PCO2R Partnership

Plains CO_2 Reduction (PCOR) Partnership

Practical, Environmentally Sound CO_2 Sequestration

ATLAS

4th Edition

EERC
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Putting Research into Practice

UND THE UNIVERSITY OF NORTH DAKOTA

Plains CO_2 Reduction (PCOR) Partnership
ATLAS
4th Edition
2012

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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_2 emissions from stationary sources in the central interior of North America. The PCOR Partnership is led by the EERC at the University of North Dakota and is one of seven regional partnerships through the U.S. Department of Energy's Regional Carbon Sequestration Partnership initiative.

PCOR Partnership

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The following EERC research staff are focused on the execution of PCOR Partnership efforts. It is through their creative energy and collective efforts that the production of this atlas was possible:

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Contents

Image provided by Denbury Resources Inc.

Preface

Many changes have been observed in global climate over the past century, and although the debate over climate change continues, there is a growing concern that human activity is affecting climate change. Using fossil fuels to produce energy may be a contributing activity to this change. Other significant potential impacts come from deforestation, agricultural practices, and industrial processes.

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

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

This atlas provides a regional profile of CO_2 sources and potential CO_2 storage locations across the nearly 1.4 million square miles (3.6 million km^2) of the PCOR Partnership region. In the 8 years since the RCSP was founded, a wealth of new information about CCS has been discovered. This fourth edition provides an up-to-date look at PCOR Partnership activities, to include additional regional characterization and updates on full-scale demonstration activities. 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 us to meet future energy needs.

CHAPTER 1

The Challenge

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

Greenhouse Effect

The natural greenhouse effect plays an essential role in our climate patterns. The effect is the result of heat-trapping gases (also known as GHGs), which absorb heat radiated from the 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 the Earth would be about 60°F (~33°C) colder,[1] and life as it is known would not be possible.

Greenhouse Gases

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

Water vapor is the most abundant GHG in the atmosphere. As the temperature of the atmosphere rises, it can hold more water vapor. This higher concentration of water vapor is able to absorb more heat, thus further warming the atmosphere. This cycle is called a feedback loop.

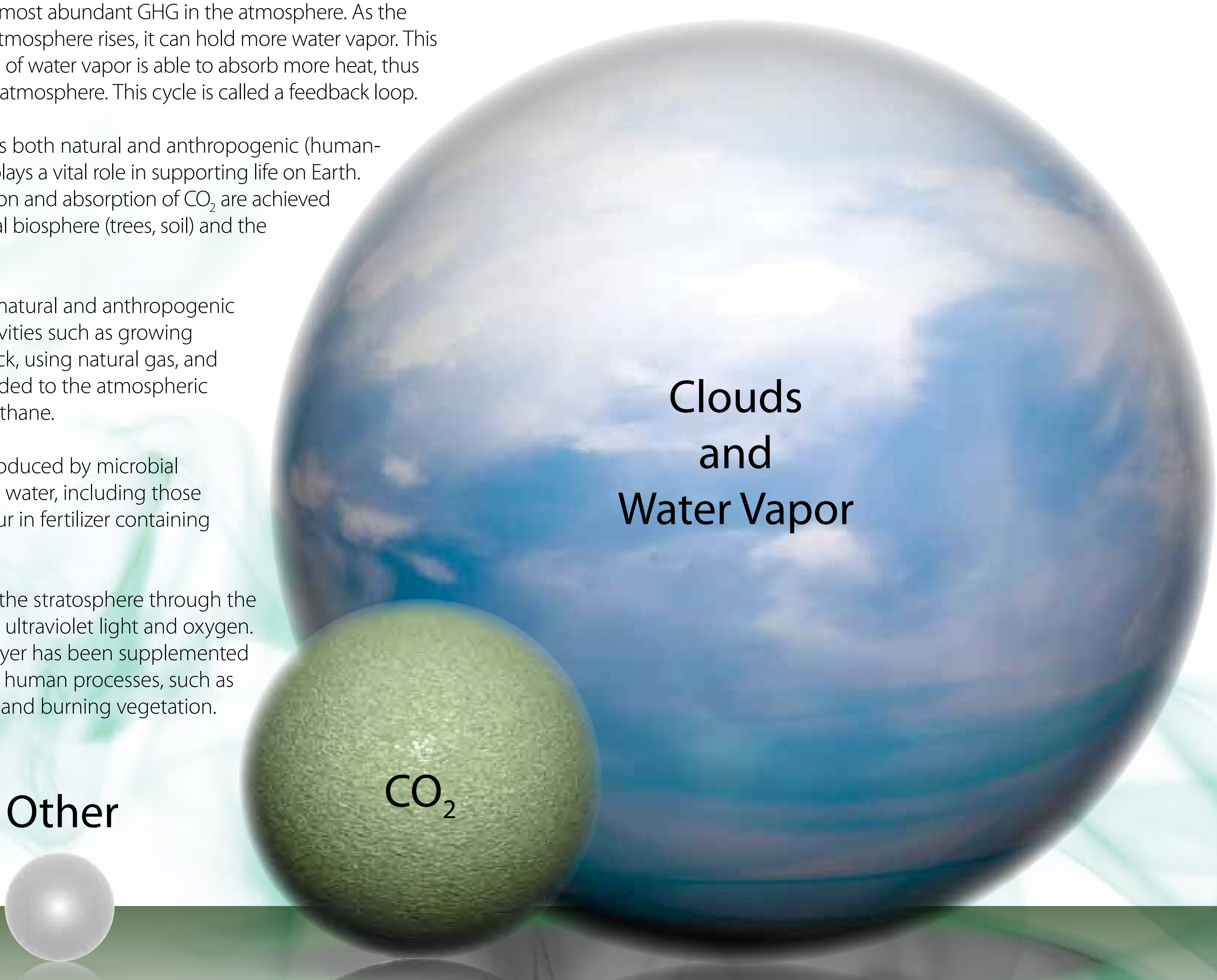
Carbon dioxide has both natural and anthropogenic (human-made) sources. CO_2 plays a vital role in supporting life on Earth. The natural production and absorption of CO_2 are achieved through the terrestrial biosphere (trees, soil) and the hydrosphere (ocean).

Methane has both natural and anthropogenic sources. Human activities such as growing crops, raising livestock, using natural gas, and mining coal have added to the atmospheric concentration of methane.

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

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

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

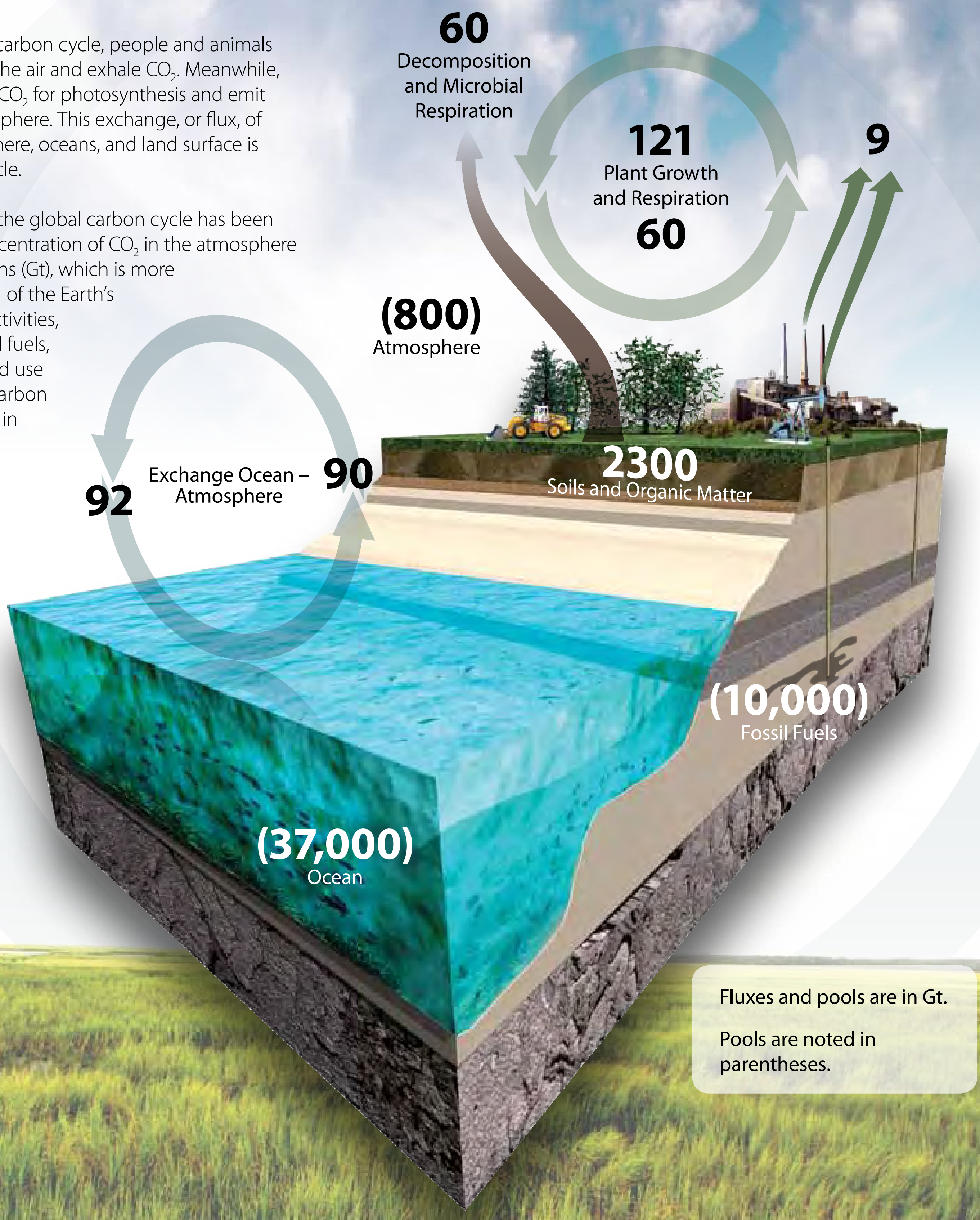


Representative GHG effect contributions.[2]

Global Carbon Cycle

As part of the natural carbon cycle, people and animals inhale oxygen from the air and exhale CO_2. Meanwhile, green plants absorb CO_2 for photosynthesis and emit oxygen back into the atmosphere. This exchange, or flux, of carbon among the atmosphere, oceans, and land surface is called the global carbon cycle.

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



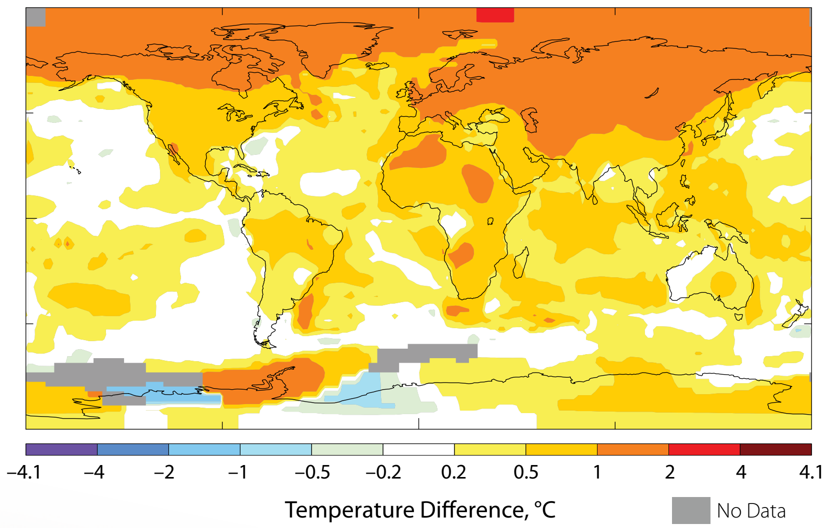
Fluxes and pools are in Gt.

Pools are noted in parentheses.

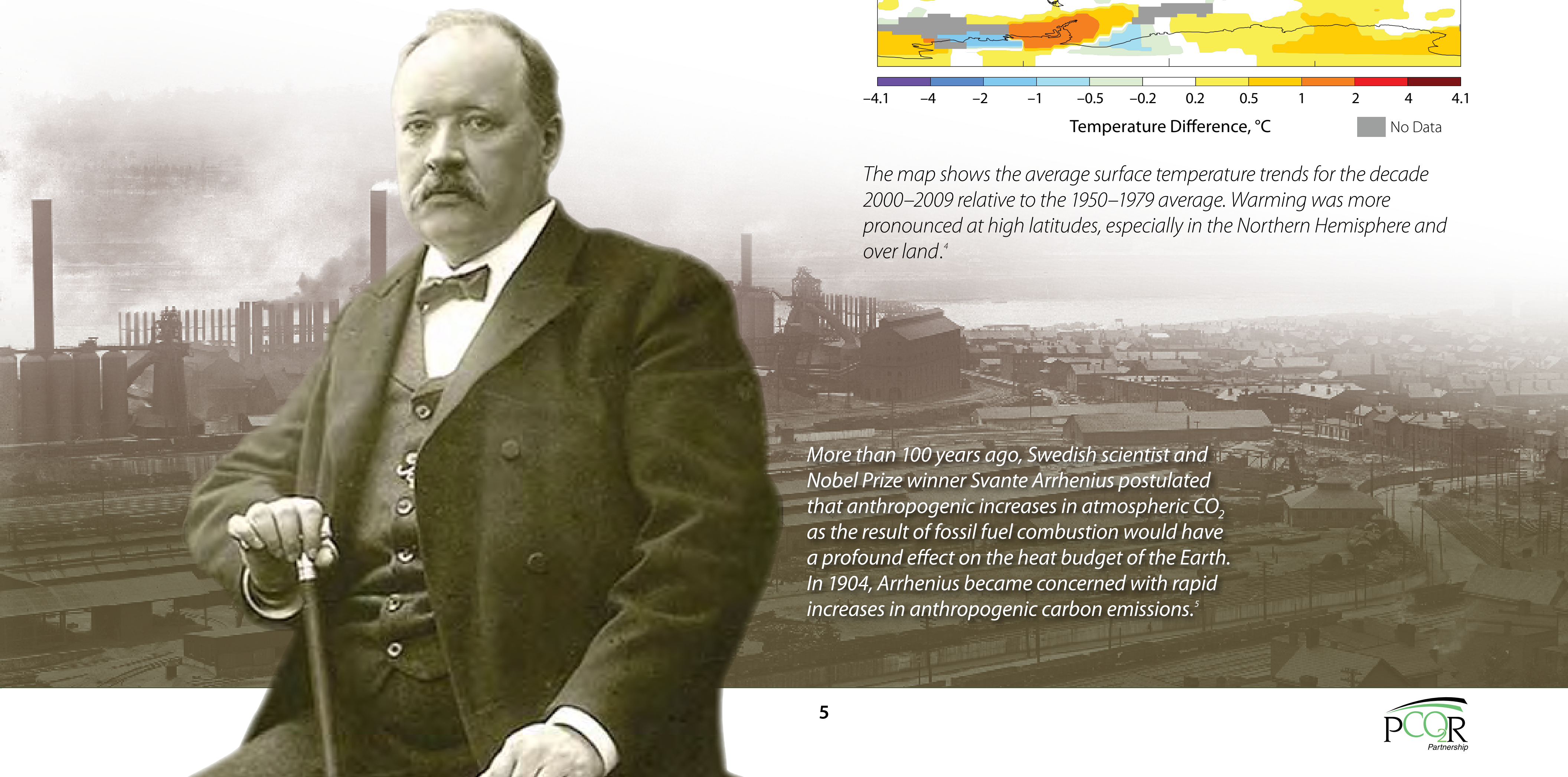
"The slight percentage of carbonic acid in the atmosphere may, by the advances of industry, be changed to a noticeable degree in the course of a few centuries."

–Svante Arrhenius, 1904

Since instrumental records of temperature began in 1861, the overall temperature of the Earth has risen by approximately 1.33°F (0.74°C), with the 1990s being the warmest decade and 1998 being the warmest year.[3] Some scientists attribute the temperature rise to human activity, but others believe it is a result of natural climate changes that have occurred over the millions of years of the Earth's existence. A large body of the scientific community believes that global climate change is a combination of natural and human-induced causes. 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 2000–2009 relative to the 1950–1979 average. Warming was more pronounced at high latitudes, especially in the Northern Hemisphere and over land.[4]



More than 100 years ago, Swedish scientist and Nobel Prize winner Svante Arrhenius postulated that anthropogenic increases in atmospheric CO_2 as the result of fossil fuel combustion would have a profound effect on the heat budget of the Earth. In 1904, Arrhenius became concerned with rapid increases in anthropogenic carbon emissions.[5]

Major Stationary CO_2 Sources

Cement Plant

Refinery

Coal-Fired Power Plant

Ethanol Plant

Anthropogenic CO_2

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

Nonstationary CO_2 emissions include activities such as using gasoline, diesel, and other fuels for transportation.

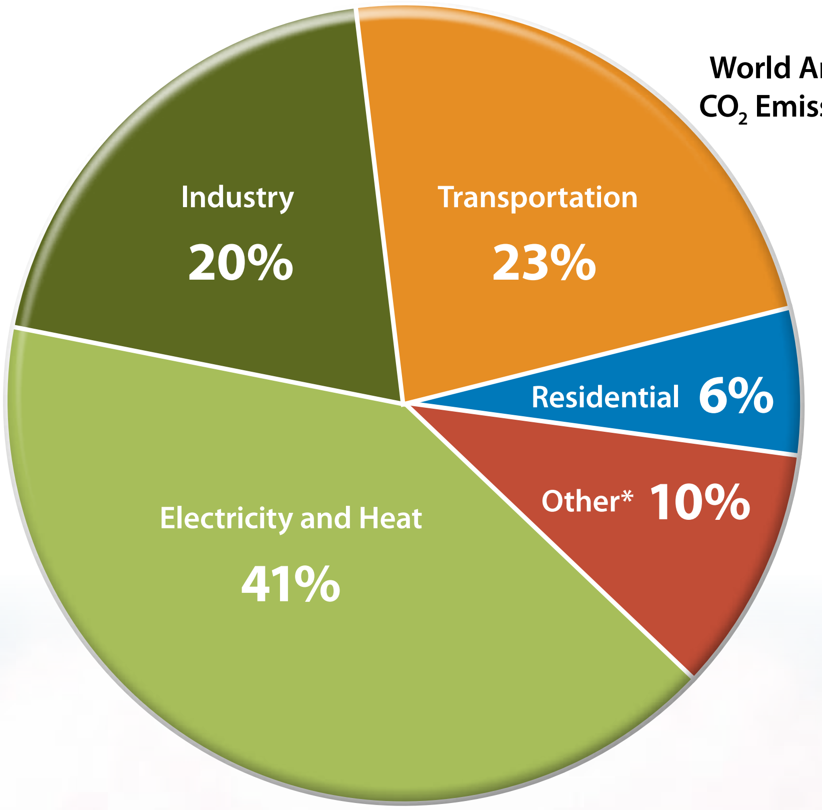
Changes in land use and land conversion are also considered a significant source of anthropogenic CO_2. This includes practices like plowing land, which releases some of the exposed carbon in the soil to the atmosphere as CO_2, and deforestation, which causes a loss of plant biomass.

What Is CO_2?

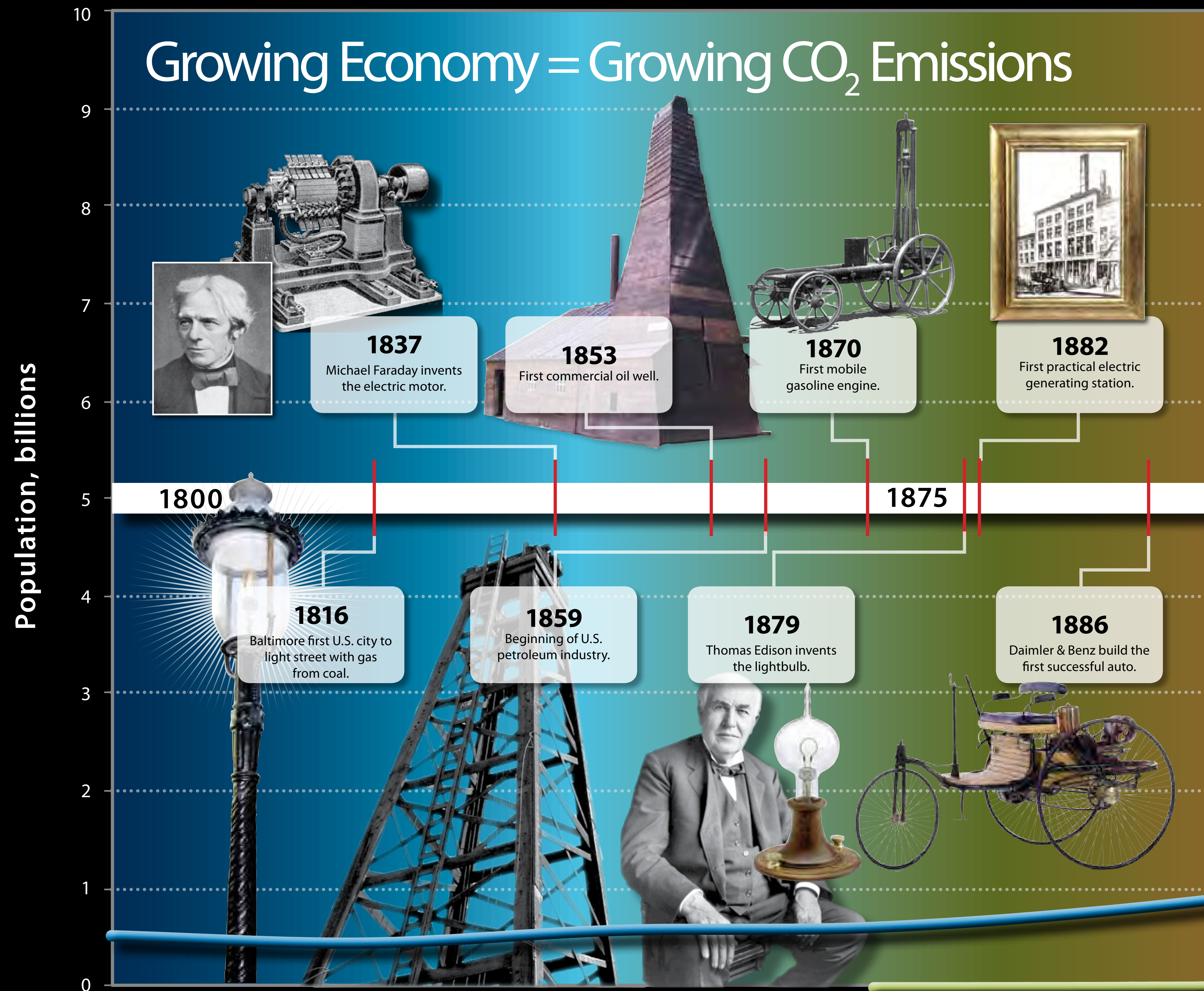
Carbon dioxide is a colorless, odorless, naturally occurring gas comprising one atom of carbon and two atoms of oxygen. At temperatures below -108°F (-76°C), CO_2 condenses into a white solid called dry ice. When warmed, dry ice vaporizes directly from a solid to CO_2 gas in a process called sublimation. With enough added pressure, liquid carbon dioxide can be formed.

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

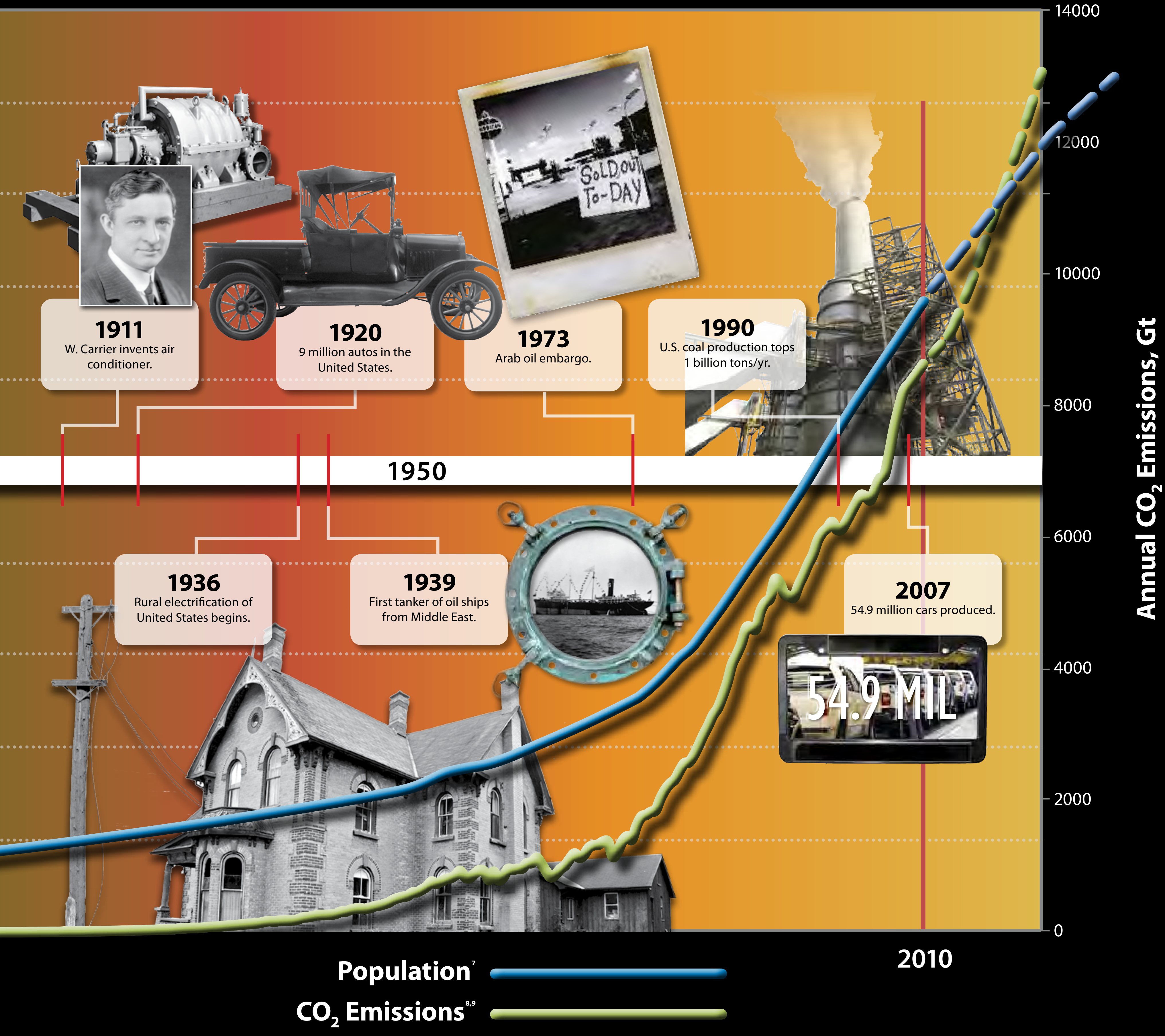
World Anthropogenic CO_2 Emissions for 2009[6]



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



The amount of CO_2 in the atmosphere was relatively constant for 10,000 years until the Industrial Revolution in the 1800s, and the amount of anthropogenic CO_2 is projected to increase considerably. Currently, the world's economies annually emit approximately 29 Gt of CO_2 to the atmosphere from the combustion of fossil fuels to produce electricity. Increasing global populations, higher standards of living, and increased demand for energy could result in as much as 9000 Gt of cumulative CO_2 being emitted to the atmosphere.[6]


14000
12000
10000
8000
6000
4000
2000
0
Annual CO_2 Emissions, Gt
1911
W. Carrier invents air conditioner.
1920
9 million autos in the United States.
1973
Arab oil embargo.
SOLD OUT TO-DAY
1990
U.S. coal production tops 1 billion tons/yr.
1950
1936
Rural electrification of United States begins.
1939
First tanker of oil ships from Middle East.
2007
54.9 million cars produced.
54.9 MIL
2010
Population[7]
CO_2 Emissions[8,9]

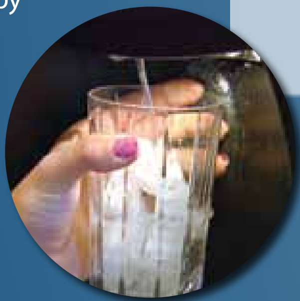
Household Carbon Footprints

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 our technologies and develop their own, they will use more and more energy.

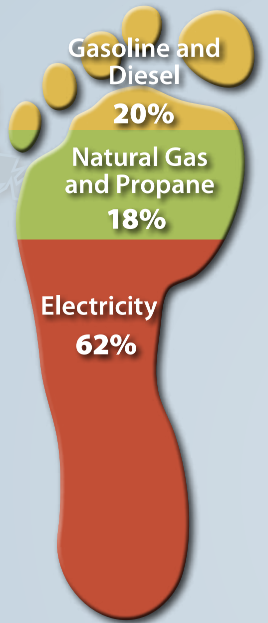
In 1930, the countries that now have the postindustrial economies generated nearly all carbon emissions from fossil fuels. Since then, global emissions have grown seven times greater. Now, postindustrial economies generate half.[10] By 2030, global emissions are projected to grow by half again; most 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 the threat of climate change?

Postindustrial Economy: **United States**

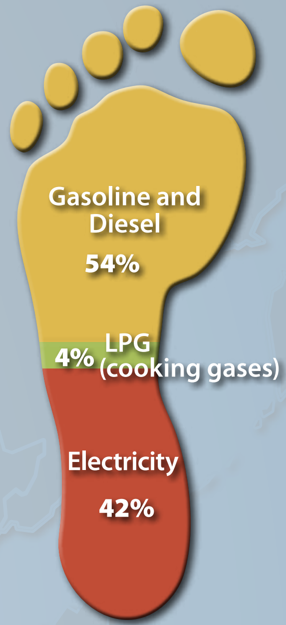


A middle class U.S. family uses fossil fuels for transportation, heating, and cooking, but most of their carbon footprint comes from the electricity they use (generated mainly from coal).

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

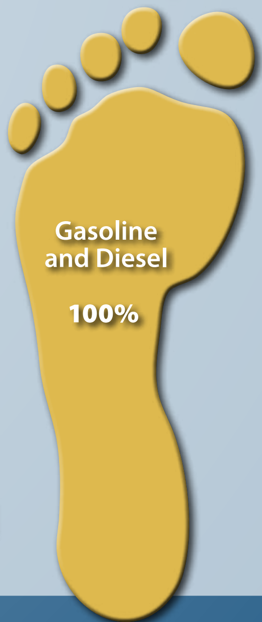
Emerging Economy: **India**

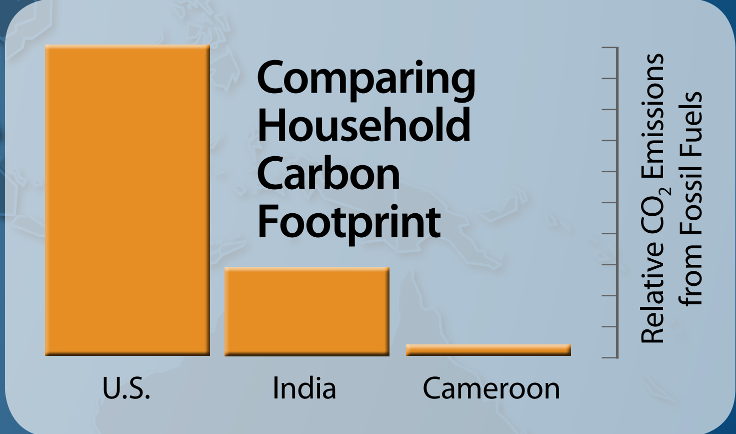
Middle class homes in India are smaller, have fewer appliances, and have no heating systems. About half of the carbon footprint for this family comes from their transportation. Most of the rest comes from the electricity they use (most made by fossil fuels).



Developing Economy: **Cameroon**

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.

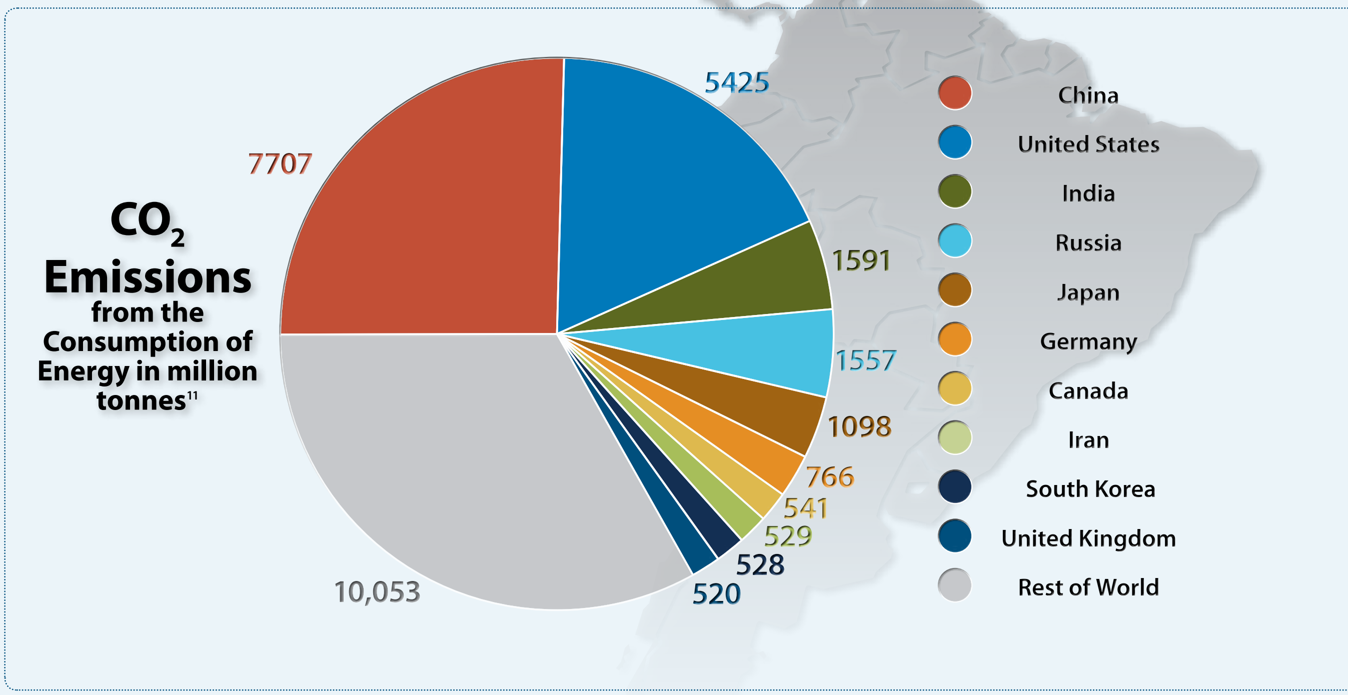
PCO2R Partnership

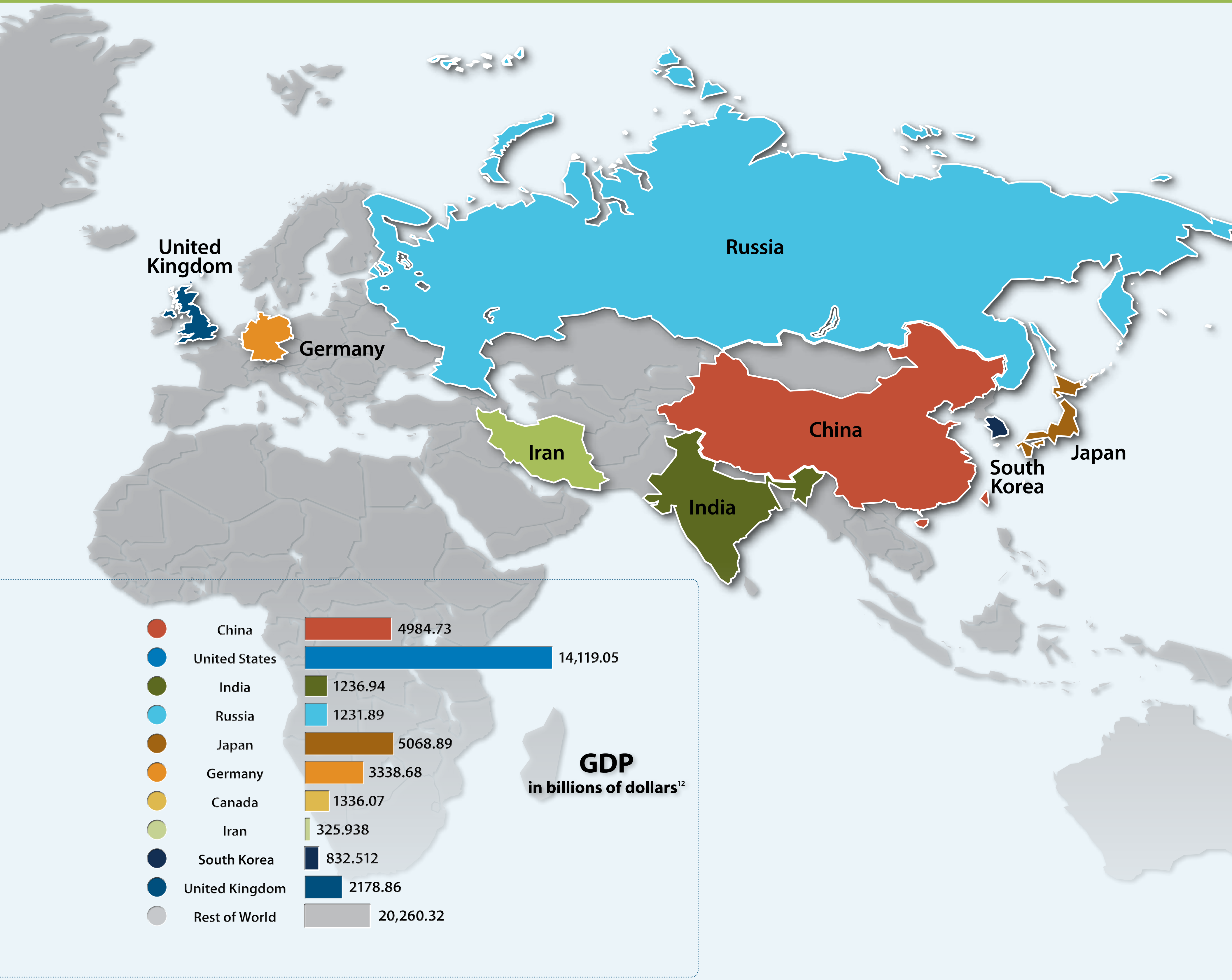
World CO_2 Emissions

Although economic growth and increases in energy use generally occur together, the degree of which they are linked varies across regions and states of economic development. The picture that emerges from these figures is one where, in general, developed countries and major emerging economy nations lead in total CO_2 emissions.

In 2009, the largest five CO_2 emitters (China, the United States, India, Russia, and Japan) comprised 45% of the total population and together produced 56% of the global CO_2 emissions and 51% of the world´s gross domestic product (GDP). Among the five largest emitters of CO_2, China, Russia, and the United States have significantly reduced their CO_2 emissions per unit of GDP over the last 20 years by improving energy efficiency and using more renewable fuels. Worldwide, the highest levels of emissions per GDP are observed for the oil- and gas-exporting regions of the Middle East.[6]

As compared to emissions per unit of GDP, the range of per capita emission levels across the world is even larger, highlighting wide divergences in the way different countries and regions use energy. Developed nations typically have high CO_2 emissions per capita, while some developing countries lead in the growth rate of CO_2 emissions. Factors such as income per capita, climate, and population density are important determinants of CO_2 emissions per capita.

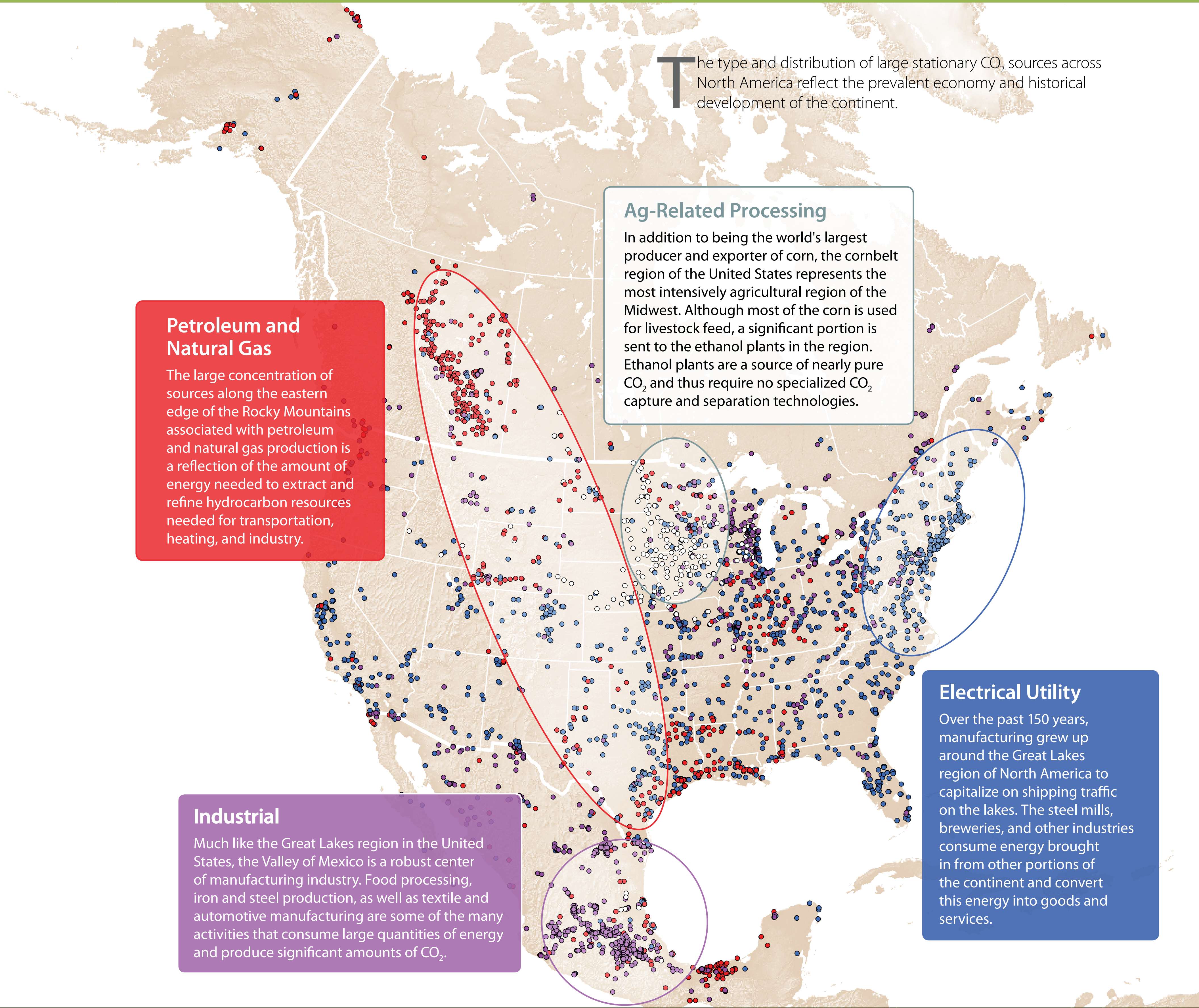



United Kingdom
Germany
Russia
Iran
China
India
South Korea
Japan
GDP
in billions of dollars[12]
China 4984.73
United States 14,119.05
India 1236.94
Russia 1231.89
Japan 5068.89
Germany 3338.68
Canada 1336.07
Iran 325.938
South Korea 832.512
United Kingdom 2178.86
Rest of World 20,260.32

North American CO_2 Sources

North American Profile

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



Ag-Related Processing

In addition to being the world's largest producer and exporter of corn, the cornbelt 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 the ethanol plants in the region. Ethanol plants are a source of nearly pure CO_2 and thus require no specialized CO_2 capture and separation technologies.

Petroleum and Natural Gas

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

Electrical Utility

Over the past 150 years, manufacturing grew up around the Great Lakes region of North America to capitalize on shipping traffic on the lakes. The steel mills, breweries, and other industries consume energy brought in from other portions of the continent and convert this energy into goods and services.

Industrial

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

Potential Impacts of Climate Change

No one knows the exact consequences of this upsurge of CO_2 in the atmosphere, but climate-related changes have already been observed globally. Climate change is expected to impact human health, natural systems, and the environment at large. Potential consequences include:[14]

- 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_2 Solution

Addressing climate change is a large-scale, global challenge that is compounded by our growing demand for energy. To stabilize CO_2 at levels that would prevent anthropogenic interference with the climate system, there needs to be a substantial reduction in the amount of CO_2 released by human activity.

A number of techniques can be employed to reduce CO_2 emissions, including energy conservation, using fossil fuels more efficiently, and increasing the use of renewable (i.e., wind, solar, geothermal, hydropower) and nuclear energy. But in the face of growing world populations and rising worldwide standards of living, CCS has the potential to significantly reduce CO_2 levels more than any other single technique. 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 could process 20% to 40% of world CO_2 emissions by 2050.[15]


CO2
CO2
CO

CHAPTER 2

Carbon Management

The need to stabilize atmospheric concentrations of CO_2 requires a suite of carbon management solutions, including energy efficiency, using less carbon-intensive fuels, enhancing natural carbon uptake in the biosphere, and broadening the use of renewable energy. Terrestrial storage techniques can be used to better manage the CO_2 naturally stored on the Earth's surface, but one of the most promising approaches involves capturing CO_2 from the exhaust gas at large stationary sources and placing the CO_2 underground into long-term storage. This option is referred to as CCS and is at the forefront for decreasing GHG emissions while retaining our existing energy generation infrastructure. This chapter covers some of the fundamental components of CCS.

Terrestrial Carbon Storage

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

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

Steady State

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

Benefits of Terrestrial Storage

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

Mechanisms for Terrestrial Storage

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

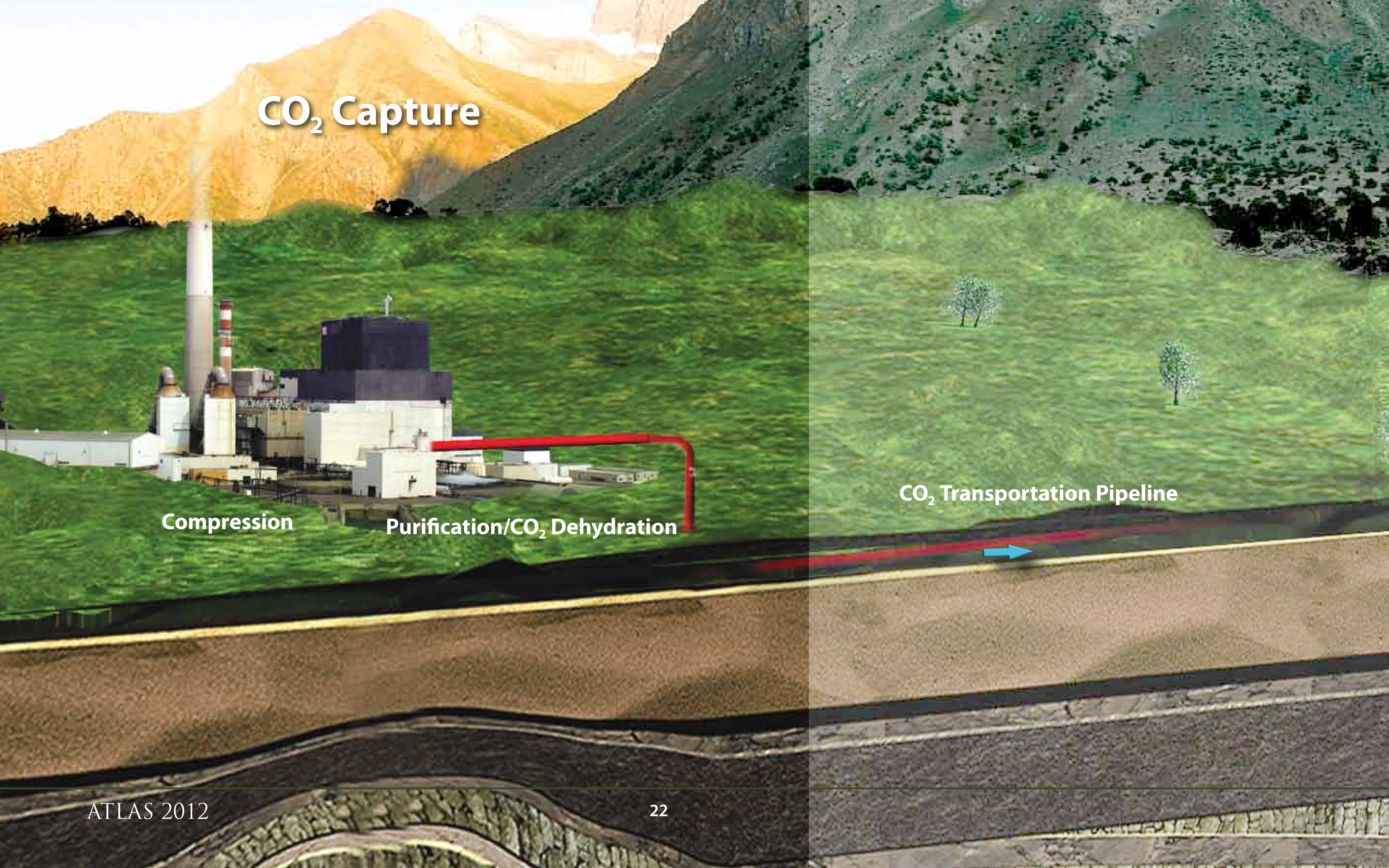
- Conservation tillage
- Reducing soil erosion and minimizing soil disturbance
- Using buffer strips along waterways
- Enrolling land in conservation programs
- Restoring and better managing wetlands and degraded soils
- Eliminating summer fallow
- Using perennial grasses and winter cover crops
- Fostering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

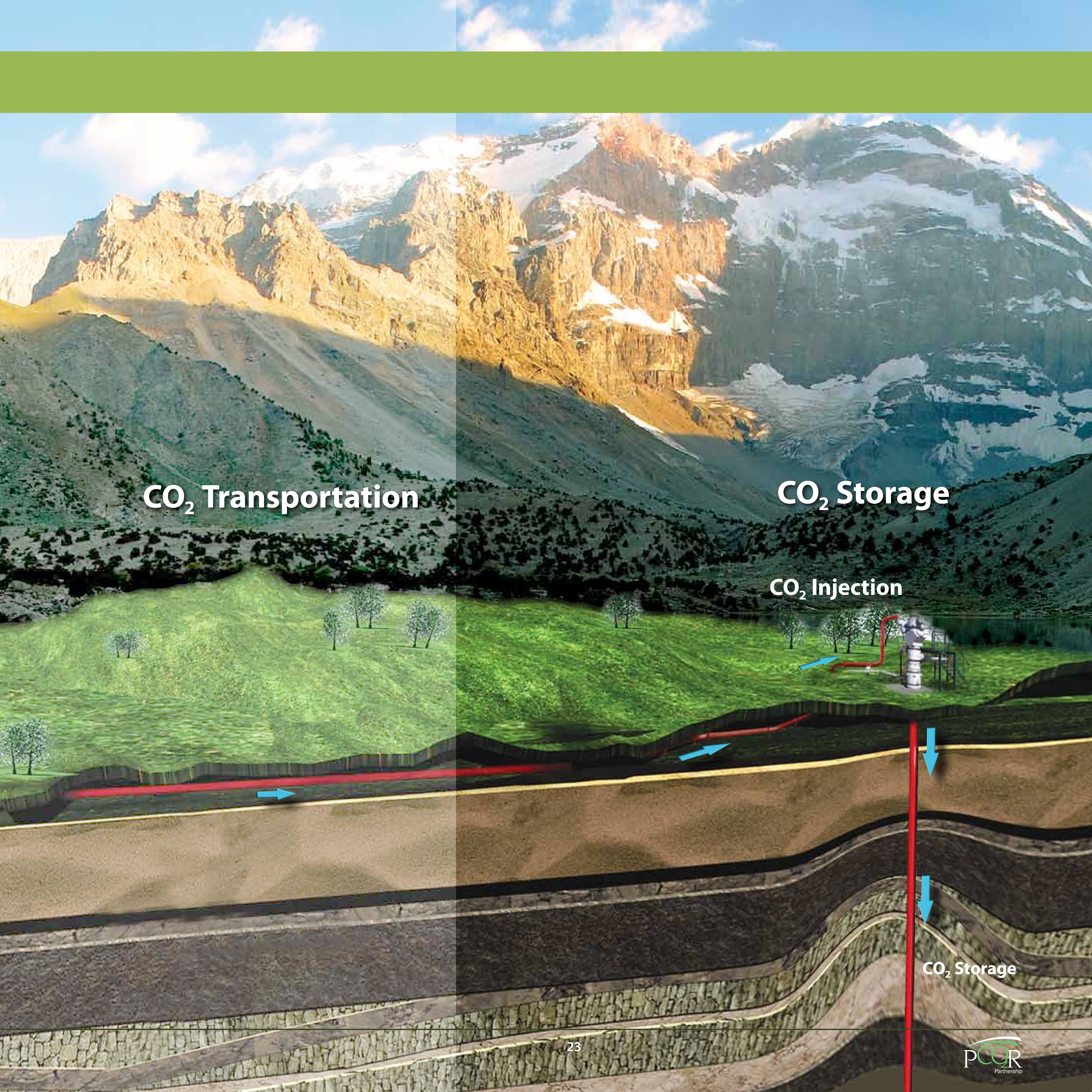
Terrestrial carbon storage is a near-term approach to reducing GHGs.

Carbon Capture and Storage

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

Instead of releasing CO_2 to the atmosphere, CCS involves capturing the CO_2 and separating it from other gases, pressurizing the CO_2 to a liquid or dense fluid state, transporting it to an appropriate storage location, and injecting it into deep underground geologic formations for permanent isolation from the atmosphere.

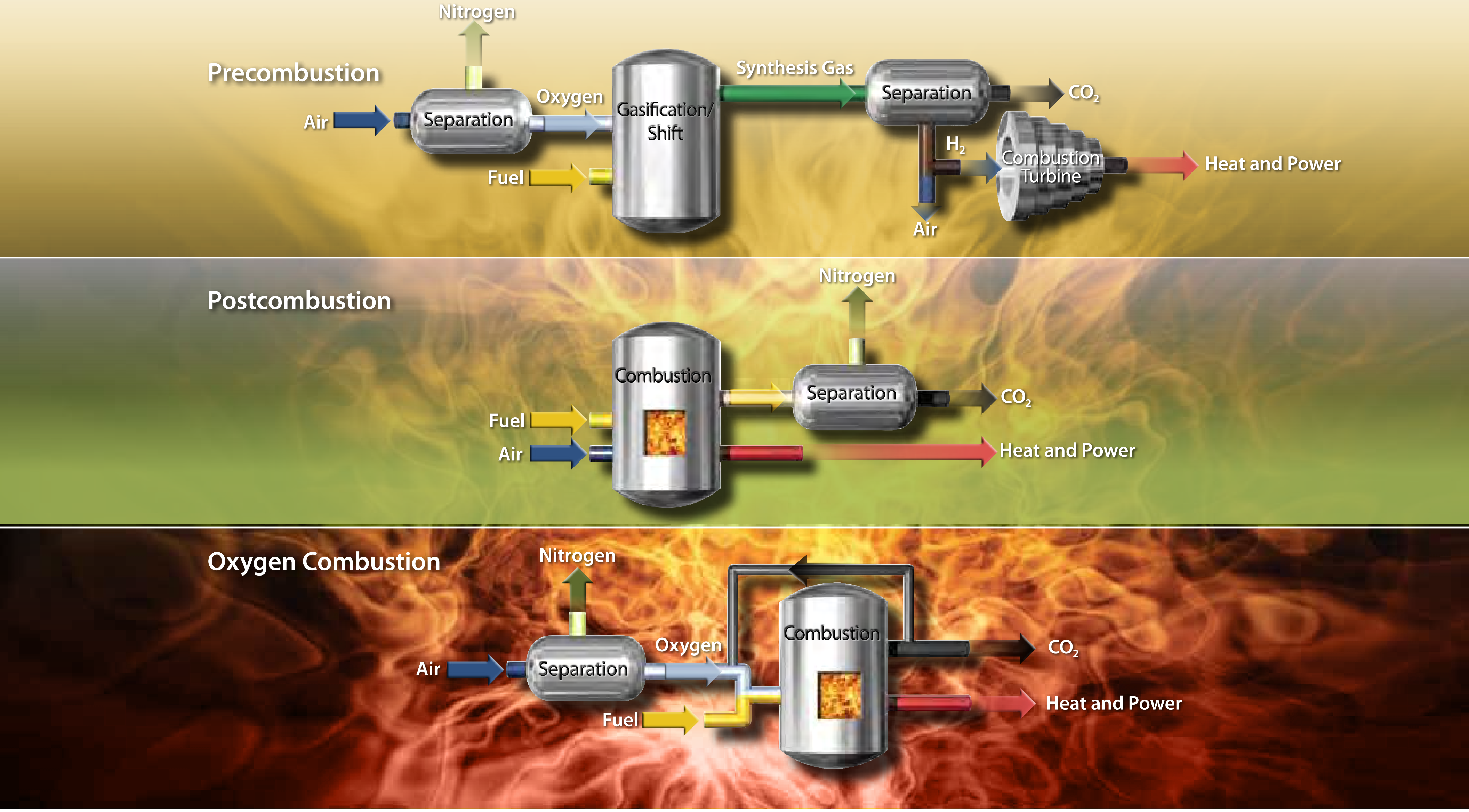



CO_2 Transportation
CO_2 Storage
CO_2 Injection
CO_2 Storage
PCOR Partnership

CO_2 Capture

Capture is defined as the removal of CO_2 that would otherwise be emitted to the atmosphere. Capture can be performed at one of three points in the energy-production process: before, during, or after combustion. The precombustion technologies consist of capture of CO_2 in conjunction with either gasification or methane reforming to produce hydrogen for use in a combustion turbine. Capture during combustion is possible when the oxygen source is pure oxygen rather than mixed in air. To maintain the correct boiler temperature, some flue gas is recycled to the boiler during oxygen combustion,[16] meaning that the atmosphere in the boiler is not pure oxygen but rather a mixture consisting primarily of oxygen and CO_2. The majority of capture technologies focus on separating low-concentration CO_2 from the exhaust gas stream after combustion takes place; this is called postcombustion capture.

Because the concentration of CO_2 in typical power plant flue gas is so low (ranging from 3% by volume for some natural gas-fired plants to about 13% by volume for coal-fired plants),[17] any postcombustion capture process must be sized to handle the entirety of the exhaust gas. The large scale of equipment, quantities of chemicals required, and energy needed to operate the capture system make it relatively expensive. In fact, the cost of capturing the CO_2 can represent three-fourths of the total cost of a CCS operation.[17] Because capture is the most costly portion of a CCS project, research is being performed to develop more efficient CO_2 capture processes and improve the economics of existing ones. CO_2 capture has been demonstrated at several gas-fired and coal-fired boilers at small scales. Natural gas-processing and fertilizer industries are already capturing CO_2 at commercial scale, and the Great Plains Synfuels Plant uses precombustion techniques to separate CO_2 from its lignite-derived synthetic natural gas.



CO_2 Separation and Compression

When CO_2 is captured, it oftentimes needs to be separated from other gases and then compressed prior to being transported to the storage site. The separation of CO_2 is performed as a part of many industrial processes. However, existing separation technologies are not yet optimized for routine application on a typical power plant exhaust stream.

After the CO_2 is captured and separated, it must be compressed into a supercritical or liquidlike state for either storage prior to truck transport or pipelined to the storage site. CO_2 must be compressed to about 1200 to 1500 pounds per square inch (psi) for transport in a pipeline to ensure that CO_2 remains in a dense liquid state. Because compression is energy-intensive, improved compression methods are under development.

CO_2 Transportation Infrastructure

After CO_2 is captured, separated, and compressed, the next step is transporting it to a storage site. Given the quantities of CO_2 that are likely to be captured from coal-fired power plants, pipelines appear to be the most likely mode for transporting the captured gas to geologic storage sites. Currently, about 4000 miles (6437 km) of CO_2 pipeline is in service in North America today, with hundreds of miles of additional pipeline under construction or planned.[18]

Image provided by Denbury Resources Inc.

For over 30 years, CO_2 has been safely transported via pipeline. Pipelines are a proven technology that requires no new development, only implementation. CO_2 pipelines are similar in design and operation to natural gas pipelines, although the higher pressures needed for CO_2 transportation require construction using thicker-walled carbon steel pipe.

Building a regional CO_2 pipeline infrastructure for CCS activities will require thoughtful planning as to whether to construct specific pipelines connecting individual CO_2 sources with geologic sinks in a one-at-a-time manner or if it will be more advantageous to construct a CO_2 pipeline network that can connect many large stationary sources with major geologic sinks. If a network of shared pipelines is implemented, common carrier issues such as those related to CO_2 stream quality may need to be addressed.

Although the total length of CO_2 pipelines is far less than that of natural gas and hazardous liquid pipelines, injury and property damage data suggest that CO_2 pipelines are safer. Strategies undertaken to manage risks include the inclusion of fracture arresters approximately every 1000 feet (300 m), block valves to isolate pipe sections if they leak, the use of advanced seals, and automatic control systems that monitor volumetric flow rates and pressure.

NO serious human injuries or fatalities have been reported as a result of CO_2 transportation via pipeline.[19]

Image provided by Denbury Resources Inc.

Image provided by Denbury Resources Inc.

Long-Term Geologic Storage

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

Geologic Storage Criteria

Geologic storage involves injecting captured anthropogenic CO_2 into deep underground geologic formations. These formations, or CO_2 sinks, exist in a variety of configurations in sedimentary basins and include unminable coal beds, oil and gas reservoirs, and deep geologic layers that contain very salty water (also known as brine or saline formations). Scientists have identified many potentially suitable areas across the globe that have the capacity to securely hold hundreds of years of anthropogenic CO_2 emissions deep underground.

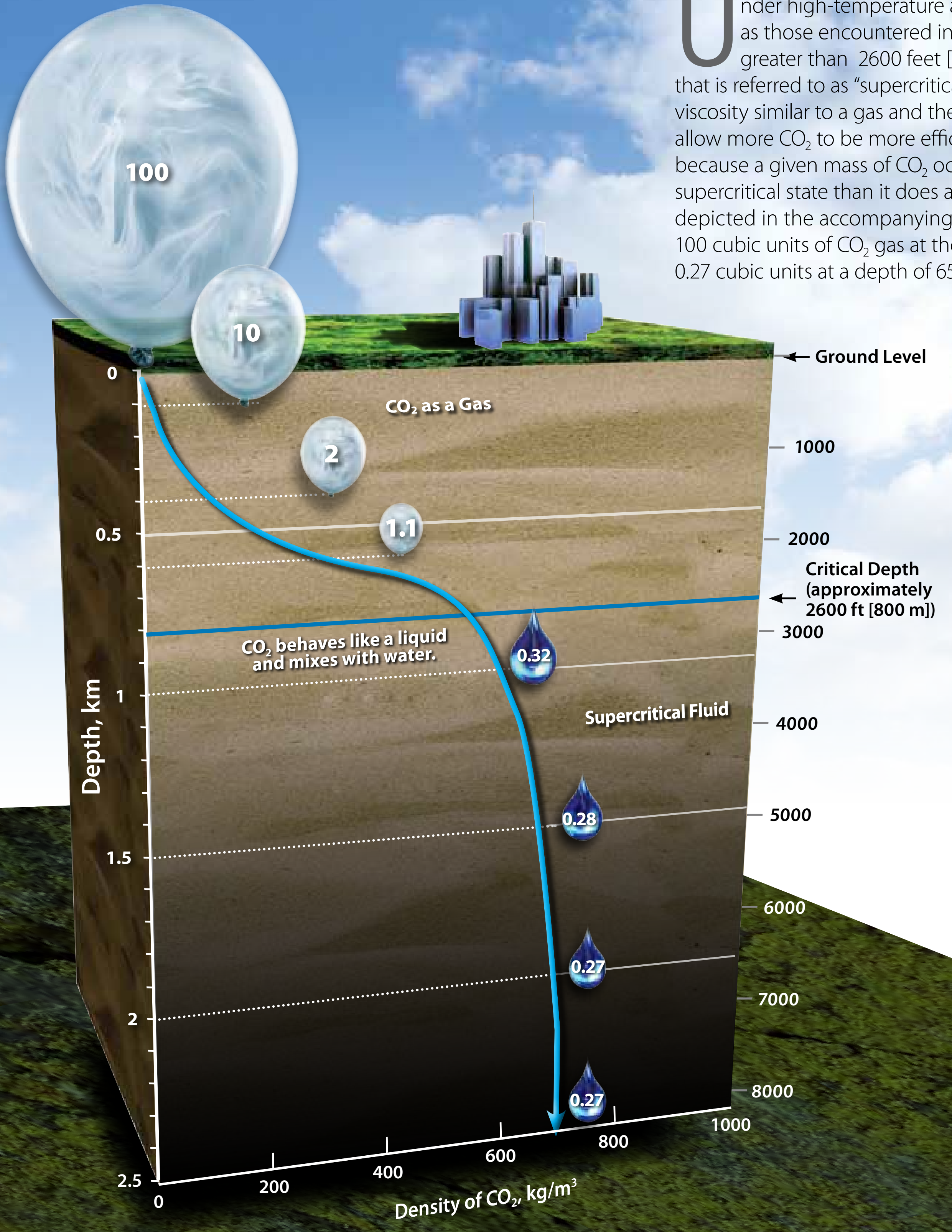
Geologic Sink Characteristics

Site selection is central to the secure, long-term storage of CO_2 because successful geologic storage requires that CO_2 stay in place and not pose a danger to human health and the environment. To be considered for storage, geologic sinks should:

- Be capable of holding large volumes of CO_2 in place for a long period of time.
- Be overlain by thick, laterally continuous cap rock that prevents upward migration or by comparable structural traps.
- Be at depths that take advantage of dense-phase CO_2 (typically >2600 feet [800 m]).
- Have formation water salinities greater than 10,000 mg/L.

Supercritical CO_2

Under high-temperature and high-pressure conditions, such as those encountered in deep geologic formations (typically greater than 2600 feet [800 m]), CO_2 will exist in a dense phase that is referred to as "supercritical." At this supercritical point, CO_2 has viscosity similar to a gas and the density of a liquid. These properties allow more CO_2 to be more efficiently stored deep underground because a given mass of CO_2 occupies a much smaller space in the supercritical state than it does as a gas at the surface. This concept is depicted in the accompanying illustration that shows a volume of 100 cubic units of CO_2 gas at the surface only occupies a volume of 0.27 cubic units at a depth of 6500 feet (2 km).



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

Trapping CO_2 in Rocks

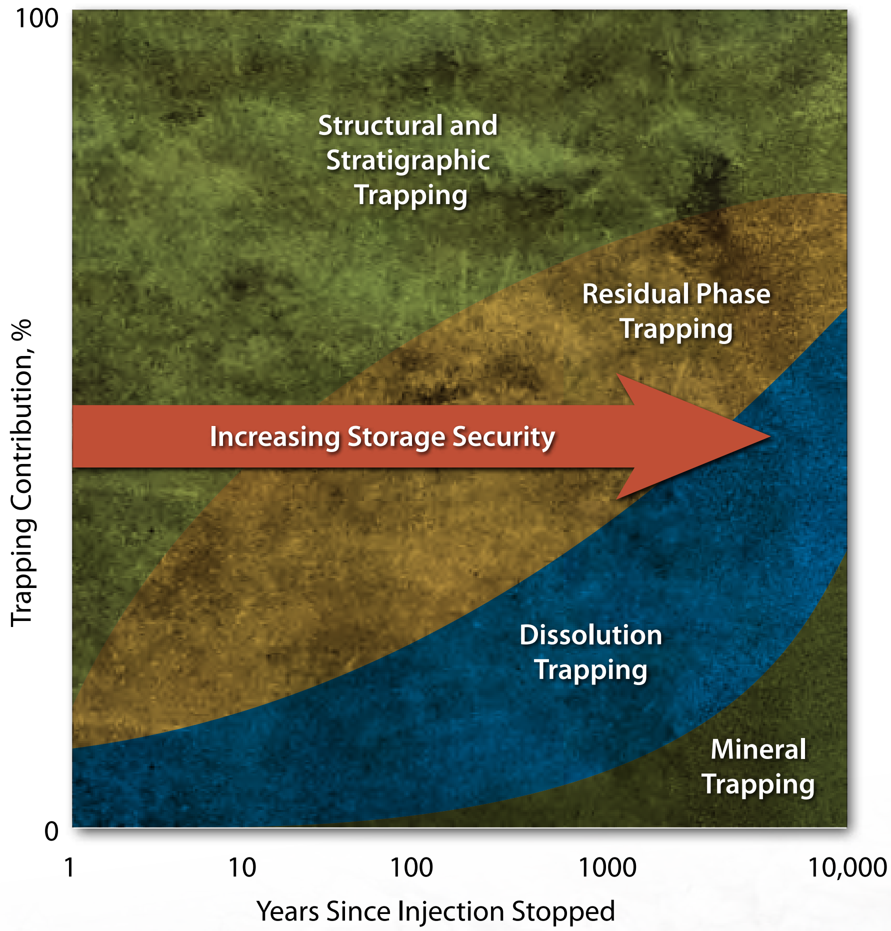
Several mechanisms function to trap and store CO_2 in deep geologic formations.

Structural and Stratgraphic Trapping – Because it is less dense than the saline water in the formation, the supercritical CO_2 injected deep (more than 2600 feet [800 m]) underground will rise up through the porous rocks of the target zone until it reaches the top of the formation. Once it reaches the top of the target zone, it will become trapped by a thick, laterally continuous and impermeable layer of cap rock, such as shale. The structural configuration of the containing formation can also act to contain the CO_2. Often these configurations resemble an upside-down bowl.

Residual Phase Trapping – At a basic level, reservoir rock acts like a tight, rigid sponge. Prior to injection, the pores of the rocks are filled with saline water and, in some cases, hydrocarbons. As injected supercritical CO_2 moves through the pores, some of the fluid is left behind as residual droplets in the pore spaces and will be effectively stuck and not able to move even under high pressure.

Dissolution Trapping – Just as sugar dissolves in water, some of the CO_2 will dissolve into saltwater in the pore spaces. Because the water with dissolved CO_2 is denser than the surrounding water, it will sink to the bottom of the formation and be held in place by the less dense fluids above.

Mineral Trapping – The last stage of CO_2 trapping involves the chemical reaction between the dissolved CO_2 in the formation fluids with the minerals in the target formation and cap rock to form new solid carbonate minerals, thus effectively locking the CO_2 in place.



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

Enhanced Oil Recovery

Enhanced oil recovery could increase domestic oil production by

25%

in two decades.

CO_2 Gets the Oil Out

Most oil is extracted in three distinct phases: primary, secondary, and tertiary (or enhanced) recovery. Primary and secondary recovery operations often leave more than two-thirds of the oil in the reservoir. Injecting CO_2 into the reservoirs through a process called enhanced oil recovery (EOR) can recover some of that remaining oil. It is estimated that EOR alone could increase U.S. domestic oil production by 25% in two decades,[20] thereby reducing the need to import as much oil.

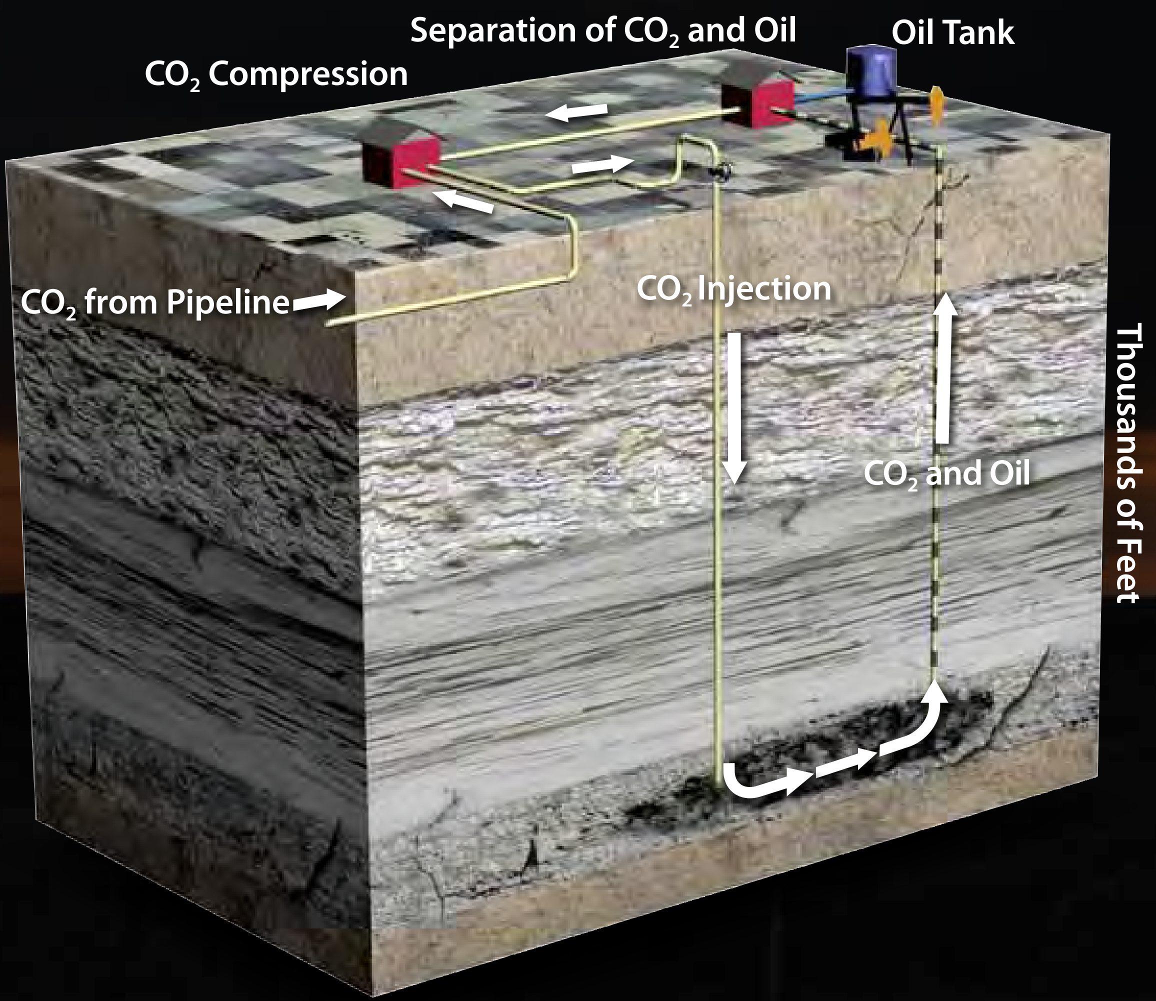
How EOR Works

When CO_2 comes into contact with oil, a significant portion dissolves into the oil, reducing oil viscosity and increasing its mobility. This, combined with the increased pressure, can result in increased oil production rates and an extension of the lifetime of the oil reservoir. However, not all reservoirs are good candidates for CO_2-based EOR. Factors such as geology, depth, and the nature of the oil itself will determine the effectiveness of CO_2 for EOR.

Naturally occurring CO_2 can be found in the subsurface in many areas, and since the 1970s, oil field operators in West Texas have safely pumped millions of tons of CO_2 underground into oil-producing formations to increase oil production. This practice continues today and has spread to other oil-producing states and provinces. These technologies have good environmental and safety track records and have helped pave the way for CCS.

Economics of EOR

Aside from non-market-based incentives, CO_2 storage in many geologic sinks is not generally economically viable under current market conditions. However, EOR is a proven, economically viable technology for CO_2 storage that can provide a bridge to future non-EOR-based geologic storage.



PCOR Partnership

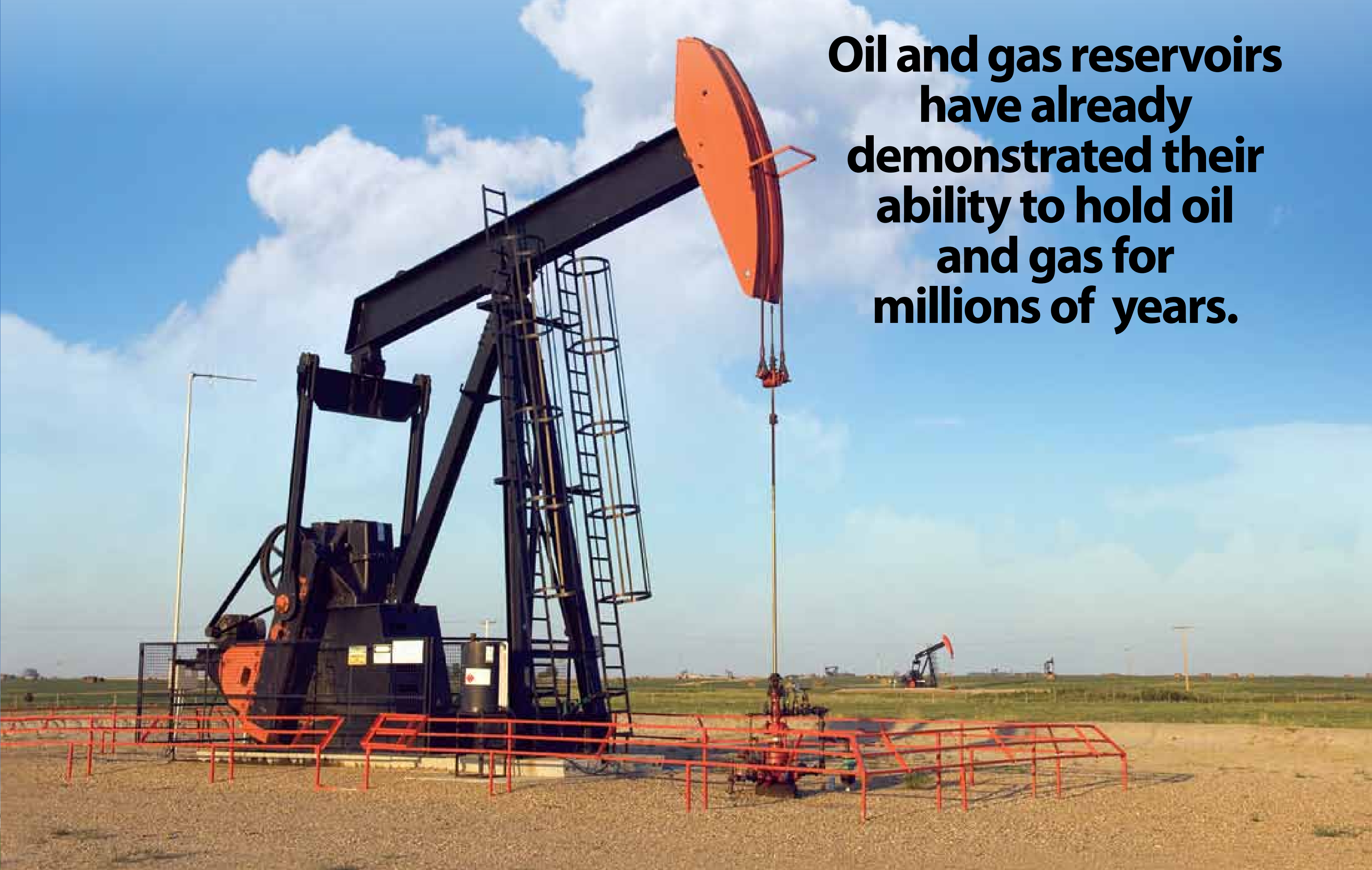
Oil Fields of the United States and Canada

CO_2 in Oil Fields

The geology of CO_2 storage is analogous to the geology of petroleum exploration: the search for oil is the search for stored hydrocarbons. Oil fields have many characteristics that make them excellent target locations to store CO_2. Therefore, the geologic conditions that are conducive to hydrocarbon accumulation are also the conditions that are conducive to CO_2 storage. The three requirements for trapping and accumulating hydrocarbons are a hydrocarbon source, a suitable reservoir, and impermeable vertical seals.

A single oil field can have multiple zones of accumulation that are commonly referred to as pools, although specific legal definitions of fields, pools, and reservoirs can vary for each state or province. Once injected into an oil field, CO_2 may be stored in a pool through dissolution into the formation fluids (oil and/or water); as a buoyant supercritical-phase CO_2 plume at the top of the reservoir (depending on the location of the injection zone within the reservoir); and/or by mineralization through geochemical reactions with CO_2, formation waters, and/or formation rock matrix.

Oil and gas reservoirs have already demonstrated their ability to hold oil and gas for millions of years.



North American Sedimentary Basins

CO_2 in Saline Formations

Sedimentary basins are relatively large areas of Earth's surface that, for various reasons, have subsided over long periods of geologic time. This subsidence allowed for the accumulation of sediments that eventually lithified into rock. Areas where the accumulation of sediment are thick enough (>2600 feet [800 m]) may have an arrangement of rock layers suitable for CO_2 storage.

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

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

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

Putting TDS Levels into Perspective

Water Source	TDS, mg/L
Lake Superior[23]	~63
Missouri River[24]	~250
Drinking Water[25]	<500*
Ocean Water[26]	35,000
Great Salt Lake[27]	50,000 to 270,000
Dead Sea[28]	350,000

* U.S. EPA secondary drinking water standard.

Salinity

The salinity of water in saline formations 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).

The U.S. Environmental Protection Agency (EPA) has ruled that CO_2 cannot be injected into geologic formations where the TDS level is less than 10,000 mg/L. This stipulation is meant to protect valuable underground sources of drinking water (USDW) which may, in the future, be used for drinking water or other municipal water uses. Many of the saline formations targeted for CO_2 storage have TDS values greater than 50,000 mg/L, and some deeper portions of sedimentary basins have TDS values near 300,000 mg/L. It should be pointed out that not all lower TDS waters are suitable groundwater resources. It is not uncommon for oil reservoirs to 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.

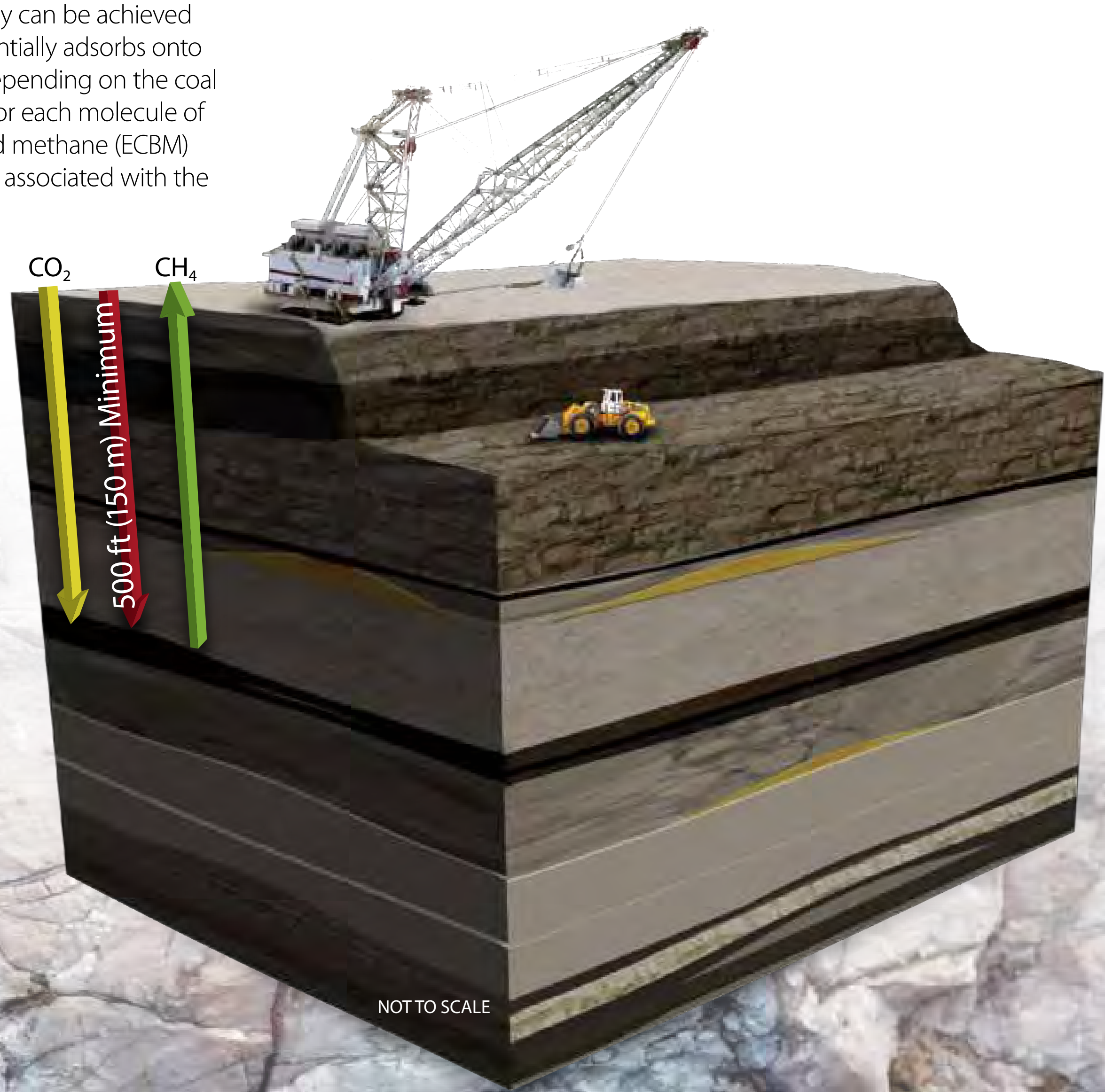
Coal Regions of the United States and Canada

CO_2 in Unminable Coal

Because of their fractured nature, coal seams have a relatively large internal surface area, and these surfaces have the capacity to accumulate large amounts of gases. Some gases, such as CO_2, have a higher affinity for the coal surfaces than others, such as nitrogen. As a result, coal seams that are too deep (generally >500 feet [150 m]) or too thin to be economically mined may prove to be viable sites for CO_2 storage. Carbon storage in unminable coal seams relies on the adsorption of CO_2 on the coal and the permeability of the coal bed. The more microstructures there are in the coal, the more surface area it has for the CO_2 to accumulate onto.

In addition to being potential sinks for CO_2 storage, many coal beds contain commercial quantities of adsorbed natural gas (methane). As with oil reservoirs, initial coalbed methane (CBM) recovery methods can leave methane in the coal seam. Additional CBM recovery can be achieved by sweeping the coal bed with CO_2, which preferentially adsorbs onto the surface of the coal, displacing the methane. Depending on the coal rank, up to 13 molecules of CO_2 can be adsorbed for each molecule of methane that is displaced.[29] This enhanced coalbed methane (ECBM) procedure could create revenue to offset the costs associated with the injection and storage of CO_2 in coal beds.

World CO_2 storage capacity in coal seams is estimated to be 40 billion tons.[30]



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

CHAPTER 3

The PCOR Partnership

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

DOE's Regional Carbon Sequestration Partnerships

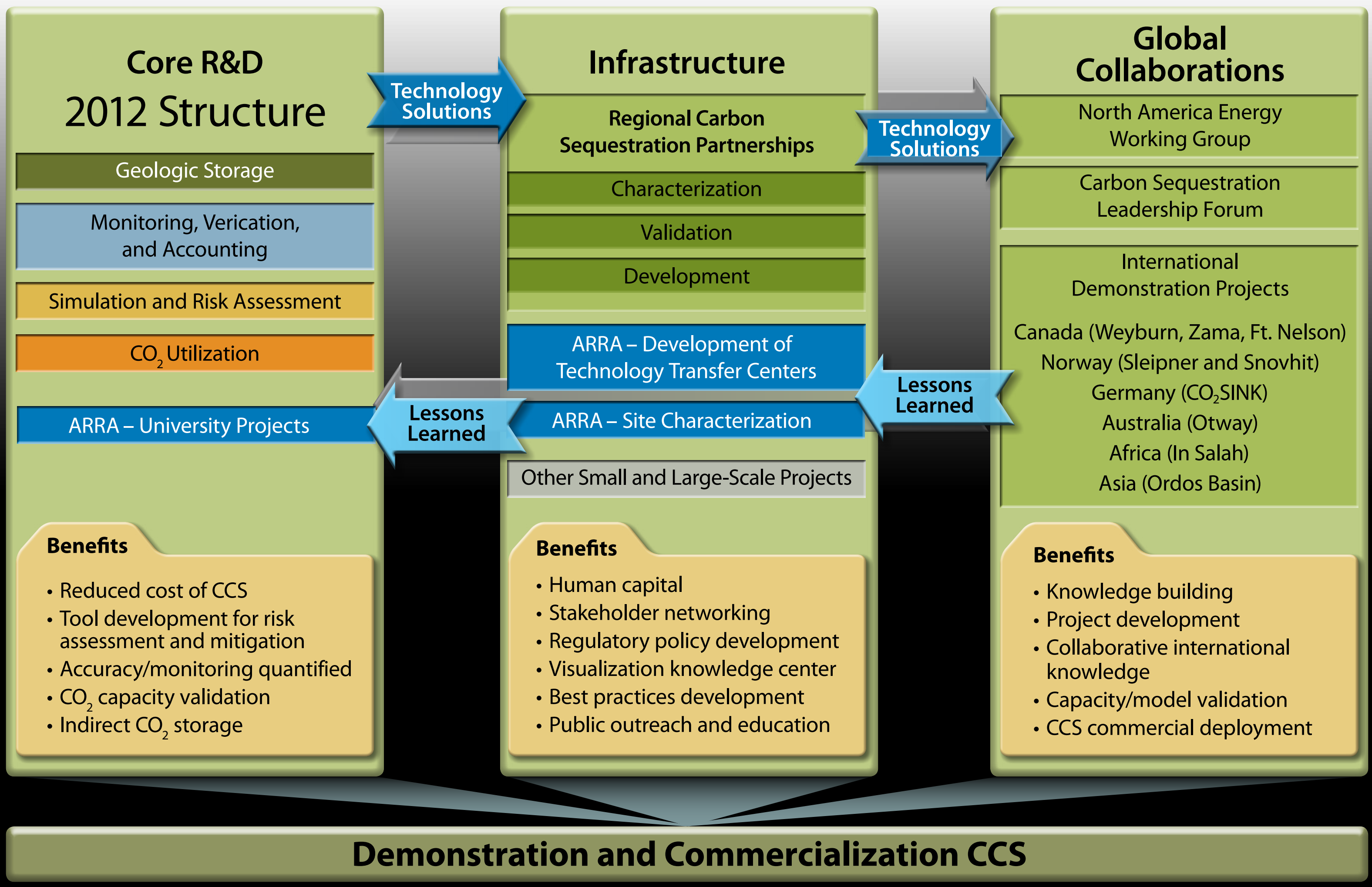
If the decision is made that carbon storage must be implemented in the United States on a broad scale over the next 10–20 years, it will take a concerted effort. Federal and state agencies will need to work in cooperation with technology developers, regulators, and others to put into place the economic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

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

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

U.S. Department of Energy • Office of Fossil Energy
National Energy Technology Laboratory

Carbon Sequestration Program with ARRA* Projects



* American Recovery and Reinvestment Act.

Image adapted from DOE NETL RCSP Program.

PCOR Partnership Region

The PCOR Partnership is managed by the Energy & Environmental Research Center (EERC) in Grand Forks, North Dakota.

The PCOR Partnership region covers over 1.4 million square miles in the central interior of North America and includes all or part of nine U.S. states and four Canadian provinces.

PCOR Partnership Activities

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

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

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

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

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

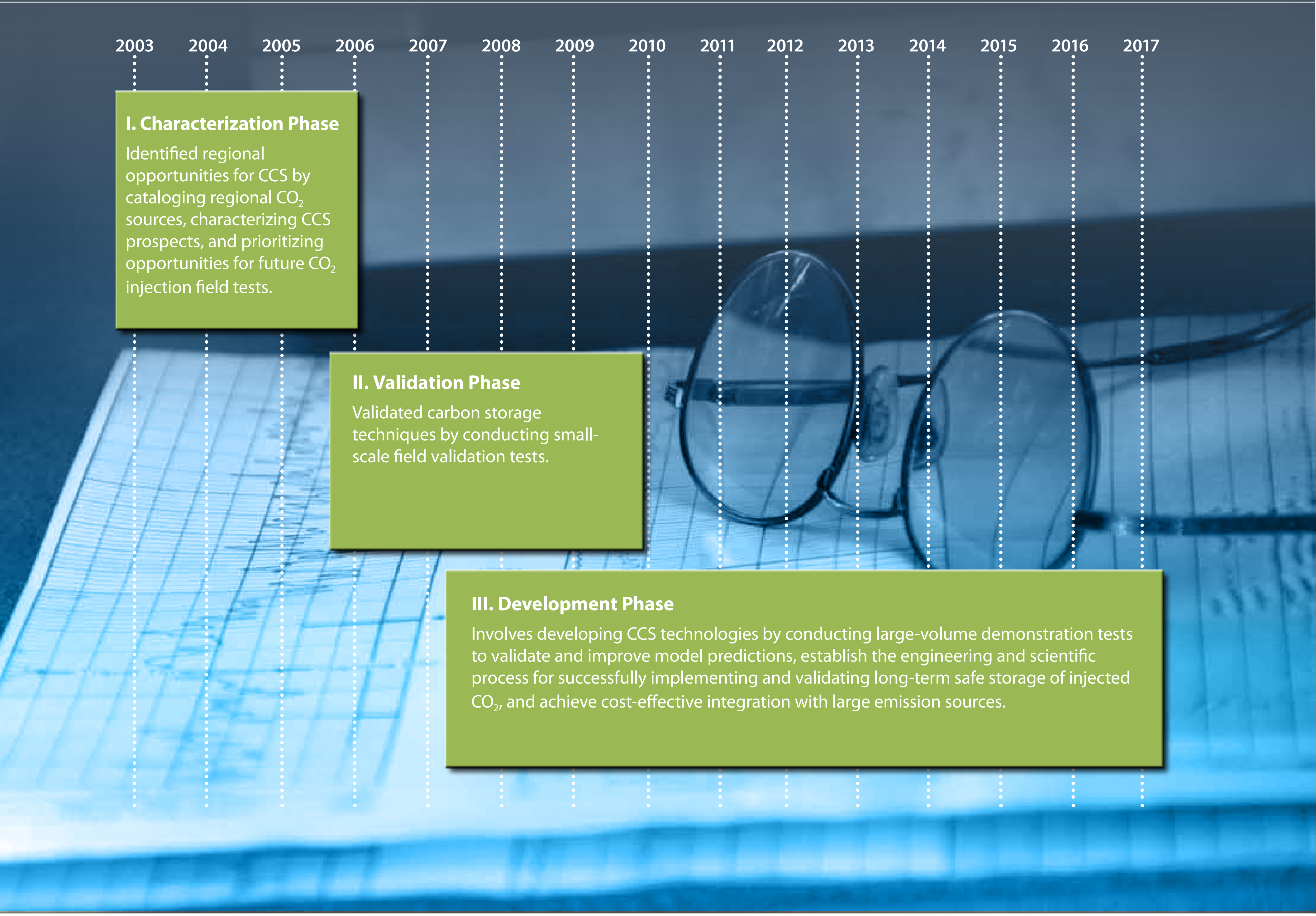
Operational Monitoring and Modeling – The PCOR Partnership develops data sets for large-volume CO_2 injection tests that 1) verify that injection operations do not adversely impact human health or the environment and 2) account for the storage of injected CO_2 for the purpose of developing an understanding of the process for monetizing carbon credits.

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

Project Phases

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

Fiscal Year (October 1 – September 30)



I. Characterization Phase

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

II. Validation Phase

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

III. Development Phase

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

Regional Vision

The PCOR Partnership has developed a regional vision for the widespread commercial development of CCS which includes several key elements:

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

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

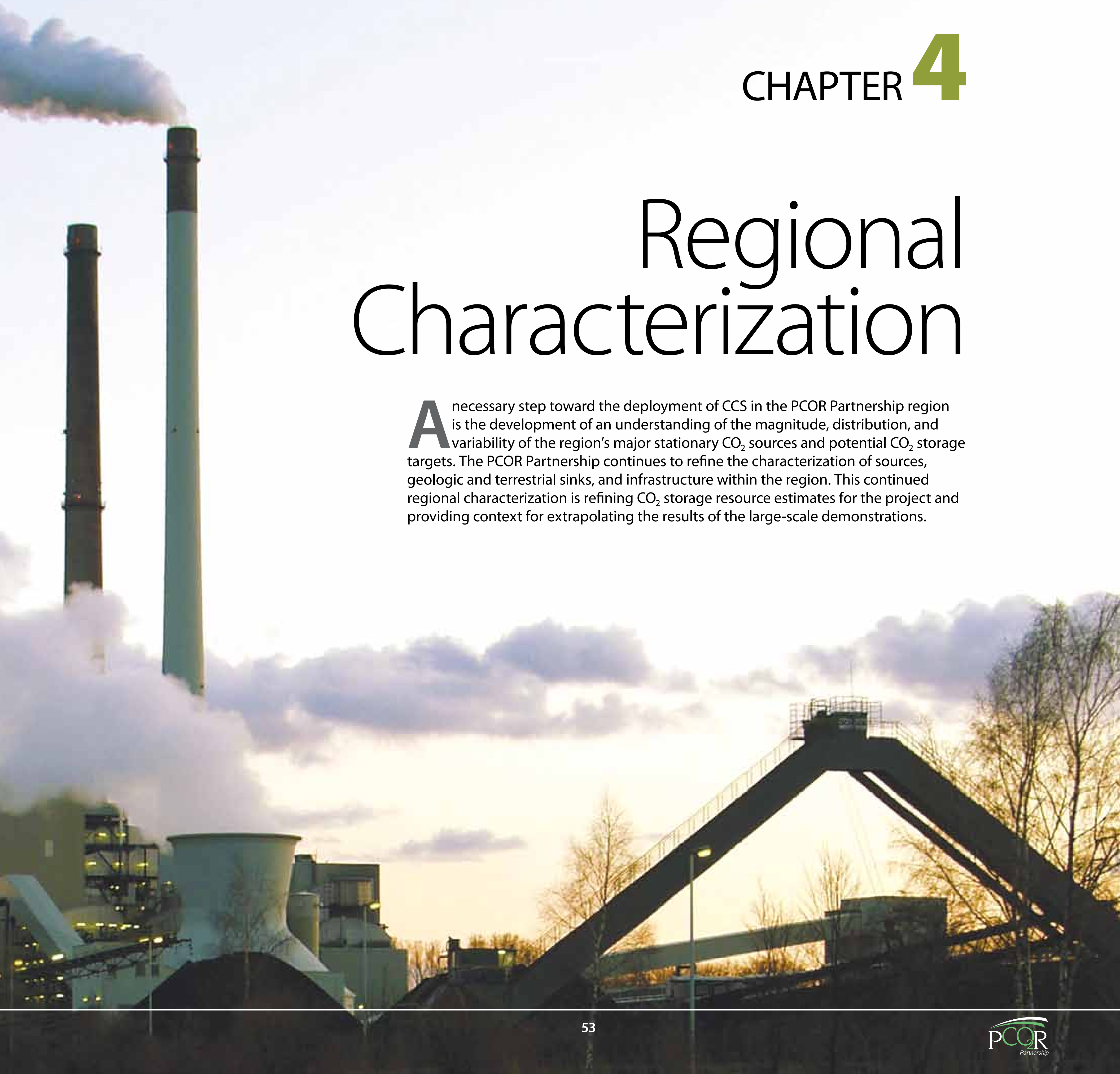
PCOR Partnership Partners

PCOR Partnership 2003 – Present

- U.S. Department of Energy / NETL
- EERC Energy & Environmental Research Center, Putting Research into Practice / UND The University of North Dakota
- Abengoa Bioenergy
- Air Products
- Alberta Energy
- AERI Alberta Energy Research Institute
- Alberta Innovates Technology Futures
- ALLETE
- Ameren
- ACCCE American Coalition for Clean Coal Electricity
- American Lignite Energy
- Apache Canada Ltd.
- Aquistore
- Baker Hughes
- Basin Electric Power Cooperative
- Bechtel
- Biorecro
- Blue Source
- BNI Coal
- BC Oil & Gas Commission
- C12 Energy
- CCX Chicago Climate Exchange
- CMG
- Dakota Gasification Company
- Denbury
- Ducks Unlimited Canada, Conserving Canada's Wetlands
- Ducks Unlimited
- British Columbia, The Best Place on Earth, Ministry of Energy, Mines and Petroleum Resources
- Eagle Operating Inc.
- EICCD
- Enbridge
- Encore Acquisition Company
- ERCB Energy Resources Conservation Board
- AGS Alberta Geological Survey
- Environment Canada
- Excelsior Energy
- Fischer Oil and Gas, Inc.
- Great Northern
- Great River Energy
- Halliburton
- Hess
- Huntsman
- Husky Energy
- Indian Land Tenure Foundation
- Interstate Oil & Gas Compact Commission
- DNR
- Kiewit
- Lignite Energy Council
- Manitoba
- Manitoba Hydro
- Marathon
- MEG Energy
- Melzer Consulting
- Minnesota Pollution Control Agency
- minnesota power
- Minnkota Power Cooperative, Inc.
- Missouri Department of Natural Resources
- Missouri River Energy Services
- Montana-Dakota Utilities Co.
- Montana Department of Environmental Quality
- Murex Petroleum Corporation
- National Commission on Energy Policy
- Natural Resources Canada
- Nebraska Public Power District, Always there when you need us
- Nexant
- North American Coal Corporation
- North Dakota Department of Commerce, Office of Renewable Energy and Energy Efficiency
- North Dakota Department of Health
- North Dakota Geological Survey
- North Dakota Oil and Gas Division
- Industrial Commission of North Dakota Lignite Research, Development and Marketing Program
- Industrial Commission of North Dakota Oil and Gas Research Council
- North Dakota Natural Resources Trust
- North Dakota Petroleum Council
- NDSU North Dakota State University
- Otter Tail Power Company
- Oxand Risk Management Solutions
- PTRC Petroleum Technology Research Centre
- PTTC Technology Connections
- Pinnacle, A Halliburton Service
- Prairie Public
- Pratt & Whitney, A United Technologies Company
- Praxair, Making our planet more productive
- Ramgen Power Systems
- RPS Energy
- Saskatchewan Ministry of Energy and Resources
- SaskPower
- Schlumberger Carbon Services
- Shell Canada Limited
- Spectra Energy
- Strategic West Energy Ltd.
- Suncor Energy
- TAQA
- Tesoro
- TGS
- University of Alberta
- University of Regina
- USGS, science for a changing world
- Weatherford
- Advanced Geotechnology
- Western Governors' Association
- Westmoreland Coal Company
- Williston Basin Interstate Pipeline Company
- Wisconsin Department of Agriculture, Trade & Consumer Protection
- Wyoming Office of State Lands and Investments
- Xcel Energy

Since its inception in 2003, the PCOR Partnership has brought together more than 100 public and private sector stakeholders with vast expertise in power generation, energy exploration and production, geology, engineering, the environment, agriculture, forestry, and economics. Partners are the backbone of the PCOR Partnership and provide data, guidance, financial resources, and practical experience with CCS and terrestrial sequestration.

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

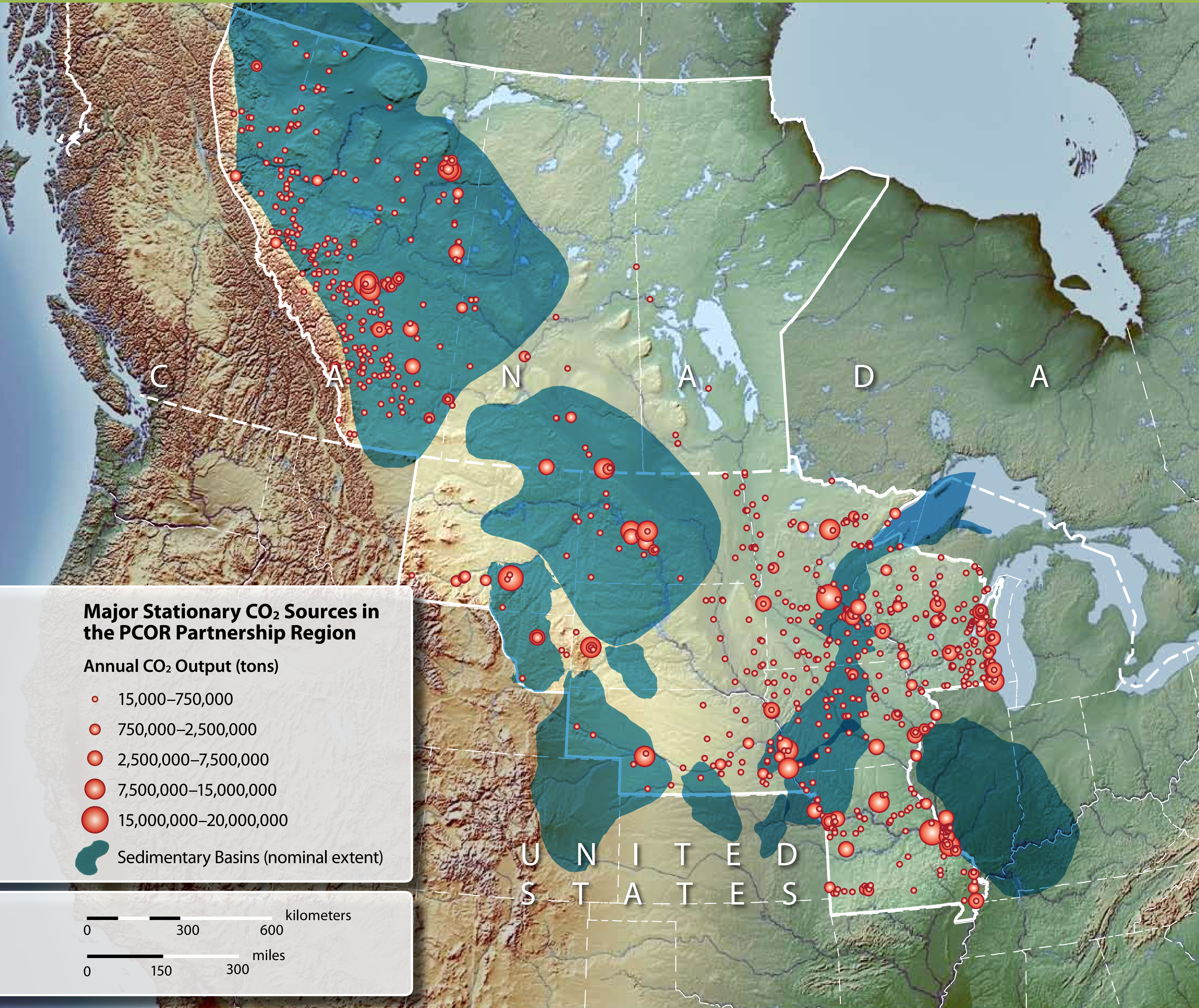


CHAPTER 4

Regional Characterization

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

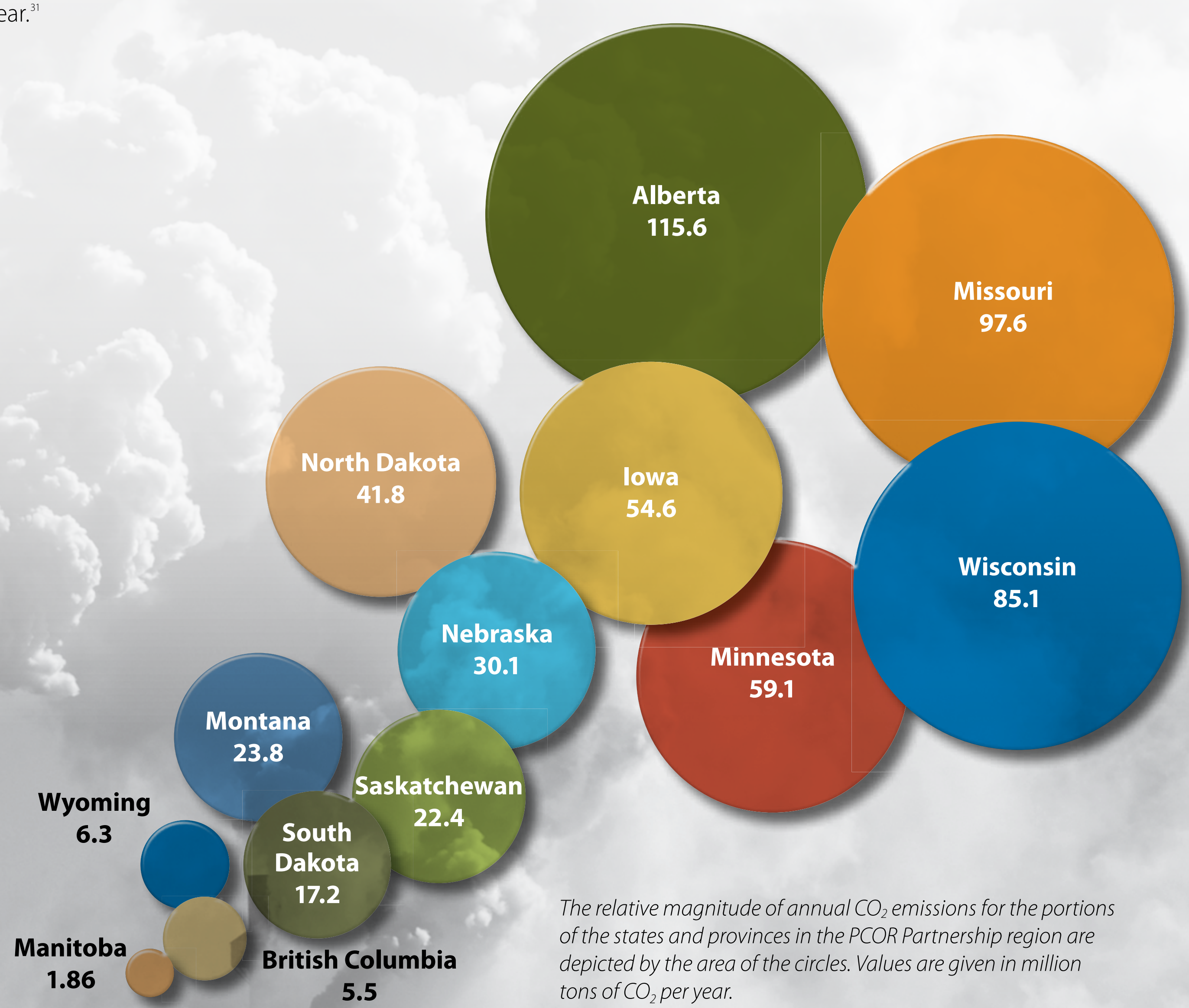
Distribution of Major Stationary CO_2 Sources



CO_2 Sources

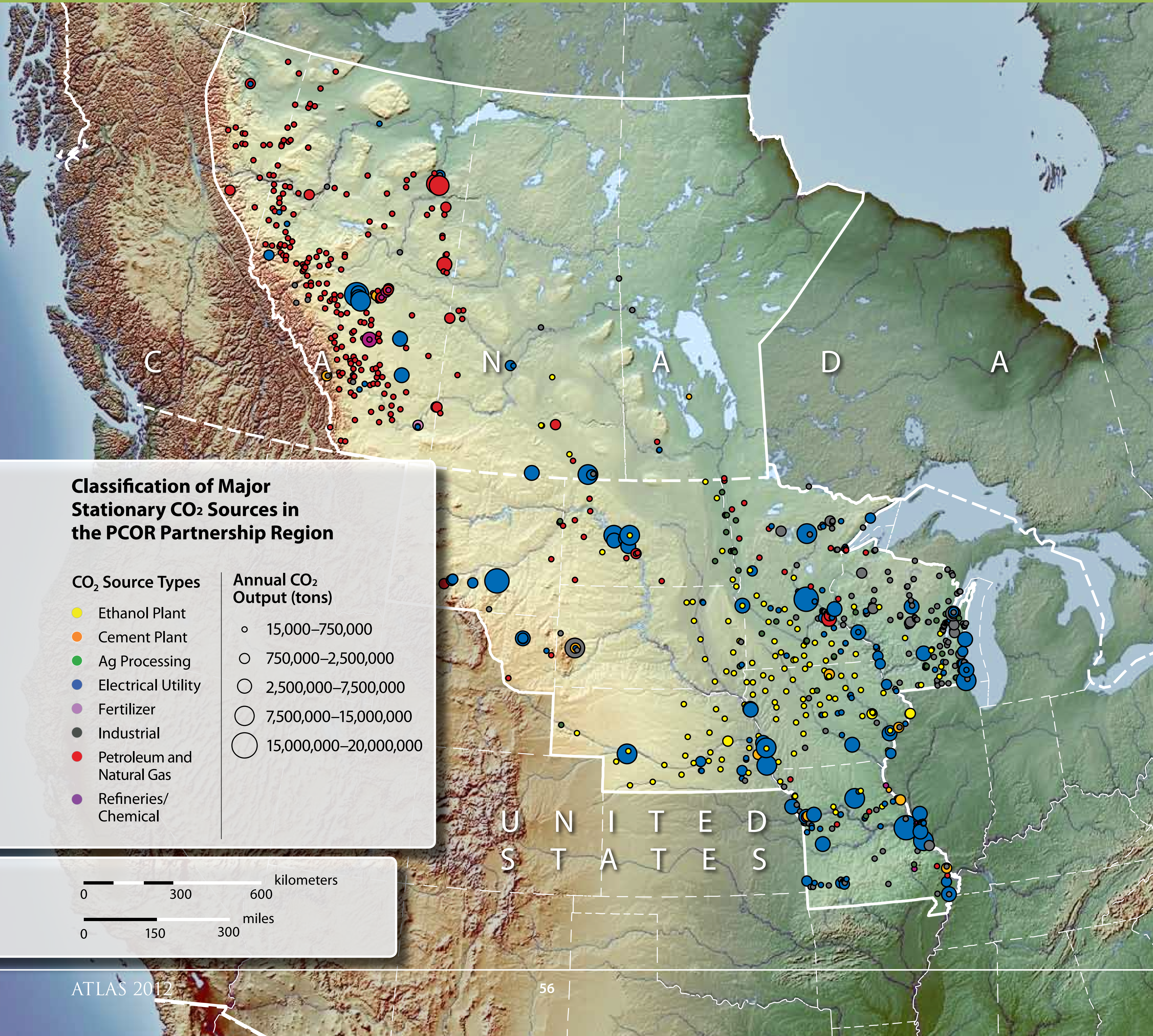
The PCOR Partnership has identified, quantified, and categorized 963 stationary sources in the region that have an annual output of greater than 15,000 tons (13,600 tonnes) of CO_2. These stationary sources have a combined annual CO_2 output of nearly 593 million tons (510 tonnes) or 9.7 trillion cubic feet (275 billion m^3). Although not a target source of CO_2 for geologic storage, the transportation sector in the U.S. portion of the PCOR Partnership region contributes nearly 188 million additional tons (170 tonnes) of CO_2 to the atmosphere every year.[31]

The annual output from the various large stationary sources ranges from under 100,000 tons for industrial and agricultural processing facilities that make up the majority of the sources in the region, up to nearly 18 million tons for the largest coal-fired electric generation facility. Fortunately, many of the large point sources are located in areas that are favorable for CO_2 storage because of their concurrence with deep sedimentary basins, such as those areas in Alberta, North Dakota, Montana, and Wyoming.



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

Classification of Major Stationary CO_2 Sources

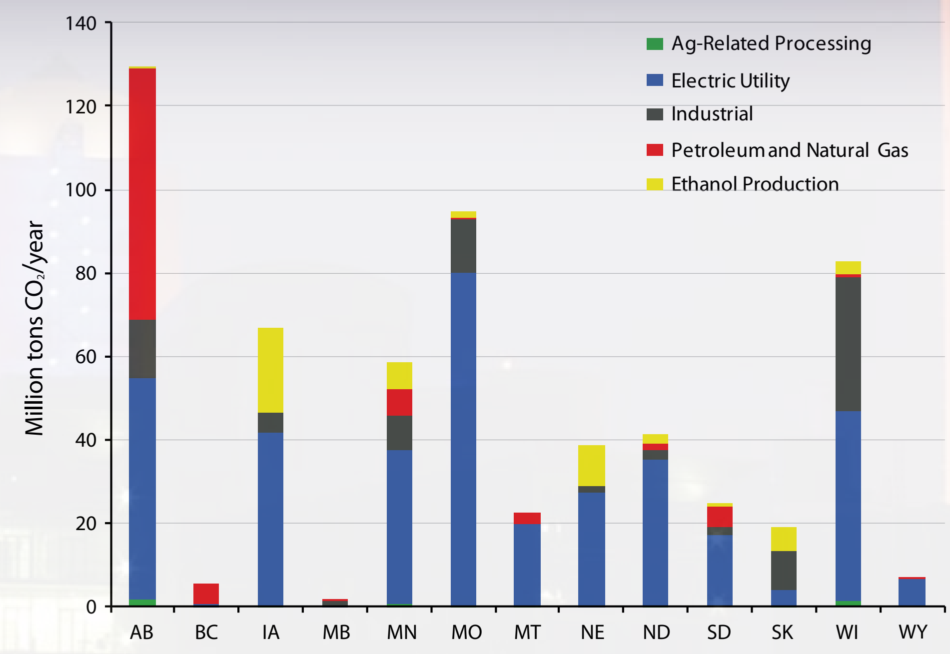


CO_2 Sources by Type

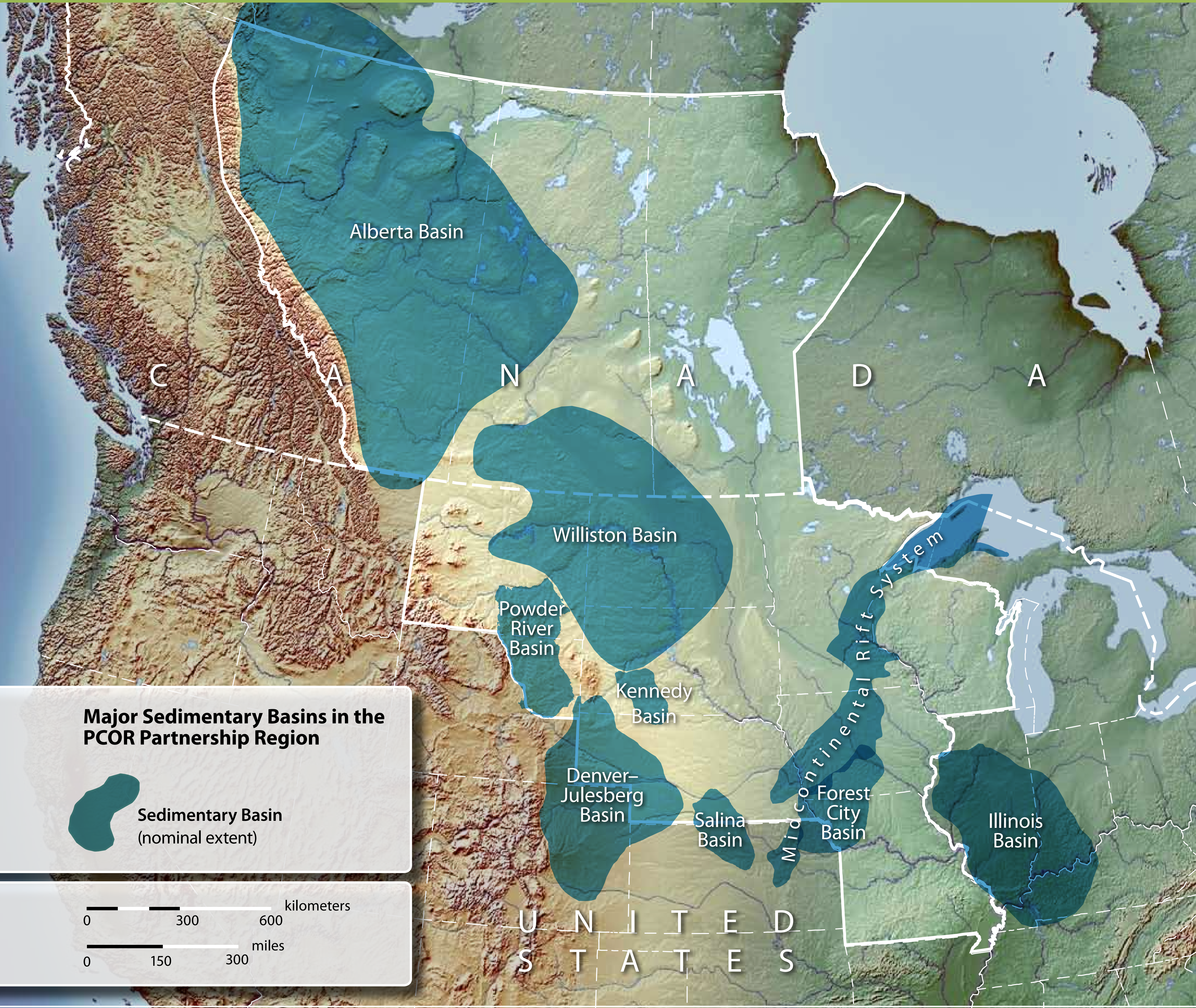
The geographic and socioeconomic diversity of the PCOR Partnership region is reflected in the diversity of the carbon dioxide sources found there. CO_2 is emitted from electricity generation; energy exploration and production activities; agricultural processing; fuel, chemical, and ethanol production; and various manufacturing and industrial activities. The majority of the region's emissions from stationary sources come from just a few source types. About two-thirds of the CO_2 is emitted during electricity generation. Additional significant emissions come from industrial sources, petroleum refining and natural gas processing, ethanol production, and agricultural processing.

The emission profile (i.e., the percentage of CO_2 emissions from all the various source types) for the Canadian portion of the PCOR Partnership is virtually identical to that of Canada as a whole. When compared to the total U.S. CO_2 emissions, the states in the PCOR Partnership region emit relatively more CO_2 from electric utilities and less from industries and transportation.

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



Major Regional Sedimentary Basins



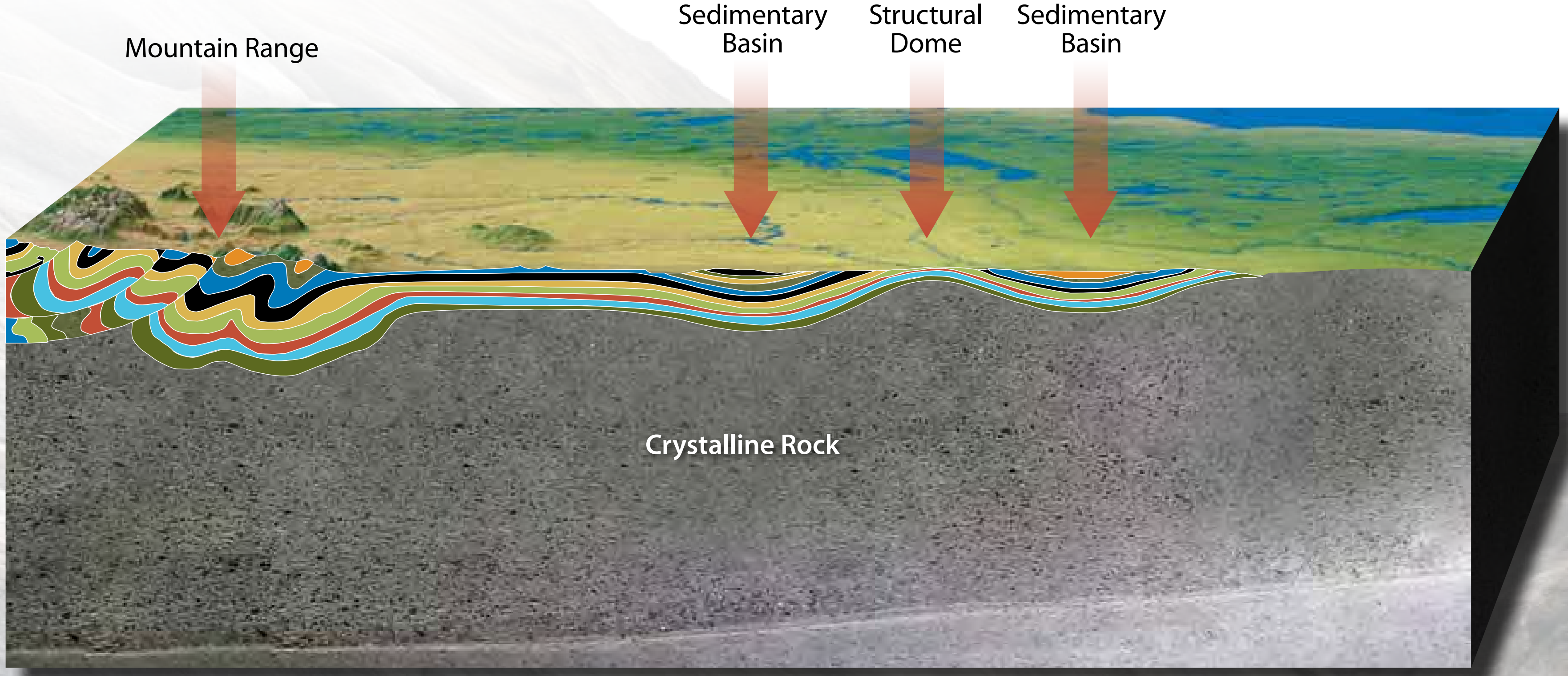
CO_2 Storage Opportunities

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

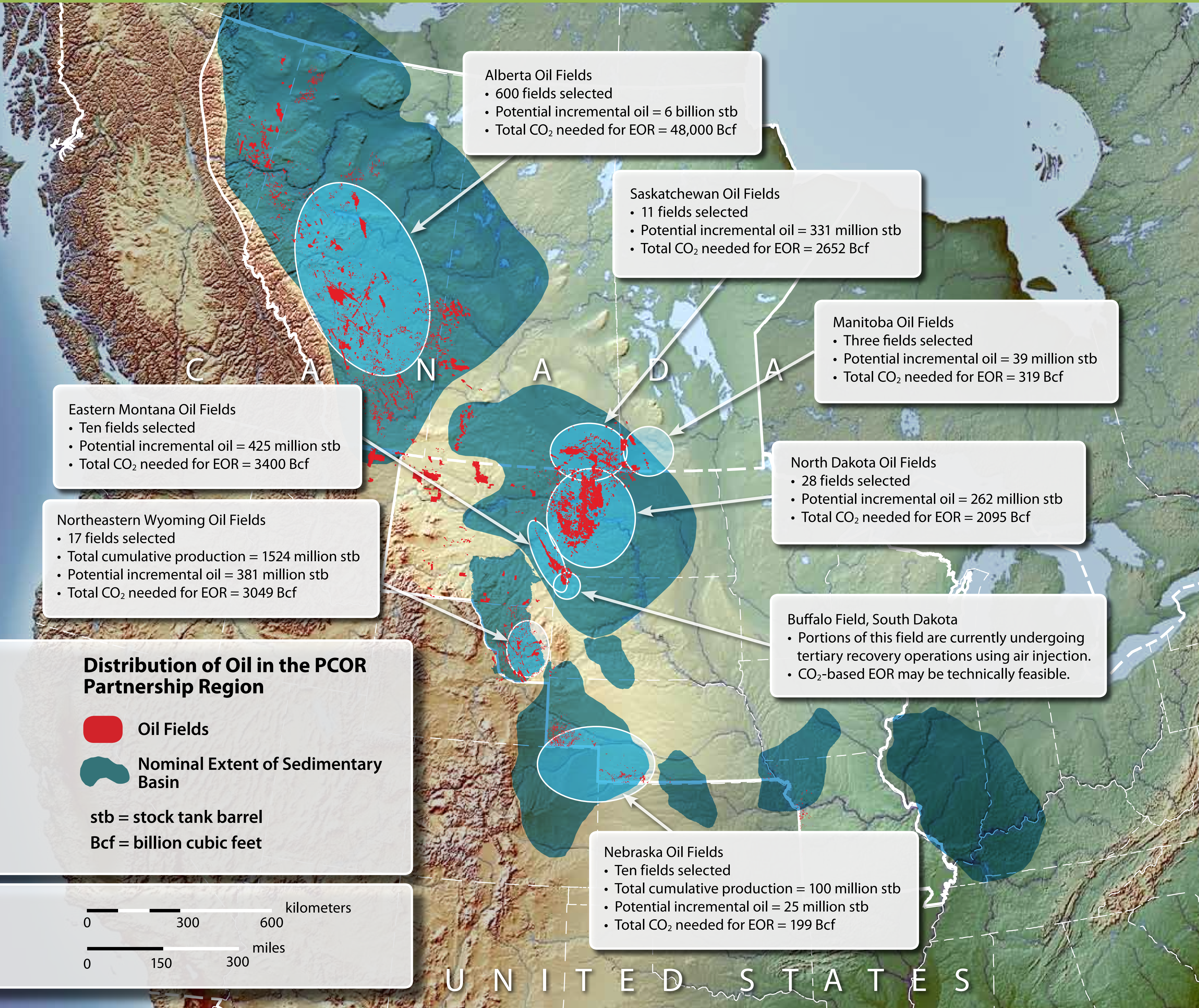
Midcontinental Rift System

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 Midcontinental 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 Midcontinental Rift System has a low probability for CO_2 storage.[32]



Enhanced Oil Recovery Potential



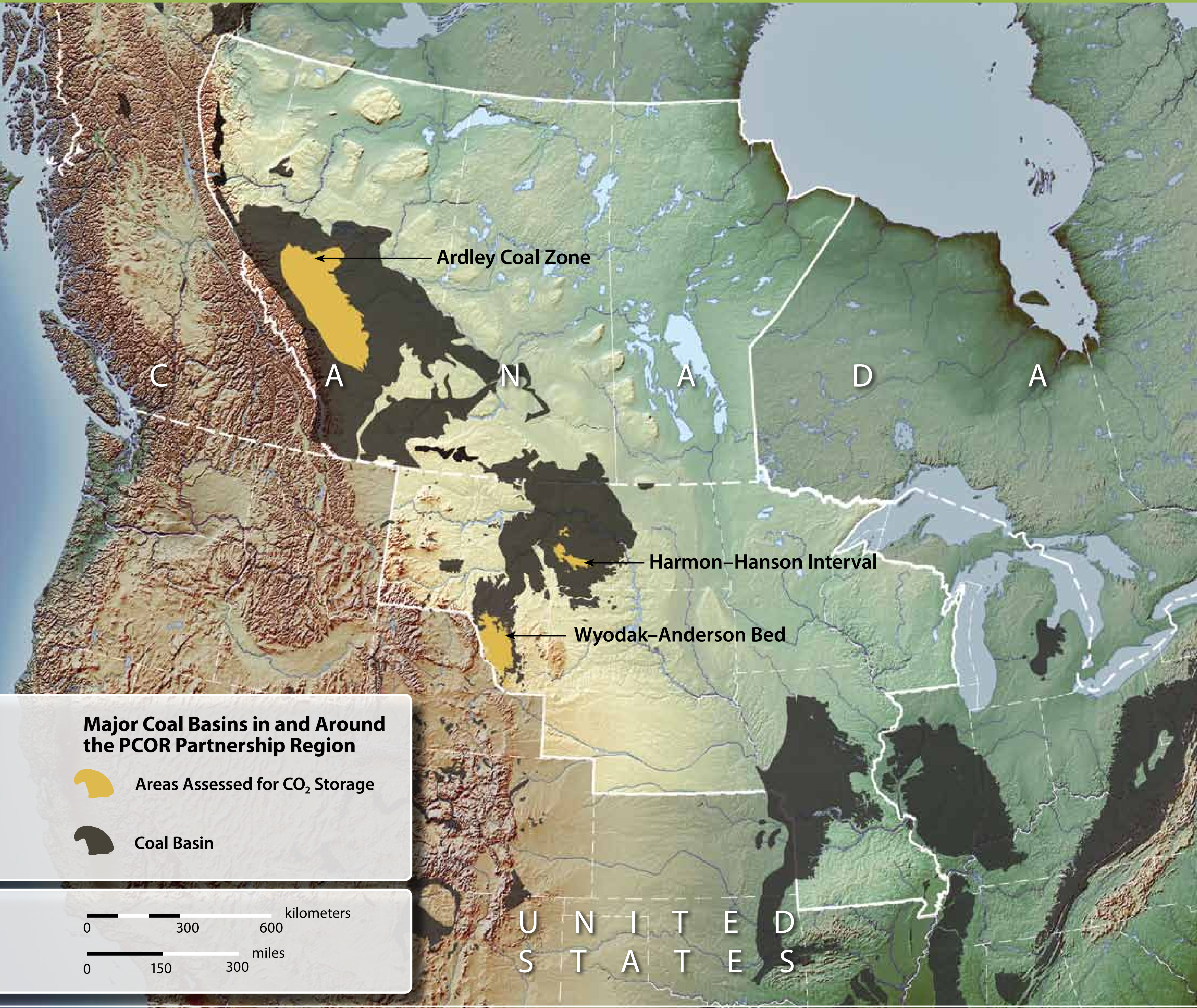
CO_2 Storage in Oil and Gas Fields

Although oil was discovered in the PCOR Partnership region in the late 1800s, significant development and exploration did not begin until the late 1920s. The body of knowledge gained in the nearly 90 years of exploration and production of hydrocarbons in this region is a significant step toward understanding the mechanisms for secure storage of significant amounts of CO_2. Today, oil is drawn from the many oil fields in the PCOR Partnership region from depths ranging from 200 to 4000 feet (60 to 1220 m) to 12,000 to 16,000 feet (3600 to 4900 m).

Reconnaissance-level CO_2 storage capacities were estimated for selected oil fields in the Williston, Powder River, Denver–Julesberg, and Alberta Basins. Two 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 storage capacity of over 3.5 billion tons (3.2 billion tonnes) of CO_2 with a cummulative incremental oil recovery of over 7 billion stb.

Regionally, over 3.5 billion tons of CO_2 storage potential in oil and gas fields and 7 billion bbl of incremental oil.

Major Coal Basins



CO_2 Storage in Unminable Coal

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

Three deep major coal horizons in the PCOR Partnership region have been characterized with respect to CO_2 storage: the Wyodak–Anderson bed in the Powder River Basin, the Harmon–Hanson interval in the Williston Basin, and the Ardley coal zone in the Alberta Basin. The total maximum CO_2 storage resource potential for all three coal deposits is approximately 8 billion tons (7.3 billion tonnes).[33–35]

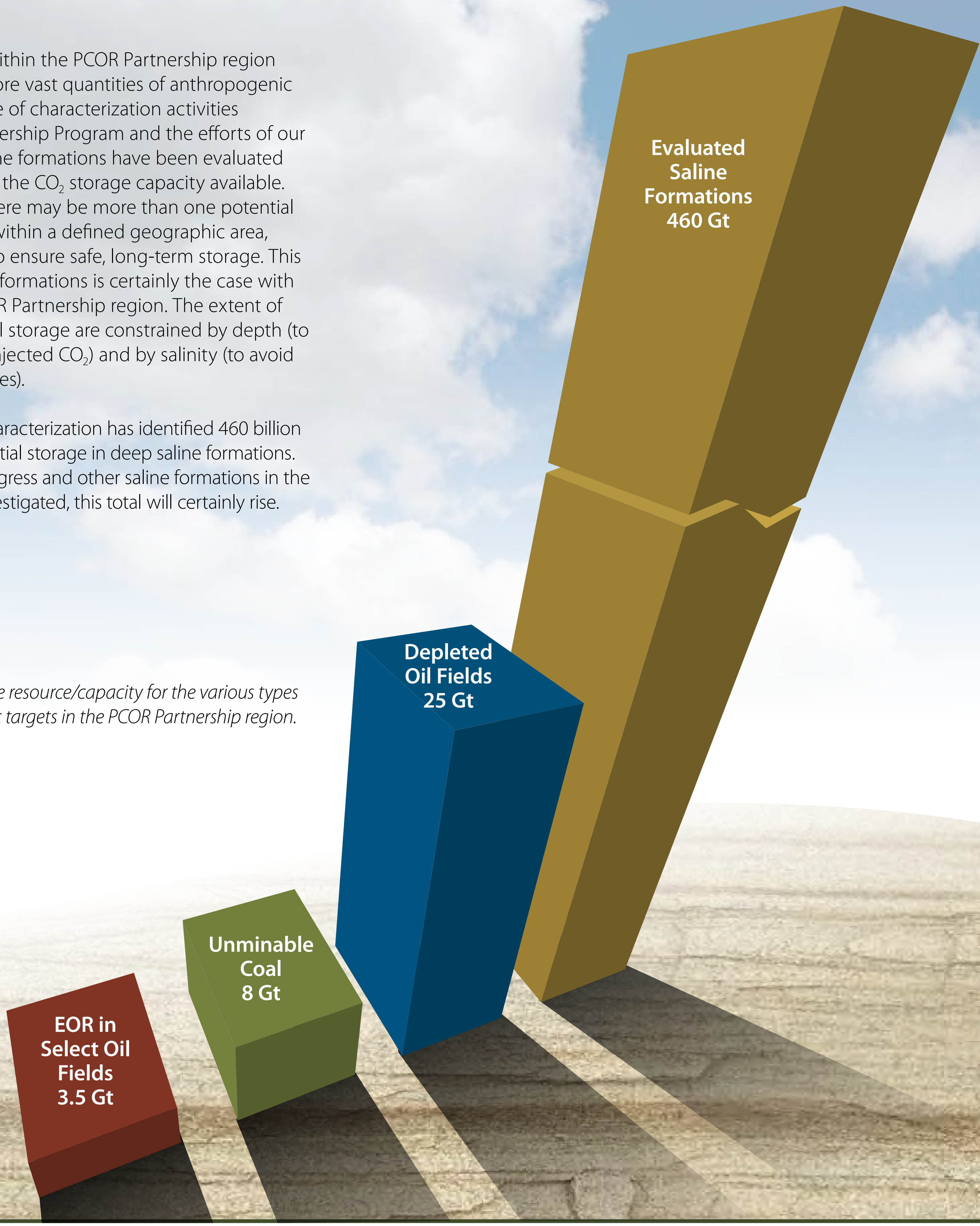
In the Powder River Basin area of northeastern Wyoming, the CO_2 storage potential for the areas where the coal overburden thickness is >1000 feet (300 m) could store all of the current annual CO_2 emissions from nearby power plants for about the next 150 years.[35]

Evaluated Suitable Saline Formations

CO_2 Storage in Saline Formations

Deep saline formations within the PCOR Partnership region have the potential to store vast quantities of anthropogenic CO_2. Through the course of characterization activities associated with the PCOR Partnership Program and the efforts of our partners in Canada, several saline formations have been evaluated to determine the magnitude of the CO_2 storage capacity available. In many sedimentary basins, there may be more than one potential target horizon for CO_2 storage 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 areas identified for potential storage are constrained by depth (to ensure optimal density of the injected CO_2) and by salinity (to avoid protected groundwater resources).

To date, reconnaissance-level characterization has identified 460 billion tons (417 billion tonnes) 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.



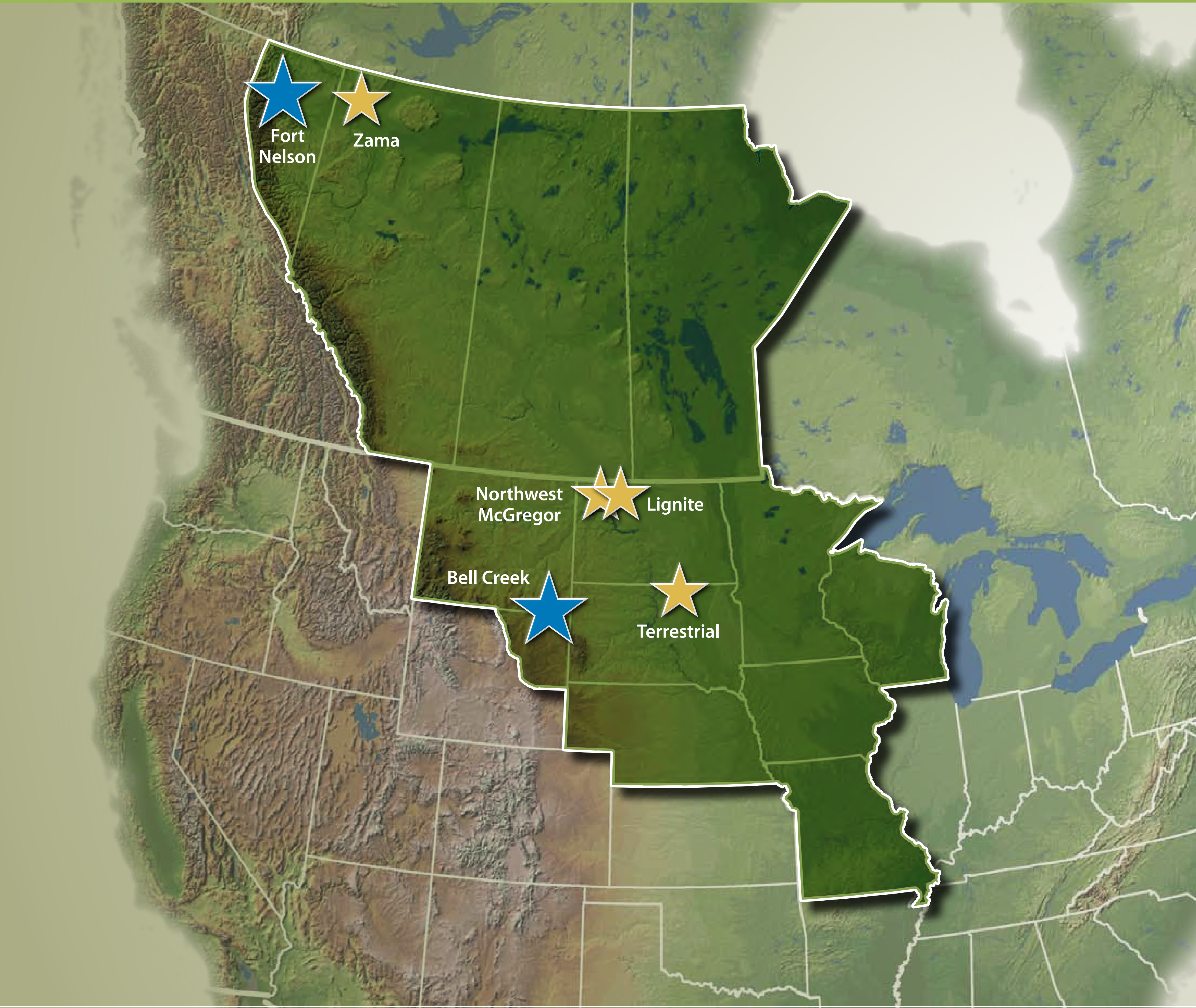
CO_2 storage resource/capacity for the various types of geologic targets in the PCOR Partnership region.

CHAPTER 5

Field-Based Activities

Experts agree it may take decades to implement the full range of options under consideration to effectively manage CO_2 released from human activity. Billions of tons of CO_2 may require long-term storage, and the PCOR Partnership region has significant capacity for long-term CO_2 storage. As a result, the PCOR Partnership is developing and has carried out a variety of field projects to demonstrate and optimize practical and environmentally sound geologic CO_2 storage and terrestrial sequestration in the region.

Demonstrating CCS



CCS in Action

The PCOR Partnership is working to demonstrate and optimize practical and environmentally sound CO_2 storage in the region. From 2005 to 2009, the PCOR Partnership conducted four field validation projects that demonstrated the effectiveness of CO_2 storage in different settings and under varying conditions. Currently, the PCOR Partnership is working on two commercial-scale, long-term demonstration projects to demonstrate that the CO_2 storage sites have the potential to store regional CO_2 emissions safely, permanently, and economically.

Phase II Field Scale

Zama Field Validation Test

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

Lignite Field Validation Test

Investigated the ability of unminable lignite seams to act as sinks for CO_2 during simultaneous CO_2 storage and ECBM production.

Northwest McGregor Field Validation Test

Evaluated the potential for geologic storage of CO_2 in a deep carbonate reservoir for the dual purpose of CO_2 storage and EOR at depths greater than 8000 feet (2440 m).

Terrestrial Field Validation Test

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

Phase III Commercial Scale

Fort Nelson Demonstration

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

Bell Creek Demonstration

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

Prairie Pothole Region

The Prairie Pothole Region (PPR) is a major biogeographical region that encompasses approximately 347,000 mi² (222 million acres [900,000 km²]).[37] This region accounts for up to 70% of wild duck production in North America[38] 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 terrestrially storing CO_2 at multiple sites located in the PPR.

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

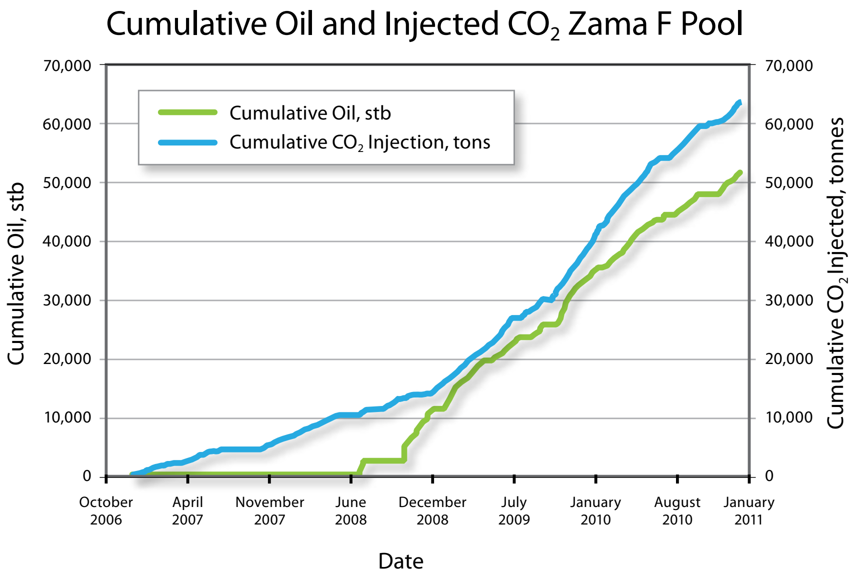
As part of this project, soil and gas samples were collected from restored grasslands, native prairie, cropland, and wetlands of various age from throughout the PPR. In addition to carbon uptake and storage measurements, CH_4 and N_2O gas fluxes were measured to estimate the net GHG flux of each management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

The project also demonstrated that restoration of previously farmed wetlands results in the rapid replenishment of soil organic carbon lost to cultivation at an average rate of 1.1 tons per acre per year (0.4 tonnes per hectare per year).[39] 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 300,000 acres (1200 km^2). Oil production in the Zama Field is primarily from reservoirs in pinnacle reefs. To date, over 800 pinnacles have been discovered in the Zama subbasin, with an average size of about 40 acres (0.16 km^2) at the base and about 400 ft (120 m) high.

CO_2-Rich Gas in a Pinnacle Reef Structure



Over 72,000 tons (65,000 tonnes) of acid gas has been utilized for EOR operations, resulting in an additional 52,000 barrels of oil production. While 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.

In October 2005, the Zama oil field became the site of acid gas (approximately 70% CO_2 and 30% H_2S [hydrogen sulfide]) injection for the simultaneous purpose of EOR, H_2S disposal, and CO_2 storage. Injection took place at a depth of 5000 feet (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. Prior to this project, the CO_2 portion of the acid gas was vented to the atmosphere, and sulfur was separated from the H_2S and stockpiled in solid form on-site. This project enabled the simultaneous beneficial use of each of these materials to produce more oil and reduce GHG emissions.

MVA

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

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

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

carbon sequestration leadership forum

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

Lignite Field Validation Test

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

CO_2 in an Unminable Lignite Seam

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

CO_2 Injection

Approximately 90 tons of CO_2 was injected over roughly a 2-week period into a 10–12-foot (3–4-m)-thick coal seam at a depth of 1100 feet (335 m). CO_2 injection was accomplished using a single injection well, which was surrounded by four monitoring wells. These monitoring wells employed various technologies to track the presence and movement of CO_2 in the lignite coal seam.

MVA

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

Results

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

Northwest McGregor Field Validation Test

Williston Basin oil fields may have over 500 million tons of CO_2 storage resources with potential EOR operations. Oil is produced from at least a dozen rock formations at depths ranging from less than 3000 feet (1000 m) to greater than 14,000 feet (4300 m). This field validation test evaluated the effectiveness of CO_2 for EOR and storage using huff 'n' puff techniques at depths greater than 8000 feet (2440 m) into a fractured carbonate reservoir.

CO_2 in a Deep Oil Reservoir

The PCOR Partnership, working closely with Eagle Operating, Inc. (Eagle), conducted field, laboratory, and modeling activities to determine the effects of injecting CO_2 into a carbonate formation in the Northwest McGregor oil field in North Dakota. The activities evaluated the potential dual purpose of CO_2 storage and EOR in carbonate rocks deeper than 8000 feet (2440 m). A technical team that included Eagle, the EERC, Praxair, and Schlumberger Carbon Services conducted a variety of activities to inject CO_2 into the target oil reservoir using a huff 'n' puff approach and evaluated the effect that injected CO_2 has on the ability of the oil reservoir to store CO_2 and produce incremental oil.

Huff 'n' Puff

A CO_2 huff 'n' puff test was conducted for a well producing oil from a formation at a depth of approximately 8050 feet (2450 m) in the Northwest McGregor oil field. As an initial pilot-scale test, 440 tons (400 tonnes) of CO_2 was injected into a single well and allowed to "soak" for several weeks (the huff). The well was then placed back into production, and the amount of incremental petroleum fluids produced was measured (the puff).

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

Results

Overall, the results of the field demonstration indicate that:

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

Commercial-Scale Demonstrations

In 2007, the PCOR Partnership entered into the Development Phase scheduled to be conducted until 2017. 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.

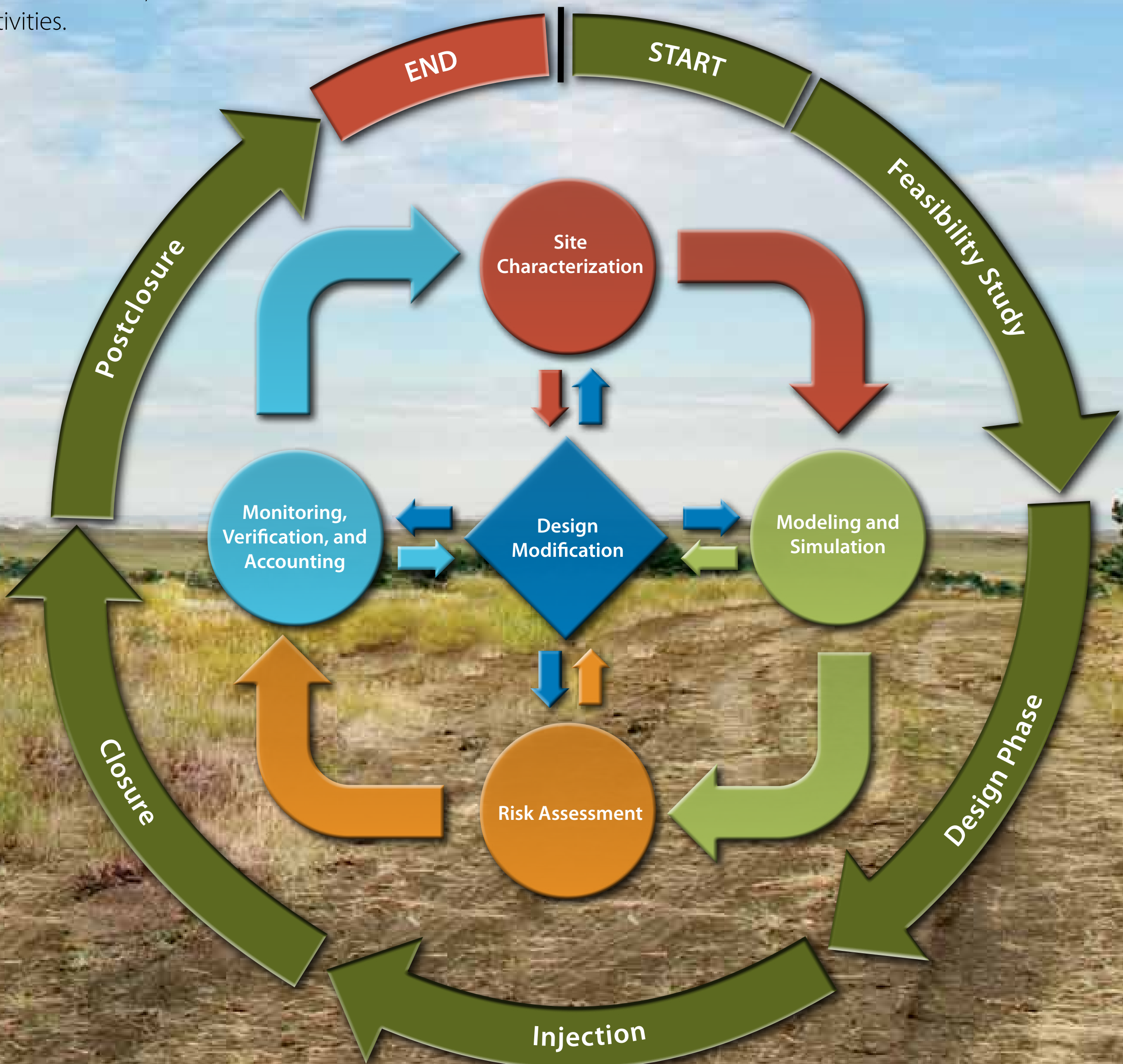
Each of the RCSP large-volume demonstration projects tests is designed to demonstrate that the CO_2 storage sites have the potential to store regionally significant quantities of CO_2 emissions safely, permanently, and economically. Results from these efforts will provide the foundation for CCS technology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

Through its role in the RCSP Development Phase, the PCOR Partnership has teamed with industrial partners to conduct two commercial-scale CCS demonstrations in the region. One of the large-scale tests will demonstrate CO_2 storage in a saline formation, while the other will be a combined CCS and EOR demonstration project. The sources of CO_2 in both demonstrations are natural gas-processing facilities. The sources of CO_2 in both demonstrations are natural gas-processing facilities, with injections starting as early as 2013. Across the country, other RCSPs have begun or are planning commercial-scale demonstrations.

Denbury Onshore, LLC (Denbury), is currently preparing the Bell Creek oil field for CO_2 injection operations. As part of the field reactivation, all the pump jacks are being taken down and replaced by simple wellheads. Artificial lift will be used until the phase is developed and CO_2 injection begins. Ultimately, no pump jacks will be needed as the current plan is to use the injection of CO_2 and water to build up reservoir pressure to a point where the production wells will flow with no additional pumping.

Philosophy of Approach

The PCOR Partnership is developing a philosophy that integrates site characterization, modeling and simulation, risk assessment, and MVA strategies into an iterative process to produce meaningful results for large-scale CO_2 storage projects. Elements of any of these activities are crucial for understanding or developing the other activities. For example, as new knowledge is gained from site characterization, it reduces a given amount of 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.



Monitoring, Verification, and Accounting

MVA capabilities are critical to ensuring the long-term viability of CCS: satisfying both technical and regulatory requirements. MVA is applicable to both terrestrial and geologic CO_2 storage. Terrestrial MVA must overcome difficulties in assessing carbon storage in large ecosystems (such as forests) and in gauging carbon storage potential in various types of soils. Geologic MVA strategies are required through all phases of CO_2 storage, including capture and separation, transportation, injection, and long-term storage. MVA provides reasonable assurance that CO_2 will stay where it was intended.

The implementation of MVA serves to:

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

MVA Techniques

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

Fort Nelson Demonstration 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 nearly 460 Gt of CO_2 capacity resource currently estimated in regional saline formations.

Geologic Storage of Sour CO_2

Led by Spectra Energy Transmission (SET), the Fort Nelson CCS Feasibility Project, an international collaboration which includes industry, government, universities, and technologists, has initiated potentially the largest application of deep saline geologic storage in North America. The project aims to reduce CO_2 emissions from SET's Fort Nelson natural gas-processing plant by injecting approximately 2.4 million tons (2.2 million tonnes) of CO_2 annually into a deep carbonate formation for long-term geologic storage.

The Fort Nelson CCS Feasibility Project provides a unique opportunity to develop a set of cost-effective, risk-based monitoring techniques for large-scale storage of sour CO_2 in deep saline formations. An approach is being used that integrates site characterization, modeling and simulation, risk assessment, and MVA into an iterative process. Elements of any of these activities are crucial for understanding and developing the other activities. The lessons learned and best practices employed will provide the data, information, and knowledge needed to develop similar CCS projects across the region.

Status

The PCOR Partnership's role in the Fort Nelson CCS project will run from 2007 to 2017. The injection site was chosen in 2008, and the drilling for the exploration well and shallow groundwater-monitoring wells was completed in the spring of 2009. Large-scale injection is planned to begin in 2016, and SET intends to continue injection of sour CO_2 over the remaining operational lifetime of the Fort Nelson gas-processing plant which is estimated to be more than 25 years. An MVA plan will be implemented to monitor the underground movement of CO_2. The MVA data may also be used to modify and improve the injection design, if needed. A comprehensive report will be issued at the completion of the project.

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

Bell Creek Demonstration Project

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

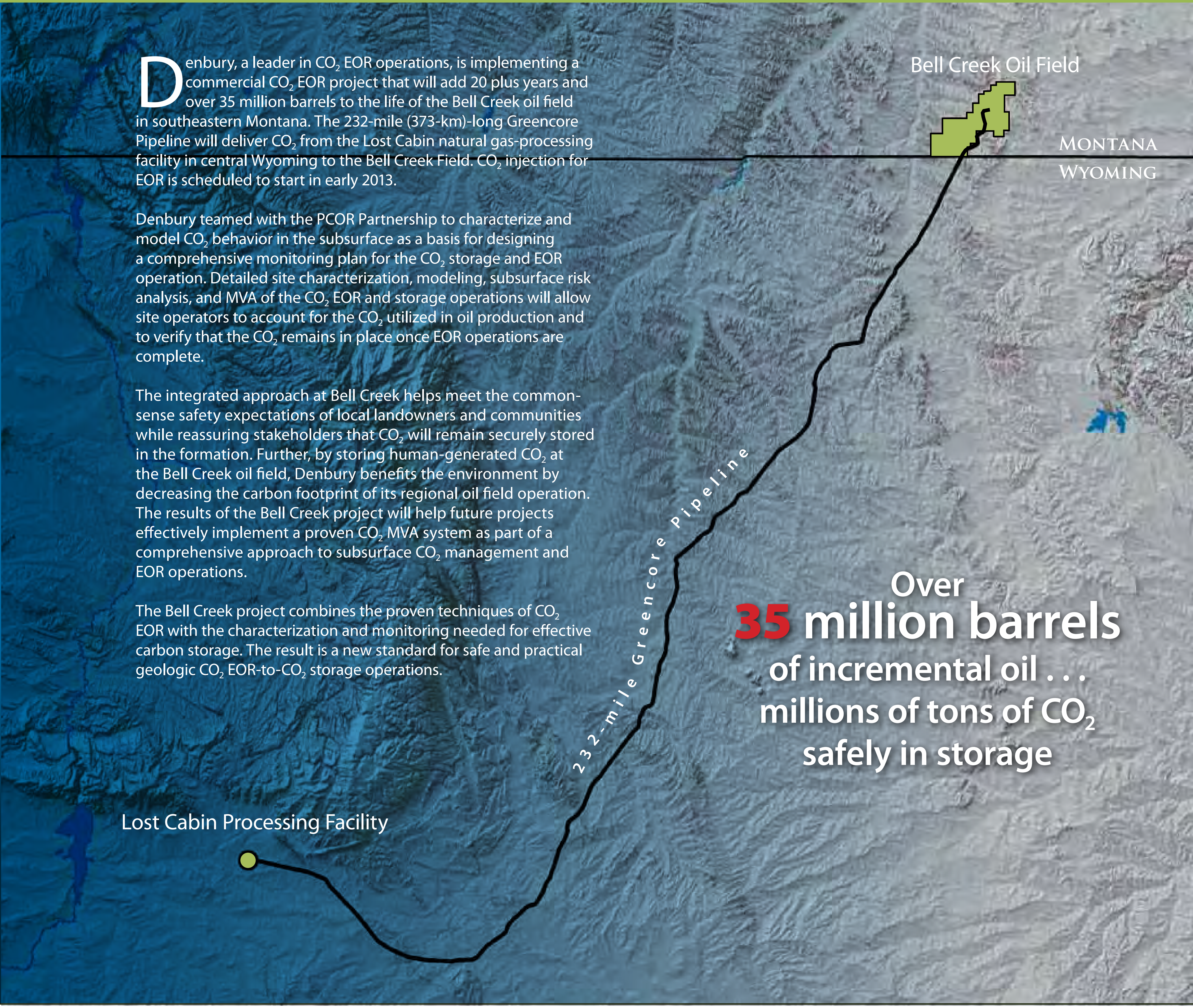
CO_2 Injection for Enhanced Oil Recovery

Denbury, a leader in CO_2 EOR operations, is implementing a commercial CO_2 EOR project that will add 20 plus years and over 35 million barrels to the life of the Bell Creek oil field in southeastern Montana. The 232-mile (373-km)-long Greencore Pipeline will deliver CO_2 from the Lost Cabin natural gas-processing facility in central Wyoming to the Bell Creek Field. CO_2 injection for EOR is scheduled to start in early 2013.

Denbury teamed with the PCOR Partnership to characterize and model CO_2 behavior in the subsurface as a basis for designing a comprehensive monitoring plan for the CO_2 storage and EOR operation. Detailed site characterization, modeling, subsurface risk analysis, and MVA of the CO_2 EOR and storage operations will allow site operators to account for the CO_2 utilized in oil production and to verify that the CO_2 remains in place once EOR operations are complete.

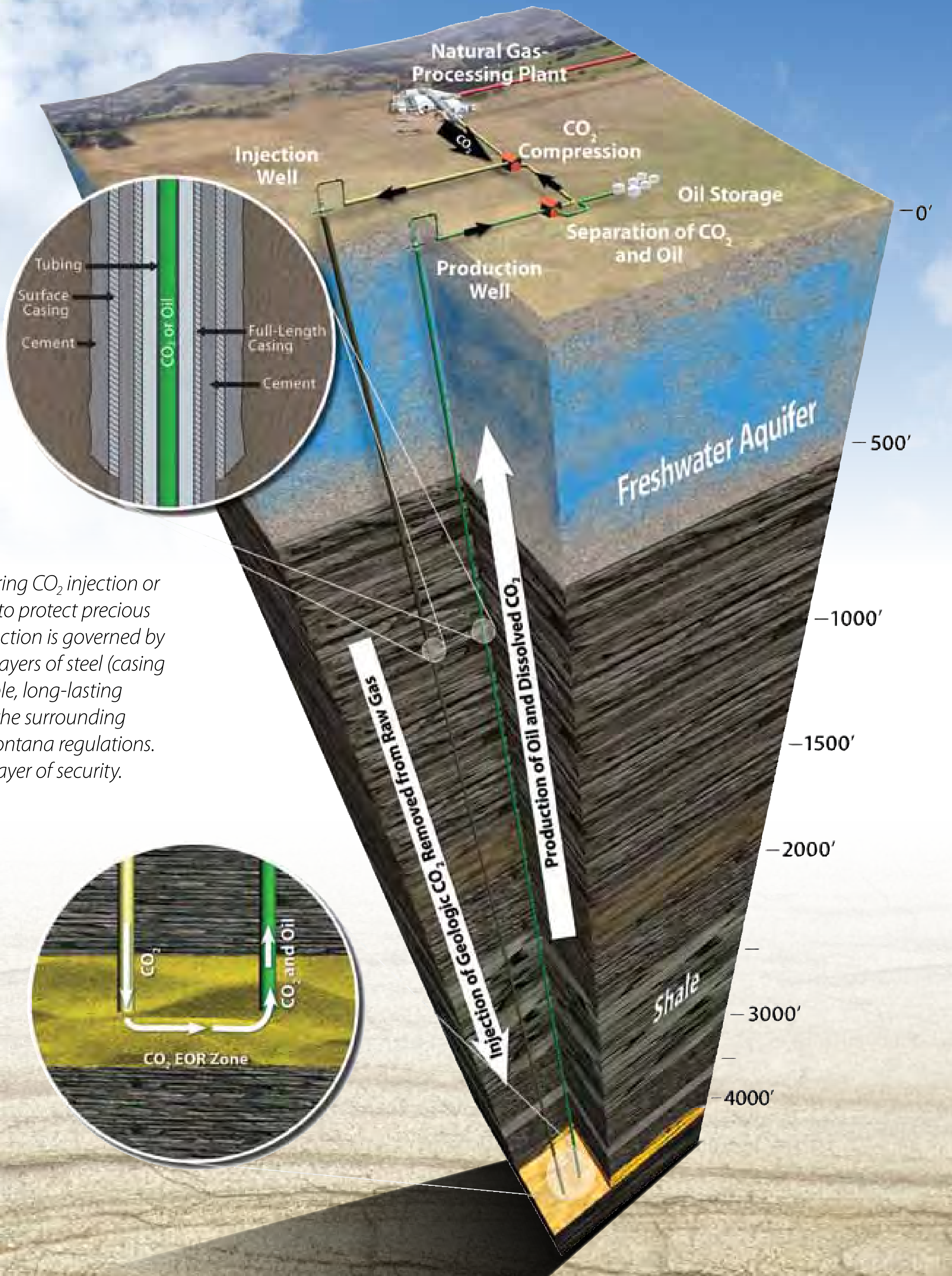
The integrated approach at Bell Creek helps meet the common-sense safety expectations of local landowners and communities while reassuring stakeholders that CO_2 will remain securely stored in the formation. Further, by storing human-generated CO_2 at the Bell Creek oil field, Denbury benefits the environment by decreasing the carbon footprint of its regional oil field operation. The results of the Bell Creek project will help future projects effectively implement a proven CO_2 MVA system as part of a comprehensive approach to subsurface CO_2 management and EOR operations.

The Bell Creek project combines the proven techniques of CO_2 EOR with the characterization and monitoring needed for effective carbon storage. The result is a new standard for safe and practical geologic CO_2 EOR-to-CO_2 storage operations.



Over 35 million barrels of incremental oil . . . millions of tons of CO_2 safely in storage

Bell Creek – Layers of Security



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

Bell Creek – Monitoring

Monitoring of the surface, near-surface, and deep subsurface environment is an essential component of any carbon storage project.

The purpose of surface and near-surface monitoring is twofold: 1) to establish preinjection conditions for naturally occurring CO_2 levels in surface water, soil, and shallow groundwater aquifers in the vicinity of the carbon storage formation and 2) to provide a source of data to show that surface and near-surface environments remain unaffected by the injection process throughout the life of the project.

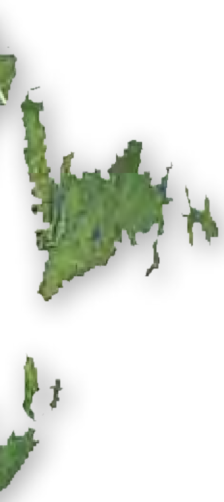
The primary purpose of deep subsurface monitoring is to track the movement of CO_2 in the subsurface in order to evaluate the CO_2 storage efficiency of the CO_2 EOR program and to predict and understand the ultimate fate of CO_2 within the storage reservoir.

A combination of permanent downhole monitoring equipment (pressure gauges and fiber optic cable capable of measuring the temperature profile of the wellbore), time-lapse well logs, seismic 4-D surveys, and wellhead pressure and flow rate sensors will be utilized to provide key information about reservoir behavior and subsurface CO_2 migration and saturations during and after injection.

These same instruments will also provide a check to ensure the injection process is behaving as predicted and allow for real-time detection of anomalies in order to ensure optimal CO_2 storage and oil recovery in a safe and efficient manner.

Demonstrating CCS Throughout the Region

The PCOR Partnership region in central North America has geologic characteristics that make it ideal for CCS. 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. Weyburn–Midale Project[40]

Projected Size: 44 million tons (40 million tonnes) of CO_2 storage and at least 122 million barrels of incremental oil production
Start Date: 2000
CO_2 is captured from the Dakota Gasification Company's Great Plains Synfuels Plant in Beulah, North Dakota, United States, and piped 205 miles into the Weyburn and Midale oil fields in Saskatchewan, Canada, for EOR.

2. The Aquistore Project[41]

Projected Size: Injection could reach 1760 tons (1600 tonnes) of CO_2 a day
Start Date: 2013
CO_2 will likely be obtained from the Boundary Dam Integrated CCS Demonstration Project in Canada and be piped 3 to 6 miles to a deep saline formation in the Williston Basin.

3. Heartland Area Redwater Project (HARP)[42]

Projected Size: >1.1 million tons (1 million tonnes) of CO_2 a year and produce 10,000–15,000 barrels of oil a day
Start Date: 2015
CO_2 produced from the Alberta Industrial Heartland region, Canada's largest hydrocarbon-processing region, will be stored in the saline aquifer portion of the Redwater Leduc Reef.

4. Quest CCS Project[43]

Projected Size: 1.1 million tons (1 million tonnes) of CO_2 a year
Start Date: 2015
CO_2 from Shell's Scotford Upgrader near Edmonton, Alberta, Canada, which processes heavy oil from the Athabasca oil sands, will be transported by pipeline to an injection location north of Shell Scotford.

5. The Swan Hills In Situ Coal Gasification (ISCG)/Sagitawah Power Project[44]

Projected Size: 1.4 million tons (1.3 million tonnes) of CO_2 a year
Start Date: 2015
The project will convert underground coal into a synthetic gas via ISCG at a new power generation facility located near Whitecourt, Alberta, Canada. The captured CO_2 created during the process will be used for EOR in the Swan Hills area.

6. The Boundary Dam Integrated CCS Demonstration Project[45]

Projected Size: 1.1 million tons (1 million tonnes) a year of GHG emission reductions
Start Date: 2014
This SaskPower project will rebuild a coal-fired generation unit at the Boundary Dam Power Station in Estevan, Saskatchewan, Canada, and equip it with a fully integrated carbon capture system, allowing for the capture of CO_2 for EOR.

CO_2 Capture at Great Plains Synfuels Plant

The CO_2 used in the Weyburn–Midale project comes from the Dakota Gasification Company's Great Plains Synfuels Plant, the only commercial-scale coal gasification plant in the United States that manufactures natural gas. Today, the synfuels plant exports about 152 million cubic feet (4.3 million m^3) a day of CO_2 to Canada—about 50% of the CO_2 produced when running at full rates. This is more CO_2 than any other EOR project in the world! As of December 31, 2010, the synfuels plant had captured more than 22 million tons (20 million tonnes) of CO_2.[46]

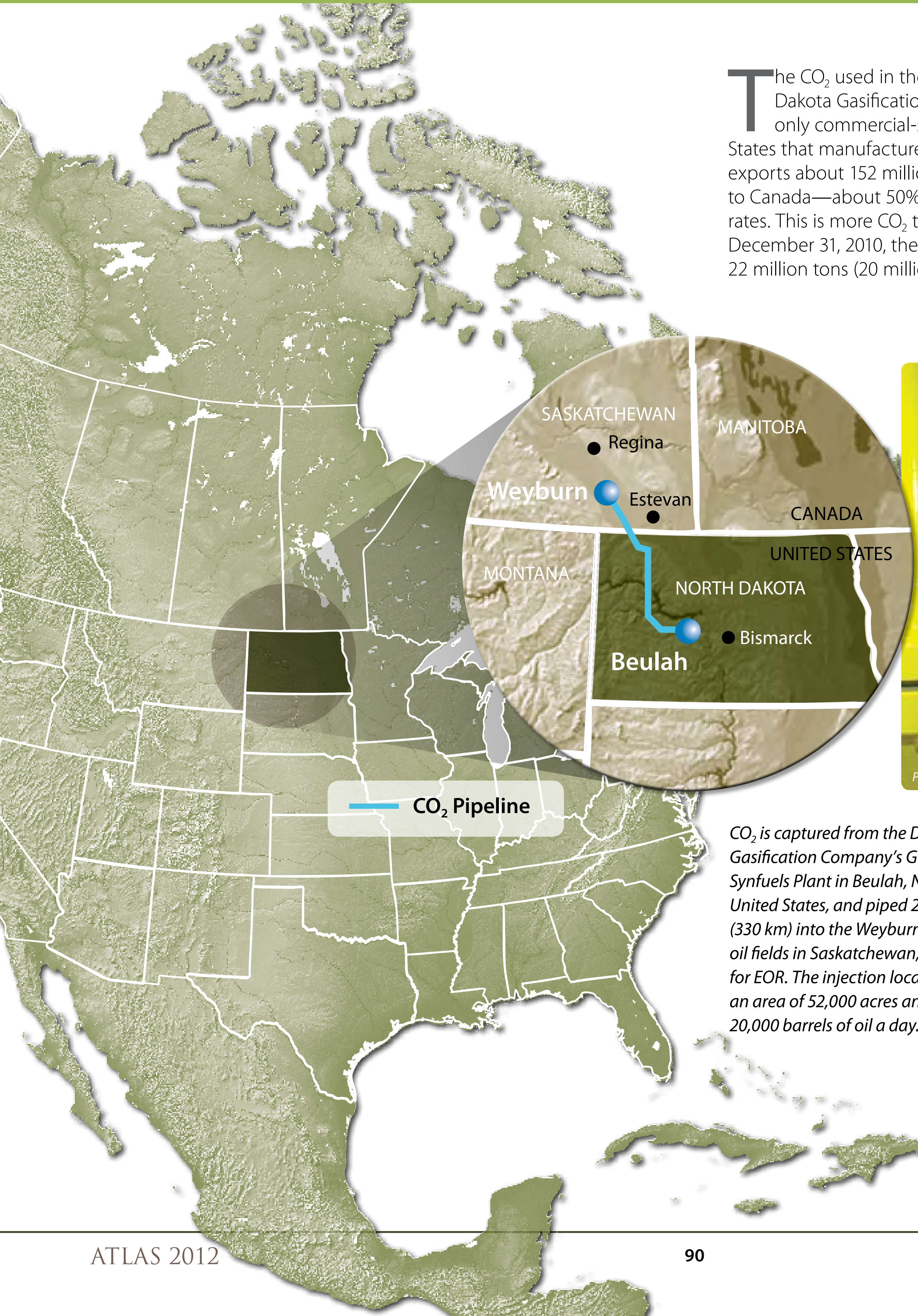


Photo courtesy of Basin Electric Power Cooperative.

CO_2 is captured from the Dakota Gasification Company's Great Plains Synfuels Plant in Beulah, North Dakota, United States, and piped 205 miles (330 km) into the Weyburn and Midale oil fields in Saskatchewan, Canada, for EOR. The injection location covers an area of 52,000 acres and produces 20,000 barrels of oil a day.

Weyburn–Midale CO_2 Monitoring and Storage Project

Launched in 2000, this 11-year $85 million international project, managed by the Petroleum Technology Research Centre (PTRC), studies CO_2 injection and underground storage in depleted oil fields for EOR. The project's Final Phase (2005–2011) built on the successes of the First Phase (2000–2004) to deliver the framework necessary to encourage implementation of CO_2 geologic storage worldwide. While there are emission trading projects being developed internationally, the Weyburn–Midale project is essentially the first project where physical quantities of CO_2 are being traded between two countries.

It is anticipated that the site will store 44 million tons (40 million tonnes) of CO_2 that would have otherwise been vented into the atmosphere. At the end of oil recovery operations, the project is expected to produce at least 122 million barrels of incremental oil which will extend the life of the Weyburn Field by approximately 20–25 years and increase oil production 34%.[40]

Weyburn–Midale is the world's first CCS project where CO_2 is traded between two countries.

PTRC Final-Phase Project Partners

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

CO_2 Capture at Boundary Dam

SaskPower is leading the development of the world's largest integrated clean coal/CCS project at the Boundary Dam Power Station in Estevan, Saskatchewan, Canada. The Boundary Dam Integrated Carbon Capture and Storage Demonstration Project is a Can$1.2 billion government–industry partnership between the Government of Canada, the Government of Saskatchewan, SaskPower, and private industry. The Boundary Dam project will reduce CO_2 emissions by approximately 1.1 million tons (1 million tonnes a year). Nearly all of the captured CO_2 will be sold to oil companies to be used in EOR operations. The remaining CO_2 will likely be used at the Aquistore Project to demonstrate CO_2 storage in a deep saline formation.

This leading-edge project, which is expected to begin operations in 2014, will determine the technical, economic, and environmental performance of clean coal/CCS technology.[45]

Project goals are as follows:

- To demonstrate an economically and technically feasible method for environmentally sustainable coal-fired power generation in Saskatchewan.
- To determine the technical, economic, and environmental performance of CCS technology.
- To reduce GHG emissions by approximately 1 million tonnes a year.
- To design and implement the world's first fully integrated commercial-scale CCS project on an existing coal-fired power station.
- To demonstrate a viable path for other Saskatchewan coal-fired generating units.
- To influence the creation of industrywide CCS regulations and policies.

Photo provided by and is property of SaskPower.

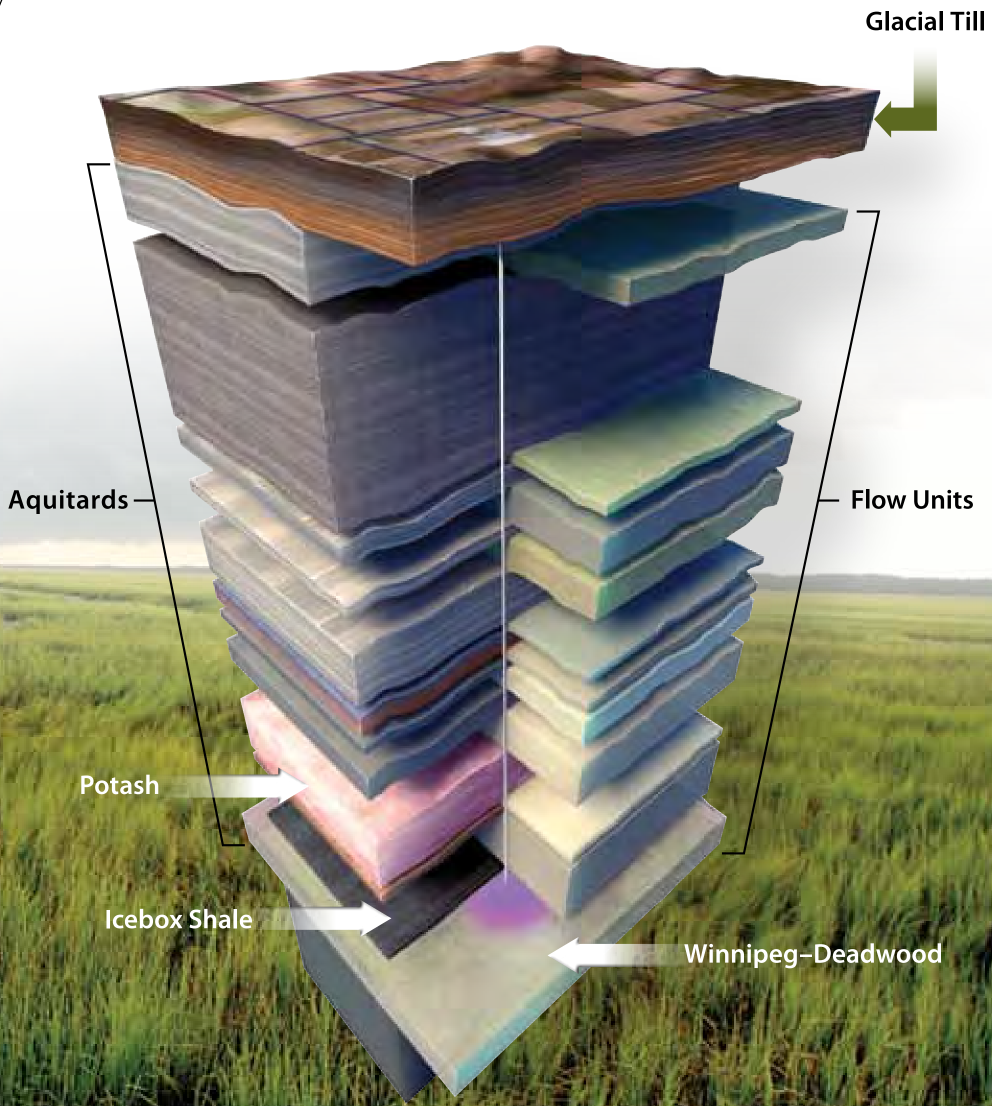
The Aquistore Project

The Aquistore Project, managed by PTRC, will be integrated with the SaskPower Boundary Dam CCS project and be among the first projects in Canada to demonstrate CO_2 injection, transportation, and storage in a deep saline formation, which is widely regarded as one of the most promising techniques to mitigate GHG emissions.

Primary objectives of the project are to:

- Demonstrate that CCS methods involving CO_2 storage in a deep, saline water-bearing geologic formation are safe, workable solutions for reducing GHG emissions.
- Demonstrate and validate effective technologies for characterizing and monitoring carbon storage in deep saline formations that may be widely applicable.
- Assist in the development of essential connections among industries implementing or considering this technology, policymakers drafting regulations around CCS, financial institutions trying to understand the economic implications of business within a carbon-managed environment, and the public learning about, and living with, the technology.

The Aquistore Project will adapt existing and develop new MVA technologies to suit CO_2 storage in deep saline formations and report on the feasibility of long-term CO_2 storage in these formations. As the project matures, it will serve to verify technical and economic components required for commercialization and widespread industry acceptance of CCS.[40]



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 CCS 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.

To that end, a U.S. Presidential Interagency Task Force on CCS was formed to develop a plan to overcome the barriers of widespread, cost-effective deployment of CCS within 10 years.[47] 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 as well as daily changes in federal agency announcements, this atlas will provide general overviews of select rules and policies currently under debate; this atlas can be considered to be up to date as of January 2012, unless otherwise noted.

PCOR Partnership Regulation Activities

International Involvement

Interstate Oil & Gas Compact Commission

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

Regional Outreach

Regulatory Roundup

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

Past Regulatory Roundup Meetings

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

U.S. Presidential Interagency Task Force on CCS

In February 2010, an Interagency Task Force on CCS was established by U.S. President Obama. The Task Force comprises 14 executive departments and federal agencies and is cochaired by DOE and EPA. The Task Force was charged with proposing a plan to overcome the barriers of widespread, cost-effective deployment of CCS within 10 years, with a goal of bringing five to ten commercial demonstration projects online by 2016. The following are Task Force recommendations to address the legal and regulatory barriers to CCS.

Enhance Regulatory and Technical Capacity

Federal and state agencies should work together to enhance regulatory and technical capacity for safe and effective CCS deployment:

- EPA, in coordination with DOE, the U.S. Department of the Interior (DOI), and state agencies, should develop capacity-building programs for underground injection control regulators.
- EPA should leverage existing efforts of the RCSPs and identify data needs and tools to support regulatory development, permitting, and project development.

Work with Long-Term Stewardship Issues

Recommendations regarding long-term stewardship need further study. By early 2012, EPA, DOE, DOI, the U.S. Department of Justice, and the U.S. Department of the Treasury should provide recommendations in the context of existing and planned regulatory frameworks. Options to consider include the following:

- Reliance on the existing framework
- Adoption of substantive or procedural limitations on claims
- Creation of an industry-financed trust fund
- Transfer of liability to the federal government with certain contingencies
- No use of open-ended federal indemnification

Assess Statutory Requirements

DOE and EPA should track regulatory implementation for early commercial CCS demonstration projects and consider whether additional statutory revisions are needed.

Create Federal Agency Roundtable

DOE and EPA should create a federal agency roundtable to act as a single point of contact for project developers. The roundtable should create a technical committee comprising various experts to conduct periodic reviews of CCS demonstration projects to track progress and identify additional research, risk management, and regulatory needs.

Current EPA Regulations

EPA is developing policies and regulation with profound effects on CCS implementation. In December 2010, EPA finalized authority to permit CO_2 long-term geologic storage wells in all 50 states under the authority of the Safe Drinking Water Act's Underground Injection Control (UIC) Program. Additionally, EPA requires geologic storage projects to comply with the Mandatory Reporting of Greenhouse Gases Rule (40 CFR 98).[48]

Underground Injection Control Program

This rule establishes federal requirements for the underground injection of CO_2 for the purpose of long-term underground storage, or geologic storage. Numerous elements of the rule deal with various aspects of permitting and operating a UIC Class VI injection well, such as site characterization requirements, well construction and operation requirements, and postinjection site care. Additionally, a series of guidance documents provide information and possible approaches for addressing each of these elements. These guidance documents follow the sequence of activities that an owner or operator will perform over time at a proposed and permitted site.

In the final rule, EPA gave states a deadline of September 6, 2011, to apply for primary enforcement responsibility, or primacy, over Class VI wells. No states met this deadline; therefore, as of September 7, 2011, EPA directly implements the Class VI Program nationally. As a result, in order to permit a CO_2 geologic storage project, potential owners or operators of a CO_2 geologic storage well need to submit a permit application to the appropriate EPA regional office.

Mandatory Greenhouse Gas Reporting Rule (MRR)

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

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

In addition, Subpart RR reporters must also develop and submit a monitoring, reporting, and verification (MRV) plan to EPA.

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_2 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.

Alberta has legislation in place for pore space issues and long-term stewardship.

North Dakota has legislation in place for pore space issues and long-term stewardship.

Montana has legislation in place for pore space issues and long-term stewardship. Rule development will begin once primacy for underground injection of CO_2 for storage purposes is received from EPA.

Wyoming has legislation in place for pore space ownership.

South Dakota does not have legislation in place or any rules adopted or under development.

Nebraska does not have legislation in place or any rules adopted or under development.

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

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

Manitoba does not have any legislation in place or rules adopted or under development.

Saskatchewan's legislation has been passed, and rules are being developed for CCS.

Minnesota does not have legislation in place or any rules adopted or under development.

Wisconsin does not have any legislation in place or rules adopted or under development.

Iowa does not have any legislation in place or rules adopted or under development.

Missouri does not have any legislation in place or any rules adopted or under development.

Carbon Markets

With increasing concerns over climate change, a momentous surge of interest in the various methods of carbon sequestration is occurring. Because of this surge, voluntary and potential future compliance-related carbon markets are rapidly developing.

Carbon markets provide an opportunity for entities looking to offset emissions and for investors to speculate on the future value of carbon credits. Without the presence of rigid regulatory oversight, the evolution of the voluntary carbon market in the United States has been largely determined by market participants and their objectives. Participants wishing to partake in the voluntary carbon market find a myriad of GHG registries, exchange platforms, and voluntary standards in which to enroll.

Carbon market trading provides a mechanism to put a monetary value on something that was previously free: the ability to release CO_2 into the air. Carbon markets were established to stabilize CO_2 in the atmosphere through emission reductions by either preventing CO_2 from getting into the atmosphere or pulling CO_2 out of the atmosphere.

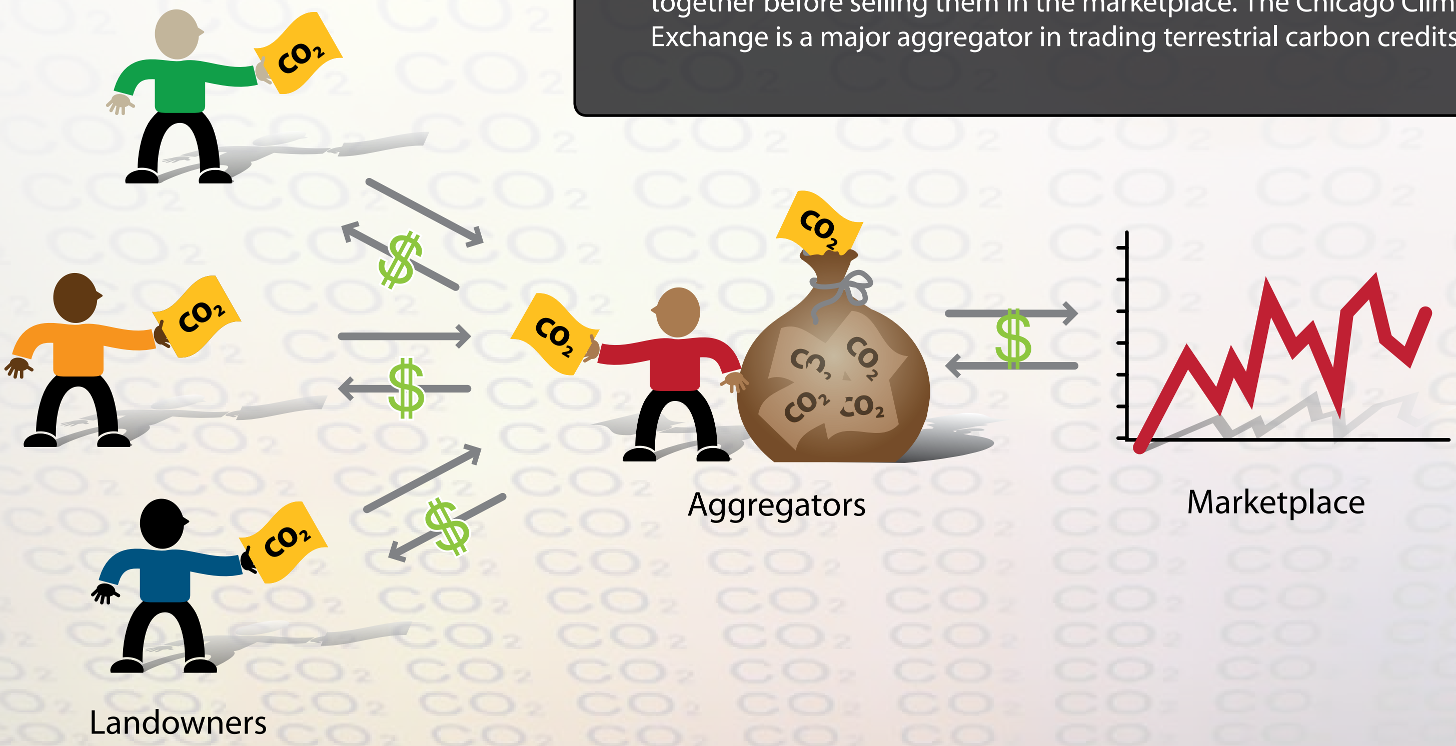
Carbon Offsets

Carbon offsets are also known by a number of other names, such as carbon credits, verified emission reductions, and certified emission reductions. A carbon offset can be created by:

1. **Identifying carbon reduction projects** such as planting and conserving trees, storing CO_2, becoming more energy-efficient, or investing in renewable energy production.
2. **Quantifying the volume of carbon reduced.** One carbon offset typically represents the reduction of 1 tonnes of CO_2 or its equivalent in other GHGs.
3. **Verifying carbon reductions via a third-party auditor.** All trading countries maintain an inventory of emissions, and North American trading groups maintain inventories at the state level through the Climate Registry.
4. **Offering carbon credits for sale into the market** on a mandatory or voluntary basis. In a **mandatory carbon market**, a cap-and-trade system sets limits (caps) on the amount of CO_2 that can be emitted. If an entity cannot meet that limit, it can purchase (trade) allowances from an entity that emits less CO_2. These units can then be traded as a commodity between countries and among industries within countries. In a **voluntary carbon market**, an entity that typically is not subject to mandatory limitations chooses to offset its carbon emissions by purchasing carbon allowances from a third party. The third party then uses the money toward a project that reduces CO_2 in the atmosphere.

Aggregators

An aggregator is any company that collects, combines, completes the administrative work, and brokers the exchange of carbon credits. Because exchanges incur transaction costs when offset credits are bought and sold, aggregators prefer to buy credits from individuals and bundle the credits together before selling them in the marketplace. The Chicago Climate Exchange is a major aggregator in trading terrestrial carbon credits.



CHAPTER 7

The Path Forward

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

CCS Efforts Outside North America

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

1. Ketzin

The Ketzin test site is the first European research center studying the geologic storage of CO_2 in an onshore saline aquifer. From June 2008 to January 2012, 57,400 tons (52,072 tonnes) of food-grade CO_2 have been injected, stored, and monitored. In May of 2011, the injection and storage of CO_2 from a separation process at a power plant began. The monitoring methods used at the Ketzin site are among the most comprehensive and innovative worldwide in the field of CO_2 storage. [49]

2. Snohvit

The Snohvit project involves injecting CO_2 derived from natural gas processing and storing the CO_2 in a saline formation deep below the floor of the North Sea. Injection began in April of 2008, and at full capacity, 772,000 tons (700,000 tonnes) of CO_2 will be stored a year.[50]

3. Sleipner

Started in 1996, the Sleipner project is the world's first demonstration of CO_2 capture and underground storage. The project involves commercial natural gas production coupled with the storage of ~1 Mt CO_2/year in a deep saline formation. As of December 2011, more than 11 million tons (10 million tonnes) of CO_2 has been injected and stored.[50]

4. Lacq

Since January 2010, Total, a multinational energy company, has been testing the first complete industrial-scale CCS project in Europe near the town of Lacq in southwestern France. This project involves the capture of the CO_2 emitted during combustion in a modified boiler in the Lacq industrial complex. This CO_2 is then transported by pipeline 17 miles (27 km) to the storage site at which point it is injected into a depleted gas reservoir 14,800 feet (4500 m) below the surface. During the 2-year demonstration, about 132,000 tons (120,000 tonnes) of CO_2 will be captured and stored.[51]

5. In Salah

In Salah is a pioneering, industrial-scale CCS operation that has been running in Algeria since 2004 as part of a natural gas production process operated by BP, Sonatrach, and Statoil.[52] More than 3.3 million tons (3 million tonnes) of CO_2 have already been stored in a deep saline formation almost 6600 feet (2000 m) below the Earth's surface. In total, approximately 17 million tonnes of CO_2 is expected to be stored as part of this process over a period of 20 years.[52]

6. Gorgon

The Gorgon project is planned to be the first commercial CO_2 storage project in Australia and the largest storage project in the world. Development of the project will be based on the Gorgon gas field in Australia which is one of the world's premier hydrocarbon resources. The project is projecting to store nearly 3.6 million tons (3.3 million tonnes) of CO_2 a year, beginning in late 2014.[53]

7. Otway

The Otway Project is a project under way in southwestern Victoria to demonstrate that CCS is a technically and environmentally safe way to make deep cuts into Australia's GHG emissions. The first phase of the project injected 72,000 tons (65,000 tonnes) of CO_2 into a depleted gas reservoir and includes an outstanding monitoring program, which international and national scientists believe to be the most comprehensive of its type in the world.[54]

Challenges to CCS Deployment

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

National CO_2 Policy – Currently, there is no 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 a prospective CCS deployment as being profitable over the long term, thus justifying the investment and acceptance of any risk.

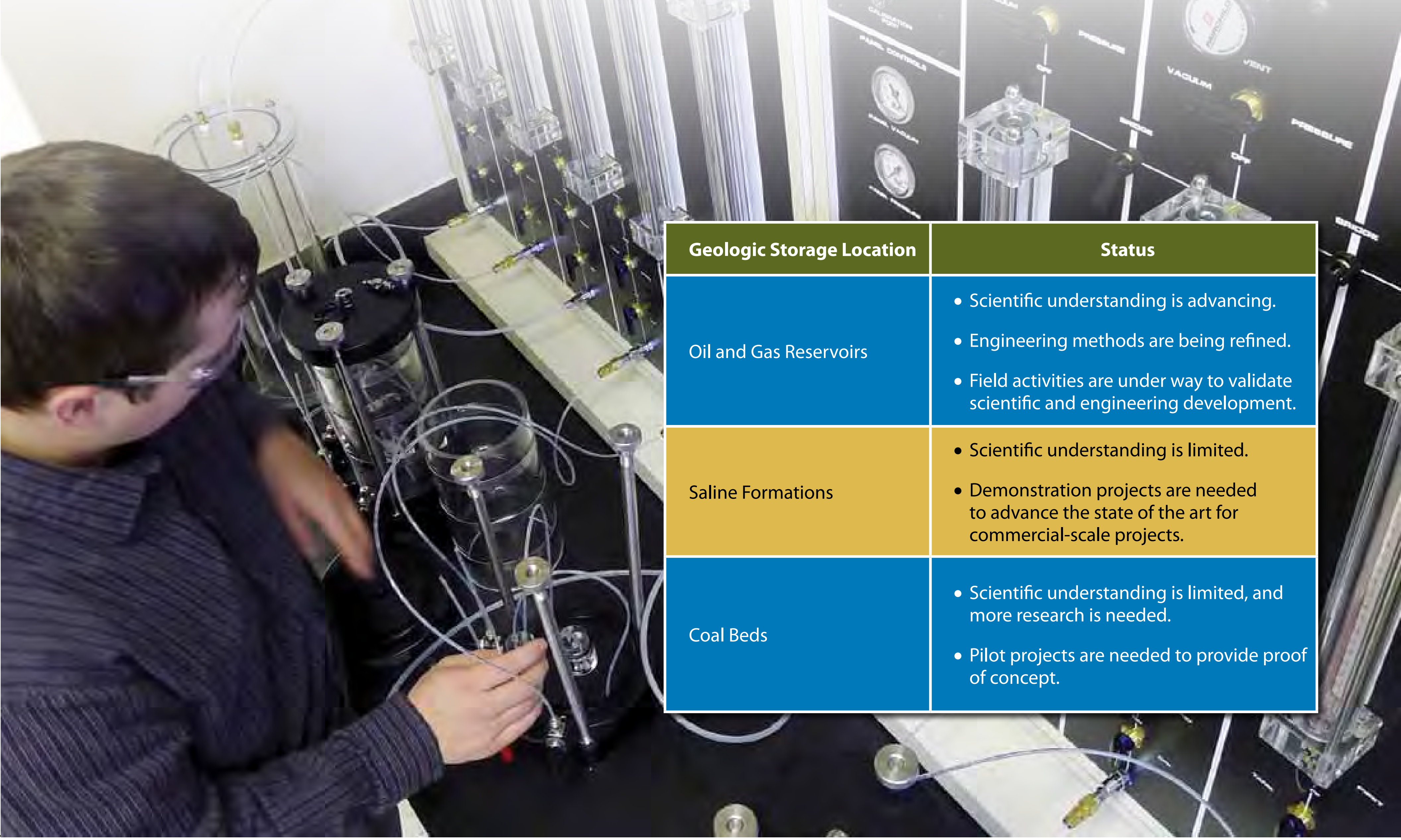
Regulations – CCS is a new type of activity, and legal frameworks for it are evolving. However, regulatory uncertainty remains a barrier to CCS deployment. Although early CCS projects can proceed under existing laws, there is limited experience at the federal and state levels in applying the regulatory 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 postinjection and may change over time. 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: State of the Science

CCS can play a vital role in reducing atmospheric CO_2 levels, while simultaneously preserving the option of using abundant and low-cost domestic fossil energy resources. The scale of CCS deployment needed to result in significant reductions, however, will require thousands of CCS deployments around the world. This raises the question of how to expand the use of CCS technologies by 3 or 4 orders of magnitude. The expansion of a new technology at that rate is challenging but achievable. Research, development, and demonstration (RD&D) programs such as those currently conducted by DOE's RCSP Program are critical for demonstrating CO_2 storage in diverse geologic settings and will establish the basis for CCS's widespread global deployment.



Geologic Storage Location	Status
Oil and Gas Reservoirs	• Scientific understanding is advancing. • Engineering methods are being refined. • Field activities are under way to validate scientific and engineering development.
Saline Formations	• Scientific understanding is limited. • Demonstration projects are needed to advance the state of the art for commercial-scale projects.
Coal Beds	• Scientific understanding is limited, and more research is needed. • Pilot projects are needed to provide proof of concept.

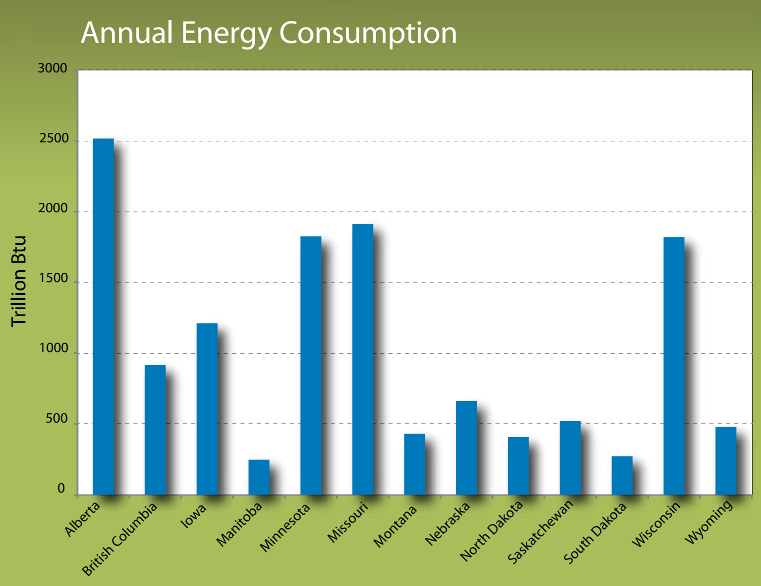
CCS Acceptance

All new technologies face challenges with respect to acceptability, especially those that involve new risks, large-scale infrastructure, government involvement, public support, and significant economic commitments—all features of CCS. Although CCS is on the cusp of commercial deployment, widespread cost-effective deployment of CSS will occur only if the technology is commercially available at economically competitive prices and supportive national policy frameworks are in place. In order for this to happen, institutions must evolve in a number of spheres: political, technical, economic, social, regulatory, and corporate.

The large-scale deployment of CCS technologies depends on them becoming trusted, commonplace technologies.

Keeping the Lights On

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[55,56] of energy a year. At the most basic level, energy is essential, but to use our resources in a sensible way without damaging our planet requires a balance between energy and the environment.



The abundant, affordable energy provided by the PCOR Partnership region's fossil fuel resources powers a very productive part of the world. For example, the three Canadian provinces of the PCOR Partnership produce over 90% of Canada's wheat, while the U.S. portion of the PCOR Partnership contributes over 30% of U.S. wheat production.[57,58] Most of the continent's barley crop, which is critical to the breweries of Milwaukee and Saint Louis, comes from North Dakota and Minnesota. Wisconsin, as the top producer of paper in the United States, generates over $12 billion in annual shipments of paper products.[59] The Missouri and Mississippi Rivers, railways, and highways of the region transport heavy machinery, construction materials, and many other consumer goods.

The PCOR Partnership is working to develop technologies that will allow for CCS. 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 the future of our culture. Our challenge is to keep the lights on while simultaneously ensuring that our environment and economy stay strong.

Public Awareness

Public awareness and support are critical to the development of new energy technologies and are widely viewed as vital for CCS projects. Whether the public will support or oppose commercial-scale CCS projects is largely unknown, and the public's reaction may be project-specific. 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, policymakers, and industry.

Our core approaches include:

Take it on the road – Presentations are being made across the PCOR Partnership region upon request. Additionally, the PCOR Partnership participates in numerous public and industry events.

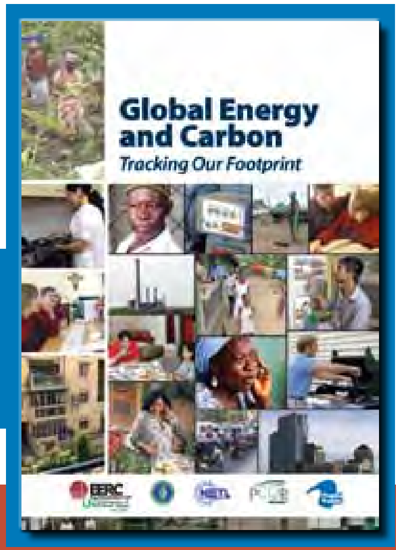
Take it viral – Separate public and partners-only Web sites provide different levels of information to various audiences.

Take it with you – Fact sheets and scientific and technical reports showcase PCOR Partnership activities.

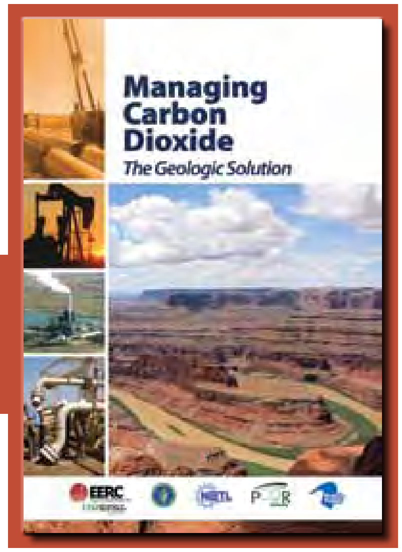
Take it to prime time – With cooperation from Prairie Public Broadcasting, the PCOR Partnership developed a series of award-winning documentaries.

To foster public awareness, the PCOR Partnership teamed with Prairie Public Broadcasting to create an exclusive documentary series about CO_2 and carbon management.

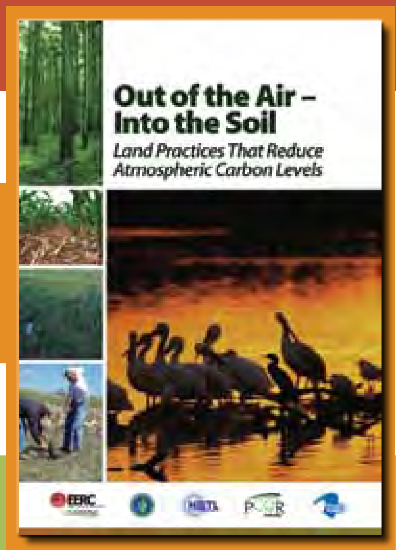
Global Energy and Carbon: Tracking Our Footprint shows how energy is used by everyday families at three levels of economic development: postindustrial (United States), emerging (India), and developing (Cameroon).



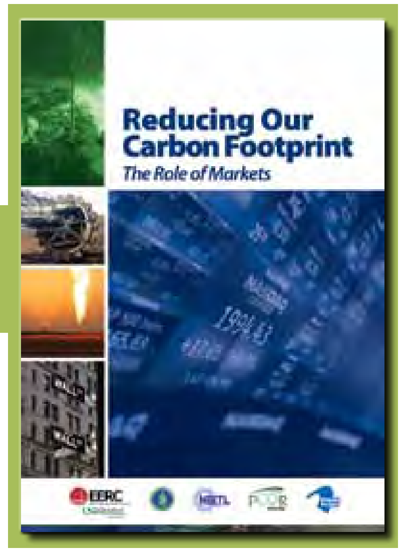
Managing Carbon Dioxide: The Geologic Solution examines the historical time line that produced the idea of geologic CO_2 storage as one of the solutions to address CO_2 emissions from human activities.



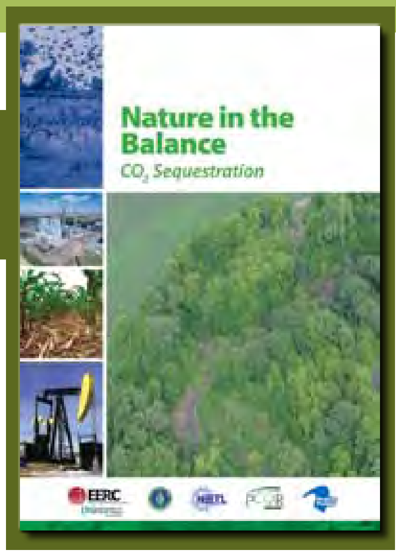
Out of the Air – Into the Soil: Land Practices That Reduce Atmospheric Carbon Levels shows examples from North and South America where effective landscape management is helping plants absorb carbon as a first step toward reducing our carbon footprint.



Reducing Our Carbon Footprint: The Role of Markets demonstrates how markets are playing a role in reducing CO_2 emissions.



Nature in the Balance: CO_2 Sequestration is full of information about anthropogenic CO_2: what it is, where it comes from, and what we can do to control it.



Ramping up CCS Development

Looking ahead, the PCOR Partnership plans to fully utilize the infrastructure of its region to maximize CO_2 injection volumes by:

1. Building upon assessments of regional storage data to verify the ability of target formations to store CO_2.
2. Facilitating the development of the infrastructure required to transport CO_2 from the source to the injection site.
3. Facilitating the development of the rapidly evolving North American regulatory and permitting framework for CO_2 storage.
4. Developing opportunities for PCOR Partnership partners to capture and store CO_2.
5. Continuing collaboration with the other RCSP Program partnerships.
6. Providing outreach and education for CO_2 storage stakeholders and the general public.

Through these efforts, the PCOR Partnership, with the other RSCP Program partners, will help enable CCS technologies to overcome a multitude of economic, social, and technical challenges, including cost-effective CO_2 capture through successful integration with fossil fuel conversion systems, effective CO_2 monitoring and verification, permanence of underground CO_2 storage, and public acceptance. These advances will allow us to continue to have access to safe, reliable, and affordable energy from fossil fuels.

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
μ	micro	10^{-6}	one-millionth
n	nano	10^{-9}	one-billionth

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

Standard Temperature	Short Ton	Tonne (metric ton)
0°C/32°F (scientific)	16.31 Mcf	17.98 Mcf
60°F (oil and gas industry)	17.24 Mcf	19.01 Mcf
20°C/68°F (utilities)	17.51 Mcf	19.30 Mcf

Mcf = 1000 ft^3

Volume

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

Weight

short ton	X	2000	=	pound
	X	0.9072	=	metric tonne
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

Further Sources of Information

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

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

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

Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGS) – CASMGS is a consortium of nine universities and one DOE national laboratory assembled to investigate the potential of agricultural soils to mitigate CO_2. www.casmgs.colostate.edu

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

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

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

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

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

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

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

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

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

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

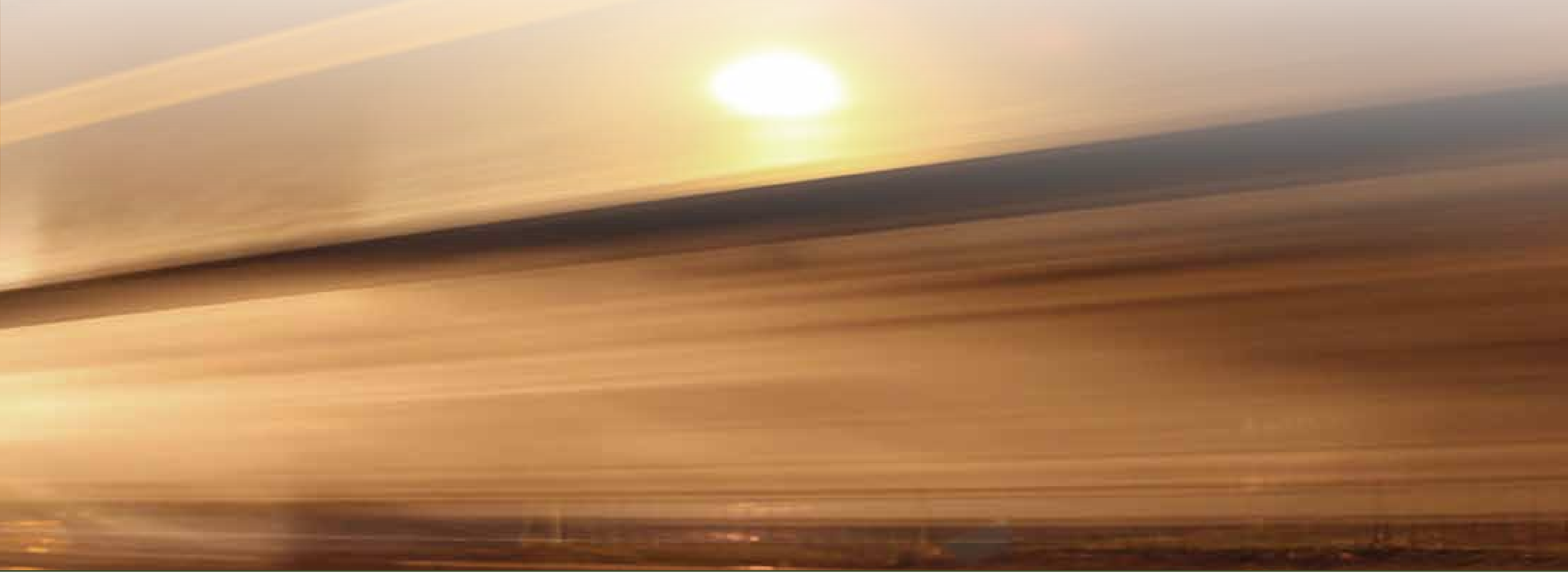
U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) – NETL is part of DOE's national laboratory system with expertise in coal, natural gas, and oil technologies; contract and project management; analysis of energy systems; and international energy issues. www.netl.doe.gov

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

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

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

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



Nomenclature

ACCCE	American Coalition for Clean Coal Electricity
ARRA	American Recovery and Reinvestment Act
BSCSP	Big Sky Carbon Sequestration Partnership
Bcf	billion cubic feet
Btu	British thermal unit
CAN	Climate Action Network
CASMGS	Consortium for Agricultural Soils Mitigation of Greenhouse Gases
CBM	coalbed methane
CCS	carbon capture and storage
CFC	chlorofluorocarbon
CH_4	methane
CO_2	carbon dioxide
CO_2CRC	Cooperative Research Centre for Greenhouse Gas Technologies
CSLF	Carbon Sequestration Leadership Forum
Denbury	Denbury Onshore LLC
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DU	Ducks Unlimited
DUC	Ducks Unlimited Canada
Eagle	Eagle Operating Group, Inc.
ECBM	enhanced coalbed methane
EERC	Energy & Environmental Research Center
EIA	Energy Information Administration
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
FE	Fossil Energy
GCCSI	Global CCS Institute
GDP	gross domestic product
GHG	greenhouse gas
Gt	gigaton
HARP	Heartland Area Redwater Project
H_2O	water
H_2S	hydrogen sulfide
IEA	International Energy Agency
IEAGHG	International Energy Agency Greenhouse Gas R&D Programme
IETA	International Emissions Trading Association
IISD	International Institute for Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
IOGCC	Interstate Oil and Gas Compact Commission
ISCG	In Situ Coal Gasification
mg/L	milligrams per liter
MGSC	Midwest Geological Sequestration Consortium
MRCSP	Midwest Regional Carbon Sequestration Partnership
MRR	Mandatory Greenhouse Gas Reporting Rule
MRV	monitoring, reporting, and verification
MVA	monitoring, verification, and accounting
MW	megawatt
NATCARB	National Carbon Sequestration Database and Geographic Information System
NDSU	North Dakota State University
NETL	National Energy Technology Laboratory
N_2O	nitrous oxide
O_3	ozone
ppm	parts per million
psi	pound per square inch
PCOR	Plains CO_2 Reduction Partnership
PPR	Prairie Pothole Region
PTRC	Petroleum Technology Research Centre
PTTC	Petroleum Technology Transfer Council
RCSP	Regional Carbon Sequestration Partnership
R&D	research and development
RD&D	research, development, and demonstration
SECARB	Southeast Regional Carbon Sequestration Partnership
SET	Spectra Energy Transmission
stb	stock tank barrel
SWP	Southwest Regional Partnership on Carbon Sequestration
TDS	total dissolved solids
UIC	underground injection control
USDW	underground source of drinking water
USGS	U.S. Geological Survey
WESTCARB	West Coast Regional Carbon Sequestration Partnership
WRI	Western Research Institute
UND	University of North Dakota
USDA	U.S. Department of Agriculture

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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.

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