughout North America and the rest of the world, making them accessible to many large-scale CO_2 sources. Saline formations suitable for CO_2 storage are made of sandstone, limestone, dolomite, or some mix of the three. Many of these formations are ideally situated to provide not only large potential for CO_2 storage but are also overlain by thick and regionally extensive cap rocks. These cap rocks function as seals to help ensure that the injected CO_2 will remain in place permanently.

> Deep saline formations account for most of the world's geologic storage resource and may provide an ideal storage option for facilities not able to take advantage of economical CO_2 EOR opportunities.



PUTTING TDS LEVELS INTO PERSPECTIVE

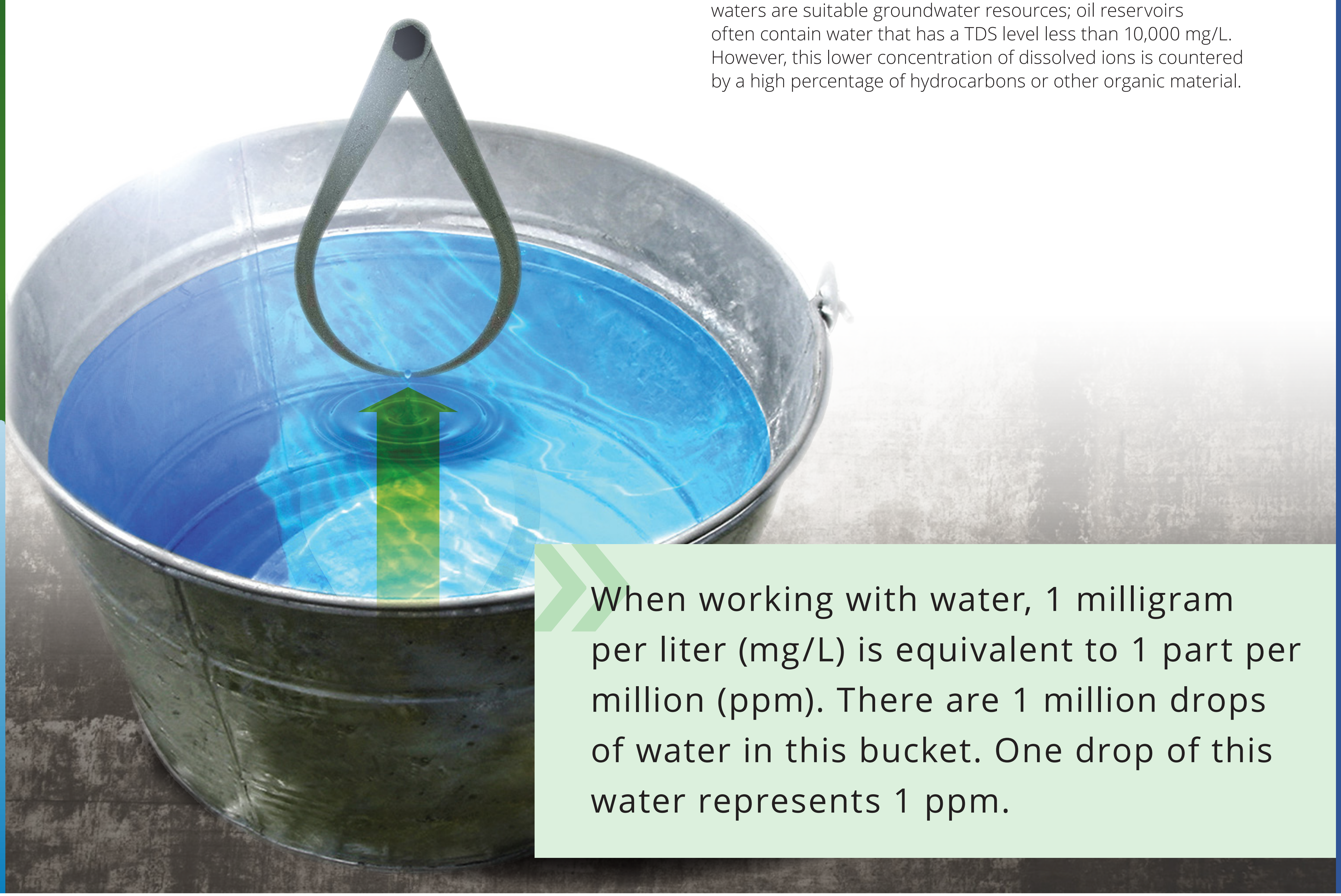
Water Source	TDS, mg/L
Lake Superior[29]	~63
Missouri River[30]	~250
Drinking Water[31]	<500*
Ocean[32]	35,000
Great Salt Lake[33]	50,000–270,000
Dead Sea[34]	350,000

* U.S. Environmental Protection Agency (EPA) secondary drinking water standard.

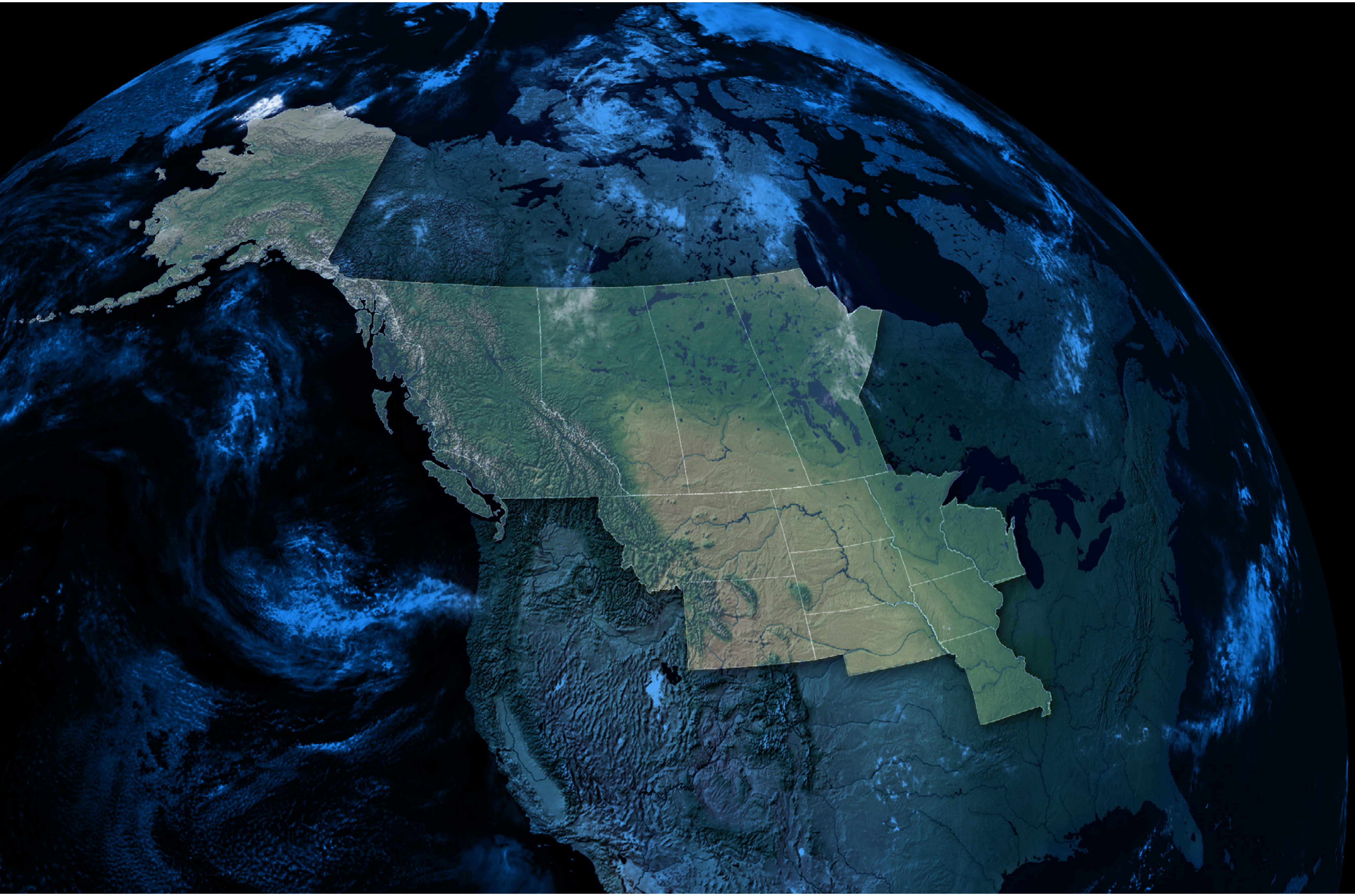
SALINITY

The salinity of water is often expressed through an analytical measurement referred to as total dissolved solids (TDS). This is a measure of the combined content of dissolved substances in water, primarily consisting of ions of inorganic salts (mainly, calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates).

In general, EPA has ruled that CO_2 cannot be injected into geologic formations where the TDS level is less than 10,000 mg/L. This stipulation is meant to protect valuable USDWs that may, in the future, be used for drinking water or other municipal water uses. Many of the saline formations targeted for CO_2 storage have TDS values greater than 50,000 mg/L, and some deeper portions of sedimentary basins have TDS values exceeding 300,000 mg/L. Not all lower-TDS waters are suitable groundwater resources; oil reservoirs often contain water that has a TDS level less than 10,000 mg/L. However, this lower concentration of dissolved ions is countered by a high percentage of hydrocarbons or other organic material.



When working with water, 1 milligram per liter (mg/L) is equivalent to 1 part per million (ppm). There are 1 million drops of water in this bucket. One drop of this water represents 1 ppm.

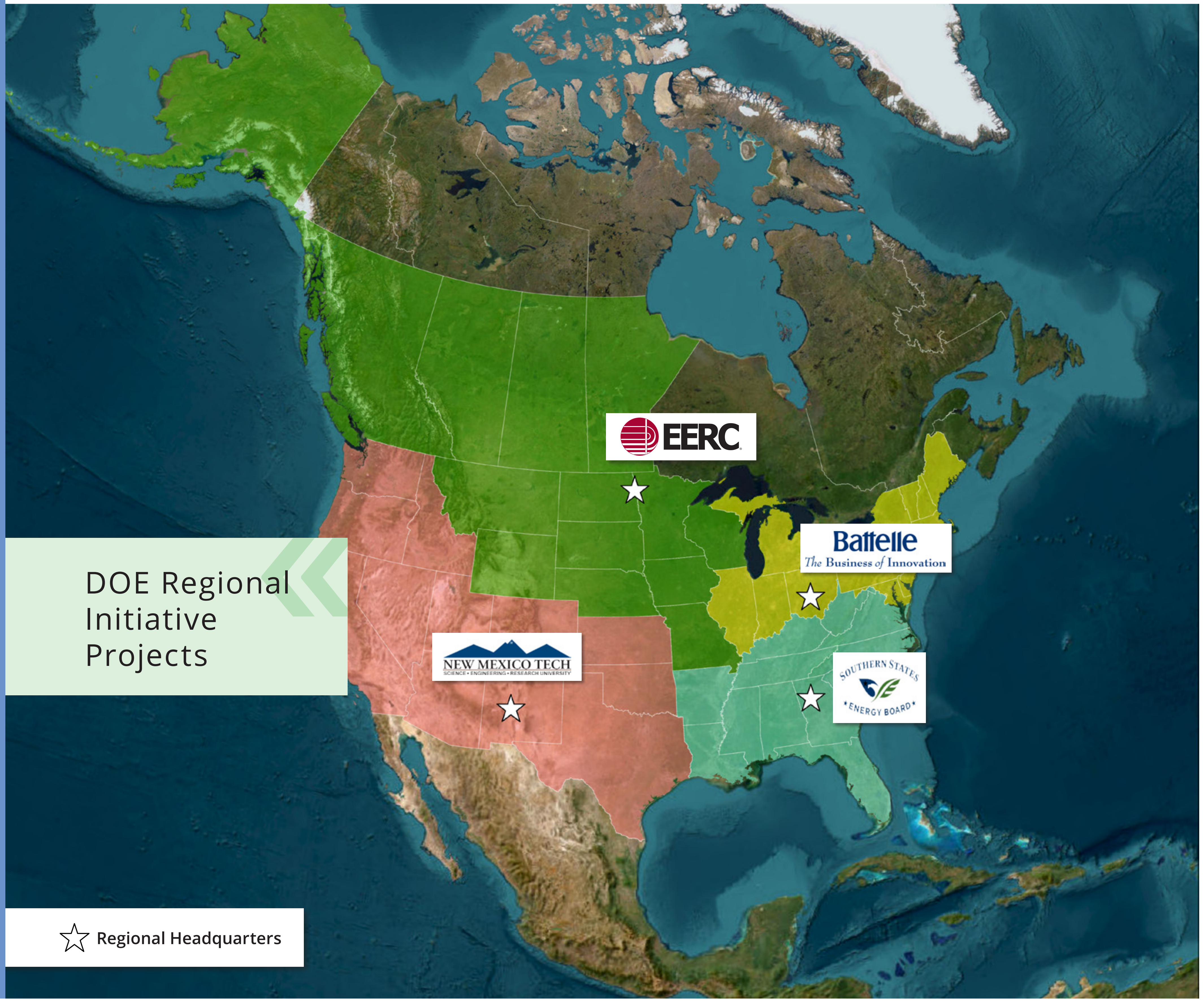


CHAPTER 3

THE PCOR PARTNERSHIP

Because CCUS requires a new combination of existing and novel technologies, research and demonstration are needed to advance our knowledge of their potential to better manage CO_2. The PCOR Partnership is assessing and prioritizing the opportunities for CO_2 storage in the region and working to resolve the technical, regulatory, and environmental challenges to the most promising storage opportunities. At the same time, the PCOR Partnership informs policymakers and the public about CO_2 sources, storage strategies, and storage opportunities.

THE RCSP INITIATIVE PROGRAM



The Regional Carbon Sequestration Partnership (RCSP) Initiative is a key component of the U.S. Department of Energy's (DOE's) Carbon Storage Program efforts to validate geologic storage technologies and support commercialization of CCUS. Since 2003, the DOE RCSPs have been developing expertise in all aspects of CCUS through activities ranging from laboratory- and modeling-based investigations to large-scale field tests. The RCSP Program is recognized internationally for its contributions to the science and technology of subsurface characterization, design, operation, and monitoring for geologic storage.

The PCOR Partnership is one of four regional initiative projects established in 2019 from the RCSP Program. Under this DOE-supported initiative, the PCOR Partnership continues to serve its region and broad stakeholder base to advance and accelerate CCUS deployment. Each of the four partnerships is identifying and addressing knowledge gaps and technical challenges as well as disseminating knowledge to accelerate commercial CCUS deployment. Each partnership will leverage its region's strengths to identify and promote potential infrastructure and/or CCUS projects that will enable the low-CO_2-emission industries of the future.

ADVANCED STORAGE R&D

Wellbore Integrity and Mitigation

Storage Complex Efficiency and Security

Monitoring, Verification, Accounting (MVA), and Assessment

STORAGE INFRASTRUCTURE

Regional Carbon Sequestration Partnership Program

Characterization Field Projects (onshore and offshore)

Fit-for-Purpose Projects

RISK AND INTEGRATION TOOLS

THE DOE CARBON STORAGE PROGRAM[35] comprises three technology areas: storage infrastructure; advanced storage research and development (R&D); and risk and integration tools, which cuts across and links the other two.

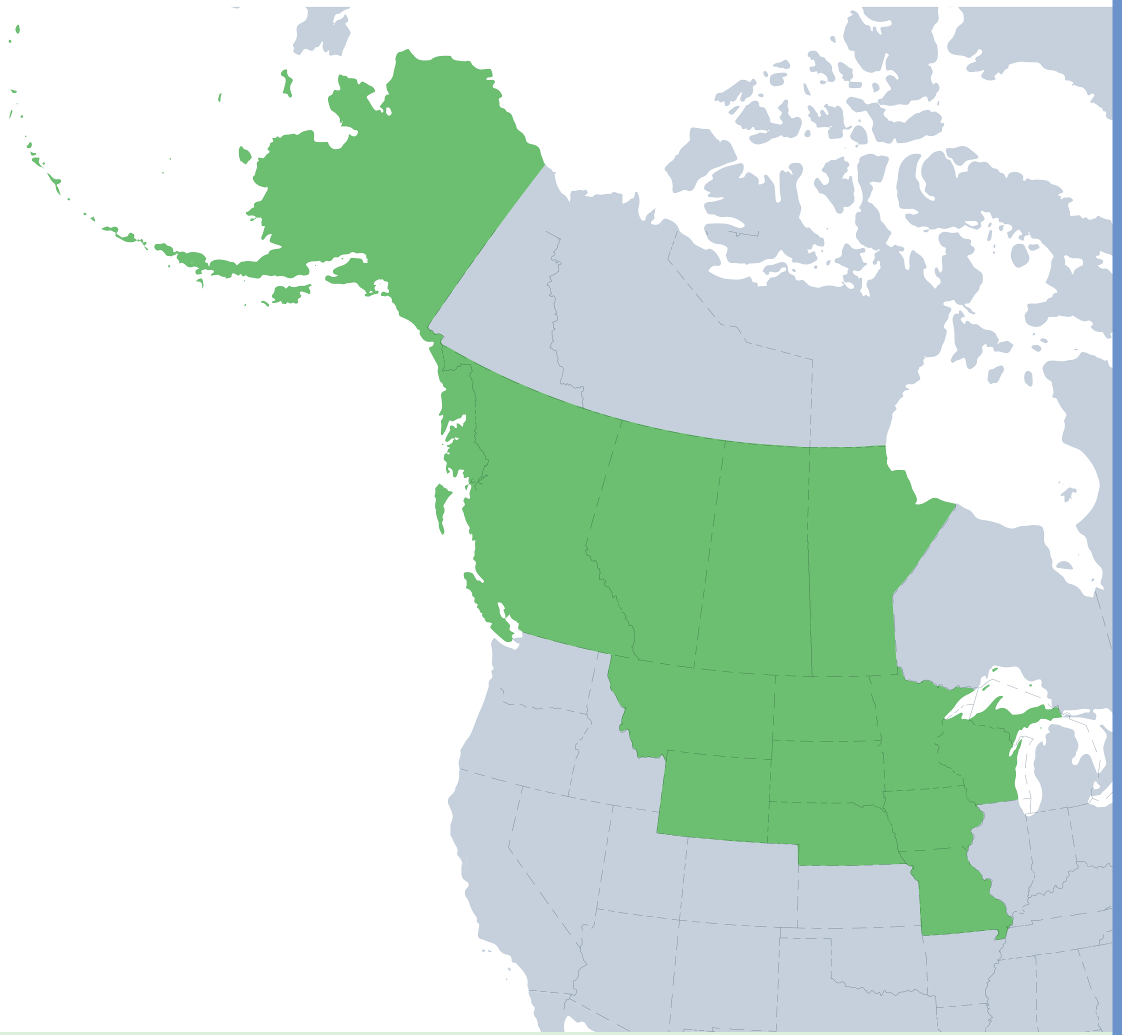
PCOR PARTNERSHIP INITIATIVE REGION

The PCOR Partnership Initiative region covers nearly 6.2 million square kilometers from Missouri to Alaska, including ten U.S. states and four Canadian provinces.

PCOR PARTNERSHIP

The EERC leverages the combined years of experience of the PCOR Partnership and the Partnership for CO_2 Capture (PCO_2C) to address regional capture, transport, use, and storage challenges facing commercial CCUS deployment by:

- Strengthening the technical foundation for geologic CO_2 storage and EOR.
- Advancing capture technology.
- Improving application of monitoring technologies.
- Promoting integration between capture, transportation, use, and storage industries.
- Providing scientific support to regulatory agencies and policymakers.



The PCOR Partnership—funded by DOE's National Energy Technology Laboratory (NETL), the North Dakota Industrial Commission (NDIC), and partner organizations—is accelerating the commercial deployment of CCUS. The EERC leads the PCOR Partnership, with support from the University of Wyoming and the University of Alaska Fairbanks.

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY | EERC UND UNIVERSITY OF NORTH DAKOTA | North Dakota Industrial Commission | UAF Institute of Northern Engineering University of Alaska Fairbanks | UNIVERSITY OF WYOMING School of Energy Resources

PHASED APPROACH

The DOE RCSP Program began with three phases that ran from 2003 to 2019 and laid the foundation for CCUS commercialization by validating and demonstrating the capacity for permanent, economical, and safe geologic storage of CO_2. The work during the RCSP Program helped to establish effective methods and reliable approaches to developing and deploying CCUS projects across the different RCSP regions.

PHASE I (CHARACTERIZATION)

Beginning in 2003, Phase I consisted of characterizing regional CO_2 emission sources and potential geologic storage locations within each RCSP region.

PHASE II (VALIDATION)

Beginning in 2005, validation of the most promising regional storage opportunities was addressed through a series of small-scale field projects in various carbon storage targets such as saline formations, coal seams, basalt formations, and terrestrial systems. The validation projects provided valuable information on reservoir and seal properties of formations as well as initial validation of geologic modeling and field monitoring technologies.

PHASE III (DEVELOPMENT)

In 2007, Phase III focused on large-scale field projects in saline formations and oil and gas fields, with the target goal of injecting at least 1 million metric tons per project. These large-scale demonstration projects advanced CCUS project management knowledge and supported the development of storage-related technologies in characterization, geologic modeling and simulation, risk assessment, mitigation, and monitoring.

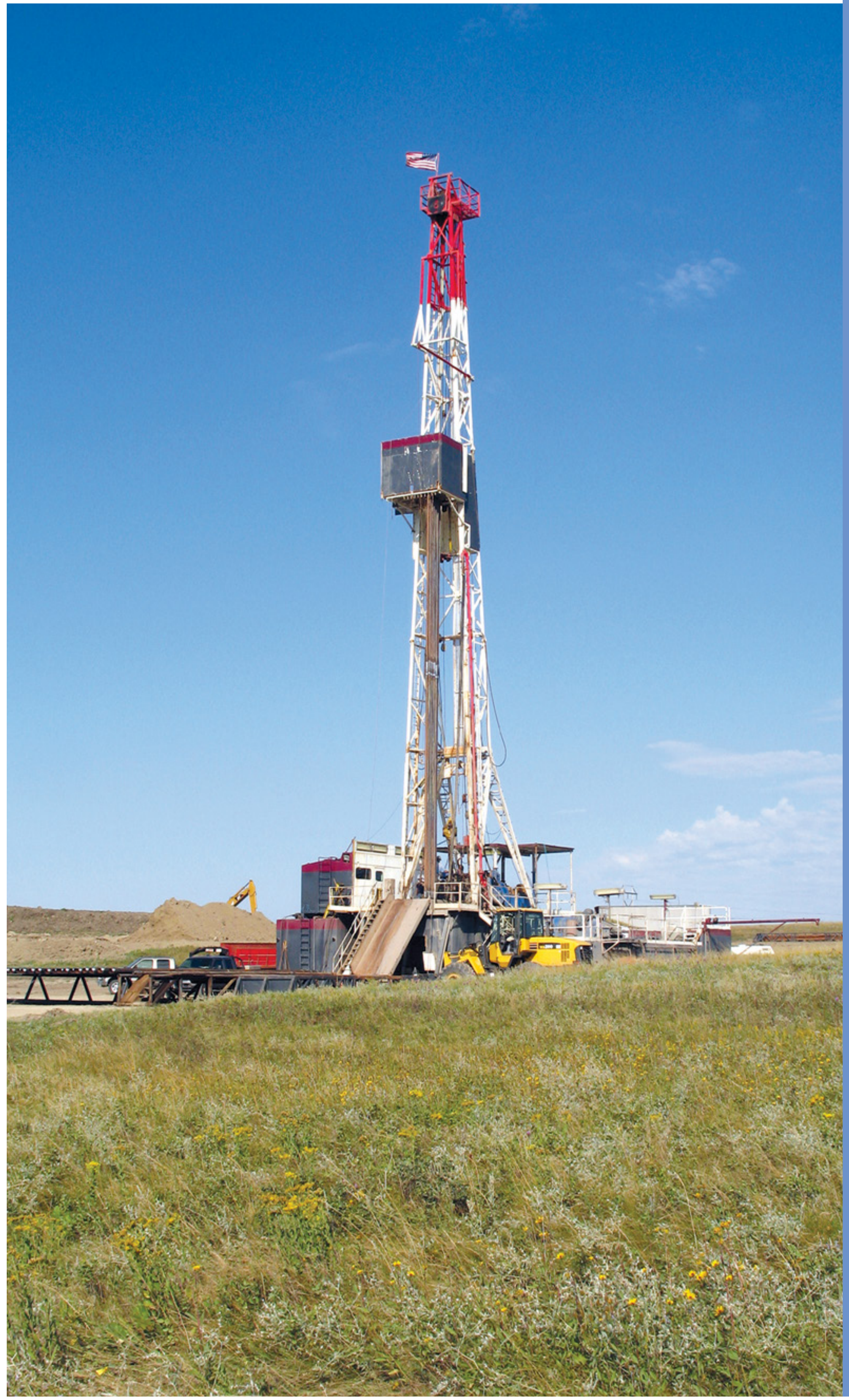
CHARACTERIZATION PHASE

During Phase I, the PCOR Partnership assessed and prioritized opportunities for storage in the region and helped address the technical, regulatory, and environmental barriers to the most promising storage opportunities. The effort resulted in practical and environmentally sound strategies for carbon management in the PCOR Partnership region, derived from assessments of CO_2 emission sources, sinks, regulations, deployment challenges, transport considerations, and capture and separation technologies.

Phase I activities identified four source–sink combinations in the Williston and Alberta sedimentary basins that merited field validation testing in Phase II.

Learnings from Phase I include the following:

- Multiple CO_2 storage targets exist within the PCOR Partnership region, including oil fields, saline formations, and coal seams.
- The presence of CO_2 sources and storage options and their relative proximity to each other support the deployment of CCUS projects within the PCOR Partnership region.



VALIDATION PHASE

The goal of Phase II was to validate technologies and to demonstrate CCUS in locations in the PCOR Partnership region that could support future full-scale geologic and terrestrial storage opportunities. From 2005 to 2009, the PCOR Partnership conducted four field validation projects that demonstrated the effectiveness of CO_2 storage in different settings and under varying conditions. The field validation tests demonstrated the CO_2 storage potential of multiple storage targets, including deep carbonate formations, lignite coals, pinnacle reef structures, and the prairie pothole wetlands.

In addition to the validation projects, several supporting activities were conducted during Phase II, including 1) refinement of regional characterization of storage opportunities, 2) clarification of the regulatory and permitting requirements for geologic CO_2 storage, 3) detailed review of commercial CO_2 capture technologies, 4) integration of regional efforts with other DOE RCSPs, and 5) continuation of local and regional public outreach initiatives.

Phase II Validation Projects

ZAMA FIELD

Determined acid gas injection for the purpose of acid gas disposal, geologic storage of CO_2, and EOR. Prior to this project, the CO_2 portion of the acid gas was vented to the atmosphere, while sulfur was separated and stockpiled in solid form on-site. This project enabled the simultaneous beneficial use of each of these materials to produce more oil and reduce GHG emissions.

LIGNITE FIELD

Investigated the ability of unminable lignite seams to store CO_2 during enhanced coalbed methane (ECBM) production. The validation test demonstrated CO_2 did not significantly move away from the injection wellbore and was contained within the coal seam, suggesting that comparable operations could be successfully implemented at other field sites.

NORTHWEST MCGREGOR FIELD

Evaluated the potential for injecting CO_2 into a deep carbonate reservoir for the dual purpose of CO_2 storage and EOR at depths greater than 2000 meters. The results indicated that CO_2-based huff 'n' puff operations are a technically viable option for improving oil recovery in deep carbonate reservoirs, even those with relatively low primary permeability.

TERRESTRIAL FIELD

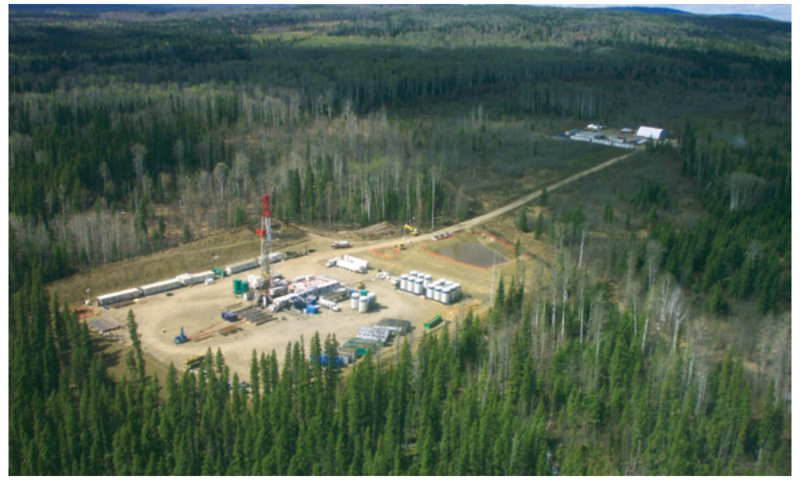
Developed the technical capacity to systematically identify and apply alternative land-use management practices to the prairie pothole ecosystem (at both local and regional scales) that result in GHG reductions and potentially salable carbon offsets. The project demonstrated that restoring previously farmed wetlands replenishes soil organic carbon lost to cultivation at the average rate of 0.4 tonnes per hectare per year.

DEVELOPMENT PHASE

In 2007, the PCOR Partnership entered Phase III, the development phase, with the goal of demonstrating large-scale CO_2 storage. The RCSP Phase III projects had a target of injecting at least 1 million metric tons of CO_2 and set out to demonstrate that the CO_2 could be injected and stored safely, permanently, and economically. Results from these efforts provided the foundation for CCUS technology commercialization.

The PCOR Partnership teamed with industrial partners to develop two commercial-scale CCUS demonstrations in the region. One of the large-scale tests focused on CO_2 storage in a saline formation, while the other investigated associated CO_2 storage resulting from EOR.

Phase III Commercial Demonstration Projects



FORT NELSON FEASIBILITY PROJECT

Investigated the feasibility of using a deep carbonate saline formation to safely and cost-effectively store CO_2 from a commercial natural gas-processing facility. The results of this project suggest that commercial-scale CCUS in the area is technically feasible and cost-effective MVA meets or exceeds the geologic storage standards of the CSA Group, Canada's standards association. The project aimed to inject approximately 2.2 million tonnes of CO_2 annually.

BELL CREEK DEMONSTRATION PROJECT

Demonstrated that commercial EOR operations can safely and cost-effectively store regionally significant amounts of CO_2. This collaborative project with Denbury Onshore, LLC (Denbury) showed that CO_2 storage can be achieved in association with EOR and that MVA methods can be used to effectively monitor CO_2 storage during regular EOR operations. During the demonstration, over 5.4 MMt of CO_2 was injected and stored through the commercial EOR process in the Bell Creek Field, while over 16 monitoring techniques were evaluated for their effectiveness in tracking subsurface CO_2.

AQUISTORE PROJECT

Provides storage to a commercial CO_2 capture plant and an active oil field for EOR operations. In addition to the Phase III large-scale demonstration projects, the PCOR Partnership supported the Aquistore project through geologic modeling and simulation. Aquistore is injecting and storing CO_2 from SaskPower's Boundary Dam Carbon Capture Facility near Estevan, Saskatchewan.

PCOR PARTNERSHIP PARTNERS

U.S. Department of Energy
National Energy Technology Laboratory
EERC
UND University of North Dakota
North Dakota Industrial Commission
UAF Institute of Northern Engineering, University of Alaska Fairbanks
University of Wyoming School of Energy Resources

Abengoa Bioenergy
Advanced Geotechnology
AES Think Big. Go Beyond.
Air Products
Alaska Asia
Alberta Energy
AGS Alberta Geological Survey
Alberta Innovates
ALLETE
ALLETE clean energy
Ameren
ACCCE American Coalition for Clean Coal Electricity
Apache
Aquistore
aramco
Arctech
ATCO Power
Avalon
Avista
Baker Hughes a GE company
Bakken Energy
Ballantyne
BND Bank of North Dakota
BARR
Basin Electric Power Cooperative
BC Oil & Gas Commission
Bechtel
BillyJack Consulting Inc.
Biorecro
BKV
Black & Veatch
bluesource
BNI Energy An ALLETE Company
bp
Burns McDonnell
C12 Energy
Carbon Alpha
Carbon America
CURC
Carbon Vault
Carbon Ventures LLC
Catahoula
Cerilon
Chevron
Class VI Solutions
ClearPath
CMC Research Institutes
CMG
Colorado
CO2SeQure
CO2 Solutions
ConocoPhillips
Constellation.
Continental Resources
C-QUEST
CSIRO
Dakota Gasification Company
Dark Vision
Delft Inversion
Delta Constructors
Denbury
devon
Ducks Unlimited
Ducks Unlimited Canada
Eagle Operating Inc.
Eastern Iowa Community Colleges
Elysian
Emerson
Enbridge
Encore Acquisition Company
Energy Capital Economic Development
ERCB Energy Resources Conservation Board
enerPLUS
Enhanced Oil Recovery Institute University of Wyoming
eni
Environment Canada
equinor
ESXPLORE
Excelsior Energy
ExxonMobil
Fischer Oil and Gas, Inc.
Frontier Carbon Solutions
GLJ
Goodnight
Great River Energy
GroundMetrics
Halliburton
Heidelberg Materials
Hess
Hilcorp Alaska
Hitachi Inspire the Next
Hunting
Huntsman
Husky Energy
HN Hydrogen Naturally
Ikon Science
INL Idaho National Laboratory
InnoTech Alberta
Oil & Gas
ION Engineering
DNR
Jackson Walker
Kiewit
KLJ
KCRC
Lignite Energy Council
Los Alamos National Laboratory
Manitoba Hydro
Manitoba
Marathon
Marathon Oil
Marubeni Itochu Steel
MBI Energy Services
MEG Energy
Melzer Consulting
metso
Midwest Generation
Minnesota Pollution Control Agency
Minnesota Power
Minnesota Public Utilities Commission
Minnkota Power Cooperative
Missouri Department of Natural Resources
Missouri River Energy Services
MEPUSA Mitsui E&P USA LLC
DEQ
Montana-Dakota
MTR Membrane Technology & Research
Murex Petroleum Corporation
National Commission on Energy Policy
Natural Resources Canada
Nebraska Public Power District
NESET
NSG
Nexant
NextStream
NTEC LLC
North American Coal
North Dakota Department of Commerce
North Dakota Environmental Quality
North Dakota Petroleum Council
NDPA North Dakota Pipeline Authority
North Dakota Public Service Commission
NDSU
North Dakota's Building Trades Unions
NorthWestern Energy
Nuverra Environmental Solutions
Occidental Petroleum
OLI systems inc.
OPPD
ONEOK
Otter Tail Power Company
Oxand
Pacific Northwest National Laboratory
PacifiCorp
Paragon
Peabody Energy
Petrobras
petro harvester
ptrc
Pinnacle
Portland General Electric
ppl
Prairie Public
Pratt & Whitney
Praxair
PSC of Wisconsin
PTTC
Puget Sound Energy
Rainbow Energy Center
Ramgen
Red Trail Energy
Repsol
RITE
Resolute
Rockall
tNavigator
RPS Energy
Saskatchewan Industry and Resources
Saskatchewan Ministry of Energy and Resources
SaskPower
Scout
seismos
Shell Canada Limited
Shell Cansolv
Silixa sense the difference
Simtech
slb
South Dakota Public Utilities Commission
Spectra Energy
State of Wyoming Clean Coal Technology Fund
Steiner Oil & Gas, LLC
Strategic West Energy Ltd.
Stress Engineering Services Inc.
Stryde
subsurface AI
Sulzer
Sumitomo Corporation of Americas
Summit Carbon Solutions
Suncor Energy
Talen Energy
Tallgrass
TAQA
TC Energy
Terracoh
Tesoro
TGS
The CETER Group, Inc.
TransAlta
Tri-Mer Corporation
Tri-State G&T
Tundra Oil & Gas
University of Alberta
University of Regina
USGS
Vault 44.01
WBI Energy
Weatherford
Western Governors' Association
Westmoreland Coal Company
Whitecap Resources Inc
White Rock Oil & Gas
Whiting
Woodside
DEQ Wyoming Department of Environmental Quality
Wyoming
ITC Wyoming Integrated Test Center
Wyoming Mining Association
Wyoming
Wyoming Public Service Commission
Xcel Energy

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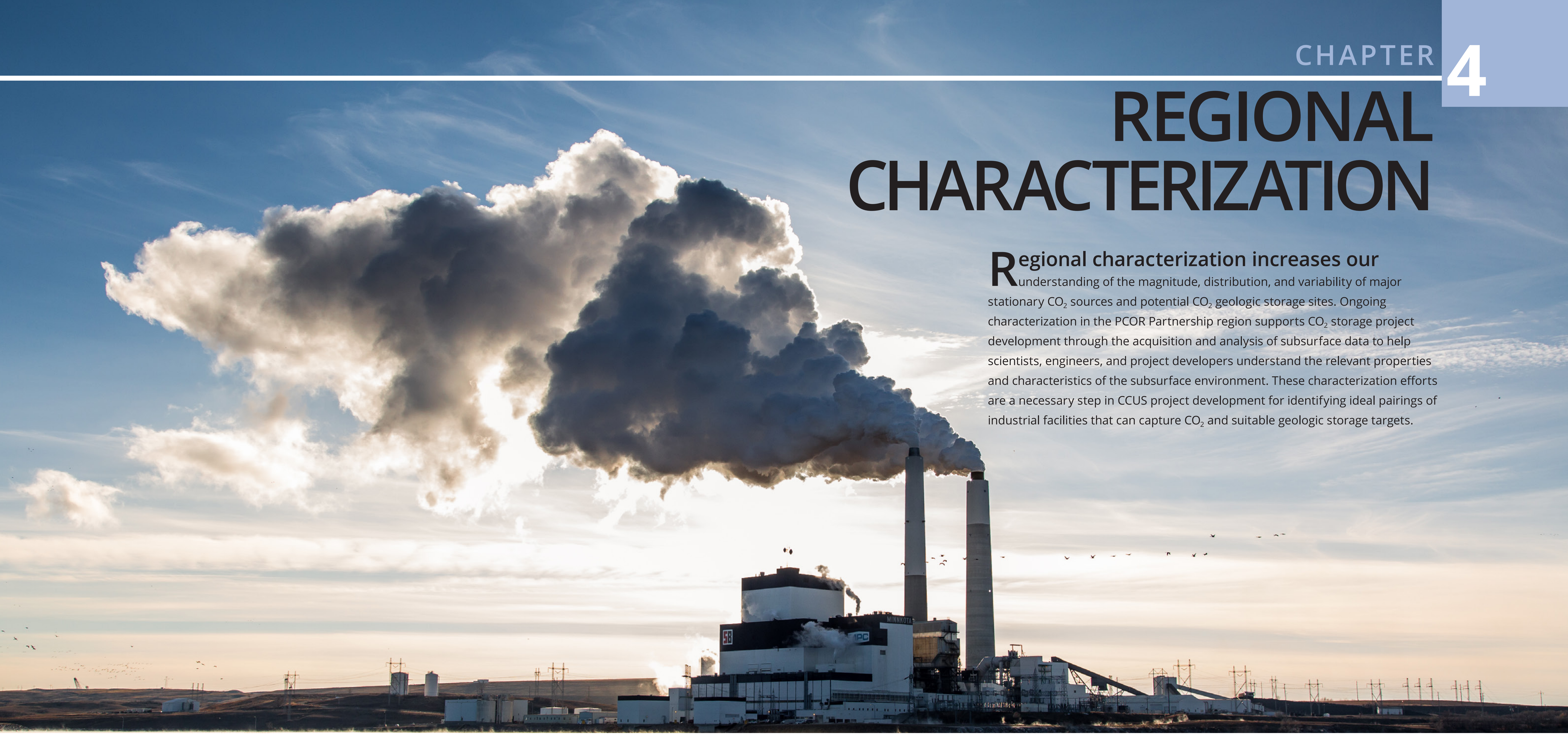
From 2003 to today, the PCOR Partnership has brought together more than 260 public and private sector stakeholders with expertise in power generation, energy exploration and production, geology, engineering, the environment, agriculture, forestry, and economics. Included in this number is the PCO$_2$C Program, with more than 40 private industry partners and focused on evaluating and developing cost-effective CO$_2$ capture solutions for utility application. The combined group of partners shown forms the foundation of the PCOR Partnership and supports its efforts by providing data, guidance, financial resources, and practical experience with CCUS.

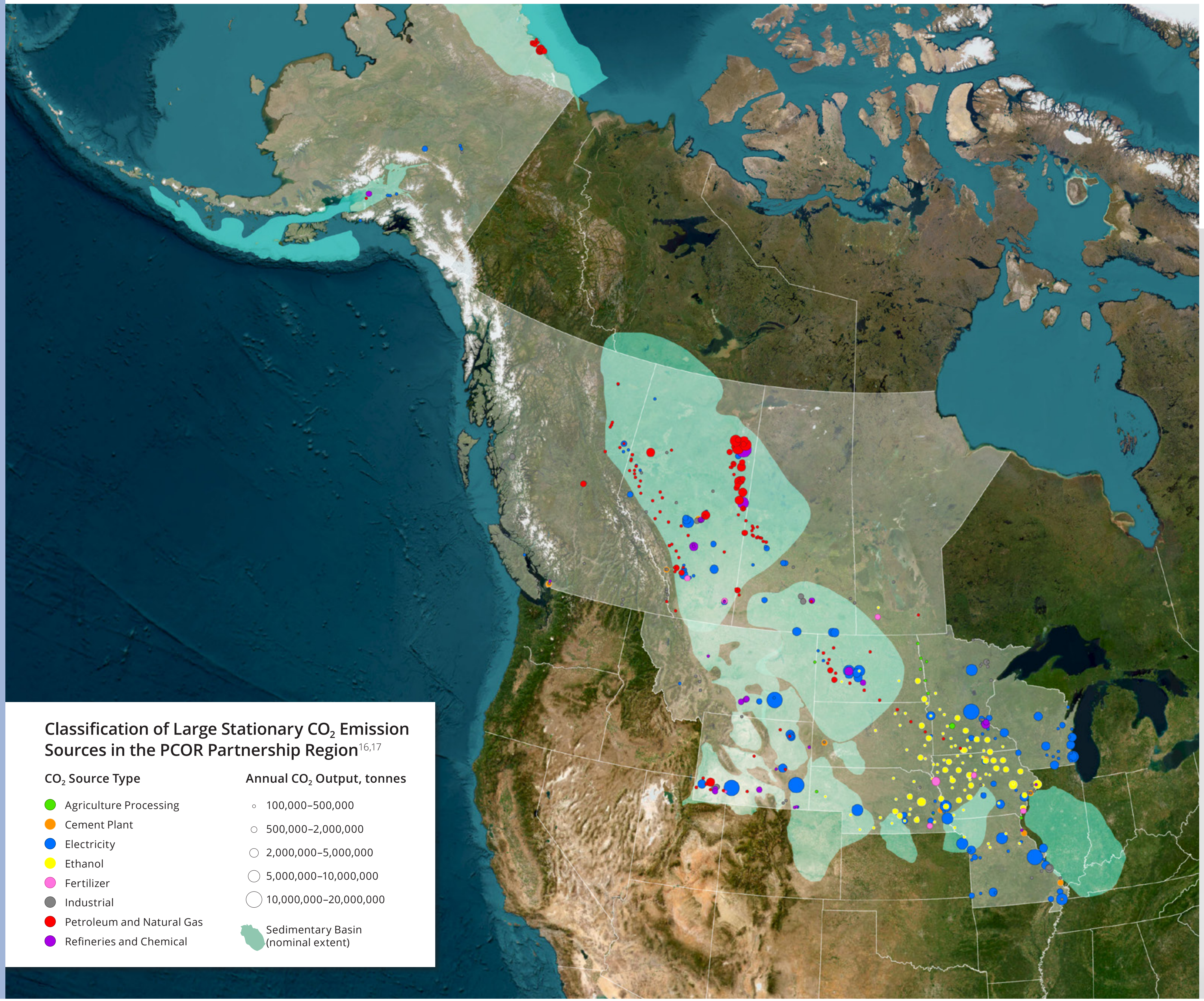
CHAPTER 4

REGIONAL CHARACTERIZATION



Regional characterization increases our understanding of the magnitude, distribution, and variability of major stationary CO_2 sources and potential CO_2 geologic storage sites. Ongoing characterization in the PCOR Partnership region supports CO_2 storage project development through the acquisition and analysis of subsurface data to help scientists, engineers, and project developers understand the relevant properties and characteristics of the subsurface environment. These characterization efforts are a necessary step in CCUS project development for identifying ideal pairings of industrial facilities that can capture CO_2 and suitable geologic storage targets.

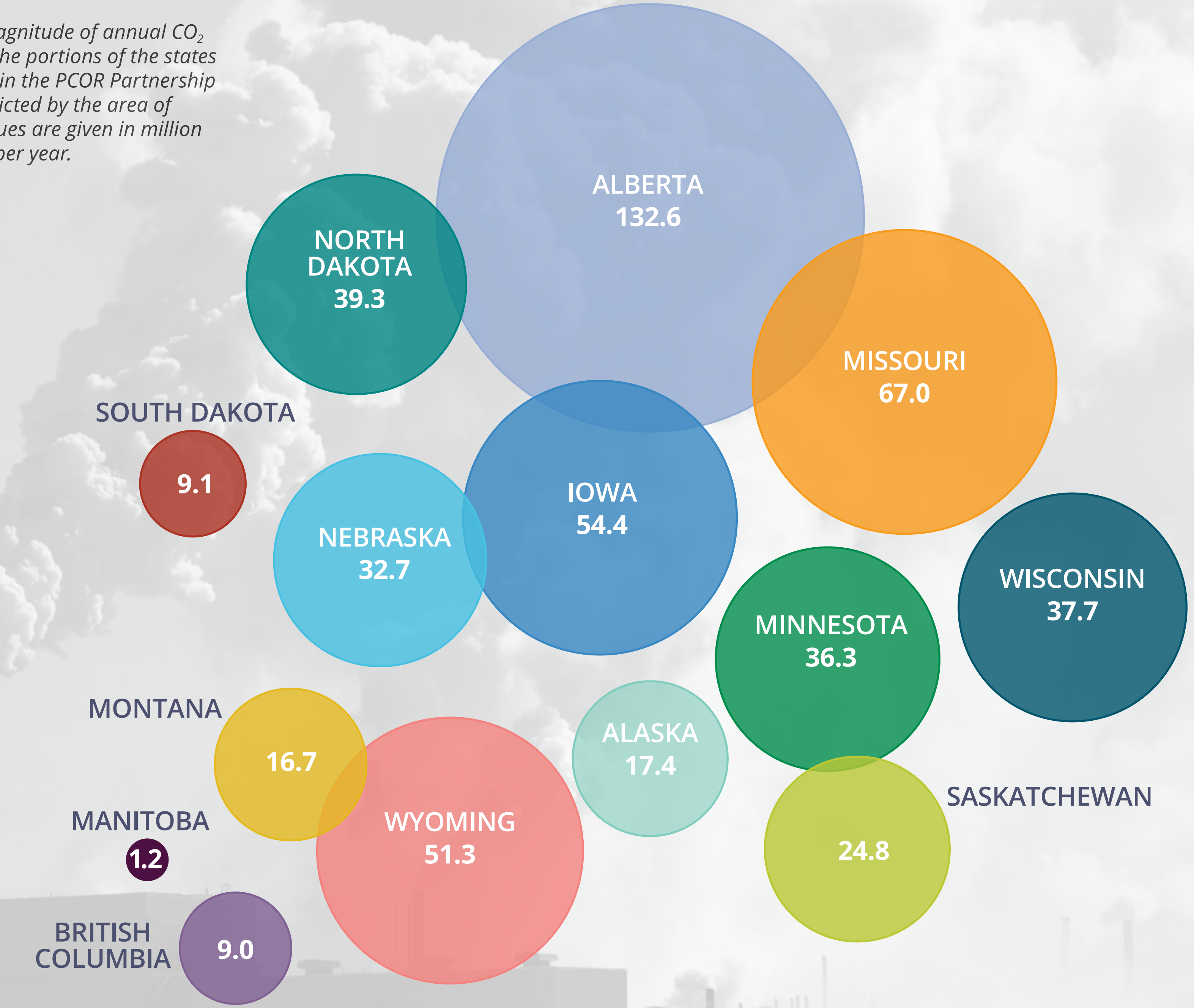
DISTRIBUTION OF LARGE STATIONARY CO_2 SOURCES



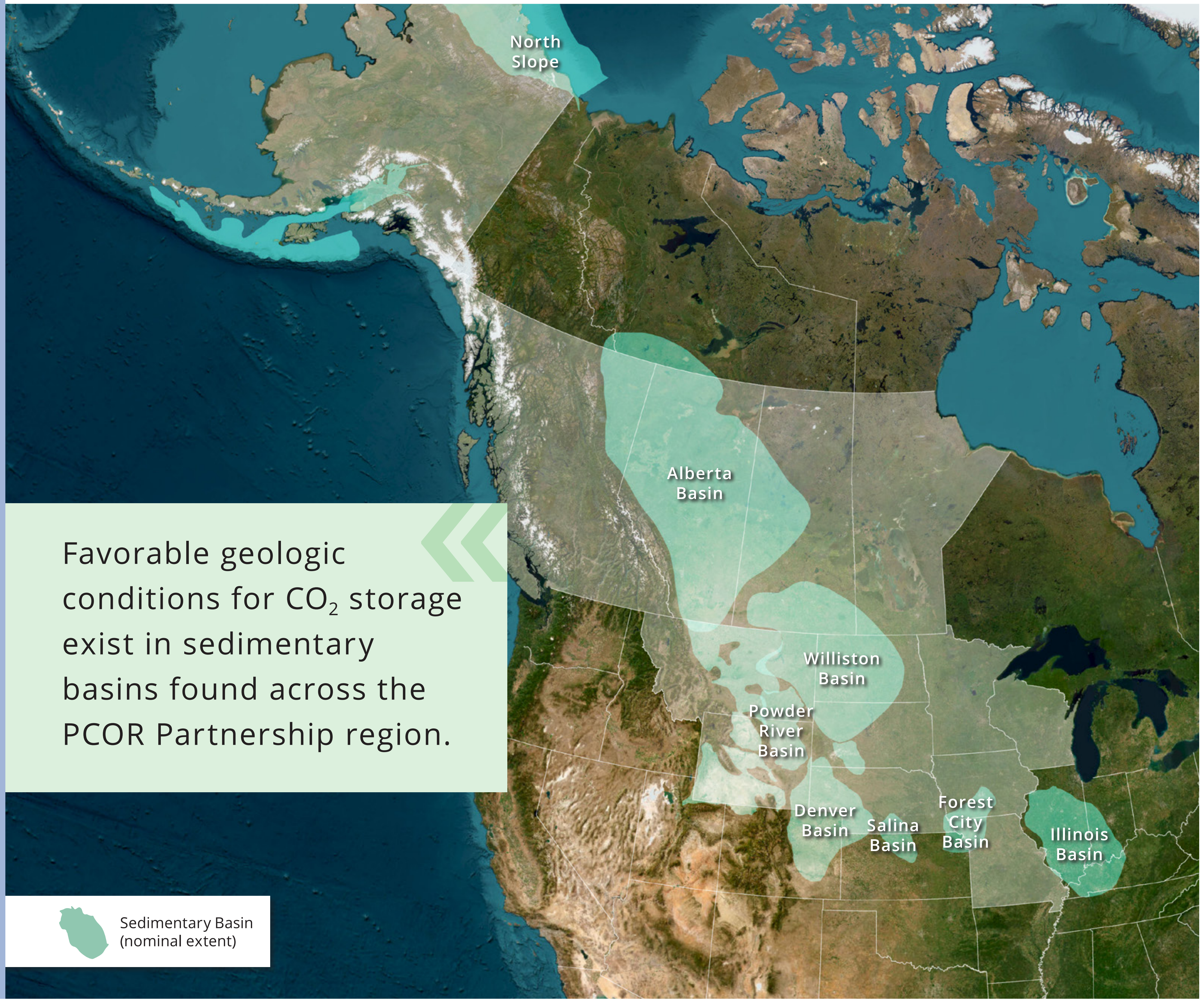
The PCOR Partnership has identified, quantified, and categorized 565 stationary sources in the region that have an annual output greater than 100,000 tonnes of CO_2. These stationary sources have a combined annual CO_2 output of over 529 MMt. Although not a target source of CO_2 for geologic storage, the transportation sector in the U.S. portion of the PCOR Partnership region contributes nearly 242 million additional tonnes of CO_2 to the atmosphere every year.[16,17,35–39]

The annual output from the various large stationary sources ranges from 100,000 tonnes for industrial and agricultural processing facilities that make up the majority of the sources in the region to over 15 MMt for the largest coal-fired electric generation facility. Fortunately, many of the large point sources are located in areas that are favorable for CO_2 storage because of their concurrence with deep sedimentary basins, such as those areas in Alberta, North Dakota, Montana, and Wyoming.

The relative magnitude of annual CO_2 emissions for the portions of the states and provinces in the PCOR Partnership region are depicted by the area of the circles. Values are given in million tonnes of CO_2 per year.



MAJOR REGIONAL SEDIMENTARY BASINS

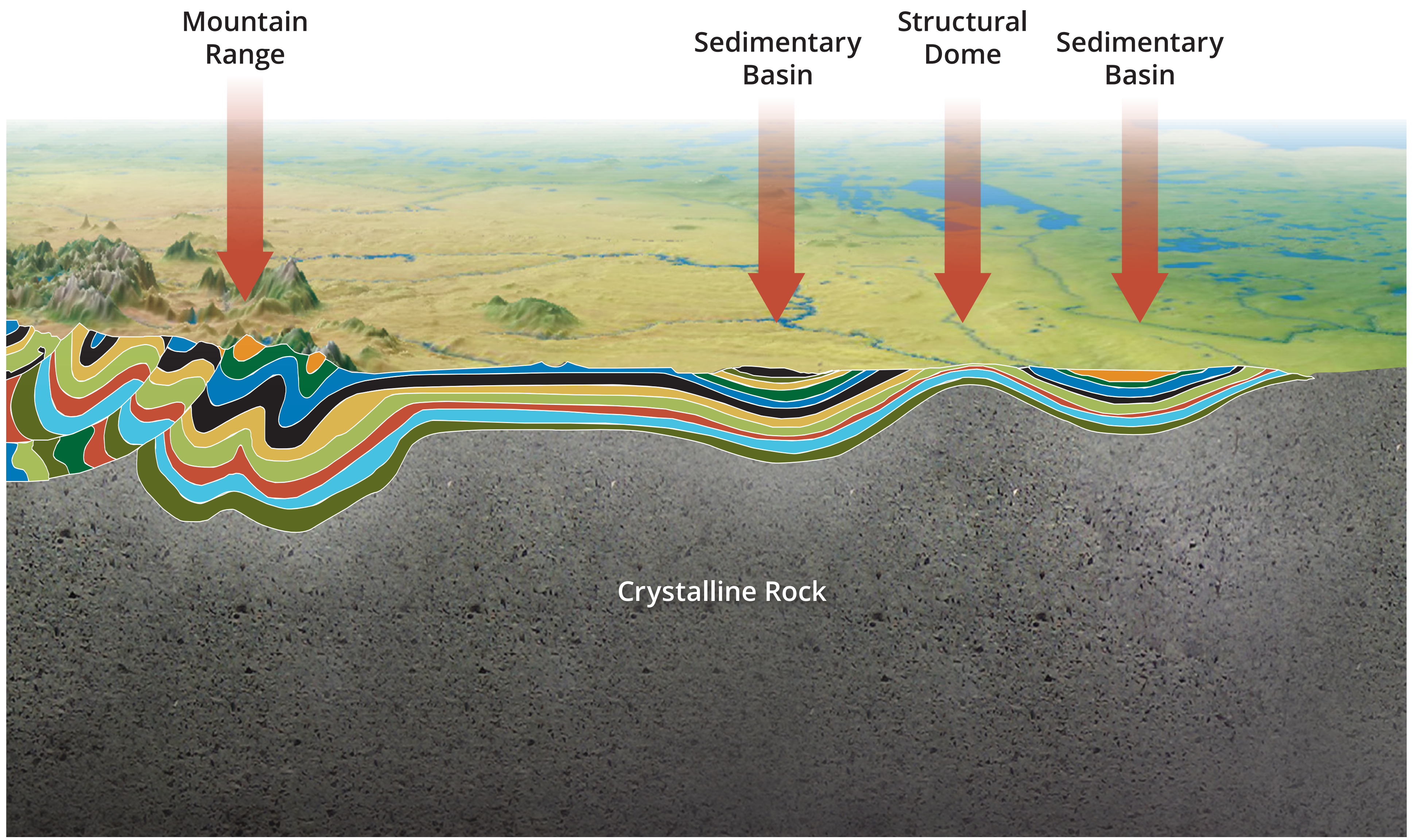


Favorable geologic conditions for CO_2 storage exist in sedimentary basins found across the PCOR Partnership region.

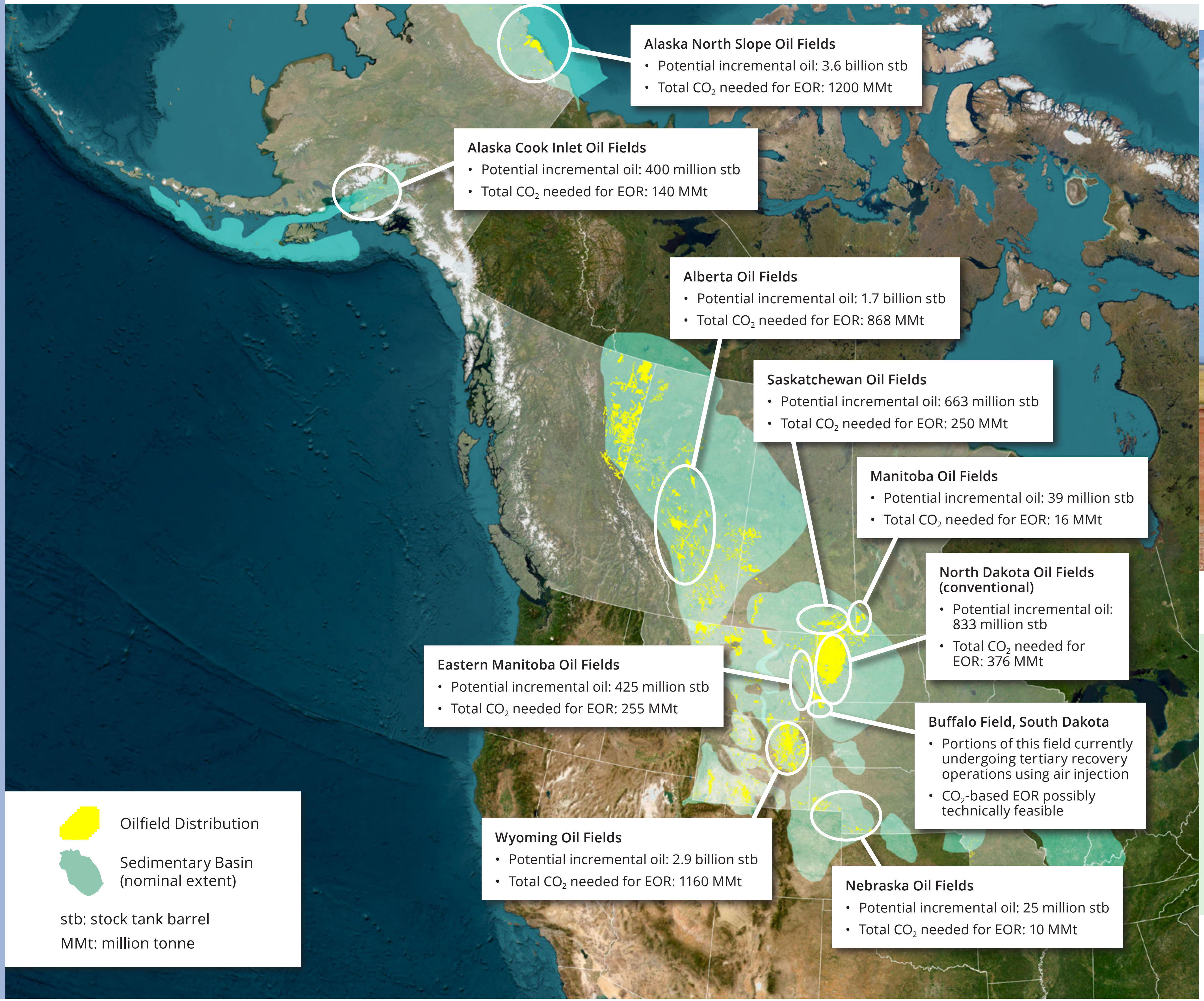
CO_2 STORAGE OPPORTUNITIES

Sedimentary basins are large regional depressions in Earth's crust. These depressions accumulate a considerable thickness of sediment that can cause further subsidence and allow for even more sediment to accumulate. As the sediments are buried, they compact under increasing pressure and then begin the process of lithification (changing to rock). Sedimentary basins vary in configuration from bowl-shaped to elongated troughs. If organic-rich sedimentary rocks occur in combination with appropriate depth, temperature, and duration of burial, hydrocarbon generation can occur within the sedimentary basin. The rich set of options for the safe, long-term geologic storage of CO_2 in the PCOR Partnership region is found in the deep portions of its extensive sedimentary basins.

Oil and gas reservoirs and deep saline formations are the two primary CO_2 storage options found within sedimentary basins. These storage formations are commonly situated vertically one above another and separated by sealing formations, an arrangement referred to as stacked storage. Stacked storage offers the potential to store the same total volume of CO_2 but with a smaller geographic footprint.



EOR POTENTIAL



Alaska North Slope Oil Fields
- Potential incremental oil: 3.6 billion stb
- Total CO_2 needed for EOR: 1200 MMt

Alaska Cook Inlet Oil Fields
- Potential incremental oil: 400 million stb
- Total CO_2 needed for EOR: 140 MMt

Alberta Oil Fields
- Potential incremental oil: 1.7 billion stb
- Total CO_2 needed for EOR: 868 MMt

Saskatchewan Oil Fields
- Potential incremental oil: 663 million stb
- Total CO_2 needed for EOR: 250 MMt

Manitoba Oil Fields
- Potential incremental oil: 39 million stb
- Total CO_2 needed for EOR: 16 MMt

North Dakota Oil Fields (conventional)
- Potential incremental oil: 833 million stb
- Total CO_2 needed for EOR: 376 MMt

Eastern Manitoba Oil Fields
- Potential incremental oil: 425 million stb
- Total CO_2 needed for EOR: 255 MMt

Buffalo Field, South Dakota
- Portions of this field currently undergoing tertiary recovery operations using air injection
- CO_2-based EOR possibly technically feasible

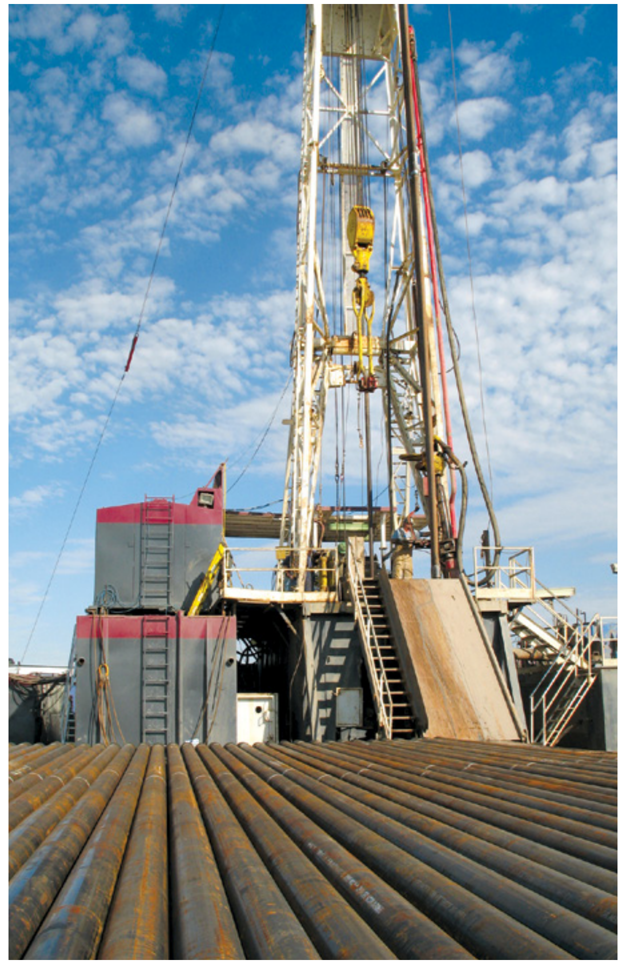
Wyoming Oil Fields
- Potential incremental oil: 2.9 billion stb
- Total CO_2 needed for EOR: 1160 MMt

Nebraska Oil Fields
- Potential incremental oil: 25 million stb
- Total CO_2 needed for EOR: 10 MMt

🟨	Oilfield Distribution
🟩	Sedimentary Basin (nominal extent)

stb: stock tank barrel
MMt: million tonne

CO_2 STORAGE IN OIL FIELDS

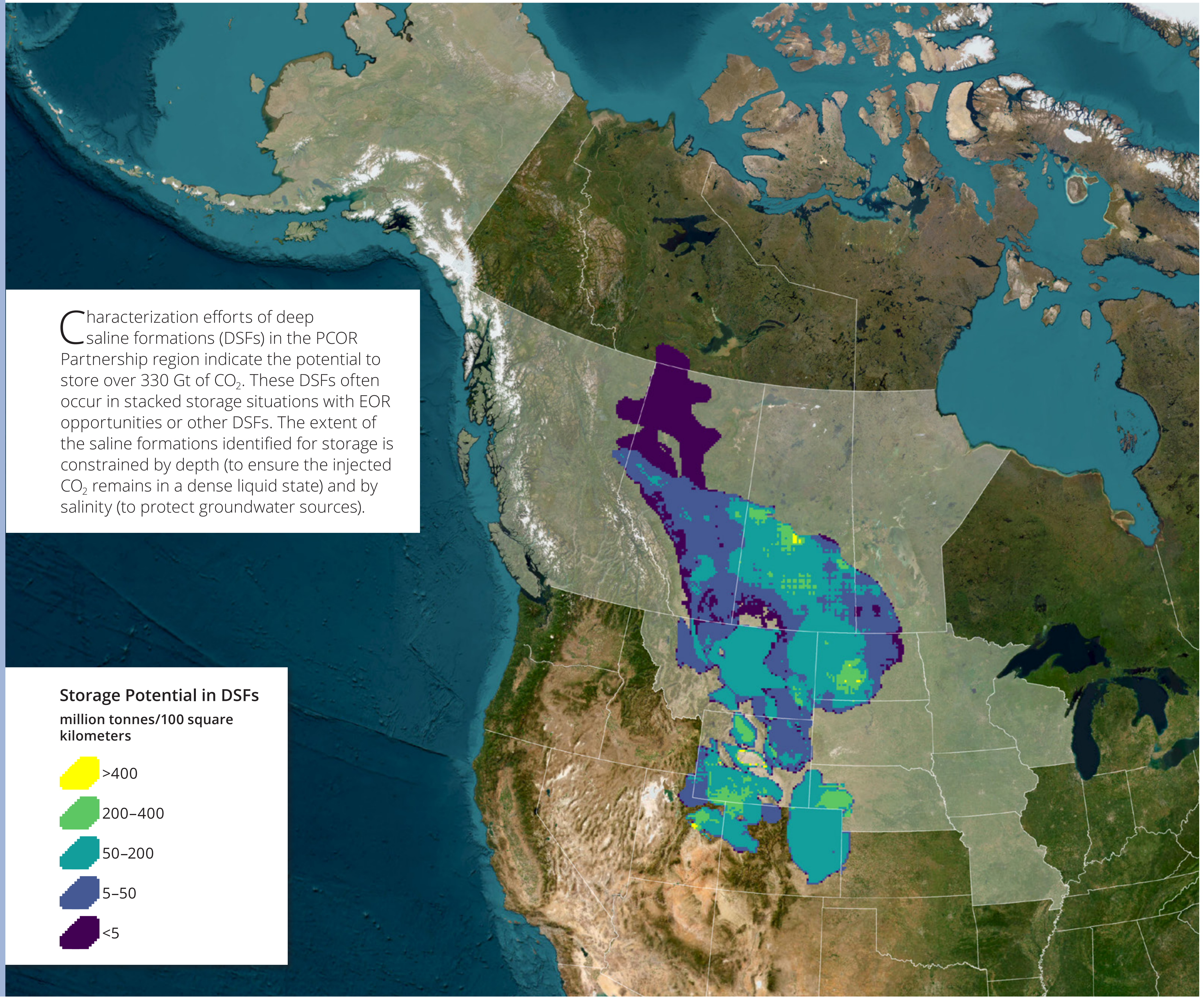


Although oil was discovered in the PCOR Partnership region in the late 1800s, significant development and exploration did not begin until the late 1920s. The body of knowledge gained in the nearly 100 years of exploration and production of hydrocarbons in this region is a significant step toward understanding the mechanisms for secure storage of significant amounts of CO_2. Today, oil is drawn from the many oil fields in the PCOR Partnership region from depths ranging from as little as 60 m to approximately 8000 m below ground level.

While the use of CO_2 in conventional reservoirs is a widely applied practice, the use of EOR in unconventional (or tight) oil reservoirs like the Bakken petroleum system (Bakken and Three Forks Formations) is a relatively new concept. Initial laboratory and field testing offers promising results that CO_2 for EOR in the Bakken may be a viable option. Current research is evaluating approaches to use CO_2 to improve Bakken oil production through field-scale injection testing. If proven viable, CO_2 EOR in unconventional reservoirs presents an opportunity for tremendous volumes of CO_2 storage and increases in oil production.

> The region has over 3700 MMt of CO_2 storage potential in conventional oil fields and 10.2 billion stb of incremental oil potential.

CO$_2$ STORAGE IN SALINE FORMATIONS



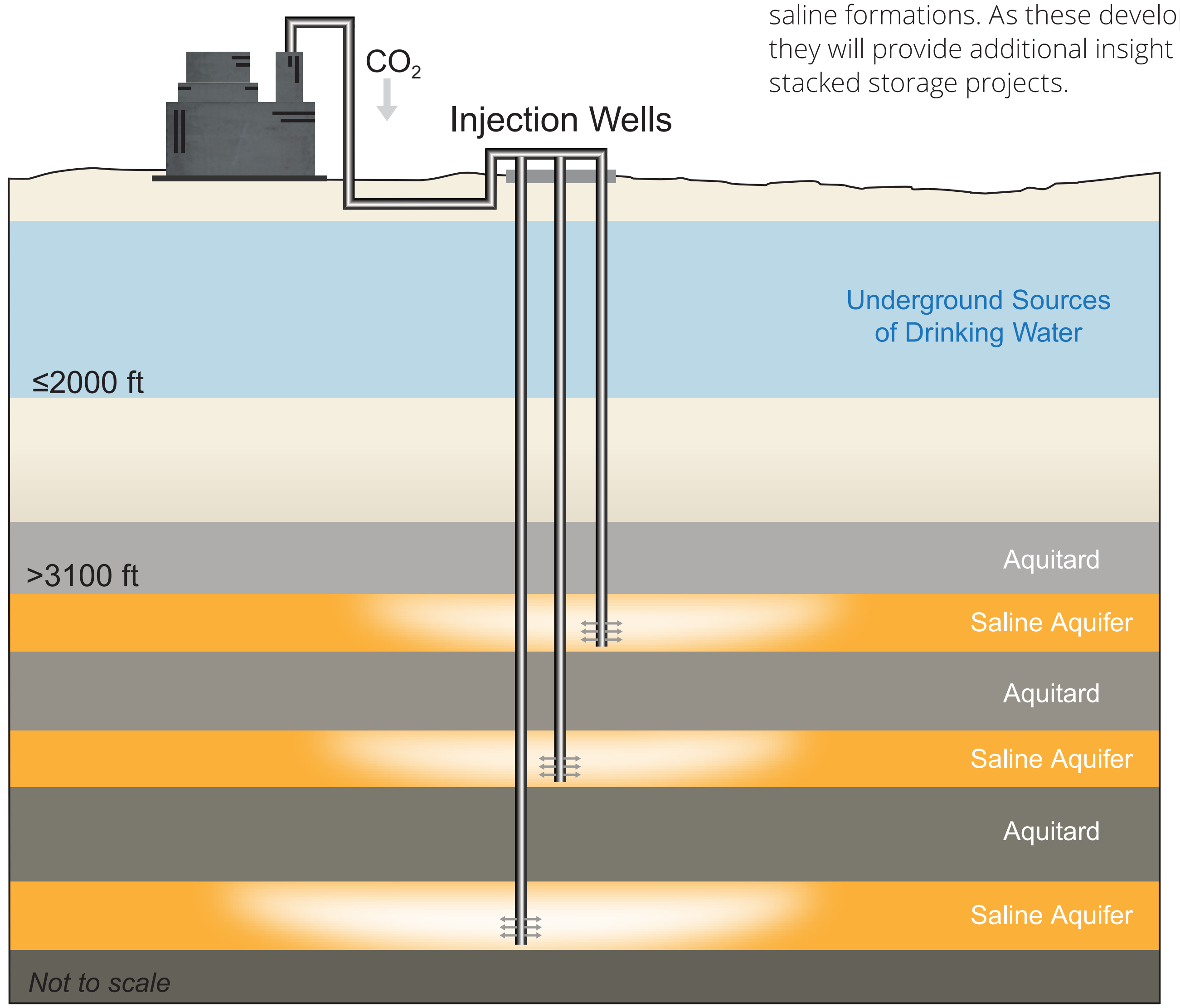
Characterization efforts of deep saline formations (DSFs) in the PCOR Partnership region indicate the potential to store over 330 Gt of CO$_2$. These DSFs often occur in stacked storage situations with EOR opportunities or other DSFs. The extent of the saline formations identified for storage is constrained by depth (to ensure the injected CO$_2$ remains in a dense liquid state) and by salinity (to protect groundwater sources).

STACKED STORAGE

Sedimentary basins comprise layers of unique geologic formations that can serve as potential storage targets (i.e., saline formations, developed oil and gas reservoirs) or as impermeable sealing formations (e.g., shales). When two or more CO$_2$ storage targets are present in the subsurface at the same geographic location, a storage project may choose to pursue a stacked storage approach. Stacked storage will typically include some combination of dedicated storage in DSFs and EOR in hydrocarbon-bearing formations.

Stacked storage allows for greater volumes of storage in a given area, and the approach also allows for a smaller project area as the volumes of CO$_2$ can be divided amongst the different storage formations. The reduced project area would reduce the project's monitoring area, number of legacy wellbores, and number of landowners in the project area. By placing more than one injection well at a location (i.e., multiwell pads), surface facilities and CO$_2$ distribution systems can be consolidated, which can minimize environmental risks and impacts.

While stacked storage projects have yet to start operating in the PCOR Partnership region, multiple projects in various stages of development are considering stacked storage scenarios. These projects include DOE CarbonSAFE (Carbon Storage Assurance Facility Enterprise) projects in North Dakota, Wyoming, and Nebraska, and they are in multiple sedimentary basins, including the Williston, Powder River, and Denver–Julesburg. Additionally, in Canada, the Alberta Basin is estimated to have stacked storage capacity for up to ten deep saline formations. As these developing projects come online, they will provide additional insight and guidance for future stacked storage projects.



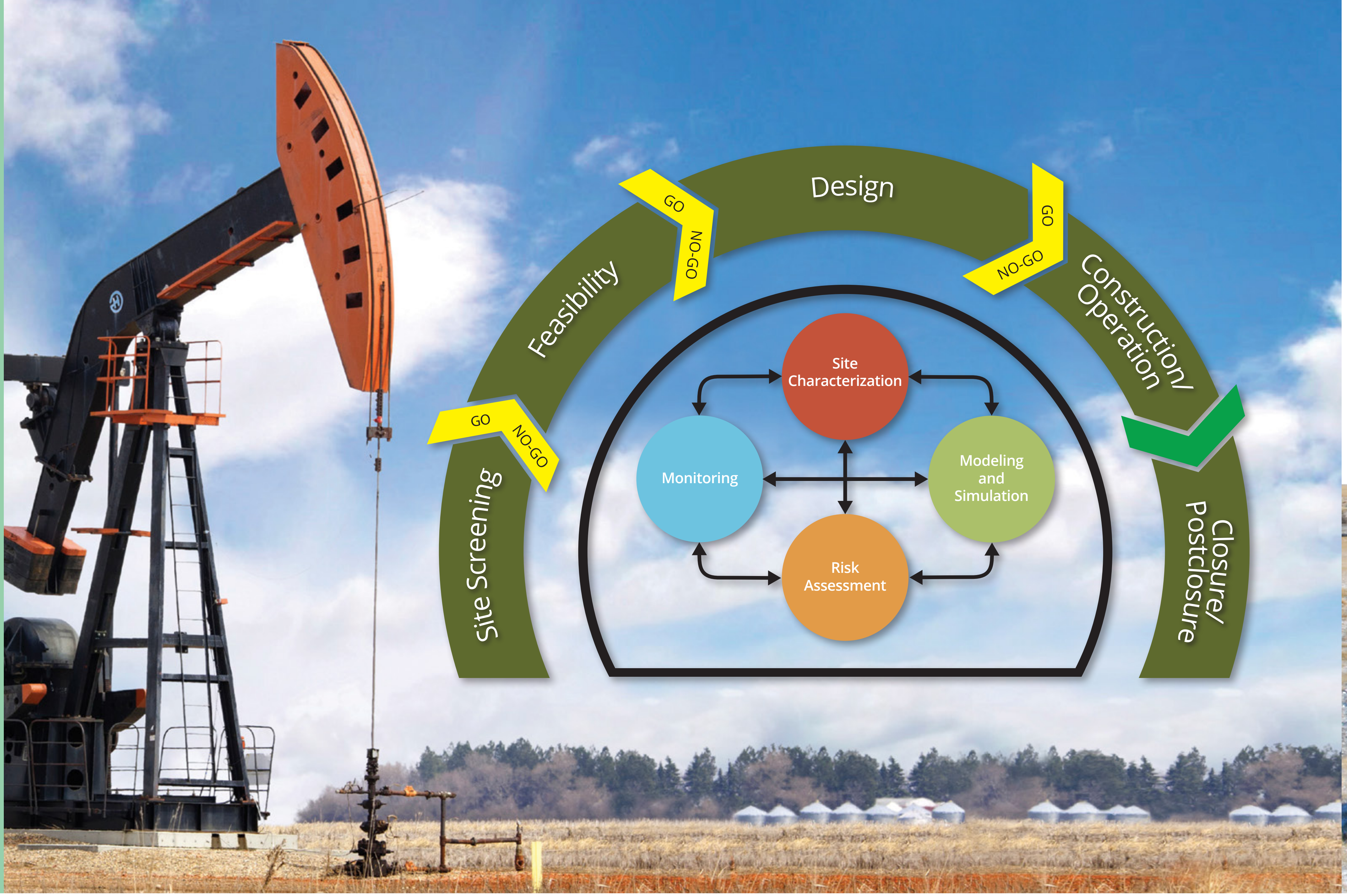
CHAPTER 5

TAKING ACTION

The pathway to developing a commercial CCUS project includes an iterative assessment of a prospective CO_2 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 CO_2 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 CO_2 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.

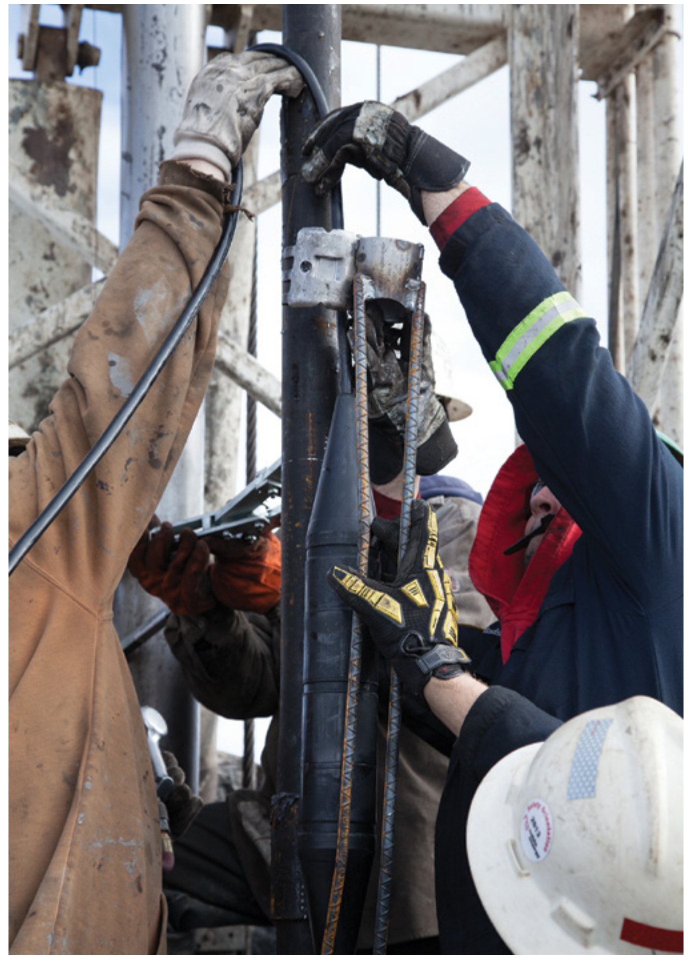


SITE CHARACTERIZATION

Site characterization comprises collection, analysis, interpretation, and application of data to understand CO_2 storage potential and assess factors that could impact CO_2 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 CO_2 migration pathways, assess technical subsurface risks, and aid in the monitoring of CO_2 migration in the subsurface. These elements of the project help evaluate expected and actual performance during commercial-scale CO_2 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.

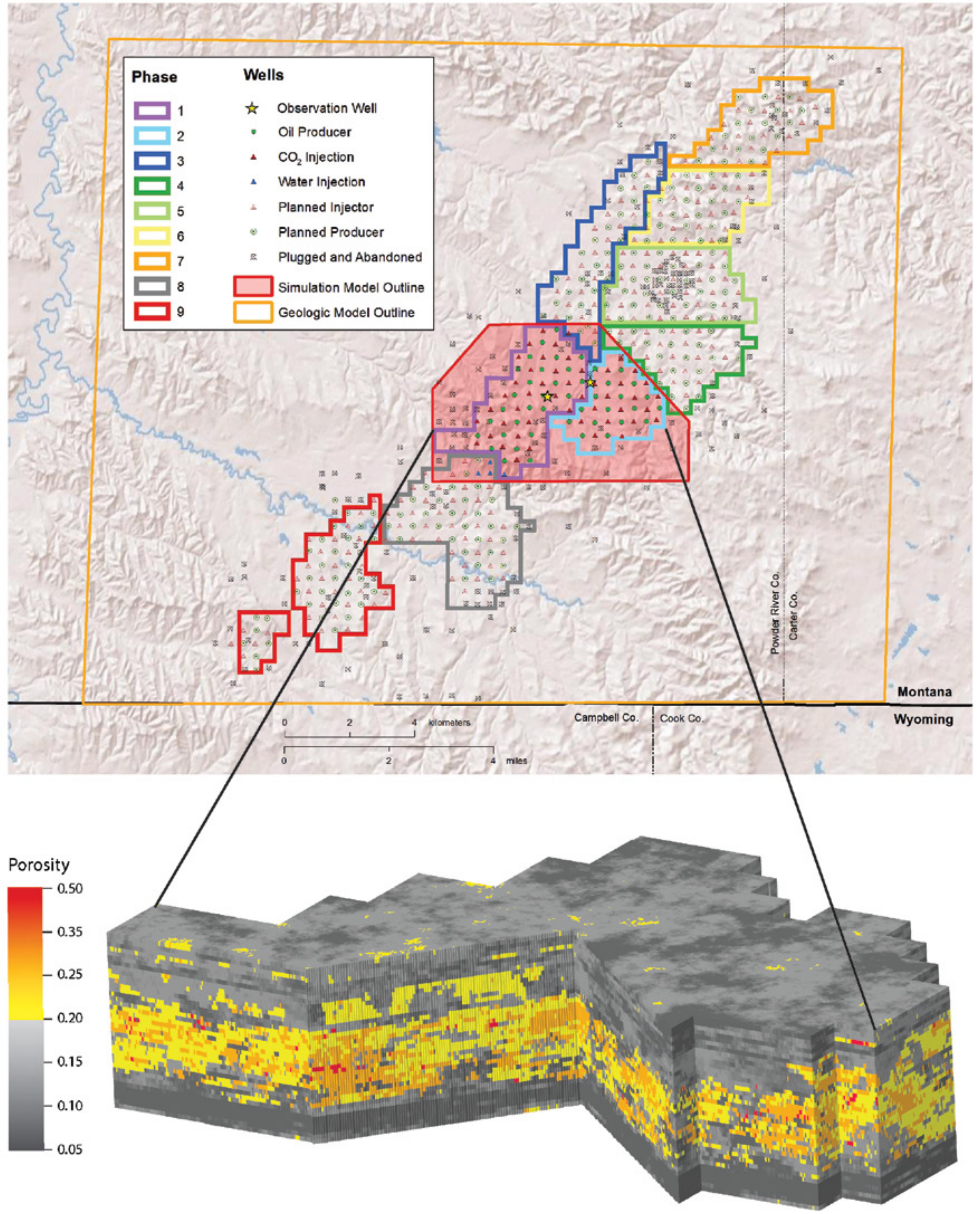


SIMULATION AND MODELING

A geologic model is a computerized 3D rendering of the subsurface that provides a digital framework of CO_2 reservoir complexities, critical to understanding CO_2 storage. The model provides a 3D understanding of the storage horizon and associated cap rock to allow design and implementation of a CO_2 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 CO_2 and the potential pressure effects associated with storing CO_2. These predictions are important for the design of a CO_2 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 CO_2 storage project development.

Risk is the severity of negative consequences of an event weighed against how likely those consequences are to occur. In the context of a CO_2 storage project, risks can affect operational performance and long-term reliability of CO_2 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 CO_2 storage projects in ways consistent with international standard protocols.[40–43] 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 CO_2 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).[44] These risks are refined over time as more data become available.

Risk assessment outcomes inform CO_2 storage project development through every phase. Additionally, the risk assessment informs the monitoring, reporting, and verification (MRV) plan for a CO_2 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 CO_2 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 CO_2 injection.
- Capture risk probability and impact scores from subject matter experts.
- Quantify uncertainty in the risk scores.

RISK EVALUATION

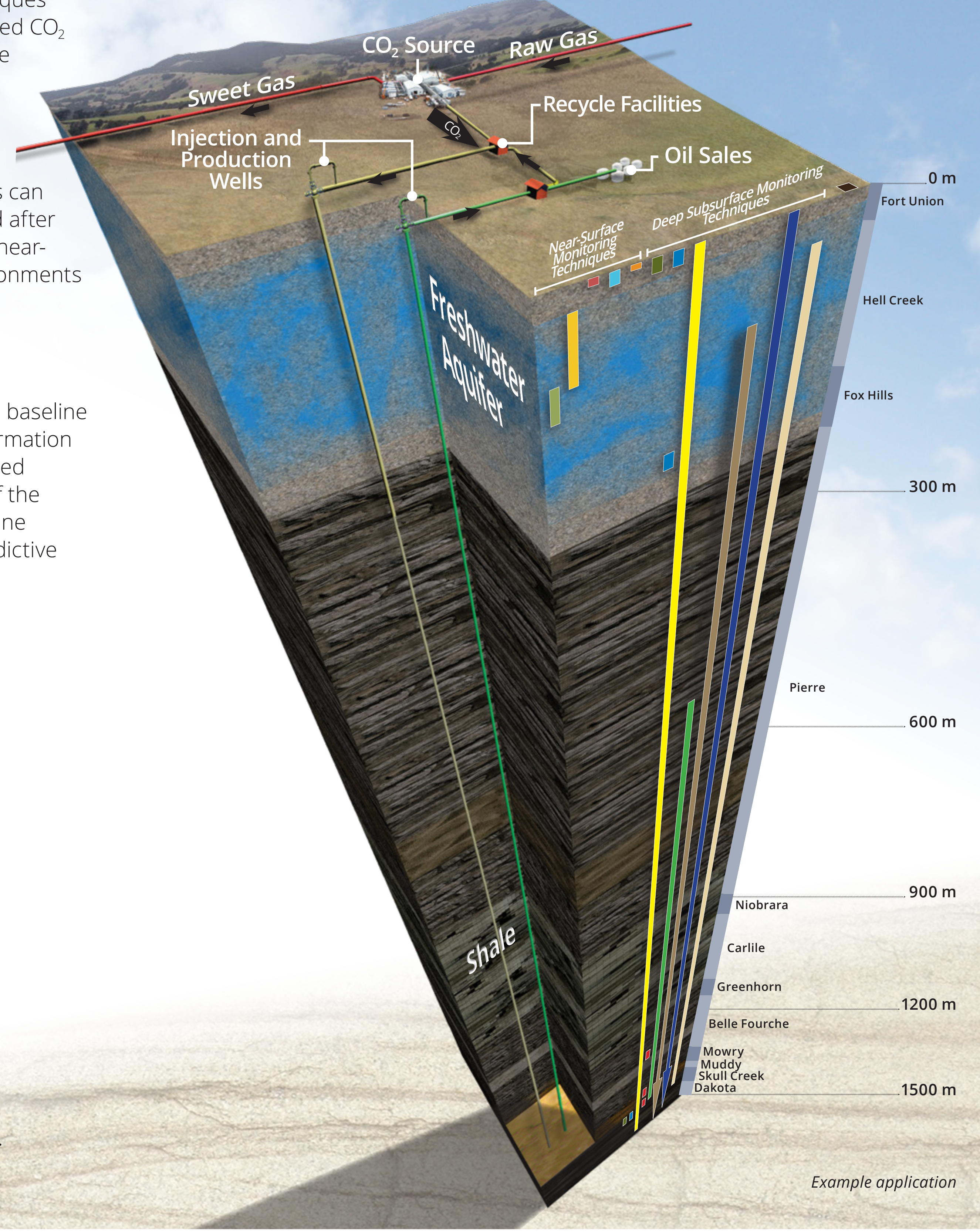
- Plot each individual risk onto a risk map, and evaluate uncertainty in the risk scores.
- Identify moderate and high-ranking risks.
- If a more quantitative evaluation is needed, then employ a probabilistic method such as Monte Carlo simulation or Bayesian methods.

MONITORING, VERIFICATION, AND ACCOUNTING

MVA is the combination of monitoring technologies and techniques used to track the migration of injected CO_2 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 CO_2 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.



Example application

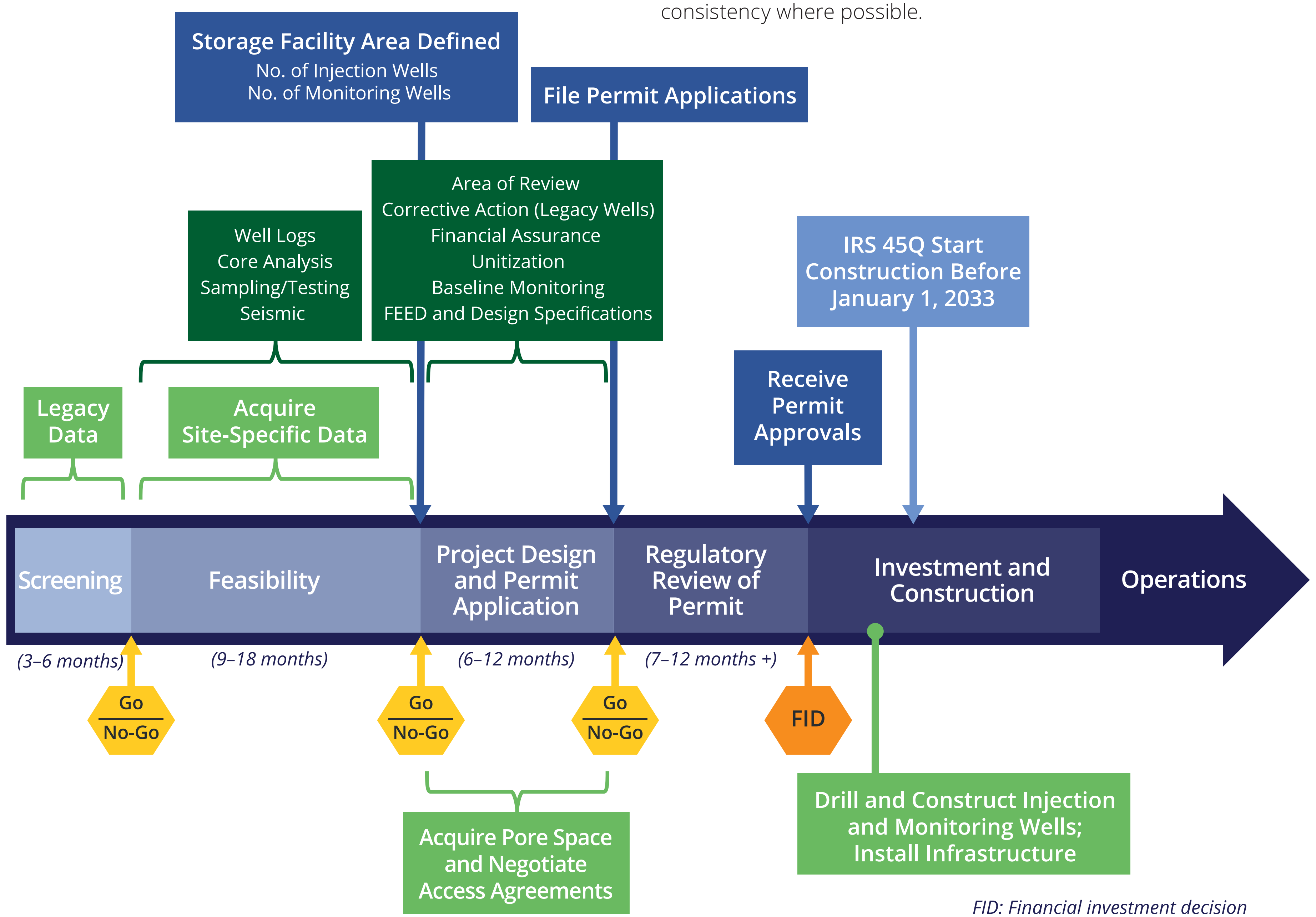
- 🟩 Fox Hills Groundwater Wells
- 🟨 Groundwater Wells
- 🟥 Surface Water
- 🟦 Soil Gas Profile Stations
- 🟧 Soil Gas Probes
- 🟩 Production and Injection Rates
- 🟦 Wellhead Pressure Monitoring
- 🟨 Temperature PDM*
- 🟥 Pressure PDM
- 🟩 3D Time-Lapse VSP**
- 🟫 3D Time-Lapse Seismic
- 🟦 Passive Seismic Monitoring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

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

A PERMITTING PROCESS

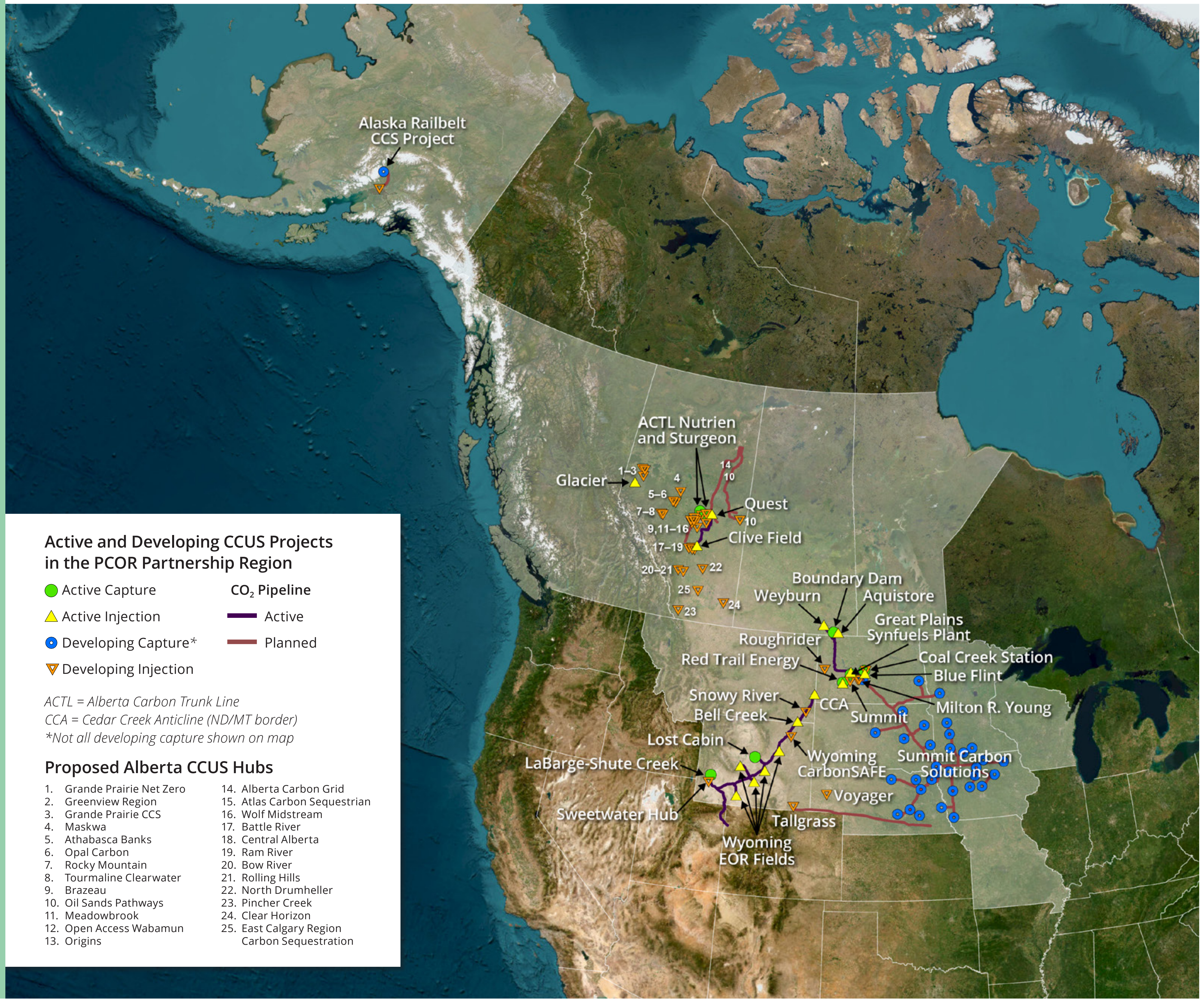
Permitting considerations for a CO_2 storage project are important, even at the earliest stages of project development. Data and information about project feasibility and geologic suitability of the potential storage site(s) will eventually be used to support the permits needed to store CO_2. The figure below shows the CCUS project development and permitting process for North Dakota, which begins with 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, 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 and beyond to support the permitting process and find ways to promote permit application consistency where possible.



FID: Financial investment decision
FEED: Front-end engineering and design

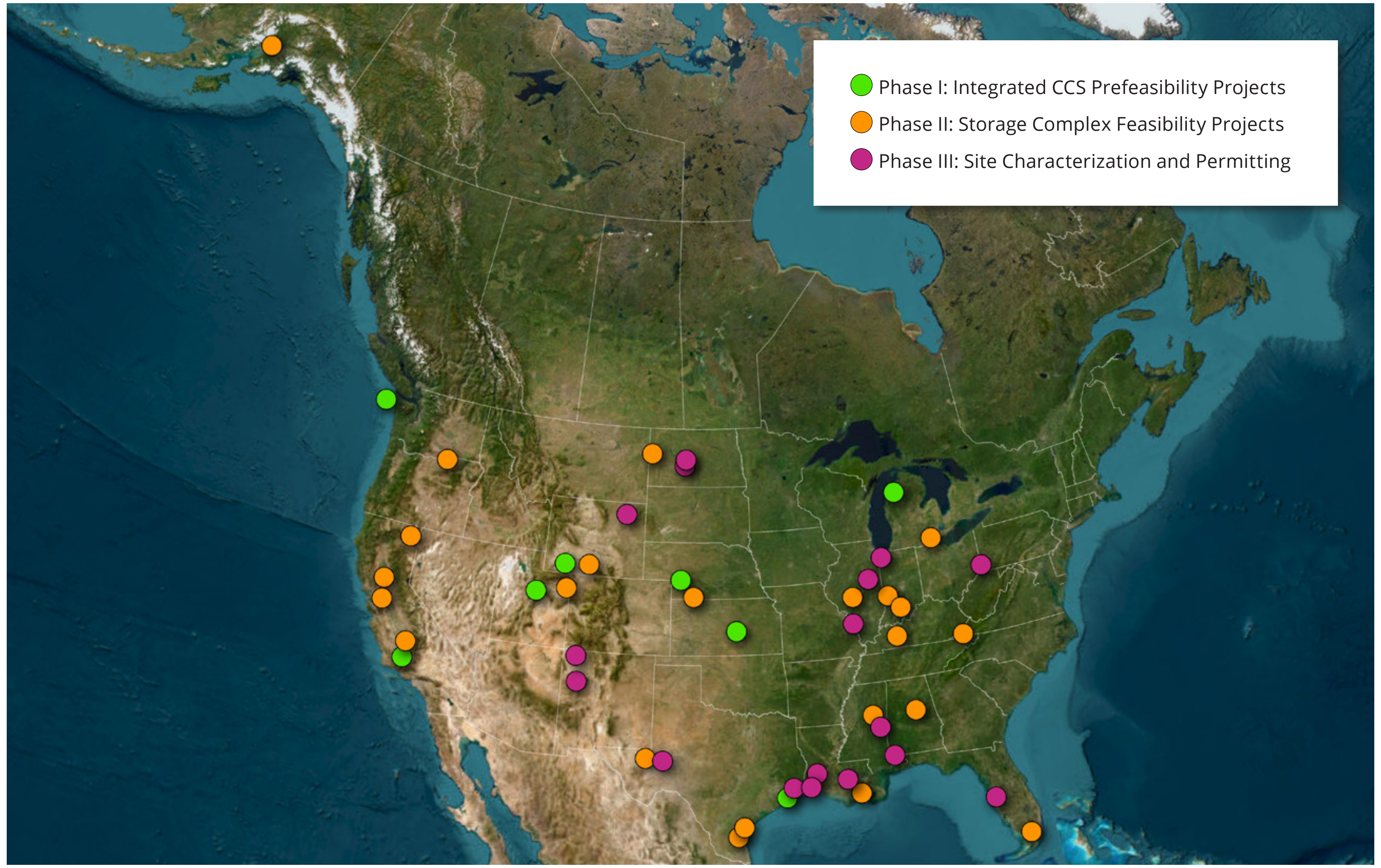
ACTIVE AND DEVELOPING CCUS PROJECTS



CARBONSAFE PROJECTS ACROSS THE UNITED STATES

The CarbonSAFE Initiative began in 2016 with the goal of addressing the key gaps on the critical path toward CCUS deployment. Building upon the knowledge and experience of RCSP efforts, this initiative is performing identification and detailed characterization of geologic storage sites. The vision of CarbonSAFE is to understand the development of a CCUS storage complex from the feasibility study until the point of injection through the following phases of project progress: integrated CCUS prefeasibility, storage complex feasibility, site characterization and permitting, and construction. CarbonSAFE will reduce technical risk, uncertainty, and the cost of commercial-scale saline storage projects. Results will improve the understanding of project screening, site selection, characterization, baseline MVA procedures, and information necessary to submit appropriate permit applications for such projects.

The CarbonSAFE effort contributes to furthering the development and refinement of technologies and techniques critical to the characterization of potential storage complexes over 50 million metric tons. Project research will provide insight into the integration of site characterization information into reservoir simulations and design of injection and monitoring strategies. The progress made by CarbonSAFE will instill greater confidence that commercial-scale CCUS projects can be integrated in a technically and economically feasible manner.[45]

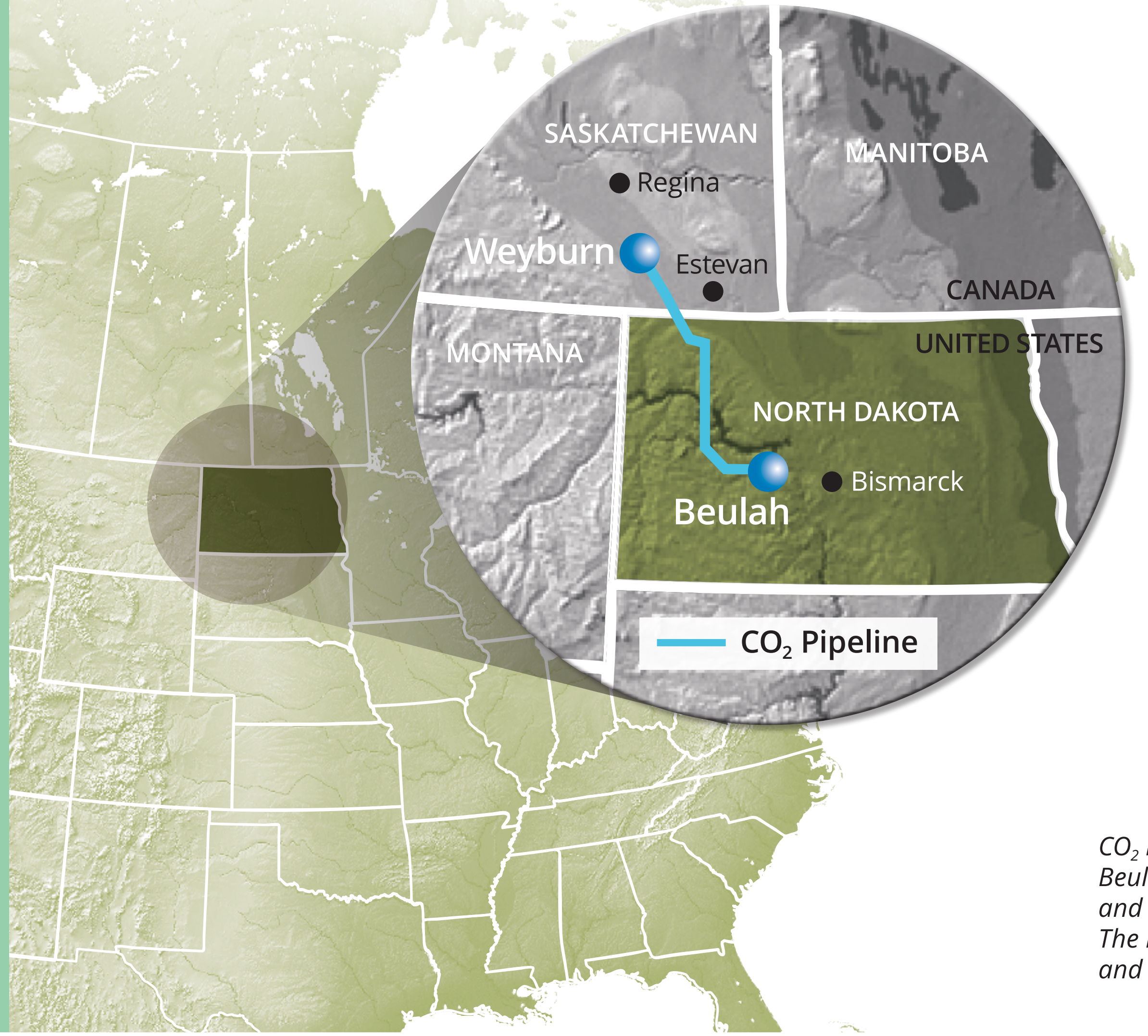


CO_2 CAPTURE AT GREAT PLAINS SYNFUELS PLANT

The majority of the CO_2 used in the Weyburn–Midale EOR project comes from Dakota Gasification Company's (DGC's) Great Plains Synfuels Plant, the only commercial-scale coal-to-natural gas facility in the United States. In November 2020, the synfuels plant reached a milestone: capturing 40 million metric tons of CO_2 since 2000. Approximately 2 million metric tons of CO_2 is captured each year, making it one of the largest carbon capture facilities in the world.[46]

DGC and its Canadian subsidiary, Souris Valley Pipeline Ltd., operate a 205-mile pipeline to transport the CO_2 from the synfuels plant in Beulah, North Dakota, to the Weyburn and Midale oil fields in southeasern Saskatchewan for EOR. CO_2 EOR at Weyburn has stored 36 million metric tons of CO_2 to date.[47]

In July 2020, during the COVID-19 pandemic, DGC shipped its first beverage-grade CO_2 captured from the Great Plains Synfuels Plant's ammonia production facility; the shipment was for 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, DGC worked with the North Dakota Department of Health to provide beverage-grade liquefied CO_2 to aid in keeping the COVID-19 vaccine at the recommended storage temperature.[46]



CO_2 is captured from DGC's Great Plains Synfuels Plant in Beulah, North Dakota, 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 23,000 barrels of oil a day.[47]

CO_2 MONITORING AND STORAGE PROJECT

Injection of CO_2 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.[48] Since inception, CO_2 injection into the Weyburn Field has averaged 1.7 million tonnes of CO_2, with more than 36 million tonnes of CO_2 stored[47] mainly sourced from the Great Plains Synfuels Plant but with an additional supply of CO_2 from Boundary Dam since 2014.[49]

The Midale Field was operated by Apache Canada until it was sold to Cardinal Energy Ltd. in 2017.[50] In 2020, approximately 188,000 tonnes of CO_2 was injected in the Midale unit. Since 2005, nearly 5 million tonnes of CO_2 has been injected.[51] As of 2023, the sale of CO_2 from DGC to Whitecap Resources and Cardinal Energy Ltd. represents the only instances of large quantities of captured CO_2 being traded across an international border.

> Supplies from Great Plains to Weyburn and Midale represent the first case of CO_2 being traded between two countries.

CO$_2$ CAPTURE AT BOUNDARY DAM

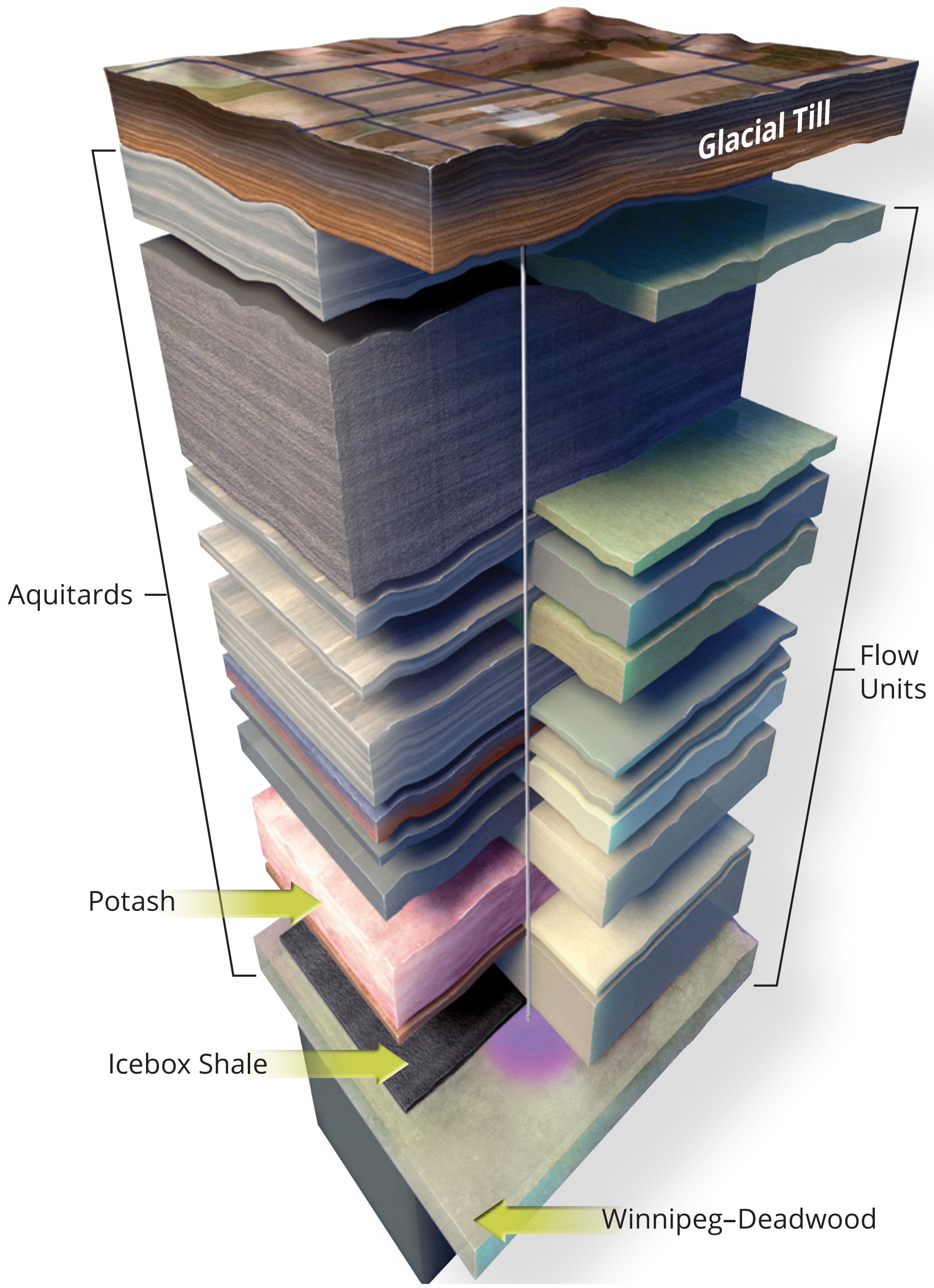
The Boundary Dam Carbon Capture Project is the world's first commercial-scale, fully integrated CCUS project at a coal-fired power station, with postcombustion capture of CO$_2$ from the rebuilt Unit 3. The capital cost of Can$1.2 billion was supported by funding from the provincial government of Saskatchewan and the federal government of Canada. Operated by the government-owned utility SaskPower, the project is designed to capture up to 1 MMt of CO$_2$ per year; between the commencement of operations in October 2014 and January 2023, SaskPower reports that over 5 million metric tons of CO$_2$ was captured.[52]

Unit 3 provides 115 MW of power. In addition to reducing CO$_2$ emissions from Unit 3 by up to 90%, the capture process removes 100% of SO$_2$ emissions, which are converted to sulfuric acid for industrial use.

The main destination for captured CO$_2$ is the Weyburn oil field, with Whitecap Resources transporting the purchased CO$_2$ 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 CO$_2$.

THE AQUISTORE PROJECT

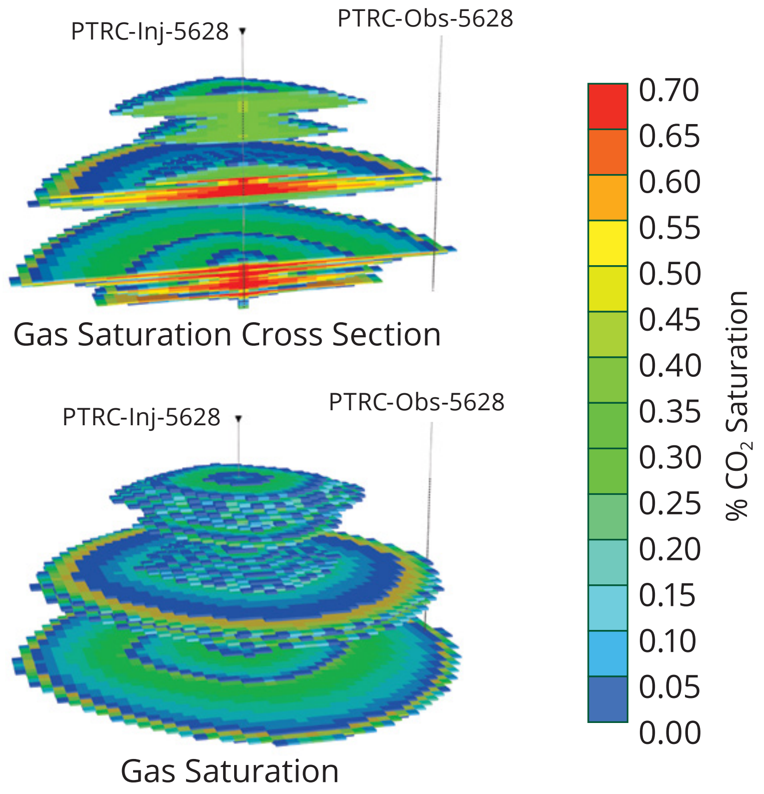
Aquistore is a dual-purpose project.[53] From a commercial perspective, Aquistore provides a dedicated storage option for unsold CO$_2$ from Boundary Dam—in effect providing buffer storage to prevent any need for SaskPower to vent CO$_2$ from capture operations. Injection commenced in April 2015, making Aquistore the first dedicated storage project to operate in Canada. As of February 2023, over 500,000 tonnes of CO$_2$ had been injected.[54]



Injection of CO$_2$ 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.[53]

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 that 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.[55]



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

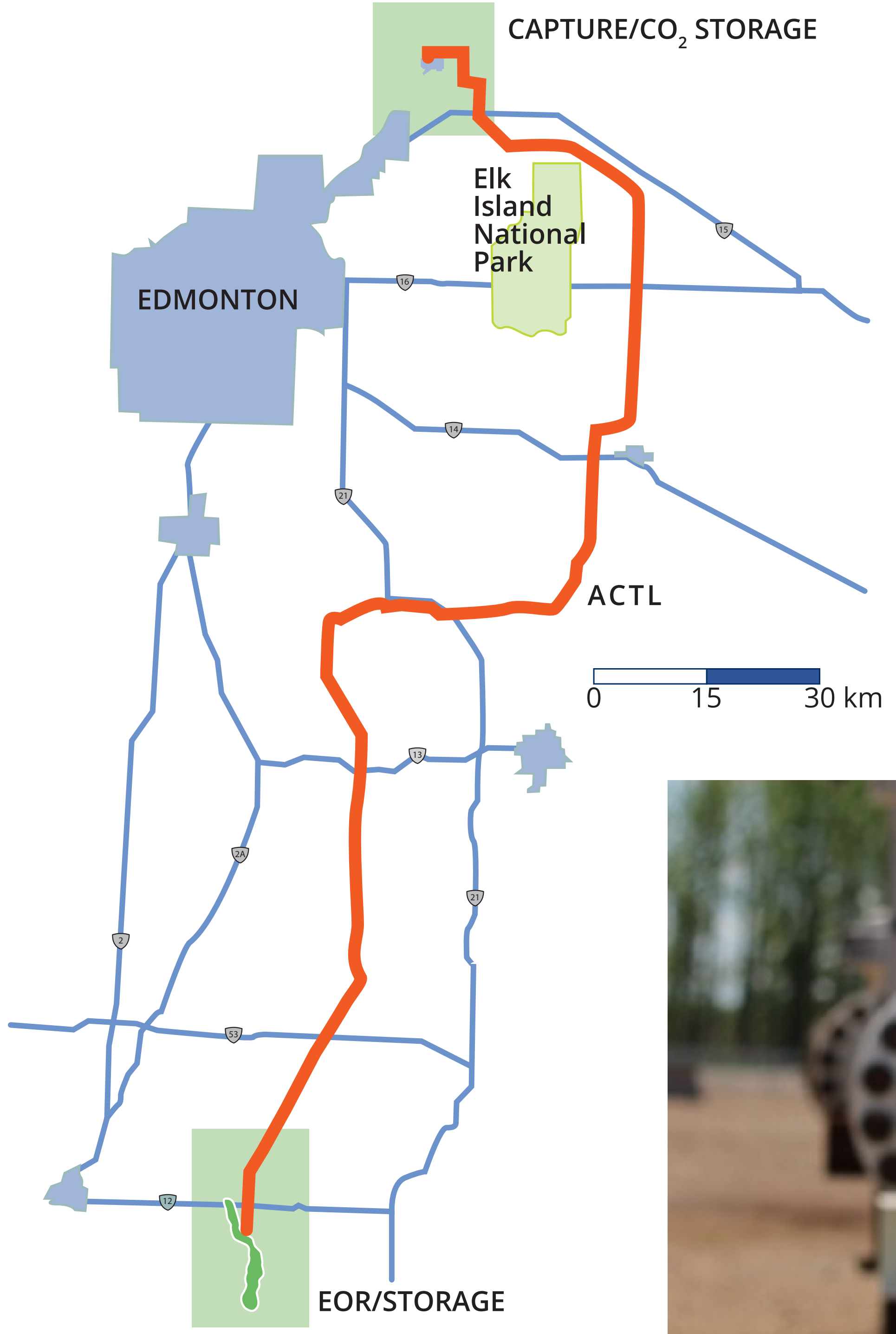
QUEST CARBON CAPTURE AND STORAGE PROJECT

Shell Canada Energy commenced operations at Quest, a fully integrated CCUS project located northeast of Edmonton, Alberta, in November 2015. As of the end of 2022, the Quest project captured and stored 7.7 million tonnes of CO_2. The cost to operate Quest is about 35% lower than what was forecast in 2015, and if Quest was built today, it would cost about 30% less thanks to capital efficiency improvements.[56]

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 CO_2 emissions from the upgrading operations by approximately one-third.

Captured CO_2 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 MMt of CO_2 over the anticipated 25-year life of the upgrader, although the storage reservoir has a much greater storage potential.

ALBERTA CARBON TRUNK LINE



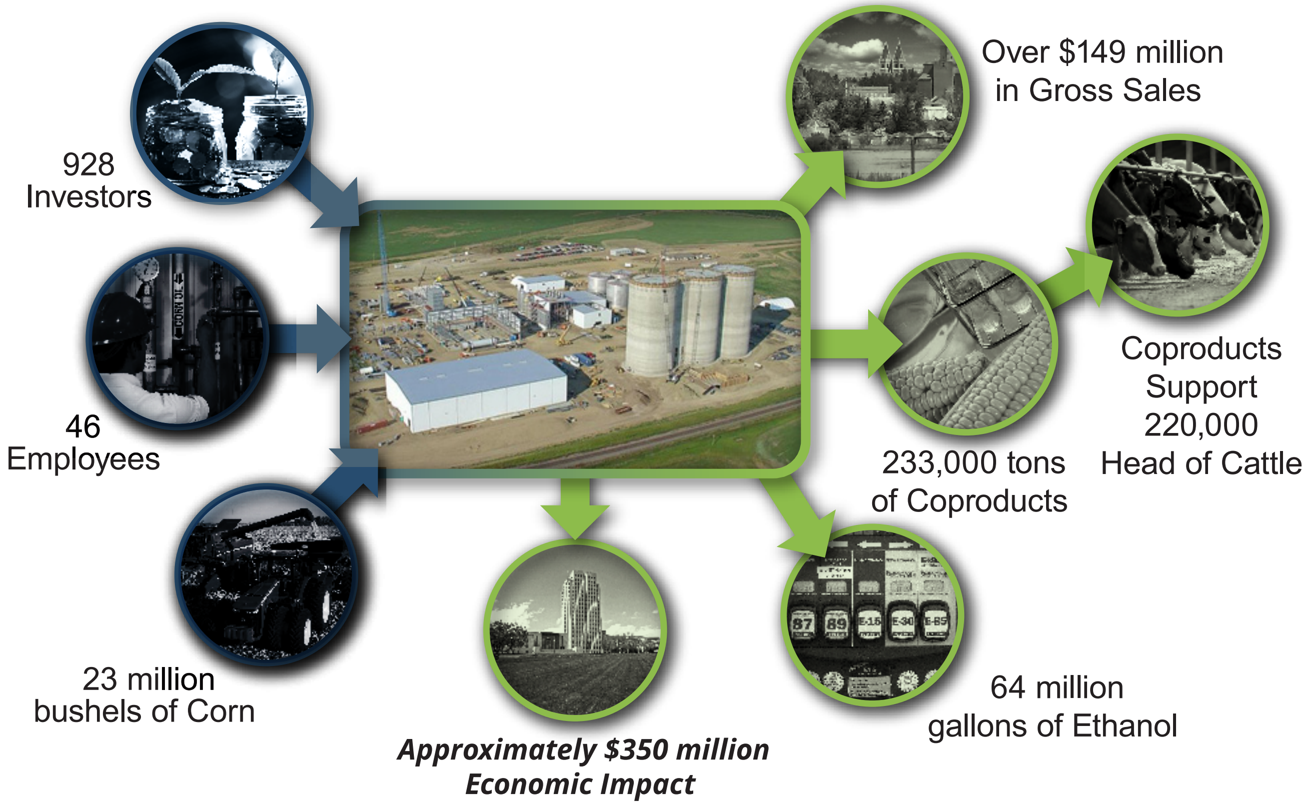
The ACTL system is the world's newest integrated, large-scale CCUS system.[57] Located in central Alberta, CO_2 captured from the NWR (North West Redwater Partnership) Sturgeon Refinery and the Nutrien Fertilizer facility is transported down a 40-cm-diameter, 240-km-long pipeline to mature oil fields 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 CO_2 to mature oil and gas reservoirs for use in EOR and permanent storage. The ACTL can transport up to 14.6 MMt of CO_2 per year, and as of July 2023, more than 4 million metric tons of CO_2 had been injected and stored in the Clive oil field.[58]

RED TRAIL ENERGY

Red Trail Energy, LLC (RTE), an ethanol producer near Richardton, North Dakota, is operating a CO_2 capture facility adjacent to the RTE ethanol facility to ultimately inject about 180,000 tonnes of CO_2 annually more than a mile below RTE property for permanent storage. After a 5-year investigative period conducted by the EERC, in partnership with the NDIC Renewable Energy Program and DOE, the RTE project was determined a technically viable option for significantly reducing CO_2 emissions from ethanol production.

This project resulted in the first permitted geologic storage facility in North Dakota, Red Trail Richardton Ethanol Broom Creek Storage Facility No. 1, and was established with formal approval of RTE's North Dakota CO_2 storage facility (Class VI) permit on October 19, 2021. Major activities included drilling a stratigraphic test (coring, testing, logging) well followed by extensive laboratory analyses and evaluation, modeling and simulation of potential CO_2 injection and storage, and continued collaboration with incentive and regulatory officials.

RTE established commercial contracts for the capture facility, installation of wells and monitoring equipment, flowline, and other carbon capture system infrastructure. When injection started on June 16, 2022, RTE became the first active Class VI project in North Dakota. Over the first year and a half of operations, RTE injected nearly 250,000 metric tons, for an average of about 500 metric tons per day, essentially meeting the designed goals of the system.



Approximately $350 million Economic Impact

RED TRAIL ENERGY

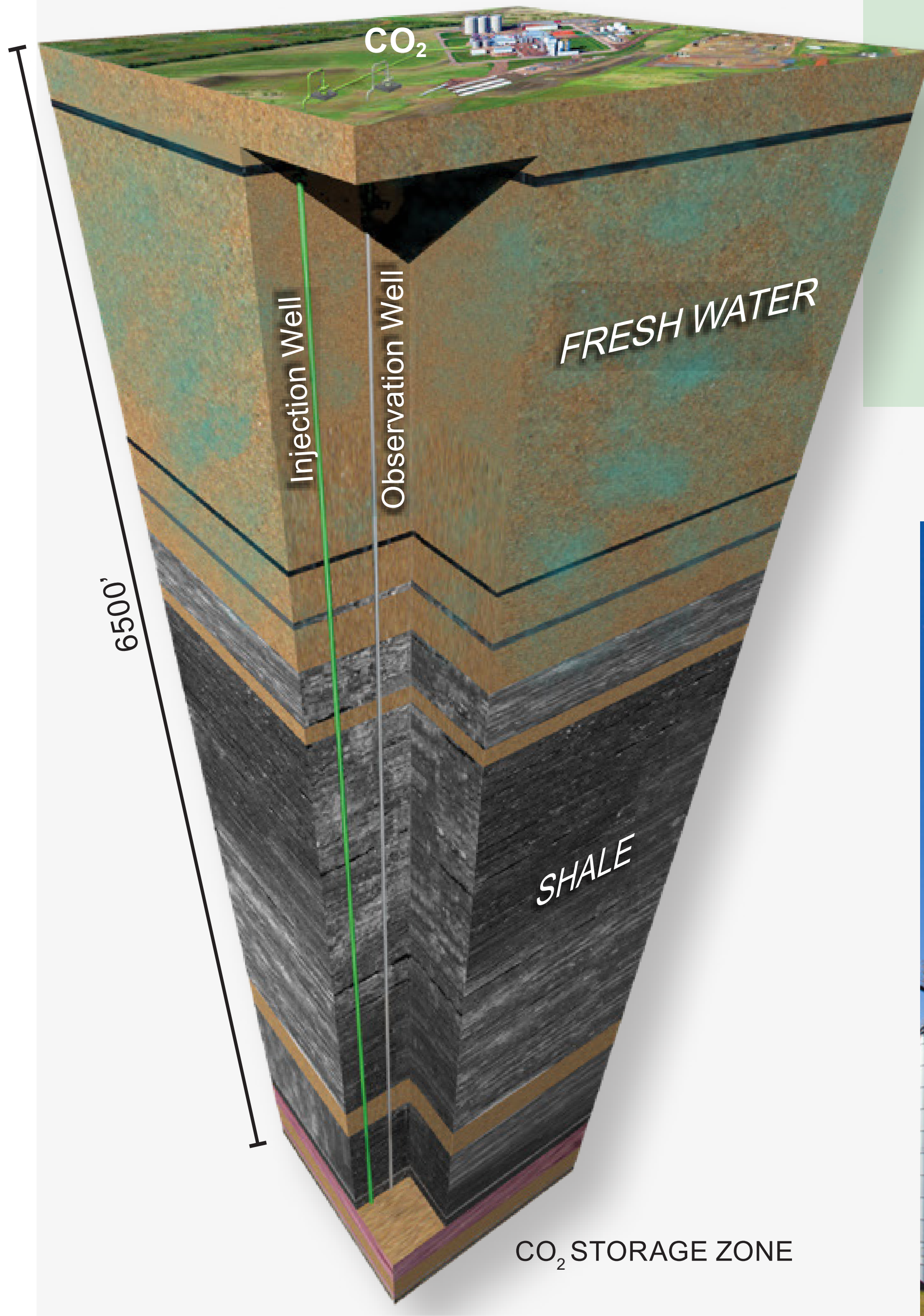
EERC
UND UNIVERSITY OF NORTH DAKOTA

renewable ENERGY PROGRAM
NORTH DAKOTA INDUSTRIAL COMMISSION

U.S. DEPARTMENT OF ENERGY

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

> Since beginning injection in June 2022, the RTE project has injected over 250,000 tonnes of CO_2, meeting designed capacities with no significant safety or operational issues, all while being within budget. Any slowdowns in CO_2 injections have only been a result of ethanol production slowdowns or project maintenance and upgrades.



PROJECT TUNDRA (CARBONSAFE NORTH DAKOTA)

Project Tundra is designed to capture 90% of the CO_2 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 (Minnkota) 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 project period 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.

As part of the CarbonSAFE project, two North Dakota CO_2 storage facility permit applications were approved in January 2022, the second and third approved storage facility applications in the state. The project has also developed and received approval in April 2022 for an EPA-compliant MRV plan that meets the requirements of the IRS 45Q tax incentive program. Further, the project had a draft environmental assessment approved in August 2023 that has been published for public comment and, as of March 2024, is awaiting final approval.

As of March 2024, Project Tundra received approval for installation of Class VI injection wells. Minnkota is approaching a FID to begin construction of the project's capture system and injection and monitoring wells.

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.

PROJECT TUNDRA

Minnkota Power
COOPERATIVE
A Touchstone Energy® Cooperative

EERC
UND UNIVERSITY OF NORTH DAKOTA

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

CMG

slb

Square Butte
ELECTRIC COOPERATIVE

January 2022	Storage Facility Permit Applications Approved
April 2022	EPA MRV Plan Approved
August 2023	Draft Environmental Assessment Approved
2027	First CO_2 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 CO_2 emissions from coal-based electricity generation facilities near Gillette, Wyoming. The Wyoming CarbonSAFE team is characterizing the subsurface geology for suitability for CO_2 storage, preparing permitting documents, working to integrate CO_2 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 is committed to developing robust monitoring plans and communicating project details to the public.

INTEGRATED TEST CENTER

Dry Fork Station also houses the Integrated Test Center (ITC), which is among a select few facilities in the world that provides space for technology developers to evaluate technologies using actual coal-based flue gas from an operating coal-fired power plant. ITC is a public–private partnership—under UWY SER's supervision—fostering the next generation of energy technology. ITC allows for real-world testing at an active power plant and alleviates typical concerns of being able to transfer technology from a lab to a plant.

> Wyoming's Carbon Valley: a trifecta of private, state, and federal interests leveraging one another toward a common goal: CCUS.

Center of Excellence for Economic Geology Research – School of Energy Resources
University of Wyoming – School of Energy Resources
U.S. Department of Energy
National Energy Technology Laboratory
Basin Electric Power Cooperative – A Touchstone Energy® Cooperative
EERC – University of North Dakota
Enhanced Oil Recovery Institute
Carbon GeoCycle
slb
CMG
WMPA – Wyoming Municipal Power Agency
Advanced Resources International, Inc.

CHAPTER 6

ACCELERATING CCUS

A diverse commercial CCUS industry has begun to emerge in the PCOR Partnership region. Using a variety of business models, the active commercial CCUS projects are integrating private investment with federal and state incentives, such as the 45Q tax and Low-Carbon Fuel Standard (LCFS) programs. Further CCUS deployment in the PCOR Partnership region will build on the current commercial activity and be accelerated by facilitating the development of projects currently in the planning stages, supporting regional infrastructure, and investigating and addressing remaining barriers to widespread CCUS adoption.

CHALLENGES TO CCUS DEPLOYMENT

To accelerate commercial deployment of CCUS across the PCOR Partnership region, CCUS must be widely accepted as a suite of trusted, economical, and conventional technologies that are part of the overall carbon management solution. For this to happen, several challenges need to be addressed.

REGULATIONS AND PERMITTING – Although much has happened in the regulatory world of CCUS (e.g., states getting primacy, states establishing pore space ownership rulings, etc.), regulatory and permitting uncertainties (e.g., compliance risks) remain a challenge to accelerating CCUS deployment. Ongoing efforts to permit CCUS projects in states with and without Class VI primacy will clarify the permitting process and establish the needed pathways to receive all necessary project approvals.

LONG-TERM LIABILITY – The project operator usually has primary responsibility for the CO_2 storage project during the injection phase. However, monitoring and remediation responsibilities may vary in the postinjection period, which may last many decades. The uncertainty in the scale and duration of postinjection responsibility may make some CCUS project developers wary.

ECONOMICS – For companies to deploy CCUS technologies, they will bear costs associated with carbon capture, transportation, and storage. Companies need to understand the existing regulatory environment and tax and other incentive programs well enough to see prospective CCUS deployment as profitable over the long term, thus justifying the investment and acceptance of any risk.

TECHNOLOGY PROOF OF CONCEPT – Although several commercial-scale CCUS projects are in place, operational experience with CCUS technologies in real-world conditions is still greatly needed. Each large-scale carbon capture project that is successful leads to the next level of understanding and improvements in permitting as well as capture, transport, and storage technologies.

INFRASTRUCTURE DEVELOPMENT – Most of the large-scale CO_2 sources in the PCOR Partnership region are not near large CO_2 storage opportunities. Increasing the adoption of CCUS will entail cost-efficient means of moving captured CO_2 to areas with ideal geologic storage opportunities. Large-scale deployment of CCUS will require a marked increase in commitment by both government and industry to plan and build the needed CO_2 transportation infrastructure.

RAMPING UP CCUS DEPLOYMENT

Looking ahead, the PCOR Partnership plans to support CCUS deployment across the region through the following activities:

1. Build upon assessments of regional storage data to verify the target formations' ability to store CO_2.
2. Facilitate the development of the infrastructure required to transport CO_2 from the source to the injection site.
3. Facilitate the development of the rapidly evolving North American regulatory and permitting framework for CO_2 storage.
4. Identify opportunities for CCUS, and support development of projects by PCOR Partnership partners.
5. Continue collaboration with the other RCSP Program partnerships.
6. Provide outreach and education for CO_2 storage stakeholders and the general public.

Through these efforts, the PCOR Partnership will help CCUS projects overcome key challenges, including cost-effective capture of CO_2, through successful integration with fossil fuel conversion systems. Advances in CCUS technology and project deployment will allow continued access to safe, reliable, and affordable energy.

REGULATION

CCUS policy is taking a prominent position in the climate management debate occurring at national, regional, and local levels, and the legal framework for the geologic storage of CO_2 continues to evolve.

In areas where extensive oil and gas production activities have taken place (in particular, EOR or acid gas injection), the regulatory framework is well established. In other jurisdictions, less regulatory framework may be in place for geologic storage of CO_2. Government organizations—which vary by jurisdiction—may have oversight for various aspects of the CCUS project, including the permitting, construction, health and safety, liability, protection of water supplies, and monitoring. EPA has promulgated rules for various aspects of carbon management and reporting; many states are moving forward with their own rules and regulations to accommodate CCUS projects.

Because of the evolving nature of regulatory frameworks at various levels of government, this atlas provides general overviews of select rules and policies currently under debate; this atlas can be considered up to date as of February 2024, unless otherwise noted.

To facilitate the exchange of information, ideas, and experiences among oil and gas regulatory officials, the PCOR Partnership hosts Regulatory Roundup meetings. The meetings inform regional regulatory officials about the current status and evolving nature of regulations that affect CO_2 capture, compression, transport, injection for CO_2 storage, or CO_2 EOR. These meetings allow for improved coordination of regulatory strategies that will ultimately enhance opportunities for CO_2 storage and CO_2 EOR in the region.

PRIMACY

EPA creates minimum regulations, and the Safe Drinking Water Act (SDWA) establishes a process for U.S. states to apply to EPA for the authority to regulate underground injection. This is known as primary enforcement authority, or primacy. When a state demonstrates to EPA that it has established an appropriate level of statutory authority and administrative regulations, EPA grants the state primacy. Under the UIC (underground injection control) Program, primacy is distinguished by individual injection well classifications.

In the PCOR Partnership region, North Dakota and Wyoming both have received Class VI primacy. If state primacy has not been established, the EPA regional office enforces the federal UIC Program regulations.

UNDERGROUND INJECTION CONTROL PROGRAM

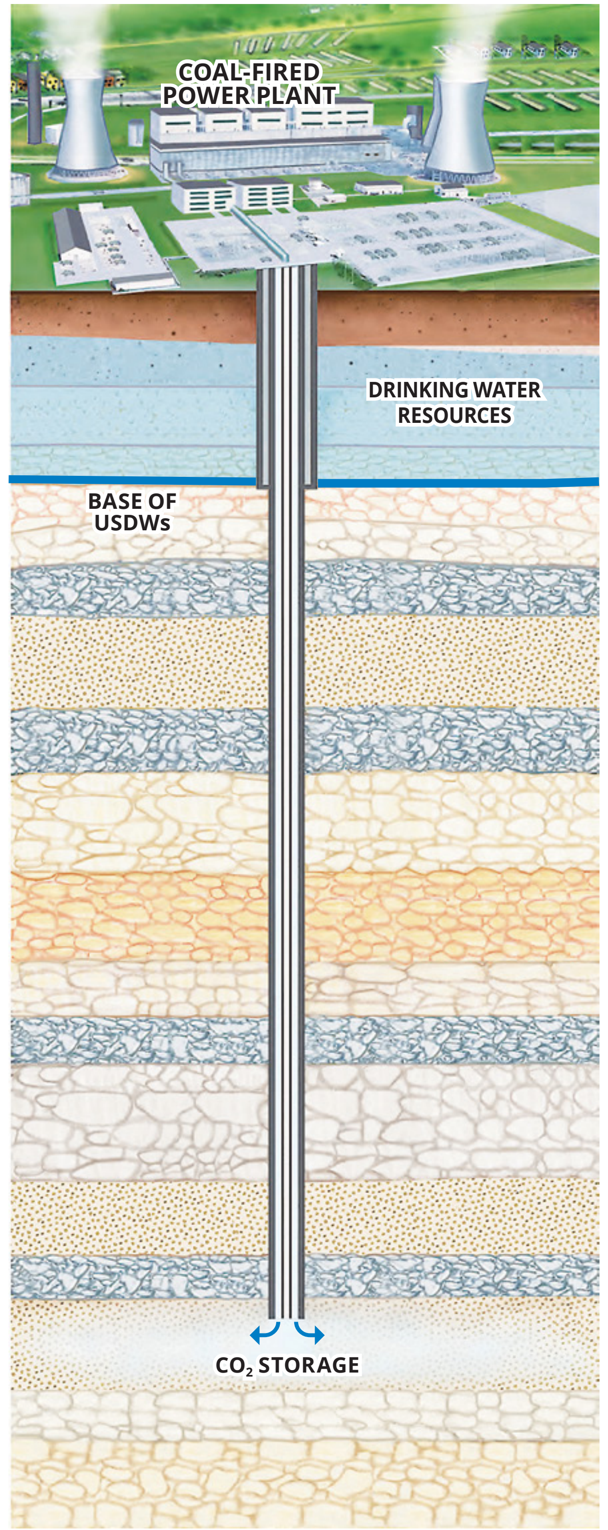
Regulations for CO_2 injection are established under the SDWA UIC Program. The UIC Program is a U.S. federal regulatory program administered by EPA and designed to protect USDWs.

In December 2010, EPA published the federal requirements for Class VI wells, which are wells used to inject CO_2 for the sole purpose of geologic storage. Class VI wells have specific criteria in place to protect USDWs. These criteria include requirements for extensive site characterization, well construction, well operation, comprehensive monitoring, financial responsibility, and reporting. EPA acknowledges that CO_2 EOR stores CO_2 while producing oil during EOR operations and that CO_2 injection under Class II rules can recognize the incidentally stored volume.

Class II wells are used only to inject fluids associated with oil and natural gas production. A Class II well can either be used for disposal purposes to inject waste fluids associated with oil and gas production or to enhance oil and gas recovery. Injection of CO_2 for EOR is regulated and permitted as a Class II injection well.

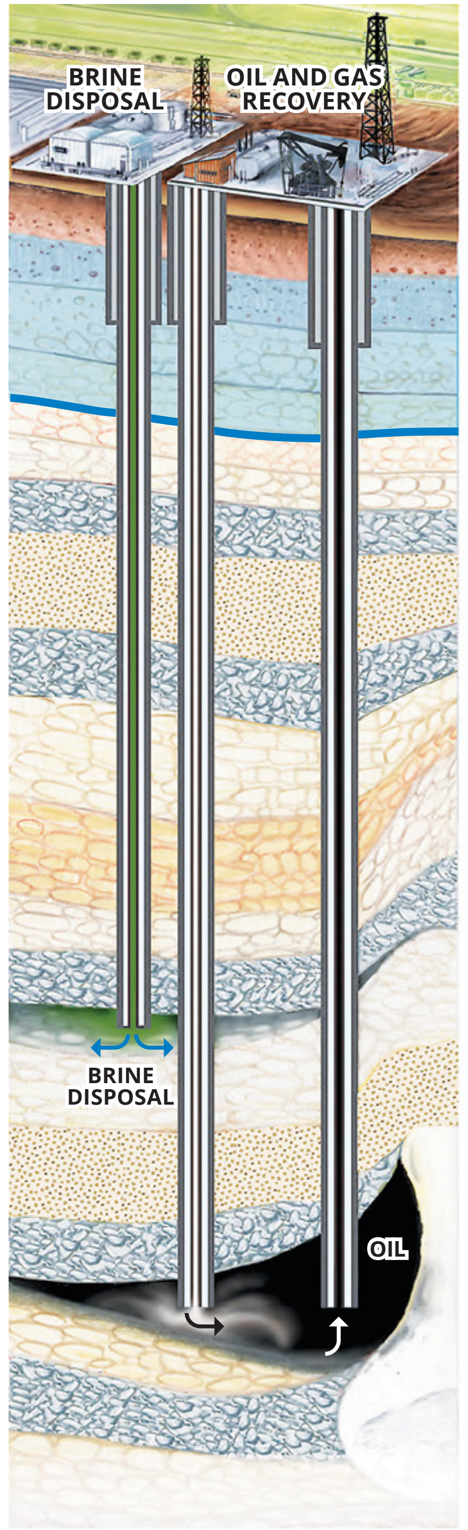
CLASS VI WELLS

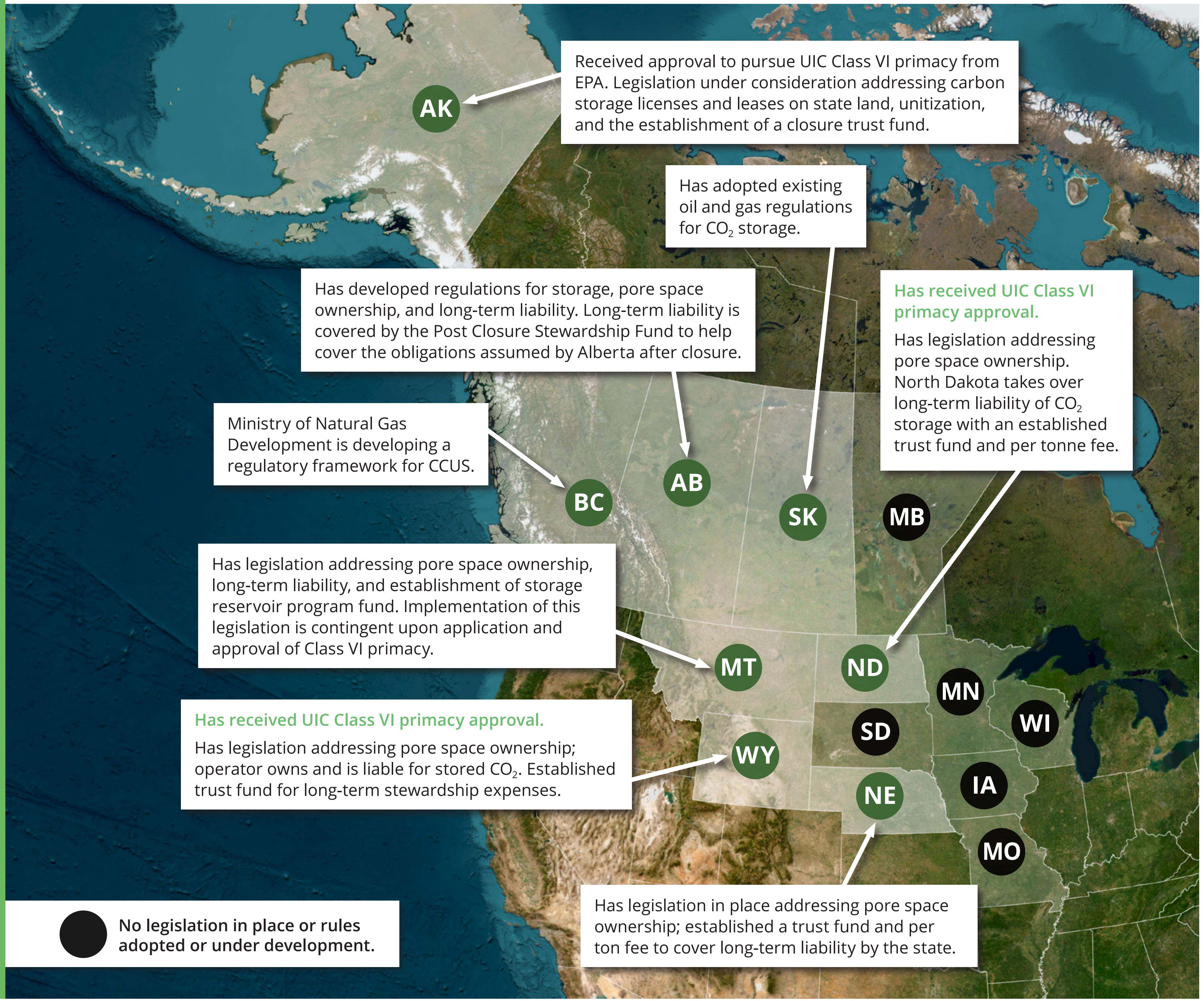
Inject CO_2 for Long-Term Storage to Reduce Emissions to Atmosphere



CLASS II WELLS

Inject Oil and Gas Production Fluids





AK: Received approval to pursue UIC Class VI primacy from EPA. Legislation under consideration addressing carbon storage licenses and leases on state land, unitization, and the establishment of a closure trust fund.

SK: Has adopted existing oil and gas regulations for CO_2 storage.

AB: Has developed regulations for storage, pore space ownership, and long-term liability. Long-term liability is covered by the Post Closure Stewardship Fund to help cover the obligations assumed by Alberta after closure.

ND: Has received UIC Class VI primacy approval.

Has legislation addressing pore space ownership. North Dakota takes over long-term liability of CO_2 storage with an established trust fund and per tonne fee.

BC: Ministry of Natural Gas Development is developing a regulatory framework for CCUS.

MT: Has legislation addressing pore space ownership, long-term liability, and establishment of storage reservoir program fund. Implementation of this legislation is contingent upon application and approval of Class VI primacy.

WY: Has received UIC Class VI primacy approval.

Has legislation addressing pore space ownership; operator owns and is liable for stored CO_2. Established trust fund for long-term stewardship expenses.

NE: Has legislation in place addressing pore space ownership; established a trust fund and per ton fee to cover long-term liability by the state.

● No legislation in place or rules adopted or under development.

PORE SPACE

Pore space can be defined as “the free space between the mineral grains of a geologic formation” or “a cavity or void, whether natural or artificially created, in a subsurface sedimentary stratum.” In either case, the cavity or space is filled with some type of fluid prior to injection: typically oil and brine in an oil field or just brine in a DSF. During CO_2 injection, the injected CO_2 displaces most of the fluid originally in the pore spaces. When developing CO_2 storage projects, project developers need to ensure they have rights to the necessary pore space in a prospective storage formation.

In many countries, subsurface pore space is owned by the federal government. In the United States, only a handful of states have clarified pore space ownership: North Dakota, Wyoming, Nebraska, Alaska, and Montana. To access the pore space needed to store CO_2, the CO_2 storage operator must pursue pore space access agreements with the parties that own the pore space. These agreements involve negotiations surrounding the value of the pore space. This value likely translates into payment terms of $/tonne/unit of land. Forced unitization (or amalgamation) of pore space is permitted in some states. In this case, if some percentage of owners agree (e.g., 60%–80%), the remaining owners can be required to participate with equitable compensation. This approach is very similar to the unitization process used in the oil and gas industry. Until there is a broader adoption of defined pore space management policy, pore space access will remain an obstacle to widespread CCUS implementation.

LONG-TERM LIABILITY

Long-term liability is broadly recognized as a significant challenge to widespread CCUS. During and immediately after the active injection phase, it is generally understood that the injection operator carries the liability for items such as personal injury, subsurface trespass, mitigation of leaks, etc. The main challenge is determining the appropriate policy framework to manage CCUS sites after closure. The time frame for geologic storage site management could extend for many decades beyond site closure. Without a clear understanding of if and how the long-term liability can be transferred to local or federal government, the investment risk to initiate a CO_2 storage project will remain high. North Dakota, Montana, Nebraska, Wyoming, and Alberta have established policies to transfer long-term liability to the state/province. These policies are the foundation for expanding this concept to additional states and provinces.

First enacted in October of 2008, Section 45Q of the U.S. tax code provides a performance-based tax credit for carbon capture projects and is intended to promote investment in CCUS implementation. To boost response to the 45Q tax credit program and broaden eligibility to other industries, the 2018 Bipartisan Budget Act reformed the tax credit program. The revised 45Q reduced the cost and risk to private capital of investing in the deployment of carbon capture technology across a range of industries.

Changes included 1) a larger credit amount; 2) a start-of construction deadline and 12-year claim period; 3) allowing the credit for CO_2 utilization in addition to EOR and for DAC, as well as allowing smaller facilities to claim the credit; and 4) allowing owners of carbon capture equipment to claim tax credits instead of the entity capturing the CO_2, which facilitates tax equity investment.

The deadline to begin construction was further extended for 2 years, to January 1, 2026, in the Taxpayer Certainty and Disaster Tax Relief Act of 2020 (Division EE of the Consolidated Appropriations Act, 2021; P.L. 116-260).

P.L. 117-169, commonly referred to as the Inflation Reduction Act of 2022 (IRA), modified and further extended the Section 45Q tax credit. In addition to modifying the base credit rates and definition of qualified facilities, the IRA allowed a larger credit for qualified facilities or carbon capture equipment that meet certain prevailing wage and apprenticeship requirements. In addition, the IRA extended eligibility to claim the credit to certain nonprofits ("direct pay") and entities without ownership interests ("transferability") and extended the deadline to begin construction to the end of 2032.[59]

	Equipment in service after 2/8/2018 and before 1/1/2023	Equipment in service after 12/31/2022 and under construction before 1/1/2033
Claim Period	12 years once facility is in service	12 years once facility is in service, 5 years if transferred
Annual Capture Requirements (metric tons)	Power: at least 500,000 DAC and other: at least 100,000	Power: at least 18,750, capture design capacity not less than 75% baseline emissions DAC: at least 1000 Other: at least 12,500
Credit Value ($/metric ton)	Saline storage: up to $50 CO_2 EOR and other: up to $35	Saline storage: base credit $17 ($36 for DAC), $85 ($180 for DAC) if requirements met CO_2 EOR and other: base credit $12 ($26 for DAC), $60 ($130) if requirements met
Eligibility	Entity that owns the capture equipment and ensures the utilization or storage	Entity that owns capture equipment and ensures utilization or storage. Direct pay may apply for certain tax-exempt entities.

In addition to federal tax incentives, North Dakota, Wyoming, and Montana offer a variety of tax incentives for projects involving CCUS.[60] For example, North Dakota eliminates sales tax on all capture-related equipment, CO_2 sold for EOR, pipeline construction, and CO_2 EOR infrastructure. In addition, North Dakota reduces the coal conversion tax when CO_2 is captured, allows for a 10-year property tax exemption on pipeline equipment, and eliminates oil and gas extraction tax for 20 years during tertiary CO_2 EOR. Wyoming has established tax incentives to spur CO_2 utilization. The state eliminates tax on the sale of CO_2 used in tertiary CO_2 EOR and allows for a severance tax credit when oil is produced from CO_2 injection. Montana offers a reduced market value property tax rate for carbon sequestration equipment. A notable law in Montana requires that all new coal plants capture and sequester at least 50% of their CO_2 emissions.

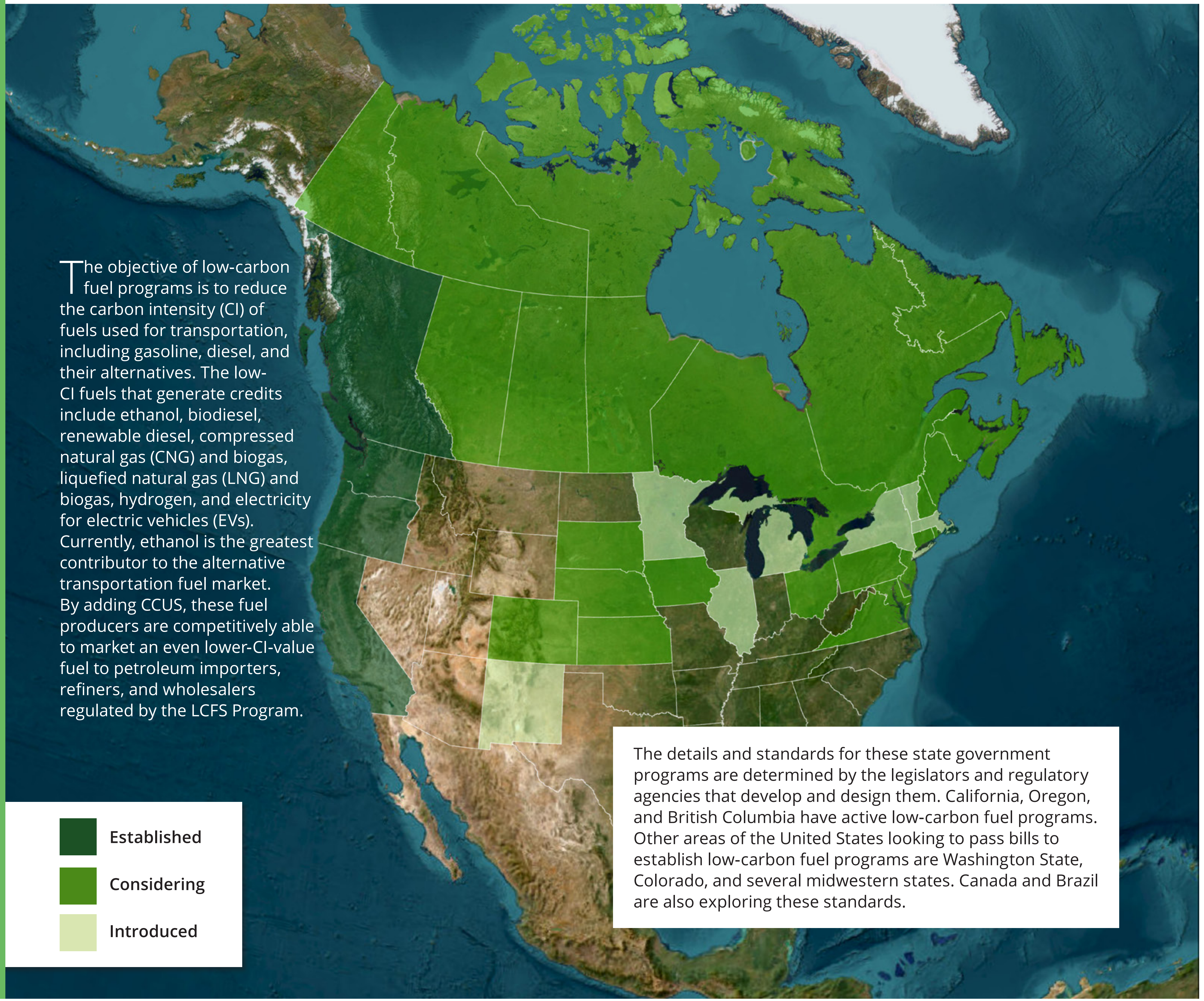
State	Incentives
North Dakota	Sales and use tax exemption Property tax exemption Gross receipts tax reduction
Wyoming	Sales tax exemption Severance tax credit
Montana	Reduced property tax

45Q Globally, the most progressive CCUS-specific incentive.[61]

Recent Actions

May 2020	IRS proposes regulation for 45Q tax credits.
December 2020	Congress approves 2-year extension of 45Q. Construction must start by January 1, 2026.
August 2022	IRS expands eligibility qualifications and extends construction start deadline to 2032.
May 2024	IRS issues final regulations for "direct pay," allowing 45Q tax credits as payment for federal income tax.

LOW-CARBON FUEL MARKETS



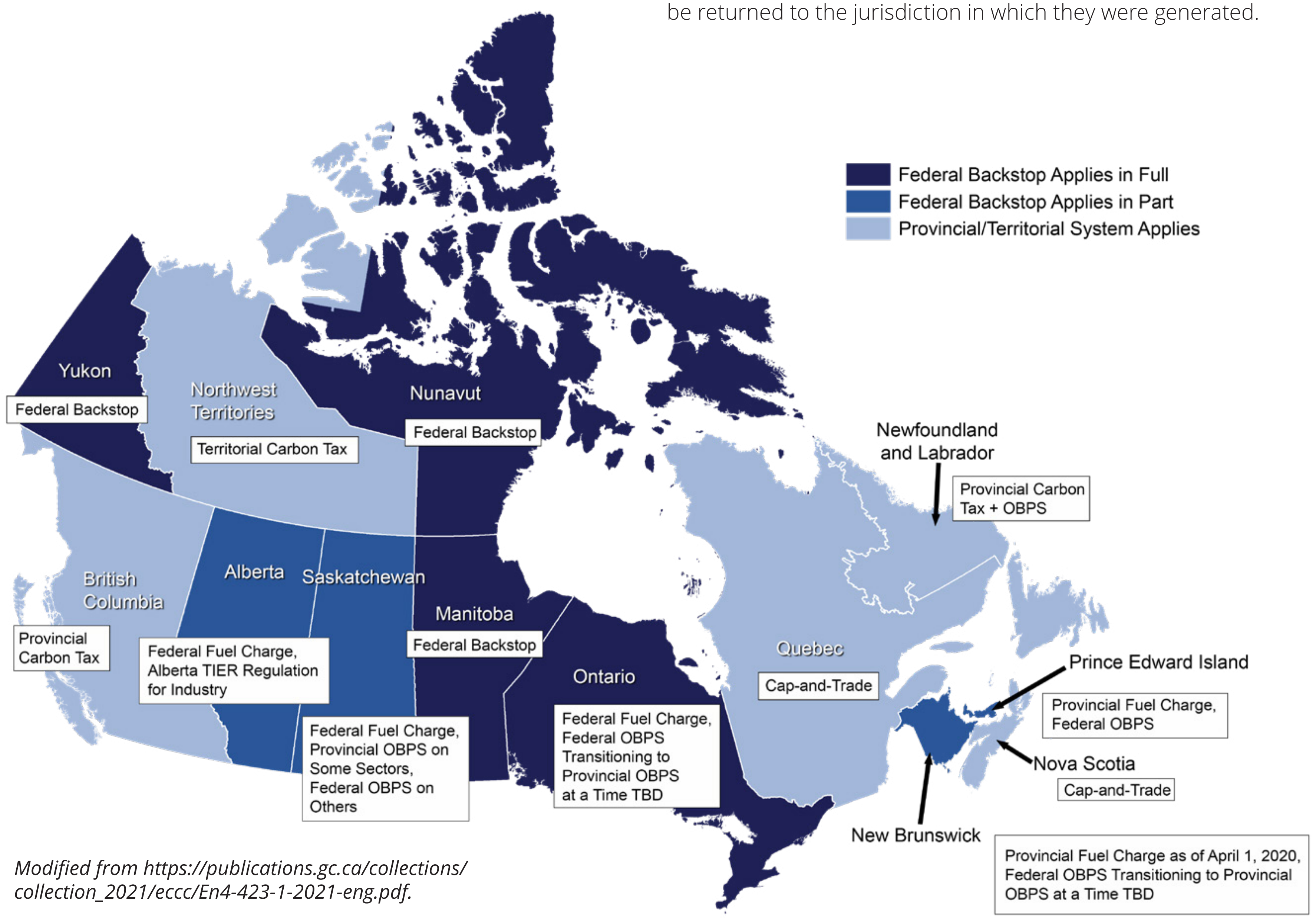
The objective of low-carbon fuel programs is to reduce the carbon intensity (CI) of fuels used for transportation, including gasoline, diesel, and their alternatives. The low-CI fuels that generate credits include ethanol, biodiesel, renewable diesel, compressed natural gas (CNG) and biogas, liquefied natural gas (LNG) and biogas, hydrogen, and electricity for electric vehicles (EVs). Currently, ethanol is the greatest contributor to the alternative transportation fuel market. By adding CCUS, these fuel producers are competitively able to market an even lower-CI-value fuel to petroleum importers, refiners, and wholesalers regulated by the LCFS Program.

The details and standards for these state government programs are determined by the legislators and regulatory agencies that develop and design them. California, Oregon, and British Columbia have active low-carbon fuel programs. Other areas of the United States looking to pass bills to establish low-carbon fuel programs are Washington State, Colorado, and several midwestern states. Canada and Brazil are also exploring these standards.

CANADIAN INCENTIVES

In its 2021 budget, the Canadian federal government proposed to introduce an investment tax credit for capital invested in CCUS projects, with the goal of reducing CO_2 emissions by at least 15 MMt annually. The investment tax credit, the Output-Based Pricing System (OBPS), will be available to multiple industrial sectors, including cement, refining, power generation, hydrogen generation, and DAC. The tax credit is not intended for CO_2 EOR projects. The credit is not yet active. It will take effect once parliament passes enabling legislation; the plan is to make it retroactive to 2022.[62,63]

In October 2016, the Canadian Prime Minister announced the Pan-Canadian Approach to Pricing Carbon Pollution, which gave provinces and territories the flexibility to develop their own carbon pollution pricing system along with guidance to ensure the systems are stringent, fair, and efficient. The Canadian federal government also committed to implementing a federal carbon pollution pricing system in provinces and territories that request it or do not have a carbon pollution pricing system that meets the federal benchmark, thus creating a federal backstop. As of 2021, the federal carbon price was Can$30/tonne; it will increase to Can$170/tonne by 2030. All direct proceeds from carbon pollution pricing under the Canadian federal system will be returned to the jurisdiction in which they were generated.



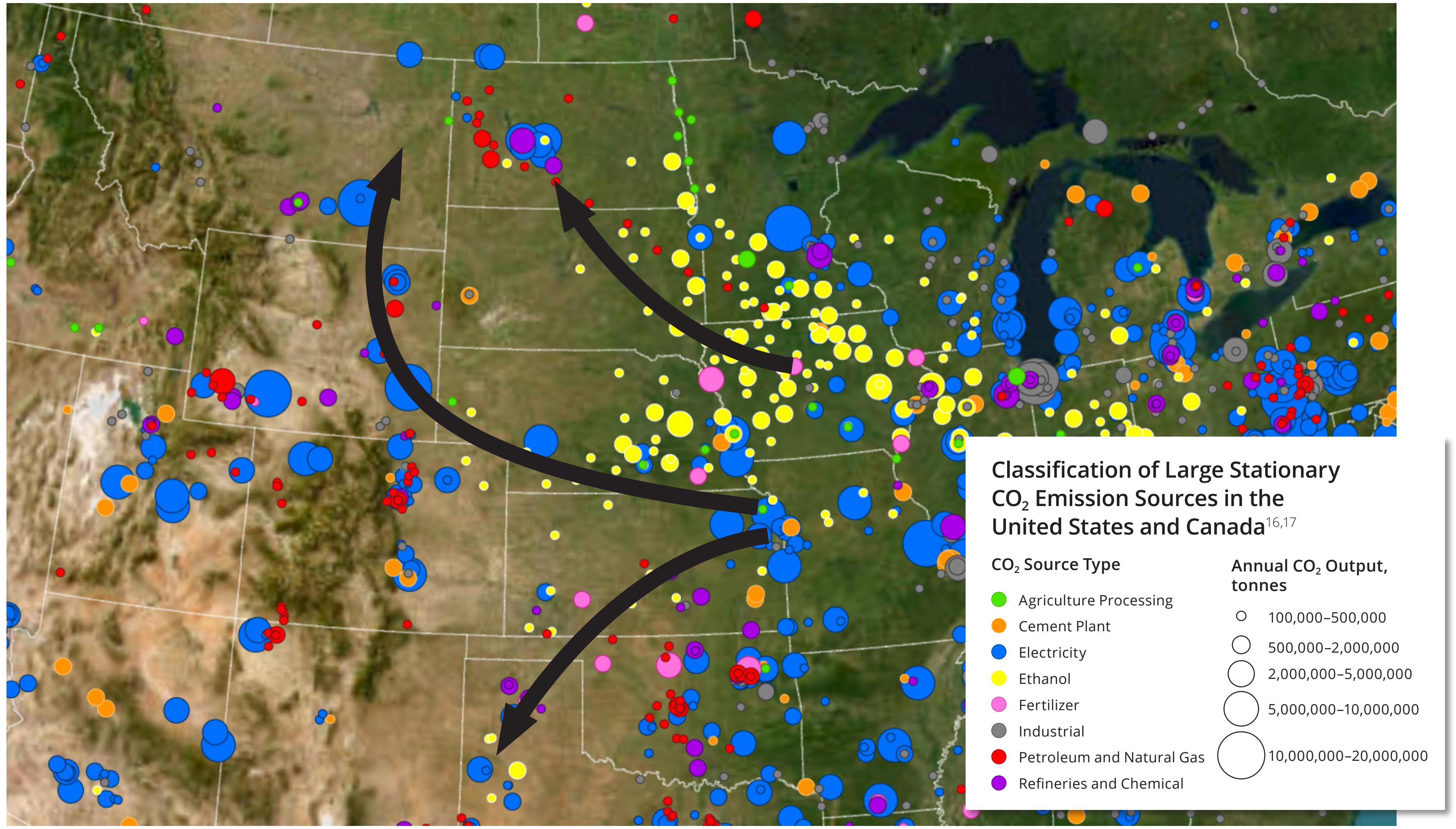
Modified from https://publications.gc.ca/collections/collection_2021/eccc/En4-423-1-2021-eng.pdf.

INFRASTRUCTURE

The United States currently has the world's most extensive CO_2 pipeline network; however, more infrastructure is needed to enable widespread deployment of CCUS in the country. For example, most of the large-scale CO_2 sources in the PCOR Partnership region are not near large CO_2 storage opportunities. Increasing the adoption of CCUS in the region will require cost-efficient means of moving captured CO_2 to areas with ideal geologic storage opportunities. Without the transport piece of the puzzle, there is little incentive to pursue the capture piece.

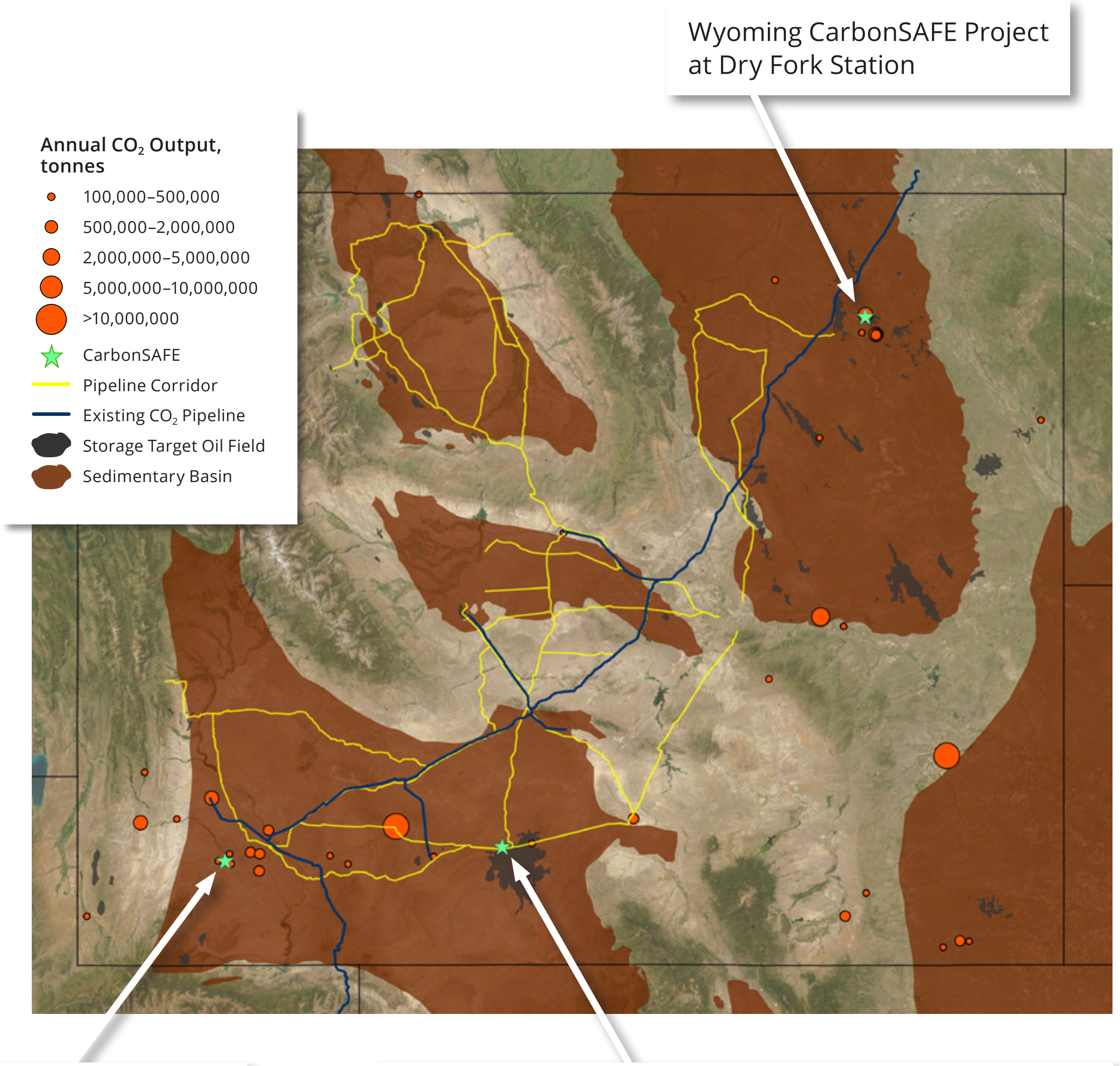
Instead of constructing many new point-to-point pipelines, a more strategic approach using prescribed trunk lines and connector pipelines would be economically advantageous for efficiently enabling widespread commercial CCUS deployment. For example, the ACTL, which had strong Canadian government infrastructure support, was designed to accomodate future expansion of CCUS. The 240-km pipeline has nearly 90% of its capacity available to accommodate future CO_2 sources. Two newly planned projects in the PCOR Partnership region involve the development of industrial CCUS hubs with shared CO_2 transport and storage infrastructure.[64] The development of additional shared infrastructure, such as pipelines, can be a strong incentive to trigger new investments.

Hypothetical CO_2 Trunk Routes



WYOMING PIPELINE CORRIDOR INITIATIVE

A notable example of facilitating infrastructure development in the PCOR Partnership region is the Wyoming Pipeline Corridor Initiative (WPCI). WPCI was formed to promote the development of a network of CO_2 pipelines throughout Wyoming for transportation of CO_2 from emission sources (such as power plants) to suitable storage locations or for other uses (such as EOR). Under the leadership of the Wyoming governor's office and in collaboration with researchers, industries, and other state agencies, WPCI proposes pipeline routes that would cover almost 2000 miles and cross federal, state, and private lands in central and eastern Wyoming. Project development continues to progress along these pipeline corridors.



Sweetwater Carbon Storage Hub CarbonSAFE Project

The Sweetwater Carbon Storage Hub CarbonSAFE project will comprise over 100,000 acres of leased pore space and over 550 million metric tons of CO_2 storage capacity. The project will provide a carbon management solution for industrial emitters in southwestern Wyoming and across the Mountain West. In December 2023, the Wyoming Department of Environmental Quality issued three Class VI UIC permits in relation to the project, which are the first to be issued in the state of Wyoming.

Williams Echo Springs CarbonSAFE Project

Started in 2023, UWY SER, in collaboration with Williams (a midstream natural gas company), is leading a storage complex feasibility study to develop a dedicated CO_2 storage hub for current and future industries in the Echo Springs area of south-central Wyoming. The 2-year study plans to permit and drill a deep stratigraphic test well and interpret the resulting data, models, and documents for further site development. Expected outcomes from the study include confirming which of the six stacked formations at Echo Springs can store at least 50 million metric tons of CO_2.

THE BUSINESS CASE FOR CCUS

Whether from a capture-ready nearly pure CO_2 source associated with an ethanol plant or from the retrofit of an 800-MW coal-fired power plant, implementing CCUS is an expensive endeavor. For an industry to move forward with a CCUS project, an appropriate business model must be adopted.

Selling captured CO_2 as a commodity is the easiest business model if the buyer and seller can agree on the CO_2 sale price and a long-term contract. This type of arrangement defines a traditional CO_2 EOR situation.

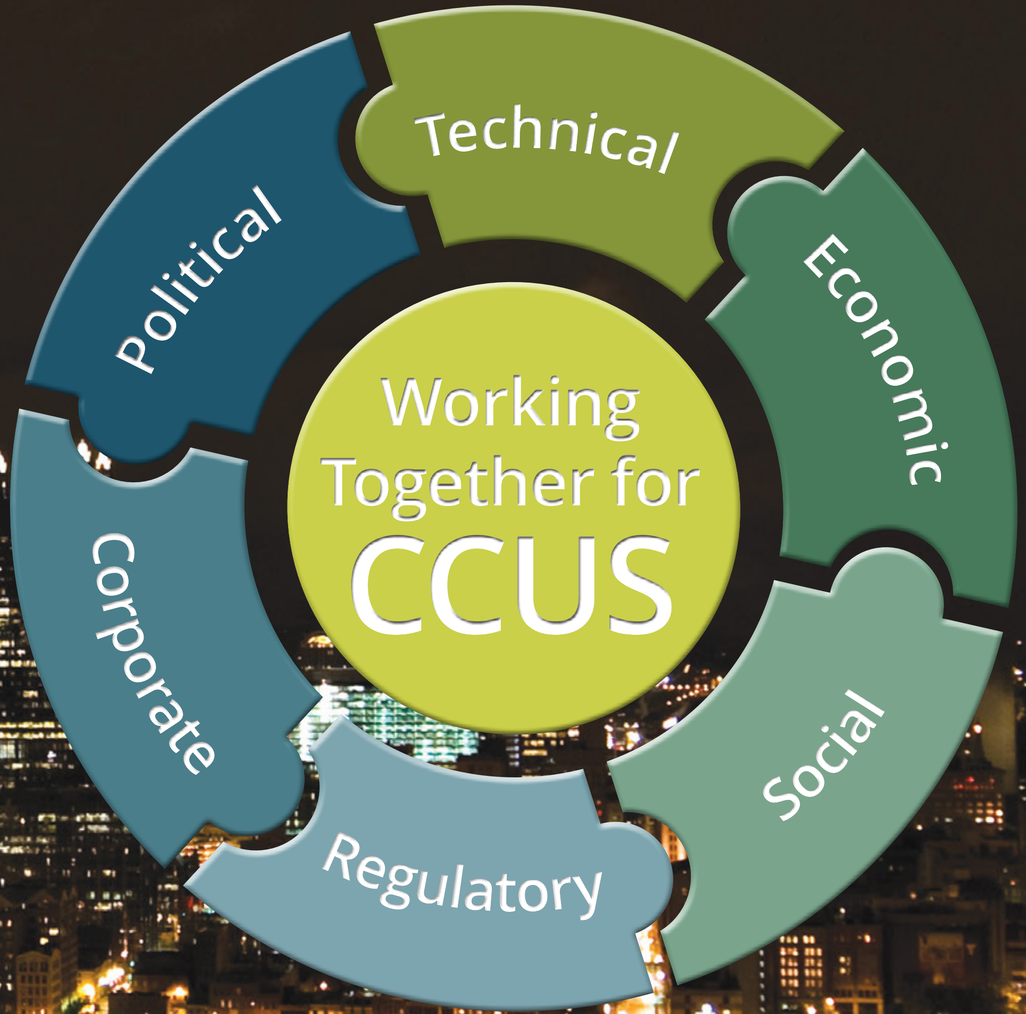
Without a market price for the CO_2 and an amicable buyer–seller relationship, alternative business cases are required. To incentivize CCUS where a market does not exist, the U.S. government has established a tax credit program for storing CO_2. The value of these tax credits provides the business case to move forward with CCUS projects to offset the cost of implementation. Canada has recently proposed an investment tax credit for capital invested in CCUS projects, with the goal of reducing emissions by at least 15 MMt of CO_2 annually.

Some CCUS projects, like those associated with ethanol plants, can bolster their business case by capitalizing on increased commodity values (more money per gallon of ethanol). Leveraging carbon markets, like the LCFS established in California or Oregon, can provide direct financial gain to an ethanol company implementing CCUS. The projects may be able to stack the financial benefits of increased commodity prices and the tax credits gained from the U.S. government. This combination is the driver for recently announced large-scale gathering and transport of CO_2 from ethanol plants in the United States.

The Canadian federal government has put a tax on CO_2 emissions (currently Can$30/tonne). Under this situation, there may be financial benefit to capture and store the CO_2 rather than pay the tax. This potential financial benefit would be the business case for CCUS.

CCUS ACCEPTANCE

CCUS can play a vital role in reducing atmospheric CO_2 levels while simultaneously preserving the option of using abundant and low-cost domestic fossil energy resources. However, the scale of CCUS deployment needed to result in significant reductions will require thousands of CCUS deployments around the world over the next three to four decades. The expansion of a new technology at that rate is challenging but achievable, particularly when the technology becomes routine and impediments are mitigated. Research, development, and demonstration (RD&D) programs, such as those currently conducted by DOE's RCSP Program, are critical for demonstrating CO_2 storage in diverse geologic settings and will establish the basis for CCUS's widespread global deployment.



ENVIRONMENTAL, SOCIAL, AND CORPORATE GOVERNANCE AND CCUS

Environmental, social, and corporate governance (ESG) are intangible factors that contribute to the sustainability and ethical impact of investments. The approach to, assessment of, and reporting of ESG factors are growing considerations for investors, shareholders, and the public who seek greater levels of transparency to evaluate risk exposure. An increasingly central aspect of many ESG assessment and rating schemes is a corporation's exposure to climate change-related risks.

Despite broad awareness of the potential for CCUS within the investment and rating communities, substantial uncertainty remains regarding its more widespread deployment. As such, CCUS is undervalued in its potential for improving a company's ESG performance.[65] Perhaps as CCUS matures, it will better boost ESG ratings. In the near term, ESG factors can play a contributing role in the development of commercial CCUS projects that are founded on more robust business cases.

ENGAGING THE PUBLIC

Public awareness and support are critical to the development of new energy technologies and are widely viewed as vital for CCUS projects. CCUS remains an unfamiliar technology to many members of the public, and local opposition to specific project proposals can be significant in some cases. However, enhanced and coordinated public outreach is improving awareness of the role of CCUS as one option to reduce GHG emissions. To that end, the PCOR Partnership is working to increase CCUS knowledge among the general public, regulatory agencies, policymakers, and industry.

Educational Workshops

Media Relations

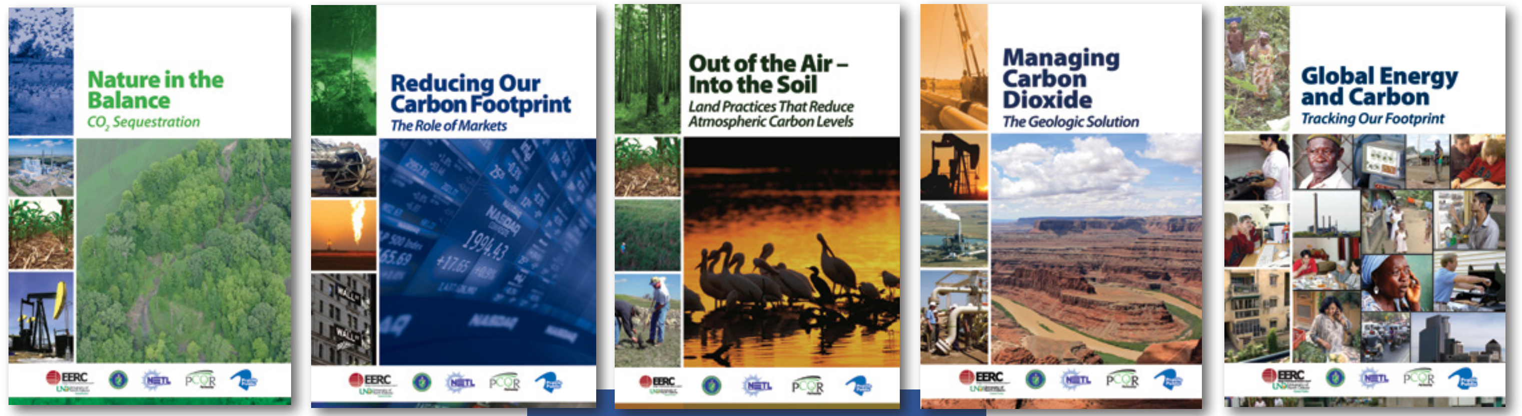
Landowner/ Stakeholder Relations

TAKE IT ON THE ROAD

Engaging the public, policymakers, and industry on CCUS remains an essential component of PCOR Partnership activities. This is done through presentations and participation at meetings and public and industry events throughout the region.

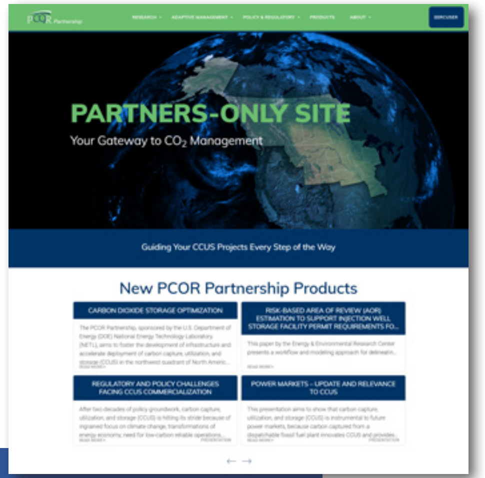
TAKE IT TO PRIME TIME

The PCOR Partnership has collaborated with Prairie Public Broadcasting to provide educational activities and documentary productions.

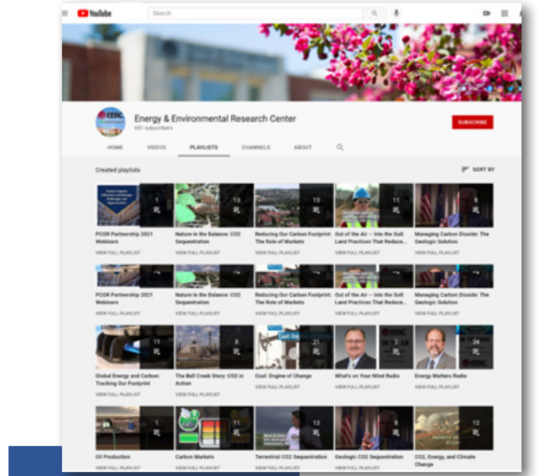


Award-Winning Documentaries

Public Web Site



Partners-Only Web Site



Video Clip Library

TAKE IT ONLINE

Separate public and partners-only websites provide information in terms and context tailored to meet the needs of the distinct demographics.

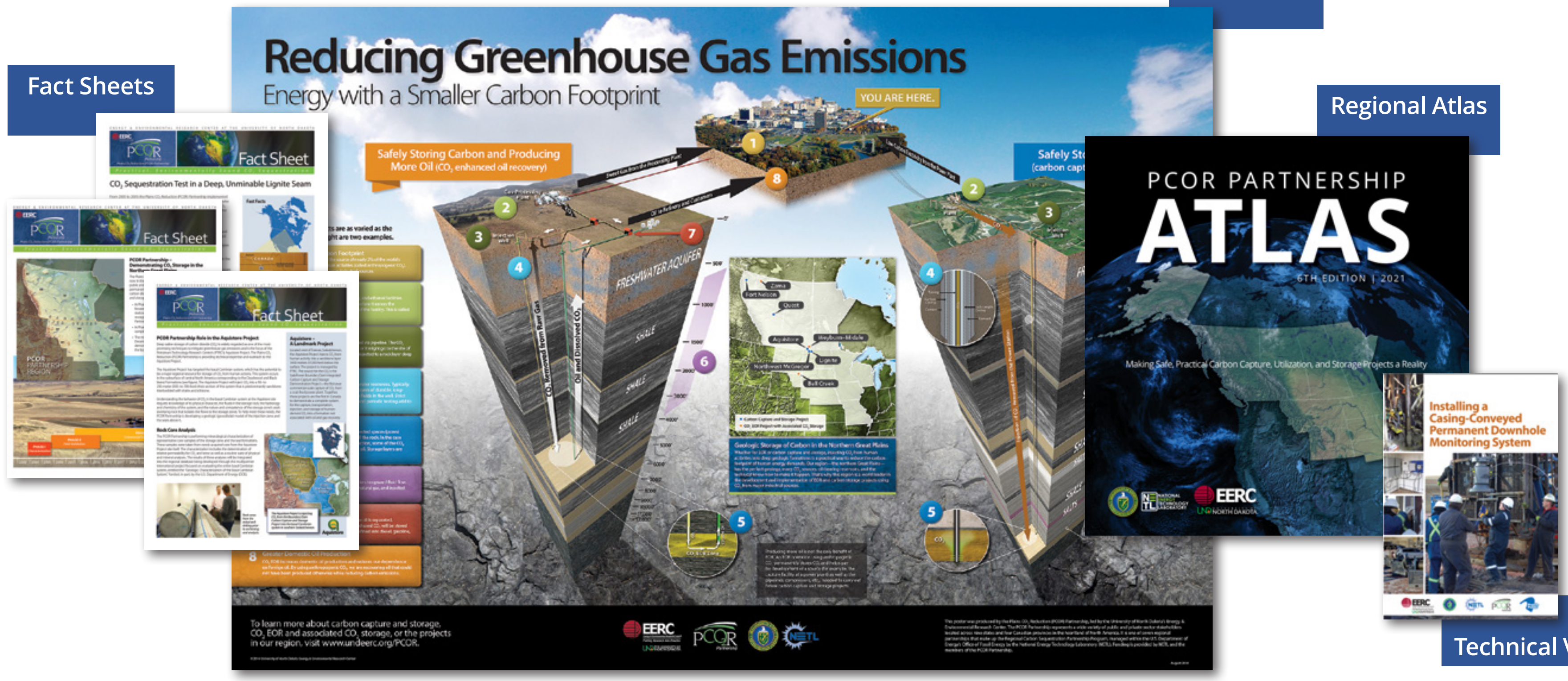
TAKE IT WITH YOU

Scientific fact sheets, presentations, posters, and reports inform technical audiences, while products such as documentaries, presentations, the regional atlas, and nontechnical posters tell the story of CCUS for a general audience.

Posters

Fact Sheets

Regional Atlas



Technical Videos

NOMENCLATURE

ACTL	Alberta Carbon Trunk Line
bbl	barrel
CarbonSAFE	Carbon Storage Assurance Facility Enterprise
CCA	Cedar Creek Anticline
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CH_4	methane
CI	carbon intensity
CO_2	carbon dioxide
CNG	compressed natural gas
CO_2eq	CO_2 equivalent
DAC	direct air capture
DGC	Dakota Gasification Company
Denbury	Denbury Onshore, LLC
DOE	U.S. Department of Energy
DSF	deep saline formation
ECBM	enhanced coalbed methane
EERC	Energy & Environmental Research Center
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ESG	environmental, social, and corporate governance
EU	European Union
EV	electric vehicle
FEED	front-end engineering and design
FID	financial investment decision
GHG	greenhouse gas
Gt	gigatonne or billion tonne
H_2O	water
IEA	International Energy Agency
InSAR	interferometric synthetic aperture radar
IRA	Inflation Reduction Act of 2022
IRS	Internal Revenue Service
ITC	Integrated Test Center
LCA	life cycle analysis
LCFS	low-carbon fuel standard
LNG	liquefied natural gas
mg/L	milligram per liter
Minnkota	Minnkota Power Cooperative
MRV	monitoring, reporting, and verification
MMt	million tonne
MVA	monitoring, verification, and accounting
MWh	megawatt-hour
NDIC	North Dakota Industrial Commission
NETL	National Energy Technology Laboratory
N_2O	nitrous oxide
NWR	North West Redwater Partnership
O_3	ozone
OBPS	Output-Based Pricing System
PCOR	Plains CO_2 Reduction (Partnership)
PCO$_2$C	Partnership for CO_2 Capture
PDM	permanent downhole monitoring
ppm	part per million
psi	pound per square inch
PTRC	Petroleum Technology Research Centre
RCSP	Regional Carbon Sequestration Partnership
R&D	research and development
RD&D	research, development, and demonstration
RTE	Red Trail Energy, LLC
SDWA	Safe Drinking Water Act
SER	School of Energy Resources
stb	stock tank barrel
TDS	total dissolved solids
UIC	underground injection control
USDW	underground source of drinking water
UWY	University of Wyoming
VSP	vertical seismic profile
WPCI	Wyoming Pipeline Corridor Initiative

CCUS UNITS AND CONVERSION FACTORS

Prefixes

T	tera	10^{12}	trillion
G	giga	10^{9}	billion
M	mega	10^{6}	million
k	kilo	10^{3}	thousand
m	milli	10^{-3}	one-thousandth
μ	micro	10^{-6}	one-millionth
n	nano	10^{-9}	one-billionth

Conversion of Mass to Volume of CO_2 (all at 1 atm)

standard temperature	short ton	tonne (metric ton)
0°C/32°F (scientific)	16.31 Mcf	17.98 Mcf
60°F (oil and gas industry)	17.24 Mcf	19.01 Mcf
20°C/68°F (utilities)	17.51 Mcf	19.30 Mcf

Mcf = 1000 ft^3

Volume

barrel of oil	X	42.00	=	U.S. gallon
	X	34.97	=	imperial gallon
	X	0.1590	=	cubic meter
U.S. gallon	X	0.0238	=	barrel
	X	3.785	=	liter
	X	0.8327	=	imperial gallon
imperial gallon	X	1.201	=	U.S. gallon

Weight

short ton	X	2000	=	pound
	X	0.9072	=	metric ton
metric ton (tonne)	X	1000	=	kilogram
	X	1.102	=	short ton

Length/Area

mile	X	1.609	=	kilometer
kilometer	X	0.6214	=	mile
hectare	X	2.471	=	acre
	X	0.0039	=	square mile
acre	X	0.4049	=	hectare
square mile	X	640.0	=	acre
	X	259.0	=	hectare
	X	2.590	=	square kilometer

Note: Most data in this atlas are described in metric units. However, some imperial units are used according to original data sources or industry standard (e.g., barrels of oil).

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FOR MORE INFORMATION

The public PCOR Partnership website contains a wealth of information related to CCUS geared toward various audiences. Visit us at **undeerc.org/pcor**.

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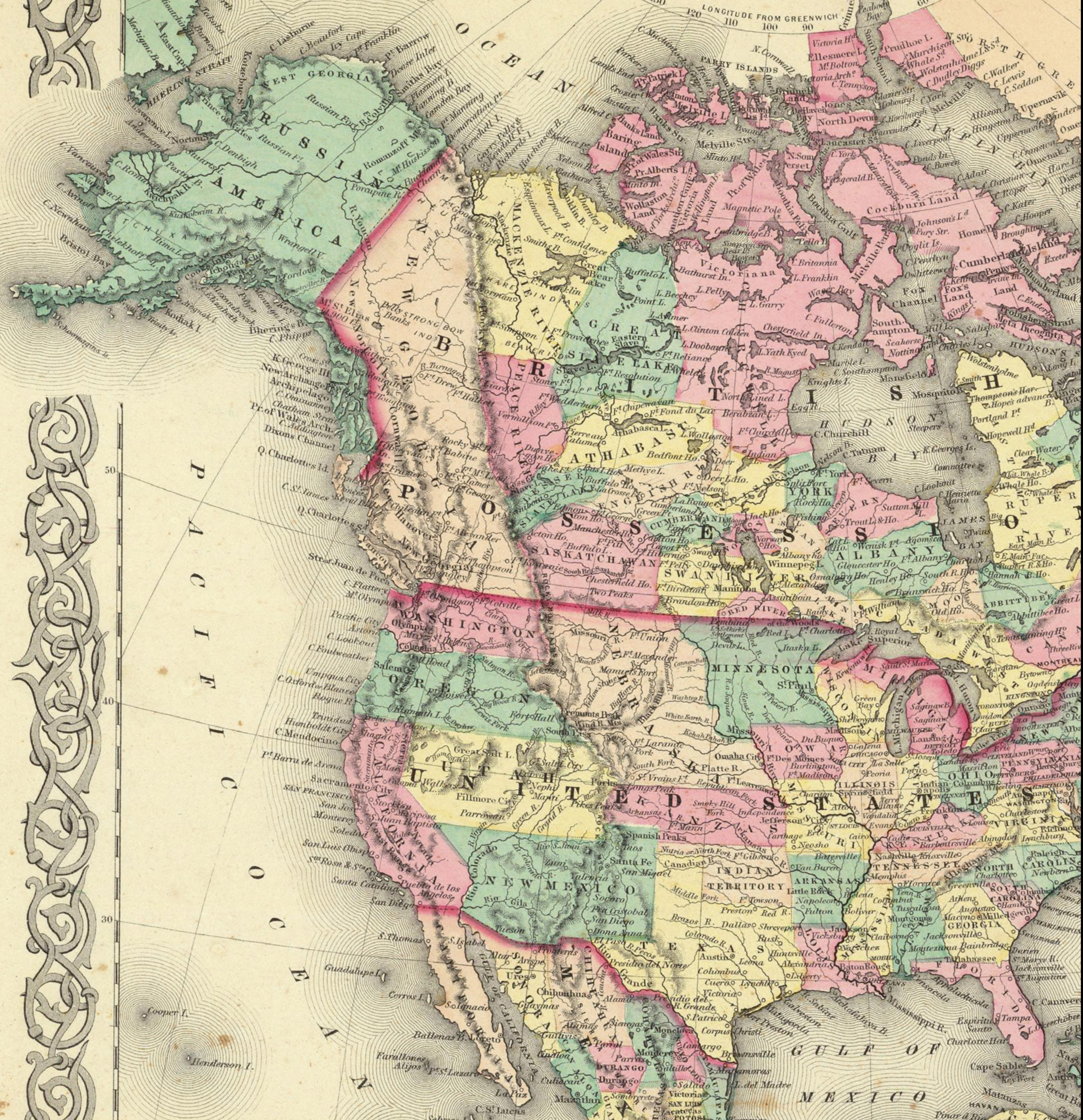
LONGITUDE FROM GREENWICH
120
110
100
90
OCEAN
BHERING STRAIT
WEST GEORGIA
RUSSIAN AMERICA
Russian Fort
Bristol Bay
Mt. St. Elias 17,900 Ft.
NEW GEORGIA
NEW CALEDONIA
BRITISH POSSESSIONS
PARRY ISLANDS
Melville I.
Banks Land
Baring Island
North Devon
Cockburn Land
Cumberland Island
Victoriana
Boothia Gulf
Magnetic Pole
MACKENZIE RIVER
GREAT SLAVE LAKE
Great Bear Lake
ATHABASCA
PEACE RIVER
SASKATCHAWAN
SWAN RIVER
CUMBERLAND
YORK
ALBANY
Hudson Bay
JAMES BAY
Southampton
Fox Channel
Hudsons Strait
EAST MAIN
CANADA
Q. Charlottes Id.
Vancouvers I.
Str. of Juan de Fuca
PACIFIC OCEAN
50
40
30
WASHINGTON
OREGON
UTAH
CALIFORNIA
NEW MEXICO
NEBRASKA
KANSAS
MINNESOTA
IOWA
WISCONSIN
MICHIGAN
MISSOURI
ILLINOIS
INDIANA
OHIO
KENTUCKY
TENNESSEE
ARKANSAS
INDIAN TERRITORY
TEXAS
LOUISIANA
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
NORTH CAROLINA
SOUTH CAROLINA
VIRGINIA
PENNSYLVANIA
NEW YORK
UNITED STATES
Great Salt L.
Lake Superior
L. Michigan
San Francisco
Sacramento
Monterey
San Diego
Santa Fe
Austin
Galveston
Brownsville
Corpus Christi
Memphis
Nashville
St. Louis
Chicago
Cleveland
Washington
Charleston
Savannah
Tallahassee
SONORA
CHIHUAHUA
DURANGO
GULF OF CALIFORNIA
GULF OF MEXICO
Cape Sable
Havana
Matanzas
Guadalupe I.
Cooper I.
Henderson I.
C. St. Lucas
La Paz
Mazatlan