PCOR PARTNERSHIP

ATLAS

5TH EDITION *REVISED*

PCO2R Partnership

Plains CO_2 Reduction (PCOR) Partnership

Practical, Environmentally Sound CO_2 Sequestration

Department of Energy · United States of America

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

EERC

UND UNIVERSITY OF NORTH DAKOTA

Plains CO_2 Reduction (PCOR) Partnership

ATLAS

5th EDITION R E V I S E D

2017

Compiled and Created by
Wes Peck, Principal Geologist
Earl Battle, Graphic Designer
Megan Grove, GIS Analyst
Kyle Glazewski, Senior Analyst

Manuscript Editor
Joyce Riske, Principal Editor, Editing and Graphics

PCOR Partnership Management
Charles Gorecki, Director of Subsurface R&D
Ed Steadman, Vice President for Research
John Harju, Vice President for Strategic Partnerships

Published by the
Energy & Environmental Research Center (EERC)
2017

The PCOR Partnership is a group of public and private stakeholders working together to better understand the technical and economic feasibility of storing CO_2 emissions from stationary sources in the central interior of North America. The PCOR Partnership is led by the EERC at the University of North Dakota and is one of seven regional partnerships through the U.S. Department of Energy's Regional Carbon Sequestration Partnership initiative.

NATIONAL ENERGY TECHNOLOGY LABORATORY

Notice

Printed in the United States of America and available from:
Energy & Environmental Research Center (EERC)
Grand Forks, ND 58202

Acknowledgments

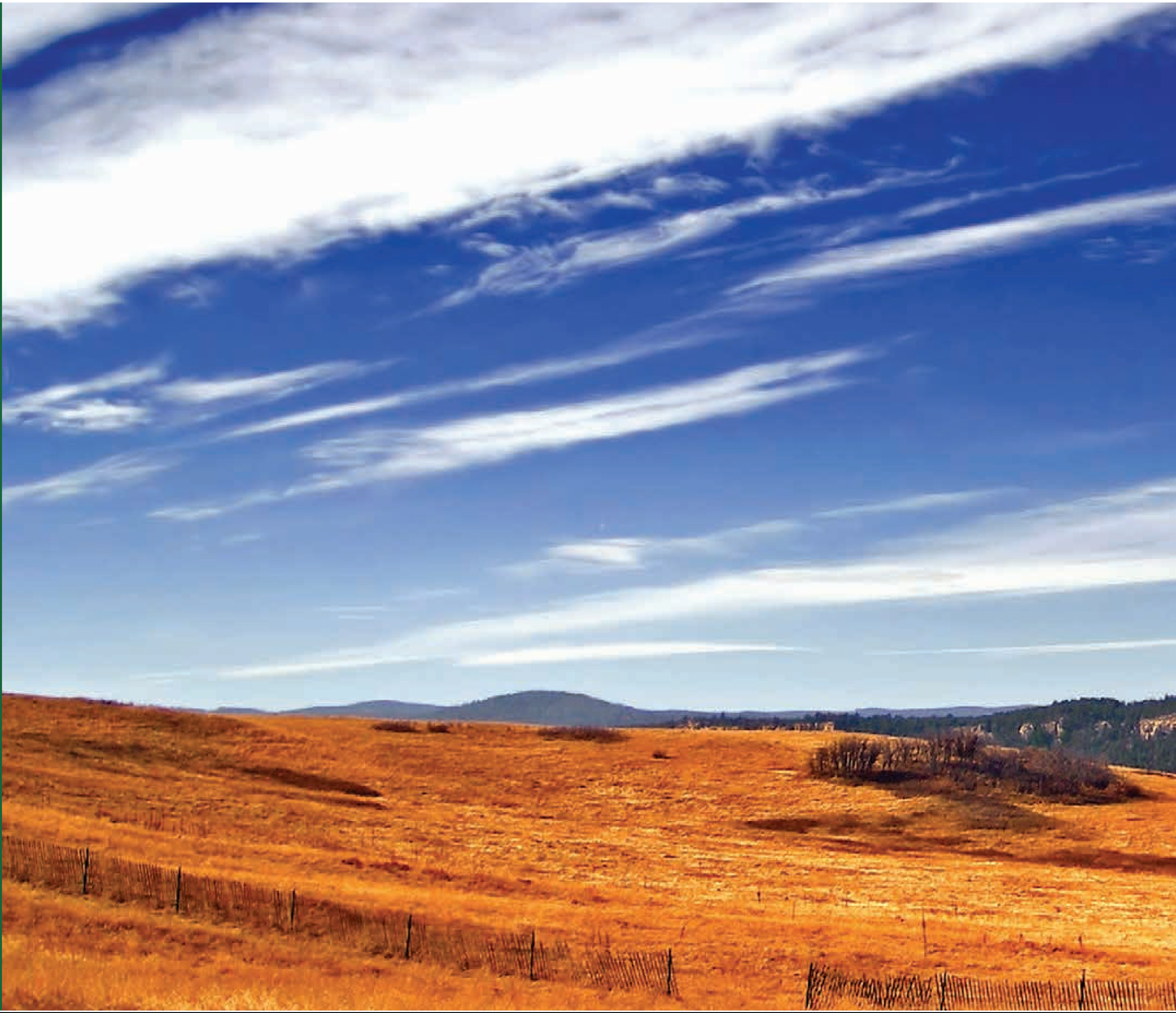
This atlas was made possible through the contributions and efforts of numerous groups from throughout the United States and Canada. We would like to acknowledge the PCOR Partnership partners for their efforts in providing much of the information used for the assessments and for cooperating with us in producing a regional portfolio for public use. We also extend our appreciation to the various federal, state, and private organizations and university groups for their cooperation in our search for data.

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 2015 and 2016. It was through their creative energy and collective efforts that the production of this atlas was possible:

Heather Altepeter, Ted Aulich, Scott Ayash, Alex Azenkeng, Nicholas Azzolina, César Barajas-Olalde, Chris Beddoe, Nicholas Bosshart, Barry Botnen, Jason Braunberger, Shaughn Burnison, Matthew Burton-Kelly, Shane Butler, Charlene Crocker, Janet Crossland, Chantsalmaa Dalkhaa, Dan Daly, Thomas Doll, Neil Dotzenrod, Janelle Ensrud, Tom Erickson, Ian Feole, Jun Ge, Kyle Glazewski, Charles Gorecki, Andrew Gorz, Megan Grove, John Hamling, John Harju, Steve Hawthorne, Jun He, Loreal Heebink, Lonny Jacobson, Melanie Jensen, Tao Jiang, Lu Jin, Nicholas Kalenze, Ryan Klapperich, Justin Kovacevich, Beth Kurz, Mark Kurz, Kerryanne Leroux, Amanda Livers, Blaise Mibeck, Mark Musich, Benjamin Oster, Wes Peck, Larry Pekot, Lucia Romuld, Olarinre Salako, Steve Schlasner, Kari Schmidt, Rhonda Shirek, Steve Smith, Jim Sorensen, Ed Steadman, Dan Stepan, José Torres Rivero, Heidi Vettleson, Tami Votava, Neil Wildgust, Jib Wilson, and Erick Zacher.

This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory under Award No. DE-FC26-05NT42592.



Contents


Image provided by Denbury Resources Inc.

Many changes have been observed in the global climate over the past century. There is growing concern that human activity, such as the use of fossil fuels for energy production, may be affecting the climate. Other significant potential impacts come from deforestation, agricultural practices, and industrial processes.

One of the ways that we can significantly reduce human-made greenhouse gas (GHG) emissions is by using carbon capture and storage (CCS). CCS offers a promising set of technologies through which carbon dioxide (CO_2) can be captured from large stationary sources and permanently stored underground.

Within central North America, the Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is investigating long-term CO_2 storage technologies to provide a safe, effective, and efficient means of managing CO_2 emissions. The PCOR Partnership is part of the U.S. Department of Energy (DOE) National Energy Technology Laboratory's (NETL's) Regional Carbon Sequestration Partnership (RCSP) initiative. The goal of this joint government–industry effort is to determine the most suitable technologies, regulations, and infrastructure needed for CCS.

This atlas provides a regional profile of CO_2 sources and potential CO_2 storage locations across the nearly 3.6 million km^2 of the PCOR Partnership region. In the 13 years since the RCSP initiative was founded, a wealth of new information about CCS has emerged. This fifth edition provides an up-to-date look at PCOR Partnership activities, to include additional regional characterization and updates on full-scale demonstration projects. Additional background information to support CCS is included to give the reader a better picture of how CCS plays a role in addressing concerns about climate change while allowing future energy needs to be met.

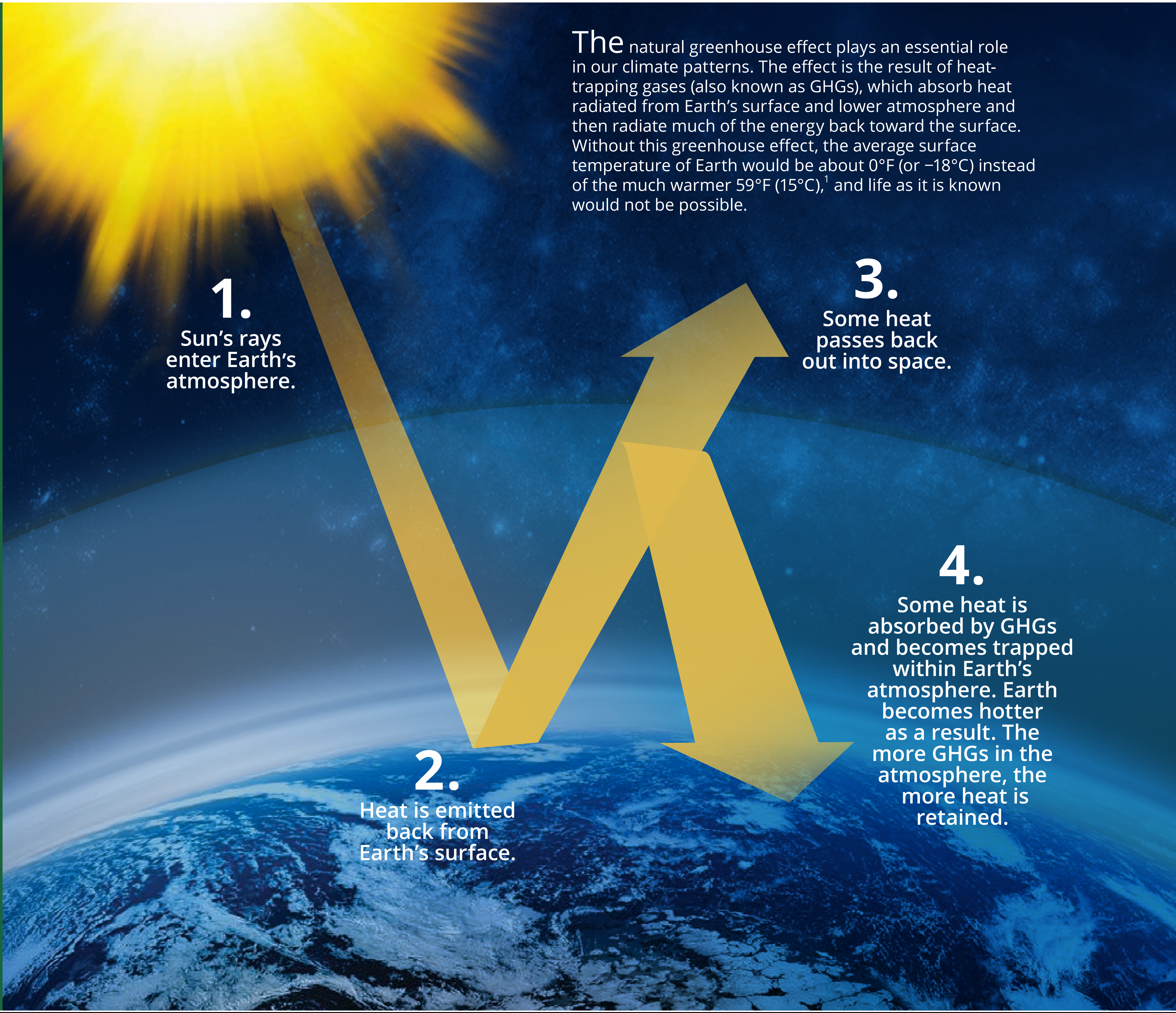
CHAPTER 1

The Challenge

Global climate change is considered to be one of the most pressing environmental concerns of our time. This concern is due, in part, to the potential magnitude of the economic, technological, and lifestyle changes that may be necessary in response. Although uncertainty still clouds the science of climate change, there is strong indication that we may need to significantly reduce human-made greenhouse gas (GHG) emissions. Carbon capture and storage (CCS) has the potential to address this challenge, and the activities conducted through the Plains CO_2 Reduction (PCOR) Partnership are playing an important role in efficiently meeting this challenge.

Greenhouse Effect

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



Many gaseous chemical compounds in Earth's atmosphere contribute to the greenhouse effect. These gases absorb infrared radiation reflected from Earth's surface and trap the heat in the atmosphere. Some occur in nature (water vapor [H_2O], carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O], and ozone [O_3]), while others are exclusively human-made (like gases used for aerosols).

Water vapor 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.

Carbon dioxide has both natural and anthropogenic (human-made) sources. CO_2 plays a vital role in supporting life on Earth. The natural production and absorption of CO_2 are achieved through the terrestrial biosphere (trees, soil) and the hydrosphere (ocean).

Methane 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.

Nitrous oxide is produced by microbial processes in soil and water, including those reactions which occur in fertilizer containing nitrogen.

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

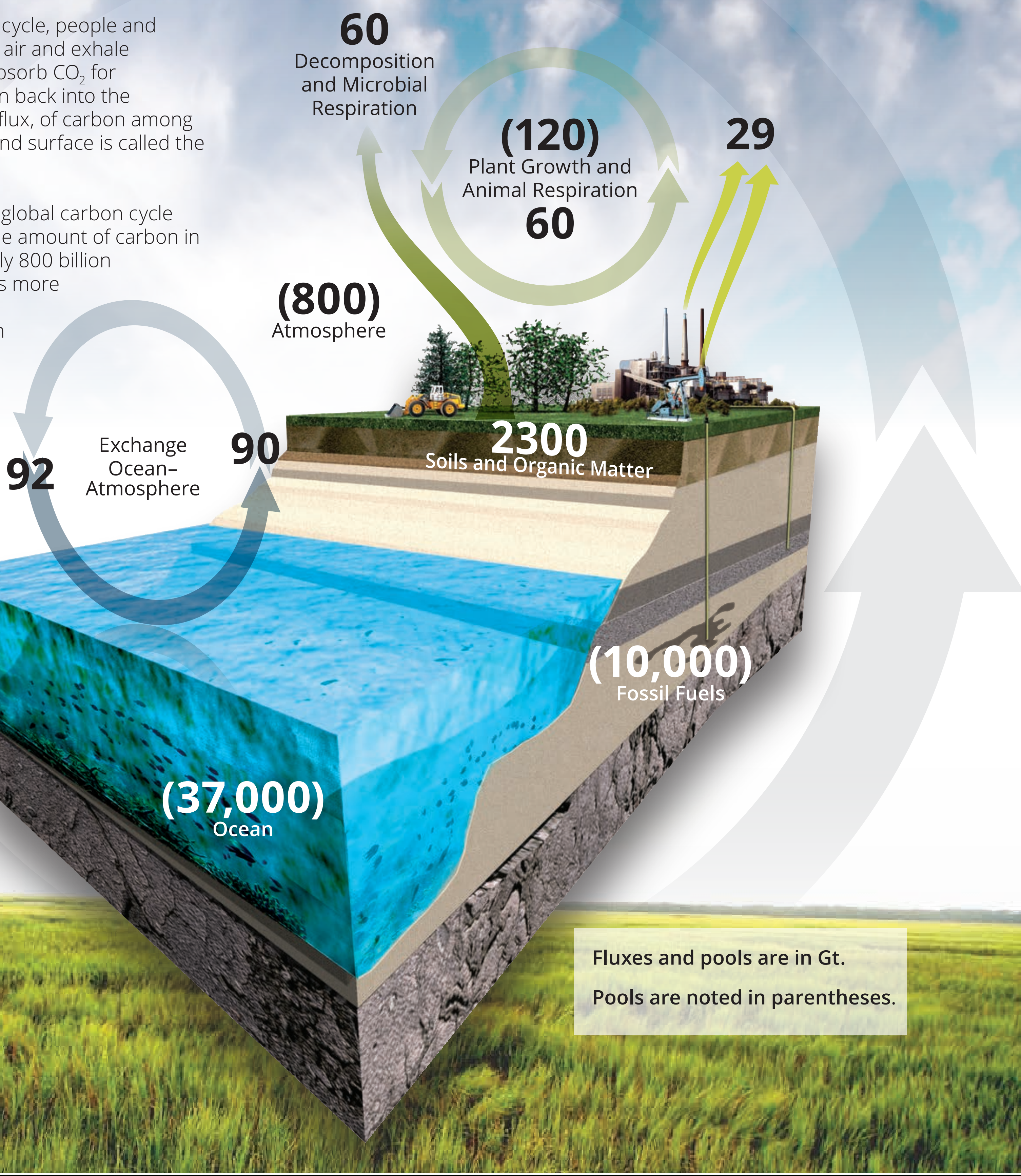
Chlorofluorocarbons (CFCs) have no natural source and are used as refrigerants, aerosol propellants, and cleaning solvents. CFC production was nearly halted after it was discovered that CFCs are able to destroy stratospheric ozone.

Representative GHG effect contributions.[2]

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. This exchange, or flux, of carbon among the atmosphere, oceans, and land surface is called the global carbon cycle.[3]

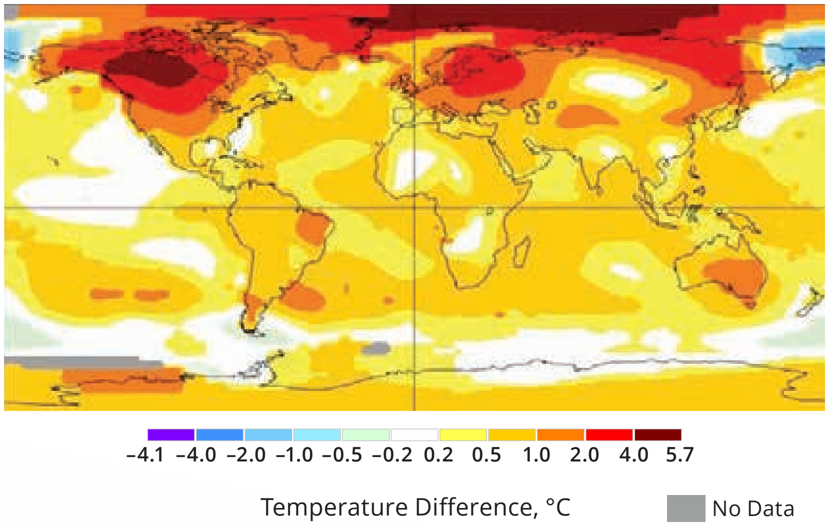
For most of human history, the global carbon cycle has been roughly in balance. The amount of carbon in the atmosphere is approximately 800 billion tonnes (or gigatons, Gt), which is more carbon than contained in all of Earth's living vegetation. Human activities, namely, the burning of fossil fuels, deforestation, and other land use activities, have altered the carbon cycle, resulting in a 35% rise in atmospheric concentrations of CO_2 since the Industrial Revolution.



"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 approximately 1.62°F (0.90°C), with 2015 being the warmest year on record according to the National Oceanic and Atmospheric Administration.[4] A majority of climate scientists attribute current changes in climate at least in part to anthropogenic (human-made) emissions, although modeled predictions of future climate change and impacts are subject to uncertainty. This observed climate change is not distributed evenly across the globe. For instance, temperature increases in the last 10 years have generally been greatest in the northern latitudes.

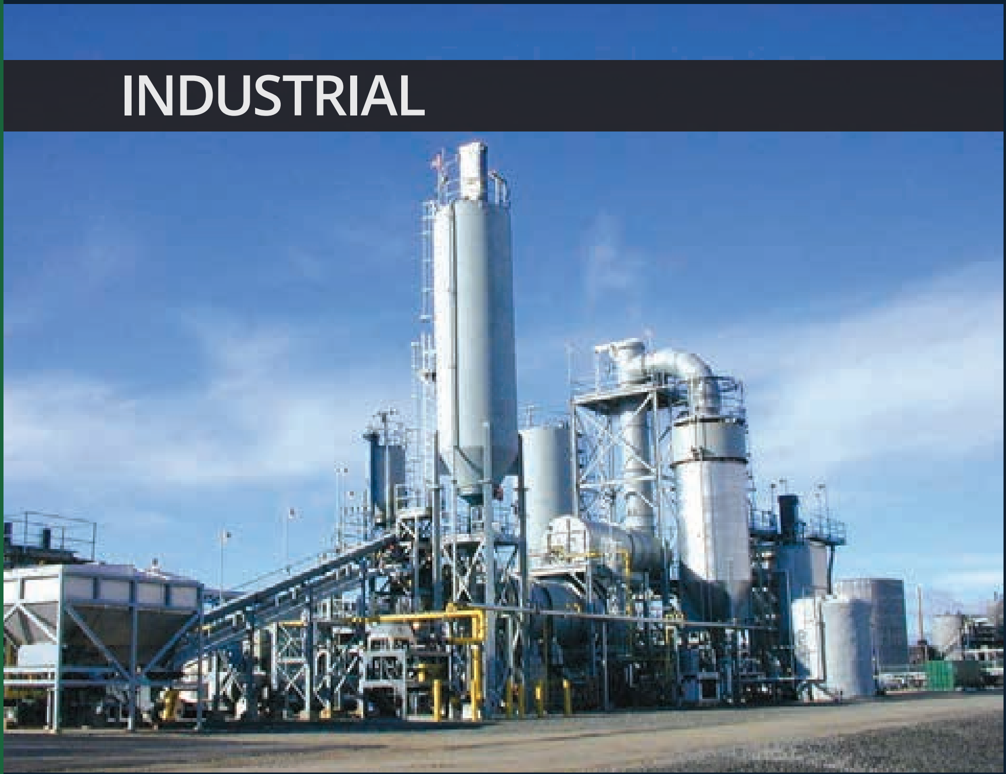


The map shows the average surface temperature trends for the decade 2005–2015 relative to the 1950–1980 average. Warming was more pronounced at high latitudes, especially in the Northern Hemisphere and over land.[5]

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 have a profound effect on the heat budget of Earth. In 1904, Arrhenius became concerned with rapid increases in anthropogenic carbon emissions.[6]

Major Stationary CO_2 Sources

INDUSTRIAL

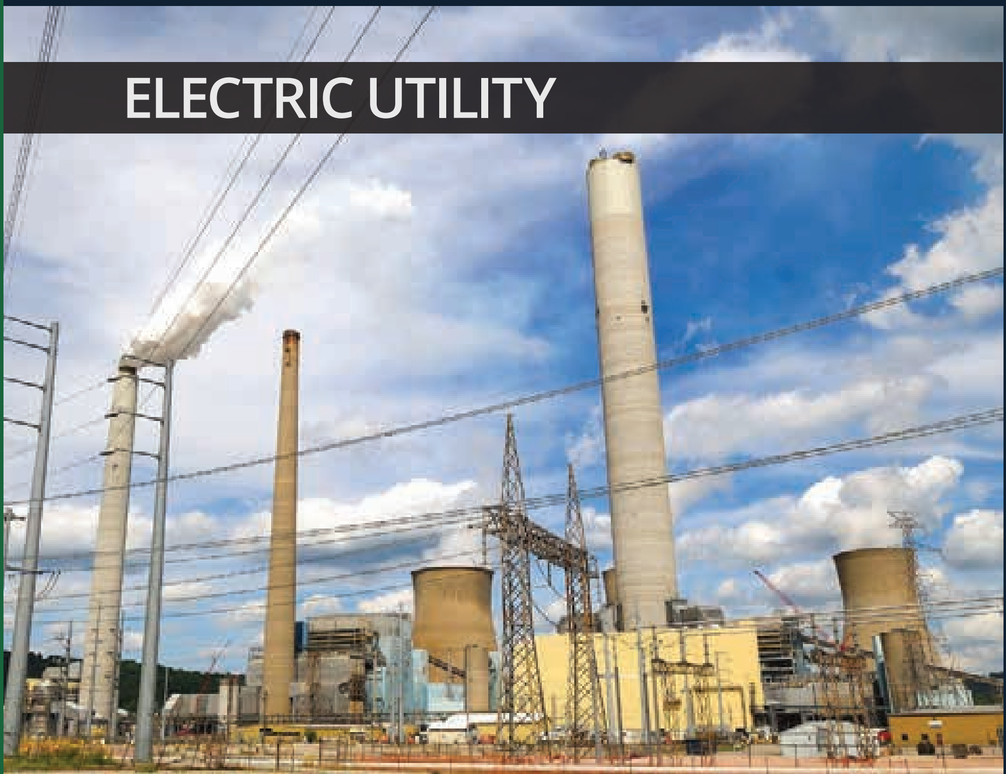


Cement Plant

PETROLEUM AND NATURAL GAS

Refinery

ELECTRIC UTILITY



Coal-Fired Power Plant

AGRICULTURE-RELATED PROCESSING

Ethanol Plant

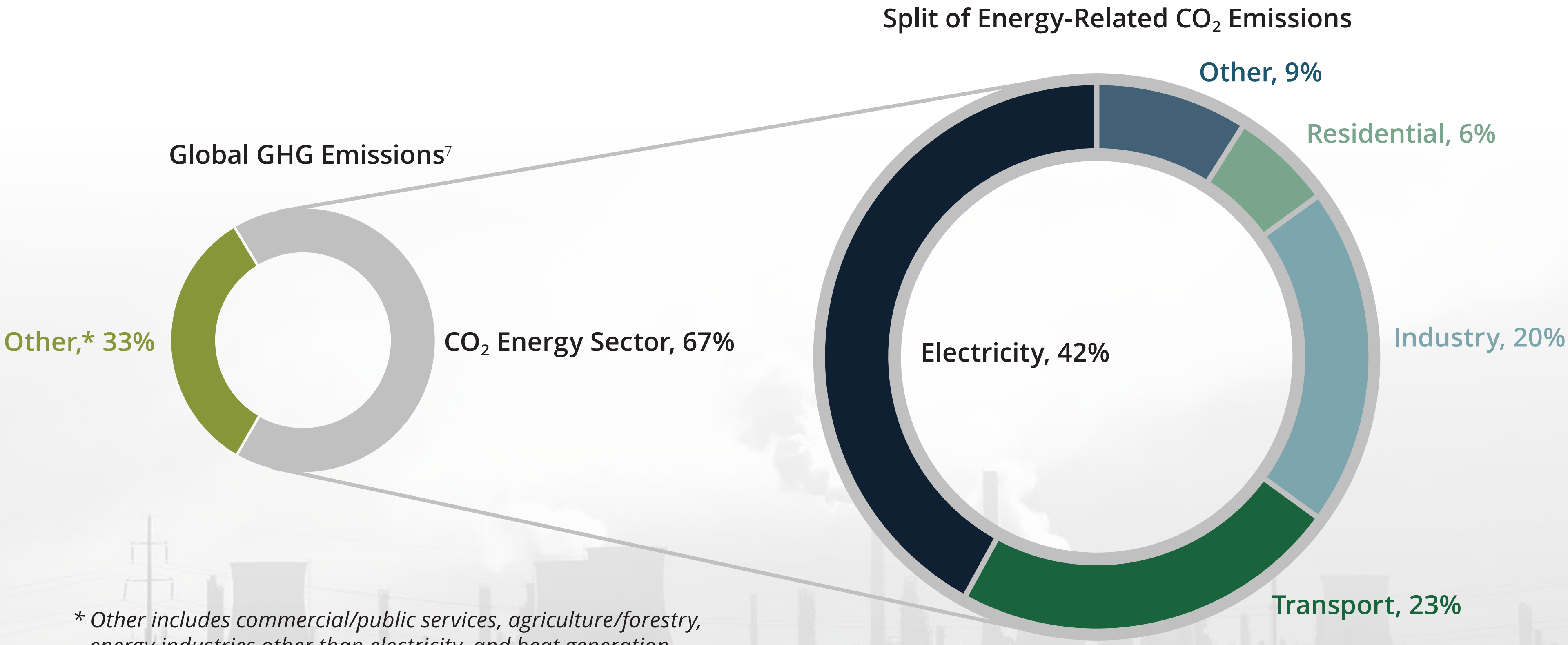
Carbon dioxide formed through human action is referred to as anthropogenic CO_2. The primary source of anthropogenic CO_2 emissions in North America is the burning of fossil fuels for energy. Industrial activities such as manufacturing cement, producing ethanol, refining petroleum, producing metals, 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 are also considered a significant source of anthropogenic CO_2. This includes practices like plowing land, which releases some of the exposed carbon in the soil to the atmosphere as CO_2, and deforestation, which causes a loss of plant biomass.

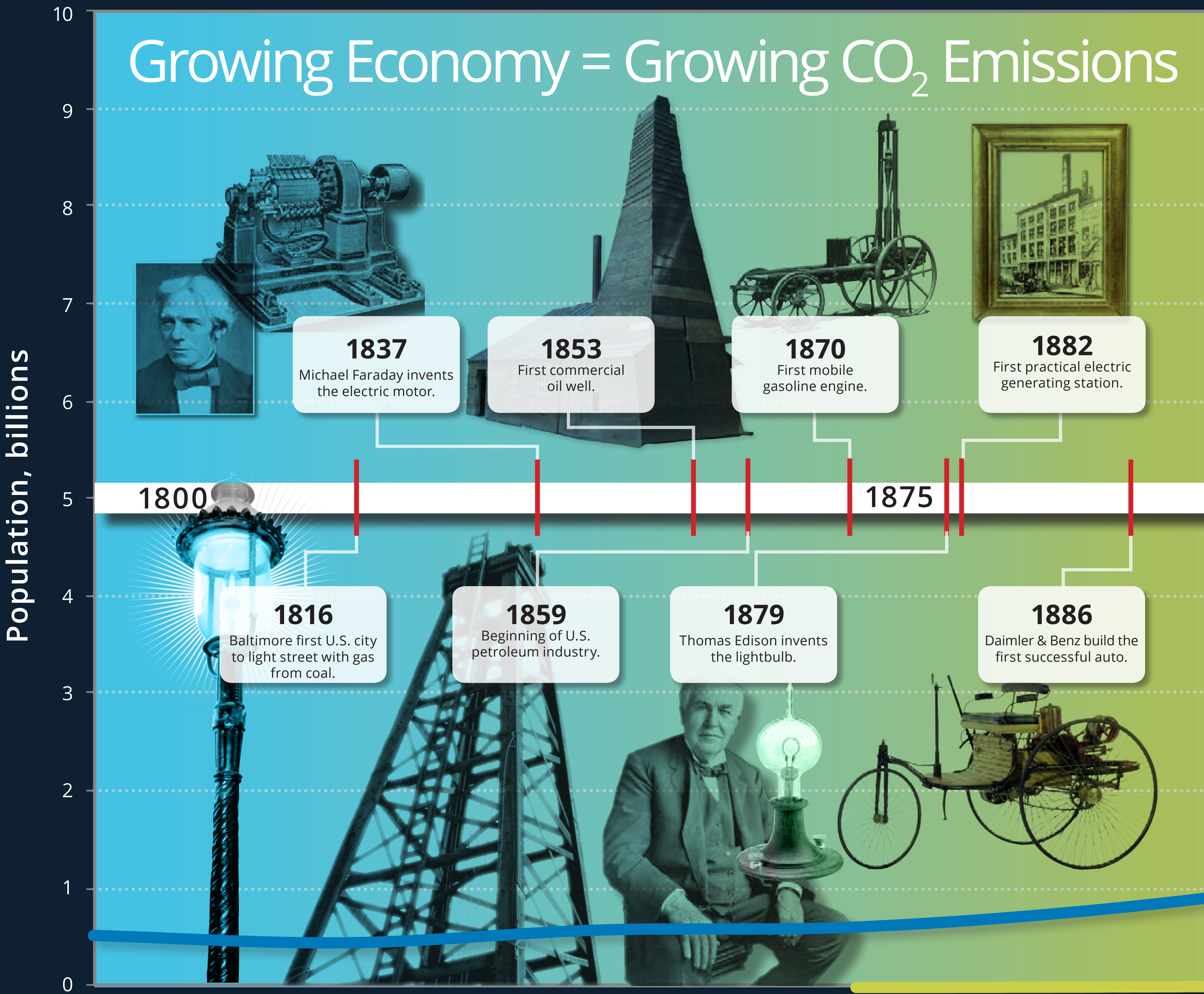
What Is CO_2?

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 CO_2 gas in a process called sublimation. With enough added pressure, liquid CO_2 can be formed.

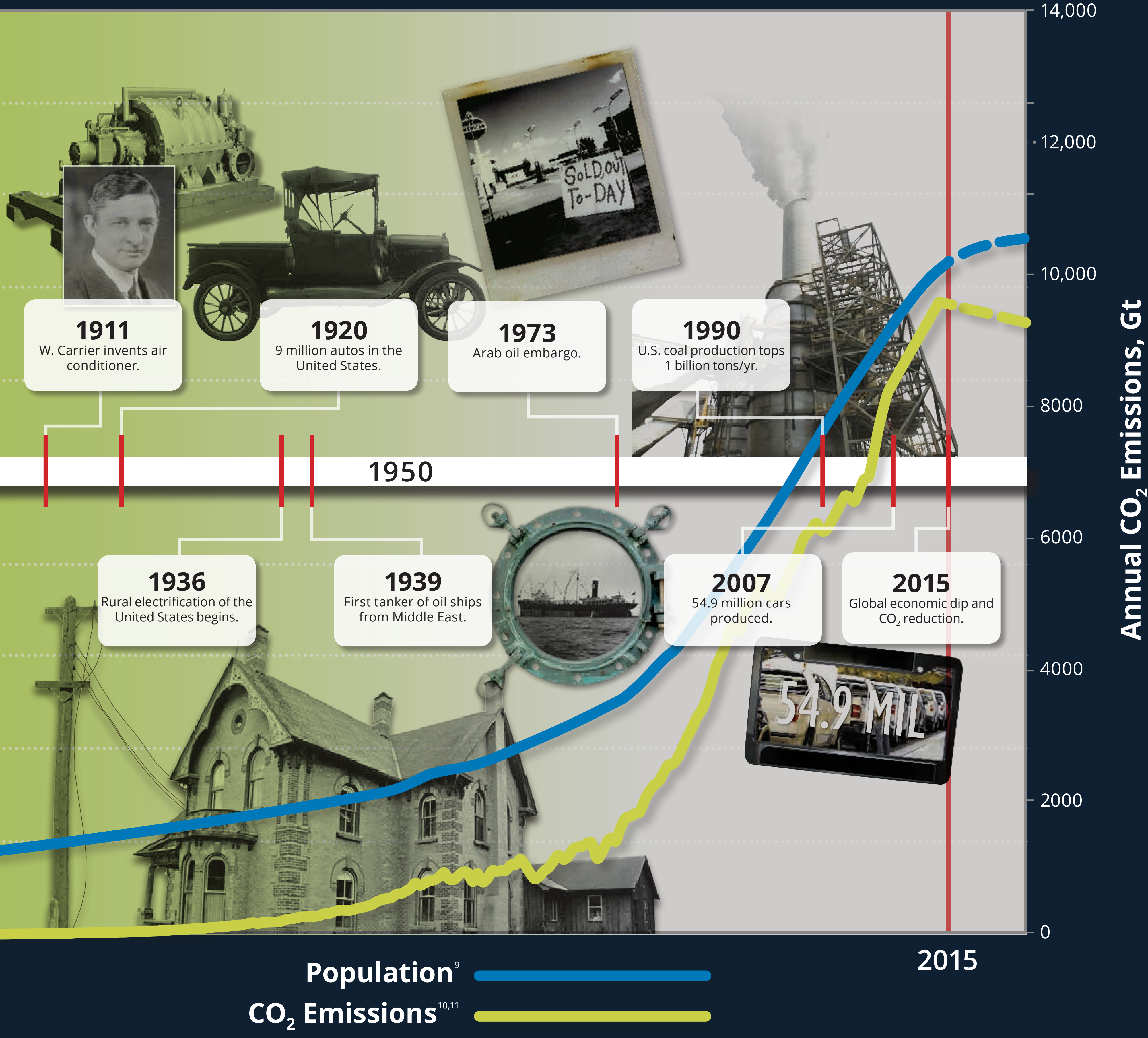
CO_2 has a number of industrial uses: in fire extinguishers (CO_2 displaces the oxygen the fire needs to burn), as a propellant in spray cans, in treatment of drinking water, for cold storage (CO_2 as dry ice), and to make bubbles in soft drinks. However, by far the largest use is in oil fields to enhance oil recovery.



** Other includes commercial/public services, agriculture/forestry, energy industries other than electricity, and heat generation.*



The amount of CO_2 in the atmosphere was relatively constant for 10,000 years until the Industrial Revolution in the 1800s, and the amount of anthropogenic CO_2 is projected to increase considerably. Currently, the world's economies annually emit approximately 29 Gt of CO_2 to the atmosphere from the combustion of fossil fuels to produce electricity. Increasing global populations, higher standards of living, and increased demand for energy could result in as much as 9000 Gt of cumulative CO_2 being emitted to the atmosphere.[8]



14,000
12,000
10,000
8000
6000
4000
2000
0
Annual CO_2 Emissions, Gt
1911
W. Carrier invents air conditioner.
1920
9 million autos in the United States.
1973
Arab oil embargo.
SOLD OUT TO-DAY
1990
U.S. coal production tops 1 billion tons/yr.
1950
1936
Rural electrification of the United States begins.
1939
First tanker of oil ships from Middle East.
2007
54.9 million cars produced.
54.9 MIL
2015
Global economic dip and CO_2 reduction.
2015
Population[9]
CO_2 Emissions[10,11]

Household Carbon Footprints

As we go about our daily lives, we all expend energy—working, eating, and sheltering our families and for transportation and play.

Households in the postindustrial world enjoy a quality of life never known before. Our everyday environment is packed with energy at our fingertips. Because most of our energy comes from fossil fuels, our lifestyle currently comes with a hefty price tag—a large carbon footprint.

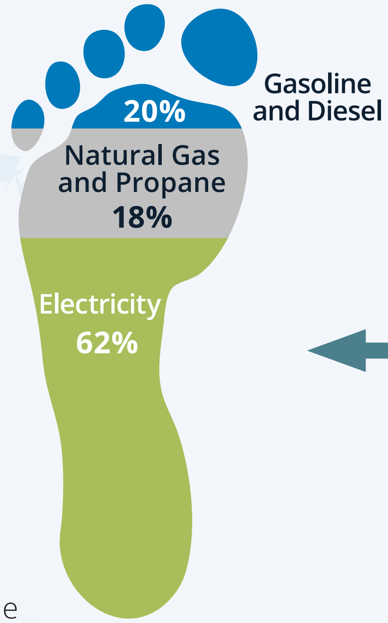
But fewer than one in five people on Earth live in the postindustrial world. Two in five live in rapidly emerging economies (2.3 billion people in China and India), and even more live in developing economies (over 3 billion people). Their household energy use is smaller than ours, and their carbon footprints are smaller too. However, they are moving toward a modern lifestyle, and as these countries adopt and develop new technologies, they will use more and more energy.

In 1930, the countries that now have the postindustrial economies generated nearly all carbon emissions from fossil fuels. Since then, global emissions have grown seven times greater. Now, postindustrial economies generate half.[12] By 2030, global emissions are projected to grow by half again; most of that increase will come from modernization in the emerging and developing economies.

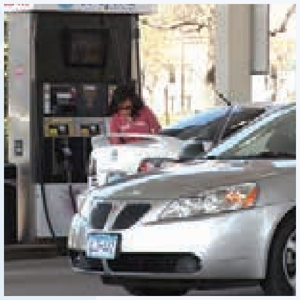
If the world continues to rely on fossil fuels, the share of carbon emissions from rapidly emerging and developing economies will surpass those of the postindustrial world as more and more of the world's economies move toward maturity.

How will we support modern lifestyles globally as we address climate change?

Postindustrial Economy: **United States**[13]



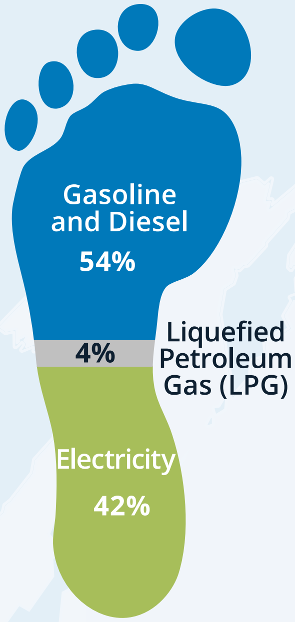
A middle class U.S. family uses fossil fuels for transportation, heating, and cooking, but most of their carbon footprint comes from the electricity they use (generated mainly from coal).

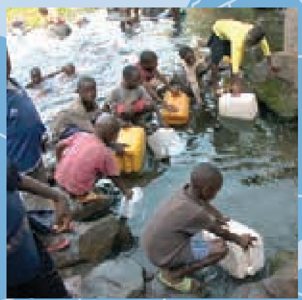


Typical carbon footprints from households in postindustrial, emerging, and developing economies.

Emerging Economy: India[13]

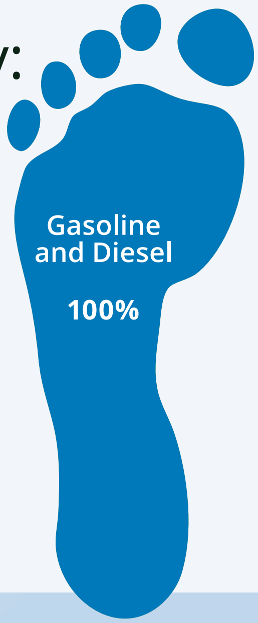
Middle class homes in India are smaller, have fewer appliances, and have no heating systems. About half of the carbon footprint for this family comes from their transportation. Most of the rest comes from the electricity they use (most made by fossil fuels).

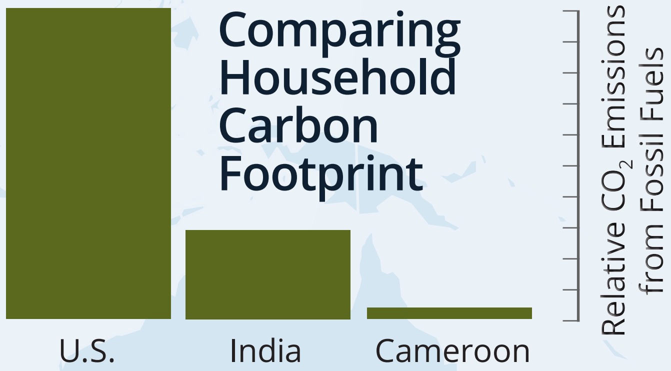




Developing Economy: Cameroon[13]

Most middle class families in Cameroon cook with wood (renewable sources of carbon, i.e., carbon-neutral) and have hydropower for electricity (mainly for lightbulbs and cell phone chargers). Their entire carbon footprint comes from occasional transportation by motorbike, car, and truck.





Household comparison: Households in the postindustrial economies like the United States have easy access to affordable energy. As energy becomes available to households in emerging and developing economies, their carbon footprints will grow too.

World CO_2 Emissions

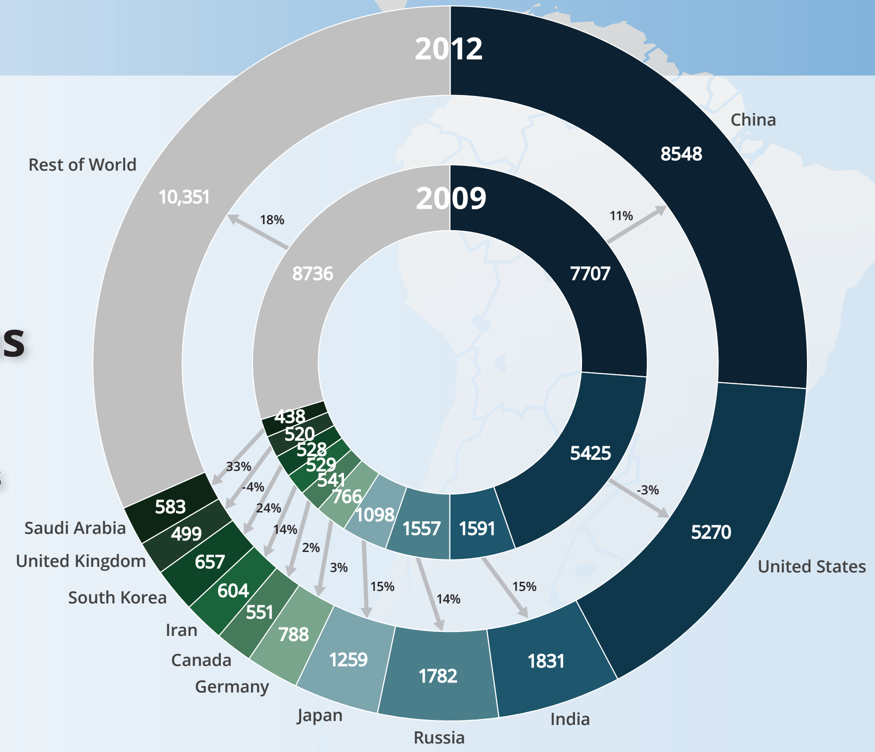
Global carbon emissions from fossil fuels have significantly increased the amount of GHG from anthropogenic sources emitted to the atmosphere. Since 1970, CO_2 emissions have increased 90%, with emissions from fossil fuel combustion and industrial processes contributing more than 75% of the total emissions.[14] To reduce the growing impact of GHG emissions on climate change, policies and regulations have been developed on a national and global level.

All member countries of the United Nations Framework Convention on Climate Change (UNFCCC) agreed to adopt a new global climate agreement in Paris as of December 2015, to take effect in 2020.[15] This agreement aims to limit the rise in global average surface temperature to below 2°C compared to preindustrial times to avoid the most dangerous impacts of climate change.

The illustration shows the percentage of change from 2009 to 2012 in global CO_2 emissions by country, highlighting the top 11 contributors. Although all countries in the top 11 are members of UNFCCC, all but two (the United States and the United Kingdom) have increased their CO_2 emissions, with the most notable increase of 33% coming from Saudi Arabia.

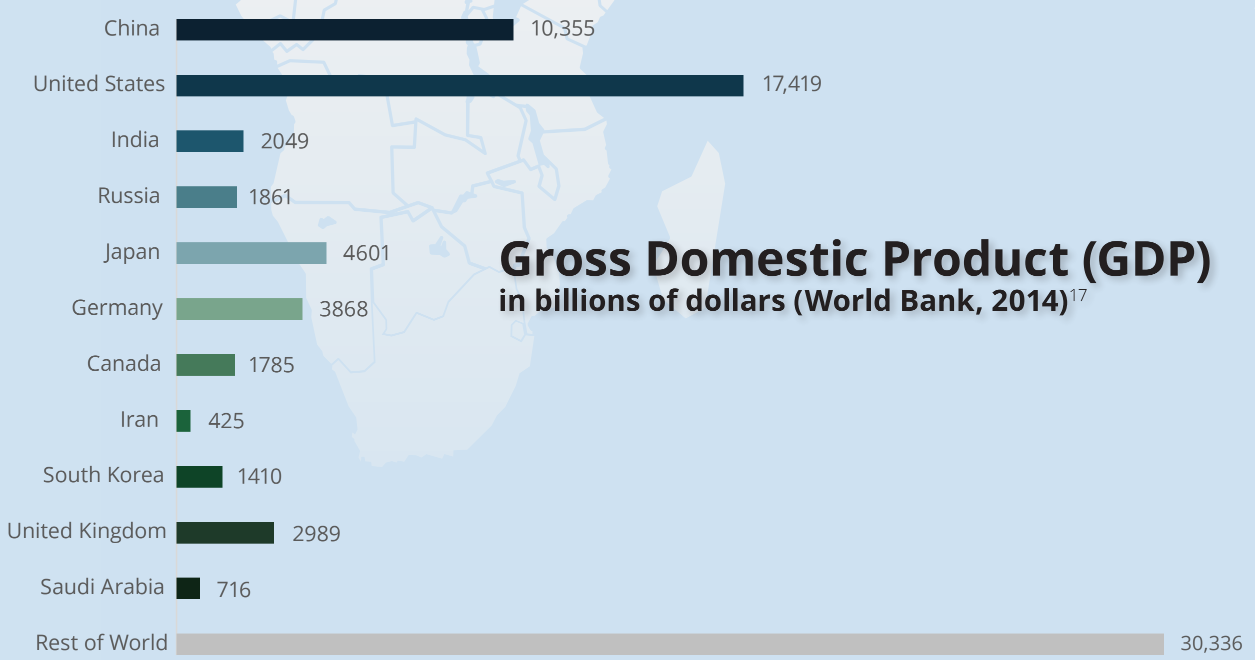
China is the largest emitter of GHG in the world, with fossil fuel burning and cement production the top contributors. The magnitude and growing annual rate of growth of China's carbon emissions make this country a major contributor to global carbon emissions and thus a priority nation for efforts in emission mitigation.[16]

CO_2 Emissions from the Consumption of Energy in million tonnes (IPCC, 2014)[14]



The percentage change of CO_2 emissions from 2009 to 2012.

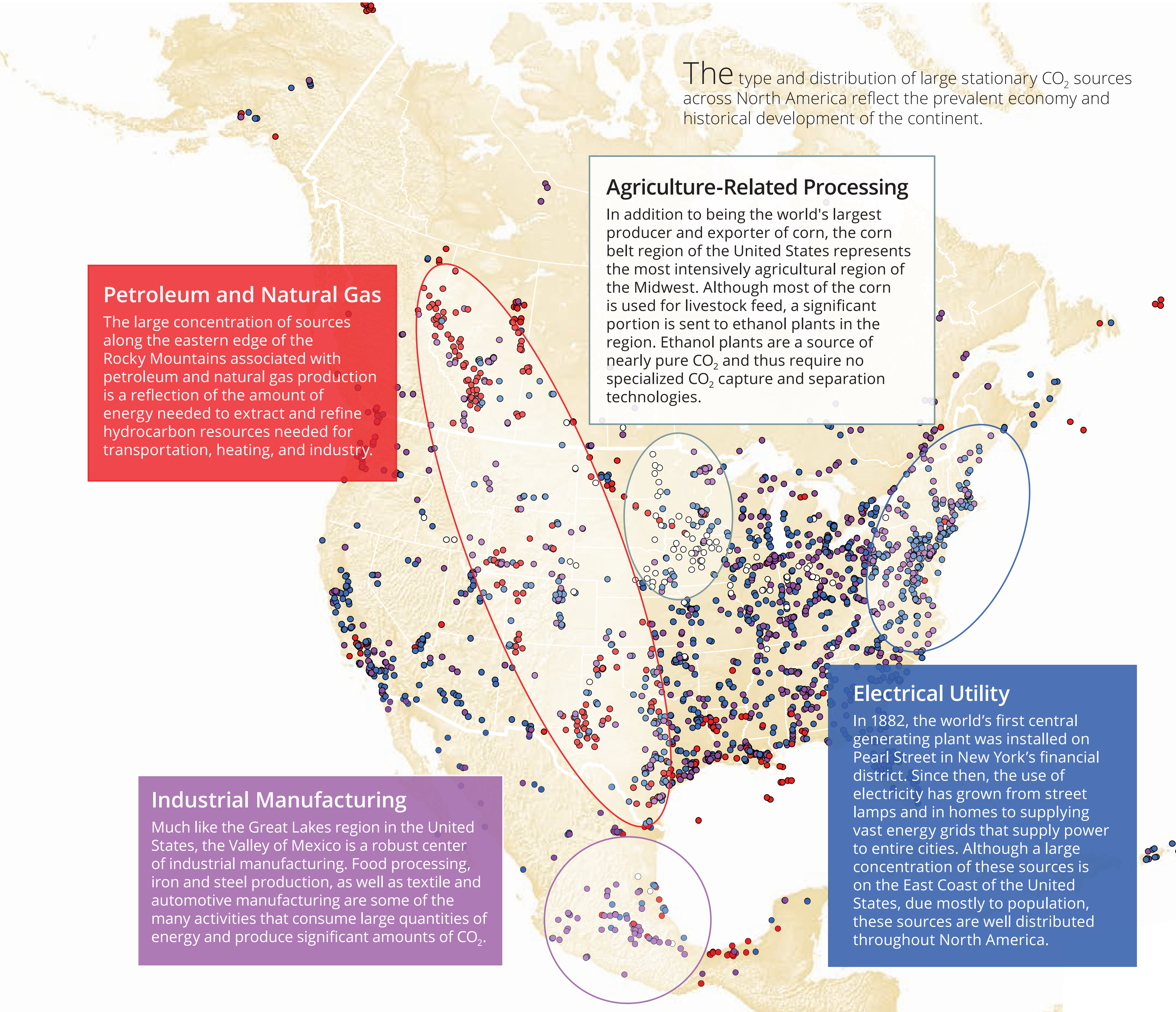
Gross Domestic Product (GDP)
in billions of dollars (World Bank, 2014)[17]



North American CO_2 Sources

North American Profile

The type and distribution of large stationary CO_2 sources across North America reflect the prevalent economy and historical development of the continent.



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 most intensively agricultural region of the Midwest. 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 is a reflection of 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 street lamps and in 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, due mostly to population, these sources are well distributed throughout North America.

Industrial Manufacturing

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

Potential Impacts of Climate Change

No one knows the exact consequences of this upsurge of CO_2 in the atmosphere, but climate-related changes have already been observed globally. Climate change is expected to impact human health, natural systems, and the environment at large. Potential consequences include:[19]

- Warming air and water.
- Change in the location and amount of precipitation.
- Increased storm intensity.
- Sea level rise.
- Reduced snow cover, glaciers, permafrost, and sea ice.
- Changes in ocean characteristics.

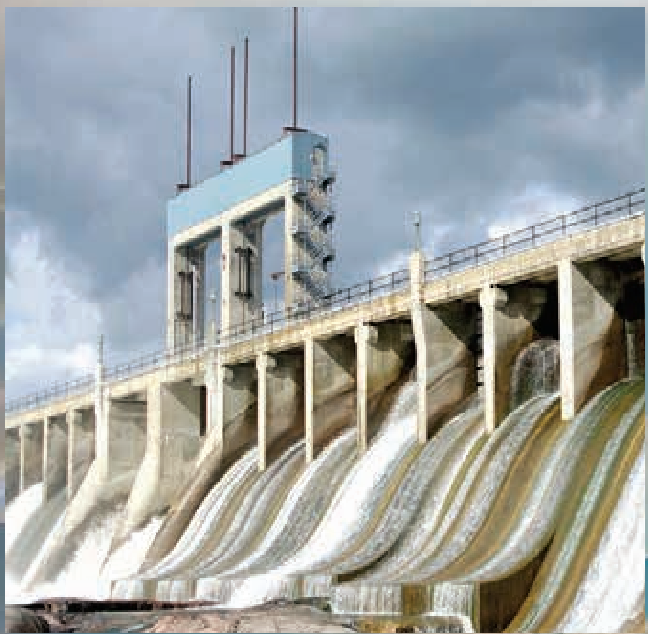
"Predictions are hard to make, especially about the future."

– Yogi Berra

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 energy conservation, 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, CCS provides an opportunity to combine the continued use of fossil fuels with a significant reduction in GHG emissions. CCS 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 CCS is developed and implemented in a practical and environmentally sound manner.

CCS can achieve 14% of the global GHG emission reductions needed by 2050 to limit global warming to 2°C (IEA [International Energy Agency]).[20]




CO_2
CO_2

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. Terrestrial storage techniques can be used to better manage the CO_2 naturally stored on Earth's surface, but one of the most promising approaches involves capturing CO_2 from the exhaust gas at large stationary sources and placing the CO_2 underground into permanent storage. This option is referred to as CCS 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 CCS.

Terrestrial Carbon Storage

Terrestrial storage is a relatively passive mechanism of CO_2 storage that occurs at Earth's surface through management practices that increase the amount of carbon stored in roots and organic matter in the soil. It can be done by 1) protecting ecosystems that store carbon in order to maintain or increase their carbon stores or 2) managing soils and plants to increase carbon storage beyond the current conditions through natural processes such as photosynthesis.

It is important to remember that terrestrial storage does not store CO_2 as a gas but stores the carbon portion of the CO_2. If the soil is disturbed and the soil carbon comes in contact with oxygen in the air, the exposed soil carbon can combine with O_2 to form CO_2 gas and reenter the atmosphere.

Steady State

Soil can only take in and store a limited amount of carbon. On average, after a 50- to 100-year time frame, the soils will have reached equilibrium and not accept any more carbon. Once this "steady state" has been reached, the carbon will remain stored in the soil as long as the land is undisturbed and conservation land management practices are continued.

Benefits

Terrestrial storage is important because it can be implemented immediately and can begin to reduce atmospheric CO_2 levels in several years. Using terrestrial storage now means we can get started on reducing CO_2 levels in the atmosphere while we adopt other carbon control measures. Terrestrial storage also has other benefits to the ecosystem, including biodiversity, water filtration, increased soil health and fertility, and many others.

Mechanisms for Terrestrial Storage

Benefits of terrestrial storage may include improved soil and water quality, reduced erosion, reduced evaporative water loss, reduced pest problems, and overall ecosystem improvement. Promising land and water management practices that can enhance the terrestrial storage of carbon include the following:

- Conservation tillage
- Reducing soil erosion and minimizing soil disturbance
- Using buffer strips along waterways
- Enrolling land in conservation programs
- Restoring and better managing wetlands and degraded soils
- Eliminating summer fallow
- Using perennial grasses and winter cover crops
- Fostering an increase in forests

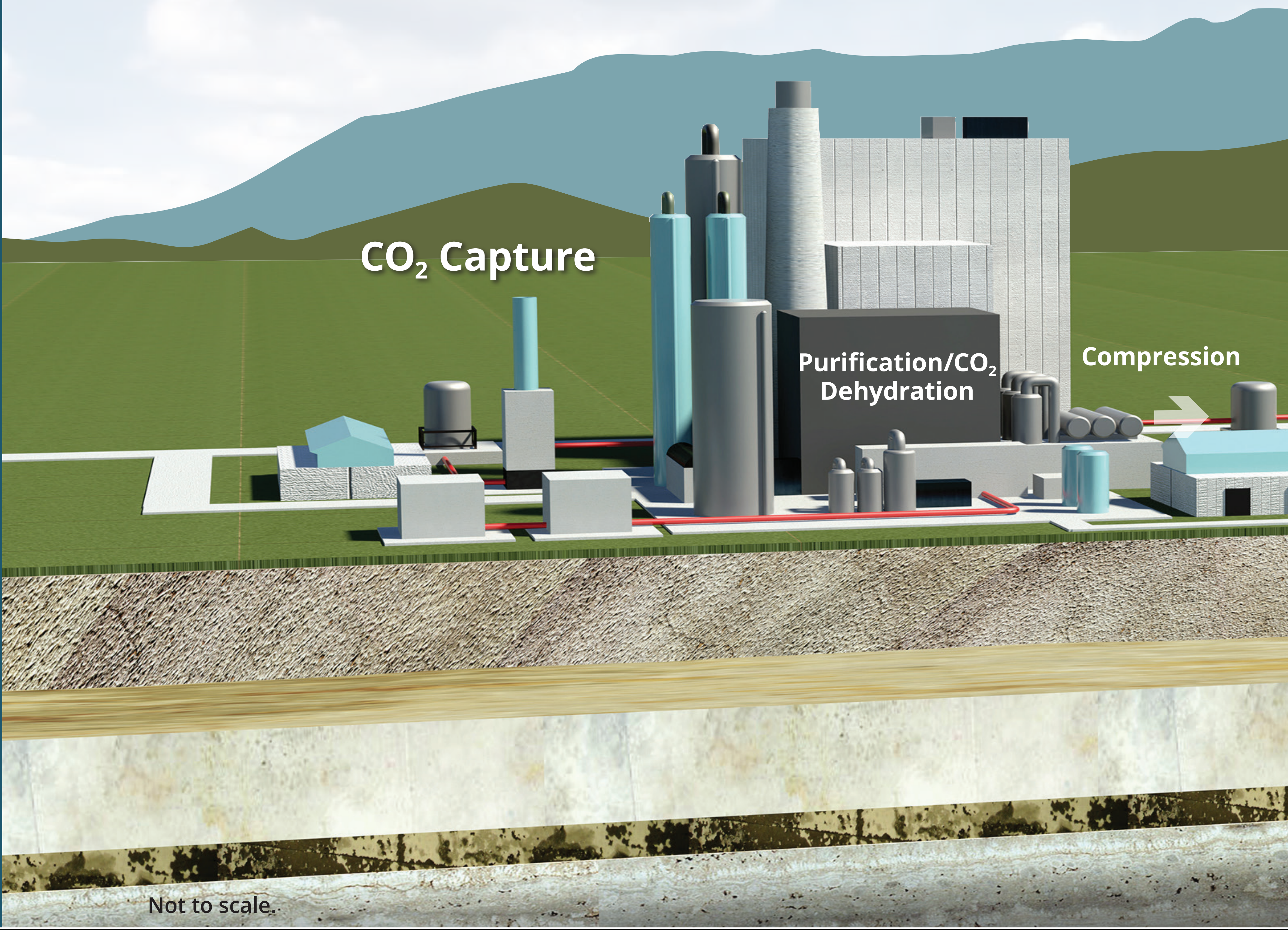
Terrestrial carbon storage is a near-term approach to reducing GHGs.

Image provided by U.S. Forest Service

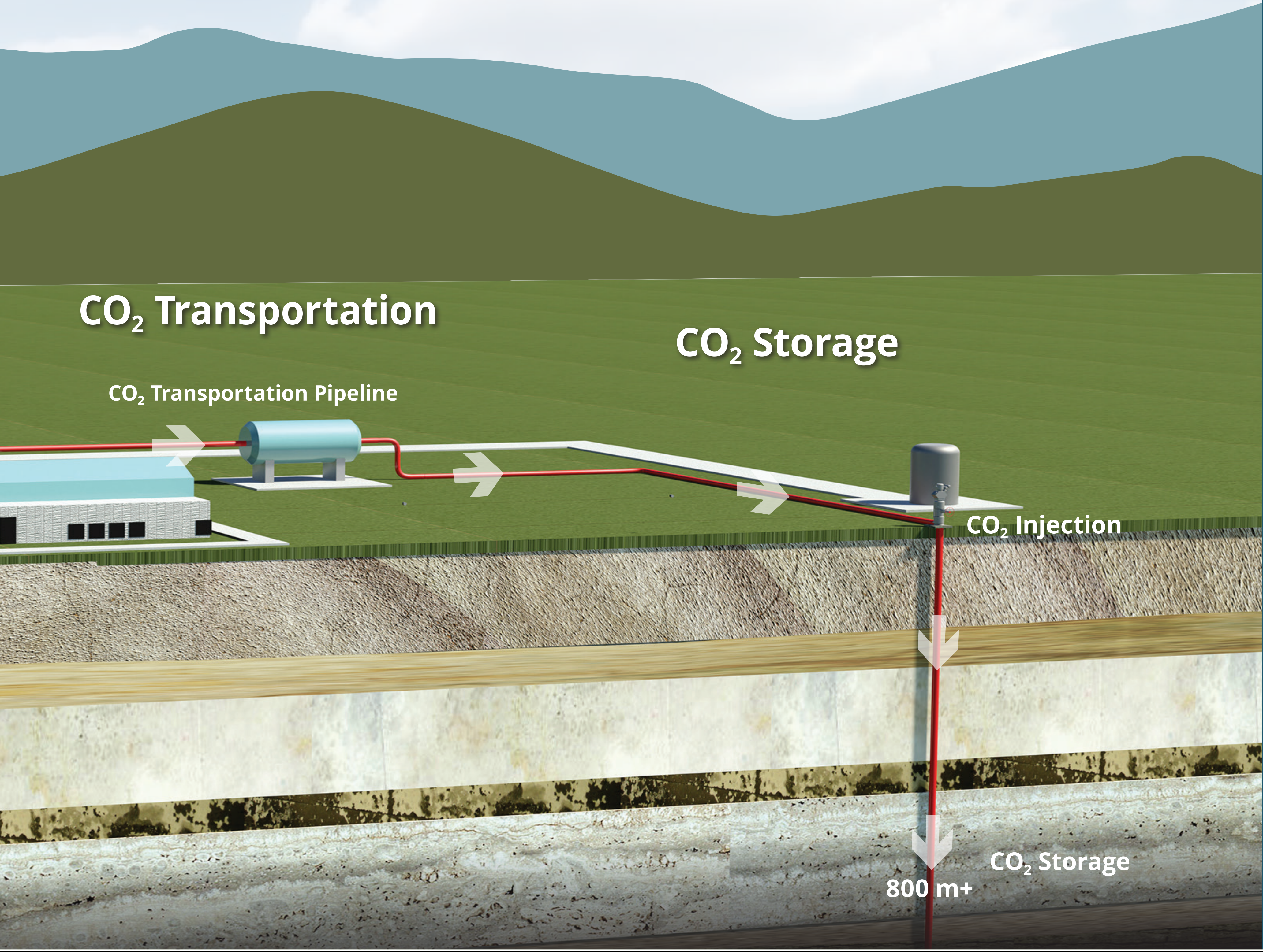
Image provided by Minnesota Pollution Control Agency

Carbon Capture 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 geologic storage, is termed CCS and includes a set of technologies that can greatly reduce CO_2 emission from large point sources such as coal- and gas-fired power plants, natural gas-processing facilities, ethanol plants, and other industrial processes.



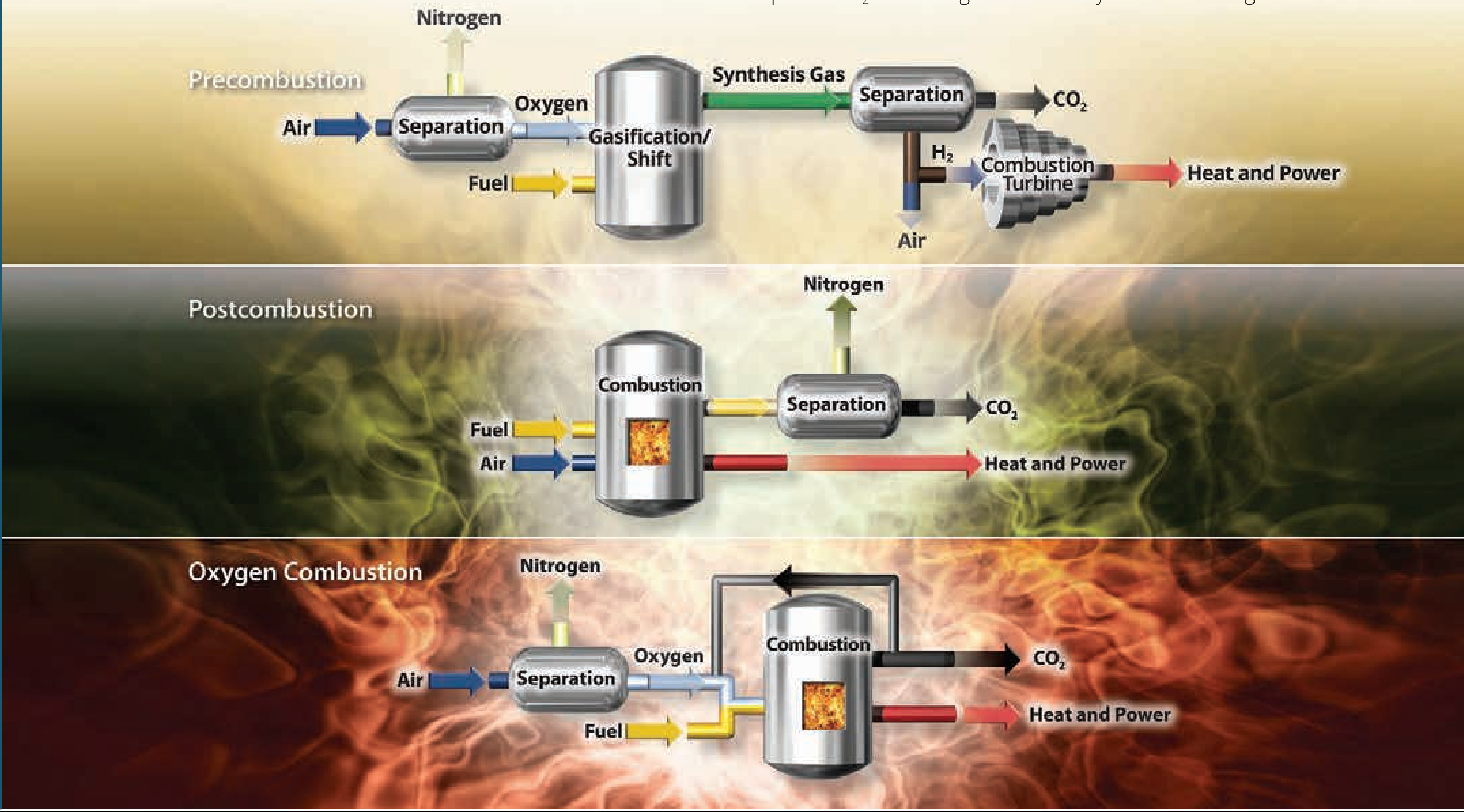
CCS involves the capture of CO_2 by separation from other gases, compression to a liquid or dense fluid state, and transport to an appropriate location for geologic storage. Injection into deep geologic formations ensures permanent storage, isolating CO_2 from the atmosphere.



CO_2 Capture from Combustion and 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,[21] meaning that the atmosphere in the boiler is not pure oxygen but rather a mixture consisting primarily of oxygen and CO_2. The majority of 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 so low (ranging from 3% by volume for some natural gas-fired plants to about 13% by volume for coal-fired plants),[22] 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 make it relatively expensive. In fact, the cost of capturing the CO_2 can represent three-fourths of the total cost of a CCS operation.[22] Because capture is the most costly portion of a CCS 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 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.



CO_2 and Compression

Captured CO_2 must be dehydrated and compressed into a supercritical or liquidlike state for either storage before truck transport or piping to the storage site. CO_2 must be compressed to at least 1200 to 1500 pounds per square inch (psi) for transport in a pipeline to ensure that CO_2 remains in a dense liquid state. 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 appear to be the most likely mode for transporting the captured gas to geologic storage sites. Currently, more than 6000 km of CO_2 pipeline is in service in North America, with additional pipeline planned or under construction.[23]

Image provided by Denbury Resources Inc.

Pipelines are a proven technology and have been used to safely transport industrial quantities of CO_2 for over 30 years. CO_2 pipelines are similar in design and operation to natural gas pipelines, although the higher pressures needed for CO_2 transportation require construction using thicker-walled carbon steel pipe.

Building a regional CO_2 pipeline infrastructure for CCS 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 offer reduced overall costs, but common carrier issues such as those related to CO_2 stream quality may need to be addressed.

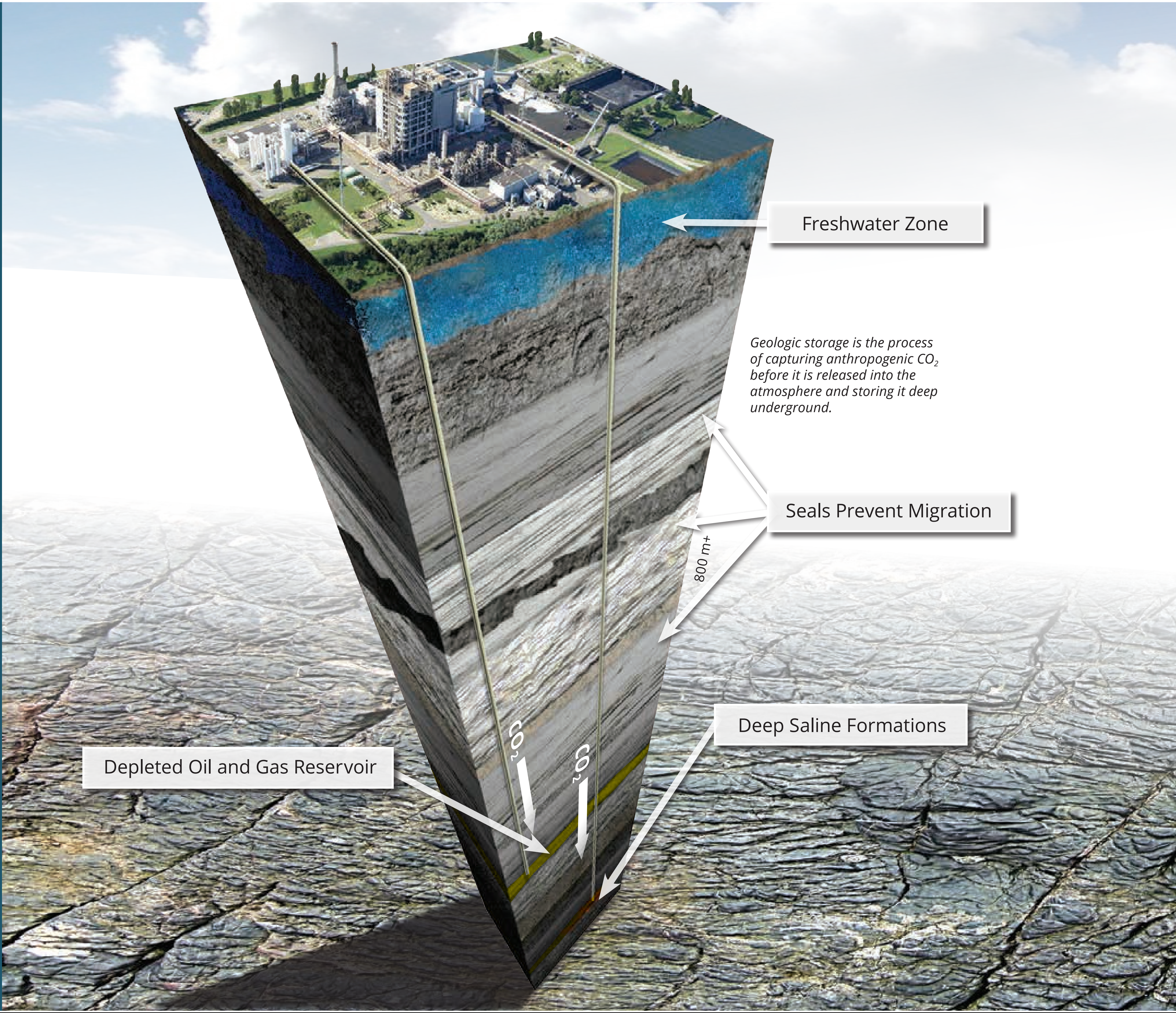
Pipelines carrying CO_2 have a superior safety record in comparison to natural gas or hazardous chemical pipelines. Strategies undertaken to manage risks include the inclusion of fracture arresters approximately every 300 m, block valves to isolate pipe sections if they leak, the use of advanced seals, and automatic control systems that monitor volumetric flow rates and pressure.

NO serious human injuries or fatalities have been reported as a result of CO_2 transport via pipeline.[24]


Image provided by Denbury Resources Inc.


Image provided by Denbury Resources Inc.

Secure Geologic Storage



Geologic storage is the process of capturing anthropogenic CO_2 before it is released into the atmosphere and storing it deep underground.

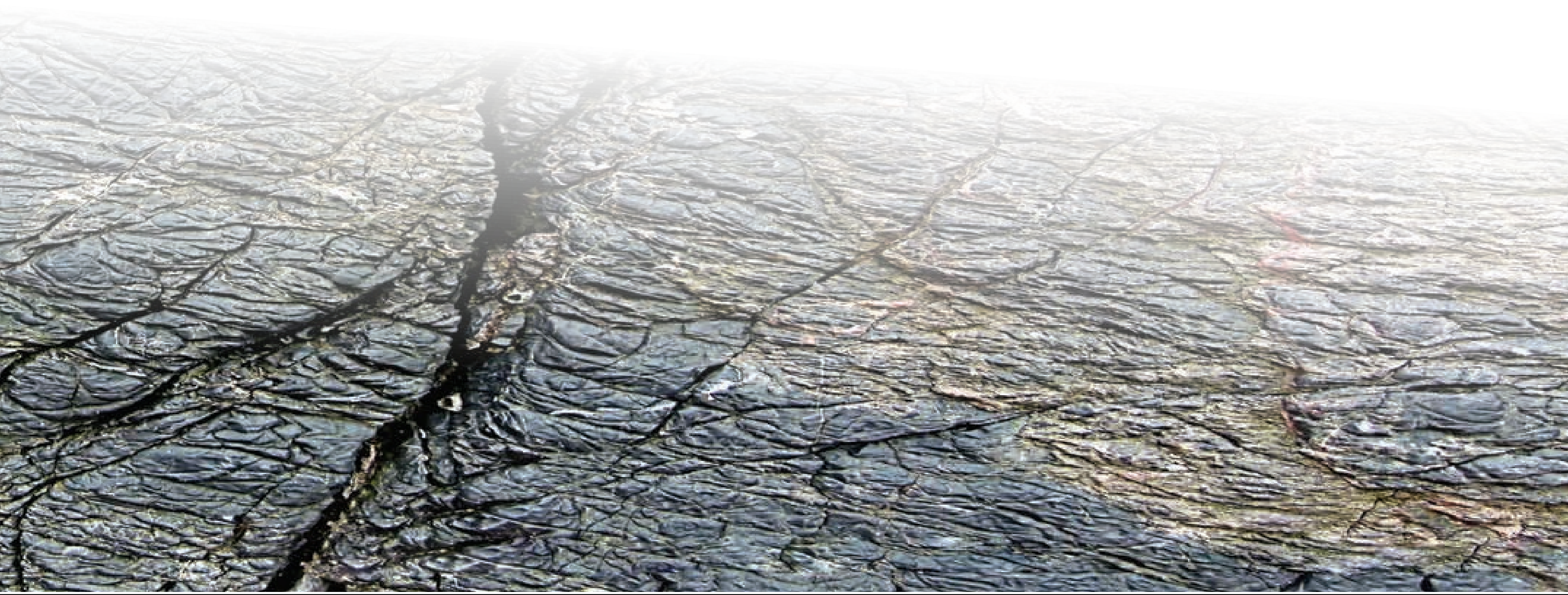
Geologic Storage Criteria

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

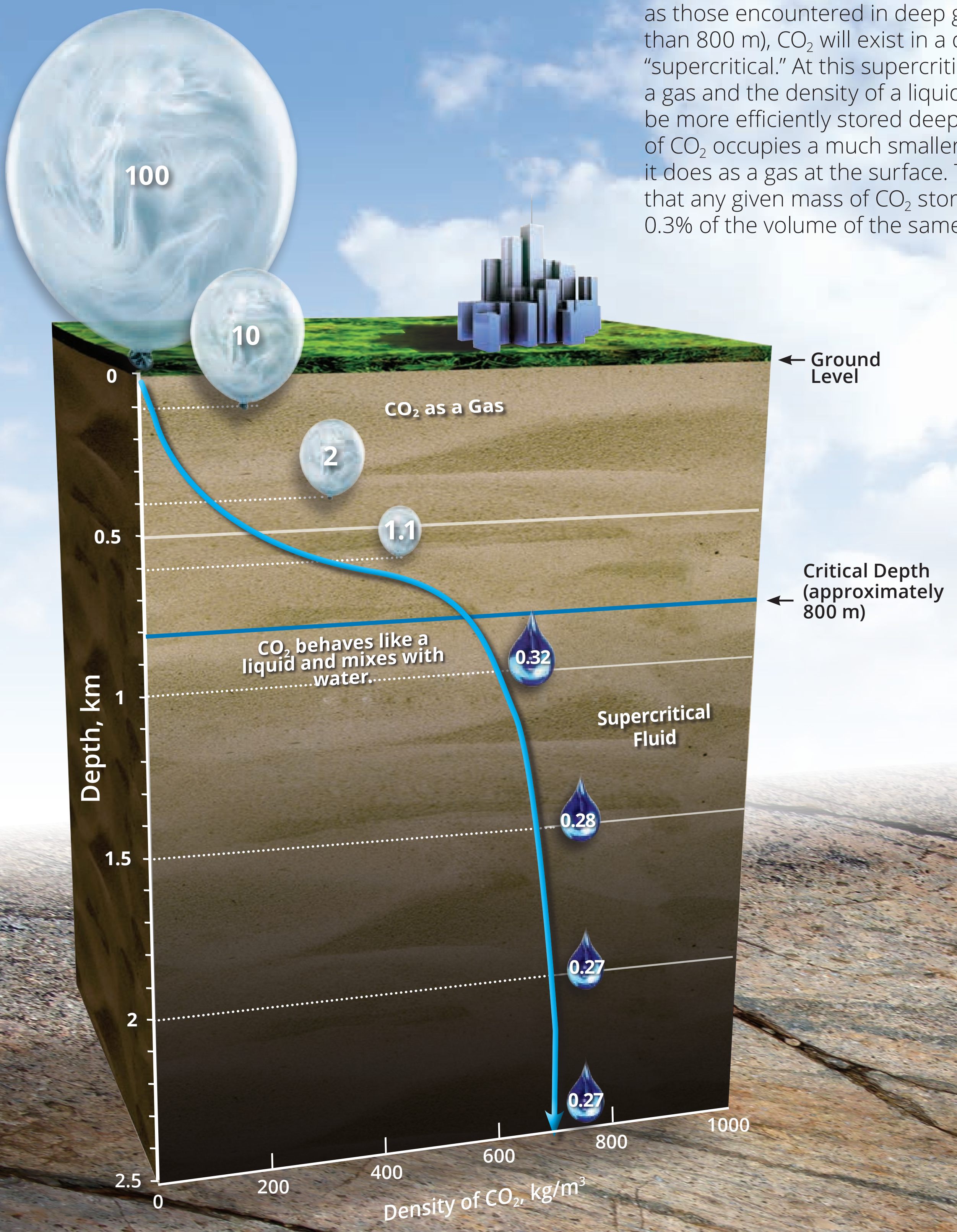
Site selection is central to the secure storage of CO_2 because successful geologic storage requires that CO_2 stay in place and not pose significant risk to human health and the environment. Storage reservoirs should:

- 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 (USDW, defined in the United States as water with salinity values less than 10,000 mg/L).



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 viscosity similar to a gas and the density of a liquid. These properties allow more CO_2 to be more 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. This liquidlike form of carbon dioxide has 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

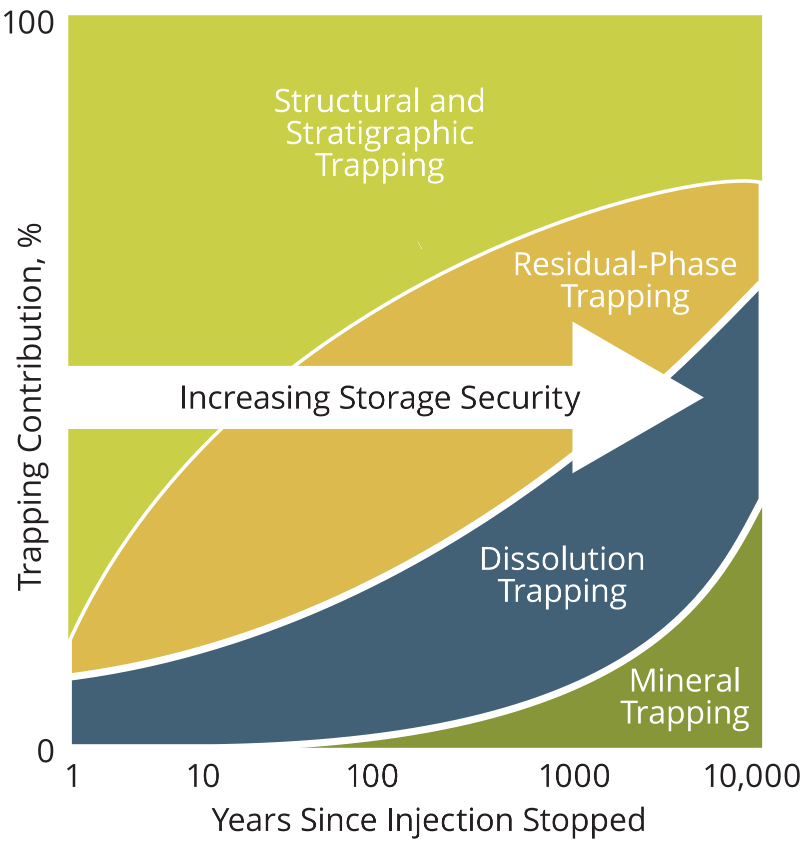
Several mechanisms function to trap and store CO_2 in deep geologic formations.[25]

Structural and Stratigraphic Trapping – Injected CO_2 is typically less dense than native pore fluids in deep geologic formations, most commonly brine. 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.

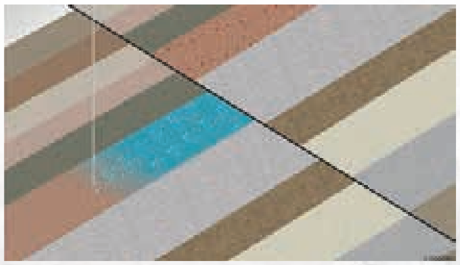
Residual-Phase Trapping – As injected CO_2 migrates through a reservoir, small droplets may become detached and remain trapped within the center of pore spaces, typically surrounded by brine. These residual droplets are effectively immobilized.

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.

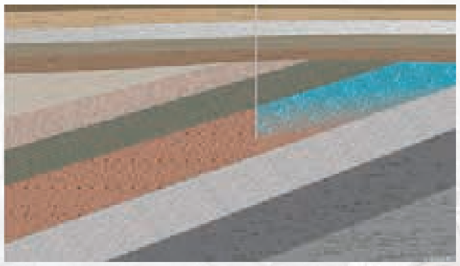
Mineral Trapping – The last stage of CO_2 trapping involves a chemical reaction between the dissolved CO_2 in the formation fluids and the minerals in the target formation and cap rock to form new solid minerals, thus effectively locking the CO_2 in place. Mineral trapping will typically occur over extended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



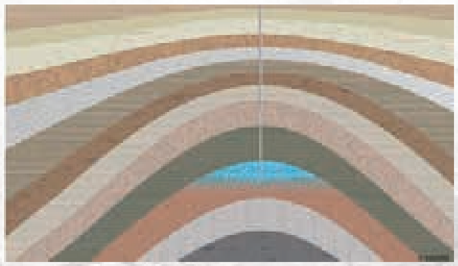
As time passes after the injection of CO_2 into a deep geologic environment, the effective trapping mechanism shifts. Storage security increases as the trapping mechanism moves from the physical process of structural and stratigraphic trapping toward geochemically based processes.



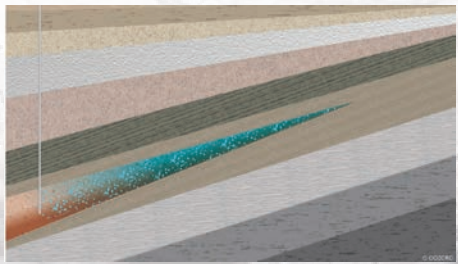
A sealing fault can line up an impervious rock layer with the formation to prevent the CO_2 from moving upward out of the formation.



The CO_2 is trapped when there is a sudden change in the rock formations, so that the CO_2 cannot move further 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 there is a change in the type of rock in the formation from a permeable rock to an impermeable rock.

Oil Fields of the United States and Canada

Distribution of Oil Fields[26]

Oil Fields

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 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

U.S. production from enhanced oil recovery (EOR) could increase to

over half a million barrels

of oil per day by 2020.[27]

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 a process called EOR can recover some of that remaining oil. It is estimated that U.S. production from EOR could increase to over half a million barrels of oil per day by 2020,[27] thereby reducing the need to import as much oil.

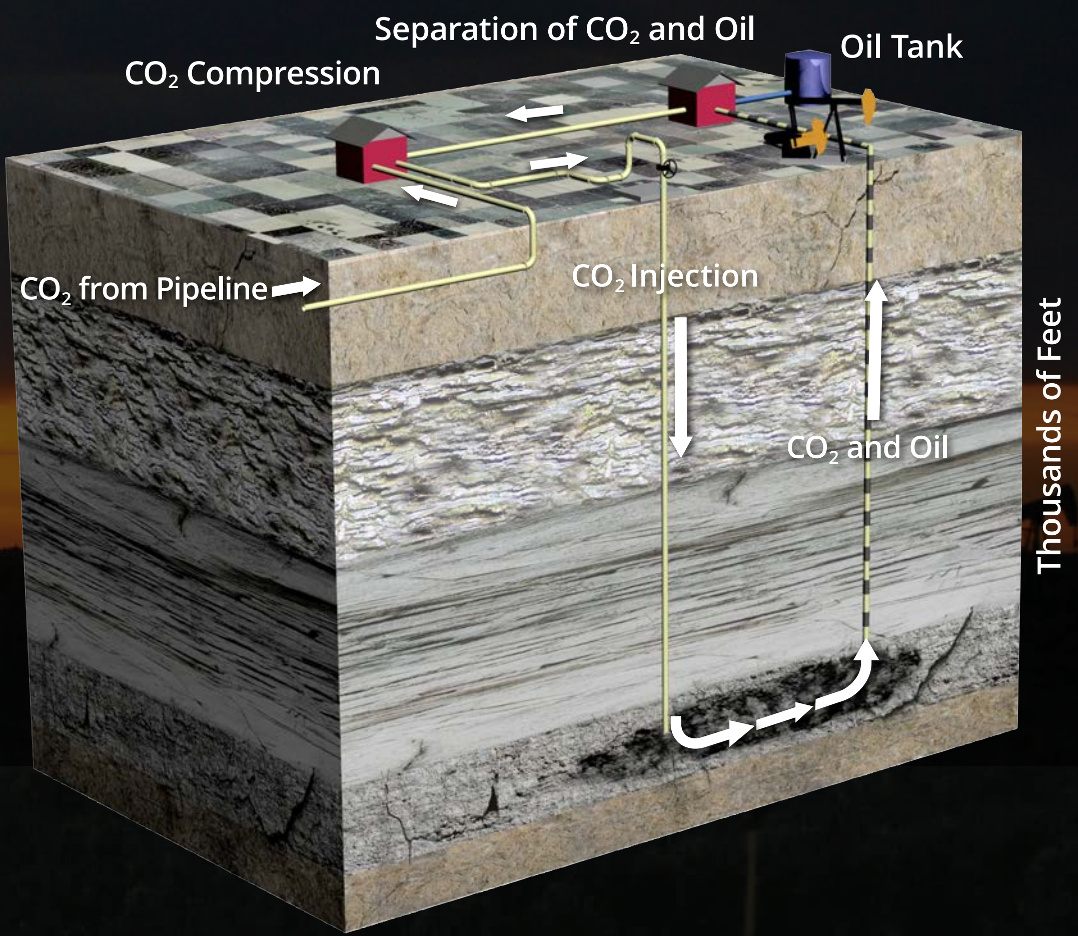
How EOR Works

When CO_2 comes into contact with oil, a significant portion dissolves into the oil, reducing oil viscosity and increasing its mobility. This, combined with the increased pressure, can result in increased oil production rates and an extension of the lifetime of the oil reservoir. However, 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 many millions of tons of CO_2 into oil fields for EOR purposes. The success of the technique has seen a steady increase in the number of fields (now over 100) employing CO_2 EOR in West Texas and other 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.

Economics of EOR

EOR is a proven, economically viable technology for CO_2 storage that can provide a bridge to future non-EOR-based geologic storage.

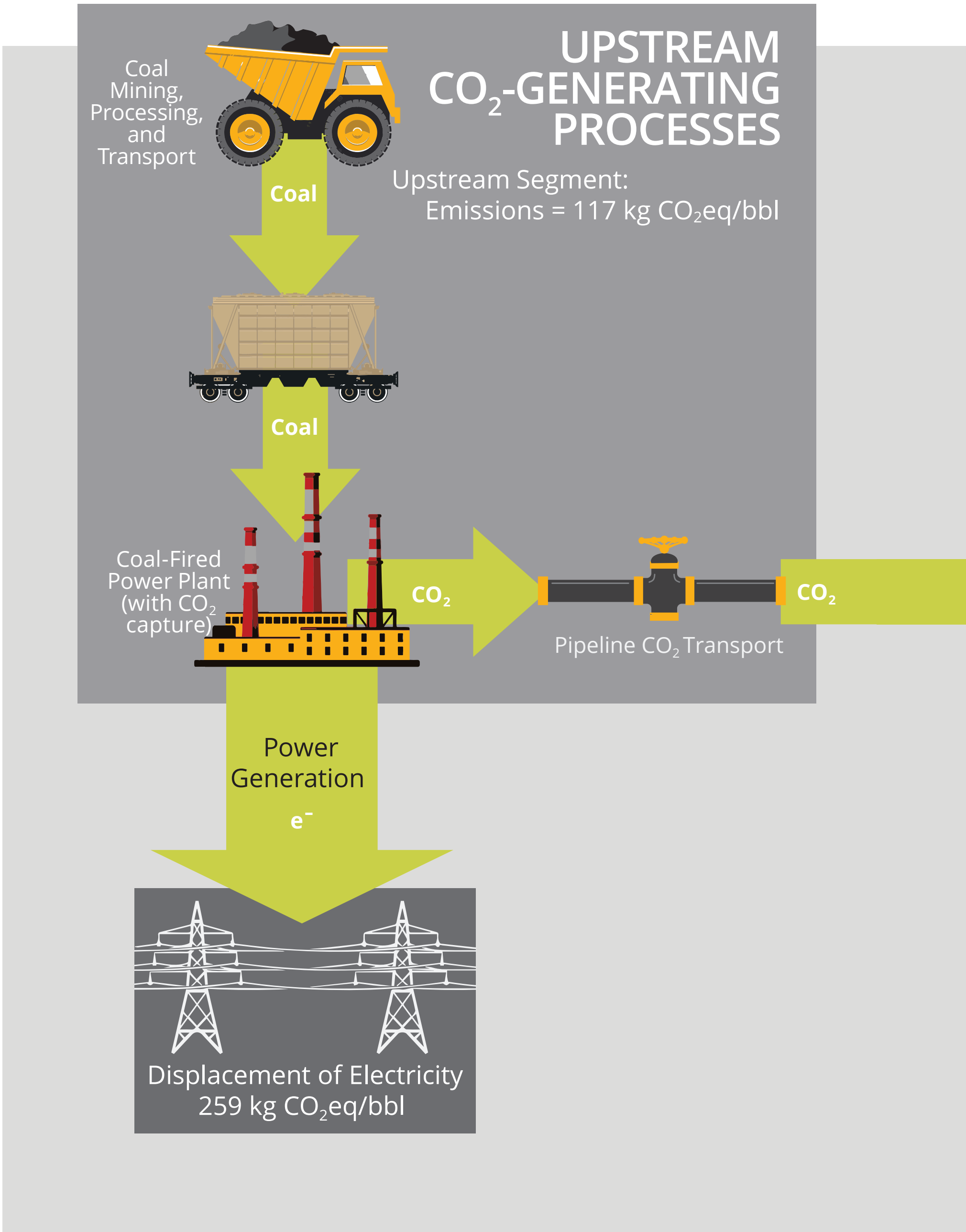


CO_2 EOR Life Cycle Analysis

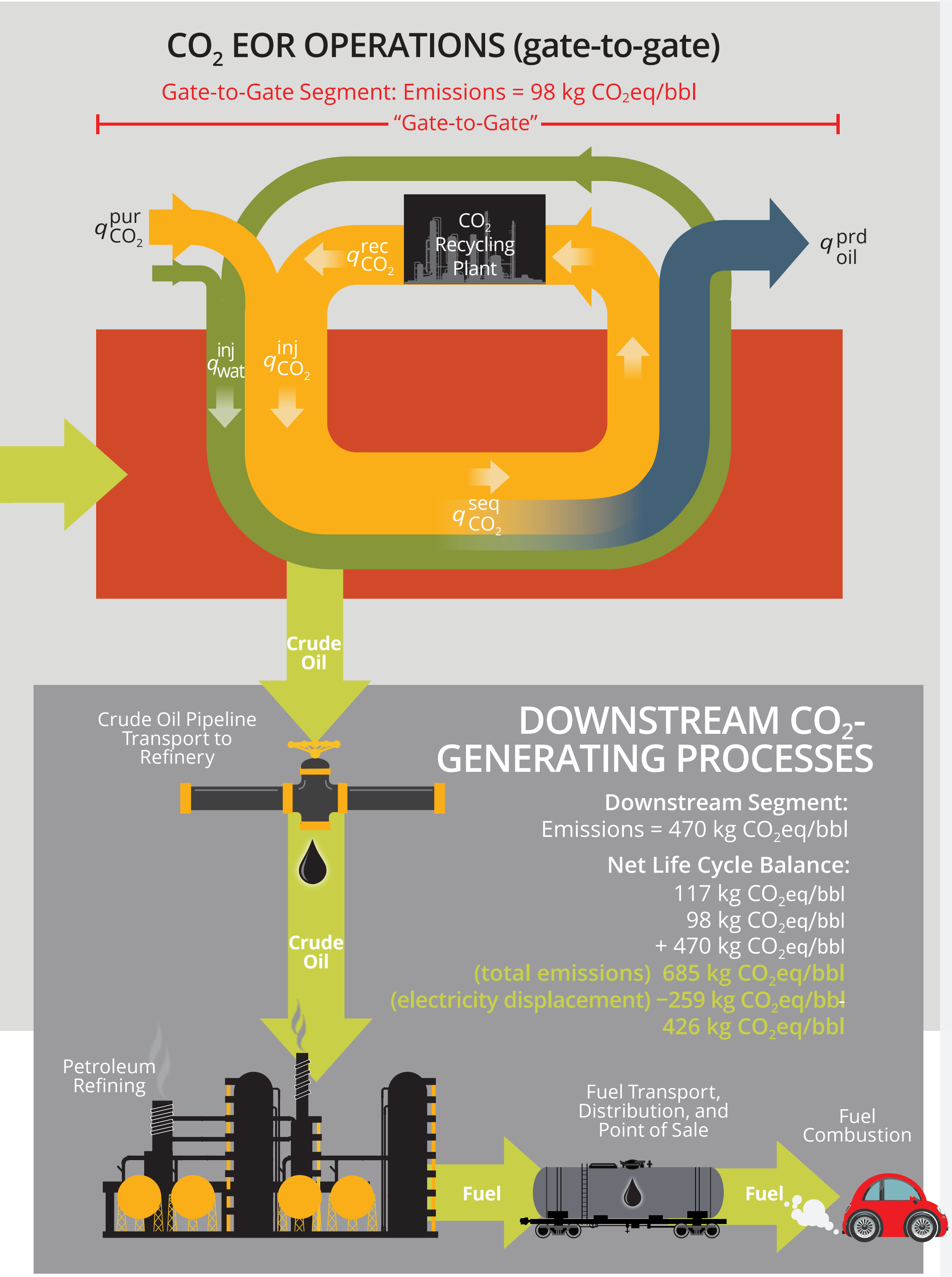
Life cycle analysis (LCA) is a useful way to account for CO_2 storage at an EOR site and to track CO_2 emissions at all stages of a CO_2 EOR project. The LCA results may then be used to evaluate the life cycle CO_2 emissions per barrel of oil produced via CO_2 EOR as compared to oil produced by other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

The Energy & Environmental Research Center (EERC) conducted a detailed LCA of CO_2 emissions associated with CO_2 EOR where the CO_2 is sourced from a coal-fired power plant.[28] The modeled system includes three segments: upstream, gate-to-gate, and downstream CO_2-generating processes. Upstream processes include 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 include 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 include crude oil transport, refining, fuel transport, and combustion. Total CO_2 emissions from upstream, gate-to-gate, and downstream segments are 685 kg CO_2eq/bbl.

However, since 85% or more of the required CO_2 is captured at the power plant, emissions associated with electricity generation are significantly reduced. This is termed displacement and would reduce the total emissions to LCA emissions of 426 kg CO_2eq/bbl for typical CO_2 EOR operations. Optimization of operations for storage could further reduce LCA emissions to 256 kg CO_2eq/bbl. The box graph shows this compares favorably to other sources of oil production.[29]

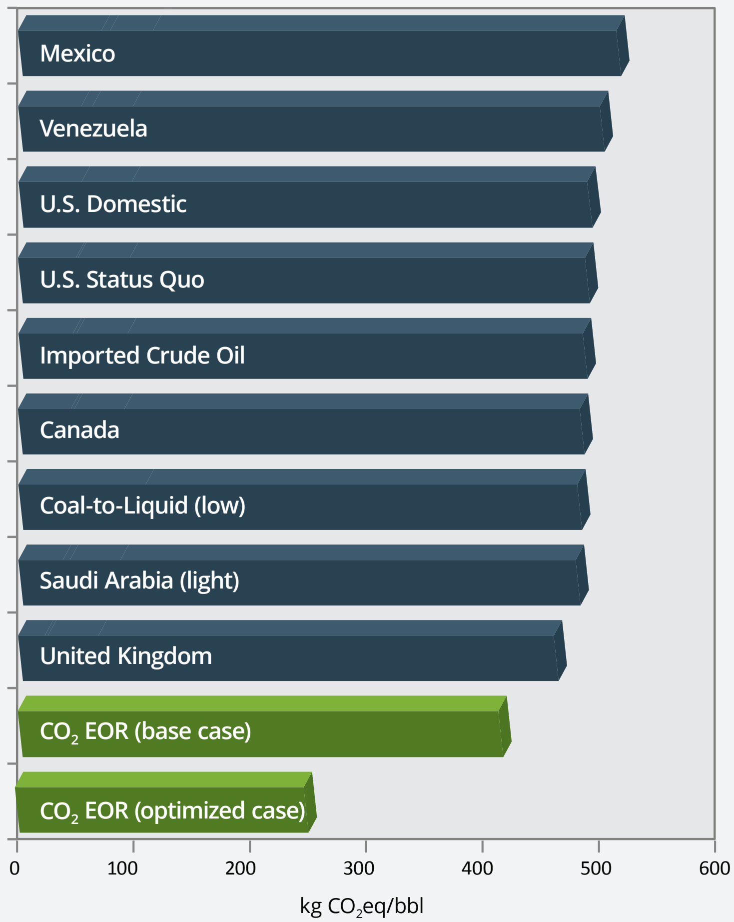


Note: Emissions are expressed as CO_2 equivalents (CO_2eq), which include CO_2, CH_4, and N_2O.



How Does Oil Produced via CO_2 EOR Compare to Oil Produced Using Conventional Methods?

Production Course[29]



North American Sedimentary Basins

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 provide an ideal storage option for facilities not able to take advantage of economic CO_2 EOR opportunities.

Deep saline formations account for most of the world's geologic storage potential.

Putting TDS Levels into Perspective

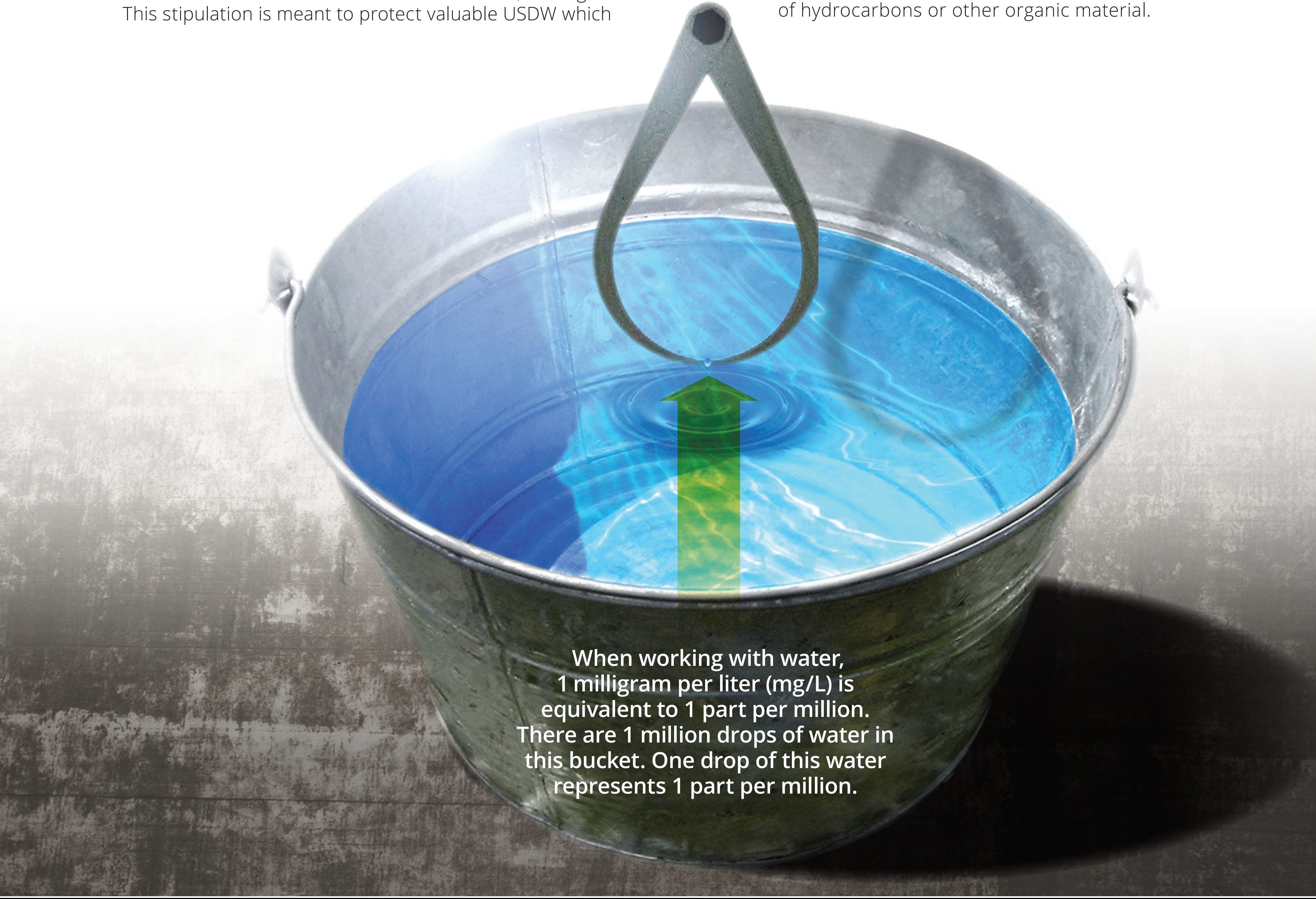
Water Source	TDS, mg/L
Lake Superior[31]	~63
Missouri River[32]	~250
Drinking Water[33]	<500*
Ocean Water[34]	35,000
Great Salt Lake[35]	50,000 to 270,000
Dead Sea[36]	350,000

* 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 or TDS. This is a measure of the combined content of dissolved substances in water, primarily represented by ions of inorganic salts (mainly, calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates).

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 USDW which 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.



Coal Regions of the United States and Canada

Distribution of North American Coal Regions[37]

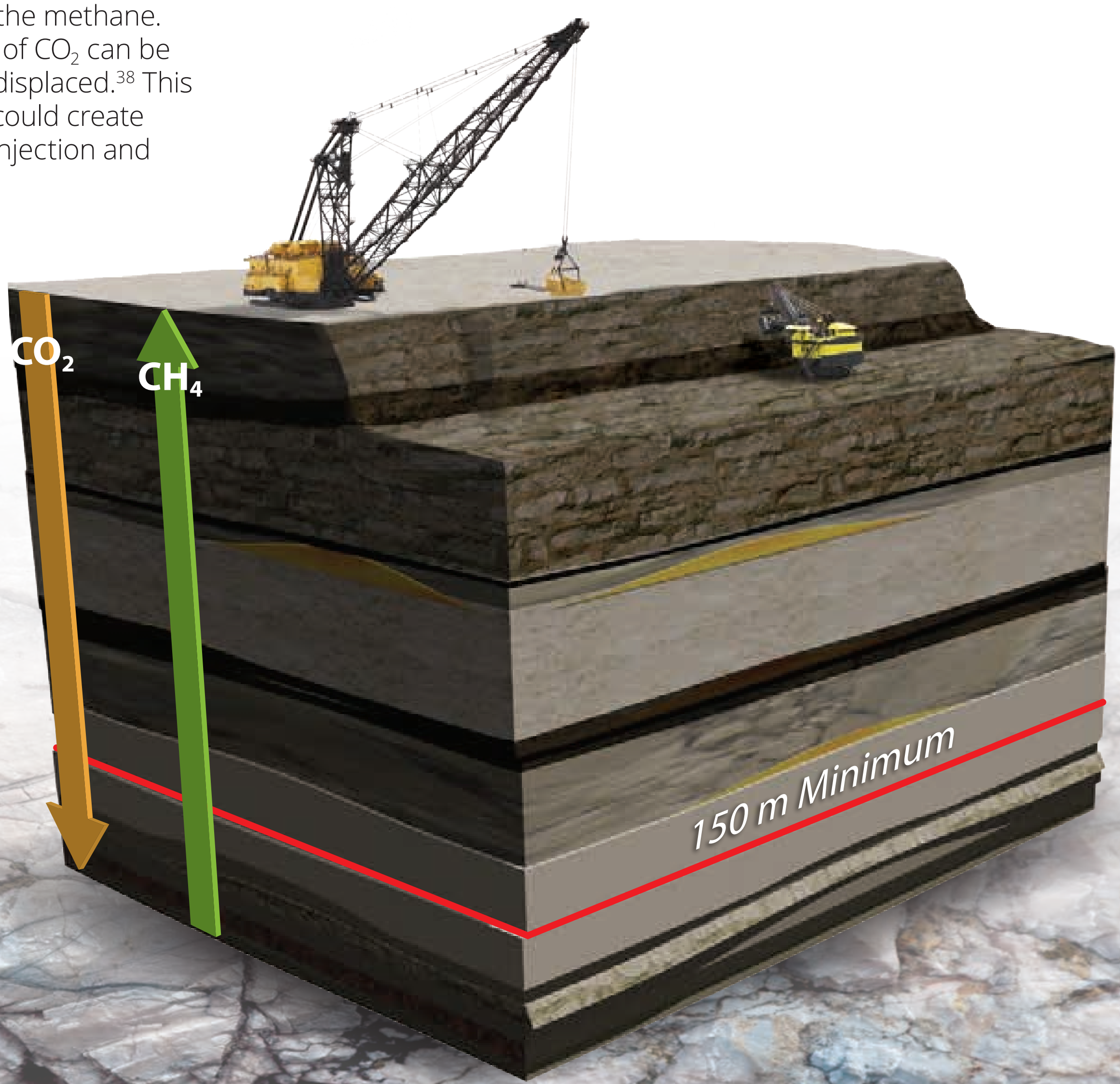
Note: Mexico has many coalfields; however, not all are pictured because of data limitations.

CO_2 in Unminable Coal

Because of their fractured nature, coal seams have a relatively large internal surface area, and these surfaces have the capacity to accumulate large amounts of gases. Some gases, such as CO_2, have a higher affinity for the coal surfaces than others, such as nitrogen. As a result, coal seams that are too deep (generally >150 m) or too thin to be economically mined may prove to be viable sites for CO_2 storage. Carbon storage in unminable coal seams relies on the adsorption of CO_2 on the coal and the permeability of the coal bed. The more microstructures there are in the coal, the more surface area it has for CO_2 to accumulate onto.

In addition to the potential for CO_2 storage, many coal beds contain commercial quantities of adsorbed natural gas (methane). As with oil reservoirs, initial coalbed methane (CBM) recovery methods can leave methane in the coal seam. Additional CBM recovery can be achieved by sweeping the coal bed with CO_2, which preferentially adsorbs onto the surface of the coal, displacing the methane. Depending on the coal rank, up to 13 molecules of CO_2 can be adsorbed for each molecule of methane that is displaced.[38] This enhanced coalbed methane (ECBM) procedure could create revenue to offset the costs associated with the injection and storage of CO_2 in coal beds.

World CO_2 storage potential in coal seams is estimated to be 40 billion tonnes.[39]



CBM recovery is achieved by sweeping the coal bed with CO_2.

CHAPTER 3

The PCOR Partnership

Because CCS requires a new combination of existing and novel technologies, research and demonstration efforts 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 policy makers and the public about CO_2 sources, storage strategies, and storage opportunities.

PCO2R Partnership

DOE's Regional Carbon Sequestration Partnerships

If the decision is made that carbon storage must be implemented in the United States on a broad scale over the next 10–20 years, federal and state agencies will need to work in cooperation with technology developers, regulators, and others to put into place the economic framework and necessary infrastructure to achieve meaningful carbon reductions.

To ensure that America was fully prepared to implement this climate change mitigation option, the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) created the Regional Carbon Sequestration Partnership (RCSP) Program. The RCSP Program is a joint government–industry effort working to determine the most suitable technologies and infrastructure needs to implement CCS in North America.

The PCOR Partnership is one of seven competitively funded Partnerships in the RCSP Program. Each of the Partnerships is developing the framework needed to validate and potentially deploy carbon storage technologies. A key goal of the RCSP Program is to evaluate numerous storage approaches to determine which are best-suited for each region. The Partnerships also identify possible regulations and the necessary infrastructure requirements needed to deploy CCS on a wide scale.

DOE • Office of Fossil Energy NETL

Carbon Sequestration Program with American Recovery and Reinvestment Act Projects[40]

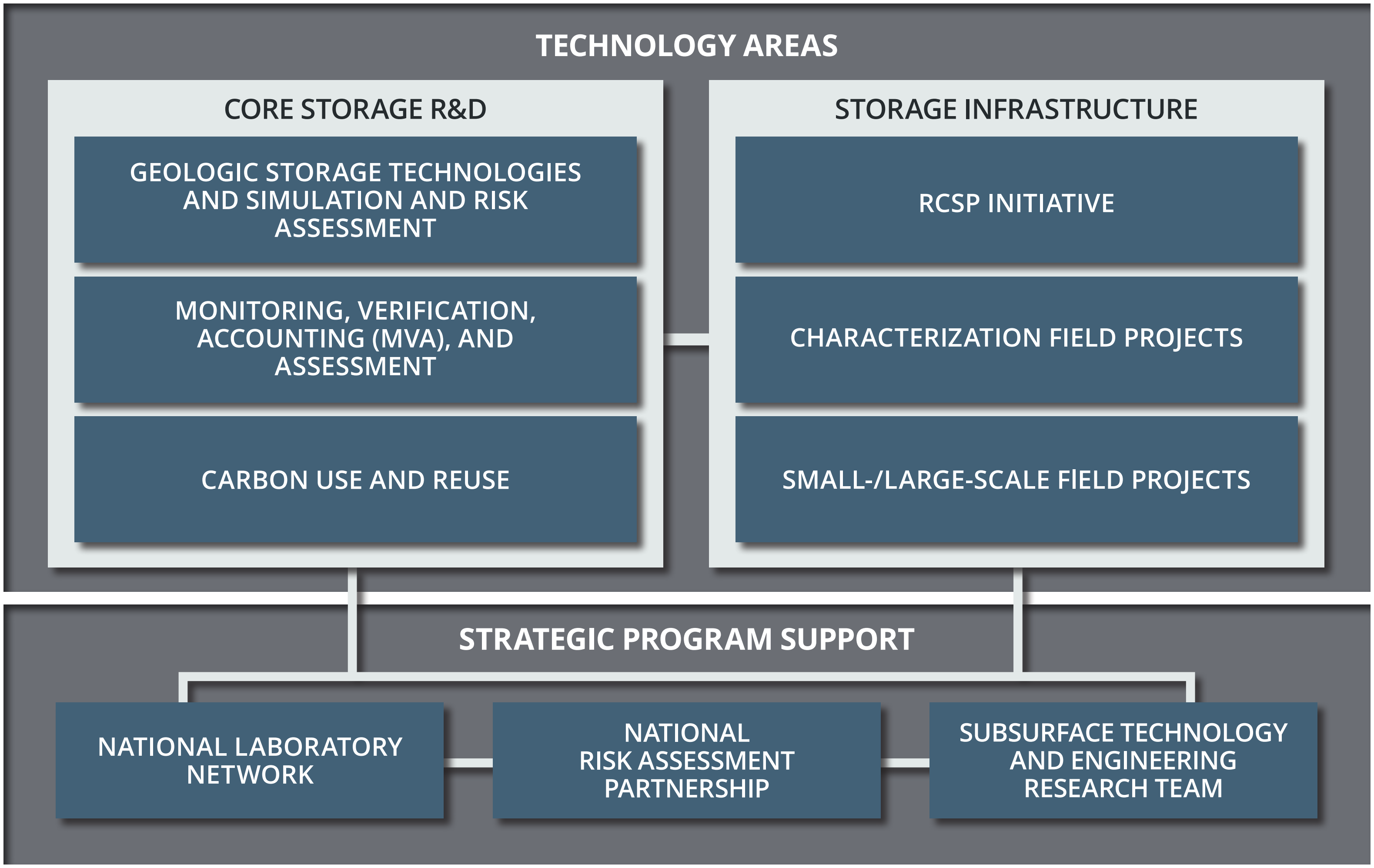
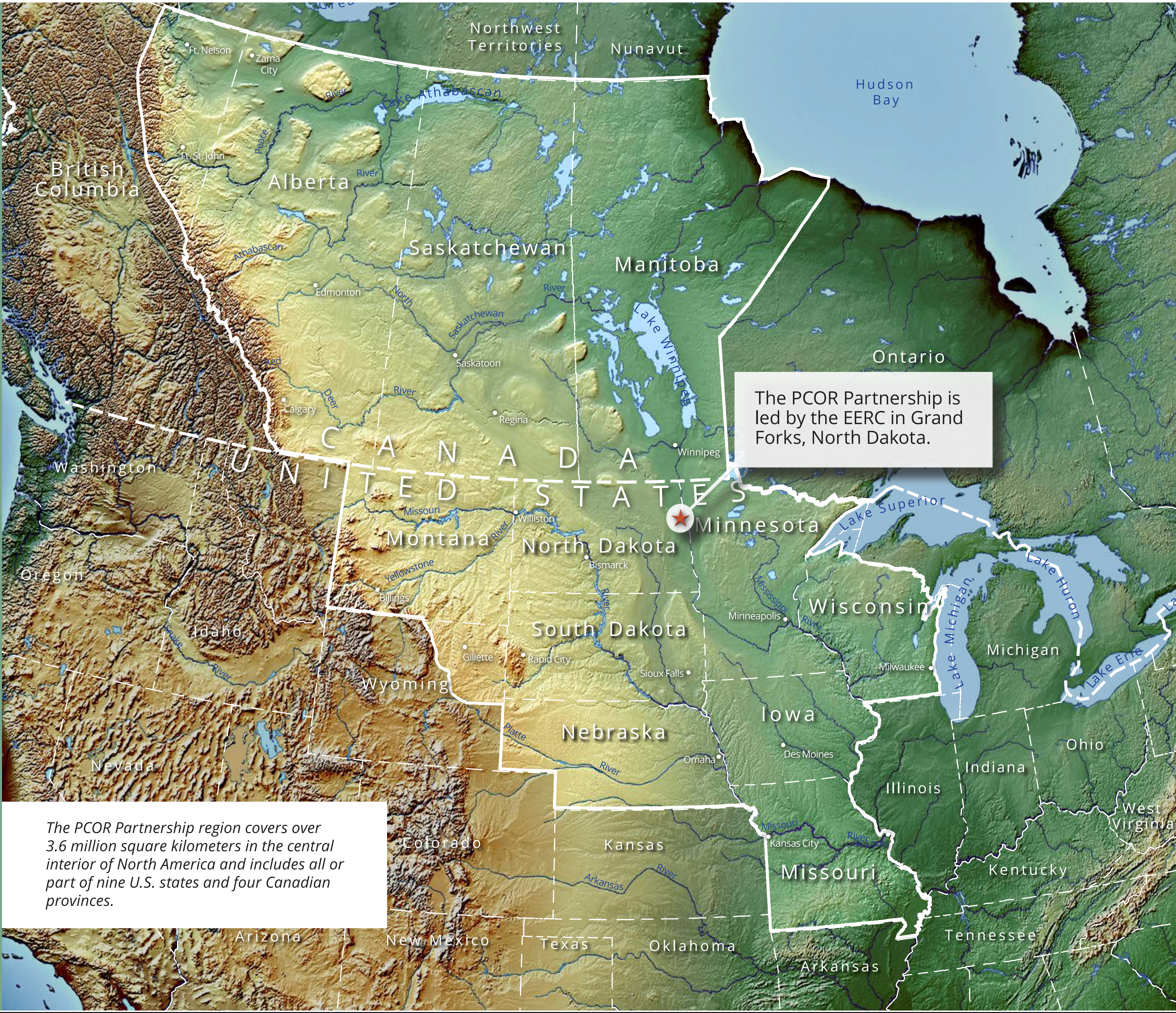


Image adapted from DOE NETL RCSP Program.

PCOR Partnership Region



The PCOR Partnership is led by the EERC in Grand Forks, North Dakota.

The PCOR Partnership region covers over 3.6 million square kilometers in the central interior of North America and includes all or part of nine U.S. states and four Canadian provinces.

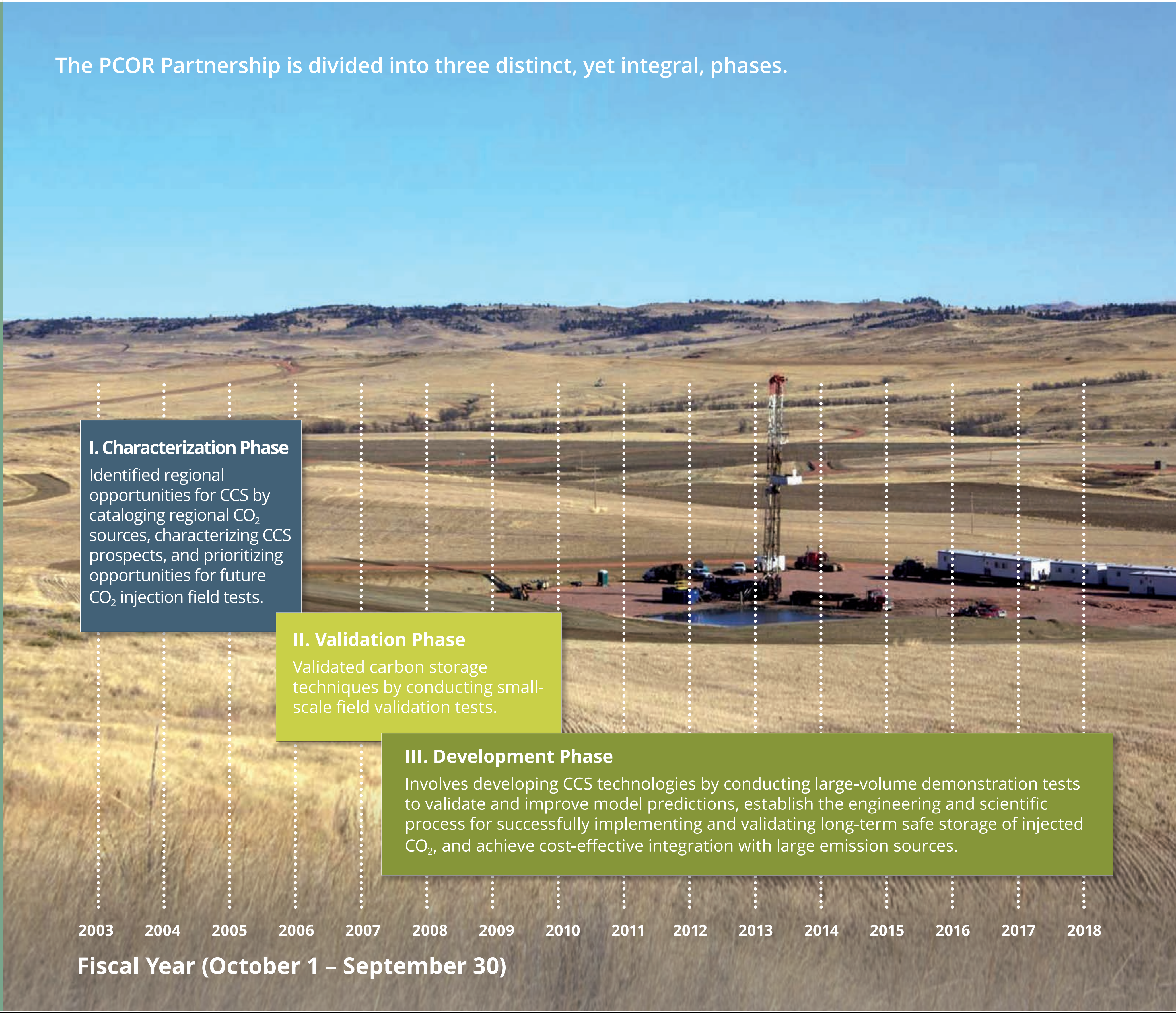
The PCOR Partnership's regional vision for the widespread commercial development of CCS includes several key elements:

1. Targeting relatively low cost anthropogenic CO_2 sources such as gas-processing facilities and ethanol plants as early implementation efforts.
2. Employing tertiary EOR opportunities as initial storage targets whenever the economics and geology are favorable.
3. Using the existing oil and gas regulatory structure and agencies for oversight.
4. Creating a protocol for the establishment of geologic storage units that are based on the standard oilfield practice of unitization.
5. Establishing rigorous site selection criteria that will allow for sufficient capacity, injectivity, containment, and cost-effective MVA procedures.
6. Developing an integrated site characterization, modeling and simulation, risk assessment, and MVA plan that continues to evolve as the project progresses and more data become available.
7. Producing the information needed for our commercial partners to account for injected CO_2 and to monetize carbon credits to reduce the costs of CCS projects.

The realization of this vision will result in the development of both saline formation storage and EOR-based storage opportunities in our region, which has extremely favorable geology and socioeconomic conditions for the widespread adoption of CCS.

Project Phases

The PCOR Partnership is divided into three distinct, yet integral, phases.



I. Characterization Phase

Identified regional opportunities for CCS by cataloging regional CO_2 sources, characterizing CCS prospects, and prioritizing opportunities for future CO_2 injection field tests.

II. Validation Phase

Validated carbon storage techniques by conducting small-scale field validation tests.

III. Development Phase

Involves developing CCS technologies by conducting large-volume demonstration tests to validate and improve model predictions, establish the engineering and scientific process for successfully implementing and validating long-term safe storage of injected CO_2, and achieve cost-effective integration with large emission sources.

PCOR Partnership Activities

Regional Characterization – The PCOR Partnership identified and continues to refine the characterization of CO_2 sources, geologic and terrestrial storage, infrastructure, and the regulatory framework within the region.

Permitting – The PCOR Partnership stays abreast of federal legislative actions occurring in the United States and Canada and follows the developments of various state, provincial, and regional initiatives to ensure partners are informed about any current or pending permitting issues.

Site Characterization and Modeling – Using sophisticated modeling and analytical techniques, the PCOR Partnership conducts in-depth analysis of field and demonstration sites to determine storage site suitability and the long-term fate of the injected CO_2 in storage formations.

Infrastructure Development – The PCOR Partnership facilitates the infrastructure planning required for CCS to be implemented on a wide-scale regional basis. This planning includes the specific infrastructure associated with the capture, dehydration, compression, and pipeline transportation of CO_2 from its source to the injection location.

CO_2 Procurement, Transportation, and Injection – Working with commercial partners, the PCOR Partnership assists in CO_2 procurement, transportation, and injection as a means of documenting critical pathways for future projects.

Operational Monitoring and Modeling – The PCOR Partnership develops data sets for large-volume CO_2 injection tests that 1) verify that injection operations do not adversely impact human health or the environment and 2) account for the storage of injected CO_2 and verify that it stays in the subsurface.

Public Outreach and Education – Raising awareness for CO_2 storage opportunities and real-world demonstrations in the region is accomplished through maintaining a public Web site, conducting public presentations, producing video documentaries, and creating outreach materials.

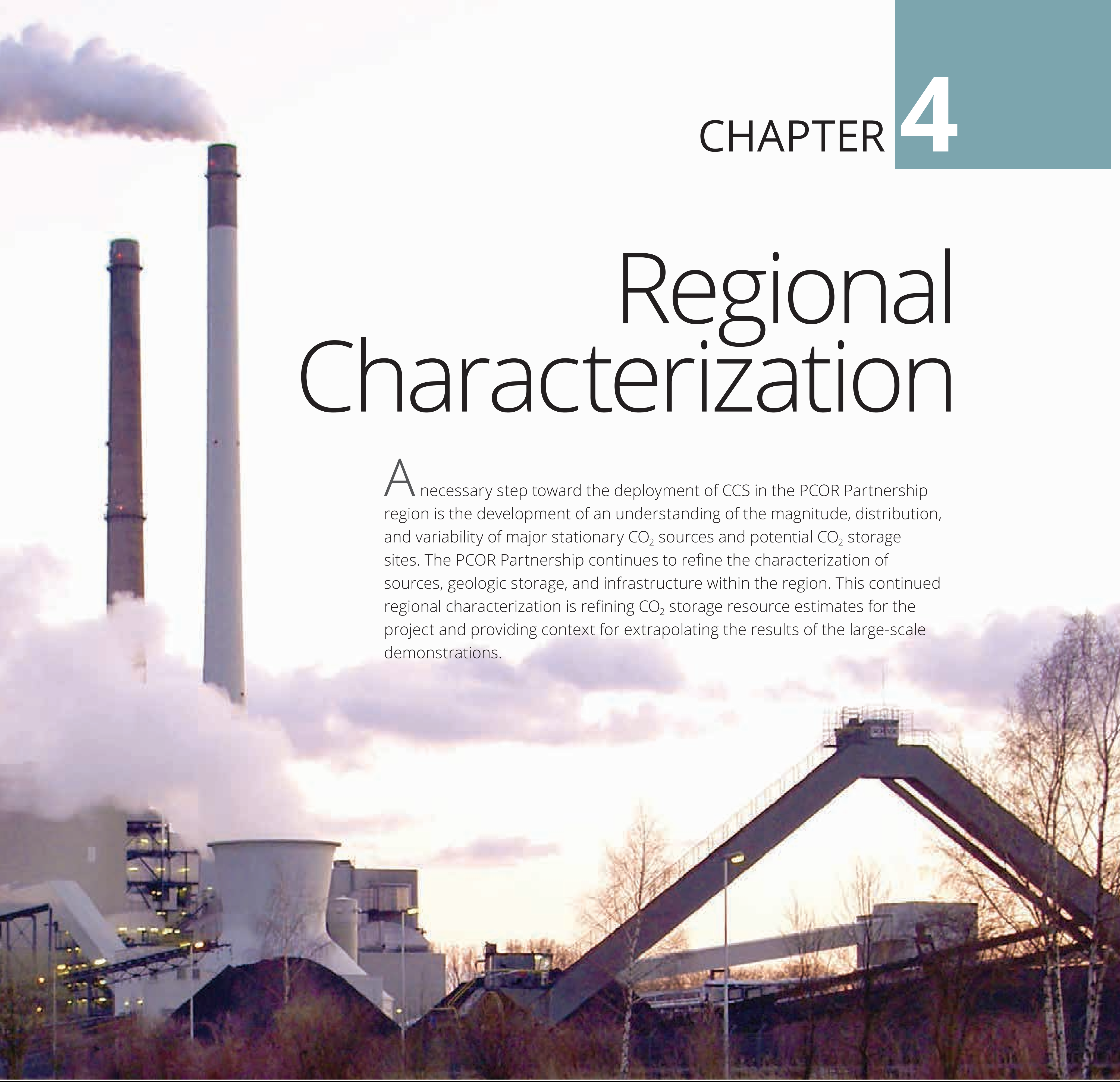
PCOR Partnership Partners

PCOR Partnership 2003 – Present

National Energy Technology Laboratory
EERC University of North Dakota
Abengoa Bioenergy
Air Products
Alberta Energy
AERI Alberta Energy Research Institute
AGS Alberta Geological Survey
Alberta Innovates Technology Futures
Allete
Ameren
ACCCE American Coalition for Clean Coal Electricity
American Lignite Energy
Apache Canada Ltd.
Aquistore
Baker Hughes
Ballantyne Oil • LLC
Basin Electric Power Cooperative
Bechtel
BillyJack Consulting Inc.
Biorecro
Blue Source
BNI Coal
British Columbia Ministry of Energy, Mines and Petroleum Resources
BC Oil & Gas Commission
C12 Energy
The CETER Group, Inc.
CCX Chicago Climate Exchange
CMG
Continental Resources
Dakota Gasification Company
Denbury
Ducks Unlimited Canada
Ducks Unlimited
Eagle Operating Inc.
EICCD
Enbridge
Encore Acquisition Company
ERCB Energy Resources Conservation Board
Environment Canada
Excelsior Energy
Fischer Oil and Gas, Inc.
GE
Great Northern
Great River Energy
Halliburton
Hess
Huntsman
Husky Energy
Indian Land Tenure Foundation
Interstate Oil & Gas Compact Commission
DNR
Kiewit
Lignite Energy Council
Manitoba
Manitoba Hydro
Marathon Oil
MBI Energy Services
MEG Energy Corp
Melzer Consulting
Minnesota Pollution Control Agency
Minnesota Power
Minnkota Power Cooperative, Inc.
Missouri Department of Natural Resources
Missouri River Energy Services
Montana-Dakota Utilities Co.
Montana Department of Environmental Quality
Murex Petroleum Corporation
National Commission on Energy Policy
Natural Resources Canada
Nebraska Public Power District
Nexant
North American Coal Corporation
North Dakota Department of Commerce
North Dakota Department of Health
North Dakota Geological Survey
North Dakota Oil and Gas Division
Industrial Commission of North Dakota Lignite Research, Development and Marketing Program
Industrial Commission of North Dakota Oil and Gas Research Council
North Dakota Natural Resources Trust
North Dakota Petroleum Council
NDPA North Dakota Pipeline Association
NDSU North Dakota State University
OPPD Omaha Public Power District
Otter Tail Power Company
Outsource Petrophysics, Inc.
Oxand Risk Management Solutions
Peabody Energy
Petro Harvester
PTRC Petroleum Technology Research Centre
PTTC Technology Connections
Pinnacle
Prairie Public
Pratt & Whitney
Praxair
Ramgen Power Systems
RPS Energy
Saskatchewan Industry and Resources
SaskPower
Schlumberger Carbon Services
Sejong University
Shell Canada Limited
Spectra Energy
Strategic West Energy Ltd.
Suncor Energy
TAQA
Tesoro
TGS
Tri-State G&T
Tundra Oil & Gas
University of Alberta
University of Regina
USGS
WBI Energy
Weatherford
Advanced Geotechnology
Western Governors' Association
Westmoreland Coal Company
Wisconsin Department of Agriculture, Trade & Consumer Protection
Wyoming Office of State Lands and Investments
Xcel Energy

Since its inception in 2003, the PCOR Partnership has brought together more than 120 public and private sector stakeholders with vast expertise in power generation, energy exploration and production, geology, engineering, the environment, agriculture, forestry, and economics. Partners are the backbone of the PCOR Partnership and provide data, guidance, financial resources, and practical experience with CCS and terrestrial sequestration.

- U.S. Department of Energy National Energy Technology Laboratory
- University of North Dakota Energy & Environmental Research Center
- Abengoa Bioenergy New Technology, Inc.
- Air Products and Chemicals, Inc.
- Alberta Department of Energy
- Alberta Department of Environment
- Alberta Energy Research Institute
- Alberta Innovates – Technology Futures
- ALLETE
- Ameren Corporation
- American Coalition for Clean Coal Electricity (ACCCE)
- American Lignite Energy
- Apache Canada Ltd.
- Aquistore
- Baker Hughes Incorporated
- Ballantyne Oil, LLC
- Basin Electric Power Cooperative
- Bechtel Corporation
- BillyJack Consulting Inc.
- Biorecro AB
- Blue Source, LLC
- BNI Coal, Ltd.
- British Columbia Ministry of Energy, Mines and Petroleum Resources
- British Columbia Oil and Gas Commission
- C12 Energy, Inc.
- The CETER Group, Inc.
- Chicago Climate Exchange
- Computer Modelling Group, Inc.
- Continental Resources, Inc.
- Dakota Gasification Company
- Denbury Resources Inc.
- Ducks Unlimited
- Ducks Unlimited Canada
- Eagle Operating, Inc.
- Eastern Iowa Community College District
- Enbridge Inc.
- Encore Acquisition Company
- Energy Resources Conservation Board/ Alberta Geological Survey
- Environment Canada
- Excelsior Energy, Inc.
- Fischer Oil and Gas, Inc.
- General Electric
- Great Northern Project Development, LP
- Great River Energy
- Halliburton
- Hess Corporation
- Huntsman Corporation
- Husky Energy Inc.
- Indian Land Tenure Foundation
- Interstate Oil and Gas Compact Commission
- Iowa Department of Natural Resources
- Kiewit Mining Group
- Lignite Energy Council
- Manitoba Geological Survey
- Manitoba Hydro
- Marathon Oil Company
- MBI Energy Services
- MEG Energy Corporation
- Melzer Consulting
- Minnesota Pollution Control Agency
- Minnesota Power
- Minnkota Power Cooperative, Inc.
- Missouri Department of Natural Resources
- Missouri River Energy Services
- Montana–Dakota Utilities Co.
- Montana Department of Environmental Quality
- Montana Public Service Commission
- Murex Petroleum Corporation
- National Commission on Energy Policy
- Natural Resources Canada
- Nebraska Public Power District
- Nexant, Inc.
- North American Coal Corporation
- North Dakota Department of Commerce Division of Community Services
- North Dakota Department of Health
- North Dakota Geological Survey
- North Dakota Industrial Commission Department of Mineral Resources Oil and Gas Division
- North Dakota Industrial Commission Lignite Research, Development and Marketing Program
- North Dakota Industrial Commission Oil and Gas Research Council
- North Dakota Natural Resources Trust
- North Dakota Petroleum Council
- North Dakota Pipeline Authority
- North Dakota State University
- Omaha Public Power District
- Otter Tail Power Company
- Outsource Petrophysics Inc.
- Oxand Risk & Project Management Solutions
- Peabody Energy
- Petro Harvester Oil & Gas, LLC
- Petroleum Technology Research Centre
- Petroleum Technology Transfer Council
- Pinnacle, a Halliburton Service
- Prairie Public Broadcasting
- Pratt & Whitney Rocketdyne, Inc.
- Praxair, Inc.
- Ramgen Power Systems, Inc.
- Red Trail Energy LLC
- RPS Energy Canada Ltd.
- Saskatchewan Ministry of Energy and Resources
- SaskPower
- Schlumberger Carbon Services
- Sejong University
- Shell Canada Energy
- Spectra Energy
- Strategic West Energy Ltd.
- Suncor Energy Inc.
- TAQA North Ltd.
- Tesoro Refinery (Mandan)
- TGS Geological Products and Services
- Tri-State Generation and Transmission Association, Inc.
- Tundra Oil and Gas Partnership Ltd.
- University of Alberta
- University of North Dakota
- University of Regina
- U.S. Geological Survey Northern Prairie Wildlife Research Center
- WBI Energy, Inc.
- Weatherford Advanced Geotechnology
- Western Governors' Association
- Westmoreland Coal Company
- Wisconsin Department of Agriculture, Trade and Consumer Protection
- Wyoming Office of State Lands and Investments
- Xcel Energy

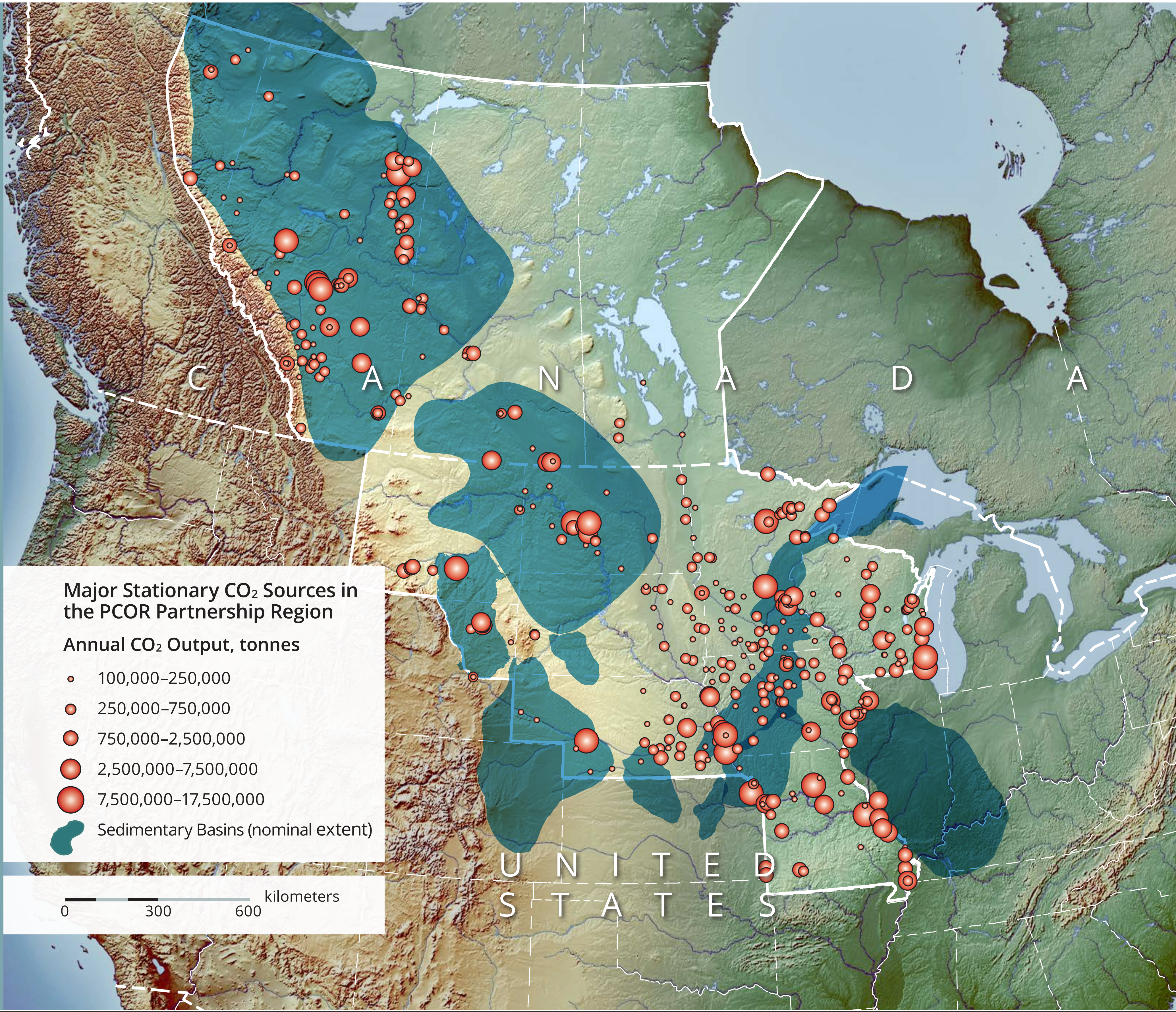


CHAPTER 4

Regional Characterization

A necessary step toward the deployment of CCS in the PCOR Partnership region is the development of an understanding of the magnitude, distribution, and variability of major stationary CO_2 sources and potential CO_2 storage sites. The PCOR Partnership continues to refine the characterization of sources, geologic storage, and infrastructure within the region. This continued regional characterization is refining CO_2 storage resource estimates for the project and providing context for extrapolating the results of the large-scale demonstrations.

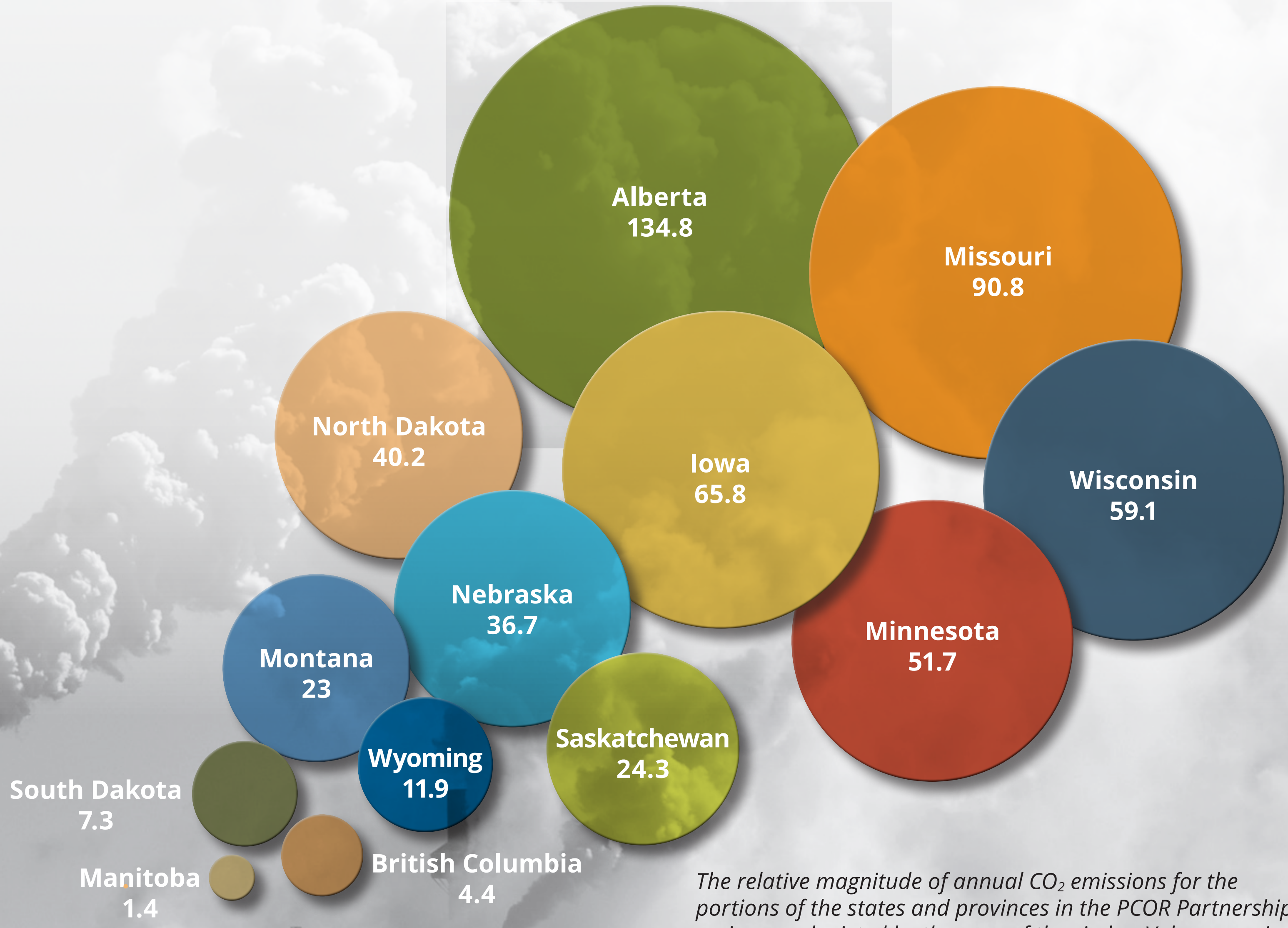
Distribution of Major Stationary CO_2 Sources



CO_2 Sources

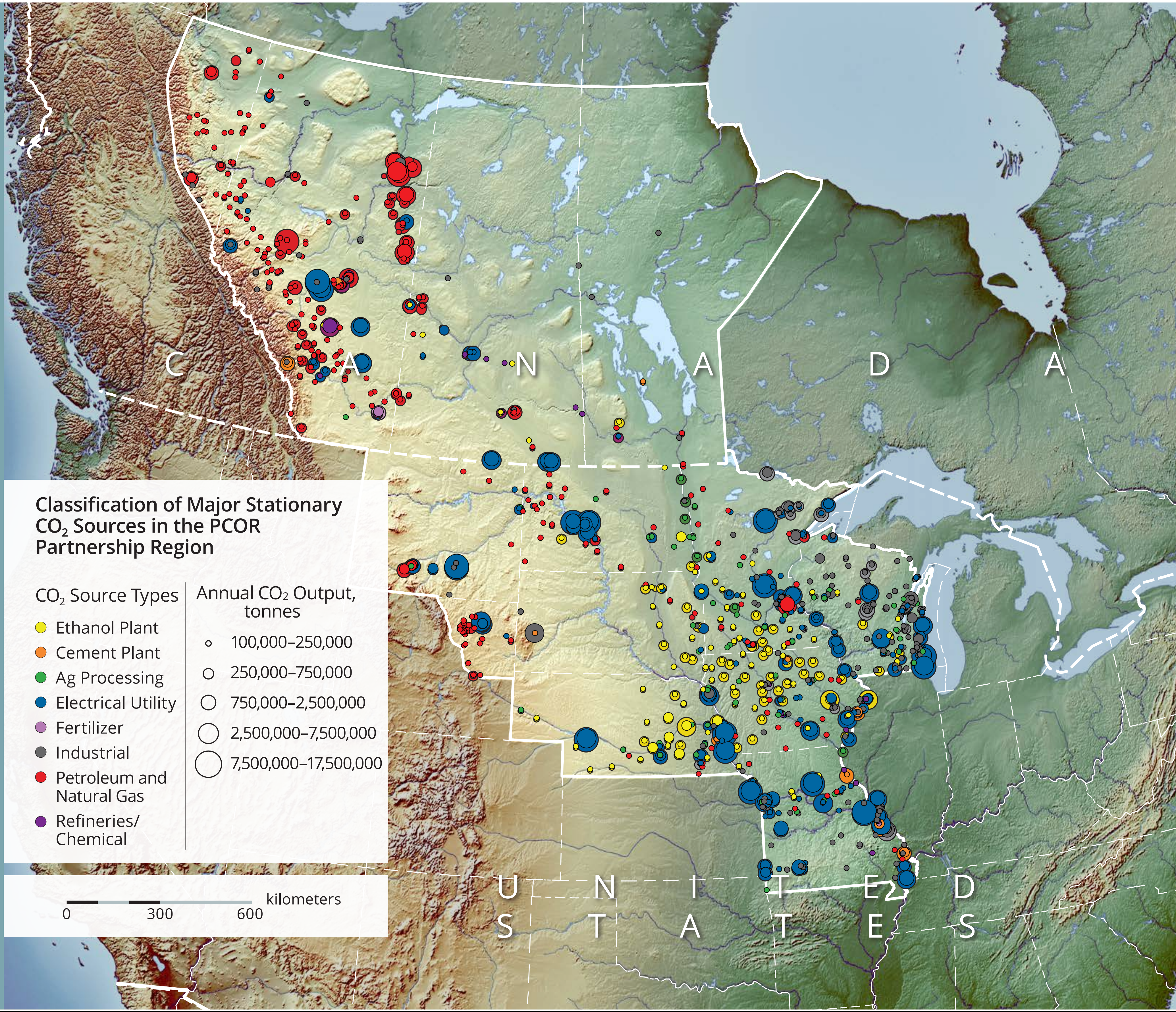
The PCOR Partnership has identified, quantified, and categorized 458 stationary sources in the region that have an annual output of greater than 100,000 tonnes of CO_2. These stationary sources have a combined annual CO_2 output of nearly 500 million tonnes (Mt). Although not a target source of CO_2 for geologic storage, the transportation sector in the U.S. portion of the PCOR Partnership region contributes nearly 158 million additional tonnes of CO_2 to the atmosphere every year.[41]

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 nearly 18 Mt 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.

Classification of Major Stationary CO_2 Sources

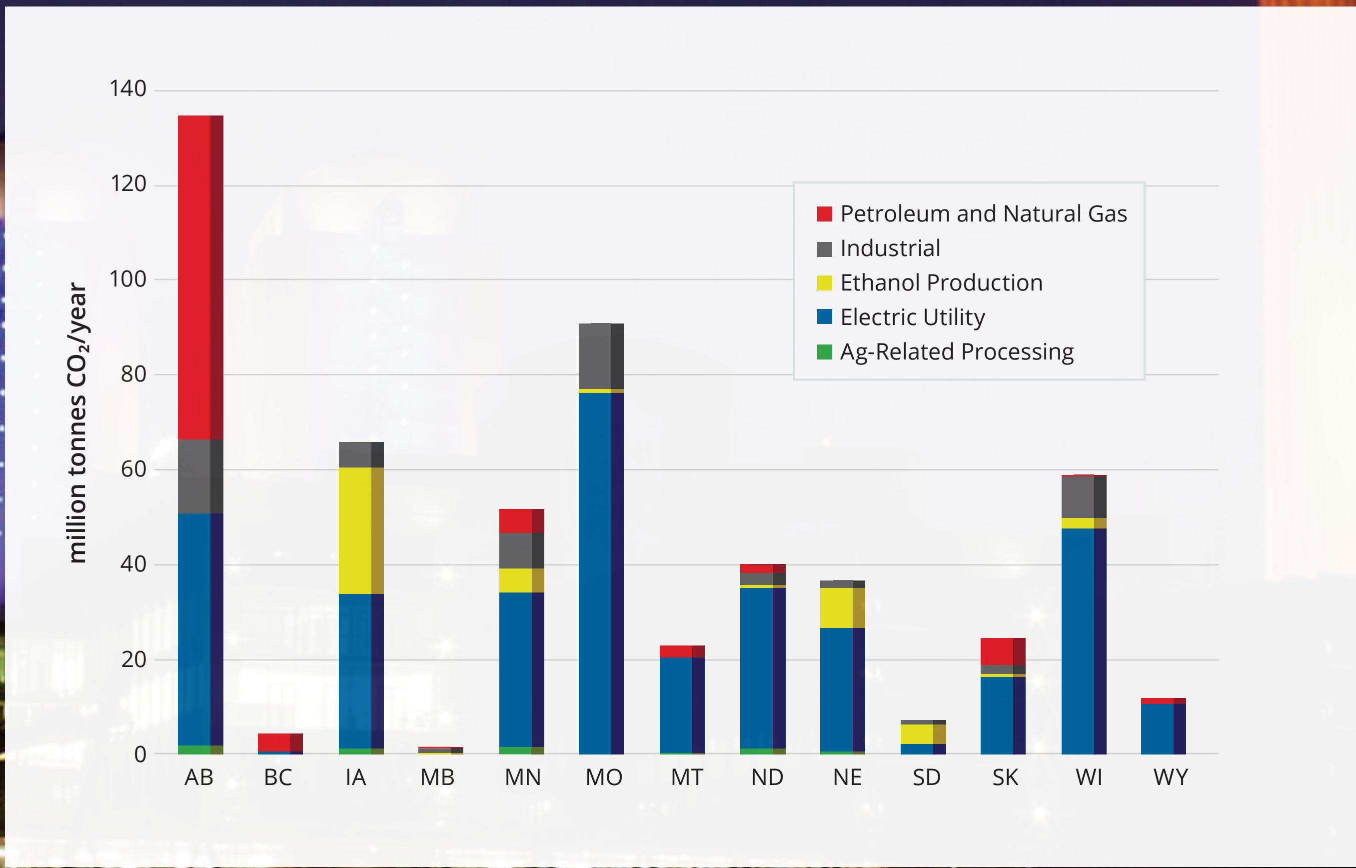


CO_2 Sources by Type

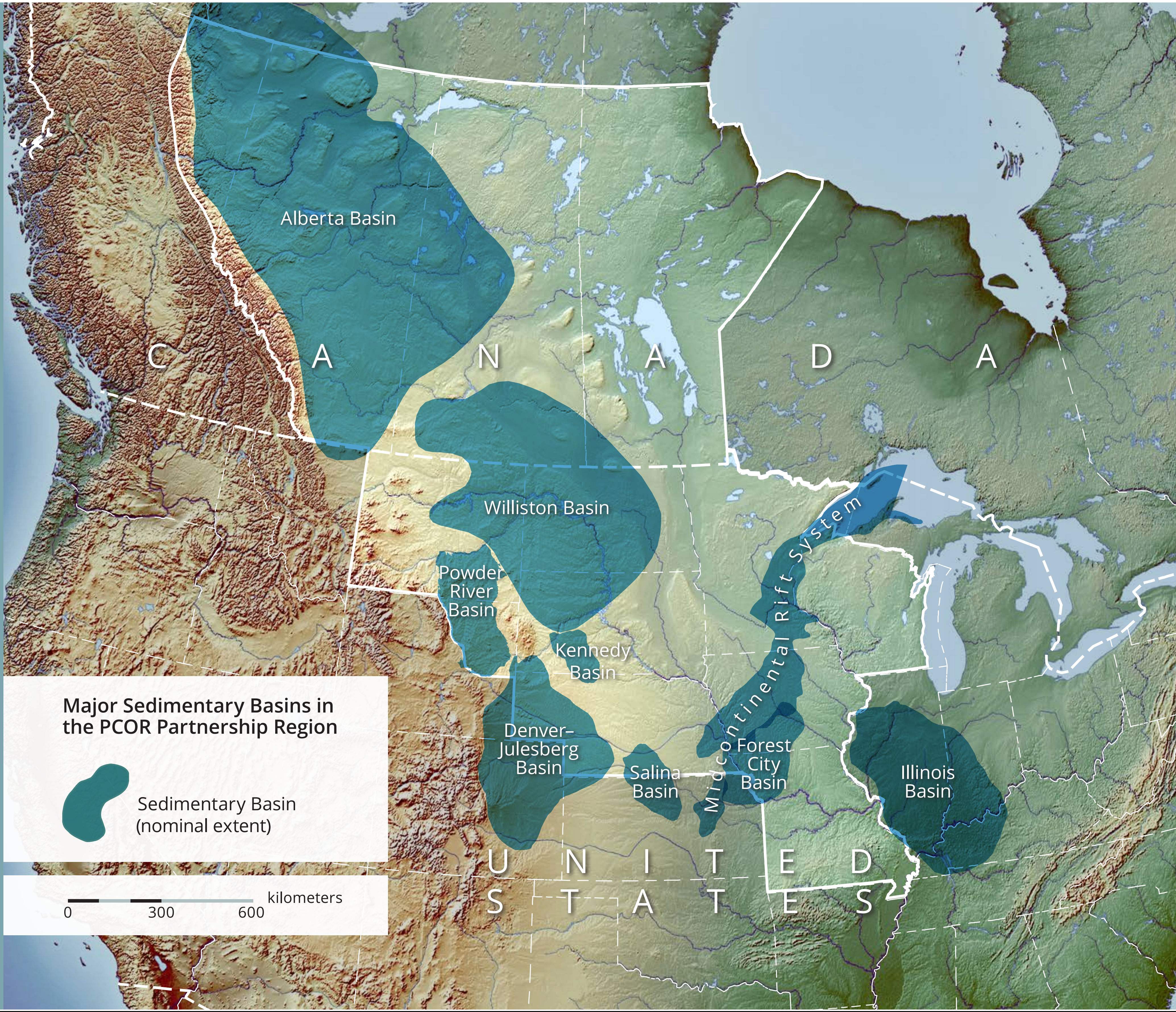
The geographic and socioeconomic diversity of the PCOR Partnership region is reflected in the diversity of the CO_2 sources found there. About two-thirds of CO_2 is emitted from electricity generation; significant emissions also result from energy exploration and production activities; agricultural processing; fuel, chemical, and ethanol production; and various manufacturing and industrial activities.

Canadian emissions within the PCOR Partnership region are dominated by Alberta, with extensive use of fossil fuel resources. When compared to total U.S. CO_2 emissions, the states in the PCOR Partnership region emit relatively more CO_2 from electric utilities and less from industries and transportation.

Although the CO_2 emissions from the individual PCOR Partnership point sources are no different from similar sources located around North America, the wide range of source types within the PCOR Partnership region offers the opportunity to evaluate the capture, transport, and storage of CO_2 in many different scenarios.



Major Regional Sedimentary Basins

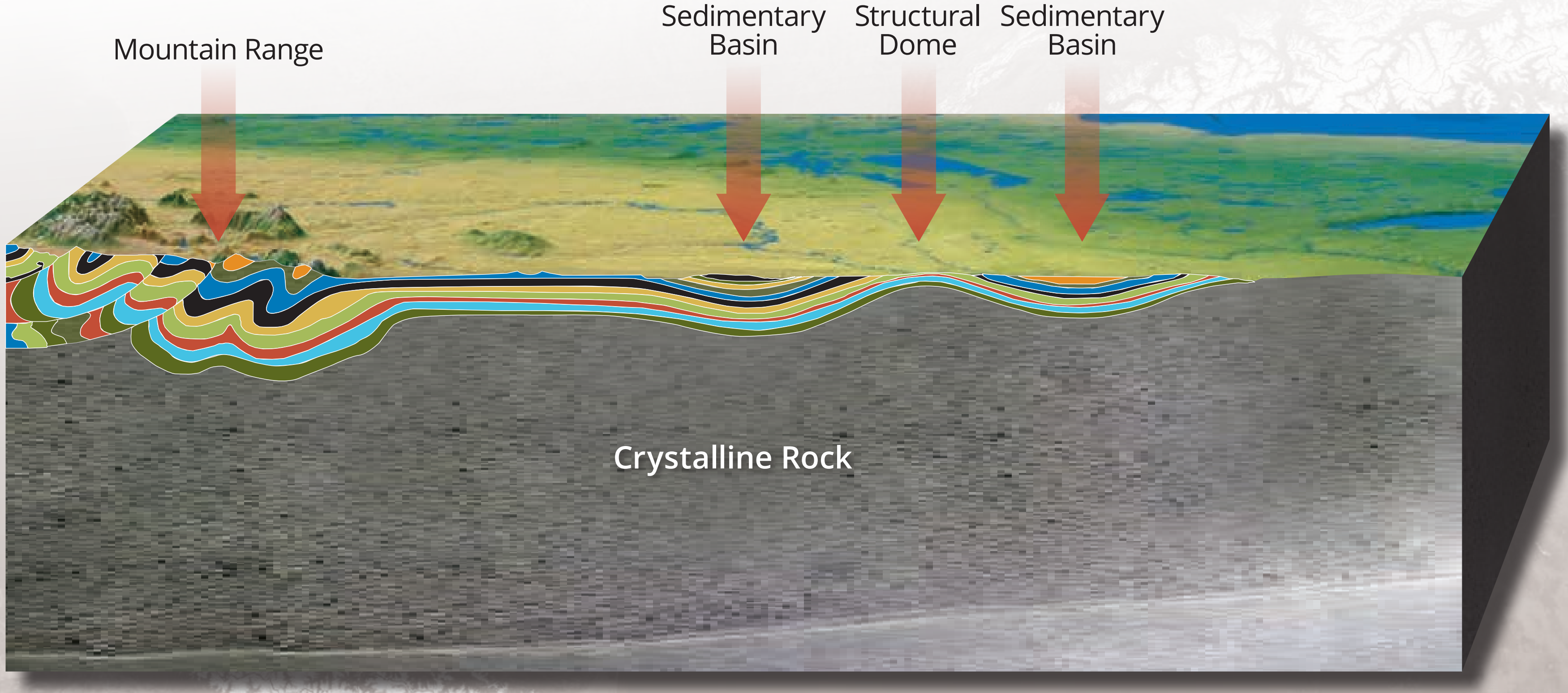


Sedimentary basins are large regional depressions in Earth's crust. These depressions accumulate a considerable thickness of sediment that can cause further subsidence and allow for even more sediments to accumulate. As the sediments are buried, they are subjected to compaction from increasing pressure 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 the extensive sedimentary basins of this region.

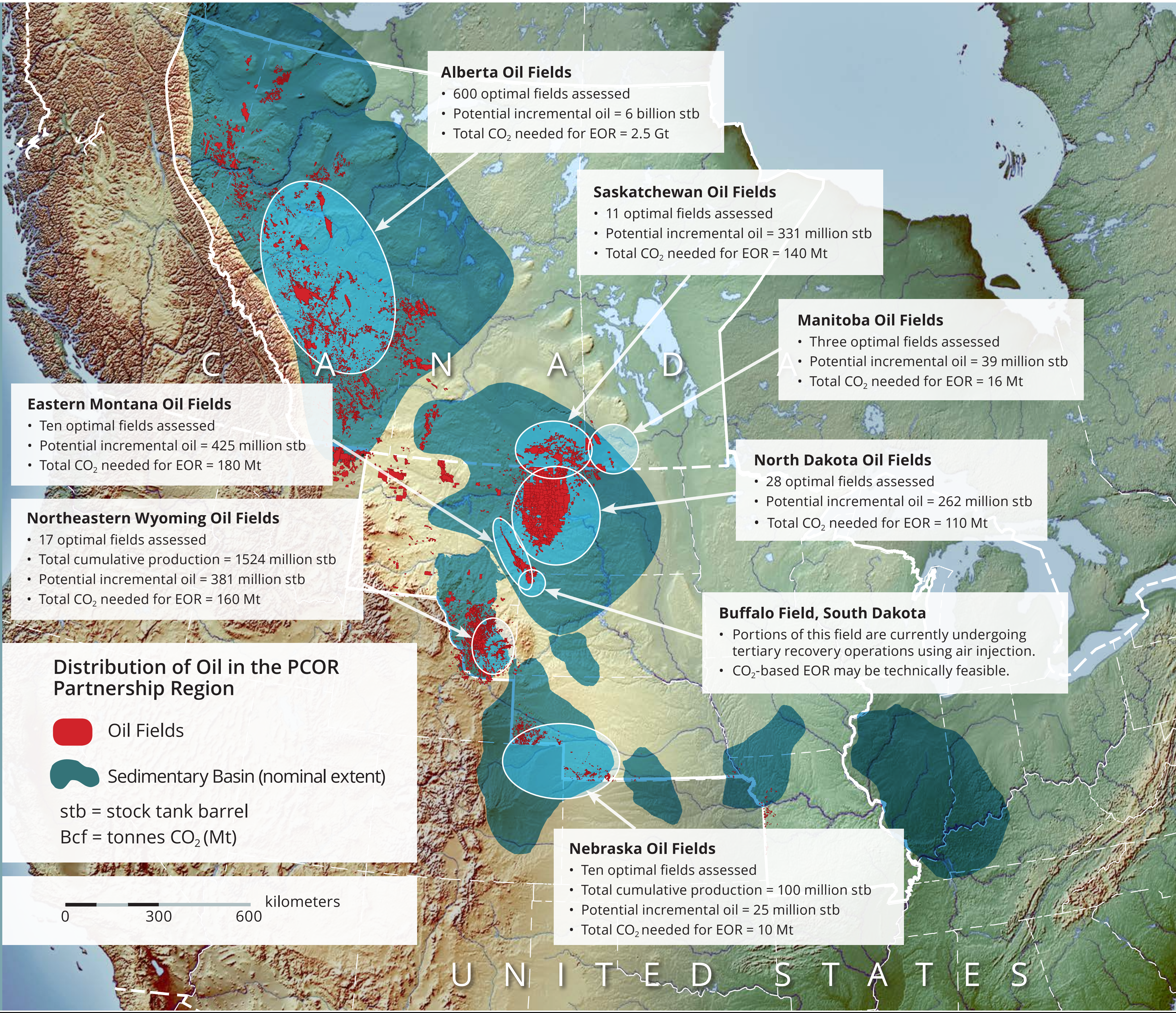
Midcontinent Rift System

The PCOR Partnership region includes other areas besides the major petroleum-producing basins that are underlain by thick sequences of sedimentary rock. One of the largest and most notable of these areas is the Midcontinent Rift System, which stretches from eastern Nebraska across central Iowa and south-central Minnesota to the western portion of Lake Superior.

This thick and deeply buried sequence of sedimentary rock is penetrated by only a few wells; thus little is known about the detailed characteristics of these rocks. However, preliminary investigations suggest that the Midcontinent Rift System has a lower potential for CO_2 storage.[42]



Enhanced Oil Recovery Potential



Alberta Oil Fields
- 600 optimal fields assessed
- Potential incremental oil = 6 billion stb
- Total CO_2 needed for EOR = 2.5 Gt

Saskatchewan Oil Fields
- 11 optimal fields assessed
- Potential incremental oil = 331 million stb
- Total CO_2 needed for EOR = 140 Mt

Manitoba Oil Fields
- Three optimal fields assessed
- Potential incremental oil = 39 million stb
- Total CO_2 needed for EOR = 16 Mt

Eastern Montana Oil Fields
- Ten optimal fields assessed
- Potential incremental oil = 425 million stb
- Total CO_2 needed for EOR = 180 Mt

North Dakota Oil Fields
- 28 optimal fields assessed
- Potential incremental oil = 262 million stb
- Total CO_2 needed for EOR = 110 Mt

Northeastern Wyoming Oil Fields
- 17 optimal fields assessed
- Total cumulative production = 1524 million stb
- Potential incremental oil = 381 million stb
- Total CO_2 needed for EOR = 160 Mt

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

Nebraska Oil Fields
- Ten optimal fields assessed
- Total cumulative production = 100 million stb
- Potential incremental oil = 25 million stb
- Total CO_2 needed for EOR = 10 Mt

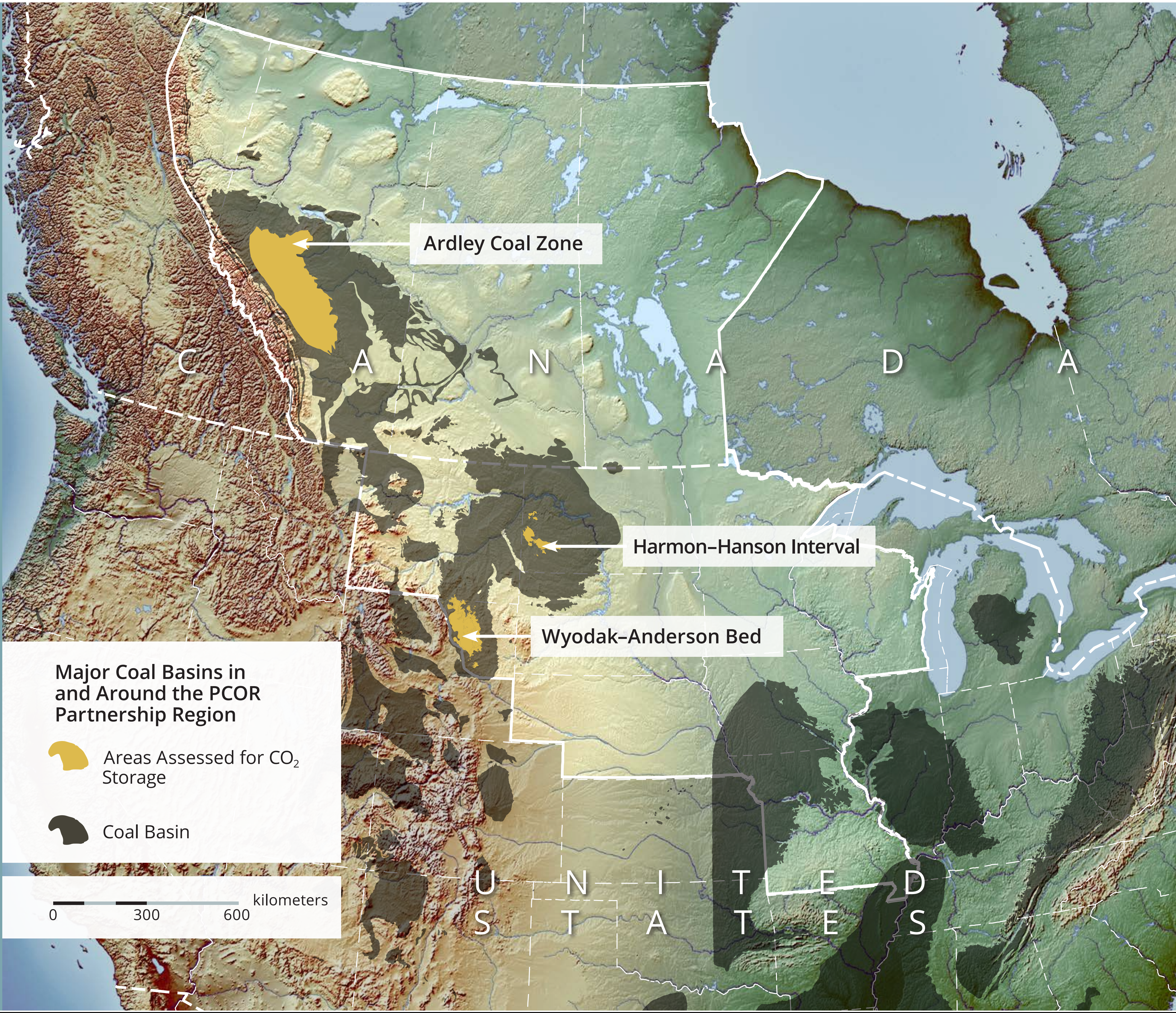
CO_2 Storage in Oil and Gas Fields

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 90 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 below ground level to approximately 8000 m.

Reconnaissance-level CO_2 storage estimates were made for selected oil fields in the Williston, Powder River, Denver–Julesberg, and Alberta Basins. Two alternative calculation methods were used, depending on the nature of the available reservoir characterization data for each field. The estimates were developed using reservoir characterization data obtained from the petroleum regulatory agencies and/or geological surveys from the oil-producing states and provinces of the PCOR Partnership region. Results of the estimates for the evaluated fields (using a volumetric method) in the four basins indicate a CO_2 storage potential of over 3.2 Gt of CO_2 with a cummulative incremental oil recovery of over 7 billion stb.

The region has over **3.2 Gt** of CO_2 storage potential in oil and gas fields and **7 billion stb** of incremental oil.

Major Coal Basins



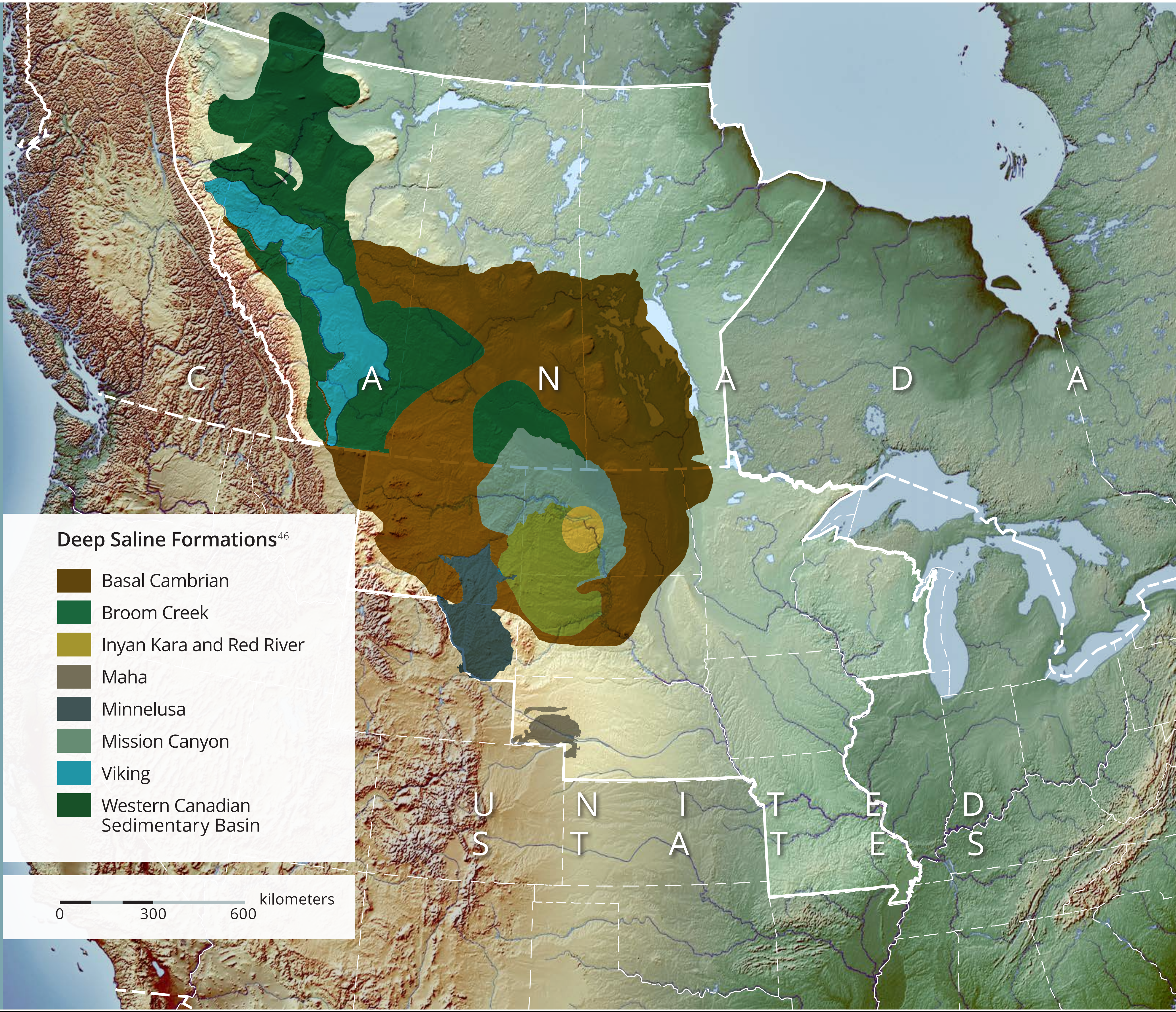
CO_2 Storage in Unminable Coal

The PCOR Partnership region is home to significant coal resources. Much of this vast resource is used to generate electricity at coal-fired power plants in the region and beyond. However, a significant portion of this resource lies at depths that are not economically recoverable. Just as with depleting oil reservoirs, unminable coal beds in the region may be a good opportunity for CO_2 storage.

Three deep major coal horizons in the PCOR Partnership region have been characterized with respect to CO_2 storage: the Wyodak–Anderson bed in the Powder River Basin, the Harmon–Hanson interval in the Williston Basin, and the Ardley coal zone in the Alberta Basin. The total maximum CO_2 storage resource potential for all three coal deposits is approximately 7.3 Gt.[43–45]

In the Powder River Basin area of northeastern Wyoming, the CO_2 storage potential for the areas where the coal overburden thickness is >300 m could store all of the current annual CO_2 emissions from nearby power plants for about the next 150 years.[45]

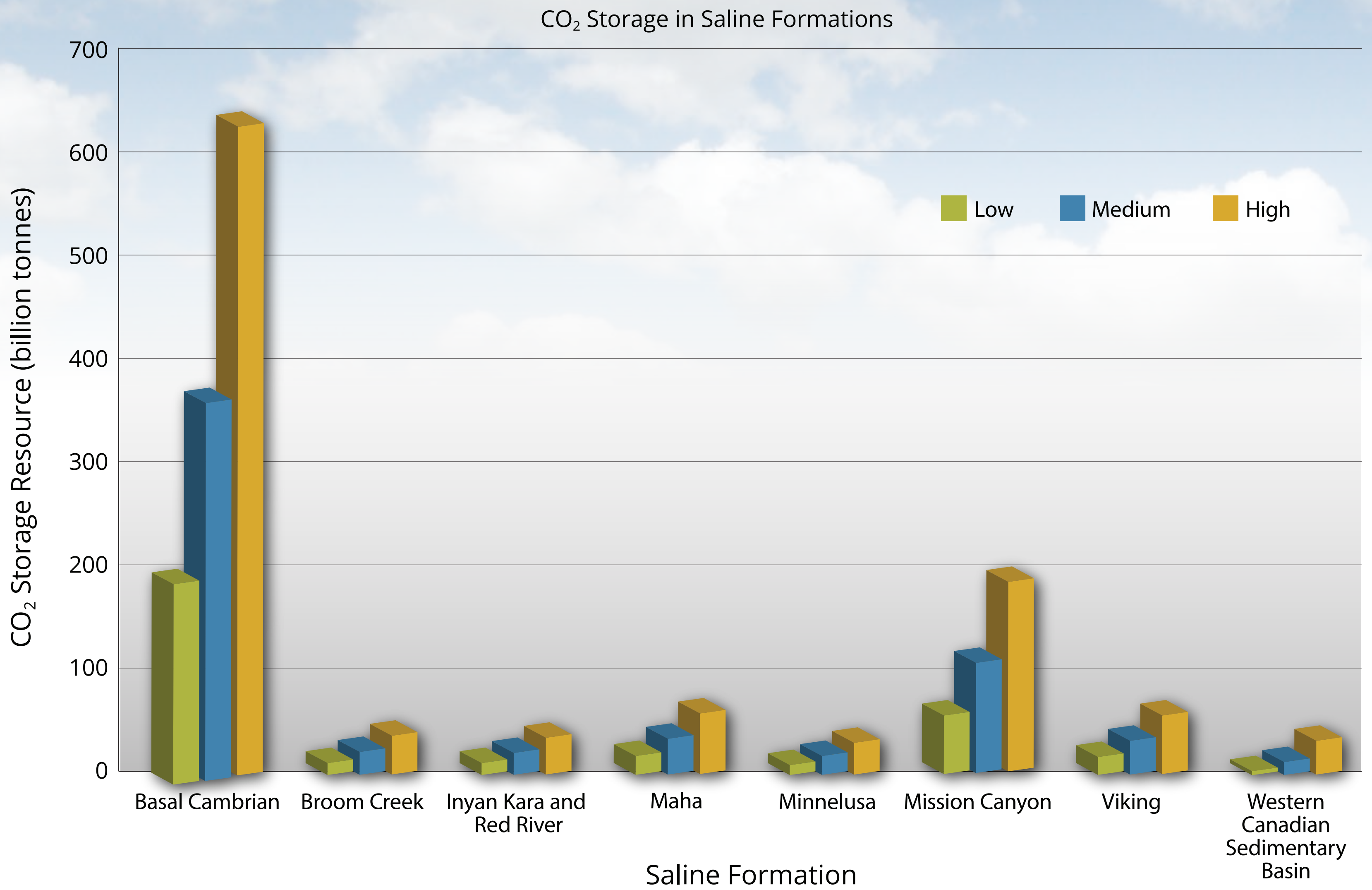
Evaluated Suitable Saline Formations



CO_2 Storage in Saline Formations

Deep saline formations within the PCOR Partnership region have the potential to store vast quantities of anthropogenic CO_2. Through the course of characterization activities associated with the PCOR Partnership Program and the efforts of our partners in Canada, several saline formations have been evaluated to determine the magnitude of the CO_2 storage resource available. In many sedimentary basins, more than one potential target horizon for CO_2 storage may exist within a defined geographic area, each with an appropriate seal to ensure safe, long-term storage. This configuration of stacked target formations is certainly the case with regard to the basins in the PCOR Partnership region. The extent of the formations identified for potential storage are constrained by depth (to ensure optimal density of the injected CO_2) and by salinity (to avoid protected groundwater resources).

To date, reconnaissance-level characterization has identified at least 330 Gt of potential storage in deep saline formations. As characterization activities progress and other saline formations in the PCOR Partnership region are investigated, this total will certainly rise.

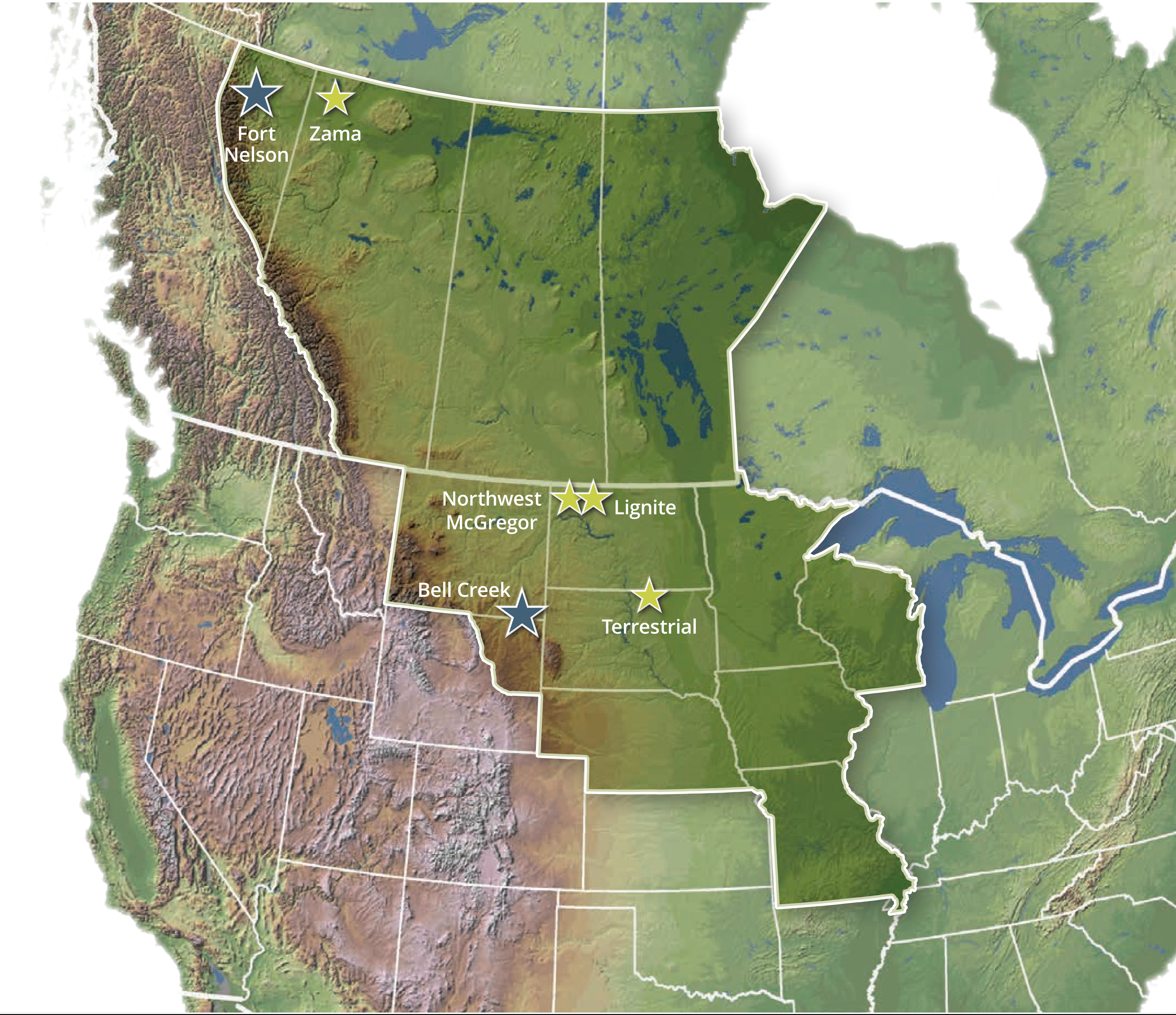


CHAPTER 5

Field-Based Activities

The full range of options required to effectively manage anthropogenic CO_2 emissions may take decades to implement. The PCOR Partnership region has significant storage resources in the context of the billions of tons of CO_2 emissions that may require mitigation. As a result, the PCOR Partnership is developing and has carried out a variety of field projects to demonstrate and optimize practical and environmentally sound geologic CO_2 storage and terrestrial sequestration in the region.

Demonstrating CCS



The PCOR Partnership is working to demonstrate and optimize practical and environmentally sound CO_2 storage in the region. 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 PCOR Partnership has worked on two commercial-scale, long-term projects to demonstrate that the CO_2 storage sites have the potential to store regional CO_2 emissions safely, permanently, and economically.

Phase II Field Scale

Zama Field Validation Test

Determined the effect of acid gas injection for the purpose of acid gas disposal, geologic storage of CO_2, and EOR.

Lignite Field Validation Test

Investigated the ability of unminable lignite seams to store CO_2 during ECBM production.

Northwest McGregor Field Validation Test

Evaluated the potential for geologic storage of CO_2 in a deep carbonate reservoir for the dual purpose of CO_2 storage and EOR at depths greater than 2000 m.

Terrestrial Field Validation Test

Developed the technical capacity to systematically identify, develop, and apply alternate land use management practices to the prairie pothole ecosystem (at both local and regional scales) that will result in GHG reductions and salable carbon offsets.

Phase III Commercial Scale

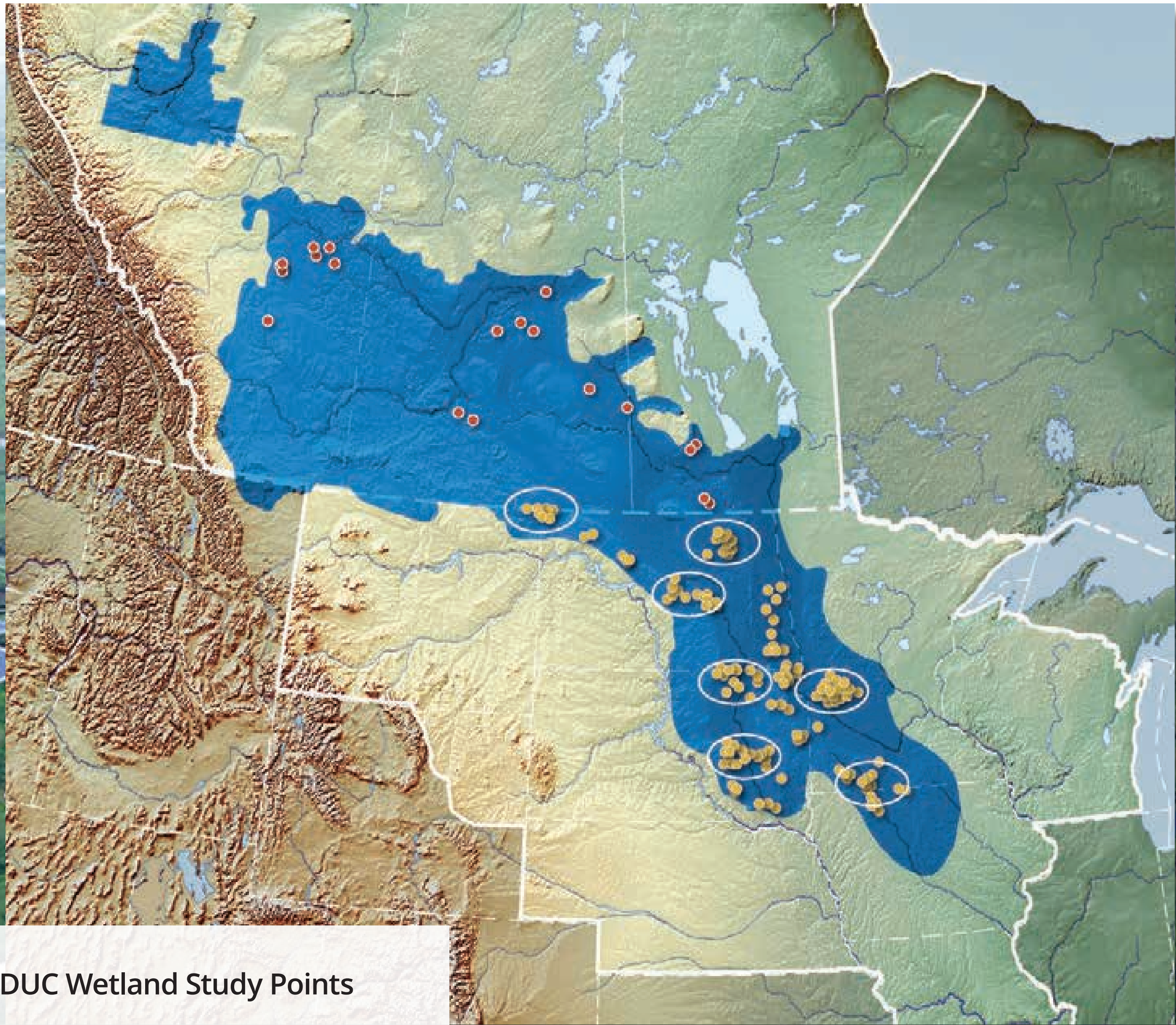
Fort Nelson Feasibility Project

Investigated the feasibility that CO_2 from a commercial natural gas-processing facility can be safely and cost-effectively stored in a deep carbonate saline formation.

Bell Creek Demonstration

Demonstrating that commercial EOR operations with simultaneous CO_2 storage can safely and cost-effectively store regionally significant amounts of CO_2.

Prairie Pothole Region



The Prairie Pothole Region (PPR) is a major biogeographical region that encompasses approximately 900,000 km^2.[47] This region accounts for up to 70% of wild duck production in North America [48] and provides important breeding and migratory grounds for many types of wildlife. The prairie potholes also provide many other ecological benefits, such as reducing erosion, improving water quality, buffering floods and storms, and providing recreational opportunities. However, as cultivated agriculture became the dominant land use, there was an extensive loss of native wetlands, resulting in the loss of significant amounts of soil organic carbon.

Terrestrial Sequestration

As part of the PCOR Partnership Program, the EERC; Ducks Unlimited (DU); Ducks Unlimited Canada, Inc. (DUC); the U.S. Geological Survey (USGS) Northern Prairie Wildlife Research Center; and North Dakota State University (NDSU) demonstrated optimal practices for storing CO_2 at multiple terrestrial sites located in the PPR.

A terrestrial field validation test was initiated to develop the technical capacity to systematically identify, develop, and apply alternate land use management practices to the prairie pothole ecosystem (at both the local and regional scale) that result in net GHG reductions and marketable carbon offsets. These land use management practices also contribute to improvements in water management and soil health.

As part of this project, soil and gas samples were collected from restored grasslands, native prairie, cropland, and wetlands of various age from throughout the PPR. In addition to carbon uptake and storage measurements, CH_4 and N_2O gas fluxes were measured to estimate the net GHG flux of each management practice. These data have been instrumental in advancing terrestrial carbon credits in the marketplace.

The project also demonstrated that restoration of previously farmed wetlands results in the rapid replenishment of soil organic carbon lost to cultivation at an average rate of 0.4 tonnes per hectare per year.[49] The fact that restored prairie wetlands are important carbon sinks provides a unique and previously overlooked opportunity to store atmospheric carbon in the PCOR Partnership region.

Zama Field Validation Test

The Zama oil field in northwestern Alberta, Canada, covers an area of about 1200 km^2. Oil production in the Zama Field is primarily from reservoirs in pinnacle reefs. To date, over 800 pinnacles have been discovered in the Zama subbasin, with an average size of about 0.16 km^2 at the base and about 120 m high.

CO_2-Rich Gas in a Pinnacle Reef Structure

In October 2005, the Zama oil field became the site of acid gas (approximately 70% CO_2 and 30% H_2S [hydrogen sulfide]) injection for the simultaneous purpose of EOR, H_2S disposal, and CO_2 storage. Injection took place at a depth of 1500 m into a carbonate pinnacle reef structure.

The PCOR Partnership conducted MVA activities at the site through September of 2009, while Apache Canada, Ltd., managed the injection and hydrocarbon recovery processes.

Acid Gas Beneficial Use

Acid gas is a by-product of oil production in the Zama Field and a subsequent fluid separation process at the on-site facilities. During the separation process, oil and gas are sent to market, while acid gas is redirected back to the field for utilization in EOR operations. Before this project, the CO_2 portion of the acid gas was vented to the atmosphere, and sulfur was separated from the H_2S 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.

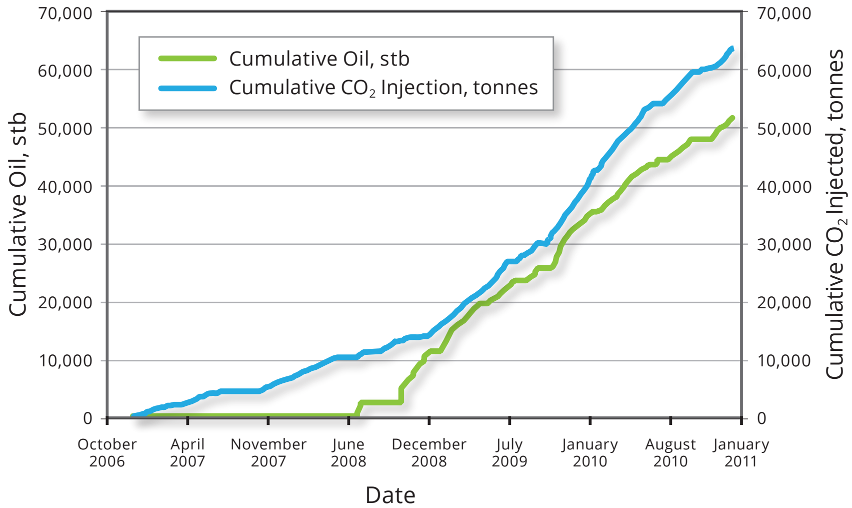
MVA

The MVA portion of the Zama project addressed three primary issues at EOR sites:

1. Verification of CO_2 and H_2S storage.
2. Development of reliable predictions regarding the long-term fate of injected acid gas.
3. Generation of data sets to support the development and monetization of carbon credits associated with the geologic storage of CO_2.

The geological and geochemical investigations were conducted at local and regional (subbasinal) scales. Geological results indicate that the likelihood of natural leakage from this system is low and regional flow is extremely slow, on the order of thousands to tens of thousands of years to migrate out of the basin. Monitoring of the site was achieved primarily through fluid sampling and pressure monitoring in both the target pinnacle reef and overlying strata.

Cumulative Oil and Injected CO_2 Zama F Pool

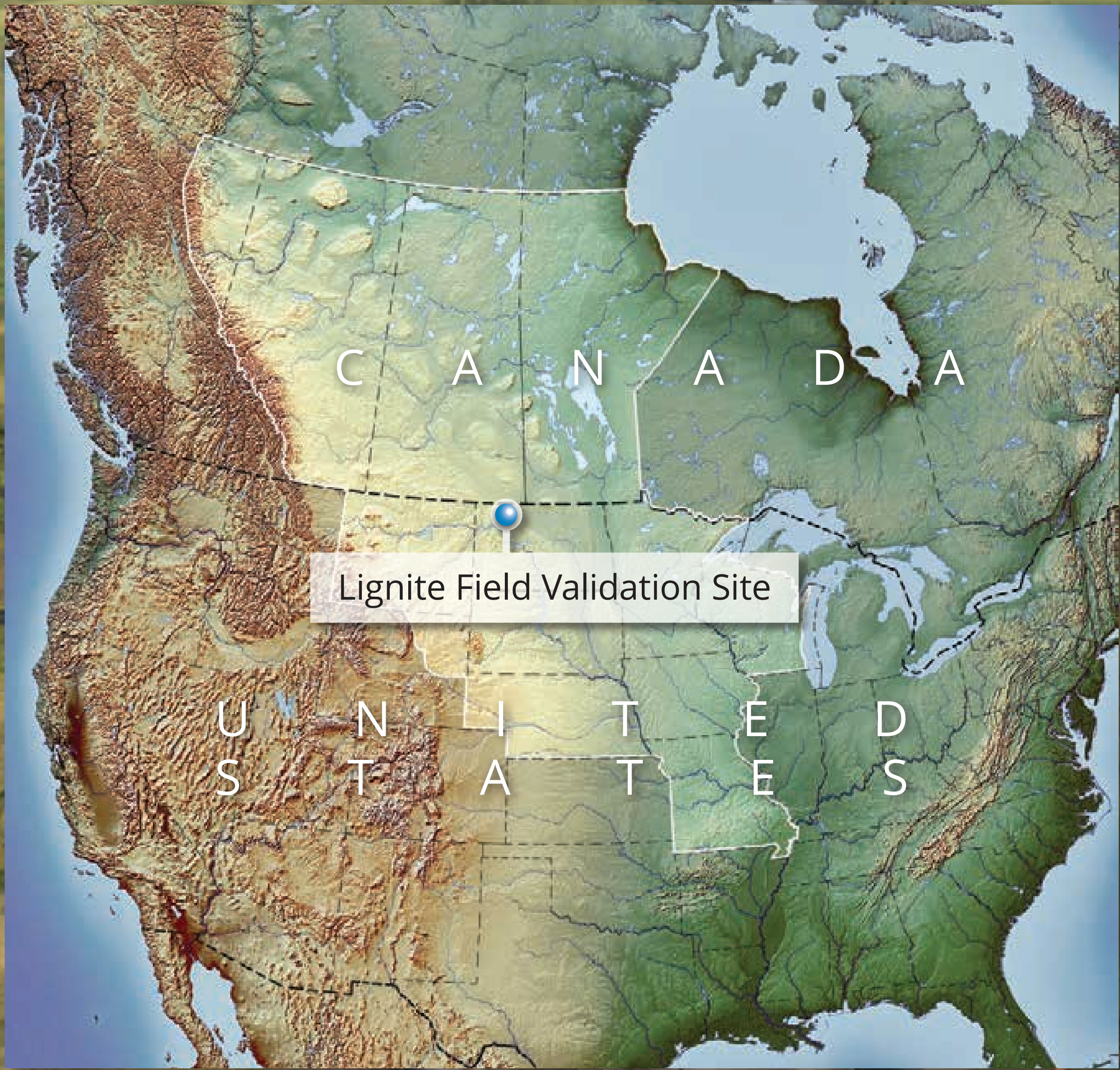


Over 65,000 tonnes of CO_2 has been utilized for EOR operations, resulting in an additional 52,000 barrels of oil production. Although this project was focused on one of the hundreds of pinnacle reefs that exist in the Zama Field, many of the results can be applied to additional pinnacles in the Alberta Basin and also to similar structures throughout the world.

carbon sequestration leadership forum

This project is recognized by the international Carbon Sequestration Leadership Forum as being uniquely qualified to fill technological gaps with regard to geologic storage of CO_2.

Lignite Field Validation Test



A significant acreage of deeply buried unminable coal is present in the Williston Basin. Regional-scale evaluations indicate that lignite coal in the Williston Basin has the potential to store over 100 years of CO_2 emissions from coal-fired power plants in North Dakota.

CO_2 in an Unminable Lignite Seam

From 2005 to 2009, a field validation test was conducted in Burke County, North Dakota, to determine the fate of CO_2 injected into a representative lignite coal seam and to uncover the potential for ECBM production.

CO_2 Injection

Approximately 90 tons of CO_2 was injected over roughly a 2-week period into a 3–4-m-thick coal seam at a depth of 330 m. CO_2 injection was accomplished using a single injection well, which was surrounded by four monitoring wells. These monitoring wells employed various technologies to track the presence and movement of CO_2 in the lignite coal seam.

MVA

MVA strategies were selected based on the characteristics of the site and included a combination of many techniques. Of these techniques, reservoir saturation tool logs and time-lapse crosswell seismic tomography provided the most valuable information. These techniques demonstrated that the CO_2 did not significantly move away from the wellbore and was contained within the coal seam for the duration of the 3-month monitoring period.

Results

This validation test demonstrated the overall feasibility of injecting CO_2 into coal seams at the field scale. It was safely executed, suggesting that similar equipment could be deployed and comparable operations could be successfully implemented at other field sites.

Northwest McGregor Field Validation Test

Williston Basin oil fields may have over 500 Mt of CO_2 storage resources with potential EOR operations. Oil is produced from at least a dozen rock formations at depths ranging from less than 1000 m to greater than 4300 m. This field validation test evaluated the effectiveness of CO_2 for EOR and storage using huff 'n' puff techniques at depths greater than 2440 m into a fractured carbonate reservoir.

CO_2 in a Deep Oil Reservoir

The PCOR Partnership, working closely with Eagle Operating, Inc. (Eagle), conducted field, laboratory, and modeling activities to determine the effects of injecting CO_2 into a carbonate formation in the Northwest McGregor oil field in North Dakota. The activities evaluated the potential dual purpose of CO_2 storage and EOR in carbonate rocks deeper than 2440 m. A technical team that included Eagle, the EERC, Praxair, and Schlumberger Carbon Services conducted a variety of activities to inject CO_2 into the target oil reservoir using a huff 'n' puff approach and evaluated the effect that injected CO_2 has on the ability of the oil reservoir to store CO_2 and produce incremental oil.

Huff 'n' Puff

A CO_2 huff 'n' puff test was conducted for a well producing oil from a formation at a depth of approximately 2450 m in the Northwest McGregor oil field. As an initial pilot-scale test, 400 tonnes of CO_2 was injected into a single well and allowed to "soak" for several weeks (the huff). The well was then placed back into production, and the amount of incremental petroleum fluids produced was measured (the puff).

Huff 'n' puff operations can be an effective means of evaluating the response of a reservoir to CO_2, both with respect to EOR and CO_2 storage. The approach is economically attractive because small-volume injections yield adequate results to determine the efficacy of larger-scale CO_2 injection.

Results

Overall, the results of the field demonstration indicate that:

- CO_2-based huff 'n' puff operations are a technically viable option for improved oil recovery in deep carbonate oil reservoirs.
- Deep carbonate oil reservoirs are reasonable targets for large-scale CO_2 storage, even those with relatively low primary permeability, such as had been reported at the Northwest McGregor Field.

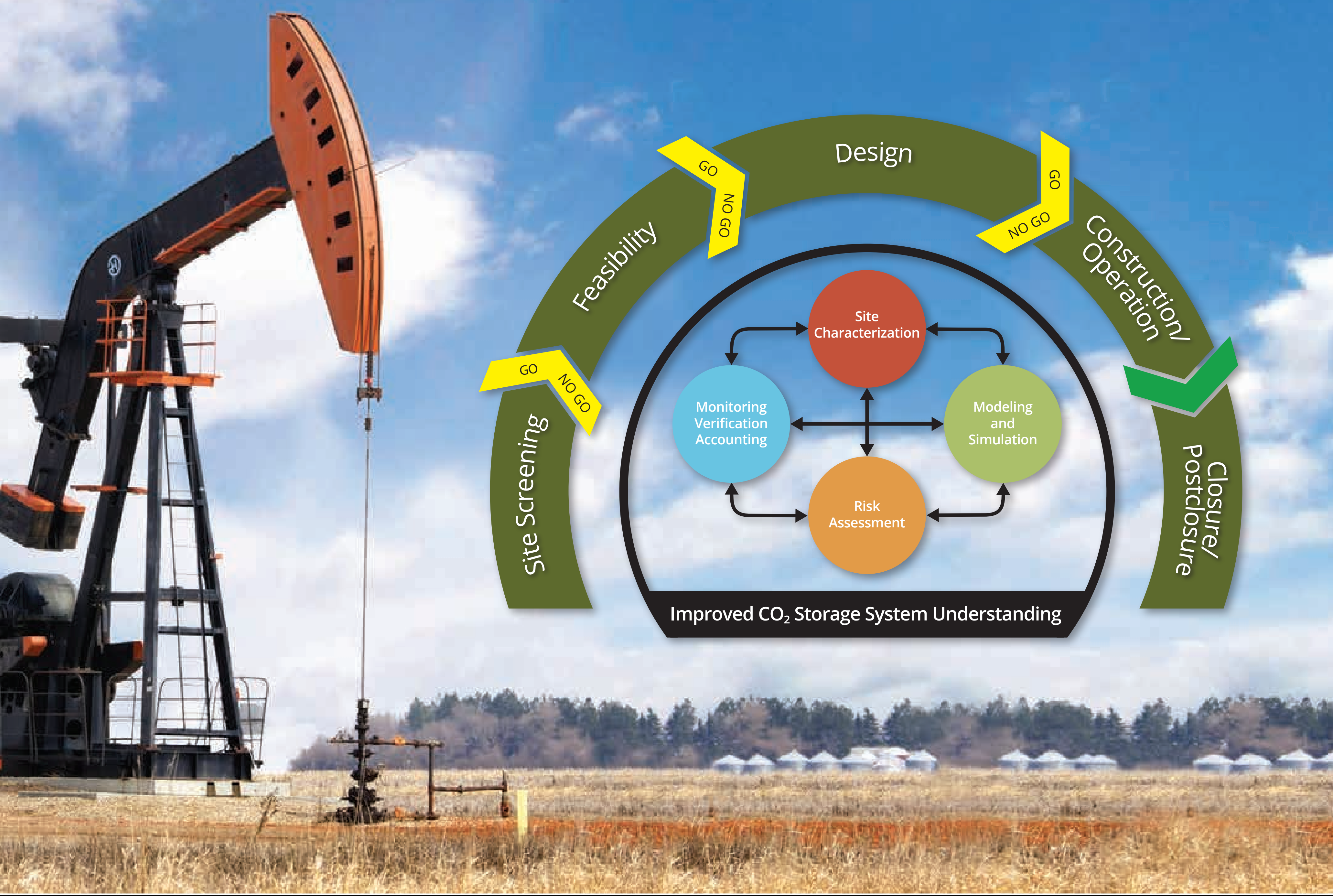
Commercial-Scale Demonstrations

In 2007, the PCOR Partnership entered into the Development Phase scheduled to be conducted until 2018. In the third phase, the goal for the PCOR Partnership and the entire RCSP Program is to validate large-scale, long-term storage across North America.

Each of the RCSP large-volume demonstration test projects is designed to demonstrate that the CO_2 storage sites have the potential to store regionally significant quantities of CO_2 emissions safely, permanently, and economically. Results from these efforts will provide the foundation for CCS technology commercialization.

Through its role in the RCSP Development Phase, the PCOR Partnership has teamed with industrial partners to conduct two commercial-scale CCS demonstrations in the region. One of the large-scale tests investigated CO_2 storage in a saline formation, while the other is combining CCS and EOR demonstration in a project that began in 2013. Across the country, other RCSPs have begun or are planning commercial-scale demonstrations.

The PCOR Partnership developed 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 an adaptive management approach.



Monitoring, Verification, and Accounting

MVA capabilities are critical to ensuring the long-term viability of CCS: satisfying both technical and regulatory requirements. MVA is applicable to both terrestrial and geologic CO_2 storage. Terrestrial MVA must overcome difficulties in assessing carbon storage in large ecosystems (such as forests) and in gauging carbon storage potential in various types of soils. MVA for storage uses a range of existing and evolving technologies from the oil and gas industry to provide assurance that injected CO_2 remains securely stored in the reservoir.

The implementation of MVA serves to:

- Protect worker health and safety.
- Ensure environmental and ecological safety.
- Verify safe and effective storage.
- Track plume migration.
- Provide early warning for out-of-zone CO_2 mitigation.
- Confirm model predictions.
- Provide assurance for carbon credits for transactions in a carbon-trading market.

MVA Techniques

Storage techniques for MVA generally include using existing technologies in new applications, such as atmospheric and remote sensing techniques, near-surface monitoring techniques, wellbore monitoring, deep subsurface monitoring, and accounting protocols. Some of the critical challenges related to MVA include the quantification and verification of stored CO_2; development of robust, flexible accounting protocols; and reducing the cost of near-term and long-term monitoring.

Fort Nelson Feasibility Project

The carbonate saline reservoirs targeted for the Fort Nelson CCS Feasibility Project are rock types common in the PCOR Partnership region. These rock types contribute greatly to the CO_2 capacity resource currently estimated in regional saline formations.

Geologic Storage of CO_2 in a Saline Formation

The Fort Nelson project, located in northeastern British Columbia, investigated the feasibility of a CCS project to mitigate the CO_2 emissions produced by Spectra Energy Transmission's (SET's) Fort Nelson Gas Plant. A technical team that included SET, the EERC, and others conducted a variety of activities to 1) determine the geologic, geochemical, and geomechanical properties of the target injection formation and key sealing formations in the vicinity of the injection site; 2) model the effects that large-scale injection of CO_2 may have on those properties as well as wellbore integrity; 3) evaluate the geologic risks of this injection process on local and regional scales based on results of the modeling effort; and 4) design a site-specific, risk-based MVA approach and technology deployment matrix to ensure safe and effective long-term CO_2 storage.

The results of characterization, modeling, and risk assessment efforts conducted as part of the Fort Nelson CCS feasibility study suggest that a commercial-scale CCS project in the Fort Nelson area may be technically feasible. The activities were compared to the Canadian Standards Association (CSA) standard for geologic storage of CO_2. Despite the challenging project location of the potential injection site, cost-effective MVA that meets or surpasses CSA standards is achievable.

Status

The Fort Nelson project originally aimed to inject approximately 2.2 million tonnes of CO_2 annually into a deep carbonate formation for long-term geologic storage. However, because of a combination of factors, including a low-price environment for natural gas and the reduced market for natural gas in the Fort Nelson area, SET suspended the project in the spring of 2015 and has no plans to conduct further activities beyond wellsite stewardship actions. However, significant accomplishments achieved since 2008 over the life of the project included many topical reports, papers, posters, and presentations that detailed the various aspects of the Fort Nelson project, including a best practices manual for CO_2 storage in deep carbonate saline formations. The lessons learned and best practices have been applied directly to other PCOR Partnership projects discussed in this atlas such as the Bell Creek and Aquistore projects.

This project is recognized by the international Carbon Sequestration Leadership Forum as being uniquely qualified to fill technological gaps with regard to geologic storage of CO_2.

Bell Creek Demonstration Project

Because natural gas-processing plants are among the few sources of relatively pure streams of CO_2 and capture is relatively easy, they will be among the first point sources of CO_2 to be targeted for CCS and CO_2 EOR projects. The Bell Creek project uses the CO_2 produced at the Lost Cabin and Shute Creek natural gas-processing plants in Wyoming. It is one of several commercial CO_2 EOR to CO_2 geologic storage projects that use CO_2 from natural gas processing.

CO_2 Injection for Enhanced Oil Recovery

The PCOR Partnership is working with Denbury Onshore, LLC (Denbury) to determine the effect of large-scale injection of CO_2 into a deep clastic reservoir for the purpose of commercial CO_2 EOR with associated CO_2 storage at Denbury's Bell Creek oil field.

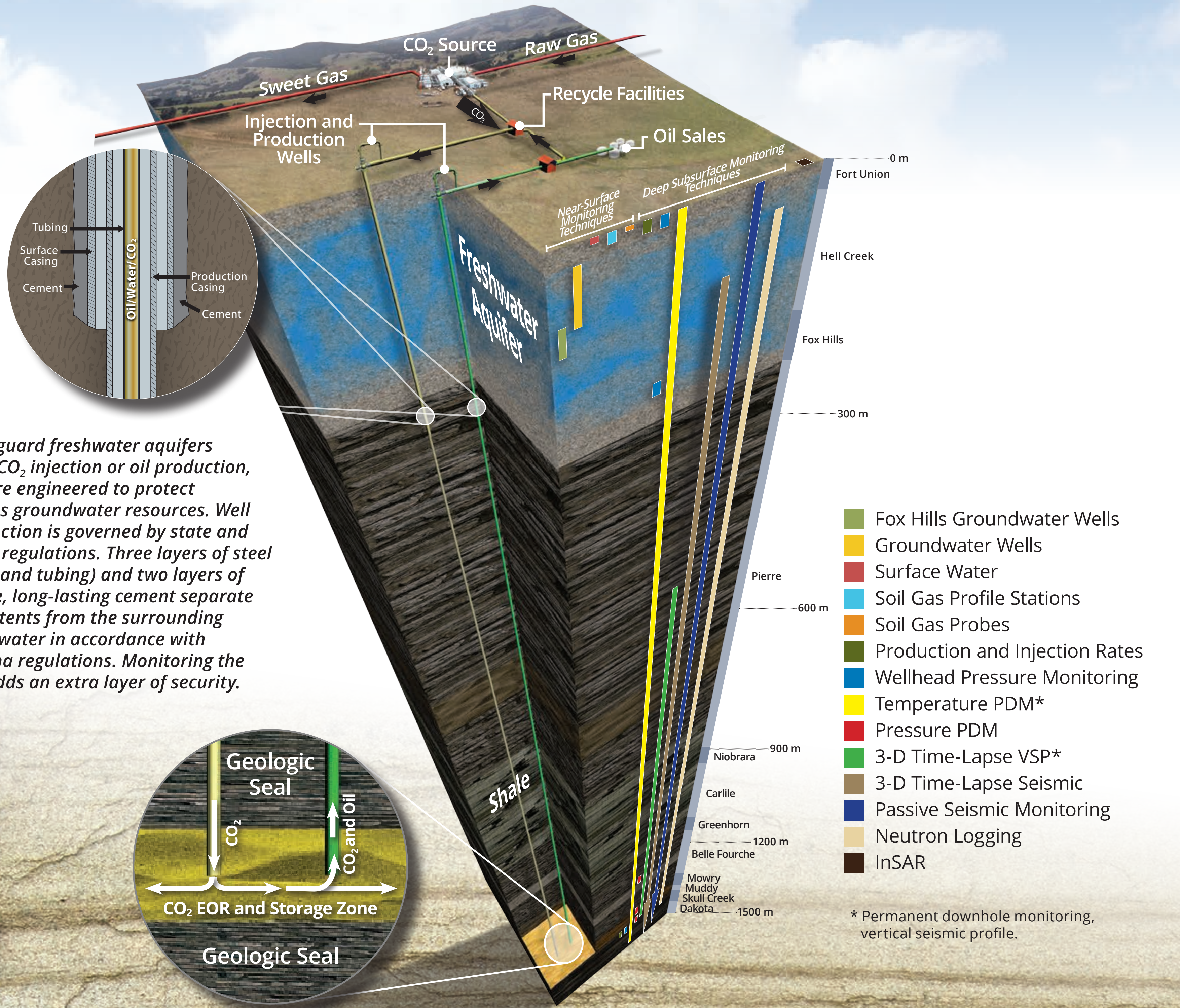
CO_2 for the project is sourced from the Lost Cabin and Shute Creek gas-processing facilities of Wyoming. The CO_2 is transported to the field at over 2600 tonnes per day via the Greencore pipeline with a tie-in from the Anadarko pipeline. The CO_2 is injected into an oil-bearing sandstone reservoir in the Muddy Formation at a depth of approximately 1400 m. CO_2 injection occurs in a staged approach (nine planned CO_2 developmental phases) across the field. The reservoir has been found to be suitable for miscible flooding conditions and is likely to meet the incremental oil production target of 40–50 million barrels. As with typical EOR procedures, recovered oil, CO_2, and water will be separated at the process/recycle facilities located on-site. Oil is sold, whereas the water and CO_2 are recycled and reinjected as part of the EOR operation.

This collaborative project is demonstrating that 1) CO_2 storage can be safely and permanently achieved on a commercial scale in association with an EOR operation, 2) oil-bearing sandstone formations are viable regional sinks for CO_2, and 3) MVA methods can be used to effectively monitor CO_2 storage in association with commercial-scale CO_2 EOR projects.

Highlights

- Injection of over 4 Mt of CO_2 (as of June 2017) since operations began at the Bell Creek site in May 2013.
- Completion of the collection of relevant baseline MVA data to aid in evaluating site security, accounting, and location of the lateral and vertical extent of CO_2 in the Bell Creek oil field.
- Production of a 20-minute video intended to acquaint a technical audience with the basics of casing-conveyed permanent downhole monitoring systems, as well as the unique field installation practices these systems require.
- Creation of a half-hour broadcast documentary that presents an overview of Denbury's commercial CO_2 EOR program at Bell Creek and its integration with the PCOR Partnership's investigation of associated CO_2 storage.

Bell Creek – Layers of Security

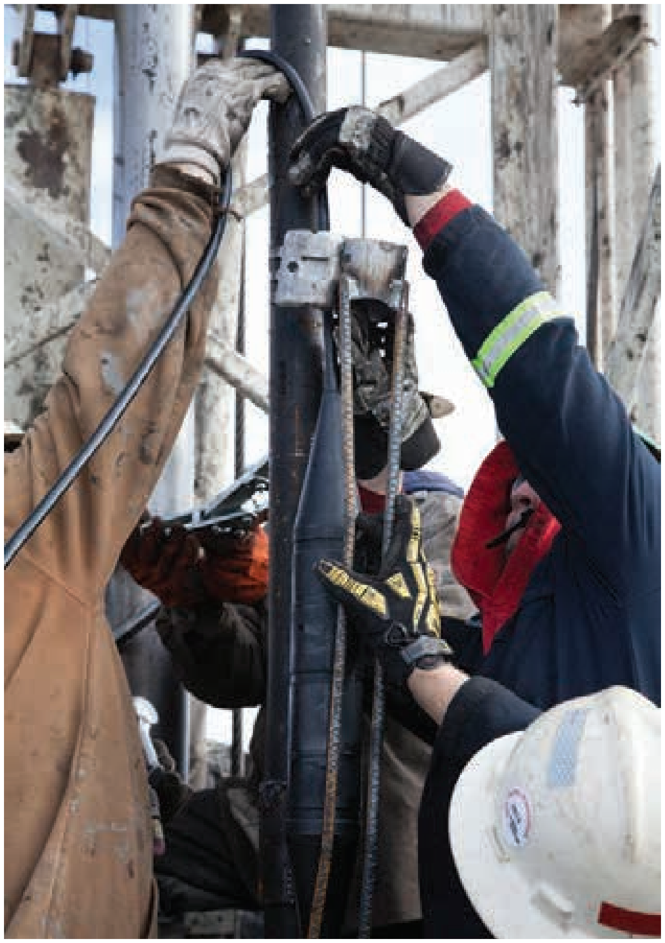


To safeguard freshwater aquifers during CO_2 injection or oil production, wells are engineered to protect precious groundwater resources. Well construction is governed by state and federal regulations. Three layers of steel (casing and tubing) and two layers of durable, long-lasting cement separate the contents from the surrounding groundwater in accordance with Montana regulations. Monitoring the wells adds an extra layer of security.

Site Characterization

The PCOR Partnership philosophy for conducting site characterization activities is to gain as much understanding of the subsurface and near-surface environment as possible from the available data sets and to maximize the utility of any new data sets generated. Baseline 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.

As part of the Bell Creek study, an EERC technical team conducted a robust characterization of the reservoir and surrounding subsurface strata of the Bell Creek oil field prior to injection from 2010 to 2013. These site characterization activities were conducted to establish baseline characteristics of the reservoir, assess the viability of the reservoir in the context of CO_2 storage, evaluate and predict reservoir and seal performance and behavior during both the injection and postinjection phases of the project, and guide monitoring efforts to track and account for CO_2 in the subsurface.



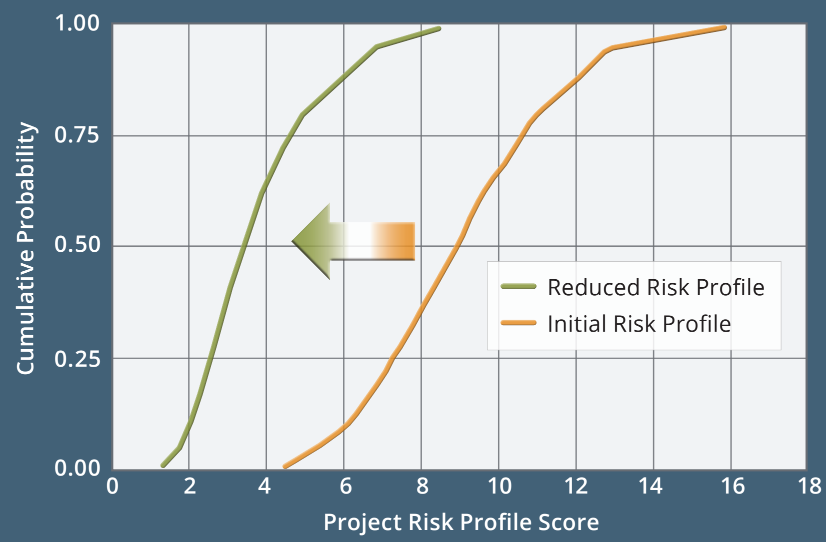
Risk Assessment, Simulation, and Modeling

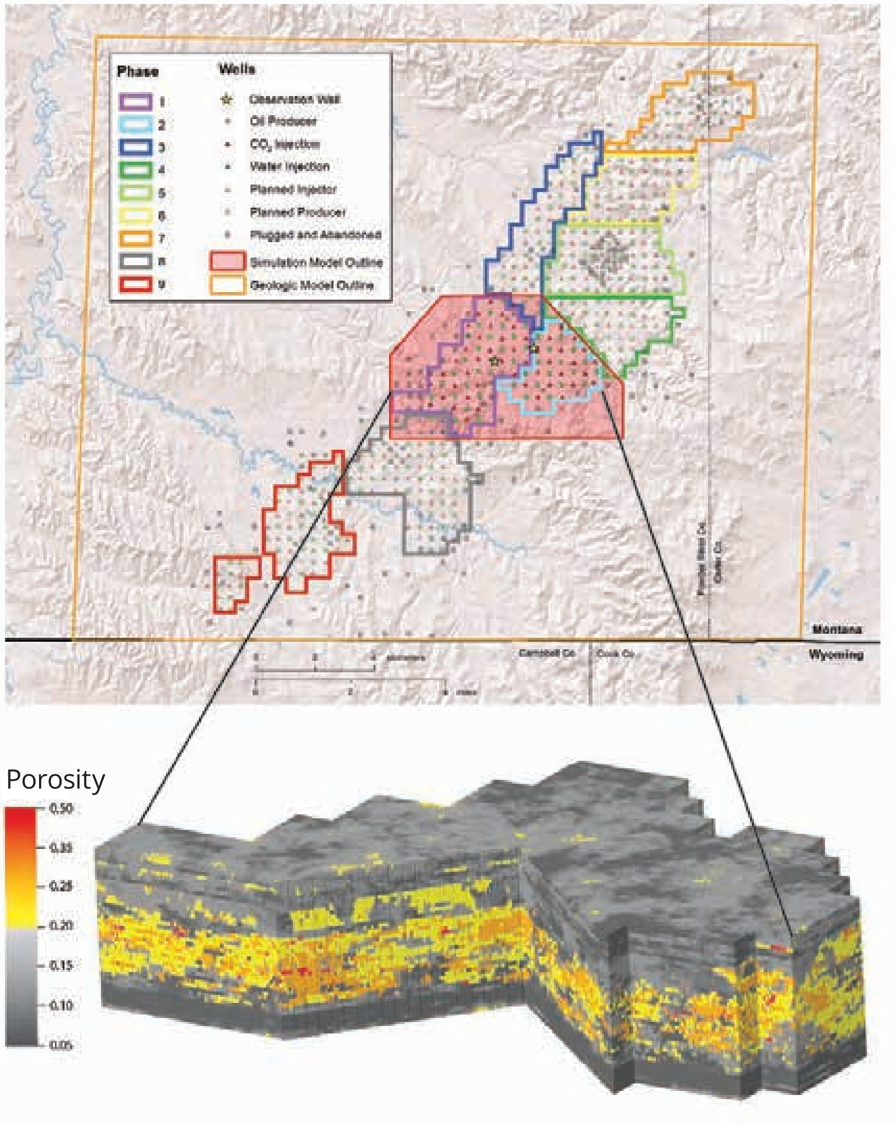
A wide variety of modeling activities have been conducted at the Bell Creek site, including multiple-sized geologic models, predictive multiphase fluid flow simulations, geomechanical modeling, and geochemical simulation. These models and simulations are used to interpret and analyze the geologic, reservoir, and fluid data and conduct predictive multiphase flow, geomechanical, and geochemical simulations to identify data gaps, identify potential risks, and guide the MVA program.

Risk management, modeling, and MVA are interrelated processes, where the results of one become the inputs of the others. This creates an iterative process to manage the risks throughout the life of the project. In the initial risk assessment, the EERC project team identified and evaluated 120 potential subsurface technical risks that were grouped into broad categories (e.g., capacity, injectivity, and retention; lateral migration; vertical migration).

Technical risks identified were determined to be adequately addressed by the current MVA program. Most risks are being monitored using more than one measurement, providing multiple lines of evidence for inferring migration of CO_2 or other fluids beyond the reservoir.

Additionally, 24 strategic risks were identified (e.g., CO_2 supply, management or policy changes) and assessed. None was found to have significant potential to negatively impact the project.





Muddy S.S (Bell Crek Field reservior)

The goal of the MVA program is to provide critical data to verify site security, evaluate reservoir behavior during injection, determine the ultimate fate of injected CO_2, and investigate mechanisms that affect CO_2 storage efficiency within the EOR process, all while operating in a manner compatible with the commercial CO_2 EOR operation. The MVA program uses time-lapse data acquisitions as part of a surface-, shallow subsurface-, and deep subsurface-monitoring effort guided by the PCOR Partnership adaptive management approach.

A suite of technology options is available for MVA programs, each technique having distinct capabilities, limitations, and costs. Further, each storage site has unique characteristics that can dictate the effectiveness of the various techniques. For this reason, the PCOR Partnership has designed a monitoring program specific to the needs of the Bell Creek Field that monitors a variety of physical phenomena using several commercially available technologies. The specific technologies selected are also designed to operate in a complementary manner where an anomalous detection from one monitoring technique can be investigated using one or more of the remaining techniques to confirm whether an issue exists. Additionally, the PCOR Partnership is evaluating each of these monitoring technologies to understand their benefits, limitations, and challenges when deployed in conjunction with a commercial CO_2 EOR operation.

Basal Cambrian Project

The oldest layers of sedimentary rock in the northern Great Plains region are dated to the Cambrian and Ordovician periods of geologic time—590 to 408 million years ago. These rock layers, consisting of sandstones, carbonates, and shales, attain thicknesses up to 305 m and reach depths of 4250 m in the center of the Williston Basin. This sequence of sedimentary rock contains very salty water (up to 10 times as salty as ocean water) and is referred to as the Cambro-Ordovician Saline System (COSS).

A 3-year binational effort between the United States and Canada was initiated to characterize a 1.34-million-km^2 area of the COSS across the northern Great Plains–Prairie region of North America and determine its CO_2 storage resource. To date, no other studies have attempted to characterize the storage resource potential of large, deep saline systems that span the U.S.–Canada international border. Significant effort was devoted to understanding the geologic and hydrogeologic architecture of the COSS and its CO_2 storage resource. Stratigraphically, the COSS is the lowermost saline system in the region and is dominated by thick, clean sandstone in Alberta and grades into alternating sandstone, shale, and carbonate lithologies in west-central North Dakota.

The results of this study show the COSS to be a large and viable target for the long-term geologic storage of anthropogenic CO_2. Modeling and simulation results indicate that although injectivity may be a challenge, it can be overcome through the use of multiple injection wells and with distribution of the CO_2 to areas of better geologic properties.

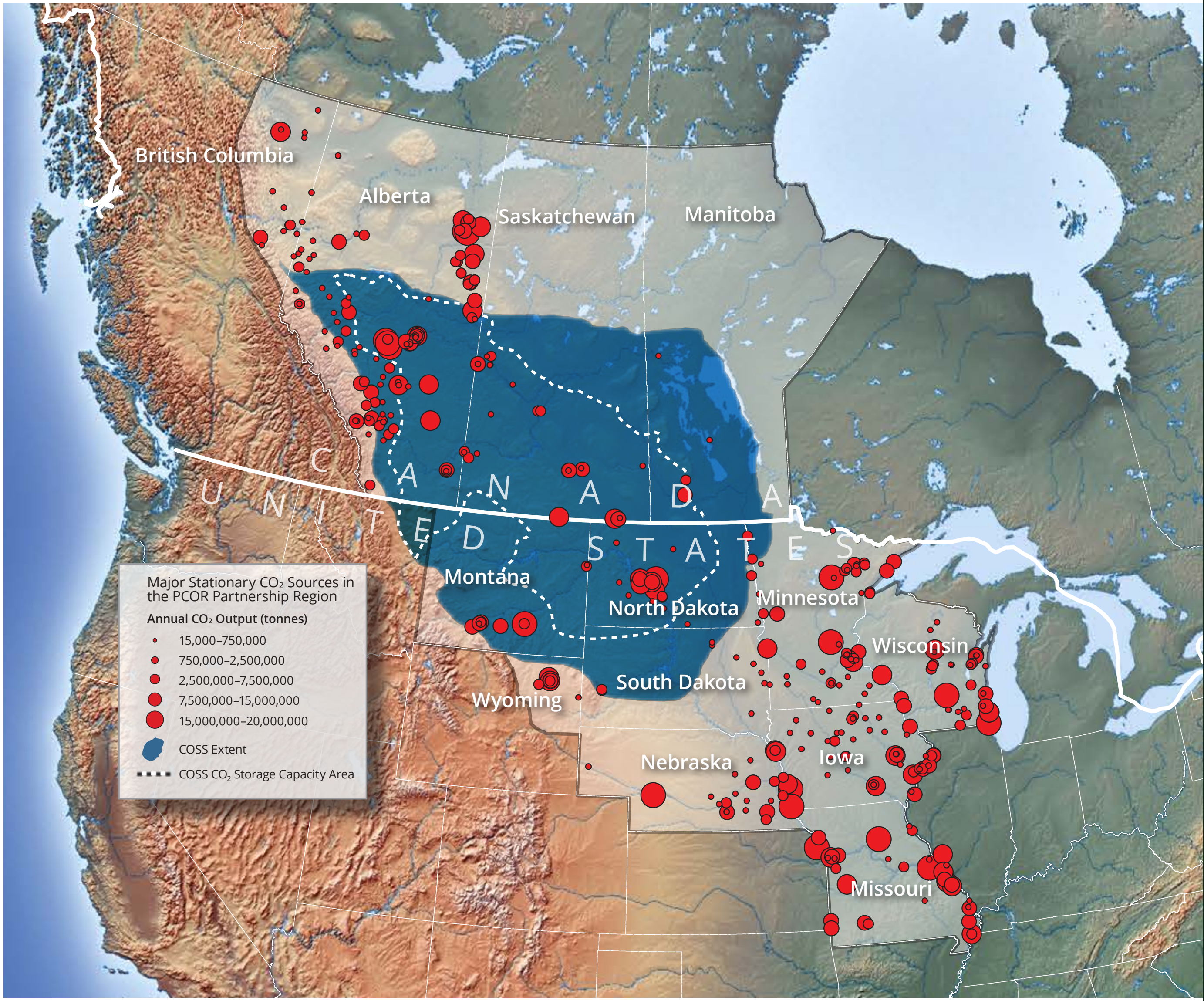
This binational collaborative effort was led on the U.S. side by the EERC through the PCOR Partnership and on the Canadian side by Alberta Innovates – Technology Futures (AITF). Other partners include:

- DOE
- Lawrence Berkeley National Laboratory
- Princeton University
- Saskatchewan Industry and Resources
- Manitoba Water Stewardship
- Manitoba Innovation – Energy and Mines
- CanmetENERGY
- Natural Resources Canada
- TOTAL E&P Ltd.
- University of Regina Petroleum Technology Research Centre (PTRC)
- North Dakota Geological Survey

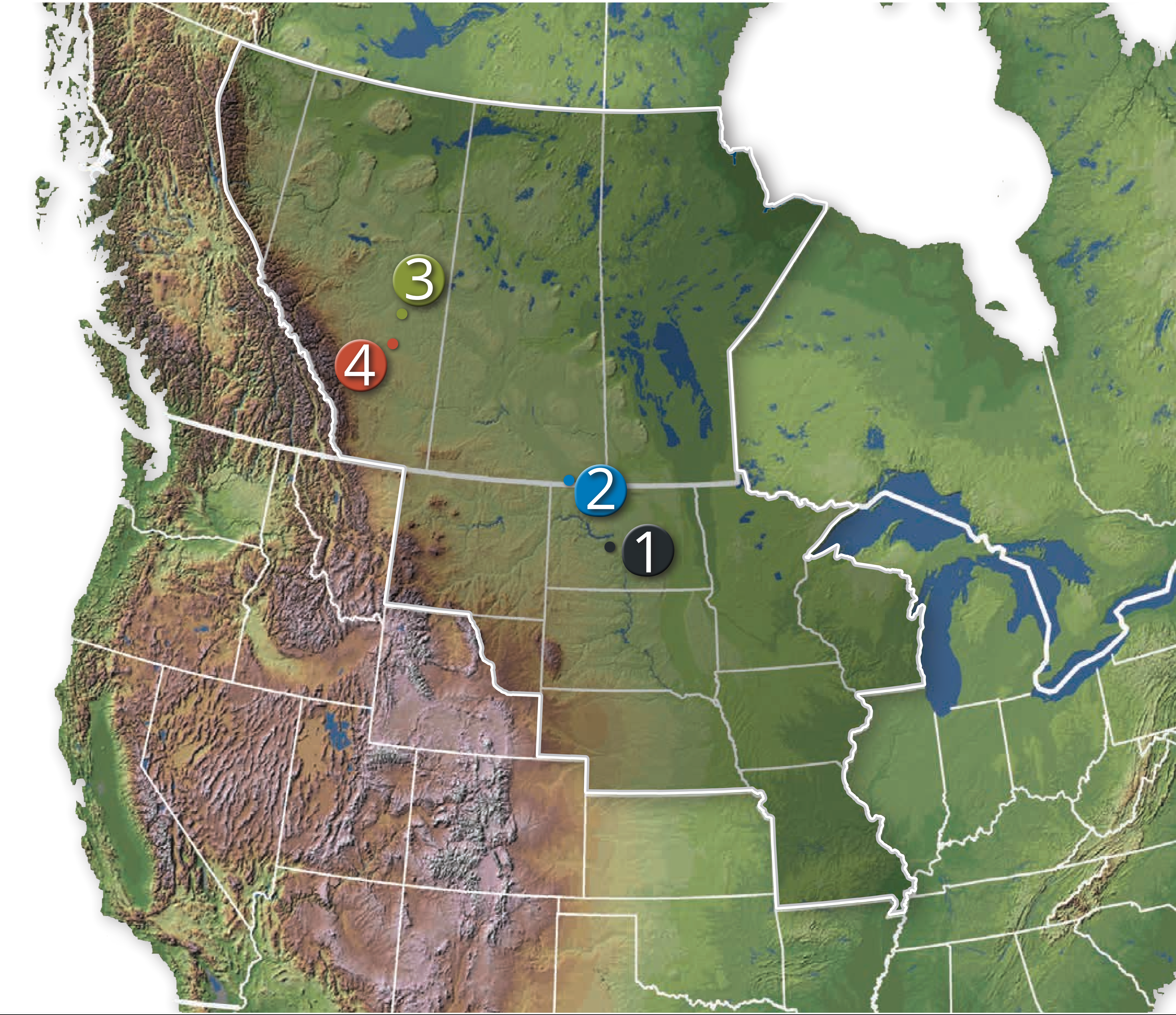
The area of the basal saline system suitable for CO_2 storage was determined using the following criteria: a) CO_2 should be stored at a lateral distance greater than 20 km from protected groundwater resources in the formation, b) porosity should be greater than 4% to ensure storage resource and injectivity, and c) CO_2 should be stored at a depth to ensure it is in a dense phase. The storage resource was estimated using thickness, porosity, and CO_2 density calculated at in situ conditions and using a storage efficiency factor. Assuming no increase in CO_2 emissions from the large stationary sources in the region and a capture efficiency of 90%, the P_{50} storage resource identified in this study will suffice to store CO_2 from these sources for over 700 years.

Range of CO_2 Storage Resource Estimates for the Portion of the COSS Suitable for CO_2 Storage at the P_{10}, P_{50}, and P_{90} Probability Levels

Probability		P_{10}	P_{50}	P_{90}
Saline Formation Efficiency Factor		1.2%	2.4%	4.1%
CO_2 Storage Resource	United States	14 Gt	28 Gt	48 Gt
	Canada	43 Gt	85 Gt	145 Gt
	Total	57 Gt	113 Gt	193 Gt



Demonstrating CCS Throughout the Region



The PCOR Partnership region in central North America has extensive fossil fuel resources and ideal geologic characteristics to support CCS deployment. As a result, a handful of CCS projects around the region are moving CCS technology forward to commercialization. In addition to the efforts of the PCOR Partnership, multiple collaborative efforts are under way with support from various government, industry, and research entities to facilitate the development and wide-scale deployment of CCS. The following list highlights a select number of these projects:

1. Great Plains Synfuels Plant, North Dakota (p. 96)

The Dakota Gasification Company has captured and transported CO_2 since 2000 at a rate of approximately 3 Mt per year via a 330-km pipeline to the Weyburn and Midale oil fields in southern Saskatchewan, Canada, for EOR purposes (p. 97).[50] These oil fields also provided the basis for a major international research effort on storage: the IEA Greenhouse Gas R&D Programme (IEAGHG) Weyburn–Midale CO_2 Monitoring and Storage Project (p. 97).

2. Boundary Dam Carbon Capture Project, Saskatchewan (p. 98)

SaskPower completed the rebuilding of Unit 3 at this coal-fired power station and began the capture of CO_2 in October 2014; at the end of September 2016, SaskPower reported that 1.15 Mt of CO_2 had been captured.[51] The project is designed to operate at a maximum rate of 1 Mt per year; the majority of captured CO_2 is transported by pipeline to the Weyburn oil field for EOR. Unsold CO_2 is diverted into a branch of the pipeline to the Aquistore site (p. 99) for dedicated storage.

3. Quest CCS Project, Alberta

Shell Canada commenced CO_2 capture from industrial hydrogen production (a heavy oil upgrader) in November 2014 and celebrated 1 Mt of capture within the first year of operations.[52] All captured CO_2 is transported by a 66-km pipeline to a dedicated storage site, also operated by Shell.

4. Alberta Carbon Trunk Line Project, Alberta

Construction of a 240-km pipeline by Enhance Energy will allow captured CO_2 from industrial sources to the north of Edmonton to be used for EOR at the Clive oil field.[53] Scheduled for operation during 2017, initial CO_2 supplied will be from an Agrium fertilizer plant (up to 0.6 Mt per year) and from the North West Sturgeon Refinery (up to 1.4 Mt per year).[54] The pipeline will be constructed with a capacity to transport up to 14.6 Mt per year to cater to additional future capture sources and EOR or dedicated storage opportunities.

CO_2 Capture at Great Plains Synfuels Plant

The CO_2 used in the Weyburn–Midale project comes from the Dakota Gasification Company's Great Plains Synfuels Plant, the only commercial-scale coal gasification plant in the United States that manufactures synthetic natural gas. Today, the synfuels plant exports about 7900 tonnes a day of CO_2 to Canada—about 50% of the CO_2 produced when running at full rates. As of December 31, 2014, the synfuels plant had captured more than 29 Mt of CO_2.

Photo courtesy of Basin Electric Power Cooperative.

CO_2 is captured from the Dakota Gasification Company's Great Plains Synfuels Plant in Beulah, North Dakota, United States, and piped 330 km into the Weyburn and Midale oil fields in Saskatchewan, Canada, for EOR. The injection location covers an area of 21,000 hectares and produces 20,000 barrels of oil a day.

The Weyburn and Midale Oil Fields and Associated IEAGHG Weyburn–Midale 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 is operated by Cenovus Energy, and by January 2016, approximately 27 Mt of CO_2 had been stored in the field[56]—mainly sourced from Great Plains but with an additional supply of CO_2 from Boundary Dam since 2014. The Midale Field is operated by Apache Canada and as of September 2016 had stored approximately 9 Mt of CO_2 sourced exclusively from Great Plains.[57] The sale of CO_2 from the Dakota Gasification Company to Cenovus Energy and Apache Canada also represents the first instance where large quantities of captured CO_2 have been traded across an international border.

Also beginning in 2000, the IEAGHG Weyburn CO_2 Monitoring and Storage Project used the Weyburn oil field and EOR operations as an opportunity to study large-scale injection and storage of CO_2 in the subsurface. Managed by PTRC, this first phase of research was completed and reported in 2004.[58] A second and final phase of research conducted between 2004 and 2012, again managed by PTRC, incorporated the Midale oil field and was reported in a supplemental issue of the *International Journal of Greenhouse Gas Control*.[59] The project demonstrated, over both phases of research, secure storage of injected CO_2 in the reservoir and the successful deployment of existing monitoring technologies to track the subsurface movement of CO_2. The research was used to compile best practices for storage in relation to site characterization, predictive modeling, monitoring, history matching, performance validation, well integrity, risk assessment, and community outreach.[60]

Supplies from Great Plains to Weyburn and Midale represent the first case where CO_2 has been traded between two countries.

PTRC Final-Phase Project Partners

- Alberta Innovates
- Apache Canada
- Aramco Services Company
- Cenovus Energy
- Chevron Corporation
- Dakota Gasification Company
- IEAGHG
- Natural Resources Canada
- Nexen Inc.
- OMV
- Research Institute of Innovative Technology for Earth
- Saskatchewan Ministry of Energy and Resources
- SaskPower
- Schlumberger Carbon Services
- Shell Canada Limited
- DOE

CO_2 Capture at Boundary Dam

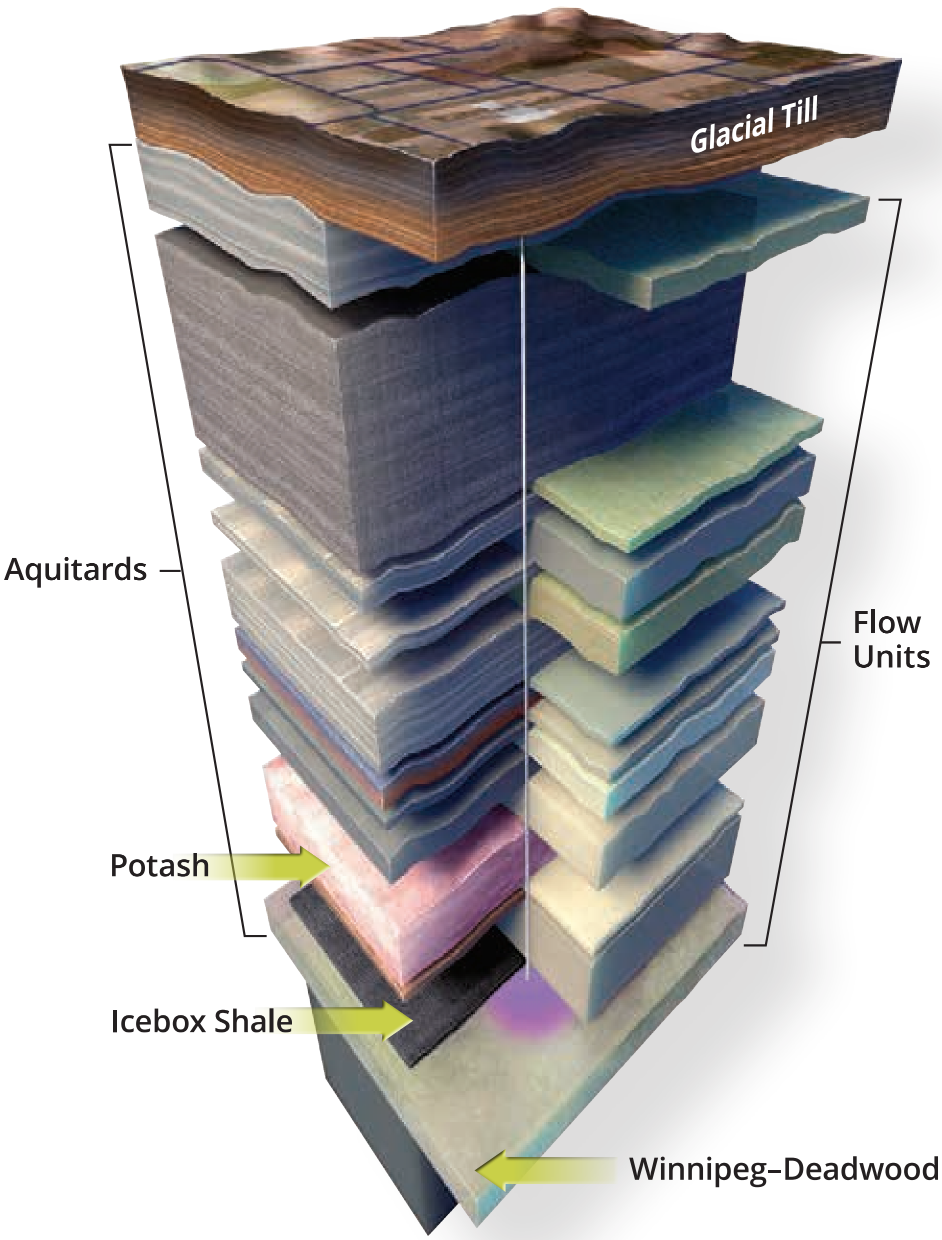
The Boundary Dam Carbon Capture Project is the world's first commercial-scale, fully integrated CCS project at a coal-fired power station, with postcombustion capture of CO_2 from the rebuilt Unit 3. The capital cost of Can$1.2 billion was supported by funding from the provincial government of Saskatchewan and the federal government of Canada. Operated by the government-owned utility SaskPower, the project is designed to capture up to 1 Mt of CO_2 per year; between the commencement of operations in October 2014 and October 2016, SaskPower reported that 1.15 Mt had been captured.[51]

Unit 3 provides 115 MW of power.[61] 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 (p. 97), with Cenovus Energy 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 (p. 99), which is designed to provide dedicated storage for unsold CO_2.

Photo provided by and is property of SaskPower.

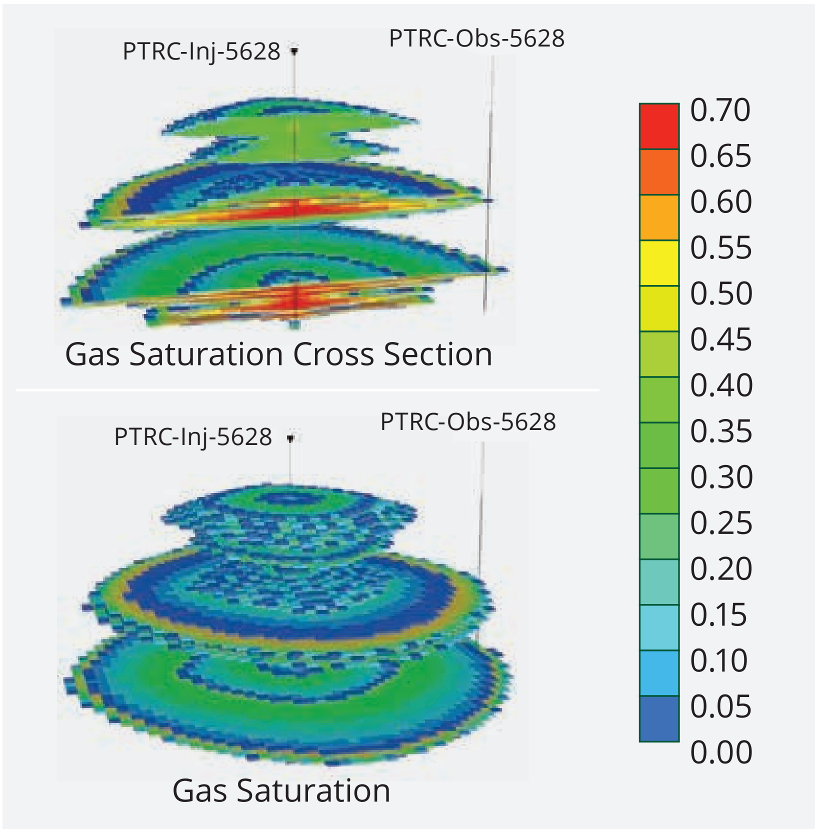
Aquistore[62] is a dual-purpose project. From a commercial perspective, Aquistore provides a dedicated storage option for unsold CO_2 from Boundary Dam—in effect, providing buffer storage so as to prevent any need for SaskPower to vent CO_2 from capture operations. Injection operations commenced in April 2015, making Aquistore the first dedicated storage project to be operating in Canada. SaskPower reported that 100,000 tonnes of CO_2 had been stored at Aquistore by November 2016.[63]



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.[64]

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

Multiple monitoring methods are under evaluation at Aquistore, representing established and novel technologies. These include cost-effective repeat 3-D seismic surveys facilitated by a permanent array of 650 surface geophones, passive seismic monitoring, and downhole monitoring including fiber-optic cables.[65]



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

Quest Carbon Capture and Storage Project

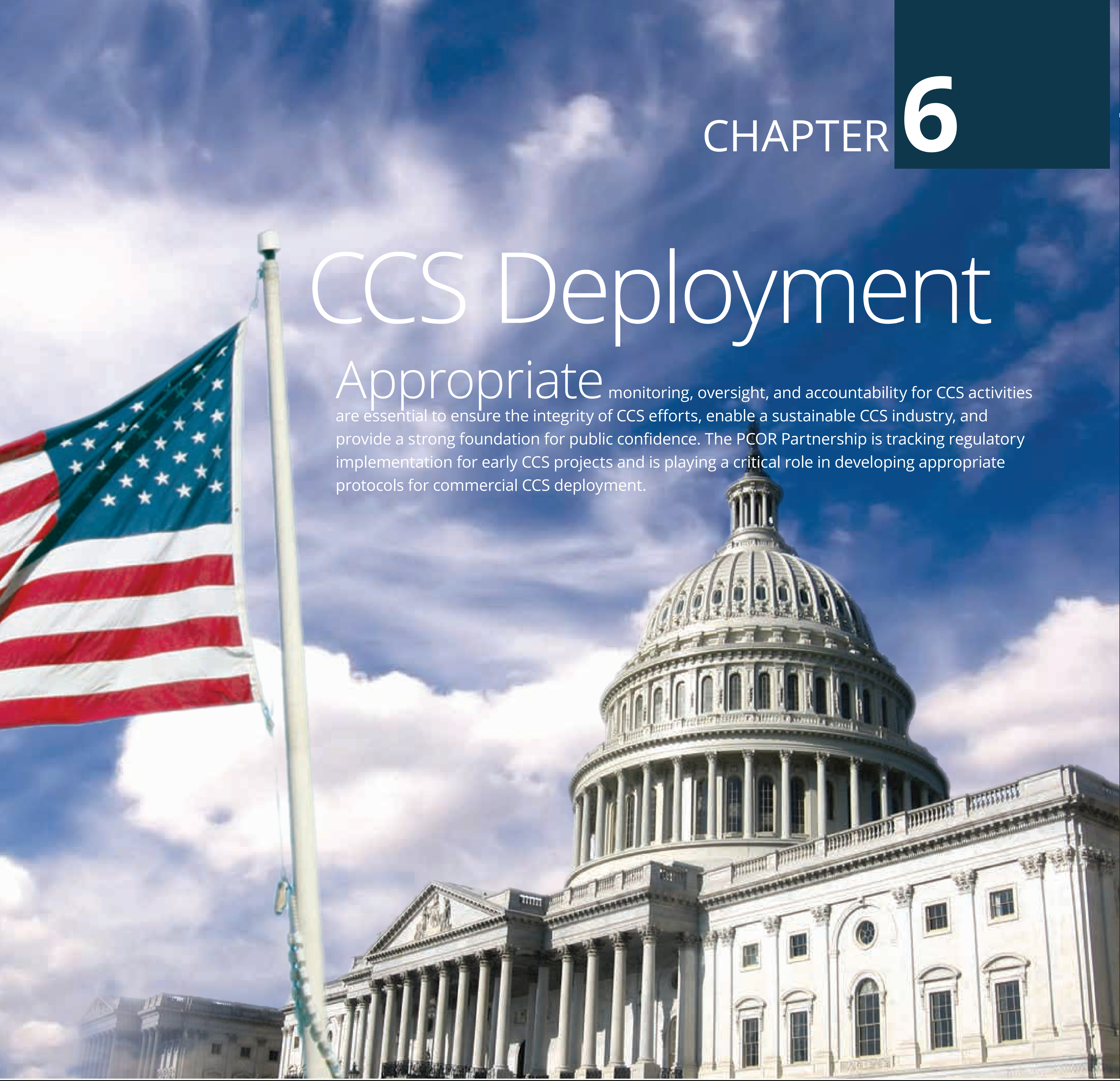
Shell Canada Energy commenced operations at Quest,[52] a fully integrated CCS project located to the northeast of Edmonton, in November 2015. The first 1 Mt of CO_2 had been successfully captured and stored by September 2016. Capital costs of the project were supported with grants from the provincial government of Alberta and the federal Canadian government; as part of these funding agreements, detailed reports and data on various aspects of the design, construction, and performance of Quest are publicly available.[66]

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 located to the north of the refinery and injected into the Basal Cambrian sandstone, a deep saline formation at a depth of around 2 km below surface. Infrastructure at the site includes three injection wells and a host of monitoring technology that provides opportunities for international research collaborations. The project is expected to store at least 27 Mt of CO_2 over the anticipated 25-year life of the upgrader,[67] although the storage reservoir has a much greater storage potential.

CHAPTER 6

CCS Deployment



Appropriate monitoring, oversight, and accountability for CCS activities are essential to ensure the integrity of CCS efforts, enable a sustainable CCS industry, and provide a strong foundation for public confidence. The PCOR Partnership is tracking regulatory implementation for early CCS projects and is playing a critical role in developing appropriate protocols for commercial CCS deployment.

The Evolution of Carbon Storage Regulations

CCS policy is taking a prominent position in the climate management debate that is occurring at national, regional, and local levels. However, because CCS is a new activity, the legal framework for it is evolving. In areas where extensive oil and gas production activities have taken place (in particular, EOR or acid gas injection), the legal framework may be relatively well advanced because of the similarity of CCS to those activities. In other jurisdictions, less of the legal framework may be in place. Government organizations—which vary by jurisdiction—may have oversight for various aspects of the CCS project, including the procedures used, 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 CCS 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 December 2016, unless otherwise noted.

PCOR Partnership Regulation Activities

International Involvement

INTERSTATE Oil & Gas COMPACT COMMISSION

Staying abreast of the latest regulatory developments is of the utmost importance for the PCOR Partnership. Participating in the Interstate Oil and Gas Compact Commission's (IOGCC's) Geological CO_2 Sequestration Task Force and Pipeline Transportation Task Force and the Presidential Interagency Task Force on CCS allows the PCOR Partnership to provide technical input to the regulation process. The PCOR Partnership also provides reviews and comments where appropriate on provincial, state, and federal rule making and reviews enacted legislation.

Regional Outreach – Regulatory Roundup

Regulatory Roundup

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.

Past Regulatory Roundup Meetings

July 22–23, 2015, Deadwood, South Dakota

June 24–25, 2014, Deadwood, South Dakota

July 30–31, 2013, Deadwood, South Dakota

July 31, 2012, Deadwood, South Dakota

October 17, 2011, Buffalo, New York

June 29–30, 2011, Bismarck, North Dakota

November 16, 2010, Tucson, Arizona

July 21–22, 2010, Deadwood, South Dakota

June 16–17, 2009, Deadwood, South Dakota

Current Regulations

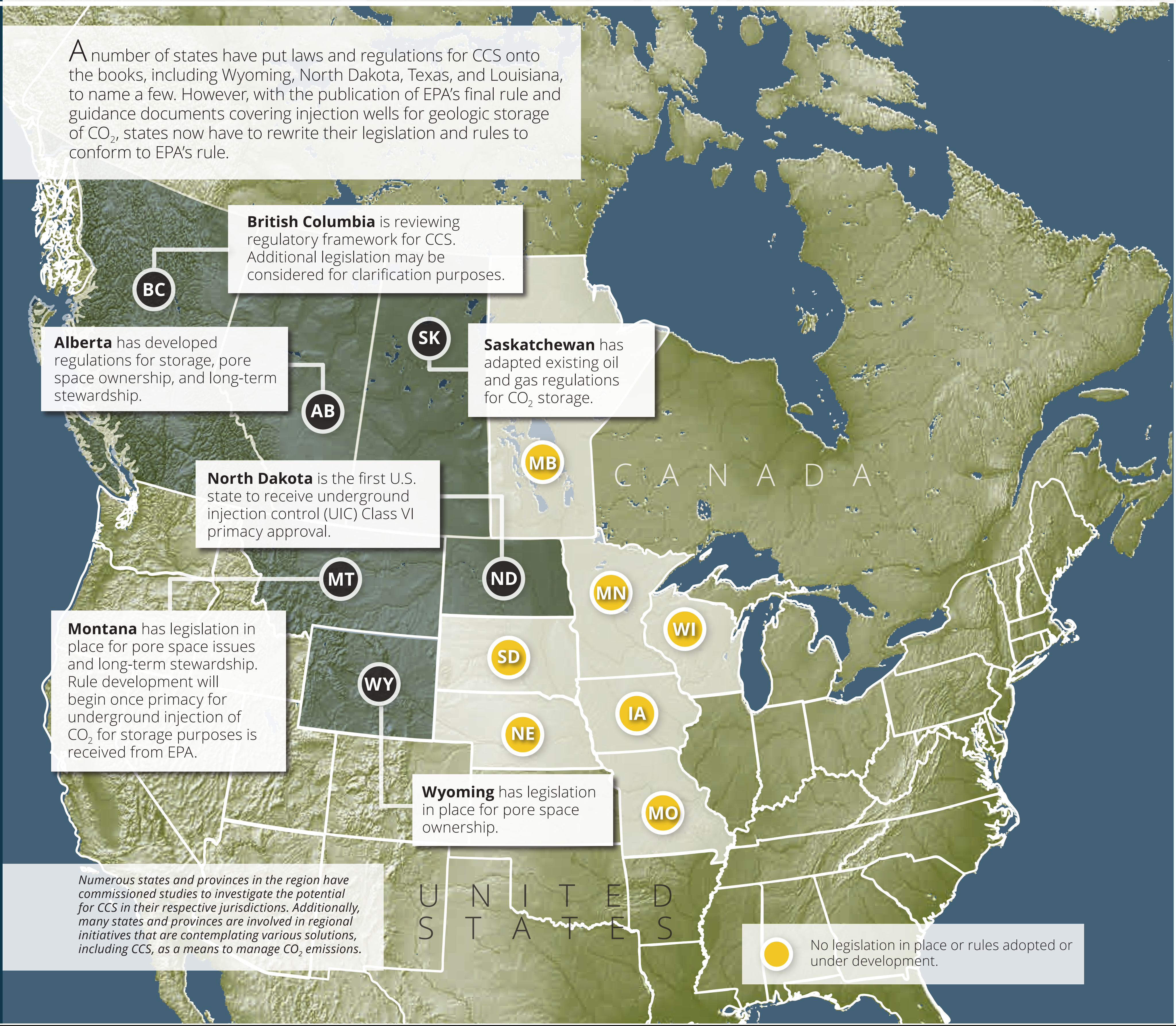
Mandatory Greenhouse Gas Reporting Rule (MRR)

EPA requires geologic storage projects to comply with the MRR. Subpart RR of the MRR refers to the injection of CO_2 for geologic storage. It covers any well or group of wells that injects CO_2 for long-term geologic storage and all wells permitted as Class VI wells. Such facilities are required to report the following:

- Source(s) of CO_2
- Mass of CO_2 received
- Mass of CO_2 produced (i.e., mixed with produced oil, gas, or other fluids)
- Mass of CO_2 emitted from surface leakage
- Mass of CO_2 equipment leaks and vented CO_2 emissions
- Mass of CO_2 stored in subsurface geologic formations

Regulatory Activities in the Region

A number of states have put laws and regulations for CCS onto the books, including Wyoming, North Dakota, Texas, and Louisiana, to name a few. However, with the publication of EPA's final rule and guidance documents covering injection wells for geologic storage of CO_2, states now have to rewrite their legislation and rules to conform to EPA's rule.



Numerous states and provinces in the region have commissioned studies to investigate the potential for CCS in their respective jurisdictions. Additionally, many states and provinces are involved in regional initiatives that are contemplating various solutions, including CCS, as a means to manage CO_2 emissions.

Underground Injection Control Program

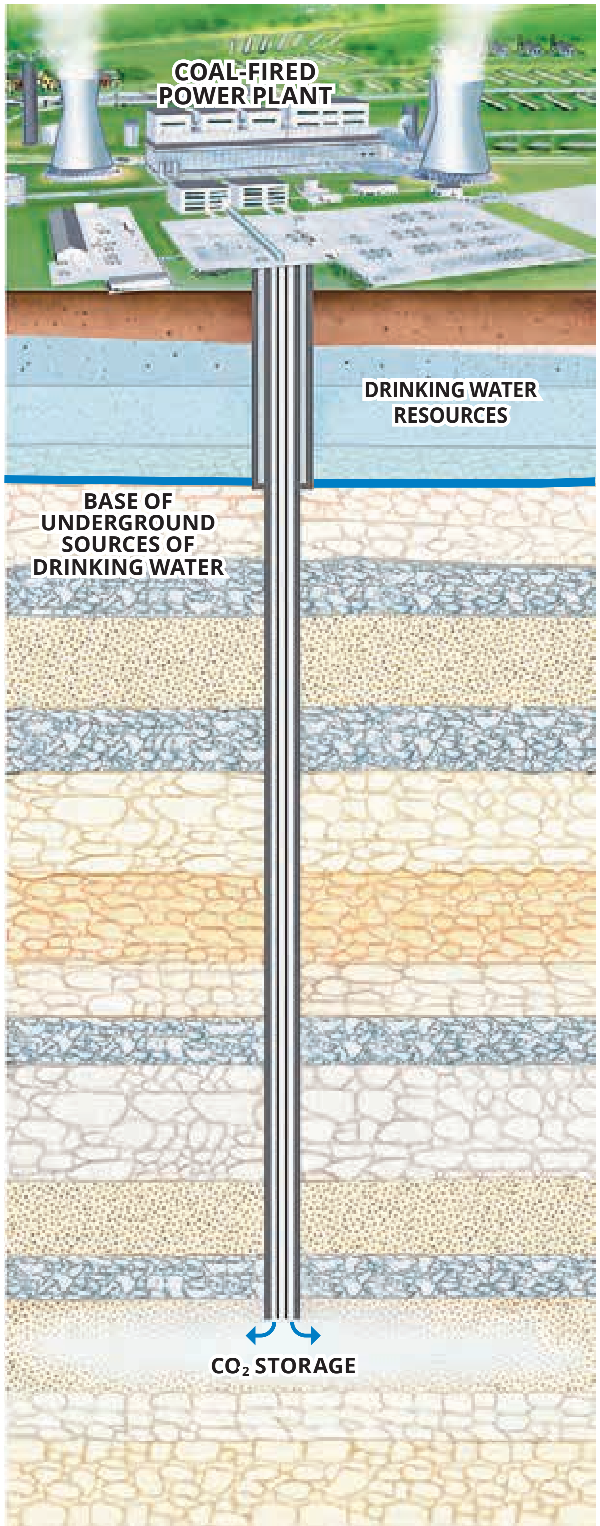
The Safe Drinking Water Act's Underground Injection Control (UIC) Program regulates the construction, operation, permitting, and closure of injection wells used to place fluids underground for storage or disposal. The program consists of six classes of injection wells based on the type and depth of the injection activity. UIC regulations are in place to ensure that injection activities will not endanger USDW.

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 does store CO_2 while producing oil during EOR operations and that CO_2 injection under Class II rules can recognize the incidentally stored volume.

Four years after submitting its application, North Dakota received its UIC Class VI regulatory authority (primacy) approval from EPA. North Dakota is the first state to have received Class VI primacy approval. In 2009, the North Dakota Legislature put the regulation of geologic sequestration into the hands of the North Dakota Industrial Commission. In 2013, the North Dakota Industrial Commission amended its rules to align them with those of EPA and submitted the Class VI UIC primacy application. With the exception of Indian lands, the North Dakota Industrial Commission, rather than EPA, is now in charge of implementing the Class VI Program throughout the state.

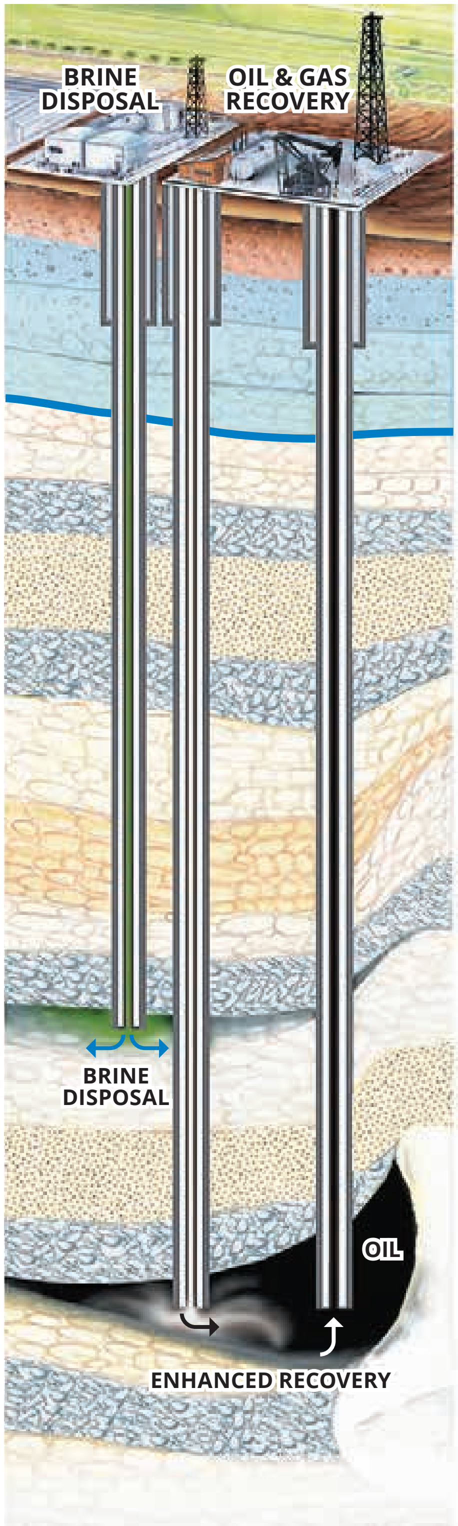
CLASS VI WELLS

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



CLASS II WELLS

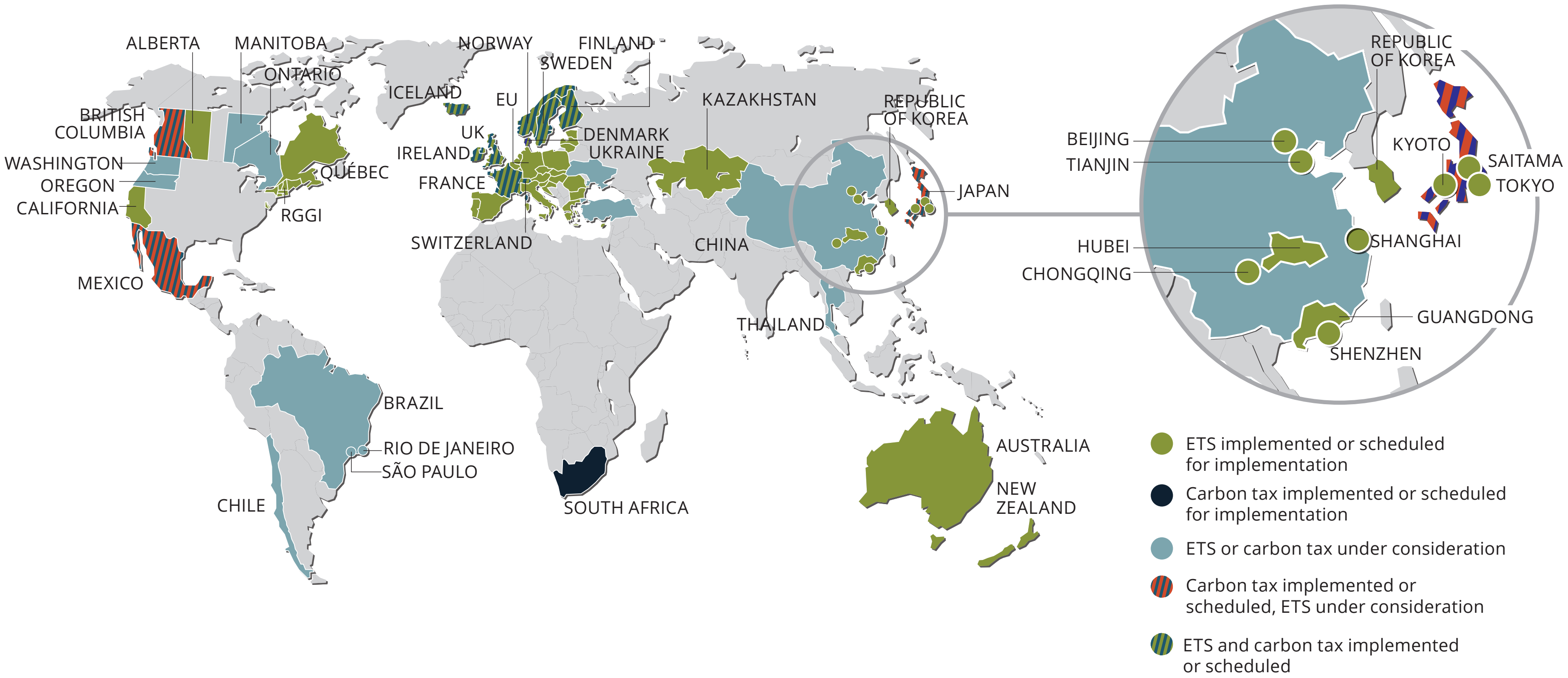
Inject Oil and Gas Production Fluids



Carbon Markets

Compliance-related carbon markets, or those which are regulated under mandatory national, regional, or international carbon reduction regimes, can be a means of encouraging either capturing CO_2 out of the atmosphere or reducing overall emissions. Two primary methods for carbon market pricing are a carbon tax or an emissions trading system (ETS). A carbon tax is a set price for emitting CO_2, which typically comes from the combustion of fossil fuels. An ETS, commonly referred to as a "cap-and-trade system," sets a maximum level of CO_2 emissions allowed. Once that level is reached, carbon credits need to be purchased from another entity that is either not reaching the maximum CO_2 emission level or is pulling CO_2 out of the atmosphere (i.e., CCS). In an ETS, the price of CO_2 is variable (market-driven), where the economy can have a direct impact on the carbon market.

Formed in 2009, the regional greenhouse gas initiative (RGGI) is the first mandatory market-based program to reduce GHG emissions in the United States. It represents a cooperative effort between Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont. In 2014, RGGI states implemented a cap of 91 million tons of CO_2.[68] With the goal to further reduce CO_2 emissions, the cap declines 2.5% each year from 2015 to 2020.[68] RGGI states sell nearly all emission allowances through auctions and invest the proceeds into energy efficiency and renewable energy. This has created more than 14,000 green jobs and has saved consumers $460 million in lower electric bills from 2012 to 2015.[69]



Summary map of existing, emerging, and potential regional, national, and subnational carbon-pricing instruments (ETS and tax).

Another example of a U.S.-based ETS is a program developed by the California Air Resources Board (CARB) known as the "Low Carbon Fuel Standard" (LCFS). The goal of LCFS is to reduce the carbon intensity (CI) of transportation fuels used in California by at least 10% by 2020 from a 2010 baseline.[70] CI is based on a LCA of all of the GHG emissions associated with producing and consuming a fuel. The standard CI value set by the CARB will decrease each year as California aims to reduce total emissions from fuels/fuel production. Participants of LCFS include fuel production facilities that need to apply to CARB and provide information about their facility to have their CI value calculated. If the CI value is below the set CI standard for a particular year, then the facility earns credits. If the facility's CI value is above the CI standard, it runs a deficit and can purchase credits from entities earning them.

Carbon markets are also being introduced on an international scale. On December 12, 2015, international delegates of UNFCCC negotiated the landmark Paris Agreement. The goal of the Paris Agreement is twofold: 1) hold the increase in the global average temperature to well below 2°C above preindustrial levels and 2) strive to limit the global temperature rise even further to below 1.5°C above preindustrial levels, since this would significantly reduce risks and impacts of climate change.[71] Parties ratified the agreement, and it went into force on November 4, 2016.

Carbon Market Reduction Strategy

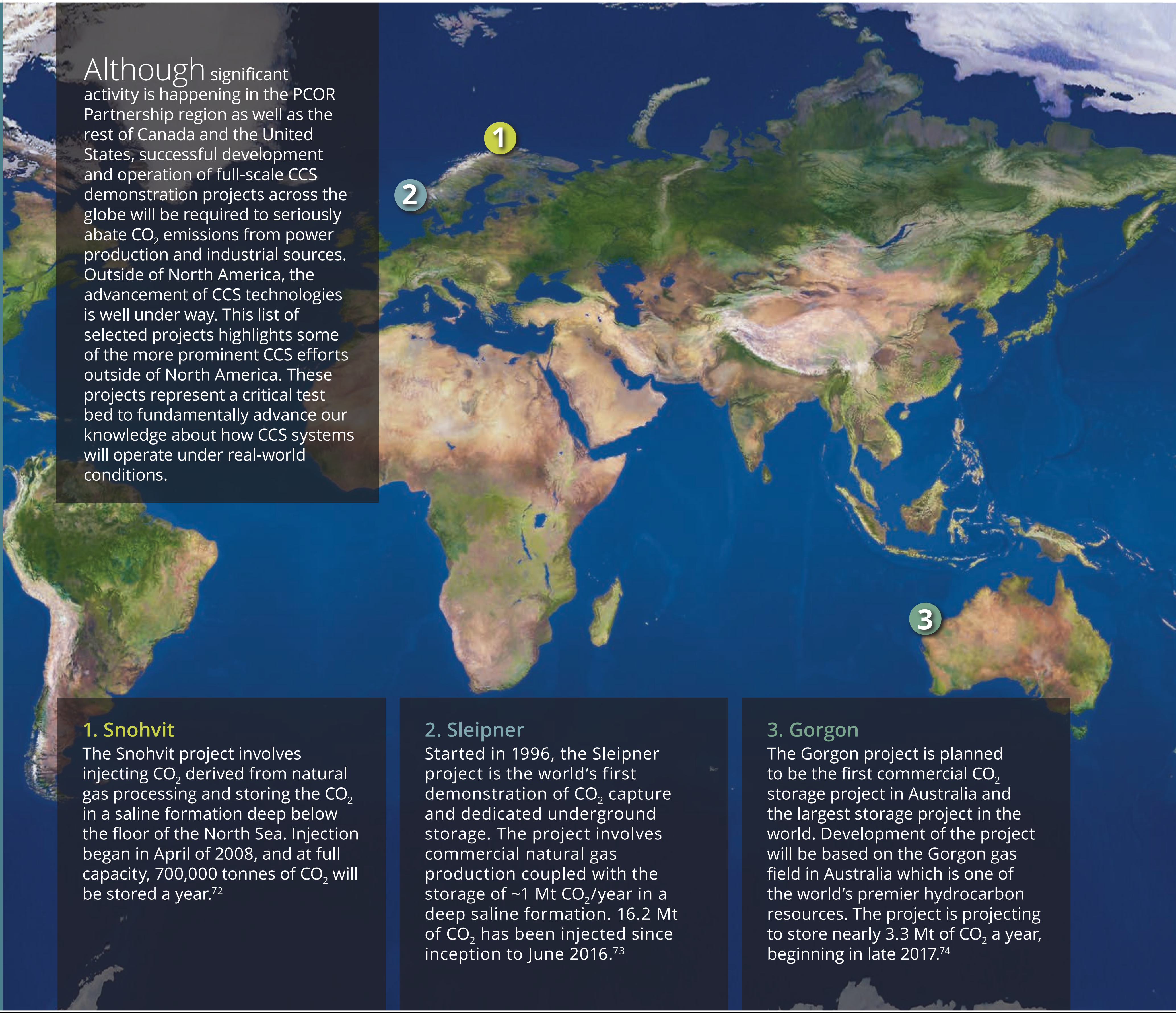
Region/Market	Carbon Reduction System	Quantity of Measured Cap
Eastern U.S.	RGGI	91 million tons of CO_2[68]
California	LCFS	≥10% CI of transportation fuels[70]
International	Paris Agreement	Global temperature hold <1.5°C[71]

CHAPTER 7

The Path Forward

CCS can play a major role in reducing GHG emissions globally. It is critical that technologies to reduce the environmental effects of fossil fuel use continue to be evaluated and developed while we explore and further develop future energy sources. The wise stewardship of our technological, social, and natural resources is essential to our future. The challenge is to meet the growing demand for energy while ensuring our environment and economy stay strong.

CCS Efforts Outside North America



Although significant activity is happening in the PCOR Partnership region as well as the rest of Canada and the United States, successful development and operation of full-scale CCS demonstration projects across the globe will be required to seriously abate CO_2 emissions from power production and industrial sources. Outside of North America, the advancement of CCS technologies is well under way. This list of selected projects highlights some of the more prominent CCS efforts outside of North America. These projects represent a critical test bed to fundamentally advance our knowledge about how CCS systems will operate under real-world conditions.

1. Snohvit

The Snohvit project involves injecting CO_2 derived from natural gas processing and storing the CO_2 in a saline formation deep below the floor of the North Sea. Injection began in April of 2008, and at full capacity, 700,000 tonnes of CO_2 will be stored a year.[72]

2. Sleipner

Started in 1996, the Sleipner project is the world's first demonstration of CO_2 capture and dedicated underground storage. The project involves commercial natural gas production coupled with the storage of ~1 Mt CO_2/year in a deep saline formation. 16.2 Mt of CO_2 has been injected since inception to June 2016.[73]

3. Gorgon

The Gorgon project is planned to be the first commercial CO_2 storage project in Australia and the largest storage project in the world. Development of the project will be based on the Gorgon gas field in Australia which is one of the world's premier hydrocarbon resources. The project is projecting to store nearly 3.3 Mt of CO_2 a year, beginning in late 2017.[74]

Challenges to CCS Deployment

The large-scale deployment of CCS technologies depends upon their becoming accepted, trusted, economical, and conventional technologies. In order for this to happen, several challenges are being addressed.

National CO_2 Policy – Currently, there is no U.S. federal policy to reduce GHG emissions. Without a policy, governments at all levels are uncertain about how to deal with climate change and carbon emissions. Should they take no action or implement carbon taxes, cap-and-trade programs, storage incentives, or other policies?

Economics – For companies to deploy CCS technologies, they will bear costs associated with carbon capture, transportation, and storage. Companies will need to understand the future regulatory environment well enough to see prospective CCS deployment as being profitable over the long term, thus justifying the investment and acceptance of any risk.

Regulations – CCS is an emerging industrial activity, and legal frameworks for it are evolving. However, regulatory uncertainty remains a barrier to CCS deployment. Although early CCS projects can proceed under existing laws, there is limited experience at the federal and state levels in applying the regulatory framework to CCS. Ongoing efforts will clarify the existing regulatory framework by developing requirements.

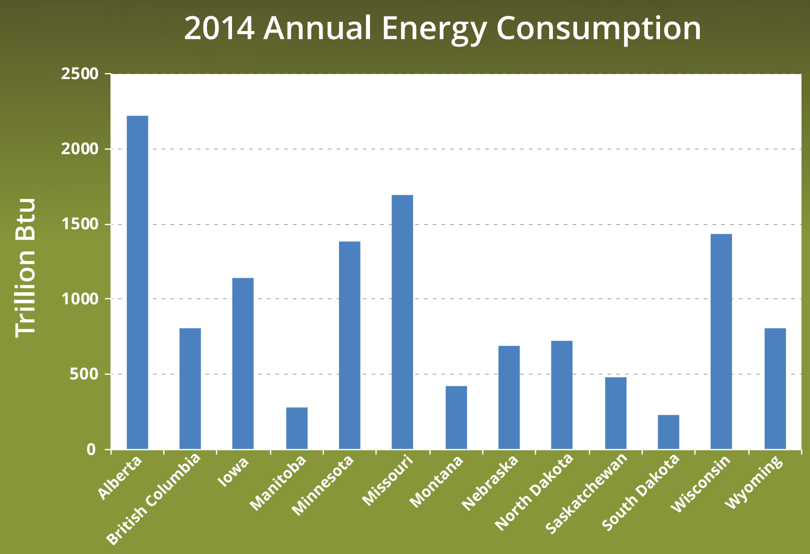
Long-Term Liability – The project operator usually has primary responsibility for the project during the injection phase. However, monitoring and remediation responsibilities may vary in the postinjection (postclosure) period. This responsibility may make some CCS project developers wary.

Technology Proof of Concept – The next decade represents a critical window with which to amass needed operational experience with CCS technologies in real-world conditions.

CCS Acceptance

CCS 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 CCS deployment needed to result in significant reductions will require thousands of CCS deployments around the world over the next 3–4 decades. The expansion of a new technology at that rate is challenging but achievable. 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 CCS's widespread global deployment.

Affordable energy not only fuels our vehicles, homes, industries, and businesses, it also fuels our economy and our quality of life. Collectively, the states and provinces of the PCOR Partnership region use approximately 12,000 trillion Btu (British thermal unit, equivalent to approximately 1055 joules) of energy a year.[75,76] The abundant, affordable energy provided by the PCOR Partnership region's fossil fuel resources powers this very productive part of the world. However, to use our resources in a sensible way without damaging our planet requires a balance between energy and the environment. In the pursuit of that balance, it is critical that technologies to reduce the environmental effects of fossil fuel use continue to be evaluated and developed while we explore and further develop future energy sources. To that end, the PCOR Partnership continues to play a key role in the development and evaluation of technologies that will assist in the deployment of CCS on a commercial scale.



Although CCS is on the cusp of commercial deployment, widespread, cost-effective deployment of CCS will occur only if the technology is commercially available at economically competitive prices and supportive national policy frameworks are in place.

The wise stewardship of our technological, social, and natural resources is essential to the future of our culture. Our challenge is to keep the lights on while simultaneously ensuring that our environment and economy stay strong.

Engaging the Public

Public awareness and support are critical to the development of new energy technologies and are widely viewed as vital for CCS projects. CCS 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 CCS as one option to reduce GHG emissions.

Developing public support for CCS is an essential component of the RCSP initiative. Within the RCSP Program, the PCOR Partnership is working to increase CCS knowledge among the general public, regulatory agencies, policy makers, and industry.

Our core approaches include:

Take it on the road – Engaging the public, policy makers, and industry on CCS remains an essential component of the PCOR Partnership activities. This is done through presentations and participation at meetings and public and industry events throughout the region.


Educational Workshops


Media Relations


Landowner/Stakeholder Relations

Take it online – Separate public and partners-only Web sites provide information in terms and context tailored to meet the needs of the distinct demographics.

Public Web Site

Video Clip Library

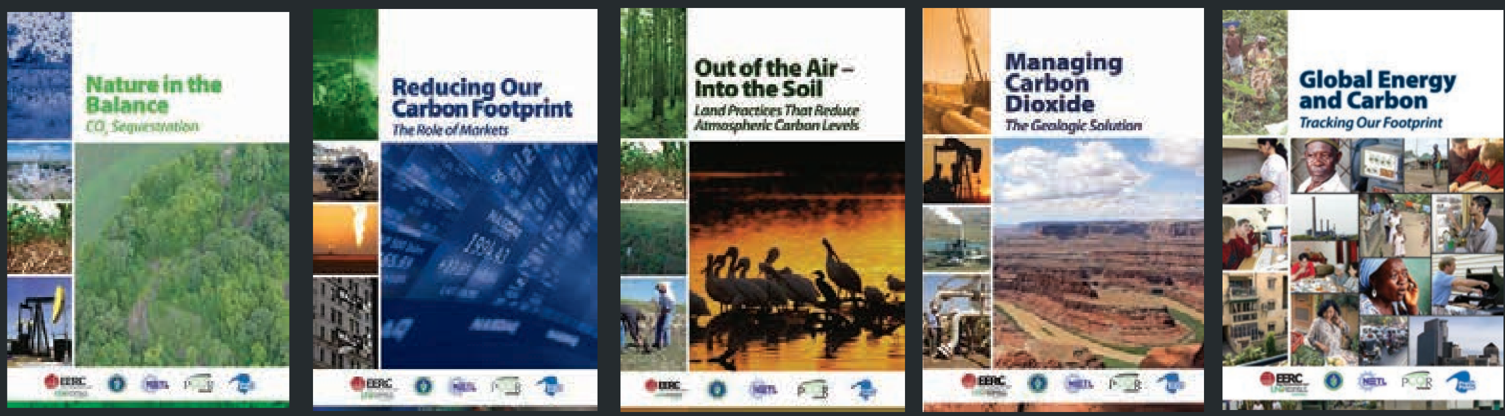
Partners-Only Web Site

Documentary Series

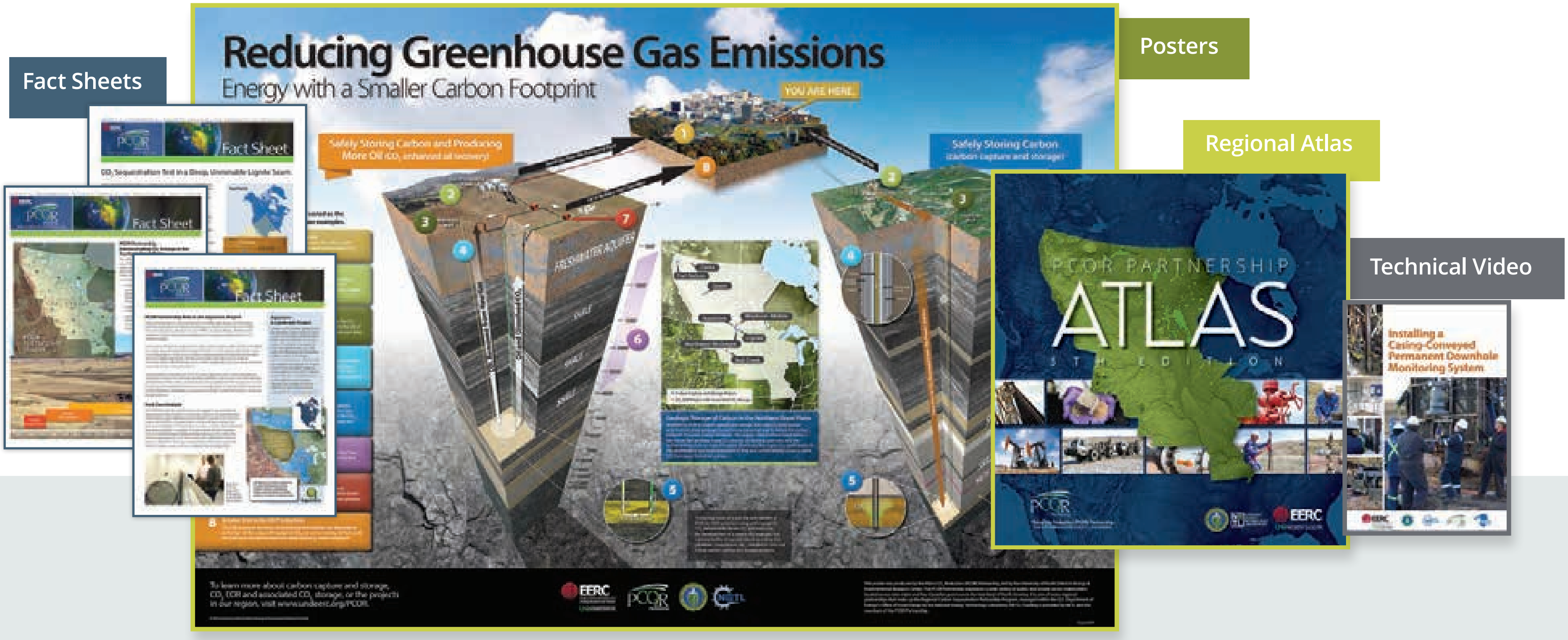
Developing public support for CCS is an essential component of the RCSP initiative. Within the RCSP Program, the PCOR Partnership is working to increase CCS knowledge among the general public, regulatory agencies, policy makers, and industry.

Take it to prime time – The PCOR Partnership continues its long-standing collaboration with Prairie Public Broadcasting to provide educational activities and documentary productions.

Award-Winning Documentaries



Take it with you – Fact sheets, scientific presentations, posters, and reports inform technical audiences, while products such as documentaries, presentations, the regional atlas, and nontechnical posters tell the story of CCS for a general audience.



Ramping up CCS Development

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

1. Build upon assessments of regional storage data to verify the ability of target formations 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 CCS 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 CCS projects overcome key challenges, including cost-effective capture of CO_2 through successful integration with fossil fuel conversion systems. Advances in CCS technology and project deployment will allow continued access to safe, reliable, and affordable energy.

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	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).

Further Sources of Information

Carbon Sequestration Leadership Forum (CSLF) – The CSLF is a panel made up of representatives from governments around the world who meet regularly to discuss CCS research and technologies and to plan joint projects.
www.cslforum.org

Climate Change Program (World Bank) – As part of a broad environmental strategy, the World Bank focuses on support for three actions to address climate change concerns: mitigation of GHG emissions, reduction of vulnerability and adaptation to climate change, and capacity building.
http://climatechange.worldbank.org

CO_2 Capture Project – The CO_2 Capture Project is an international effort funded by eight of the world's leading energy companies. This project addresses the issue of reducing emissions in a manner that will contribute to an environmentally acceptable and competitively priced continuous energy supply for the world.
www.co2captureproject.org

Cooperative Research Centre for Greenhouse Gas Technologies (CO_2CRC) – The CO_2CRC Program is a collaborative research organization focused on CO_2 capture and geological storage.
www.co2crc.com.au

Global CCS Institute (GCCSI) – This Australia-based organization works collaboratively to build and share the expertise necessary to ensure that CCS can make a significant impact on reducing the world's GHG emissions. The Institute connects parties around the world to address issues and learn from each other to accelerate the deployment of CCS projects through knowledge sharing and fact-based advocacy.
www.globalccsinstitute.com

Intergovernmental Panel on Climate Change (IPCC) – IPCC is assessing scientific, technical, and socioeconomic information relevant for the understanding of climate change, its potential impacts, and options for adaptation and mitigation.
www.ipcc.ch

International Emissions Trading Association (IETA) – IETA is a nonprofit business organization created to establish a functional international framework for trading in GHG emission reductions.
www.ieta.org

IEA Greenhouse Gas R&D Programme (IEAGHG) – This program is a major international research collaboration that assesses technologies for their potential to help achieve deep reductions in GHG emissions.
www.ieaghg.org

International Energy Agency (IEA) – IEA is an autonomous organization that has been engaged for more than a decade to design cost-effective approaches to reduce CO_2 emissions, working from the international policy architecture, to energy efficiency policy, and the promotion of clean technologies. IEA provides authoritative and unbiased research, statistics, analysis, and recommendations.
www.iea.org

Interstate Oil and Gas Compact Commission (IOGCC) – IOGCC is a multistate government agency that formed a task force of state oil and gas directors and geologists to study the issue of CO_2 sequestration and assess the interests of the states to develop pertinent model state regulations.
www.iogcc.state.ok.us

Petroleum Technology Research Centre (PTRC) – A not-for-profit research and development organization with offices and laboratories in Regina, Saskatchewan, Canada, PTRC is developing world-leading EOR and CO_2 storage technologies and manages the Weyburn–Midale CO_2 Monitoring and Storage Project and the Aquistore effort.
www.ptrc.ca

Petroleum Technology Transfer Council (PTTC) – PTTC is a national not-for-profit organization that provides a forum for technology transfer and best practices within the producer community.
www.pttc.org

The Climate Action Network (CAN) International – CAN International is a worldwide network of over 550 nongovernmental organizations working to promote government and individual action to limit human-induced climate change to ecologically sustainable levels.
www.climatenetwork.org

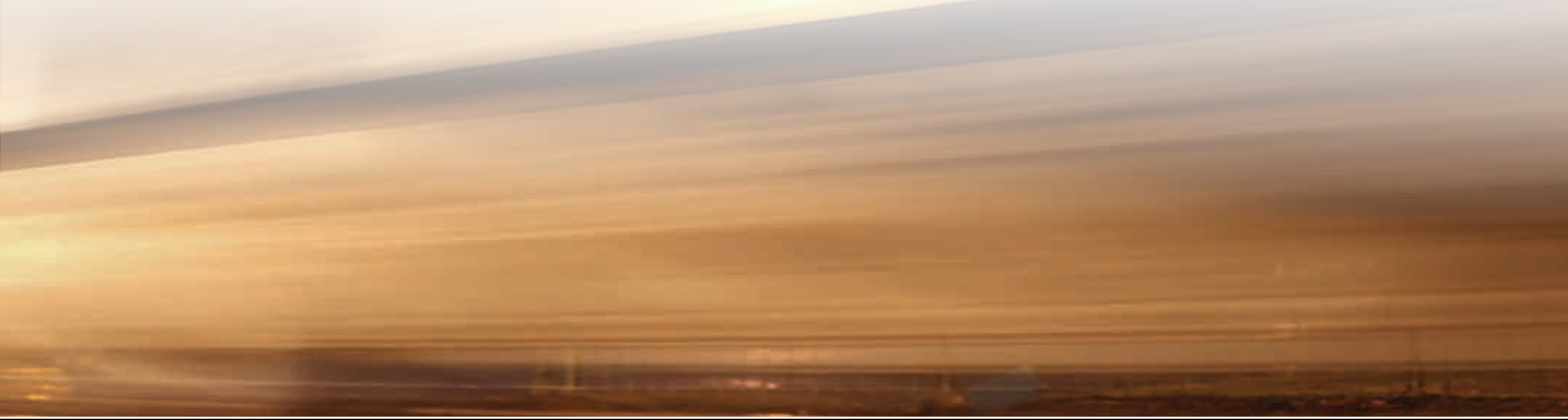
U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) – NETL is part of DOE's national laboratory system with expertise in coal, natural gas, and oil technologies; contract and project management; analysis of energy systems; and international energy issues.
www.netl.doe.gov

U.S. DOE Office of Fossil Energy (FE) – DOE FE is a lead group in the federal effort for carbon sequestration research and development.
www.fe.doe.gov

U.S. Energy Information Administration (EIA) – EIA collects, analyzes, and disseminates independent and impartial energy information to promote sound policy making, efficient markets, and public understanding of energy and its interaction with the economy and the environment.
www.eia.gov

U.S. Environmental Protection Agency (EPA) – EPA is charged with protecting human health and the environment by writing and enforcing regulations based on laws passed by Congress.
www.epa.gov

World Resources Institute (WRI) – WRI convened a group of stakeholders to develop CCS guidelines to ensure projects are conducted safely and effectively.
www.wri.org/publication/ccs-guidelines



Nomenclature

AITF	Alberta Innovates Technology Futures
bbl	barrel
Bcf	billion cubic feet
BSCSP	Big Sky Carbon Sequestration Partnership
Btu	British thermal unit
CAN	Climate Action Network
CARB	California Air Resources Board
CBM	coalbed methane
CCS	carbon capture and storage
CFC	chlorofluorocarbon
CH_4	methane
CI	carbon intensity
CO_2	carbon dioxide
CO_2CRC	Cooperative Research Centre for Greenhouse Gas Technologies
COSS	Cambro-Ordovician Saline System
CSA	Canadian Standards Association
CSLF	Carbon Sequestration Leadership Forum
Denbury	Denbury Resources Inc.
DOE	U.S. Department of Energy
DU	Ducks Unlimited
DUC	Ducks Unlimited Canada
Eagle	Eagle Operating Group, Inc.
ECBM	enhanced coalbed methane
EERC	Energy & Environmental Research Center
EIA	Energy Information Administration
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ETS	emissions trading system
FE	Fossil Energy
GCCSI	Global CCS Institute
GDP	gross domestic product
GHG	greenhouse gas
Gt	gigatonne
H_2O	water
H_2S	hydrogen sulfide
IEA	International Energy Agency
IEAGHG	International Energy Agency Greenhouse Gas R&D Programme
IETA	International Emissions Trading Association
IOGCC	Interstate Oil and Gas Compact Commission
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle analysis
LCFS	Low Carbon Fuel Standard
LPG	liquefied petroleum gas
mg/L	milligram per liter
MGSC	Midwest Geological Sequestration Consortium
MRCSP	Midwest Regional Carbon Sequestration Partnership
MRR	Mandatory Greenhouse Gas Reporting Rule
Mt	million tonne
MVA	monitoring, verification, and accounting
MW	megawatt
NDSU	North Dakota State University
NETL	National Energy Technology Laboratory
N_2O	nitrous oxide
O_3	ozone
PCOR	Plains CO_2 Reduction Partnership
PDM	permanent downhole monitoring
ppm	parts per million
PPR	Prairie Pothole Region
psi	pound per square inch
PTRC	Petroleum Technology Research Centre
PTTC	Petroleum Technology Transfer Council
RCSP	Regional Carbon Sequestration Partnership
R&D	research and development
RD&D	research, development, and demonstration
RGGI	Regional Greenhouse Gas Initiative
SECARB	Southeast Regional Carbon Sequestration Partnership
SET	Spectra Energy Transmission
stb	stock tank barrel
SWP	Southwest Regional Partnership on Carbon Sequestration
TDS	total dissolved solids
UIC	underground injection control
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USDW	underground sources of drinking water
USGS	U.S. Geological Survey
VSP	vertical seismic profile
WESTCARB	West Coast Regional Carbon Sequestration Partnership

Photo and Image Credits

Except for those noted below, all photos and images were created by the EERC or obtained from royalty-free stock.

Preface. Denbury Resources Inc., www.denbury.com/media.html (accessed August 2011).

Page 4. Modified from Global Carbon Cycle: U.S. Department of Energy Genomic Science Program, http://genomicscience.energy.gov (accessed 2016).

Page 5. Image of Svante Arrhenius: www.nndb.com/people/875/000092599.

Page 6. Industrial: Gas Technology Institute, electric utility: Cathy Haglund, agriculture-related processing: Lincolnland Agri-Energy.

Page 7. Horia Varlan.

Page 17. Electric utility: Basin Electric Power Cooperative.

Page 21. Tree planting: U.S. Forest Service; conservation tilling: Minnesota Pollution Control Agency.

Page 25. PTRC.

Page 26. Denbury Resources Inc., www.denbury.com/media.html (accessed 2011).

Page 27. Denbury Resources Inc., www.denbury.com/media.html (accessed 2011).

Page 30. Adapted from the Cooperative Research Centre for Greenhouse Gas Technologies.

Page 31. Adapted from IPCC, 2005, Carbon dioxide capture and storage, Metz, B., Davidson, O., de Coninck, H., Loos, M., and Meyer, L., eds.: United Kingdom, Cambridge University Press, 431 p.

Page 33. Paul Lowry.

Page 40. Modified from NETL 2015 Carbon Storage Atlas (5th ed.) (accessed 2016).

Page 55. Arnold Paul.

Page 59. Background image: Cameron Hibbert.

Page 68. Background image: Ken Childress.

Page 72. Background image: DU.

Page 96. Basin Electric Power Cooperative.

Page 97. PTRC.

Page 98. Provided by, and is property of, SaskPower.

Page 99. PTRC.

Page 100. Shell Canada Quest Carbon Capture and Storage Project.

Page 101. Shell Canada Quest Carbon Capture and Storage Project.

Back. A map of Louisiana and Mexico. Carte de la Louisiane et du Mexique, Dressee par P. Tardieu fils aine, Gravee par P.A.F. Tardieu pere. Paris 1820. www.davidrumsey.com/luna/servlet/detail/RUMSEY~8~1~207606~3003392 (accessed February 2017).

References

1. www.giss.nasa.gov/research/briefs/ma_01 (accessed 2016).
2. Schmidt, G.A., Ruedy, R., Miller, R.L., and Lacis, A.A., 2010, The attribution of the present-day total greenhouse effect: Journal of Geophysical Research, v. 115, D20106, doi:10.1029/2010JD014287.
3. U.S. Department of Energy, 2008, Carbon cycling and biosequestration: http://genomicscience.energy.gov/carboncycle/report/CarbonCycle012609LRnocover.pdf (accessed 2016).
4. NOAA National Centers for Environmental Information, 2016, State of the climate—global analysis for annual 2015: www.ncdc.noaa.gov/sotc/global/201513 (accessed 2016).
5. http://data.giss.nasa.gov/gistemp (accessed 2016).
6. http://earthobservatory.nasa.gov/Features/Arrhenius (accessed 2016).
7. https://www.iea.org/publications/freepublications/publication/CO_2EmissionsFromFuelCombustionHighlights2015.pdf (accessed 2016).
8. International Energy Agency, 2011, CO_2 emissions from fuel combustion—highlights: Paris, France, International Energy Agency, 134 p.
9. www.census.gov/ipc/www/worldhis.html (accessed 2011).
10. http://wds.iea.org/wds/pdf/Worldco2_Documentation.pdf (accessed 2016).
11. www.eia.gov/analysis/projection-data.cfm#intlproj (accessed 2016).
12. www.globalsherpa.org/bric-countries-brics (accessed 2016).
13. Daly, D.J., and Crocker, C.R., 2010, Global energy and carbon—tracking our footprint [DVD]: Steadman, E.N., and Dambach, B., executive producers, Fargo, North Dakota, Prairie Public Broadcasting, and Grand Forks, North Dakota, Energy & Environmental Research Center.
14. IPCC (Intergovernmental Panel on Climate Change), 2014, Climate change 2014—mitigation of climate change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
15. ec.euorope.eu/clima/policies/international/paris_protocol/index.en.htm (accessed 2016).
16. Belfer Center for Science and International Affairs, 2015, China's carbon emissions report 2015: Harvard University.
17. www.imf.org/external/pubs/ft/weo/2010/02/weodata/index.aspx (accessed 2016).
18. CO_2 sources outside the PCOR Partnership region were obtained from NATCARB.
19. U.S. Environmental Protection Agency, 2008, National Water Program strategy—response to climate change: EPA 800-R-08-001, http://water.epa.gov/ scitech/climatechange/strategy.cfm (accessed 2016).
20. www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf (accessed 2016).
21. www.powerplantccs.com/ccs/cap/con/of/of.html (accessed 2016).
22. www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf (accessed 2016).
23. www.carboncapturejournal.com/allnews.aspx (accessed 2016).
24. http://naturalgas.org/naturalgas/transport (accessed 2016).
25. Intergovernmental Panel on Climate Change, 2005, Carbon Dioxide Capture and Storage: www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf (accessed 2016).
26. Oil fields outside the PCOR Partnership region were provided by NATCARB.
27. Kuuskraa, V., and Wallace, M., 2014, CO_2-EOR set for growth as new CO_2 supplies emerge, reprint with format revisions from April 7 ed.: Oil & Gas Journal, PennWell Corporation.
28. Azzolina, N.A., Peck, W.D., Hamling, J.A., Gorecki, C.D., Ayash, S.C., Doll, T.E., Nakles, D.V., and Melzer, L.S., 2016, How green is my oil? A detailed look at greenhouse gas accounting for CO_2-enhanced oil recovery (CO_2-EOR) sites: International Journal of Greenhouse Gas Control, v. 51, p. 369–379.
29. Mangmeechai, A., 2009, Life cycle greenhouse gas emissions, consumptive water use and levelized costs of unconventional oil in North America [Ph.D. dissertation]: Carnegie Mellon University: Pittsburgh, Pennsylvania.
30. Extent of sedimentary basins provided by NATCARB.
31. www.lakesuperiorstreams.org (accessed 2016).
32. http://waterquality.montana.edu (accessed 2016).
33. http://water.epa.gov/drink/contaminants/secondarystandards.cfm (accessed 2016).
34. www.pacificro.com/watercla.htm (accessed 2016).
35. http://geology.utah.gov/online_html/pi/pi-39/pi39pg9.htm (accessed 2016).
36. www.extremescience.com/dead-sea.htm (accessed 2016).
37. Need a reference for the coal map on p. 42
38. www.coal-seq.com/memberonly/ECBM_Sequestration_Knowledge_Base/Coal-Seq%20II%20Forum%202003/Burruss2003.pdf (accessed 2016).
39. www.iea.org/Textbase/npsum/ccsSUM.pdf (accessed 2016).
40. www.netl.doe.gov/research/coal/carbon-storage/atlasv (accessed 2016).
41. Jensen, M.D., Steadman, E.N., and Harju, J.A., 2005, CO_2 source characterization of the PCOR Partnership region: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center, June 2005.

42. http://files.dnr.state.mn.us/aboutdnr/reports/MGS_CO_2_Report.pdf (accessed 2016).

43. Nelson, C.R., Steadman, E.N., and Harju, J.A., 2005, Geologic CO_2 sequestration potential of lignite coal in the U.S. portion of the Williston Basin: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center.

44. Bachu, S.B., Steadman, E.N., and Harju, J.A., 2005, Carbon dioxide storage capacity in Upper Cretaceous–Tertiary Ardley coals in Alberta: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center.

45. Nelson, C.R., Steadman, E.N., and Harju, J.A., 2005, Geologic CO_2 sequestration potential of the Wyodak–Anderson coal zone in the Powder River Basin: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center.

46. Extent of saline areas was derived from PCOR Partnership assessment activities and those of Environment Canada.

47. Mann, G.E., 1974, The Prairie Pothole Region—zone of environmental opportunity: Naturalist, v. 25, no. 4, p. 2, C. 7.

48. Wilkins, K.A., Otto, M.C., and Koneff, M.D., 2006, Trends in duck breeding populations, 1995–2006: U.S. Department of the Interior, Washington, D.C., 26 p.

49. Gleason, R.A., Euliss, N.H., Jr., McDougal, R., Kermes, K.E., Steadman, E.N., and Harju, J.A., 2005, Potential of restored prairie wetlands in the glaciated North American prairie to sequester atmospheric carbon: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center.

50. www.globalccsinstitute.com/projects/great-plains-synfuel-plant-and-weyburn-midale-project (accessed 2016).

51. www.saskpower.com/about-us/blog/bd3-status-update-september-2016 (accessed 2016).

52. www.shell.ca/en_ca/about-us/projects-and-sites/quest-carbon-capture-and-storage-project.html (accessed 2016).

53. www.globalccsinstitute.com/projects/alberta-carbon-trunk-line-actl-agrium-co2-stream (accessed 2016).

54. www.globalccsinstitute.com/projects/alberta-carbon-trunk-line-actl-north-west-sturgeon-refinery-co2-stream (accessed December 2016).

55. www.dakotagas.com/About_Us/index.html (accessed September 2016).

56. www.cenovus.com/operations/conventional-oil-natural-gas/weyburn.html (accessed December 2016).

57. Petroleum Technology Research Centre, 2016, personal communication.

58. Wilson, M., Monea, M., 2004, IEAGHG Weyburn CO_2 monitoring and storage project summary report 2000–2004, in Wilson, M., and Monea, M., eds., Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies: Petroleum Technology Research Centre, Regina, Canada.

59. Wildgust, N., Tontiwachwuthikul, P., and Gilboy, C., eds., 2013, The IEAGHG Weyburn–Midale CO_2 monitoring and storage project: International Journal of Greenhouse Gas Control, v. 16, Suppl. 1, p. S1–S308.

60. Hitchon, B., ed., 2012, Best practices for validating CO_2 geological storage—observations and guidance from the IEAGHG Weyburn–Midale CO_2 monitoring and storage project: Geoscience Publishing, 353 p.

61. www.saskpower.com/our-power-future/carbon-capture-and-storage/boundary-dam-carbon-capture-project/ (accessed 2016).

62. http://aquistore.ca, 2016, Petroleum Technology Research Centre (accessed 2016).

63. Petroleum Technology Research Centre, 2016, PTRC's Aquistore Project surpasses 100,000 tonnes of stored CO_2: http://ptrc.ca/+pub/document/AQ_News%20Release_CO_2%20Milestone.pdf (accessed 2016).

64. http://aquistore.ca/site/injection-well (accessed December 2016).

65. Rostron, B., White, D., Hawkes, C., and Chalaturnyk, R., 2014, Characterization of the Aquistore CO_2 project storage site, Saskatchewan, Canada: Energy Procedia, v. 63, p. 2977–2984.

66. www.energy.alberta.ca/ccs/3848.asp (accessed 2016).

67. www.globalccsinstitute.com/projects/quest (accessed 2016).

68. www.rggi.org (accessed 2016).

69. http://www.bloomberg.com/news/articles/2015-07-14/carbon-trading-program-generates-1-3-billion-in-u-s-northeast (accessed 2016).

70. www.arb.ca.gov/fuels/lcfs/background/basics.htm (accessed 2016).

71. http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm (accessed 2016).

72. https://www.globalccsinstitute.com/projects/sn%C3%B8hvitco2-storage-project (accessed 2016).

73. https://www.globalccsinstitute.com/projects/sleipner%C2%A0co2-storage-project (accessed 2016).

74. https://www.globalccsinstitute.com/projects/gorgon-carbondioxide-injection-project (accessed 2016).

75. http://www.statcan.gc.ca/daily-quotidien/151210/dq151210eeng.htm (accessed 2016).

76. http://www.eia.gov/beta/MER/ (accessed 2016).

For More Information

The public PCOR Partnership Web site contains a wealth of information related to CCS geared toward various audiences. Visit us at www.undeerc.org/pcor.

To learn more about the PCOR Partnership and its activities, contact:

Charles Gorecki
Director of Subsurface R&D/PCOR Partnership Program Manager
(701) 777-5355
cgorecki@undeerc.org

To obtain educational materials or schedule a presentation, contact:

Dan Daly
Senior Geologist/Public Outreach Specialist and Outreach Team Lead
(701) 777-2822
ddaly@undeerc.org

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018
(701) 777-5000
www.undeerc.org


A Map
of Louisiana
AND MEXICO.
Carte
DE LA LOUISIANE
ET DU MEXIQUE,
PARIS 1820.
RUPERT'S LAND
MISSOURI TERRITORY