

# PCOR PARTNERSHIP ATLAS

## 5TH EDITION



**Plains CO<sub>2</sub> Reduction (PCOR) Partnership**  
Practical, Environmentally Sound CO<sub>2</sub> Sequestration





# Plains CO<sub>2</sub> Reduction (PCOR) Partnership

## ATLAS

*5th Edition*

2016

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The PCOR Partnership is a group of public and private stakeholders working together to better understand the technical and economic feasibility of storing CO<sub>2</sub> 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.



# Notice

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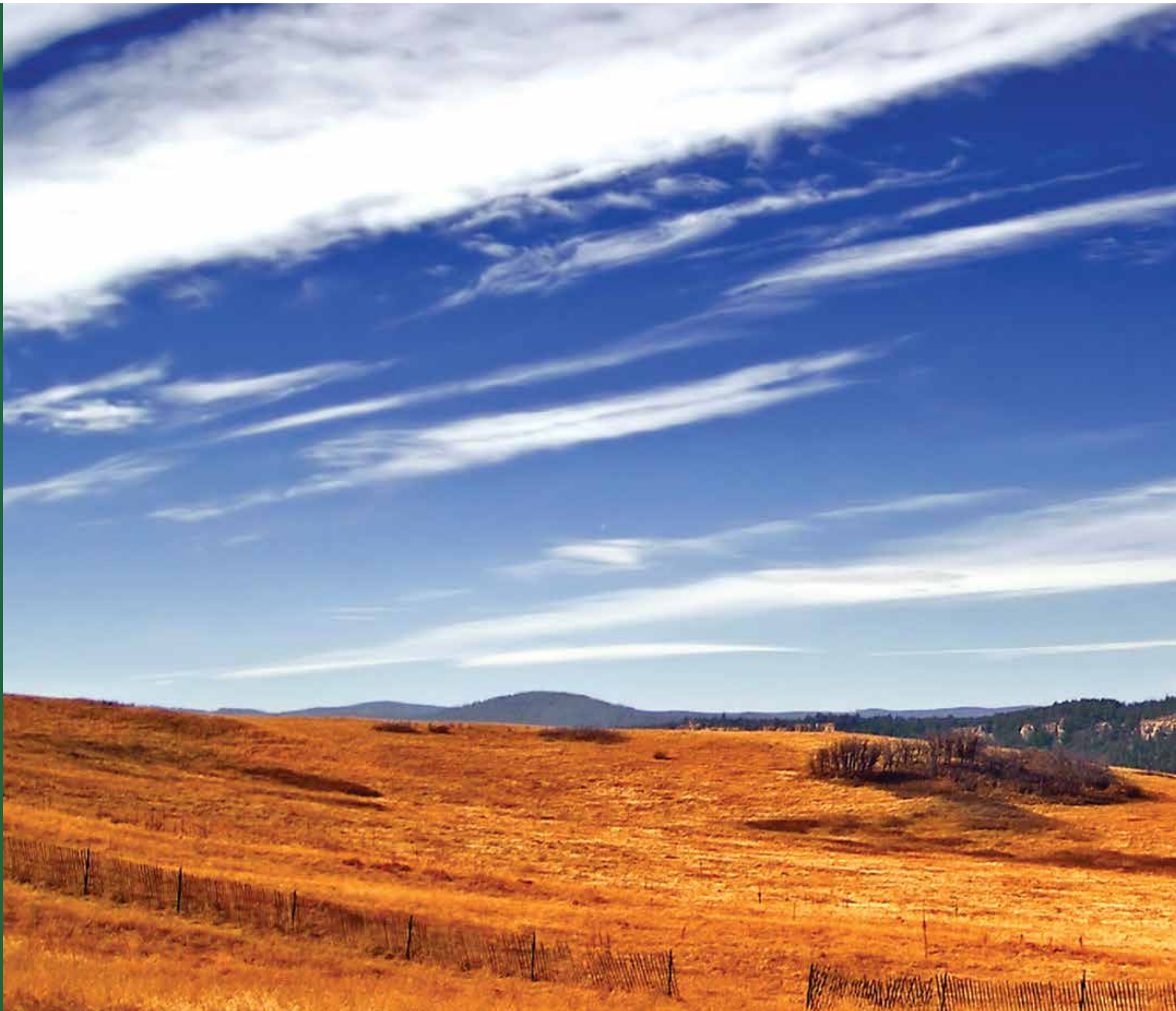
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# Preface

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<sub>2</sub>) can be captured from large stationary sources and permanently stored underground.

Within central North America, the Plains CO<sub>2</sub> Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is investigating long-term CO<sub>2</sub> storage technologies to provide a safe, effective, and efficient means of managing CO<sub>2</sub> 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<sub>2</sub> sources and potential CO<sub>2</sub> storage locations across the nearly 3.6 million km<sup>2</sup> 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<sub>2</sub> 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),<sup>1</sup> and life as it is known would not be possible.

**1.**  
Sun's rays  
enter Earth's  
atmosphere.

**2.**  
Heat is emitted  
back from  
Earth's surface.

**3.**  
Some heat  
passes back  
out into space.

**4.**  
Some heat is  
absorbed by GHGs  
and becomes trapped  
within Earth's  
atmosphere. Earth  
becomes hotter  
as a result. The  
more GHGs in the  
atmosphere, the  
more heat is  
retained.

# Greenhouse Gases

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<sub>2</sub>O], carbon dioxide [CO<sub>2</sub>], methane [CH<sub>4</sub>], nitrous oxide [N<sub>2</sub>O], and ozone [O<sub>3</sub>]), 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<sub>2</sub> plays a vital role in supporting life on Earth. The natural production and absorption of CO<sub>2</sub> 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.

Other

CO<sub>2</sub>

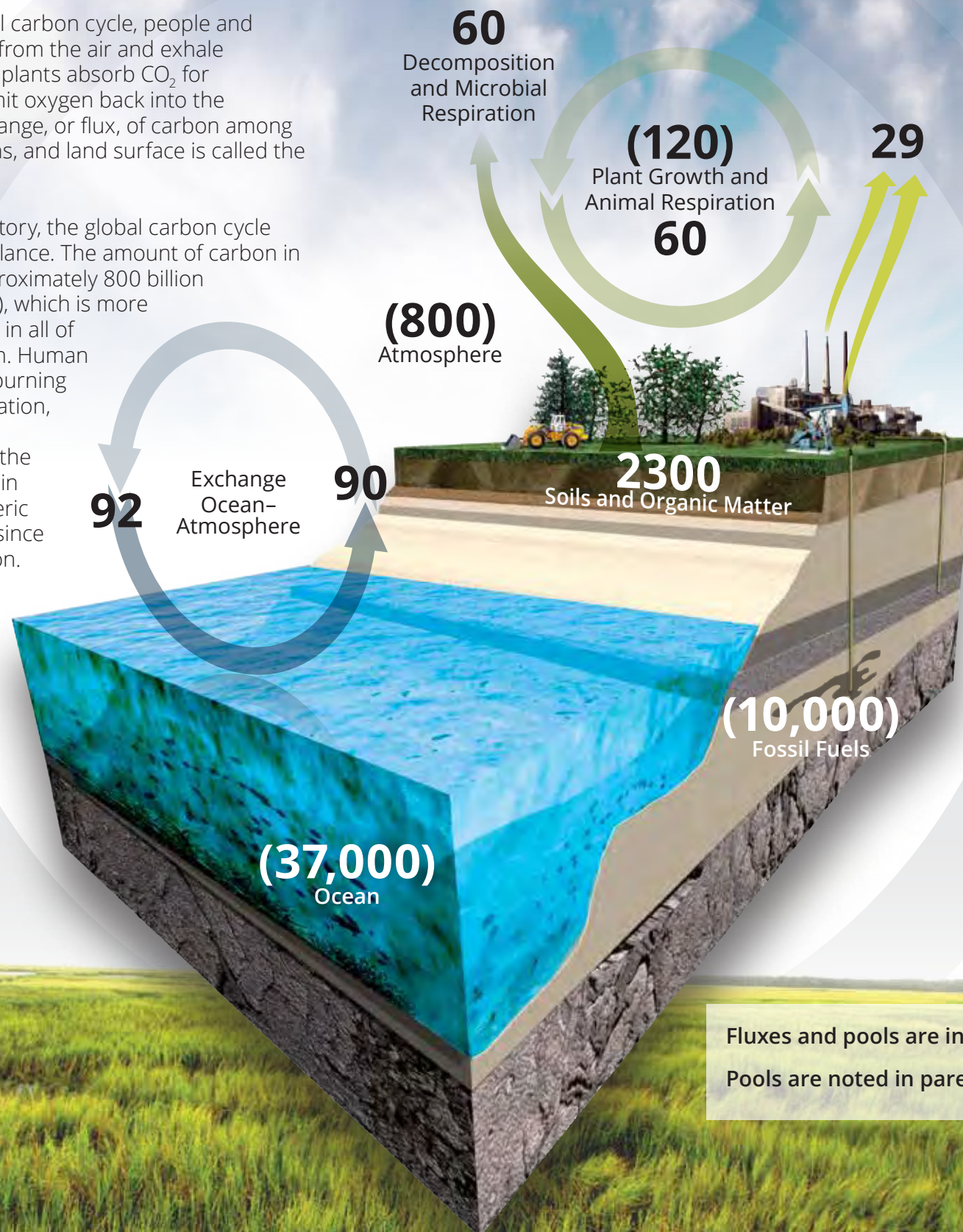
Clouds  
and  
Water Vapor

*Representative GHG effect contributions.<sup>2</sup>*

# Global Carbon Cycle

As part of the natural carbon cycle, people and animals inhale oxygen from the air and exhale CO<sub>2</sub>. Meanwhile, green plants absorb CO<sub>2</sub> 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.<sup>3</sup>

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<sub>2</sub> since the Industrial Revolution.



Fluxes and pools are in Gt.  
Pools are noted in parentheses.

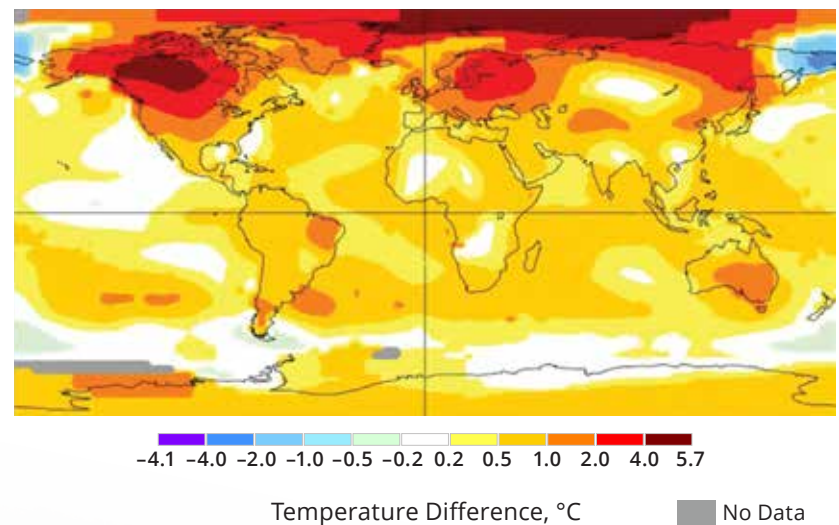
# Climate Change Patterns

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

–Svante Arrhenius, 1904



Since instrumental records of temperature began in 1880, the overall temperature of Earth has risen by approximately 1.62°F (0.90°C), with 2015 being the warmest year on record according to the National Oceanic and Atmospheric Administration.<sup>4</sup> 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.<sup>5</sup>*

*More than 100 years ago, Swedish scientist and Nobel Prize winner Svante Arrhenius postulated that anthropogenic increases in atmospheric CO<sub>2</sub> 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.<sup>6</sup>*

# Major Stationary CO<sub>2</sub> Sources

## INDUSTRIAL



Cement Plant

## PETROLEUM AND NATURAL GAS



Refinery

## ELECTRIC UTILITY



Coal-Fired Power Plant

## AGRICULTURE-RELATED PROCESSING



Ethanol Plant

# Anthropogenic CO<sub>2</sub>

Carbon dioxide formed through human action is referred to as anthropogenic CO<sub>2</sub>. The primary source of anthropogenic CO<sub>2</sub> 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<sub>2</sub>. Collectively, these are referred to as large stationary CO<sub>2</sub> point

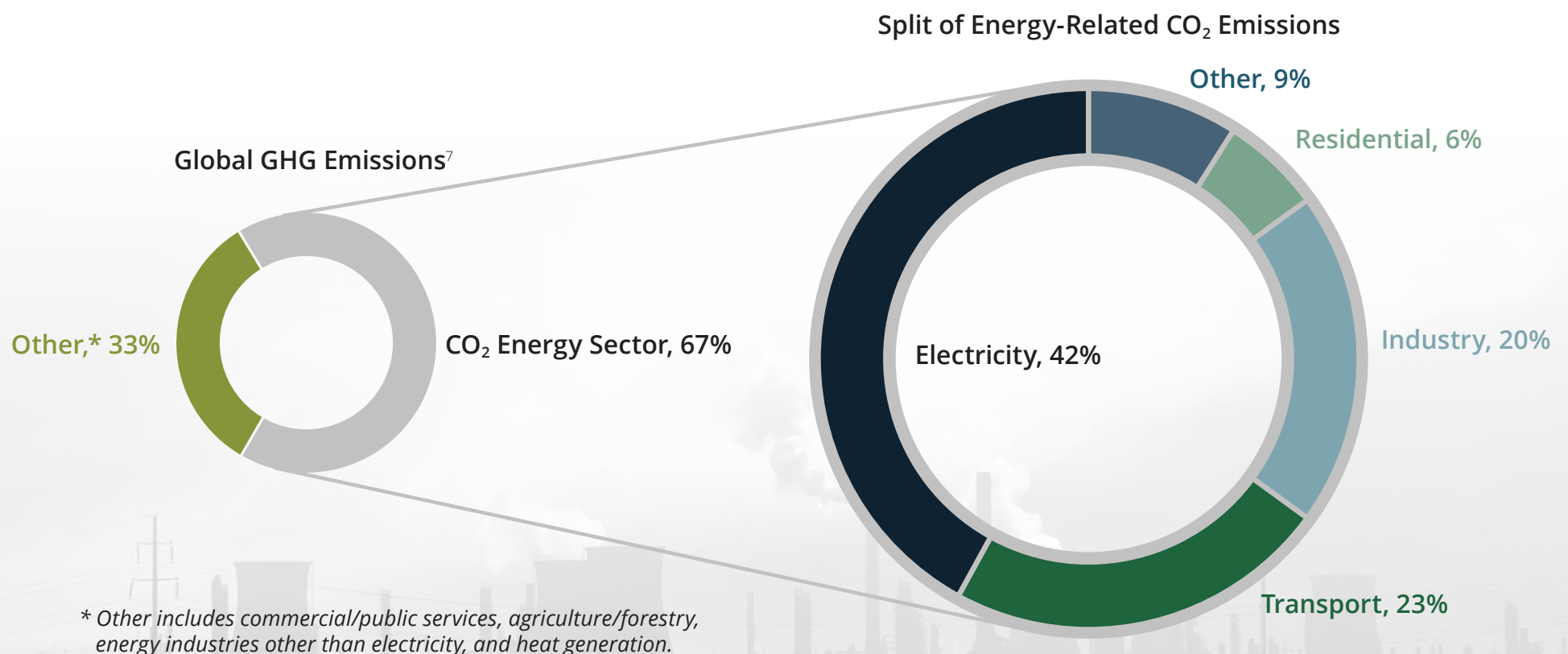
sources. Nonstationary CO<sub>2</sub> emissions include activities such as using gasoline, diesel, and other fuels for transportation.

Changes in land use and land conversion are also considered a significant source of anthropogenic CO<sub>2</sub>. This includes practices like plowing land, which releases some of the exposed carbon in the soil to the atmosphere as CO<sub>2</sub>, and deforestation, which causes a loss of plant biomass.

## What Is CO<sub>2</sub>?

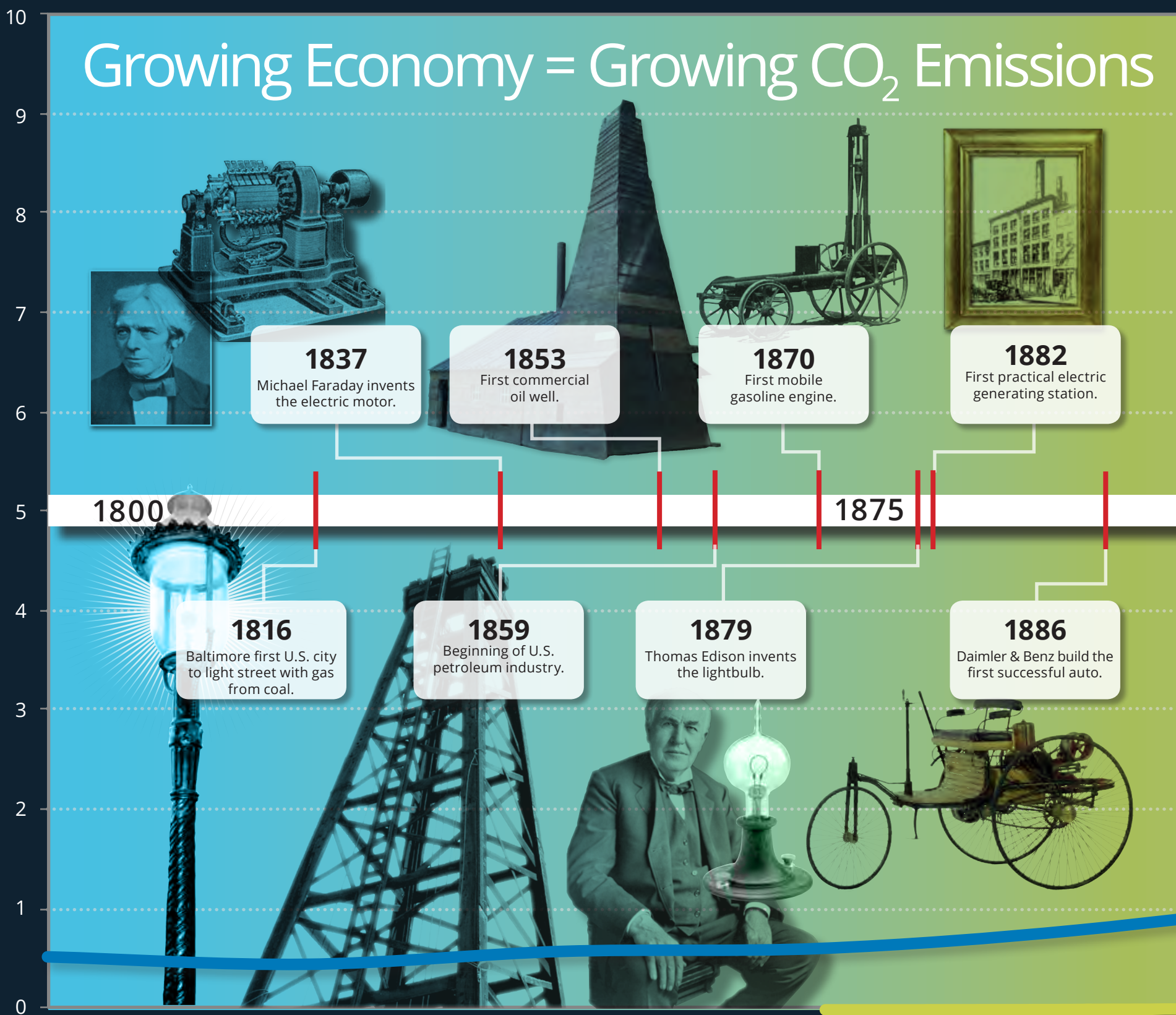
Carbon dioxide is a colorless, odorless, naturally occurring gas comprising one atom of carbon and two atoms of oxygen. At temperatures below -76°C, CO<sub>2</sub> condenses into a white solid called dry ice. When warmed, dry ice vaporizes directly from a solid to CO<sub>2</sub> gas in a process called sublimation. With enough added pressure, liquid CO<sub>2</sub> can be formed.

CO<sub>2</sub> has a number of industrial uses: in fire extinguishers (CO<sub>2</sub> displaces the oxygen the fire needs to burn), as a propellant in spray cans, in treatment of drinking water, for cold storage (CO<sub>2</sub> as dry ice), and to make bubbles in soft drinks. However, by far the largest use is in oil fields to enhance oil recovery.

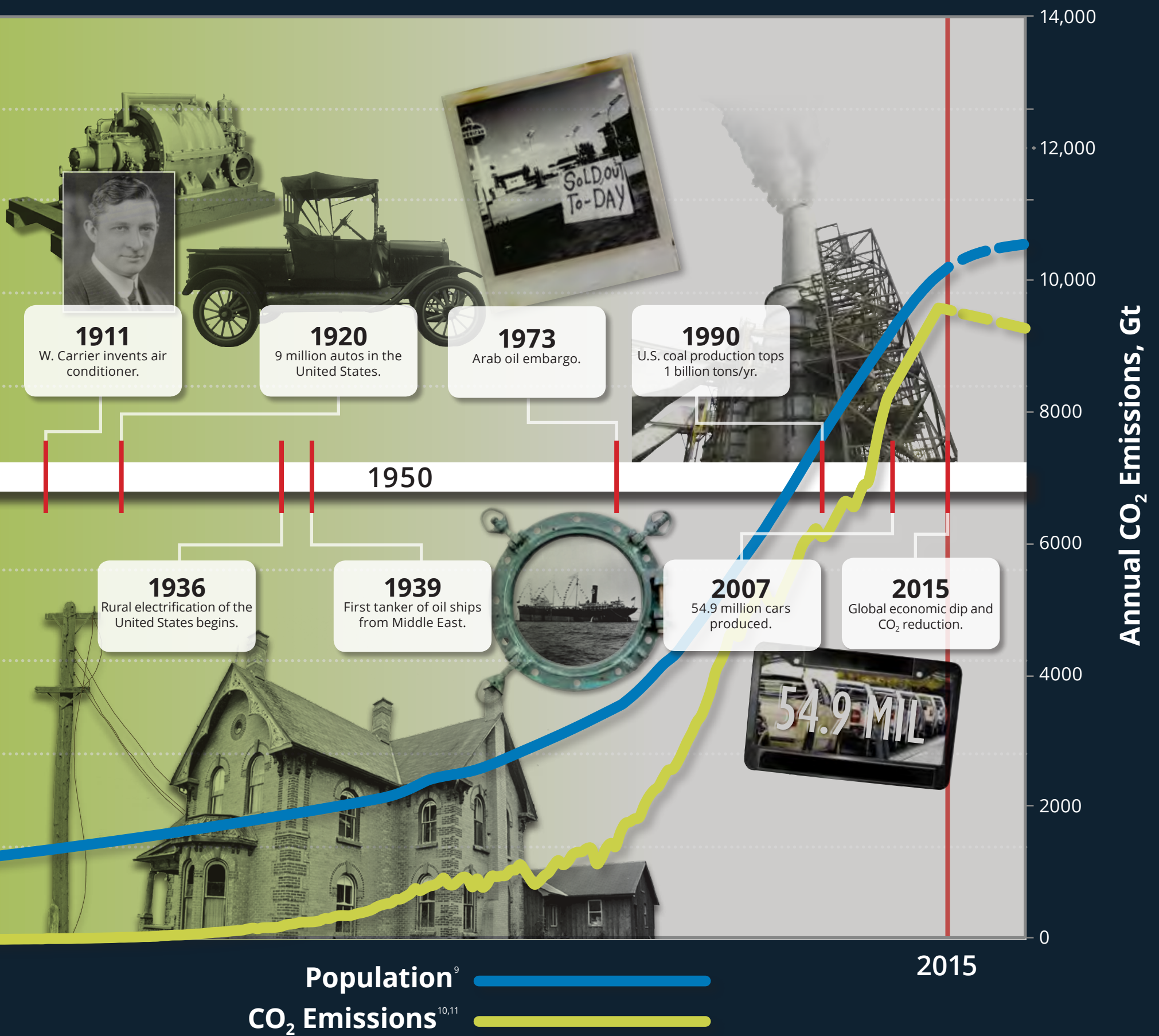


# Growing Economy = Growing CO<sub>2</sub> Emissions

Population, billions



The amount of CO<sub>2</sub> in the atmosphere was relatively constant for 10,000 years until the Industrial Revolution in the 1800s, and the amount of anthropogenic CO<sub>2</sub> is projected to increase considerably. Currently, the world's economies annually emit approximately 29 Gt of CO<sub>2</sub> 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<sub>2</sub> being emitted to the atmosphere.<sup>8</sup>



# 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.

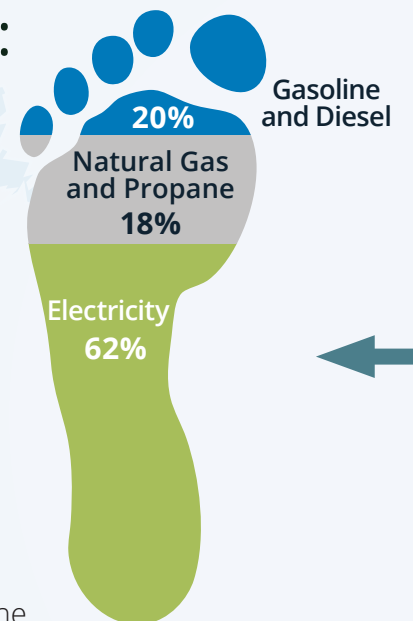
In 1930, the countries that now have the postindustrial economies generated nearly all carbon emissions from fossil fuels. Since then, global emissions have grown seven times greater. Now, postindustrial economies generate half.<sup>12</sup> By 2030, global emissions are projected to grow by half again; 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.

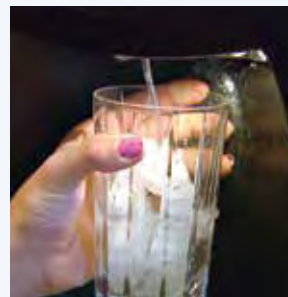
How will we support modern lifestyles globally as we address climate change?

## Postindustrial Economy: United States<sup>13</sup>

Minneapolis



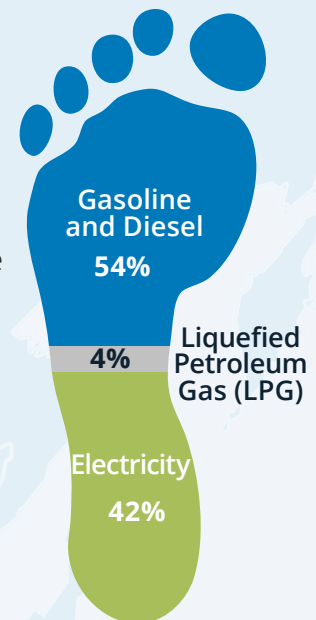
A middle class U.S. family uses fossil fuels for transportation, heating, and cooking, but most of their carbon footprint comes from the electricity they use (generated mainly from coal).



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

## Emerging Economy: India<sup>13</sup>

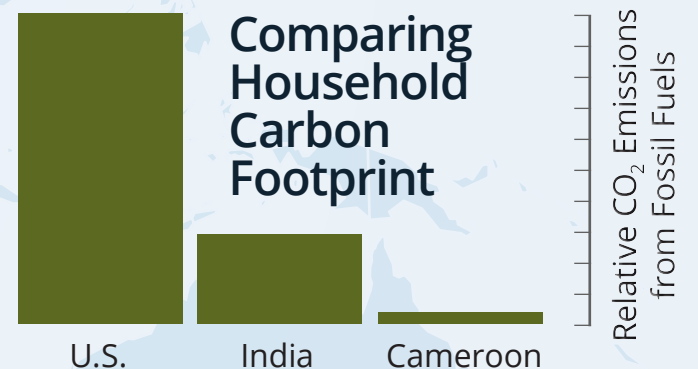
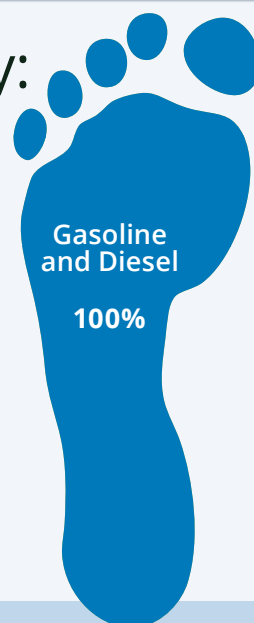
Middle class homes in India are smaller, have fewer appliances, and have no heating systems. About half of the carbon footprint for this family comes from their transportation. Most of the rest comes from the electricity they use (most made by fossil fuels).



Muyuka

## Developing Economy: Cameroon<sup>13</sup>

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.*

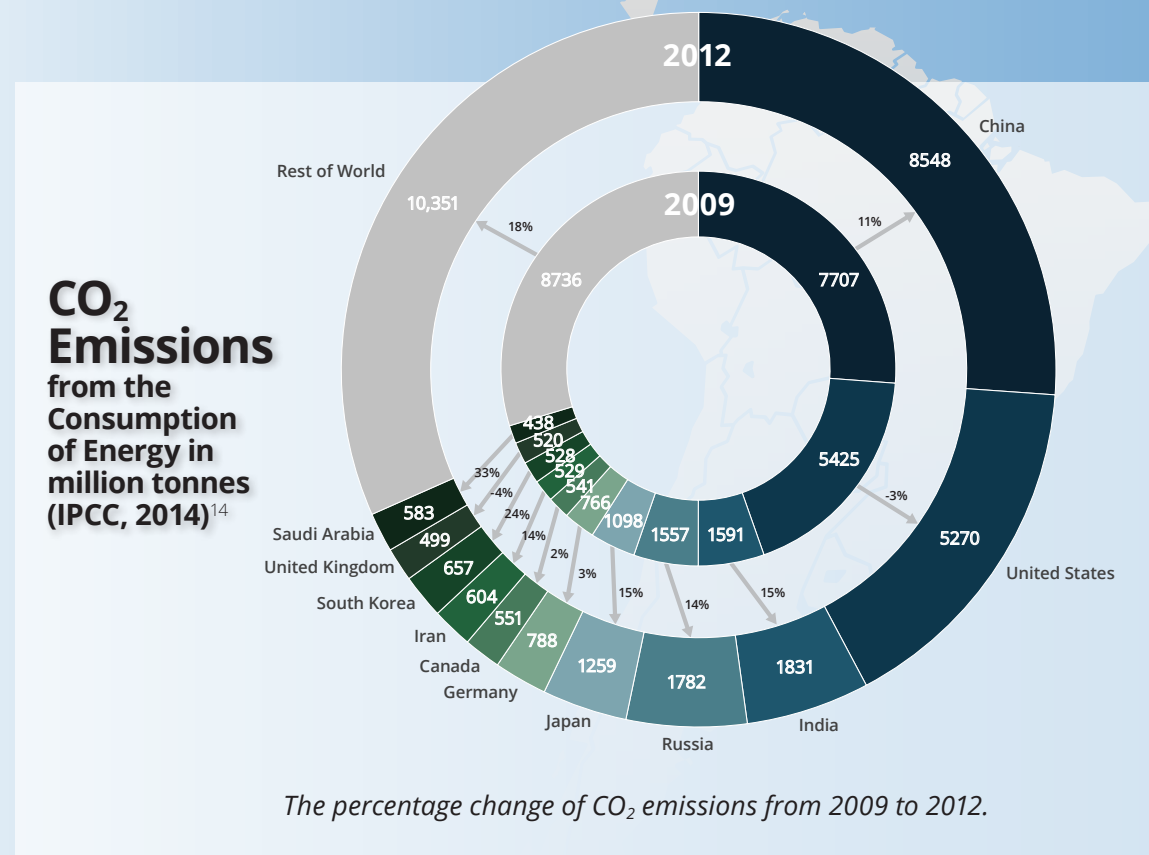
# World CO<sub>2</sub> Emissions

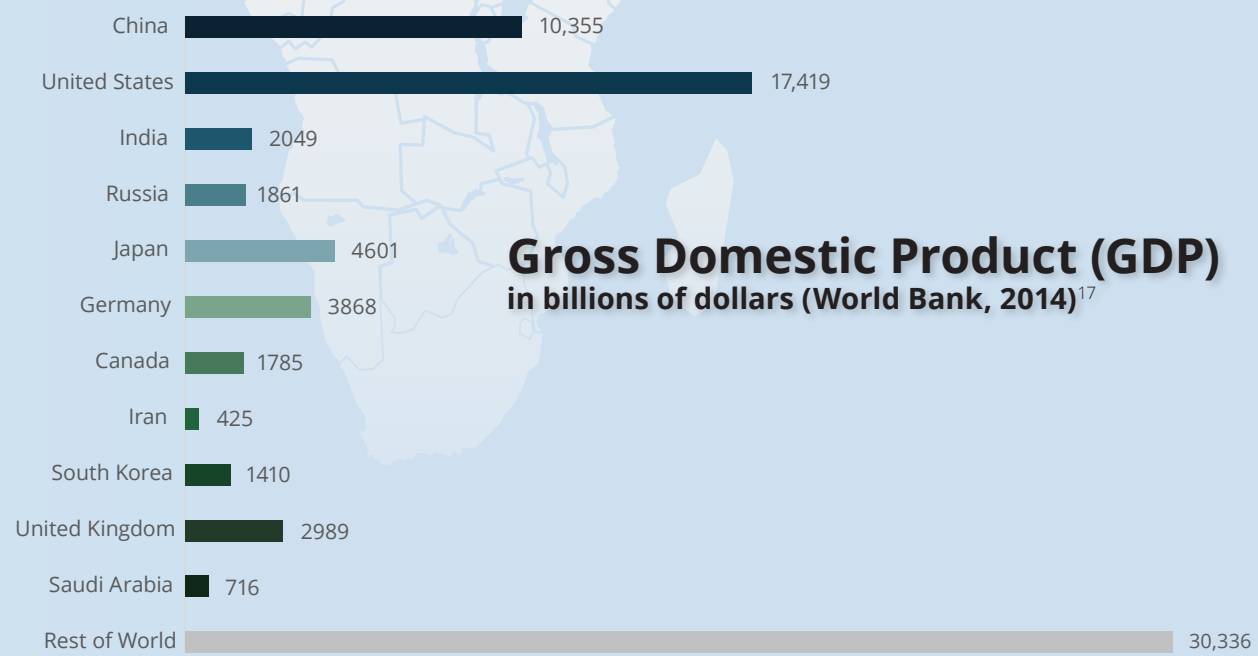
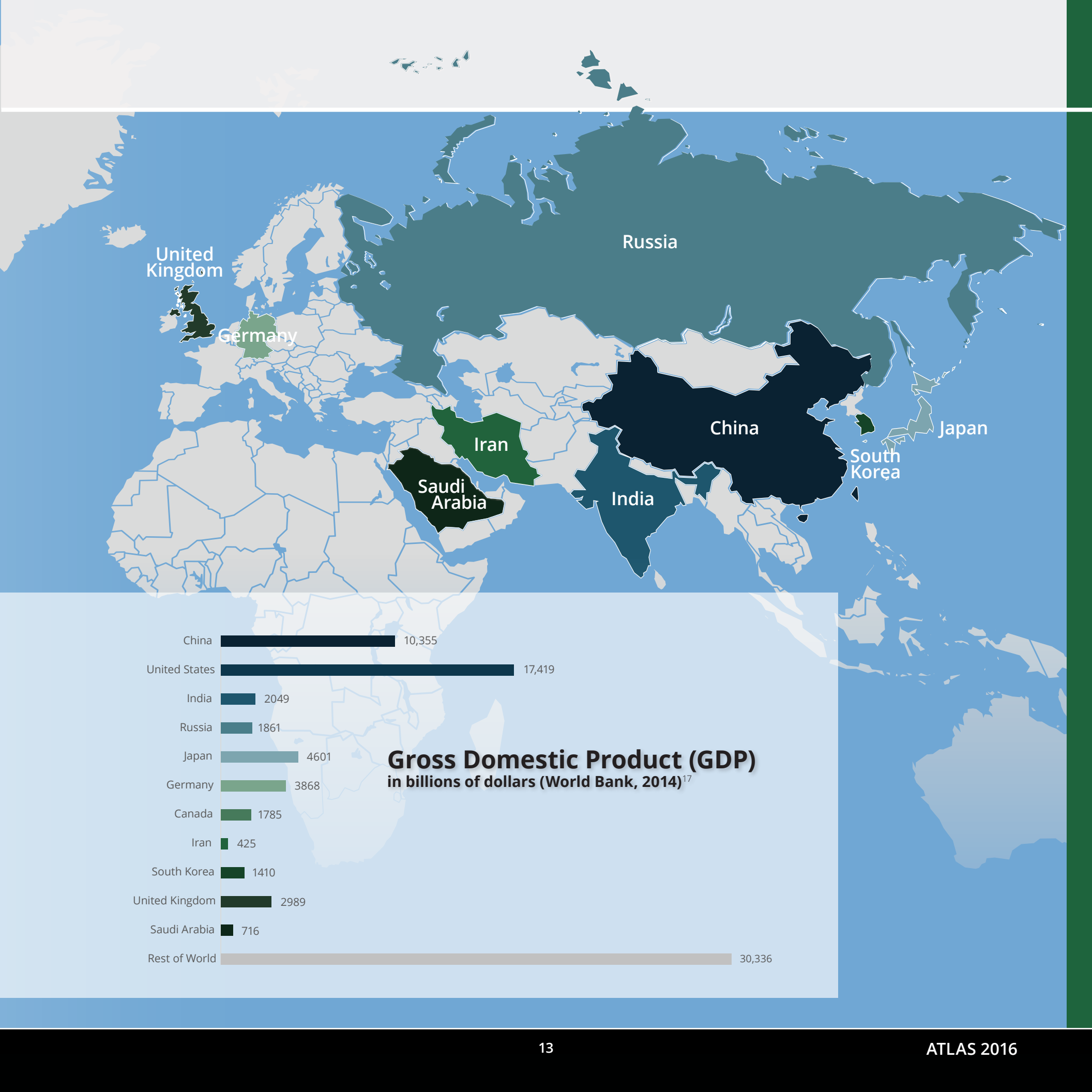
**Global** carbon emissions from fossil fuels have significantly increased the amount of GHG from anthropogenic sources emitted to the atmosphere. Since 1970, CO<sub>2</sub> emissions have increased 90%, with emissions from fossil fuel combustion and industrial processes contributing more than 75% of the total emissions.<sup>14</sup> 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.<sup>15</sup> 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<sub>2</sub> 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<sub>2</sub> 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.<sup>16</sup>





# North American CO<sub>2</sub> Sources



# North American Profile

The type and distribution of large stationary CO<sub>2</sub> sources across North America reflect the prevalent economy and historical development of the continent.

## 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.

## 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<sub>2</sub> and thus require no specialized CO<sub>2</sub> capture and separation technologies.

## 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<sub>2</sub>.

## 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.

# Potential Impacts of Climate Change

No one knows the exact consequences of this upsurge of CO<sub>2</sub> 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:<sup>19</sup>

- 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*

# Finding a CO<sub>2</sub> Solution

Addressing climate change is a large-scale, global challenge that is compounded by our growing demand for energy. To reduce the risks associated with climate change, the amount of CO<sub>2</sub> released by human activity must be substantially reduced.

A number of techniques can be employed to reduce CO<sub>2</sub> 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]).<sup>20</sup>**





CO<sub>2</sub>

CO<sub>2</sub>

CO

## CHAPTER 2

# Carbon Management

The need to stabilize atmospheric concentrations of CO<sub>2</sub> 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<sub>2</sub> naturally stored on Earth's surface, but one of the most promising approaches involves capturing CO<sub>2</sub> from the exhaust gas at large stationary sources and placing the CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> as a gas but stores the carbon portion of the CO<sub>2</sub>. 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<sub>2</sub> to form CO<sub>2</sub> 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<sub>2</sub> levels in several years. Using terrestrial storage now means we can get started on reducing CO<sub>2</sub> 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.**



# Carbon Capture and Storage

Capturing  $\text{CO}_2$  emissions from large stationary sources before the  $\text{CO}_2$  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  $\text{CO}_2$  emission from large point sources such as coal- and gas-fired power plants, natural gas-processing facilities, ethanol plants, and other industrial processes.

A 3D architectural rendering of a carbon capture and storage (CCS) facility. The facility is situated in a green field with rolling hills in the background. The main structure is a large, grey, rectangular building with several tall, blue cylindrical towers. To the left of the main building, there are smaller grey structures and a blue dome. To the right, there are more grey structures and a large white arrow pointing right, labeled 'Compression'. The entire facility is connected by a network of red and grey pipes. Below the ground level, a cross-section of the earth is shown, revealing a thick layer of brown soil and a lighter-colored rock layer. The text 'CO2 Capture' is overlaid on the left side of the facility.

**$\text{CO}_2$  Capture**

**Purification/ $\text{CO}_2$   
Dehydration**

**Compression**

Not to scale.

CCS involves the capture of CO<sub>2</sub> 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<sub>2</sub> from the atmosphere.

## CO<sub>2</sub> Transportation

CO<sub>2</sub> Transportation Pipeline

## CO<sub>2</sub> Storage

CO<sub>2</sub> Injection

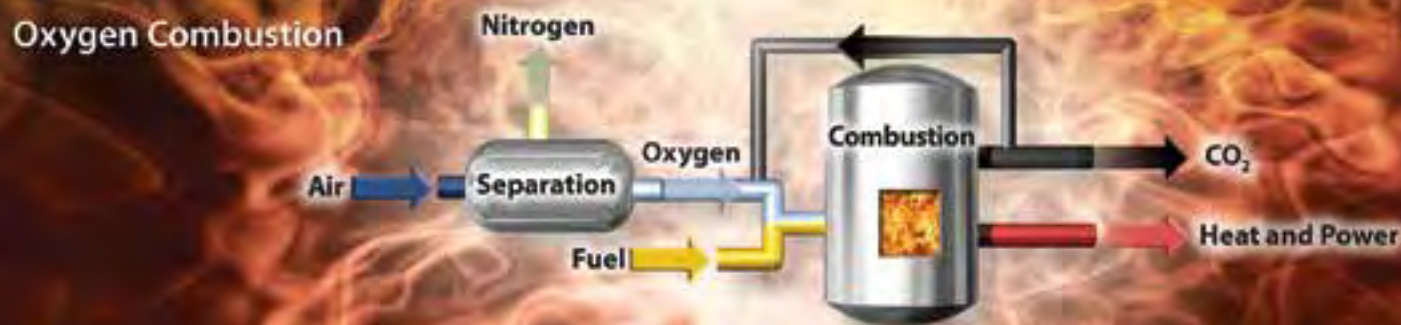
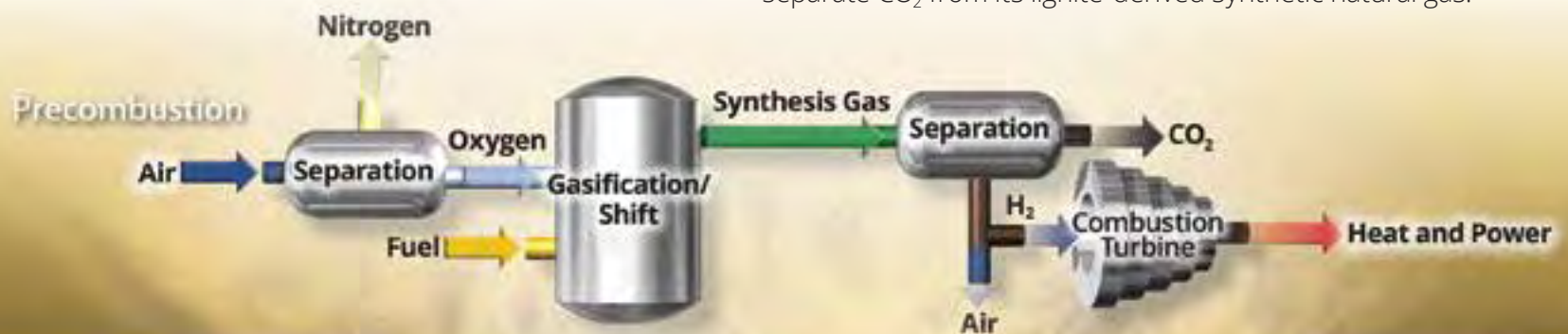
CO<sub>2</sub> Storage

800+ m

# CO<sub>2</sub> Capture from Combustion and Industrial Processes

**Capture** is the separation of CO<sub>2</sub> 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<sub>2</sub> 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,<sup>21</sup> meaning that the atmosphere in the boiler is not pure oxygen but rather a mixture consisting primarily of oxygen and CO<sub>2</sub>. The majority of capture technologies focus on separating low-concentration CO<sub>2</sub> from the exhaust gas stream after combustion takes place; this is called postcombustion capture.

Because the concentration of CO<sub>2</sub> 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),<sup>22</sup> 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<sub>2</sub> can represent three-fourths of the total cost of a CCS operation.<sup>22</sup> Because capture is the most costly portion of a CCS project, research is being performed to develop more efficient CO<sub>2</sub> capture processes and improve the economics of existing ones. CO<sub>2</sub> 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<sub>2</sub> at commercial scale, and the Great Plains Synfuels Plant in Beulah, North Dakota, uses precombustion techniques to separate CO<sub>2</sub> from its lignite-derived synthetic natural gas.



# CO<sub>2</sub> and Compression

Captured CO<sub>2</sub> must be dehydrated and compressed into a supercritical or liquidlike state for either storage before truck transport or piping to the storage site. CO<sub>2</sub> must be compressed to at least 1200 to 1500 pounds per square inch (psi) for transport in a pipeline to ensure that CO<sub>2</sub> remains in a dense liquid state. Because compression is energy-intensive, improved compression methods are under development.



# CO<sub>2</sub> Transportation Infrastructure

Following capture and compression, CO<sub>2</sub> is transported to a storage site. Given the quantities of CO<sub>2</sub> 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<sub>2</sub> pipeline is in service in North America, with additional pipeline planned or under construction.<sup>23</sup>



*Image provided by Denbury Resources Inc.*

# CO<sub>2</sub> Pipelines

Pipelines are a proven technology and have been used to safely transport industrial quantities of CO<sub>2</sub> for over 30 years. CO<sub>2</sub> pipelines are similar in design and operation to natural gas pipelines, although the higher pressures needed for CO<sub>2</sub> transportation require construction using thicker-walled carbon steel pipe.

Building a regional CO<sub>2</sub> pipeline infrastructure for CCS activities will require thoughtful planning. Pipelines may be built to connect individual CO<sub>2</sub> 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<sub>2</sub> stream quality may need to be addressed.

Pipelines carrying CO<sub>2</sub> 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<sub>2</sub> transport via pipeline.<sup>24</sup>



Image provided by Denbury Resources Inc.



Image provided by Denbury Resources Inc.

# Secure Geologic Storage



# Geologic Storage Criteria

**Geologic** storage involves injecting captured anthropogenic CO<sub>2</sub> 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<sub>2</sub>. Scientists have identified many potentially suitable areas across the globe that have the capacity to securely hold hundreds of years of anthropogenic CO<sub>2</sub> emissions deep underground.

## **Storage Reservoir Characteristics**

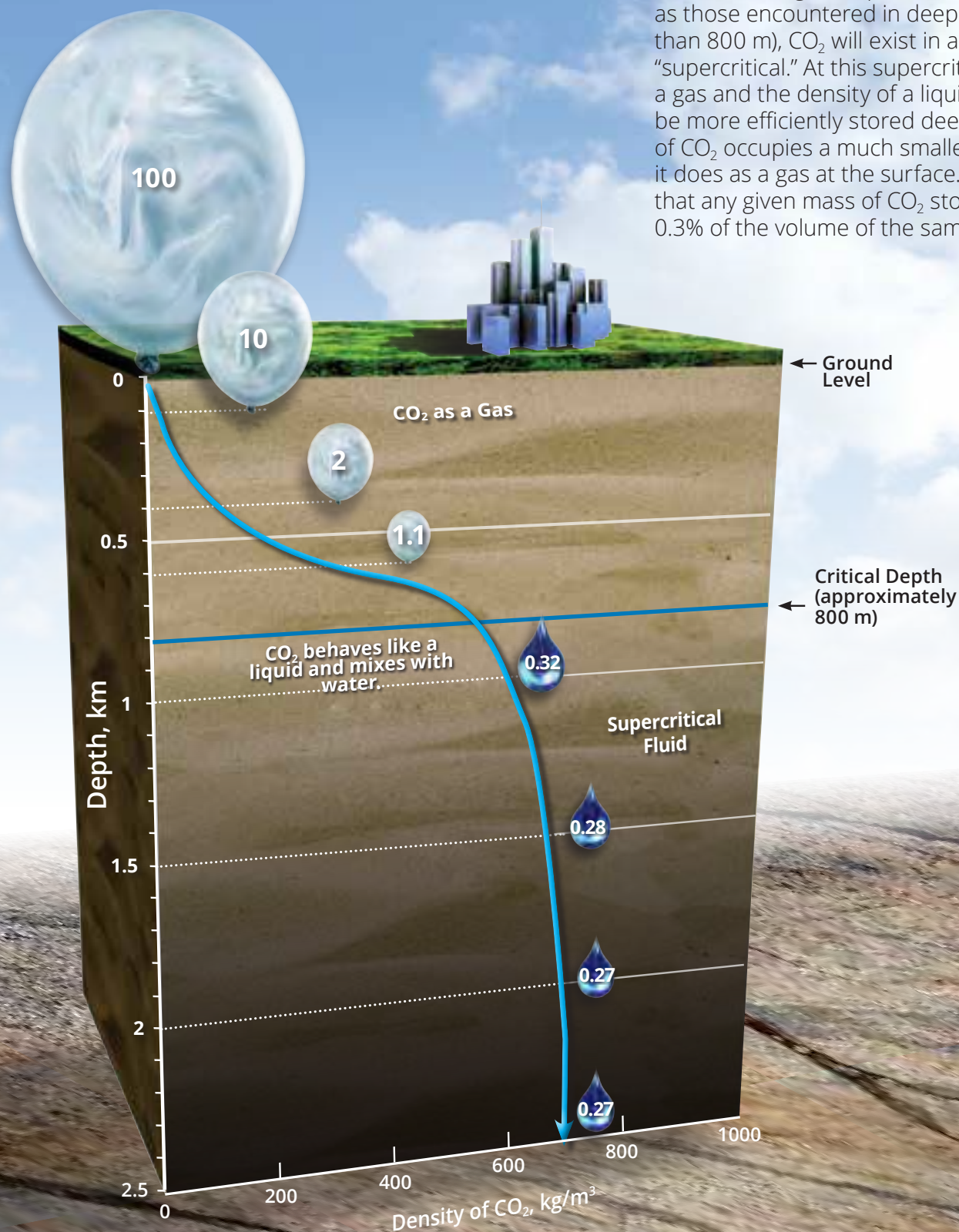
Site selection is central to the secure storage of CO<sub>2</sub> because successful geologic storage requires that CO<sub>2</sub> stay in place and not pose significant risk to human health and the environment. Storage reservoirs should:

- Be capable of storing large quantities of CO<sub>2</sub> permanently.
- Be overlain by thick, laterally continuous seals or cap rocks that prevent upward migration of CO<sub>2</sub>.
- Be at depths that take advantage of dense-phase CO<sub>2</sub> (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<sub>2</sub>

Under high-temperature and high-pressure conditions, such as those encountered in deep geologic formations (typically greater than 800 m), CO<sub>2</sub> will exist in a dense phase that is referred to as "supercritical." At this supercritical point, CO<sub>2</sub> has viscosity similar to a gas and the density of a liquid. These properties allow more CO<sub>2</sub> to be more efficiently stored deep underground because a given mass of CO<sub>2</sub> 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<sub>2</sub> stored below 800 m occupies around 0.3% of the volume of the same mass at the surface.



The supercritical state of liquidlike CO<sub>2</sub> 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<sub>2</sub> process was used, coffee was decaffeinated with chemical solvents that often left residues negatively affecting the flavor.



# Trapping CO<sub>2</sub> in Rocks

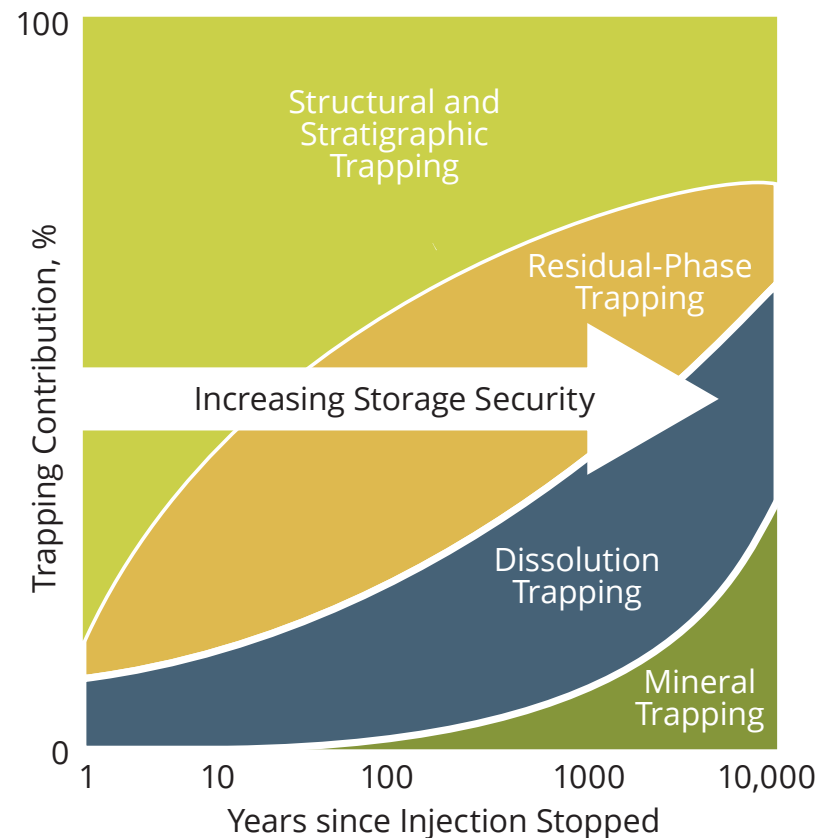
Several mechanisms function to trap and store CO<sub>2</sub> in deep geologic formations.<sup>25</sup>

**Structural and Stratigraphic Trapping** – Injected CO<sub>2</sub> is typically less dense than native pore fluids in deep geologic formations, most commonly brine. This lower density causes CO<sub>2</sub> 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<sub>2</sub> for millions of years.

**Residual-Phase Trapping** – As injected CO<sub>2</sub> 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<sub>2</sub> will dissolve into brine in the pore spaces. Brine with dissolved CO<sub>2</sub> becomes denser than the surrounding brine and will sink to the bottom of the reservoir, minimizing the possibility of further migration.

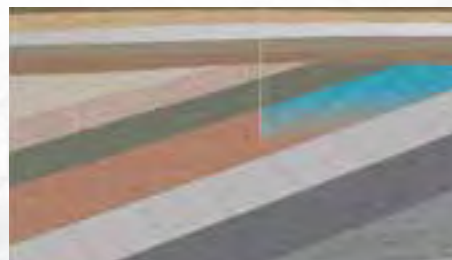
**Mineral Trapping** – The last stage of CO<sub>2</sub> trapping involves a chemical reaction between the dissolved CO<sub>2</sub> in the formation fluids and the minerals in the target formation and cap rock to form new solid minerals, thus effectively locking the CO<sub>2</sub> in place. Mineral trapping will typically occur over extended timescales and is difficult to predict with accuracy.



*As time passes after the injection of CO<sub>2</sub> 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<sub>2</sub> from moving upward out of the formation.*



*The CO<sub>2</sub> is trapped when there is a sudden change in the rock formations, so that the CO<sub>2</sub> cannot move farther upward.*



*The buoyant CO<sub>2</sub> will collect under a curved layer of impermeable rock at the highest point, unable to move out of the formation.*



*CO<sub>2</sub> 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

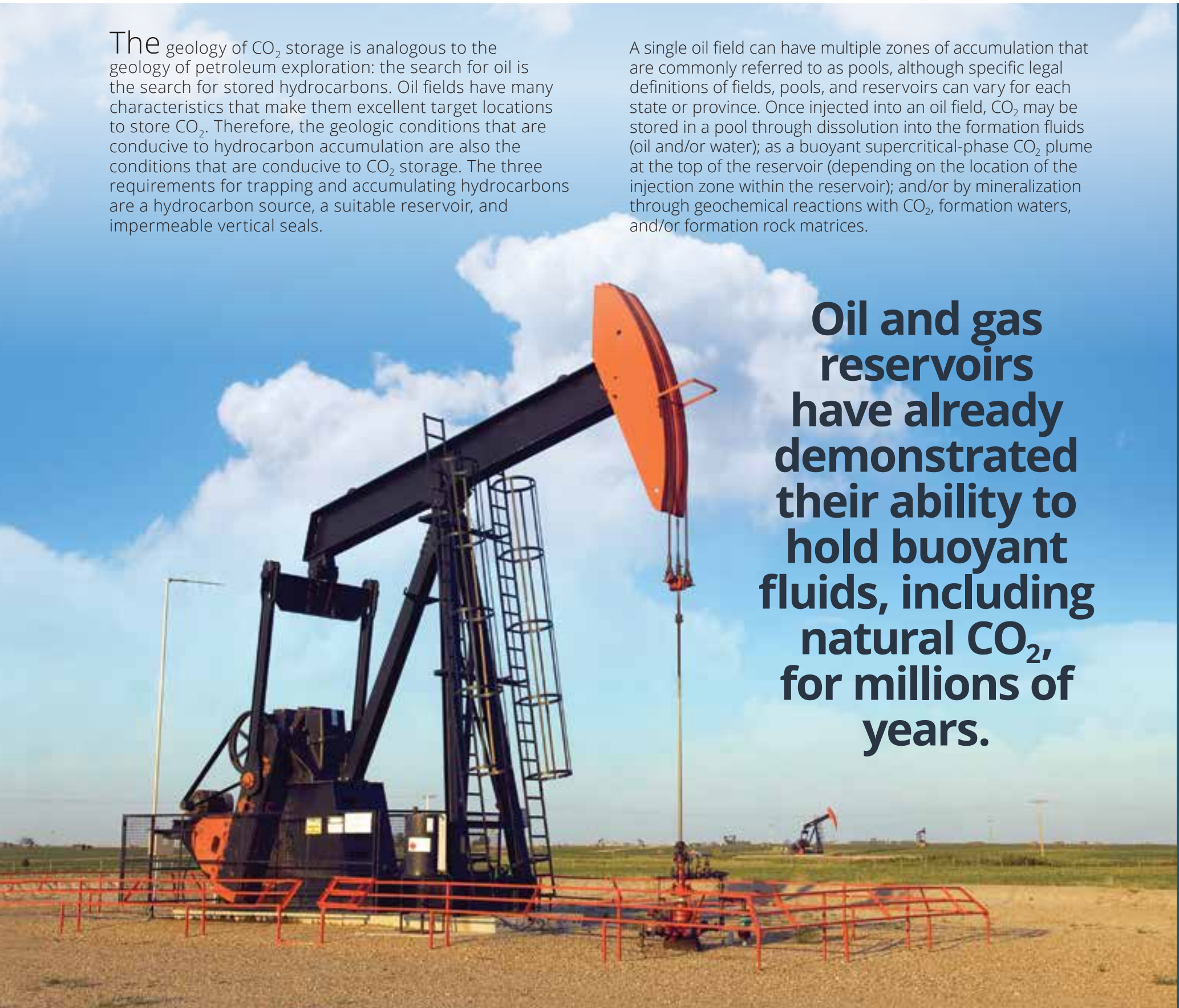


# CO<sub>2</sub> in Oil Fields


The geology of CO<sub>2</sub> 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<sub>2</sub>. Therefore, the geologic conditions that are conducive to hydrocarbon accumulation are also the conditions that are conducive to CO<sub>2</sub> 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<sub>2</sub> may be stored in a pool through dissolution into the formation fluids (oil and/or water); as a buoyant supercritical-phase CO<sub>2</sub> 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<sub>2</sub>, formation waters, and/or formation rock matrices.

**Oil and gas reservoirs have already demonstrated their ability to hold buoyant fluids, including natural CO<sub>2</sub>, for millions of years.**



# Enhanced Oil Recovery

A large silhouette of an oil pumpjack (jackal) dominates the foreground, set against a dramatic sunset sky with orange and yellow clouds. The sun is low on the horizon, creating a strong backlight effect. The pumpjack's long arm and counterweight are clearly visible.

U.S. production from  
enhanced oil recovery (EOR)  
could increase to  
**over half a  
million barrels**  
of oil per day by 2020.<sup>27</sup>

# CO<sub>2</sub> 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<sub>2</sub> 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,<sup>27</sup> thereby reducing the need to import as much oil.

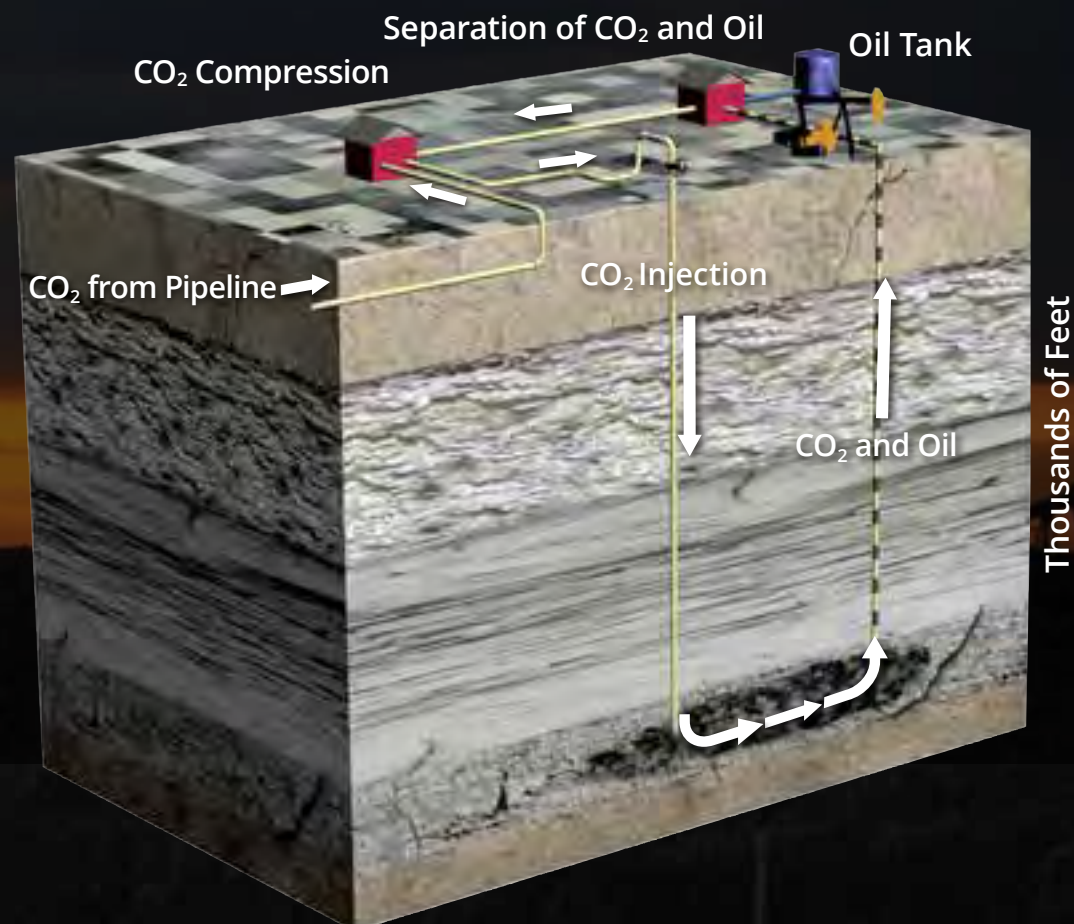
## How EOR Works

When CO<sub>2</sub> 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<sub>2</sub>-based EOR. Factors such as geology, depth, and the nature of the oil itself will determine the effectiveness of CO<sub>2</sub> for EOR.

Since the 1970s, operators in West Texas have safely pumped many millions of tons of CO<sub>2</sub> 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<sub>2</sub> EOR in West Texas and other states. Although a majority of CO<sub>2</sub> used in this process is sourced from natural underground deposits, the proportion of CO<sub>2</sub> derived from the capture of anthropogenic emissions is increasing. CO<sub>2</sub> 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<sub>2</sub> storage that can provide a bridge to future non-EOR-based geologic storage.

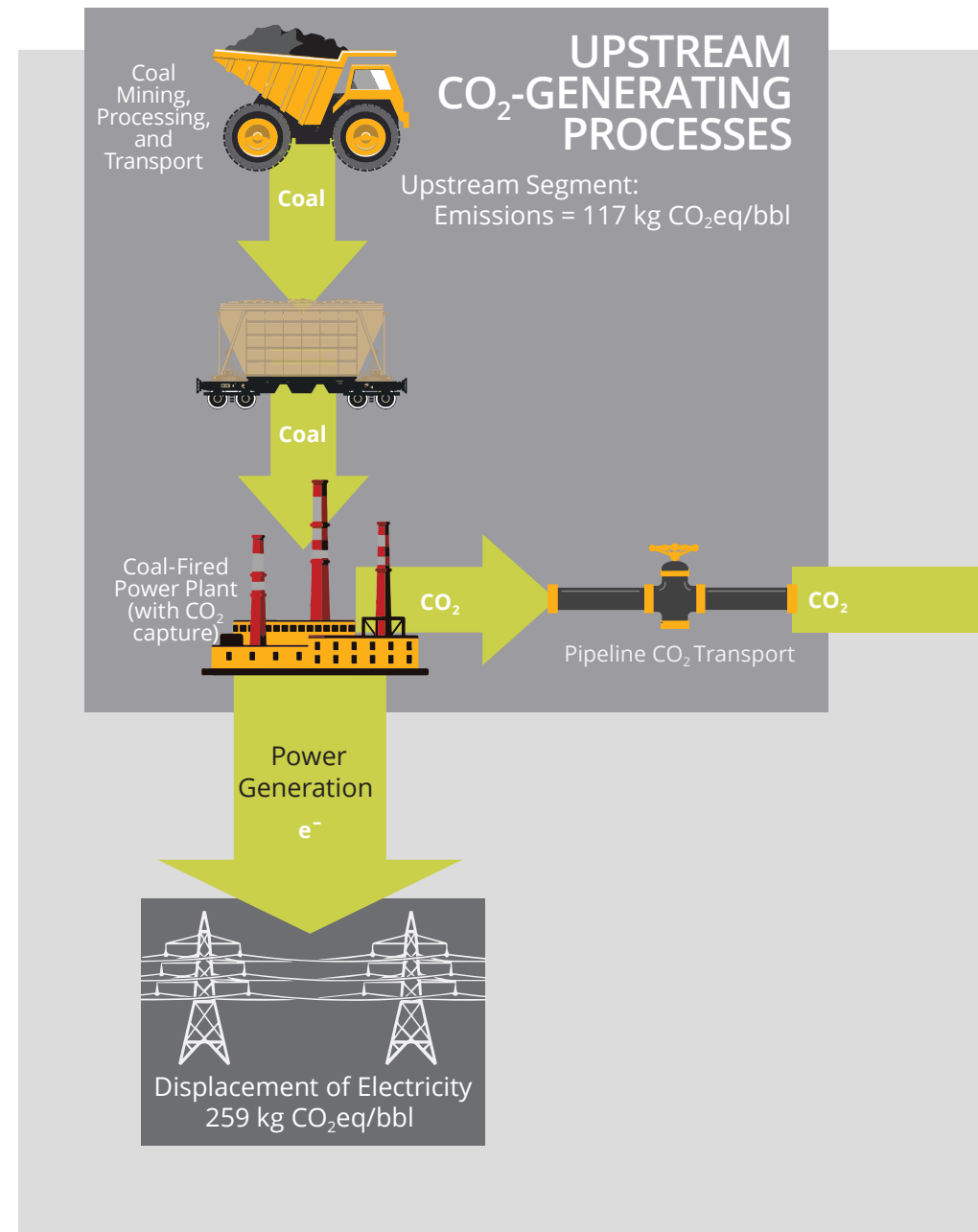


# CO<sub>2</sub> EOR Life Cycle Analysis

Life cycle analysis (LCA) is a useful way to account for CO<sub>2</sub> storage at an EOR site and to track CO<sub>2</sub> emissions at all stages of a CO<sub>2</sub> EOR project. The LCA results may then be used to evaluate the life cycle CO<sub>2</sub> emissions per barrel of oil produced via CO<sub>2</sub> EOR as compared to oil produced by other methods.

The Energy & Environmental Research Center (EERC) conducted a detailed LCA of CO<sub>2</sub> emissions associated with CO<sub>2</sub> EOR where the CO<sub>2</sub> is sourced from a coal-fired power plant.<sup>28</sup> The modeled system includes three segments: upstream, gate-to-gate, and downstream CO<sub>2</sub>-generating processes. Upstream processes include coal extraction and processing, transport, power generation with CO<sub>2</sub> capture, and CO<sub>2</sub> transport to the CO<sub>2</sub> EOR field. Gate-to-gate processes include CO<sub>2</sub> 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<sub>2</sub> emissions from upstream, gate-to-gate, and downstream segments are 685 kg CO<sub>2</sub>eq/bbl.

However, since 85% or more of the required CO<sub>2</sub> 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<sub>2</sub>eq/bbl for typical CO<sub>2</sub> EOR operations. Optimization of operations for storage could further reduce LCA emissions to 256 kg CO<sub>2</sub>eq/bbl. The box graph shows this compares favorably to other sources of oil production.<sup>29</sup>

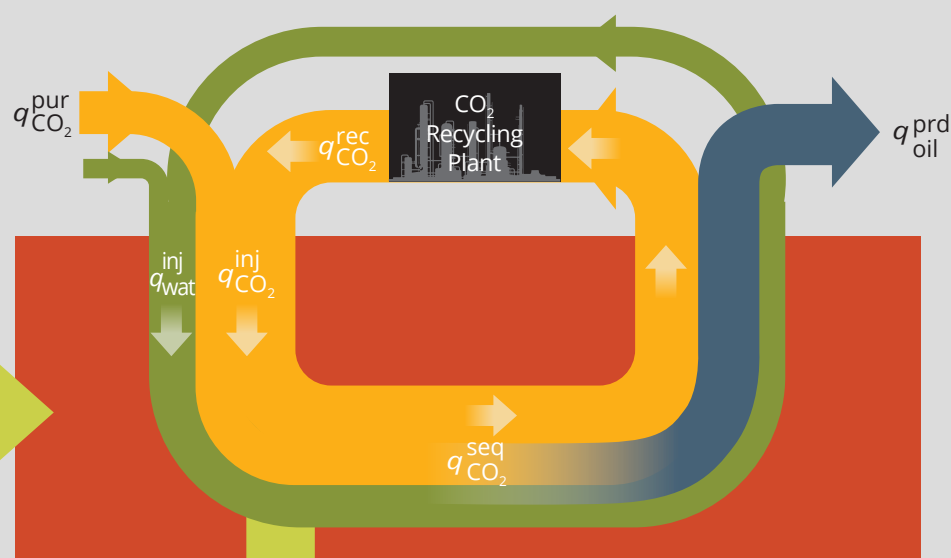


*Note: Emissions are expressed as CO<sub>2</sub> equivalents (CO<sub>2</sub>eq), which include CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O.*

## CO<sub>2</sub> EOR OPERATIONS (gate-to-gate)

Gate-to-Gate Segment: Emissions = 98 kg CO<sub>2</sub>eq/bbl

"Gate-to-Gate"



## DOWNSTREAM CO<sub>2</sub>-GENERATING PROCESSES

Downstream Segment:  
Emissions = 470 kg CO<sub>2</sub>eq/bbl

Net Life Cycle Balance:

117 kg CO<sub>2</sub>eq/bbl

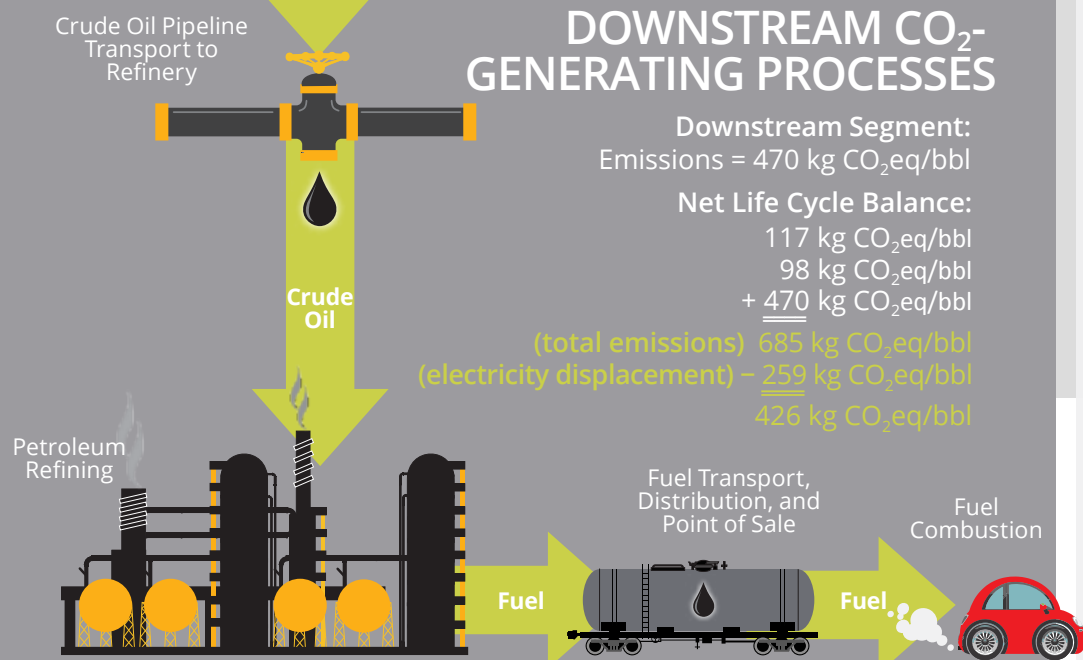
98 kg CO<sub>2</sub>eq/bbl

+ 470 kg CO<sub>2</sub>eq/bbl

(total emissions) 685 kg CO<sub>2</sub>eq/bbl

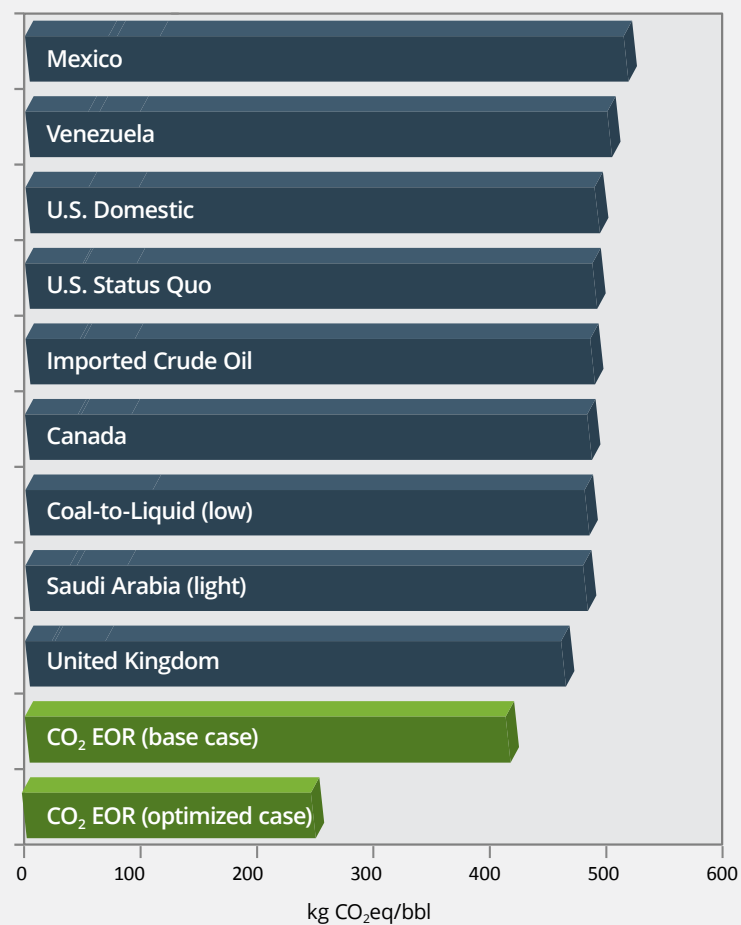
(electricity displacement) – 259 kg CO<sub>2</sub>eq/bbl

426 kg CO<sub>2</sub>eq/bbl



## How Does Oil Produced via CO<sub>2</sub> EOR Compare to Oil Produced Using Conventional Methods?

### Production Course<sup>29</sup>



# North American Sedimentary Basins




# CO<sub>2</sub> in Saline Formations

**Sedimentary** basins are relatively large areas of Earth's surface that, for various reasons, have subsided over long periods of geologic time. This subsidence allowed for the accumulation of sediments that eventually lithified into rock. Areas where the accumulation of sediments is thick enough (>800 m) may have an arrangement of rock layers suitable for CO<sub>2</sub> 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<sub>2</sub> sources. Saline formations suitable for CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> EOR opportunities.

A glass jar lying on its side, spilling white granular powder. The text is overlaid on the right side of the image.

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

# Putting TDS Levels into Perspective



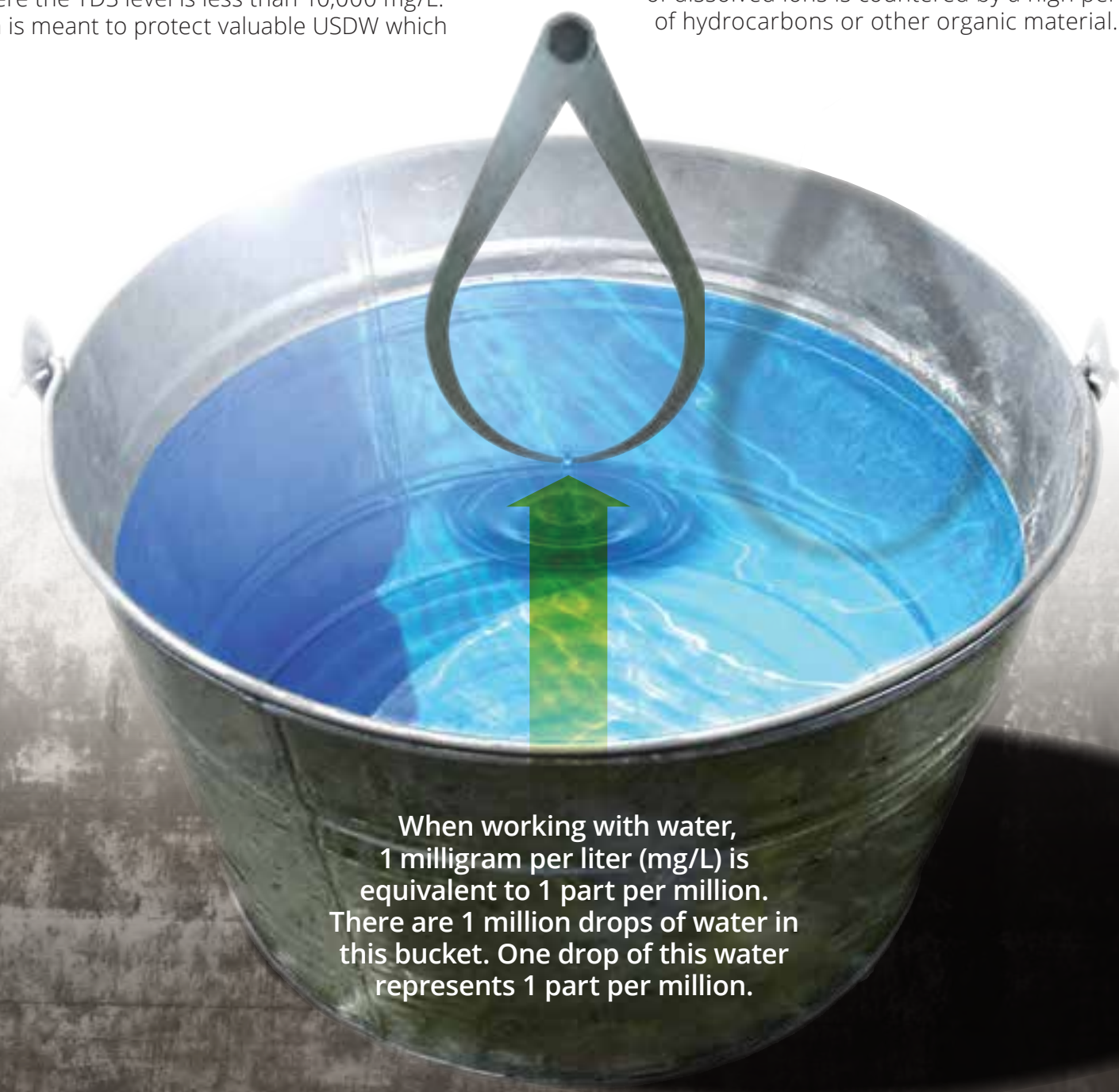
\* U.S. Environmental Protection Agency (EPA) secondary drinking water standard.

# 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<sub>2</sub> 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<sub>2</sub> storage have TDS values greater than 50,000 mg/L, and some deeper portions of sedimentary basins have TDS values exceeding 300,000 mg/L. Not all lower-TDS waters are suitable groundwater resources; oil reservoirs often contain water that has a TDS level less than 10,000 mg/L. However, this lower concentration of dissolved ions is countered by a high percentage of hydrocarbons or other organic material.



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

# Coal Regions of the United States and Canada

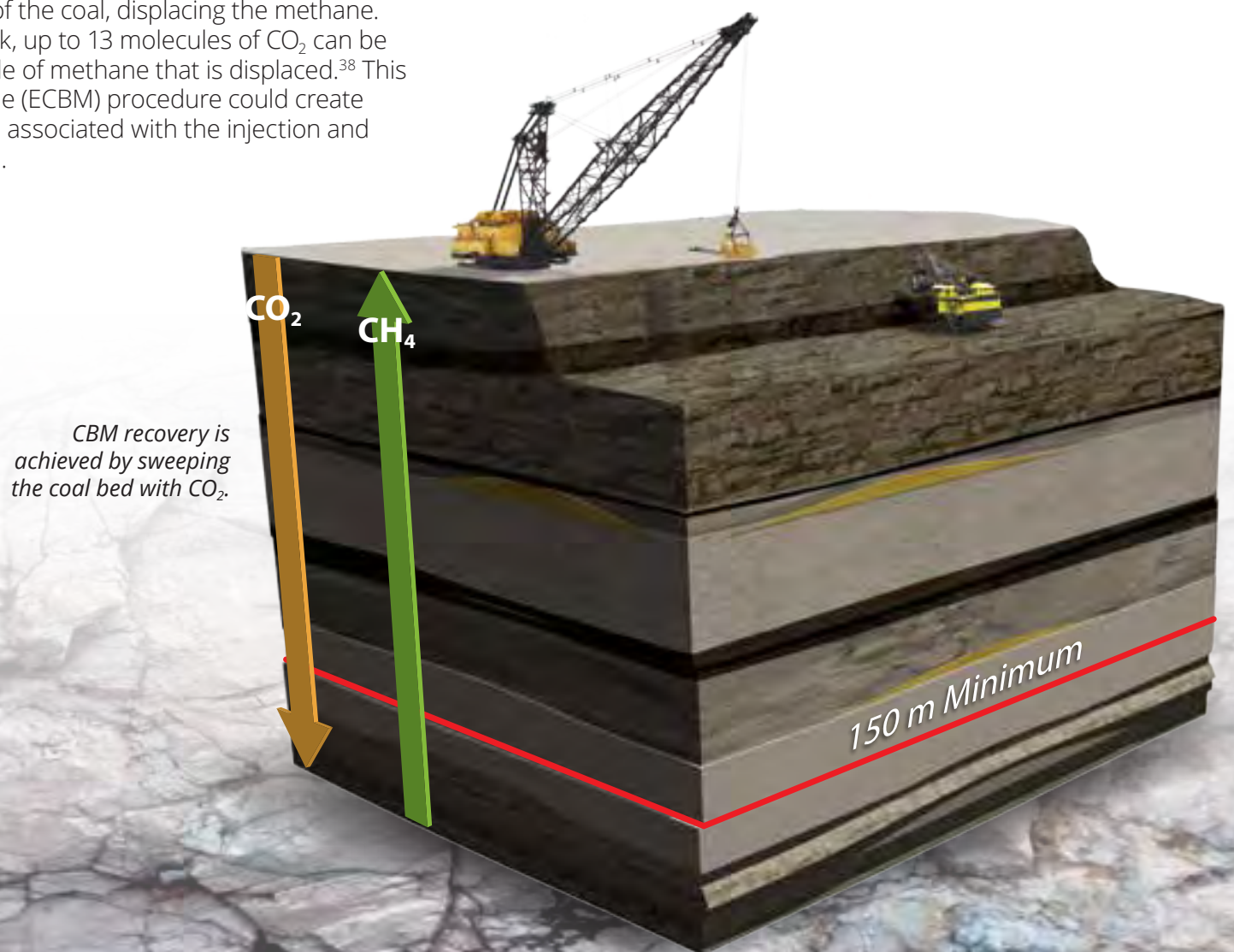


# CO<sub>2</sub> in Unminable Coal

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<sub>2</sub>, 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<sub>2</sub> storage. Carbon storage in unminable coal seams relies on the adsorption of CO<sub>2</sub> 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<sub>2</sub> to accumulate onto.

In addition to the potential for CO<sub>2</sub> 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<sub>2</sub>, which preferentially adsorbs onto the surface of the coal, displacing the methane. Depending on the coal rank, up to 13 molecules of CO<sub>2</sub> can be adsorbed for each molecule of methane that is displaced.<sup>38</sup> This enhanced coalbed methane (ECBM) procedure could create revenue to offset the costs associated with the injection and storage of CO<sub>2</sub> in coal beds.

**World CO<sub>2</sub> storage potential in coal seams is estimated to be 40 billion tonnes.**<sup>39</sup>





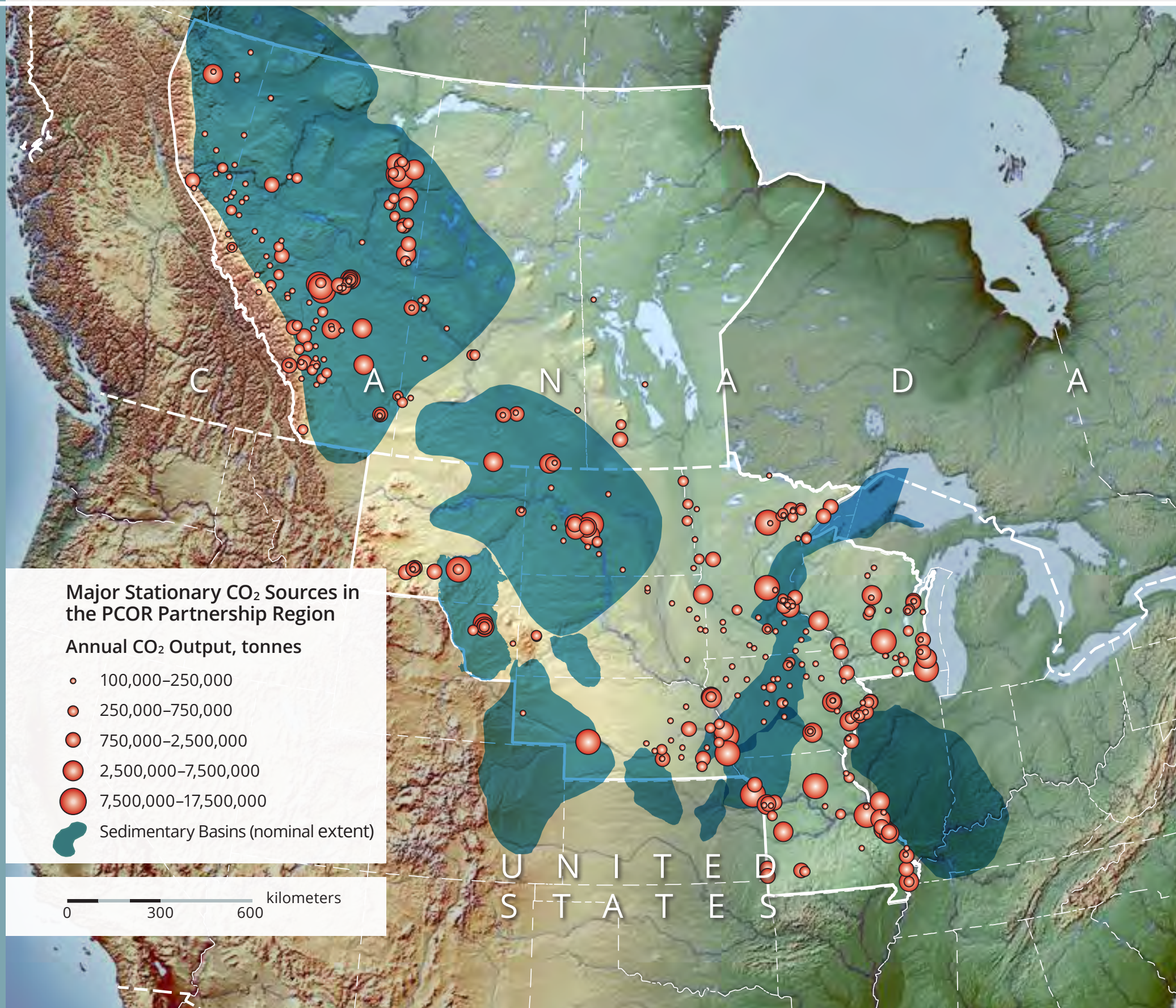
The background of the page is a photograph of an industrial facility, likely a power plant or refinery. On the left, two tall, dark smokestacks rise into the sky, with thick white plumes of smoke or steam emerging from them. Below the stacks, there are various industrial structures, including a large, light-colored cylindrical tank and a complex network of pipes and scaffolding. On the right side of the image, a large, dark, A-frame structure, possibly a conveyor system or a bridge, spans across the scene. The sky is filled with soft, white clouds, and the overall lighting suggests a hazy or overcast day. The image is partially obscured by a teal-colored vertical bar on the right side, which contains the chapter number '4'.

## 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<sub>2</sub> sources and potential CO<sub>2</sub> 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<sub>2</sub> storage resource estimates for the project and providing context for extrapolating the results of the large-scale demonstrations.

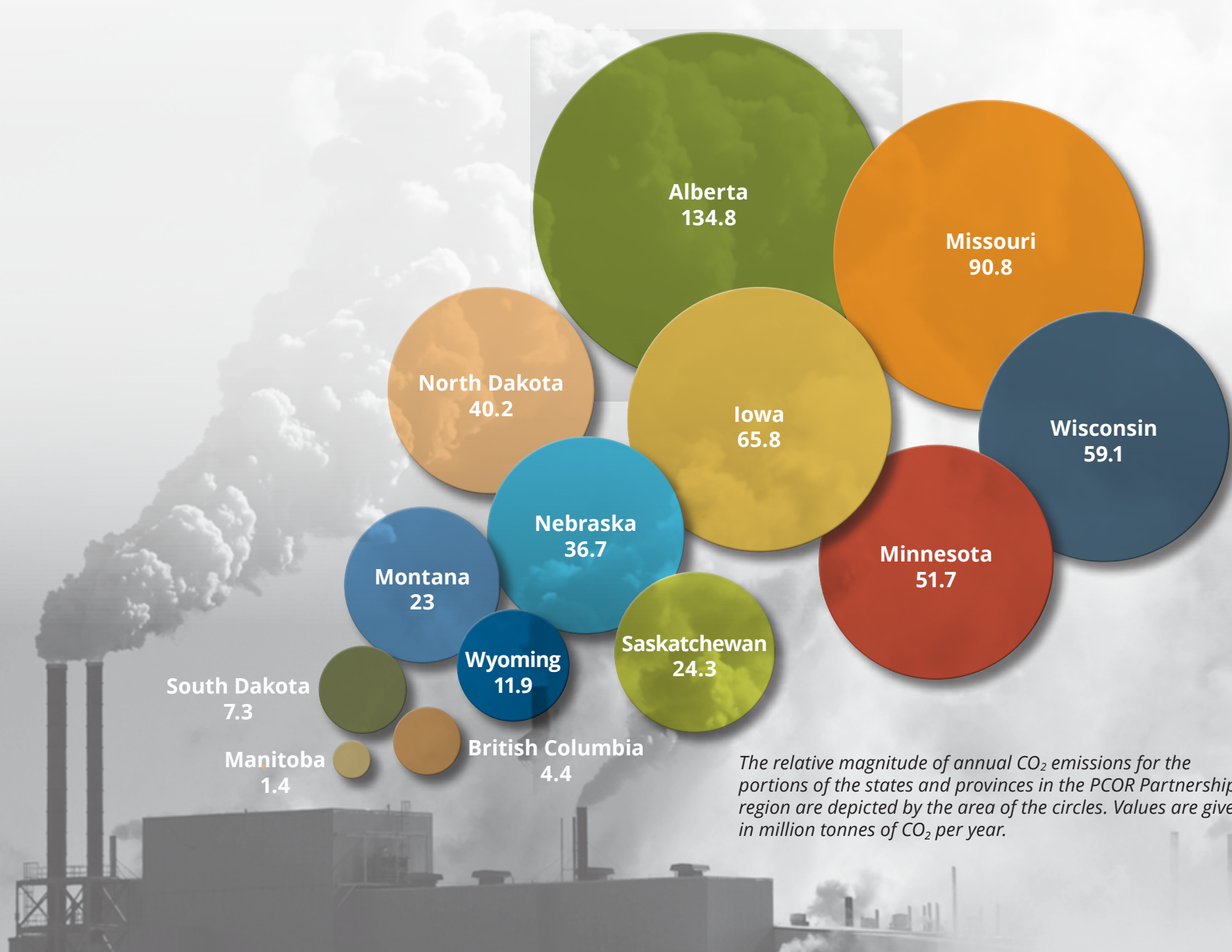
# Distribution of Major Stationary CO<sub>2</sub> Sources



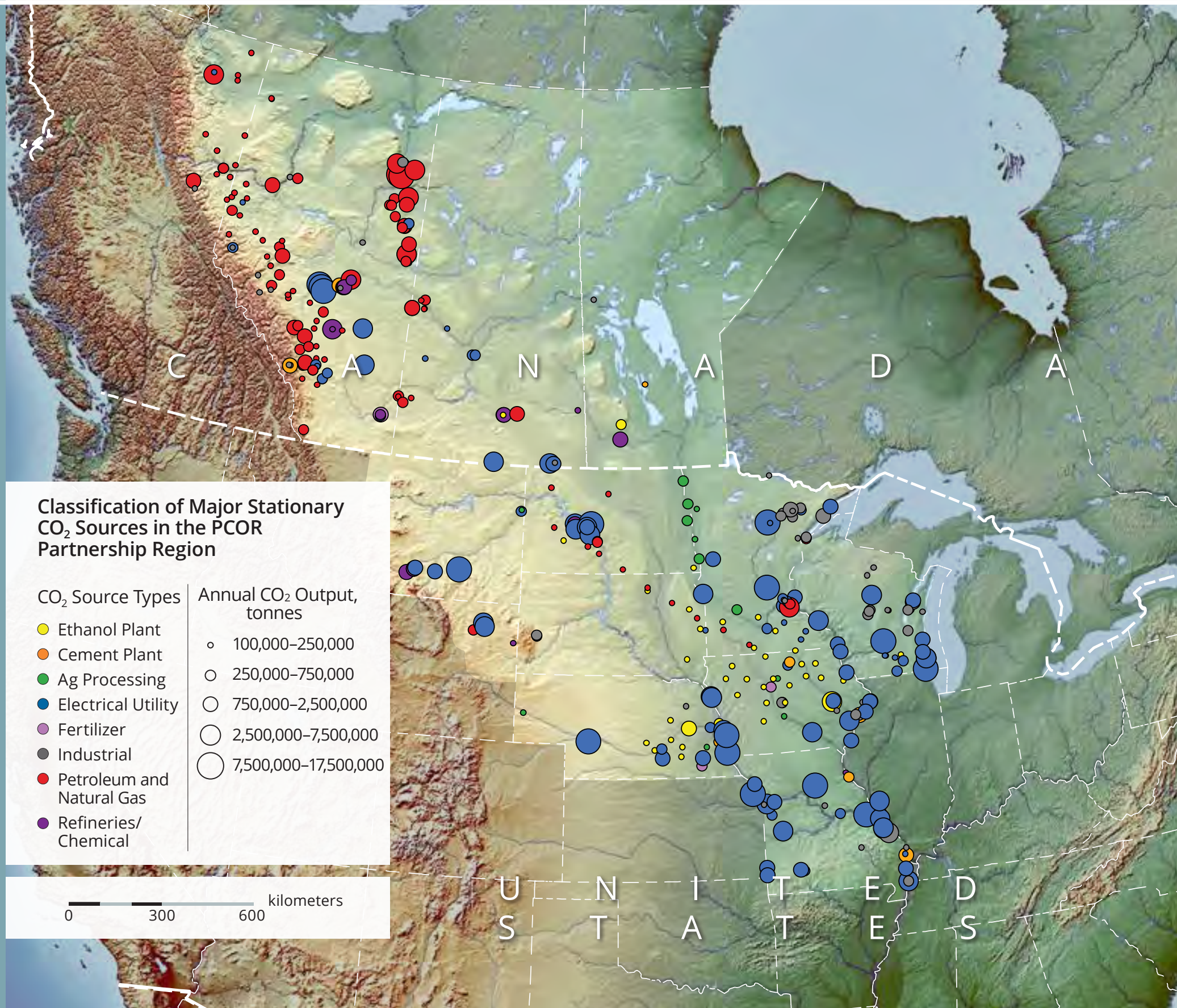
# CO<sub>2</sub> Sources

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<sub>2</sub>. These stationary sources have a combined annual CO<sub>2</sub> output of nearly 500 million tonnes (Mt). Although not a target source of CO<sub>2</sub> for geologic storage, the transportation sector in the U.S. portion of the PCOR Partnership region contributes nearly 158 million additional tonnes of CO<sub>2</sub> to the atmosphere every year.<sup>41</sup>

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<sub>2</sub> storage because of their concurrence with deep sedimentary basins, such as those areas in Alberta, North Dakota, Montana, and Wyoming.



# Classification of Major Stationary CO<sub>2</sub> Sources

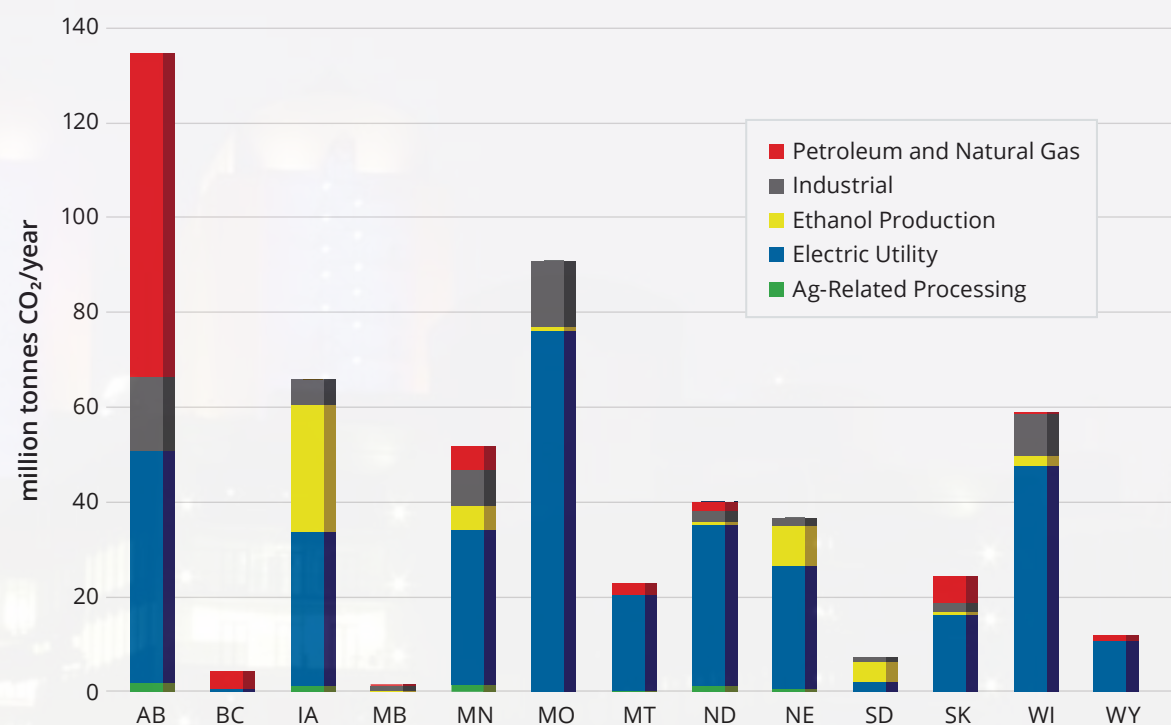


# CO<sub>2</sub> Sources by Type

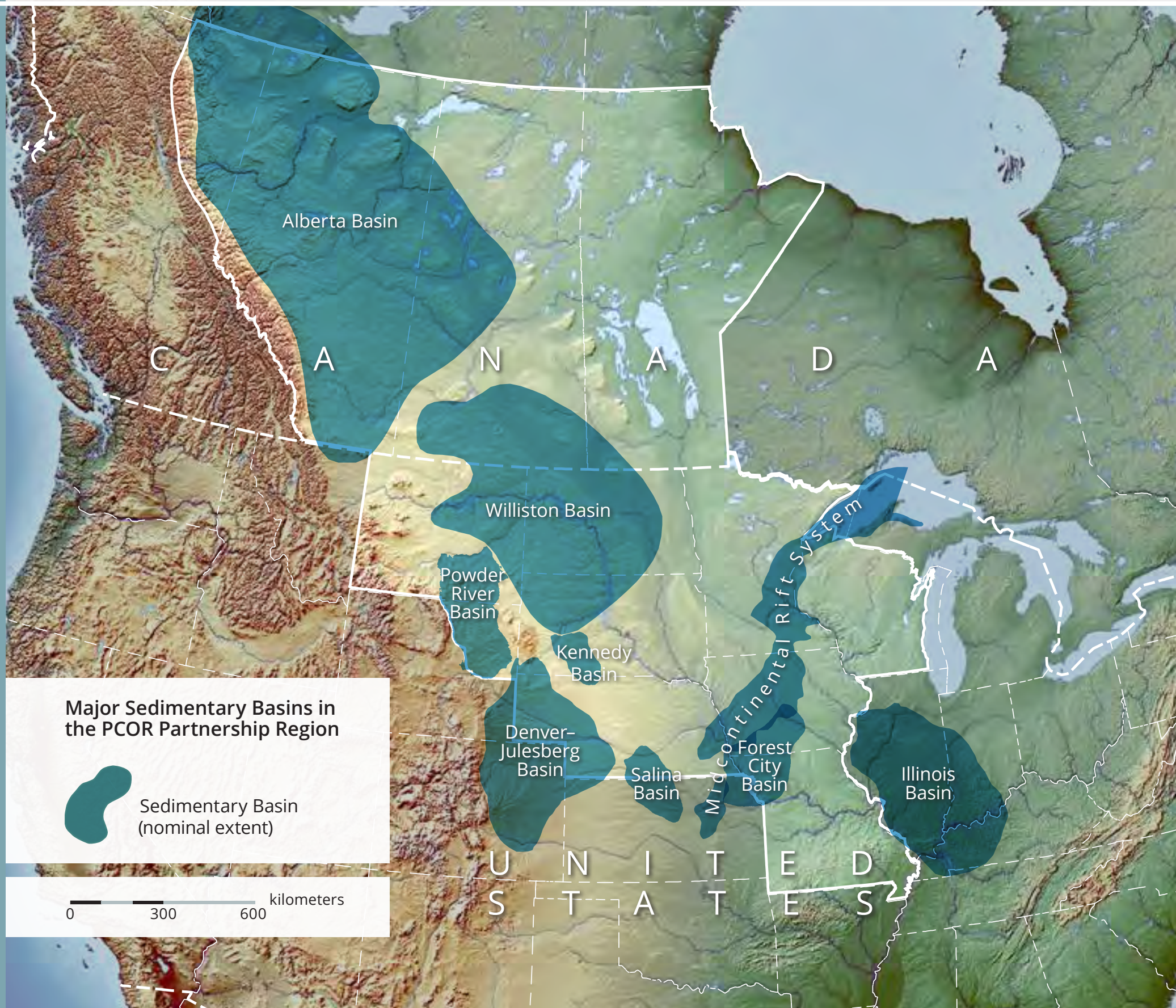
The geographic and socioeconomic diversity of the PCOR Partnership region is reflected in the diversity of the CO<sub>2</sub> sources found there. About two-thirds of CO<sub>2</sub> is emitted from electricity generation; significant emissions also result from energy exploration and production activities; 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<sub>2</sub> emissions, the states in the PCOR Partnership region emit relatively more CO<sub>2</sub> from electric utilities and less from industries and transportation.

Although the CO<sub>2</sub> 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<sub>2</sub> in many different scenarios.



# Major Regional Sedimentary Basins



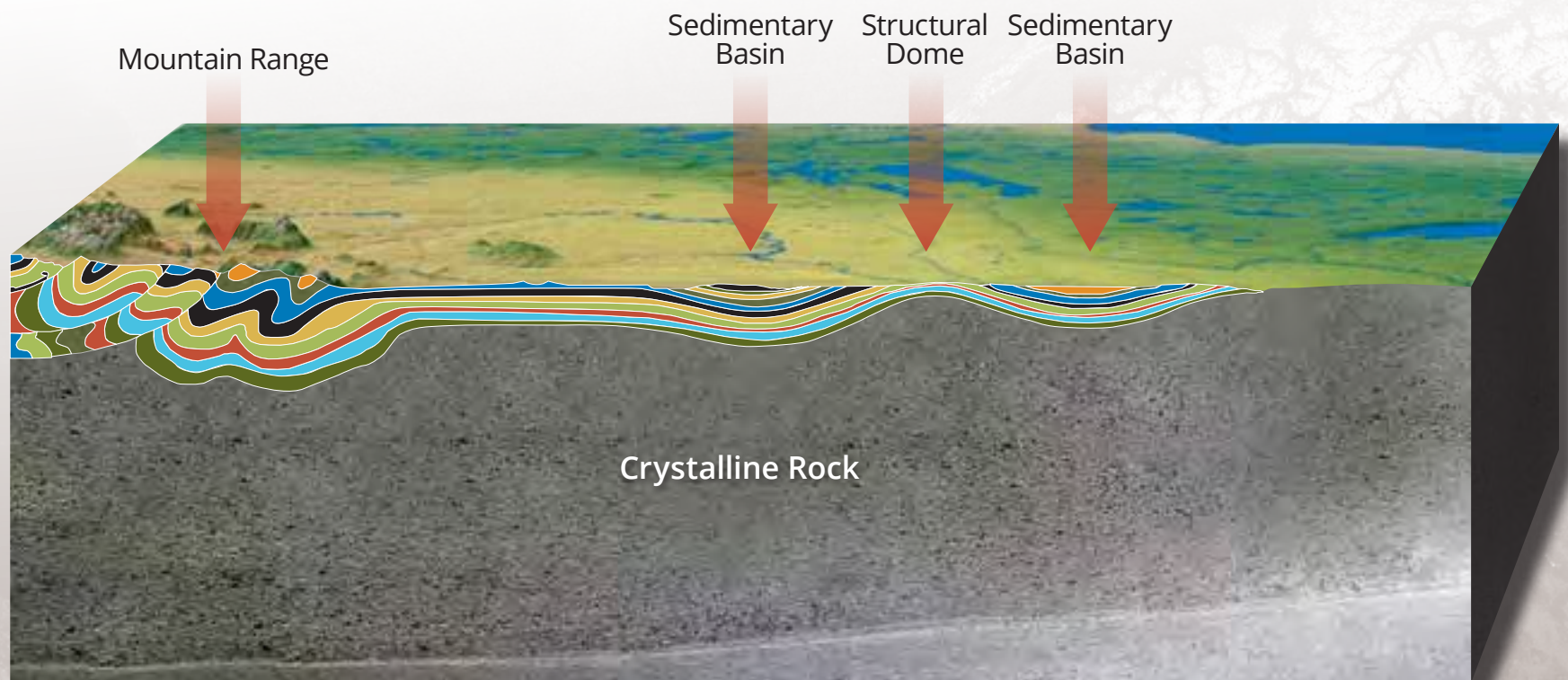
# CO<sub>2</sub> Storage Opportunities

**Sedimentary** basins are large regional depressions in Earth's crust. These depressions accumulate a considerable thickness of sediment that can cause further subsidence and allow for even more 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<sub>2</sub> in the PCOR Partnership region is found in the deep portions of the extensive sedimentary basins of this region.

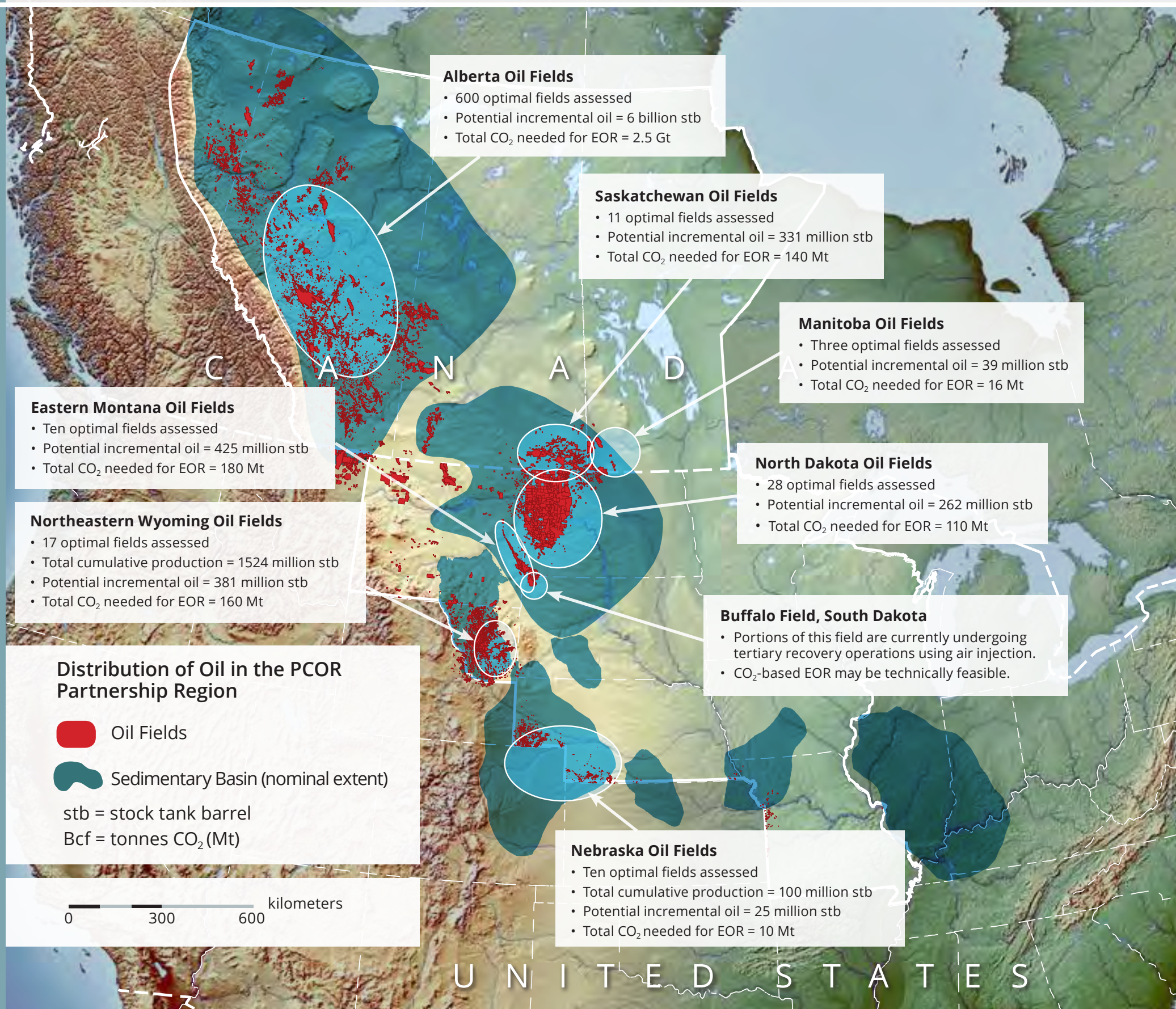
## Midcontinent Rift System

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<sub>2</sub> storage.<sup>42</sup>



# Enhanced Oil Recovery Potential



# CO<sub>2</sub> Storage in Oil and Gas Fields



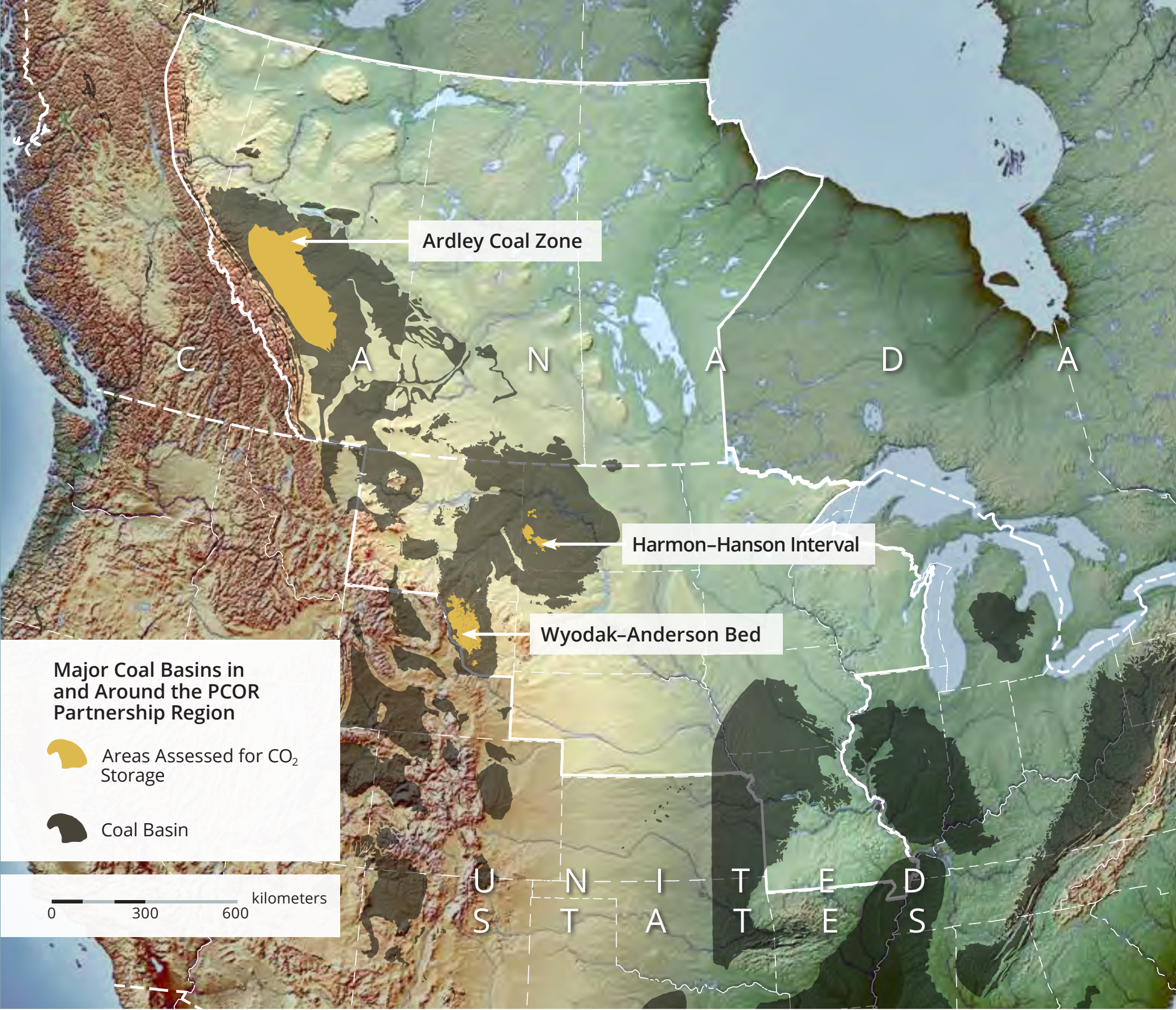
Although oil was discovered in the PCOR Partnership region in the late 1800s, significant development and exploration did not begin until the late 1920s. The body of knowledge gained in the nearly 90 years of exploration and production of hydrocarbons in this region is a significant step toward understanding the mechanisms for secure storage of significant amounts of CO<sub>2</sub>. 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<sub>2</sub> storage estimates were made for selected oil fields in the Williston, Powder River, Denver-Julesburg, 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<sub>2</sub> storage potential of over 3.2 Gt of CO<sub>2</sub> with a cumulative incremental oil recovery of over 7 billion stb.

The region has over  
**3.2 Gt**  
of CO<sub>2</sub> storage potential in  
oil and gas fields and  
**7 billion stb**  
of incremental oil.



# Major Coal Basins



# CO<sub>2</sub> Storage in Unminable Coal

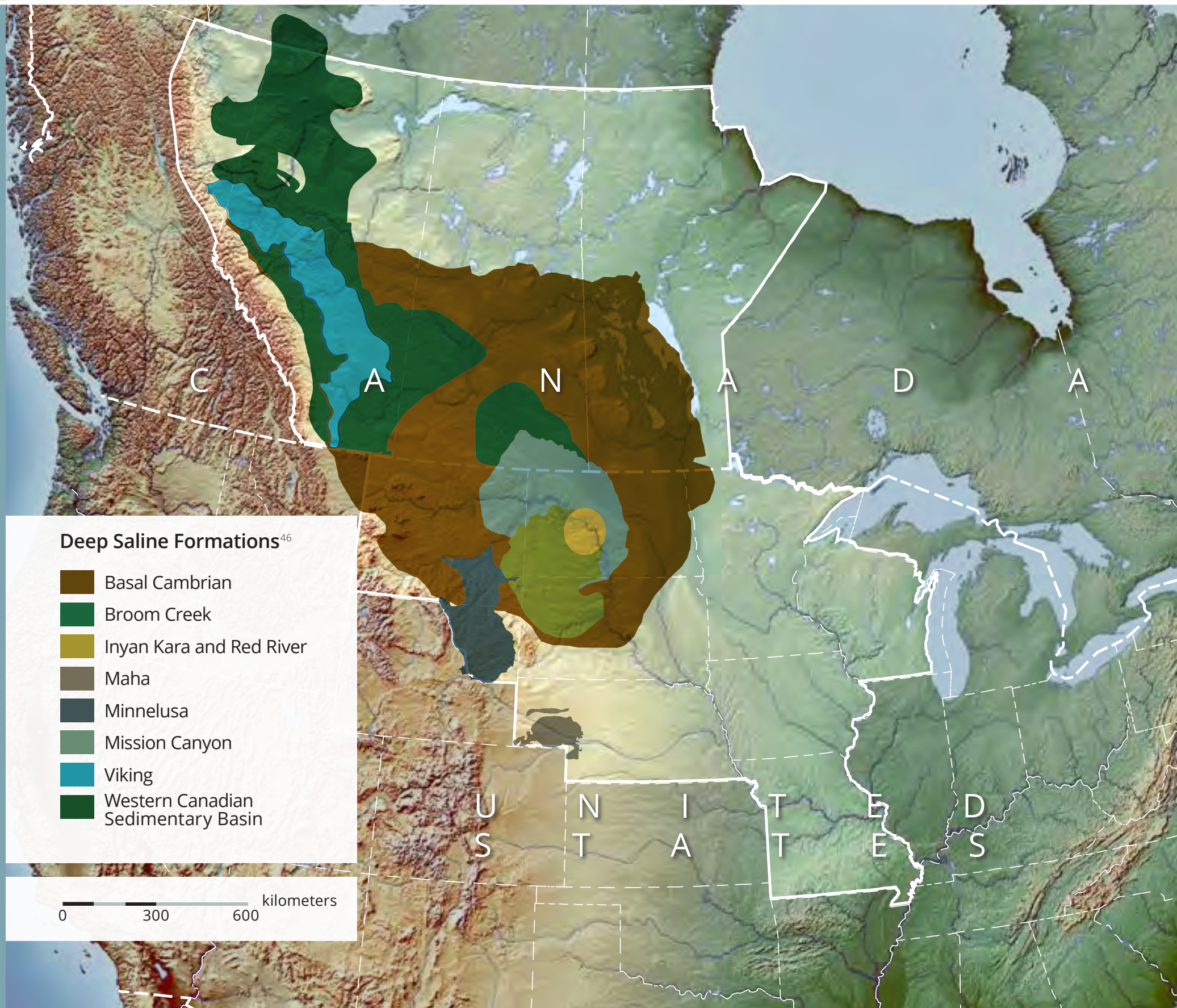
The PCOR Partnership region is home to significant coal resources. Much of this vast resource is used to generate electricity at coal-fired power plants in the region and beyond. However, a significant portion of this resource lies at depths that are not economically recoverable. Just as with depleting oil reservoirs, unminable coal beds in the region may be a good opportunity for CO<sub>2</sub> storage.

Three deep major coal horizons in the PCOR Partnership region have been characterized with respect to CO<sub>2</sub> 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<sub>2</sub> storage resource potential for all three coal deposits is approximately 7.3 Gt.<sup>43–45</sup>

In the Powder River Basin area of northeastern Wyoming, the CO<sub>2</sub> storage potential for the areas where the coal overburden thickness is >300 m could store all of the current annual CO<sub>2</sub> emissions from nearby power plants for about the next 150 years.<sup>45</sup>



# Evaluated Suitable Saline Formations

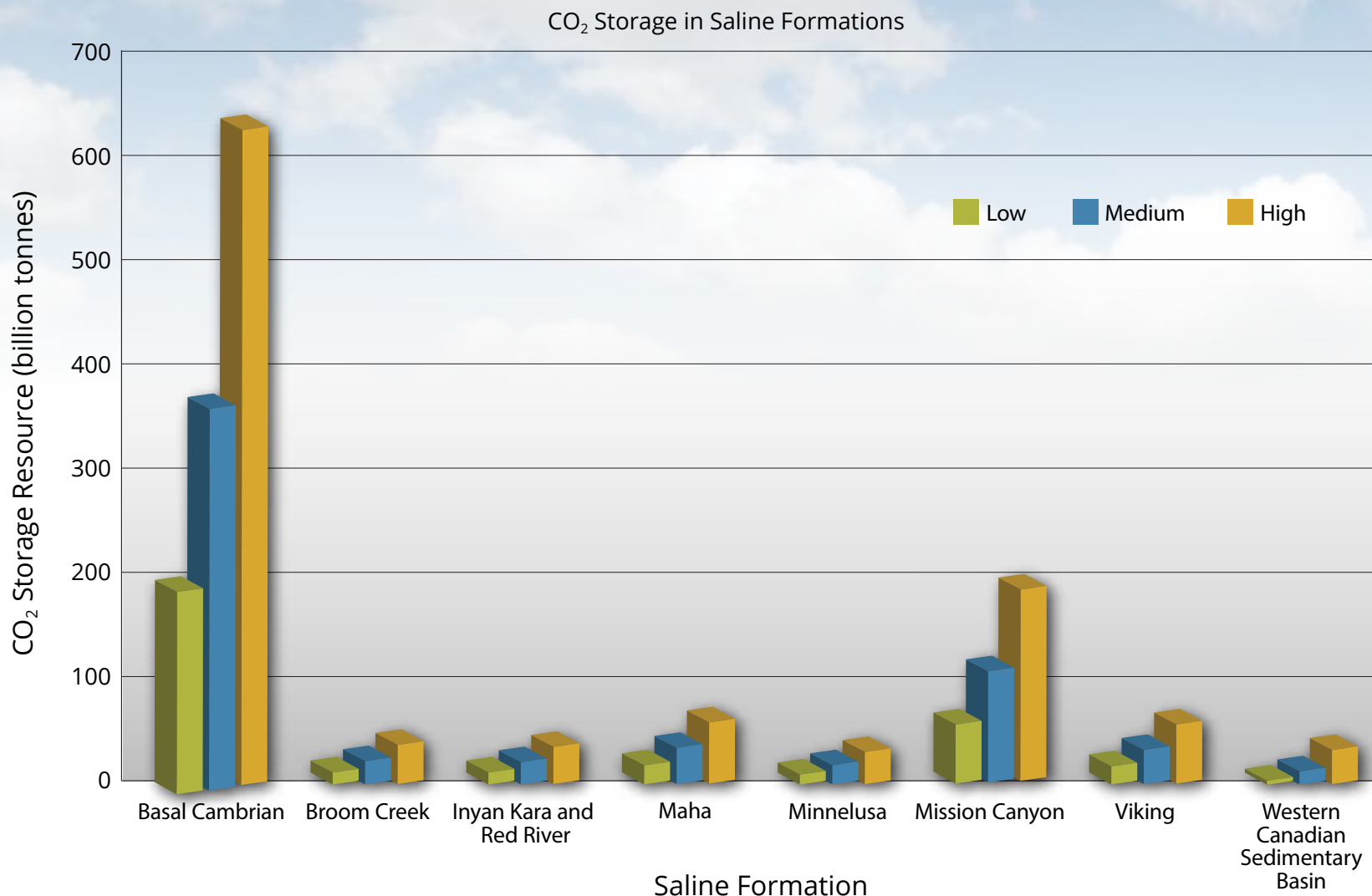


# CO<sub>2</sub> Storage in Saline Formations

Deep saline formations within the PCOR Partnership region have the potential to store vast quantities of anthropogenic CO<sub>2</sub>. 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<sub>2</sub> storage resource available. In many sedimentary basins, more than one potential target horizon for CO<sub>2</sub> 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<sub>2</sub>) 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.

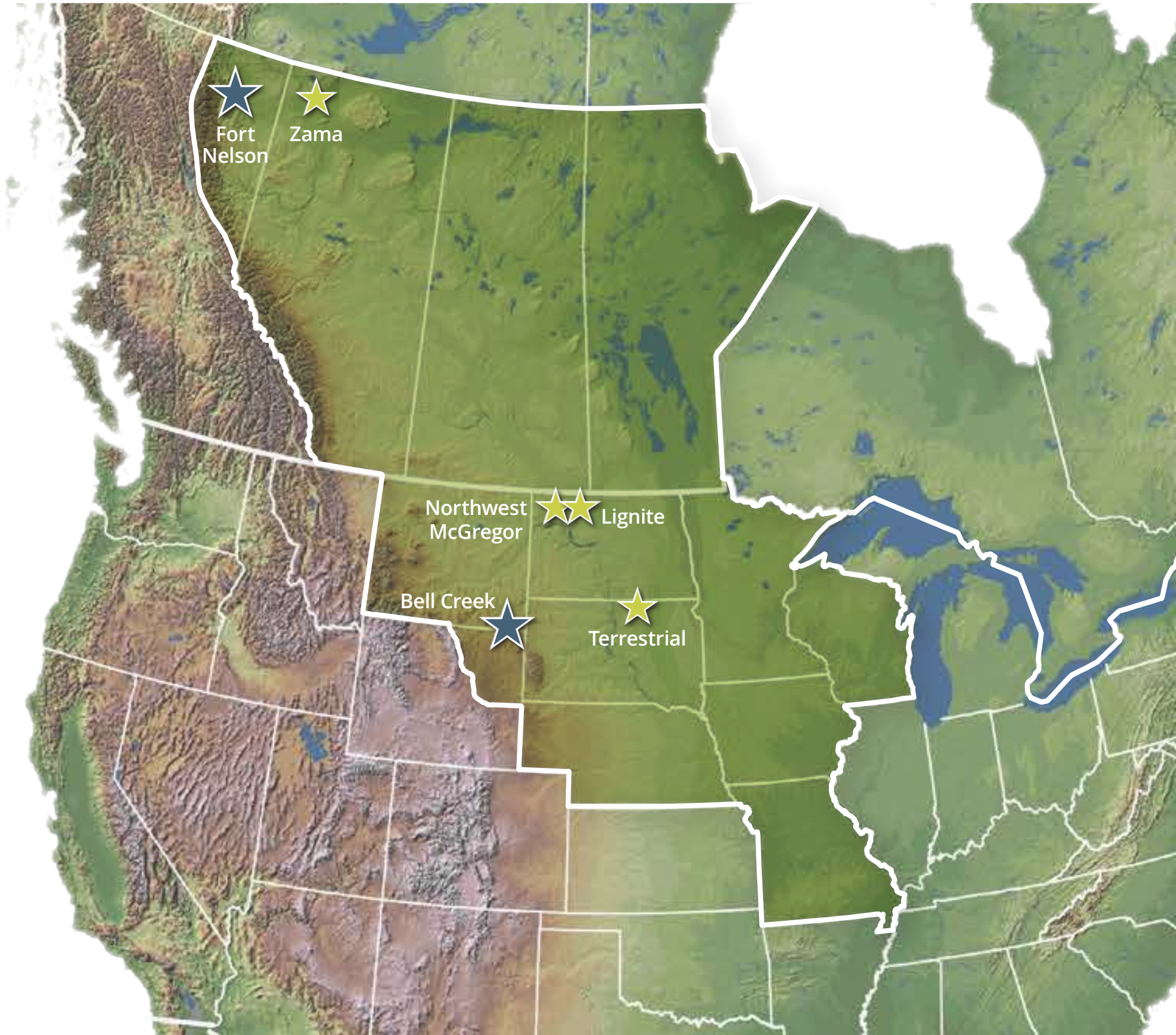




# Field-Based Activities

The full range of options required to effectively manage anthropogenic CO<sub>2</sub> emissions may take decades to implement. The PCOR Partnership region has significant storage resources in the context of the billions of tons of CO<sub>2</sub> 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<sub>2</sub> storage and terrestrial sequestration in the region.

# Demonstrating CCS

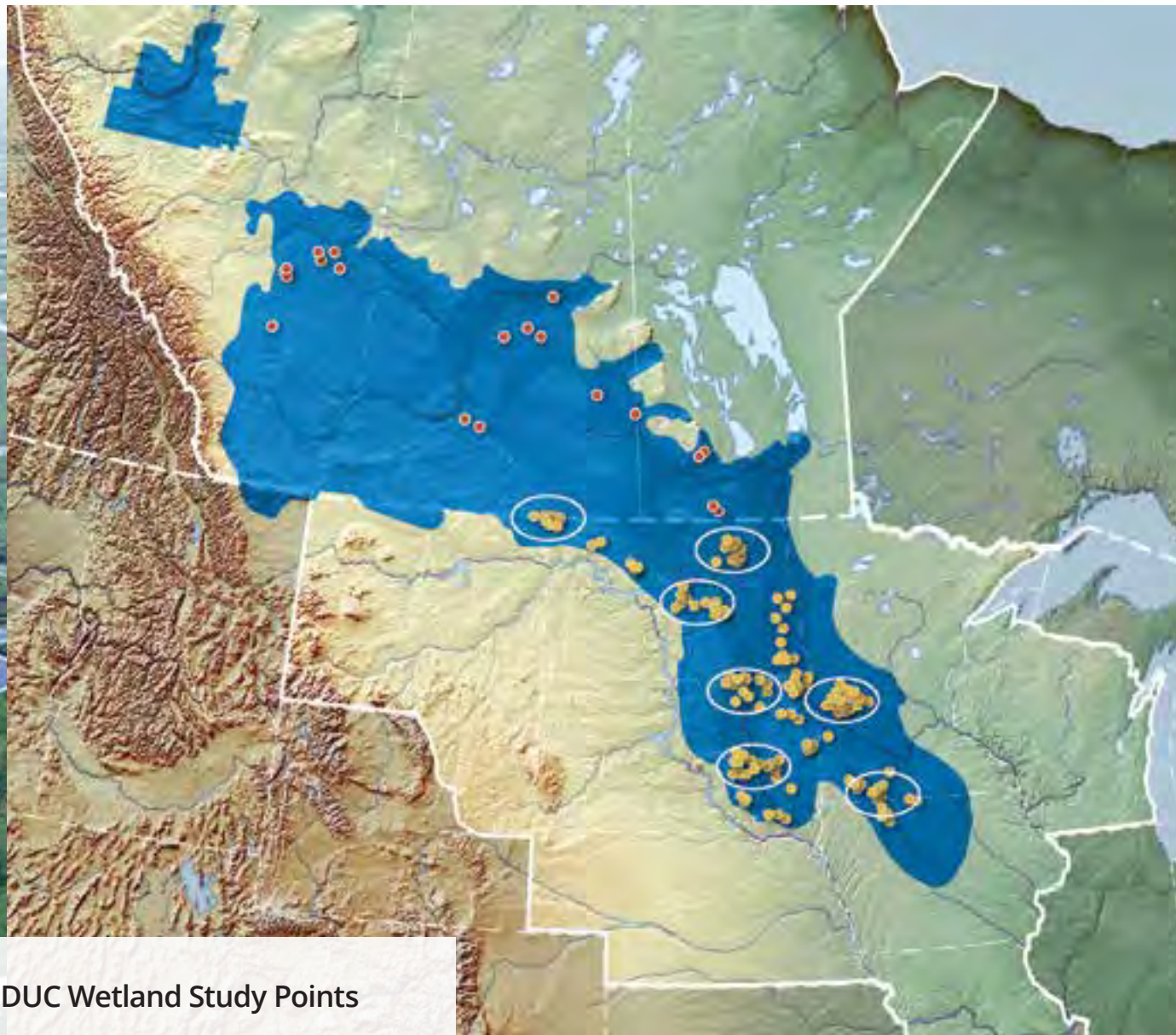




The PCOR Partnership is working to demonstrate and optimize practical and environmentally sound CO<sub>2</sub> storage in the region. From 2005 to 2009, the PCOR Partnership conducted four field validation projects that demonstrated the effectiveness of CO<sub>2</sub> storage in different settings and under varying conditions. The PCOR Partnership has worked on two commercial-scale, long-term projects to demonstrate that the CO<sub>2</sub> storage sites have the potential to store regional CO<sub>2</sub> emissions safely, permanently, and economically.

Phase II Field Scale	<b>Zama Field Validation Test</b> Determined the effect of acid gas injection for the purpose of acid gas disposal, geologic storage of CO <sub>2</sub> , and EOR.
	<b>Lignite Field Validation Test</b> Investigated the ability of unminable lignite seams to store CO <sub>2</sub> during ECBM production.
	<b>Northwest McGregor Field Validation Test</b> Evaluated the potential for geologic storage of CO <sub>2</sub> in a deep carbonate reservoir for the dual purpose of CO <sub>2</sub> storage and EOR at depths greater than 2000 m.
	<b>Terrestrial Field Validation Test</b> 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	<b>Fort Nelson Feasibility Project</b> Investigated the feasibility that CO <sub>2</sub> from a commercial natural gas-processing facility can be safely and cost-effectively stored in a deep carbonate saline formation.
	<b>Bell Creek Demonstration</b> Demonstrating that commercial EOR operations with simultaneous CO <sub>2</sub> storage can safely and cost-effectively store regionally significant amounts of CO <sub>2</sub> .

# Prairie Pothole Region



- DUC Wetland Study Points
- USGS Wetland Study Points
- DU/NDSU Wetland Study Areas
- Prairie Pothole Region

*The Prairie Pothole Region (PPR) is a major biogeographical region that encompasses approximately 900,000 km<sup>2</sup>.<sup>47</sup> This region accounts for up to 70% of wild duck production in North America<sup>48</sup> 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<sub>2</sub> 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<sub>4</sub> and N<sub>2</sub>O 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.<sup>49</sup> 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<sup>2</sup>. 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<sup>2</sup> at the base and about 120 m high.*



# CO<sub>2</sub>-Rich Gas in a Pinnacle Reef Structure

In October 2005, the Zama oil field became the site of acid gas (approximately 70% CO<sub>2</sub> and 30% H<sub>2</sub>S [hydrogen sulfide]) injection for the simultaneous purpose of EOR, H<sub>2</sub>S disposal, and CO<sub>2</sub> 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

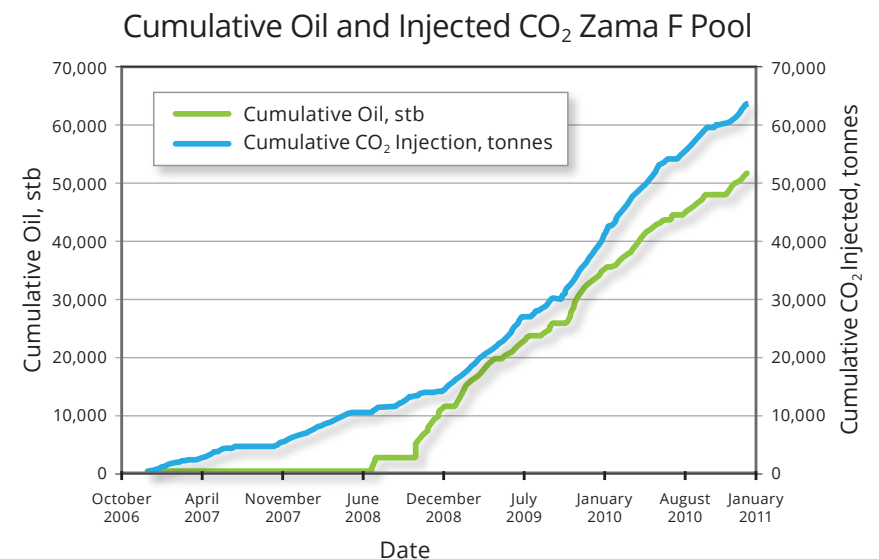
Acid gas is a by-product of oil production in the Zama Field and a subsequent fluid separation process at the on-site facilities. During the separation process, oil and gas are sent to market, while acid gas is redirected back to the field for utilization in EOR operations. Before this project, the CO<sub>2</sub> portion of the acid gas was vented to the atmosphere, and sulfur was separated from the H<sub>2</sub>S 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<sub>2</sub> and H<sub>2</sub>S 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<sub>2</sub>.

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.



**Over 65,000 tonnes of CO<sub>2</sub> 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.**



*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<sub>2</sub>.*

# 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<sub>2</sub> emissions from coal-fired power plants in North Dakota.*



# CO<sub>2</sub> 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<sub>2</sub> injected into a representative lignite coal seam and to uncover the potential for ECBM production.

## CO<sub>2</sub> Injection

Approximately 90 tons of CO<sub>2</sub> was injected over roughly a 2-week period into a 3–4-m-thick coal seam at a depth of 330 m. CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> for EOR and storage using huff 'n' puff techniques at depths greater than 2440 m into a fractured carbonate reservoir.*

# CO<sub>2</sub> 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<sub>2</sub> into a carbonate formation in the Northwest McGregor oil field in North Dakota. The activities evaluated the potential dual purpose of CO<sub>2</sub> 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<sub>2</sub> into the target oil reservoir using a huff 'n' puff approach and evaluated the effect that injected CO<sub>2</sub> has on the ability of the oil reservoir to store CO<sub>2</sub> and produce incremental oil.

## Huff 'n' Puff

A CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>, both with respect to EOR and CO<sub>2</sub> storage. The approach is economically attractive because small-volume injections yield adequate results to determine the efficacy of larger-scale CO<sub>2</sub> injection.

## Results

Overall, the results of the field demonstration indicate that:

- CO<sub>2</sub>-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<sub>2</sub> 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<sub>2</sub> storage sites have the potential to store regionally significant quantities of CO<sub>2</sub> emissions safely, permanently, and economically. Results from these efforts will provide the foundation for CCS technology commercialization.

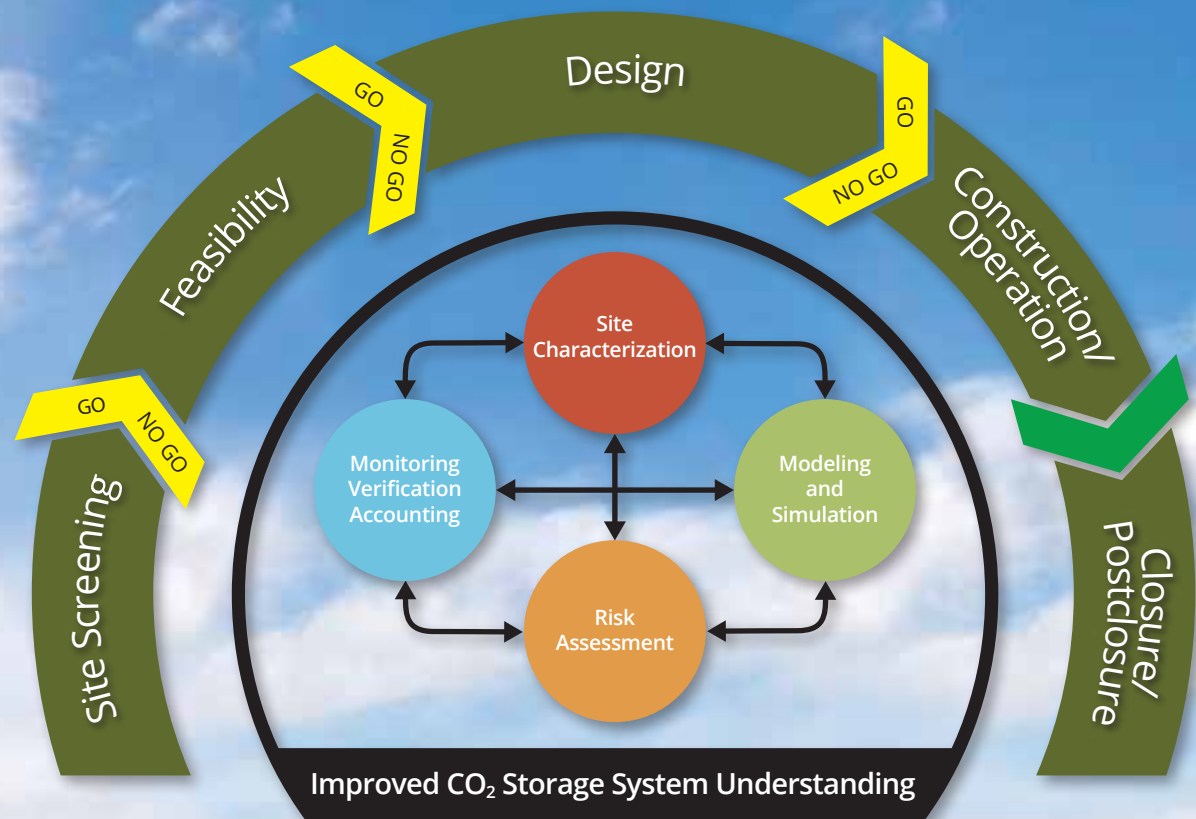
Through its role in the RCSP Development Phase, the PCOR Partnership has teamed with industrial partners to conduct two commercial-scale CCS demonstrations in the region. One of the large-scale tests investigated CO<sub>2</sub> storage in a saline formation, while the other is combining CCS and EOR demonstration in a project that began in 2013. Across the country, other RCSPs have begun or are planning commercial-scale demonstrations.



# Philosophy of Approach

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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>; 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<sub>2</sub> capacity resource currently estimated in regional saline formations.*

# Geologic Storage of CO<sub>2</sub> in a Saline Formation

The Fort Nelson project, located in northeastern British Columbia, investigated the feasibility of a CCS project to mitigate the CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>. 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<sub>2</sub> 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<sub>2</sub> 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 Aquestore 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<sub>2</sub>.*



# Bell Creek Demonstration Project



*Because natural gas-processing plants are among the few sources of relatively pure streams of CO<sub>2</sub> and capture is relatively easy, they will be among the first point sources of CO<sub>2</sub> to be targeted for CCS and CO<sub>2</sub> EOR projects. The Bell Creek project uses the CO<sub>2</sub> produced at the Lost Cabin and Shute Creek natural gas-processing plants in Wyoming. It is one of several commercial CO<sub>2</sub> EOR to CO<sub>2</sub> geologic storage projects that use CO<sub>2</sub> from natural gas processing.*



# CO<sub>2</sub> 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<sub>2</sub> into a deep clastic reservoir for the purpose of commercial CO<sub>2</sub> EOR with associated CO<sub>2</sub> storage at Denbury's Bell Creek oil field.

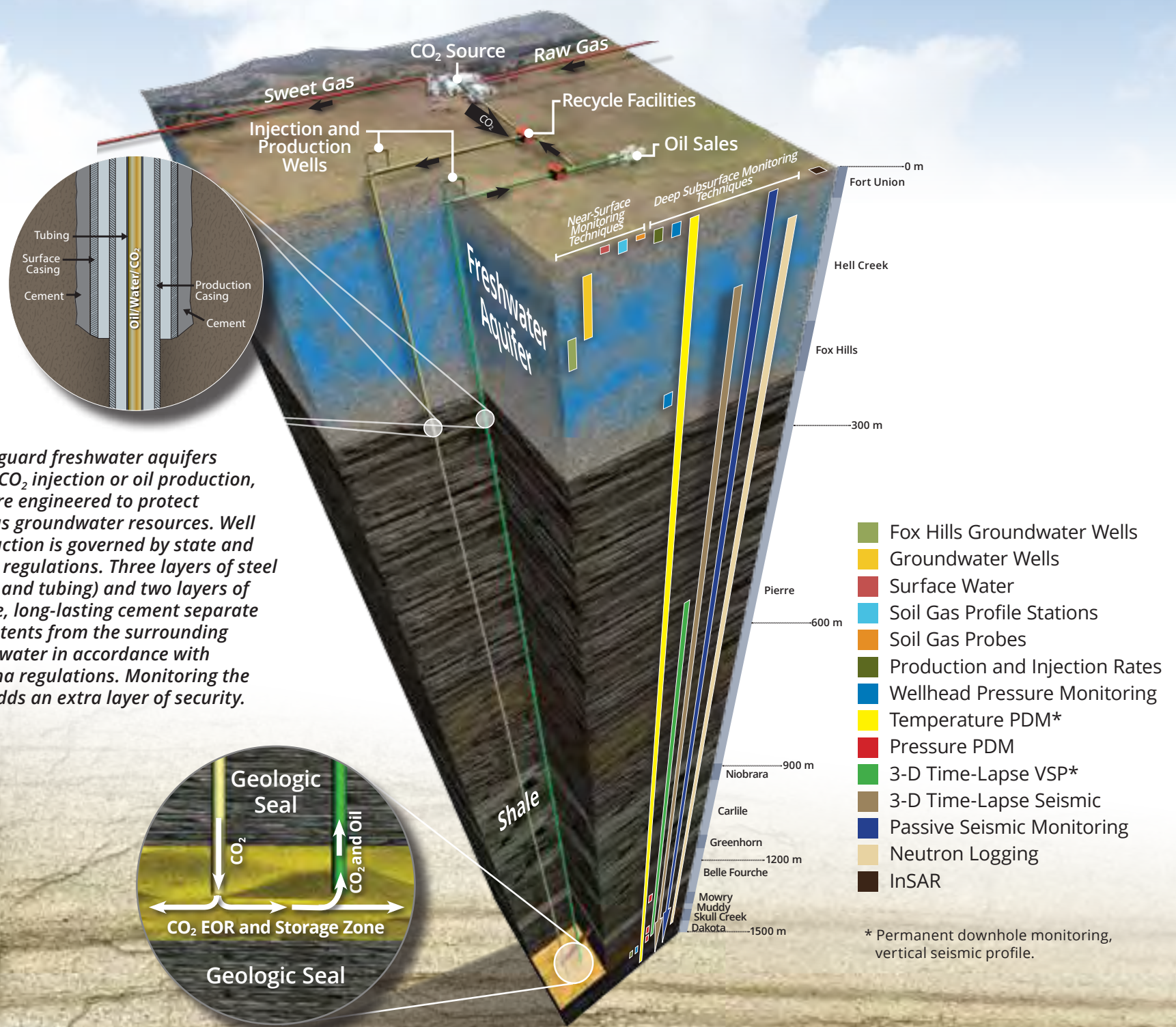
CO<sub>2</sub> for the project is sourced from the Lost Cabin and Shute Creek gas-processing facilities of Wyoming. The CO<sub>2</sub> is transported to the field at over 2600 tonnes per day via the Greencore pipeline with a tie-in from the Anadarko pipeline. The CO<sub>2</sub> is injected into an oil-bearing sandstone reservoir in the Muddy Formation at a depth of approximately 1400 m. CO<sub>2</sub> injection occurs in a staged approach (nine planned CO<sub>2</sub> 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<sub>2</sub>, and water will be separated at the process/recycle facilities located on-site. Oil is sold, whereas the water and CO<sub>2</sub> are recycled and reinjected as part of the EOR operation.

This collaborative project is demonstrating that 1) CO<sub>2</sub> 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<sub>2</sub>, and 3) MVA methods can be used to effectively monitor CO<sub>2</sub> storage in association with commercial-scale CO<sub>2</sub> EOR projects.

## Highlights

- Injection of over 3 Mt of CO<sub>2</sub> (as of March 2016) 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<sub>2</sub> 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<sub>2</sub> EOR program at Bell Creek and its integration with the PCOR Partnership's investigation of associated CO<sub>2</sub> storage.

# Bell Creek – Layers of Security

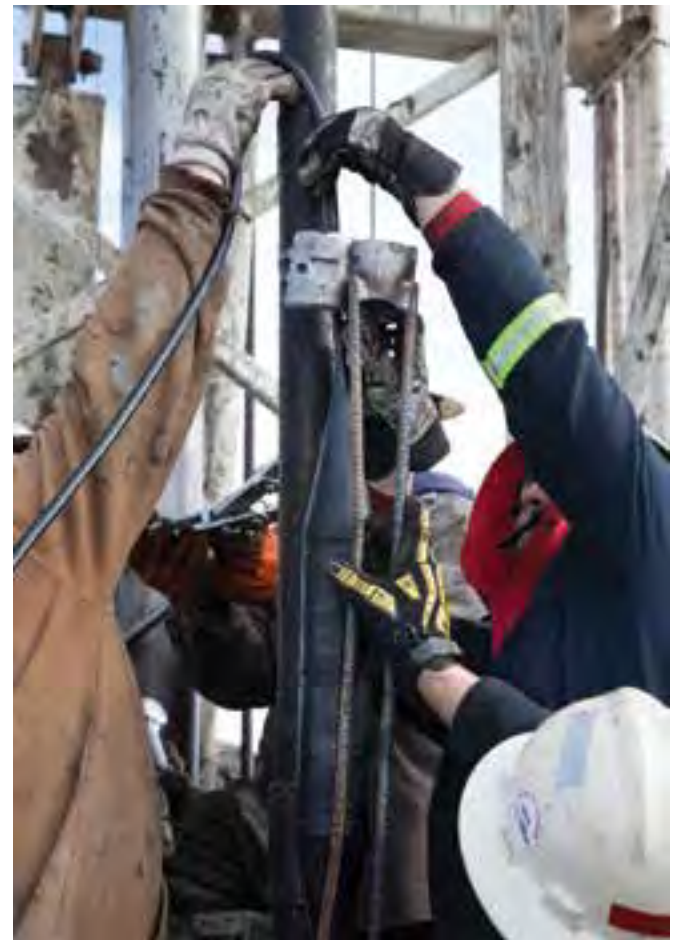


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# Site Characterization

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<sub>2</sub> migration pathways, assess technical subsurface risks, and aid in the monitoring of CO<sub>2</sub> migration in the subsurface. These elements of the project help evaluate expected and actual performance during commercial-scale CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> in the subsurface.



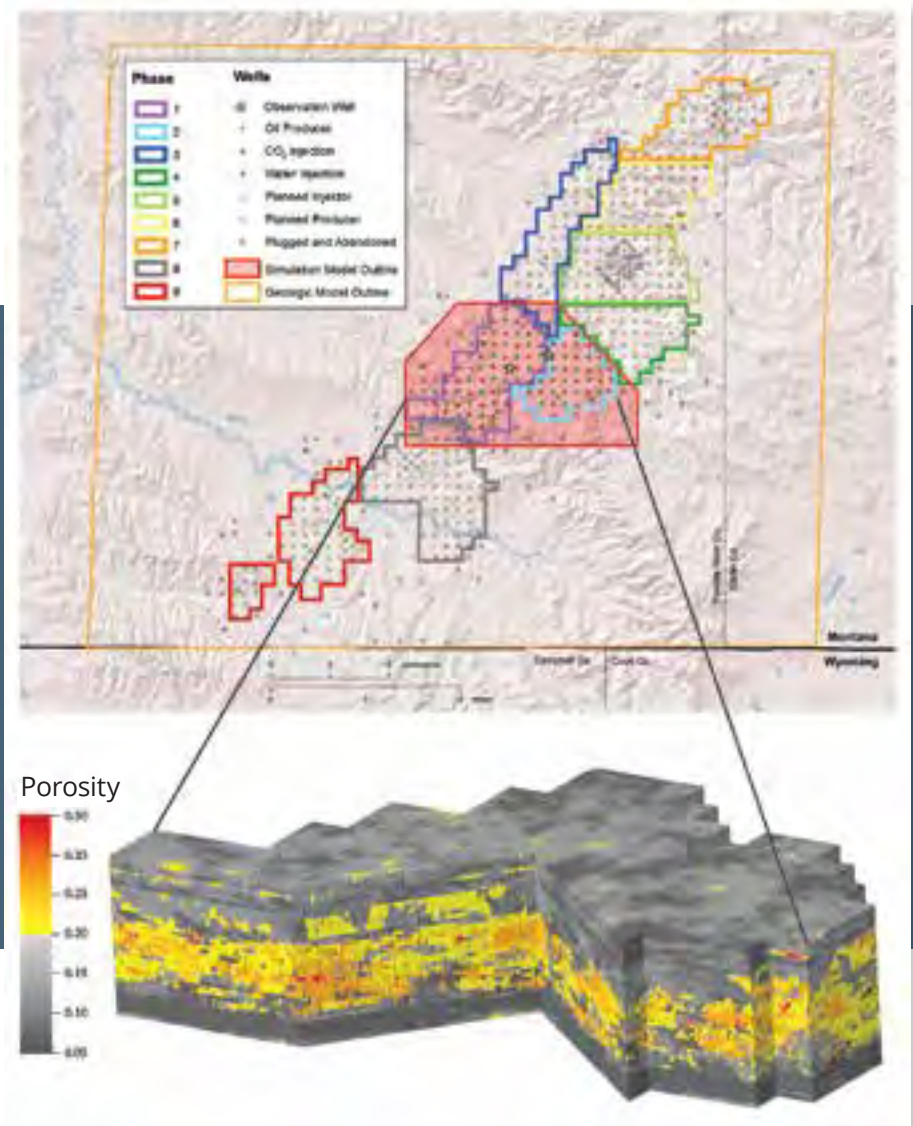
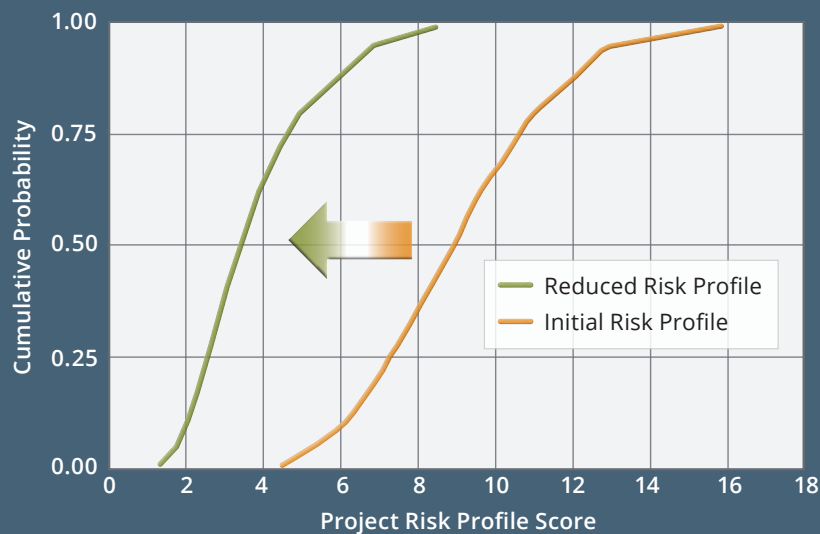
# Risk Assessment, Simulation, and Modeling

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<sub>2</sub> or other fluids beyond the reservoir.

Additionally, 24 strategic risks were identified (e.g., CO<sub>2</sub> supply, management or policy changes) and assessed. None was found to have significant potential to negatively impact the project.



*Muddy S.S. (Bell Creek Field reservoir)*

# Bell Creek – Monitoring

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<sub>2</sub>, and investigate mechanisms that affect CO<sub>2</sub> storage efficiency within the EOR process, all while operating in a manner compatible with the commercial CO<sub>2</sub> 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<sub>2</sub> 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).

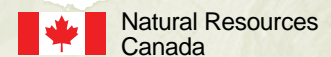
A 3-year binational effort between the United States and Canada was initiated to characterize a 1.34-million-km<sup>2</sup> area of the COSS across the northern Great Plains-Prairie region of North America and determine its CO<sub>2</sub> storage resource. To date, no other studies have attempted to 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<sub>2</sub> 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<sub>2</sub>. 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<sub>2</sub> 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 the following:

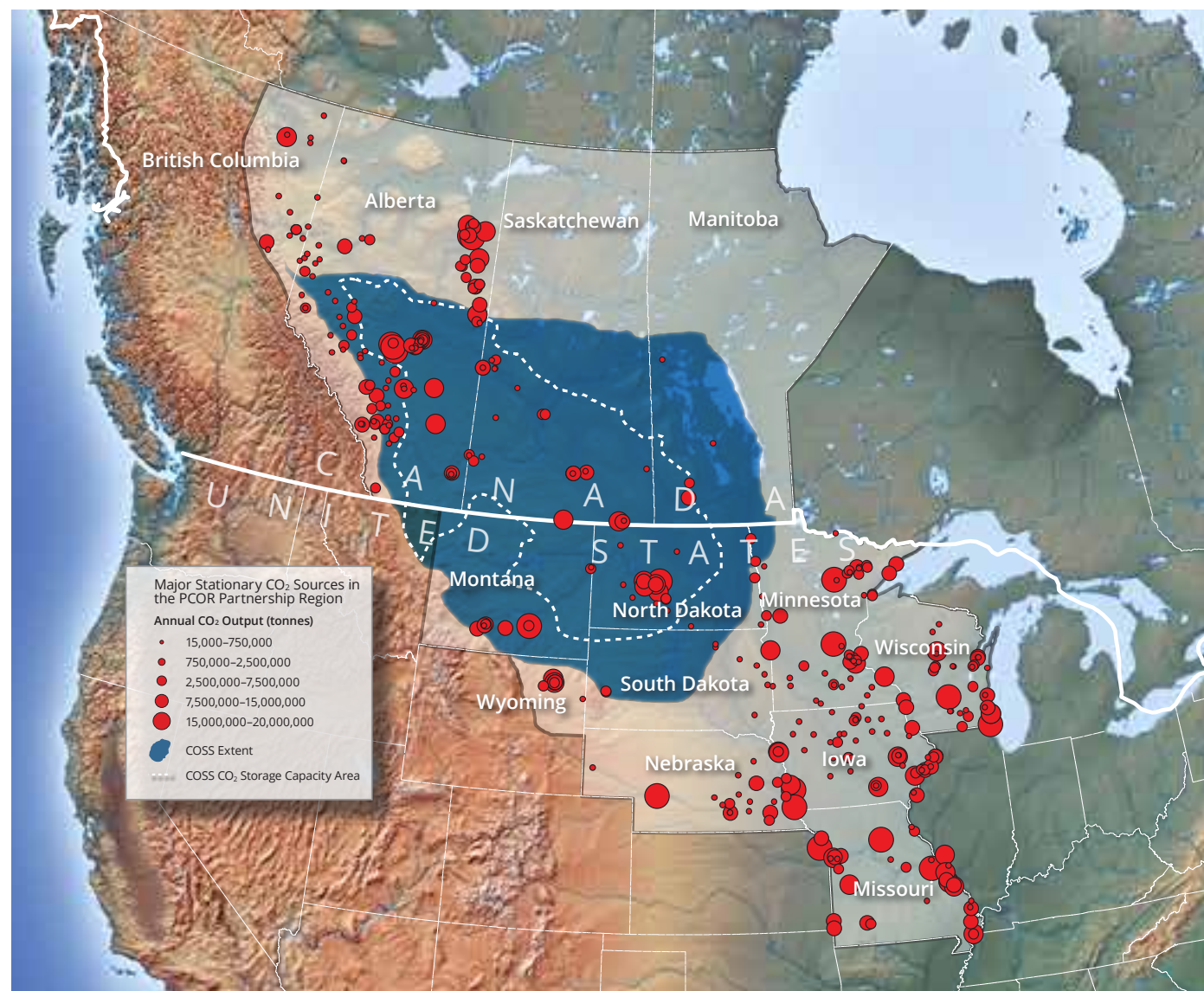
DOE  
Lawrence Berkeley National Laboratory  
Princeton University  
Saskatchewan Industry and Resources  
Manitoba Water Stewardship  
Manitoba Innovation – Energy and Mines  
CanmetENERGY  
Natural Resources Canada  
TOTAL E&P Ltd.  
Petroleum Technology Research Centre (PTRC)  
North Dakota Geological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



The area of the basal saline system suitable for CO<sub>2</sub> storage was determined using the following criteria: a) CO<sub>2</sub> 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<sub>2</sub> should be stored at a depth to ensure it is in a dense phase. The storage resource was estimated using thickness, porosity, and CO<sub>2</sub> density calculated at in situ conditions and using a storage efficiency factor. Assuming no increase in CO<sub>2</sub> emissions from the large stationary sources in the region and a capture efficiency of 90%, the P<sub>50</sub> storage resource identified in this study will suffice to store CO<sub>2</sub> from these sources for over 700 years.

Range of CO<sub>2</sub> Storage Resource Estimates for the Portion of the COSS Suitable for CO<sub>2</sub> Storage at the P<sub>10</sub>, P<sub>50</sub>, and P<sub>90</sub> Probability Levels

Probability		P <sub>10</sub>	P <sub>50</sub>	P <sub>90</sub>
Saline Formation Efficiency Factor		1.2%	2.4%	4.1%
CO <sub>2</sub> 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<sub>2</sub> 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).<sup>50</sup> 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<sub>2</sub> 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<sub>2</sub> in October 2014; at the end of September 2016, SaskPower reported that 1.15 Mt of CO<sub>2</sub> had been captured.<sup>51</sup> The project is designed to operate at a maximum rate of 1 Mt per year; the majority of captured CO<sub>2</sub> is transported by pipeline to the Weyburn oil field for EOR. Unsold CO<sub>2</sub> is diverted into a branch of the pipeline to the Aquistore site (p. 99) for dedicated storage.

### **3. Quest CCS Project, Alberta**

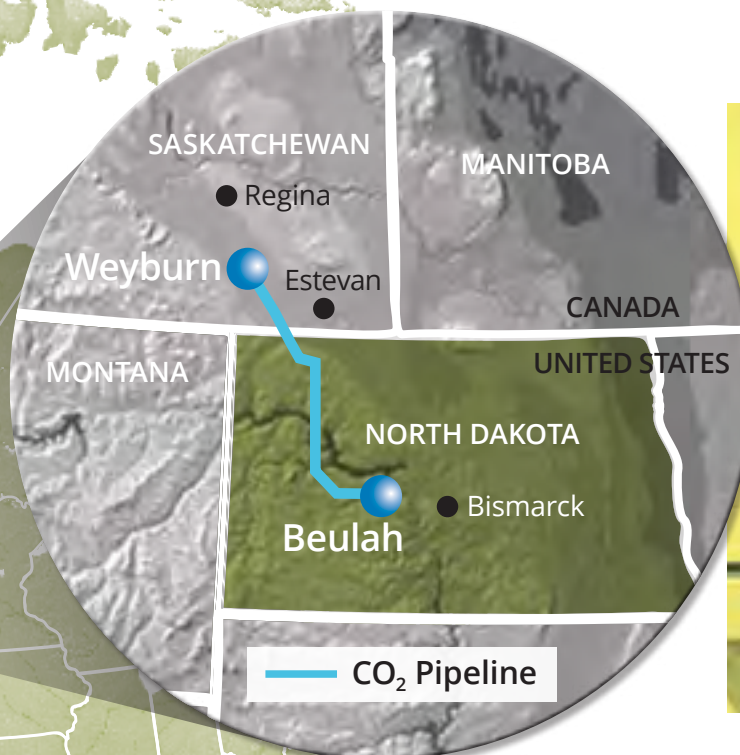
Shell Canada commenced CO<sub>2</sub> capture from industrial hydrogen production (a heavy oil upgrader) in November 2014 and celebrated 1 Mt of capture within the first year of operations.<sup>52</sup> All captured CO<sub>2</sub> is transported by a 66-km pipeline to a dedicated storage site, also operated by Shell.

### **4. Alberta Carbon Trunk Line Project, Alberta**

Construction of a 240-km pipeline by Enhance Energy will allow captured CO<sub>2</sub> from industrial sources to the north of Edmonton to be used for EOR at the Clive oil field.<sup>53</sup> Scheduled for operation during 2017, initial CO<sub>2</sub> supplied will be from an Agrium fertilizer plant (up to 0.6 Mt per year) and from the North West Redwater Sturgeon Refinery (up to 1.4 Mt per year).<sup>54</sup> 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<sub>2</sub> Capture at Great Plains Synfuels Plant

The CO<sub>2</sub> 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<sub>2</sub> to Canada—about 50% of the CO<sub>2</sub> produced when running at full rates. As of December 31, 2014, the synfuels plant had captured more than 29 Mt of CO<sub>2</sub>.



*Photo courtesy of Basin Electric Power Cooperative.*

*CO<sub>2</sub> 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.*

# CO<sub>2</sub> Monitoring and Storage Project

## The Weyburn and Midale Oil Fields and Associated IEAGHG Weyburn–Midale CO<sub>2</sub> Monitoring and Storage Project

Injection of CO<sub>2</sub> 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<sub>2</sub> had been stored in the field<sup>56</sup>—mainly sourced from Great Plains but with an additional supply of CO<sub>2</sub> 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<sub>2</sub> sourced exclusively from Great Plains.<sup>57</sup> The sale of CO<sub>2</sub> from the Dakota Gasification Company to Cenovus Energy and Apache Canada also represents the first instance where large quantities of captured CO<sub>2</sub> have been traded across an international border.

Also beginning in 2000, the IEAGHG Weyburn CO<sub>2</sub> Monitoring and Storage Project used the Weyburn oil field and EOR operations as an opportunity to study large-scale injection and storage of CO<sub>2</sub> in the subsurface. Managed by PTRC, this first phase of research was completed and reported in 2004.<sup>58</sup> 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*.<sup>59</sup> The project demonstrated, over both phases of research, secure storage of injected CO<sub>2</sub> in the reservoir and the successful deployment of existing monitoring technologies to track the subsurface movement of CO<sub>2</sub>. 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.<sup>60</sup>

**Supplies from Great Plains to Weyburn and Midale represent the first case where CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> per year; between the commencement of operations in October 2014 and October 2016, SaskPower reported that 1.15 Mt had been captured.<sup>51</sup>

Unit 3 provides 115 MW of power.<sup>61</sup> In addition to reducing CO<sub>2</sub> emissions from Unit 3 by up to 90%, the capture process removes 100% of SO<sub>2</sub> emissions which are converted to sulfuric acid for industrial use.

The main destination for captured CO<sub>2</sub> is the Weyburn oil field (p. 97), with Cenovus Energy transporting the purchased CO<sub>2</sub> 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<sub>2</sub>.

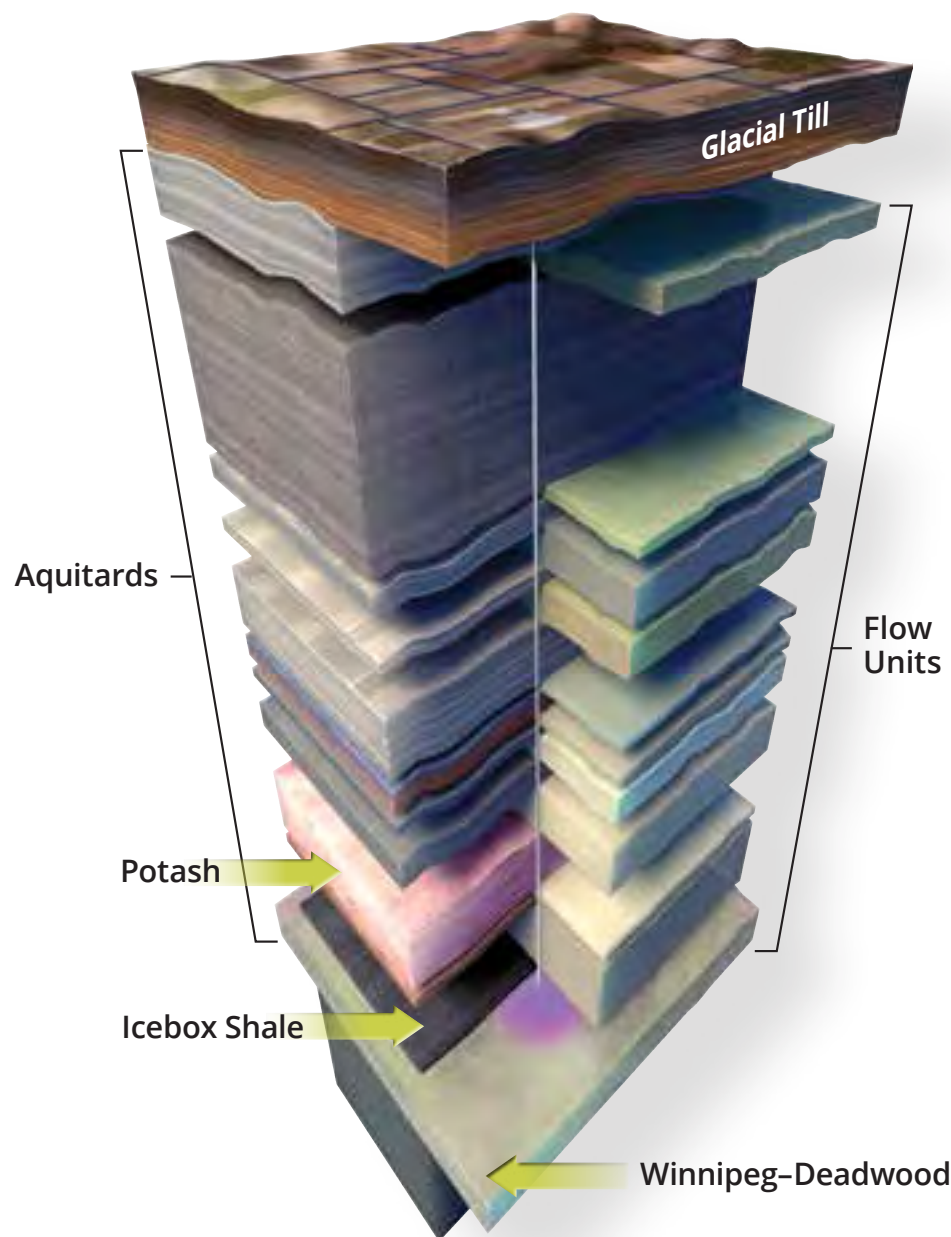


Photo provided by and is property of SaskPower.



# The Aquistore Project

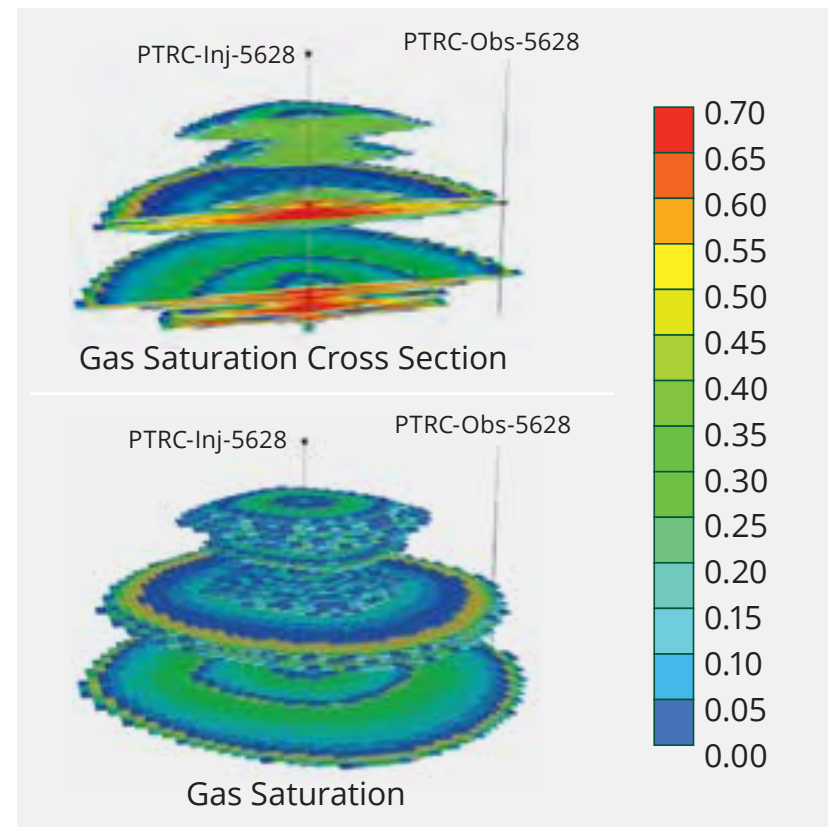
Aquistore<sup>62</sup> is a dual-purpose project. From a commercial perspective, Aquistore provides a dedicated storage option for unsold CO<sub>2</sub> from Boundary Dam—in effect, providing buffer storage so as to prevent any need for SaskPower to vent CO<sub>2</sub> from capture operations. Injection 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<sub>2</sub> had been stored at Aquistore by November 2016.<sup>63</sup>



Injection of CO<sub>2</sub> 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.<sup>64</sup>

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.<sup>65</sup>



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,<sup>52</sup> a fully integrated CCS project located to the northeast of Edmonton, in November 2015. The first 1 Mt of CO<sub>2</sub> 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.<sup>66</sup>

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<sub>2</sub> emissions from the upgrading operations by approximately one-third.





Captured CO<sub>2</sub> 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<sub>2</sub> over the anticipated 25-year life of the upgrader,<sup>67</sup> 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



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<sub>2</sub> 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<sub>2</sub> capture, compression, transport, injection for CO<sub>2</sub> storage, or CO<sub>2</sub> EOR. These meetings allow for improved coordination of regulatory strategies that will ultimately enhance opportunities for CO<sub>2</sub> storage and CO<sub>2</sub> 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<sub>2</sub> for geologic storage. It covers any well or group of wells that injects CO<sub>2</sub> 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<sub>2</sub>
- Mass of CO<sub>2</sub> received
- Mass of CO<sub>2</sub> produced (i.e., mixed with produced oil, gas, or other fluids)
- Mass of CO<sub>2</sub> emitted from surface leakage
- Mass of CO<sub>2</sub> equipment leaks and vented CO<sub>2</sub> emissions
- Mass of CO<sub>2</sub> 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 by EPA of a final rule covering injection wells for geologic storage of CO<sub>2</sub> and the pending publication by EPA of final guidance documents supplementing the EPA final rule, states now have to rewrite their legislation and rules to conform to EPA's rule.

**British Columbia** is reviewing regulatory framework for CCS. Additional legislation may be considered for clarification purposes.

**Alberta** has developed regulations for storage, pore space ownership, and long-term stewardship.

**Saskatchewan** has adapted existing oil and gas regulations for CO<sub>2</sub> storage.

**North Dakota** has legislation in place for pore space issues and long-term stewardship and has applied for Class VI primacy.

**Montana** has legislation in place for pore space issues and long-term stewardship. Rule development will begin once primacy for underground injection of CO<sub>2</sub> for storage purposes is received from EPA.

**Wyoming** has legislation in place for pore space ownership.

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<sub>2</sub> emissions.

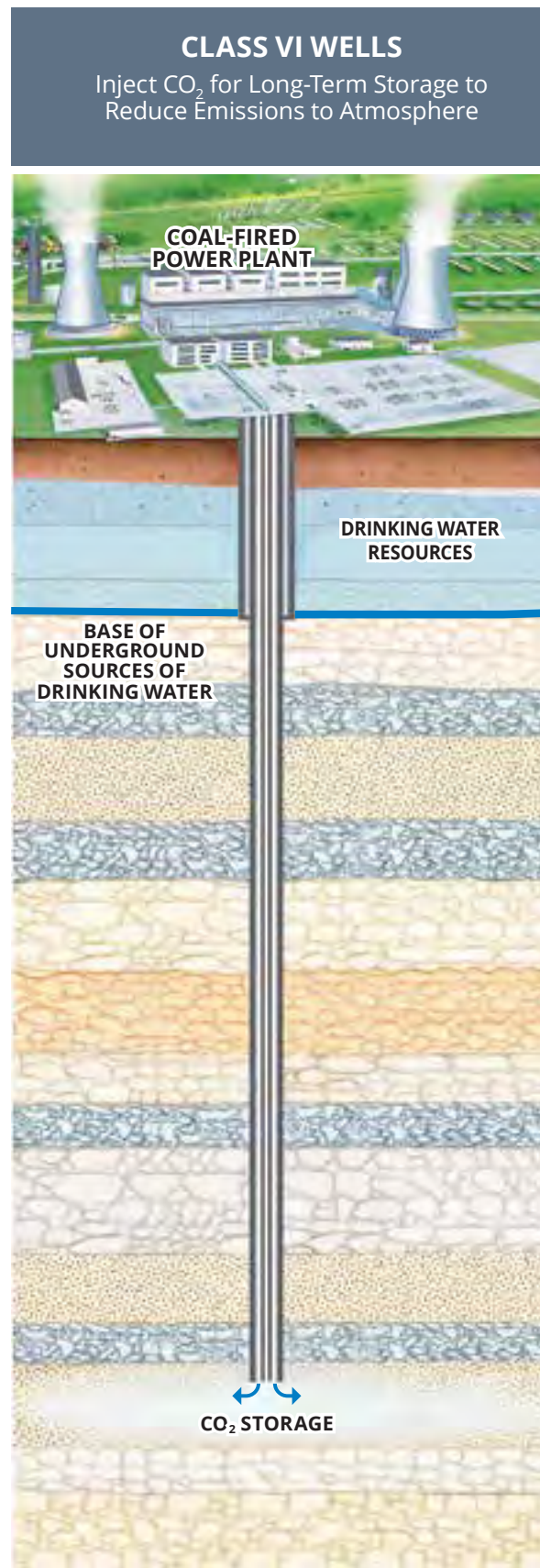
 No legislation in place or rules adopted or under development.

# 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<sub>2</sub> 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<sub>2</sub> EOR does store CO<sub>2</sub> while producing oil during EOR operations and that CO<sub>2</sub> injection under Class II rules can recognize the incidentally stored volume.

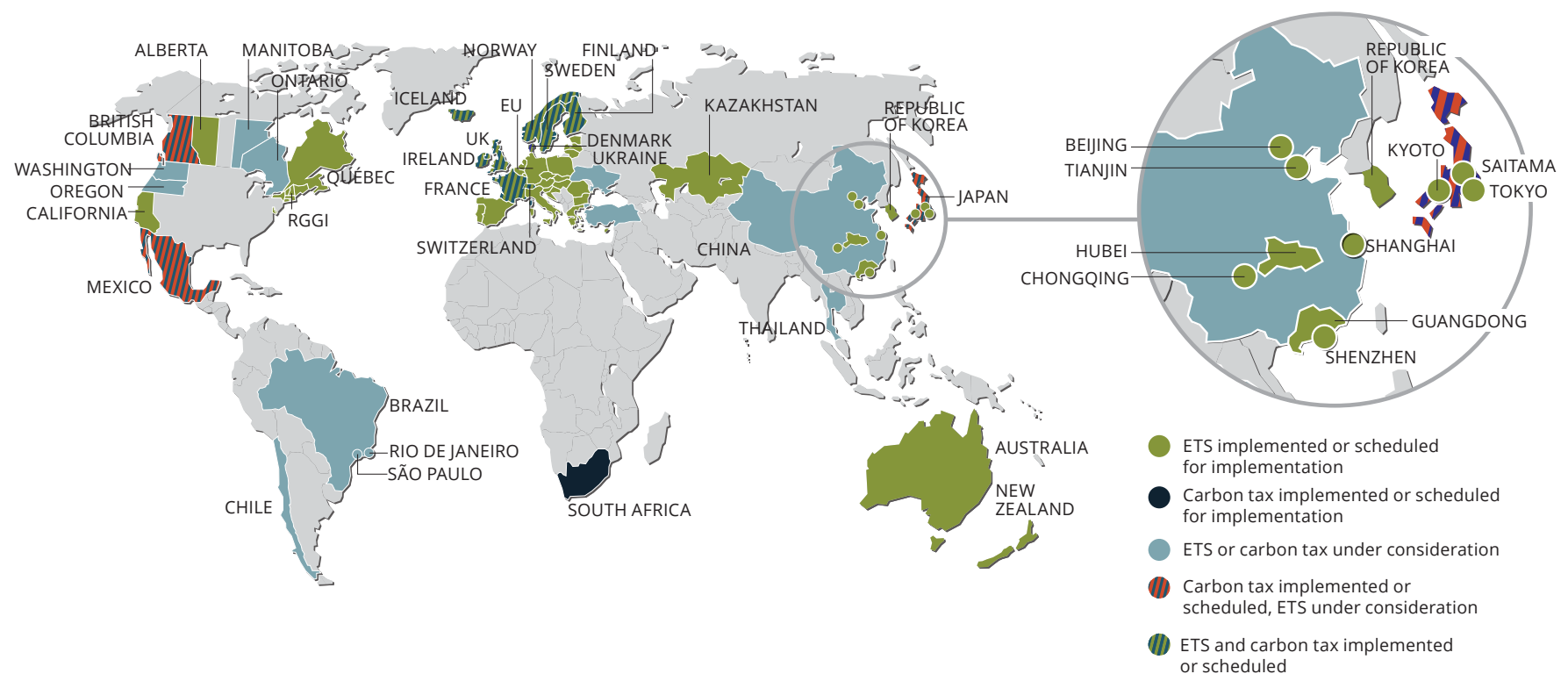
EPA gave states a deadline of September 6, 2011, to apply for primary enforcement responsibility, or primacy, over these Class VI wells. To date, EPA directly implements the Class VI Program nationally as no states have yet received primacy. As a result, to permit a CO<sub>2</sub> geologic storage project, potential owners or operators of a CO<sub>2</sub> geologic storage well need to submit a permit application to the appropriate EPA regional office.



# 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<sub>2</sub> 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<sub>2</sub>, 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<sub>2</sub> emissions allowed. Once that level is reached, carbon credits need to be purchased from another entity that is either not reaching the maximum CO<sub>2</sub> emission level or is pulling CO<sub>2</sub> out of the atmosphere (i.e., CCS). In an ETS, the price of CO<sub>2</sub> 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<sub>2</sub>.<sup>68</sup> With the goal to further reduce CO<sub>2</sub> emissions, the cap declines 2.5% each year from 2015 to 2020.<sup>68</sup> 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.<sup>69</sup>



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

# Carbon Offsets

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.<sup>70</sup> 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.<sup>71</sup> 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 <sub>2</sub> <sup>68</sup>
California	LCFS	≥10% CI of transportation fuels <sup>70</sup>
International	Paris Agreement	Global temperature hold <1.5°C <sup>71</sup>



# 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

Significant CCS activity is happening in the PCOR Partnership region as well as the rest of Canada and the United States. However, successful development and operation of full-scale CCS demonstration projects around the globe will be required to seriously abate CO<sub>2</sub> 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<sub>2</sub> derived from natural gas processing and storing the CO<sub>2</sub> 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<sub>2</sub> will be stored a year.<sup>72</sup>

## 2. Sleipner

Started in 1996, the Sleipner project is the world's first demonstration of CO<sub>2</sub> capture and dedicated underground storage. The project involves commercial natural gas production coupled with the storage of ~1 Mt CO<sub>2</sub>/year in a deep saline formation. 16.2 Mt of CO<sub>2</sub> has been injected since inception to June 2016.<sup>73</sup>

## 3. Gorgon

The Gorgon project is planned to be the first commercial CO<sub>2</sub> 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<sub>2</sub> a year, beginning in late 2017.<sup>74</sup>

# 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<sub>2</sub> 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

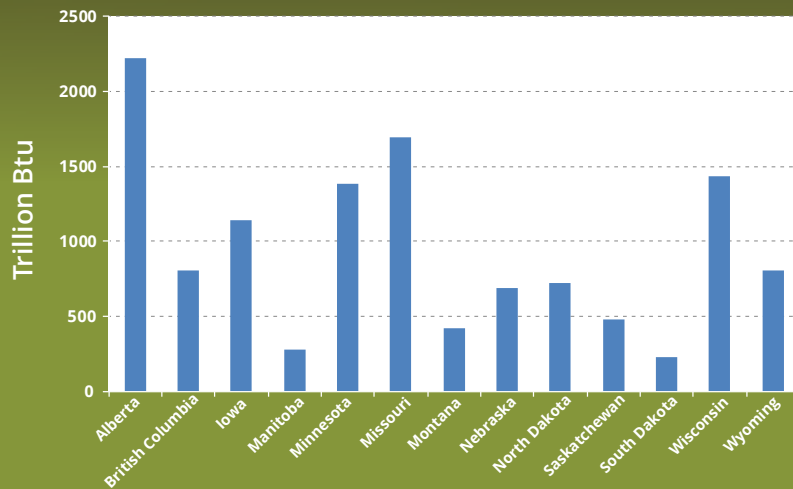
CCS can play a vital role in reducing atmospheric CO<sub>2</sub> levels while simultaneously preserving the option of using abundant and low-cost domestic fossil energy resources. However, the scale of CCS deployment needed to result in significant reductions will require thousands of CCS deployments 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<sub>2</sub> 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.<sup>75,76</sup> 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.



# Keeping the Lights On

2014 Annual Energy Consumption



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**



**Public Web Site**



**Video Clip Library**



**Partners-Only Web Site**



**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.

# 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<sub>2</sub>.
2. Facilitate the development of the infrastructure required to transport CO<sub>2</sub> from the source to the injection site.
3. Facilitate the development of the rapidly evolving North American regulatory and permitting framework for CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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.

# CCS Units and Conversion Factors

## Prefixes

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

## Conversion of Mass to Volume of CO<sub>2</sub> (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<sup>3</sup>

## 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](http://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<sub>2</sub> Capture Project** – The CO<sub>2</sub> 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](http://www.co2captureproject.org)

**Cooperative Research Centre for Greenhouse Gas Technologies (CO<sub>2</sub>CRC)** – The CO<sub>2</sub>CRC Program is a collaborative research organization focused on CO<sub>2</sub> capture and geological storage.  
[www.co2crc.com.au](http://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](http://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](http://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](http://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](http://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<sub>2</sub> 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](http://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<sub>2</sub> sequestration and assess the interests of the states to develop pertinent model state regulations.  
[www.iogcc.state.ok.us](http://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<sub>2</sub> storage technologies and manages the Weyburn–Midale CO<sub>2</sub> Monitoring and Storage Project and the Aquistore effort.  
[www.ptrc.ca](http://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](http://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](http://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](http://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](http://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](http://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](http://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](http://www.wri.org/publication/ccs-guidelines)

# Nomenclature

<b>AITF</b>	Alberta Innovates Technology Futures	<b>LCFS</b>	Low Carbon Fuel Standard
<b>bbl</b>	barrel	<b>LPG</b>	liquefied petroleum gas
<b>Bcf</b>	billion cubic feet	<b>mg/L</b>	milligram per liter
<b>BSCSP</b>	Big Sky Carbon Sequestration Partnership	<b>MGSC</b>	Midwest Geological Sequestration Consortium
<b>Btu</b>	British thermal unit	<b>MRCSP</b>	Midwest Regional Carbon Sequestration Partnership
<b>CAN</b>	Climate Action Network	<b>MRR</b>	Mandatory Greenhouse Gas Reporting Rule
<b>CARB</b>	California Air Resources Board	<b>Mt</b>	million tonne
<b>CBM</b>	coalbed methane	<b>MVA</b>	monitoring, verification, and accounting
<b>CCS</b>	carbon capture and storage	<b>MW</b>	megawatt
<b>CFC</b>	chlorofluorocarbon	<b>NDSU</b>	North Dakota State University
<b>CH<sub>4</sub></b>	methane	<b>NETL</b>	National Energy Technology Laboratory
<b>CI</b>	carbon intensity	<b>N<sub>2</sub>O</b>	nitrous oxide
<b>CO<sub>2</sub></b>	carbon dioxide	<b>O<sub>3</sub></b>	ozone
<b>CO<sub>2</sub>CRC</b>	Cooperative Research Centre for Greenhouse Gas Technologies	<b>PCOR</b>	Plains CO <sub>2</sub> Reduction Partnership
<b>COSS</b>	Cambro-Ordovician Saline System	<b>PDM</b>	permanent downhole monitoring
<b>CSA</b>	Canadian Standards Association	<b>ppm</b>	parts per million
<b>CSLF</b>	Carbon Sequestration Leadership Forum	<b>PPR</b>	Prairie Pothole Region
<b>Denbury</b>	Denbury Resources Inc.	<b>psi</b>	pound per square inch
<b>DOE</b>	U.S. Department of Energy	<b>PTRC</b>	Petroleum Technology Research Centre
<b>DU</b>	Ducks Unlimited	<b>PTTC</b>	Petroleum Technology Transfer Council
<b>DUC</b>	Ducks Unlimited Canada	<b>RCSP</b>	Regional Carbon Sequestration Partnership
<b>Eagle</b>	Eagle Operating Group, Inc.	<b>R&amp;D</b>	research and development
<b>ECBM</b>	enhanced coalbed methane	<b>RD&amp;D</b>	research, development, and demonstration
<b>EERC</b>	Energy & Environmental Research Center	<b>RGGI</b>	Regional Greenhouse Gas Initiative
<b>EIA</b>	Energy Information Administration	<b>SECARB</b>	Southeast Regional Carbon Sequestration Partnership
<b>EOR</b>	enhanced oil recovery	<b>SET</b>	Spectra Energy Transmission
<b>EPA</b>	U.S. Environmental Protection Agency	<b>stb</b>	stock tank barrel
<b>ETS</b>	emissions trading system	<b>SWP</b>	Southwest Regional Partnership on Carbon Sequestration
<b>FE</b>	Fossil Energy	<b>TDS</b>	total dissolved solids
<b>GCCSI</b>	Global CCS Institute	<b>UIC</b>	underground injection control
<b>GDP</b>	gross domestic product	<b>UNFCCC</b>	United Nations Framework Convention on Climate Change
<b>GHG</b>	greenhouse gas	<b>USDA</b>	U.S. Department of Agriculture
<b>Gt</b>	gigatonne	<b>USDW</b>	underground sources of drinking water
<b>H<sub>2</sub>O</b>	water	<b>USGS</b>	U.S. Geological Survey
<b>H<sub>2</sub>S</b>	hydrogen sulfide	<b>VSP</b>	vertical seismic profile
<b>IEA</b>	International Energy Agency	<b>WESTCARB</b>	West Coast Regional Carbon Sequestration Partnership
<b>IEAGHG</b>	International Energy Agency Greenhouse Gas R&D Programme		
<b>IETA</b>	International Emissions Trading Association		
<b>IOGCC</b>	Interstate Oil and Gas Compact Commission		
<b>IPCC</b>	Intergovernmental Panel on Climate Change		
<b>LCA</b>	life cycle analysis		

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# 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](http://www.undeerc.org/pcor).

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