PCOR PARTNERSHIP

ATLAS

6TH EDITION | 2021

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

NATIONAL ENERGY TECHNOLOGY LABORATORY
EERC
UND UNIVERSITY OF NORTH DAKOTA
PCO2R Partnership

PCOR Partnership ATLAS

6th Edition | 2021

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Published by the
Energy & Environmental Research Center (EERC)
2021

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

NOTICE

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

ACKNOWLEDGMENTS

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

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

The following EERC staff focused on the execution of PCOR Partnership efforts in 2019–2021. This atlas was possible because of their creative energy and collective efforts:

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This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory under Award No. DE-FE0031838.

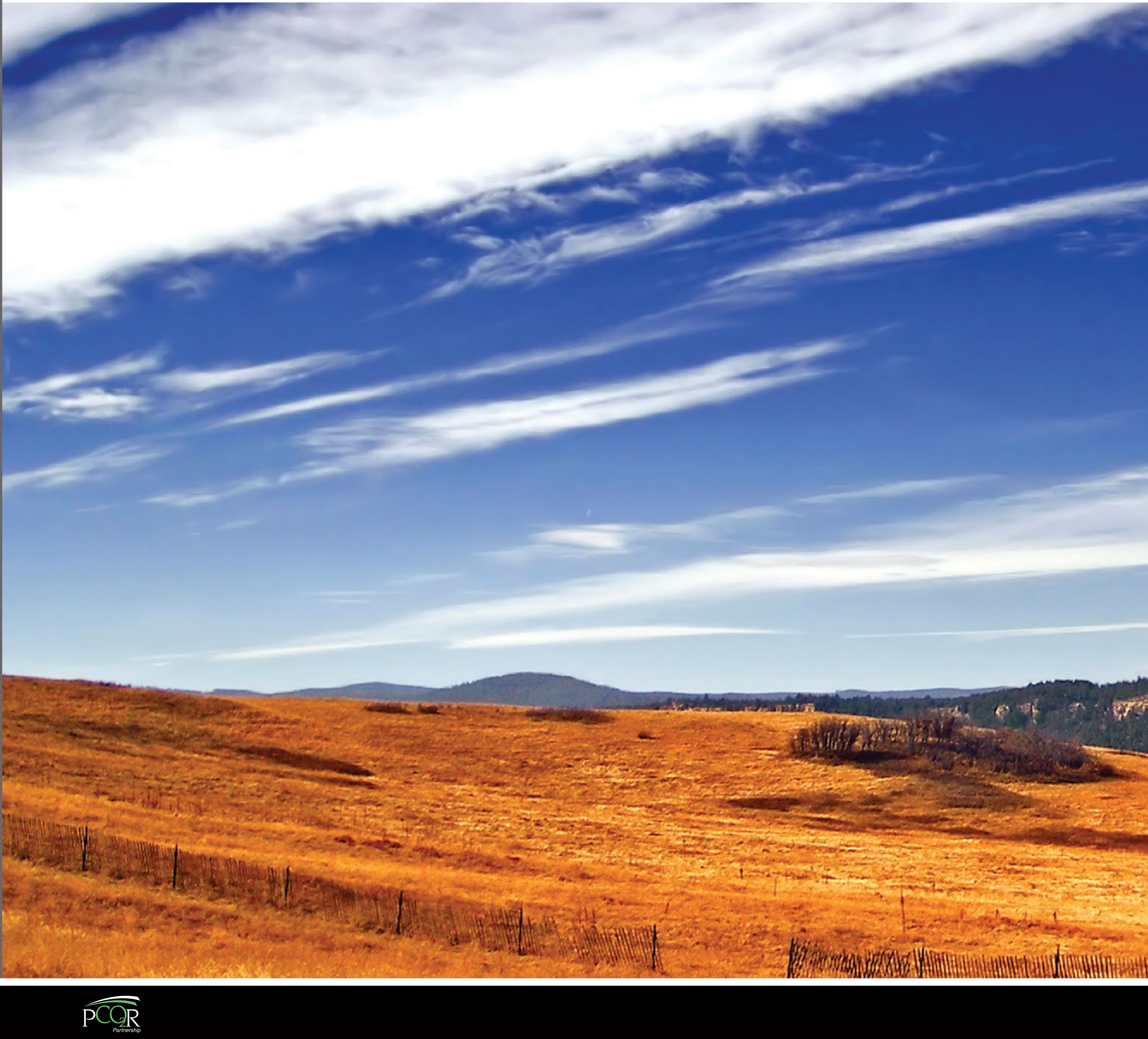

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Image provided by Denbury Resources Inc.

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

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

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

PCOR Partnership

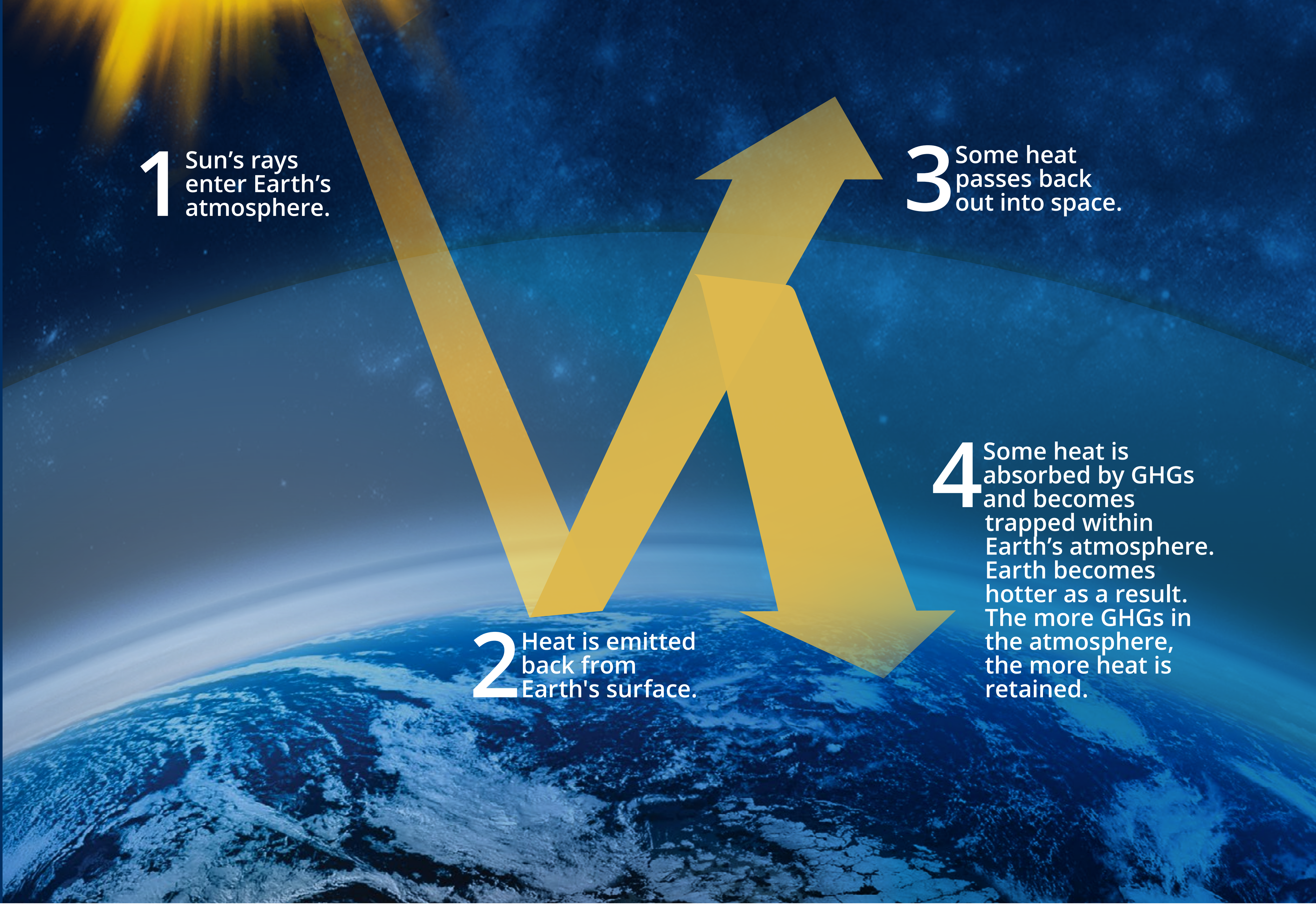
CHAPTER 1

THE CHALLENGE

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

GREENHOUSE EFFECT

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



GREENHOUSE GASES

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

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

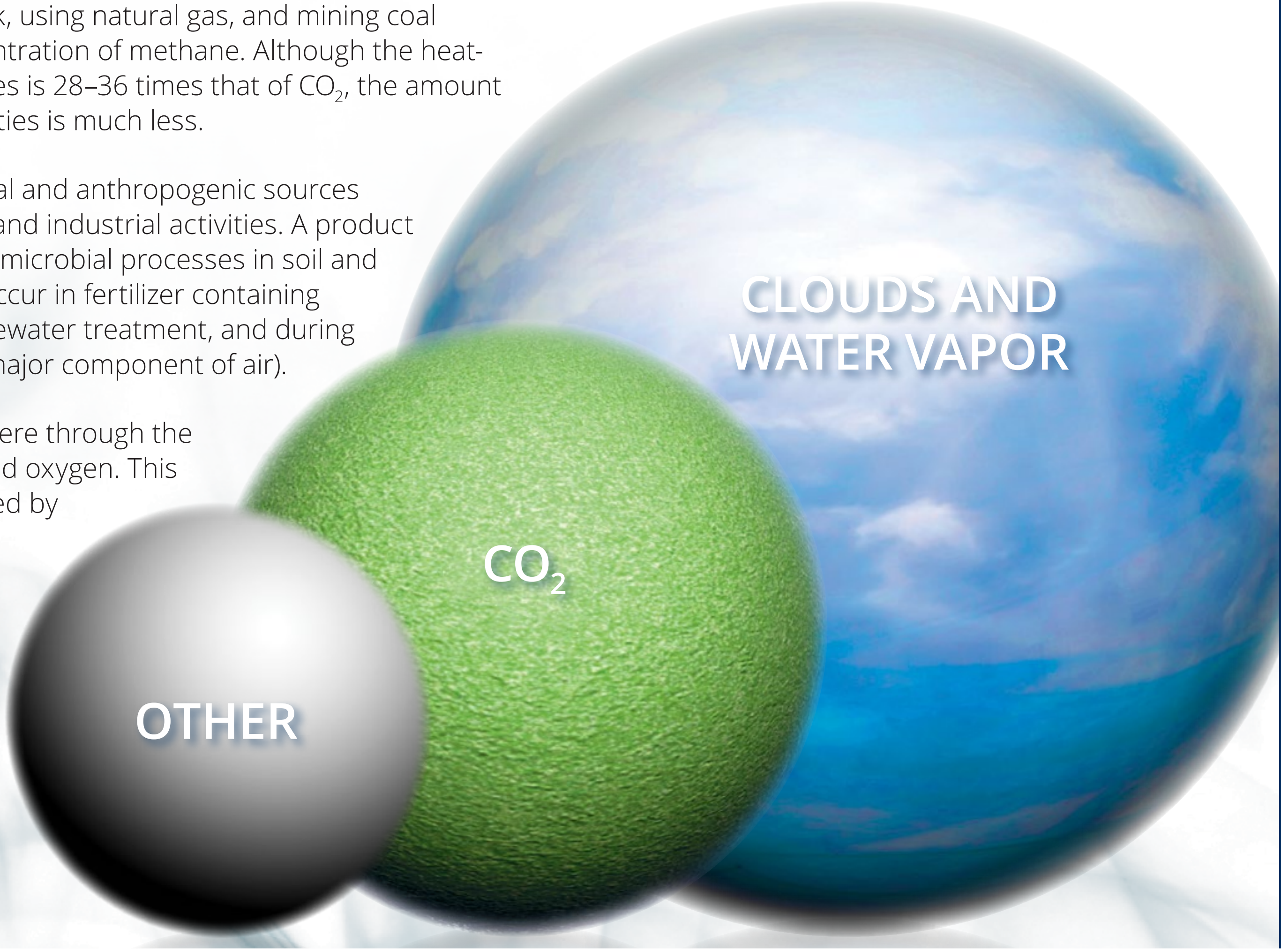
CARBON DIOXIDE has both natural and anthropogenic (human-made) sources. CO_2 plays a vital role in supporting life on Earth through the global carbon cycle. The heat-trapping capacity of CO_2 molecules is much greater than water vapor. Because its production is so prevalent in human activity, CO_2 is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

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

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

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

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

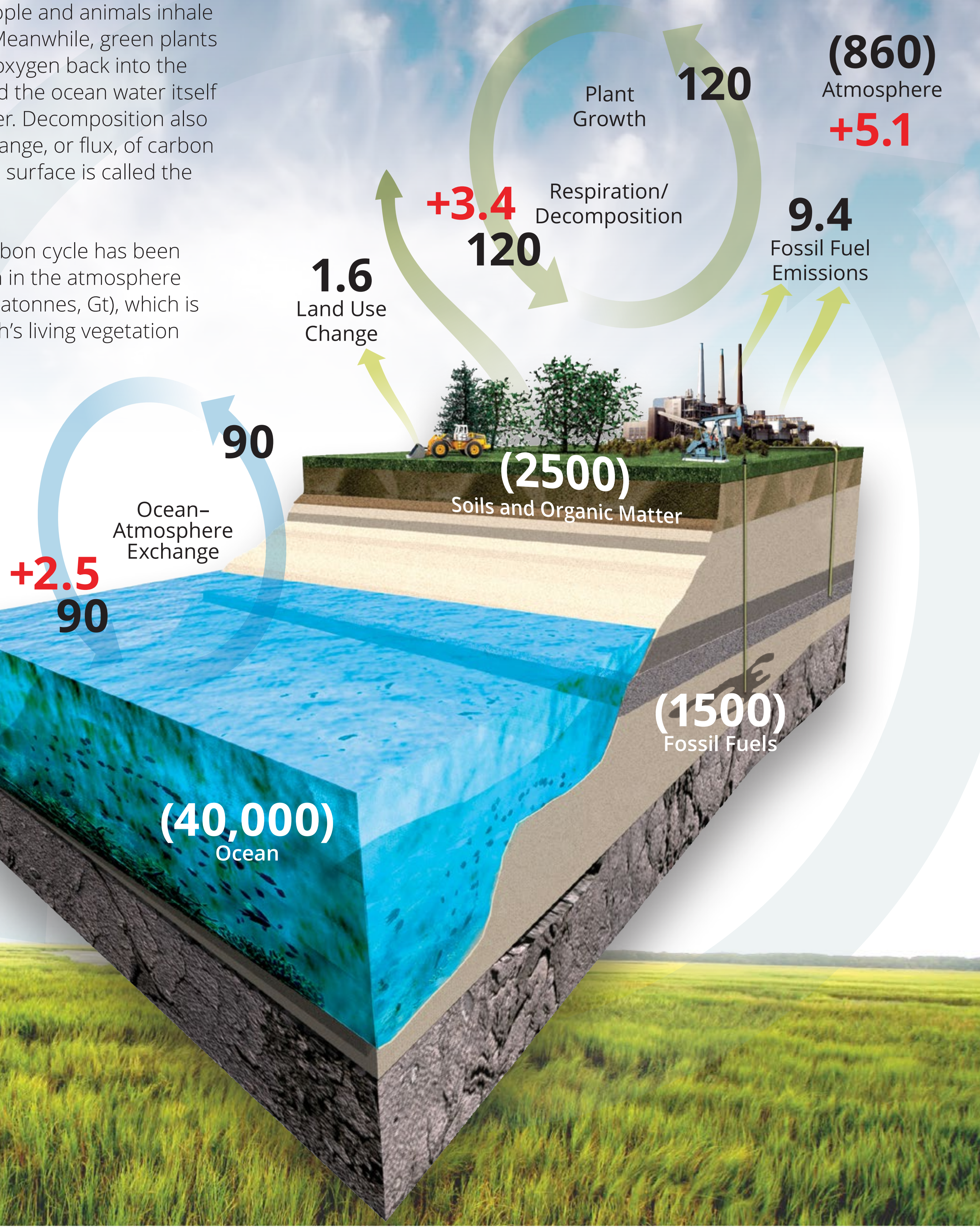


Relative total GHG effect contributions.[3]

GLOBAL CARBON CYCLE

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

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

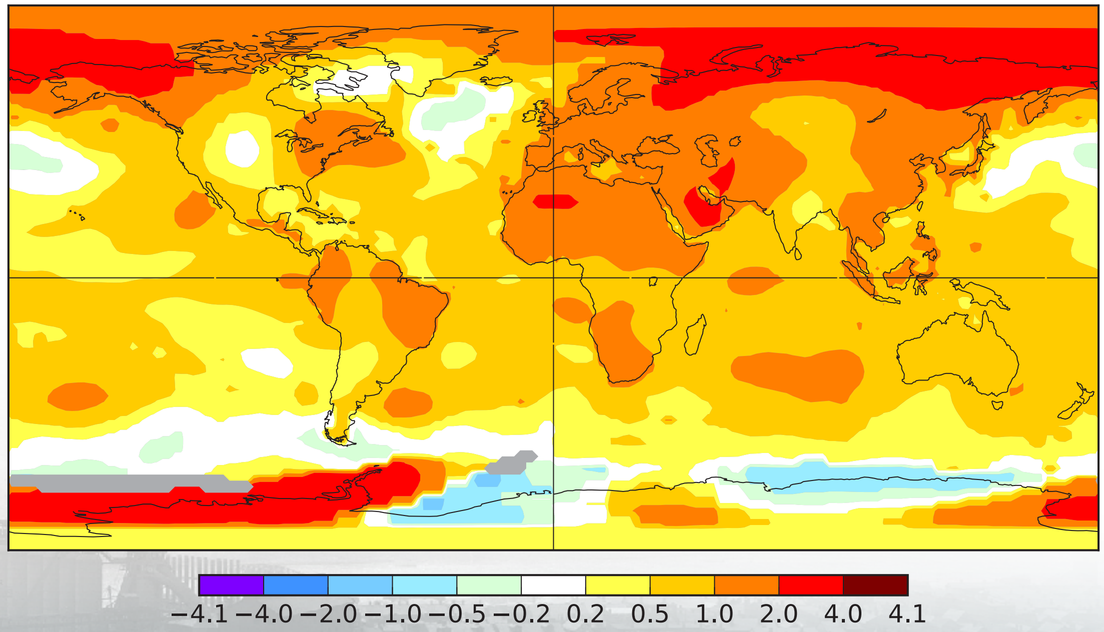


Averaged annual emissions, 2010–2019. Fluxes and pools are in GtC. Pools are noted in parentheses.

> "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 1880, the overall temperature of Earth has risen by more than 2°F (1.2°C), with 2020 being the second warmest year on record according to the National Oceanic and Atmospheric Administration.[5] The world's seven warmest years have all occurred since 2014. These rising temperatures are causing wide-ranging impacts such as the loss of sea ice and ice sheet mass, sea level rise, longer and more intense heat waves, and shifts in habitats. Most climate scientists attribute these current changes in climate at least in part to anthropogenic (human-made) GHG emissions.

The map shows the average surface temperature trends for the decade 2005–2015 relative to the 1950–1980 average. Warming was more pronounced at high latitudes, especially in the Northern Hemisphere and over land.[6]



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

MAJOR STATIONARY CO_2 SOURCES

INDUSTRIAL

Cement Plant

PETROLEUM AND NATURAL GAS

Refinery

ELECTRIC UTILITY

Coal-Fired Power Plant

AGRICULTURE-RELATED PROCESSING

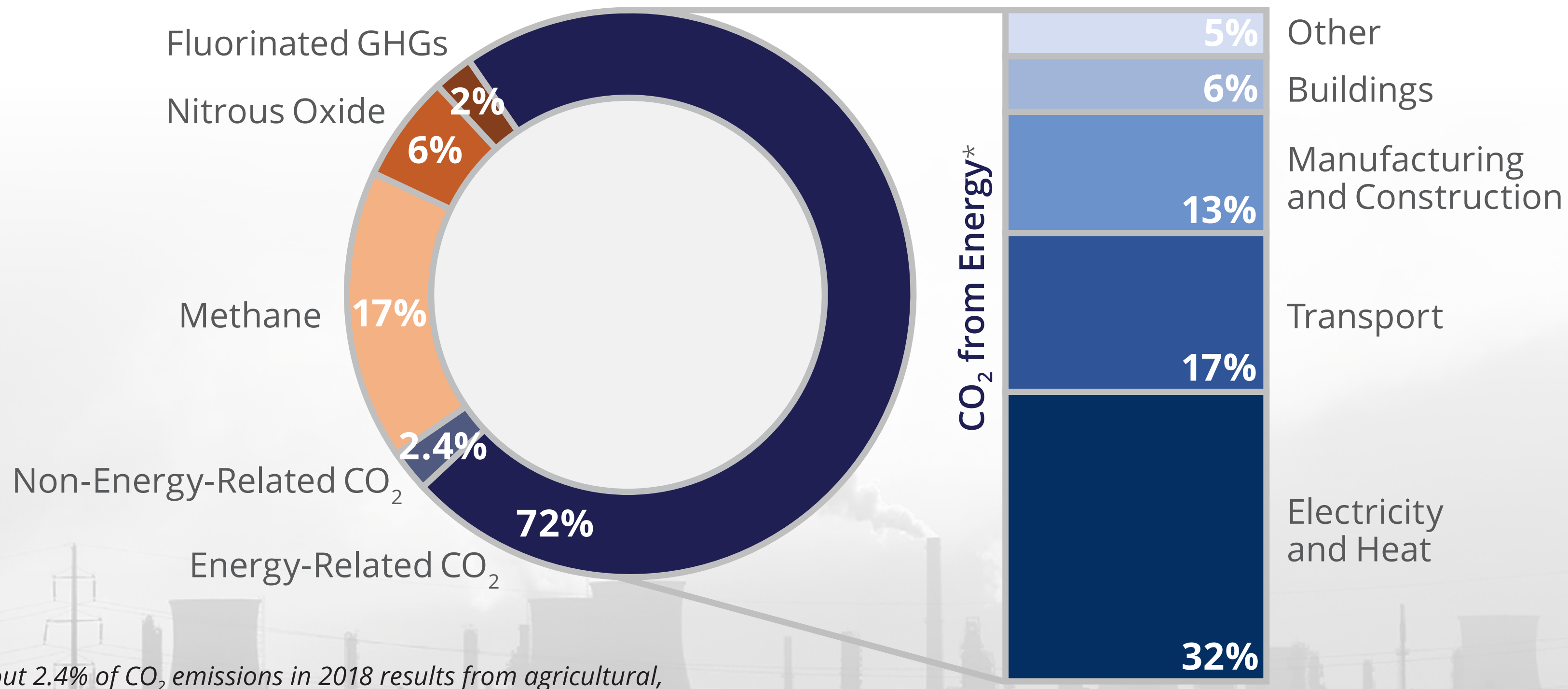
Ethanol Plant

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

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

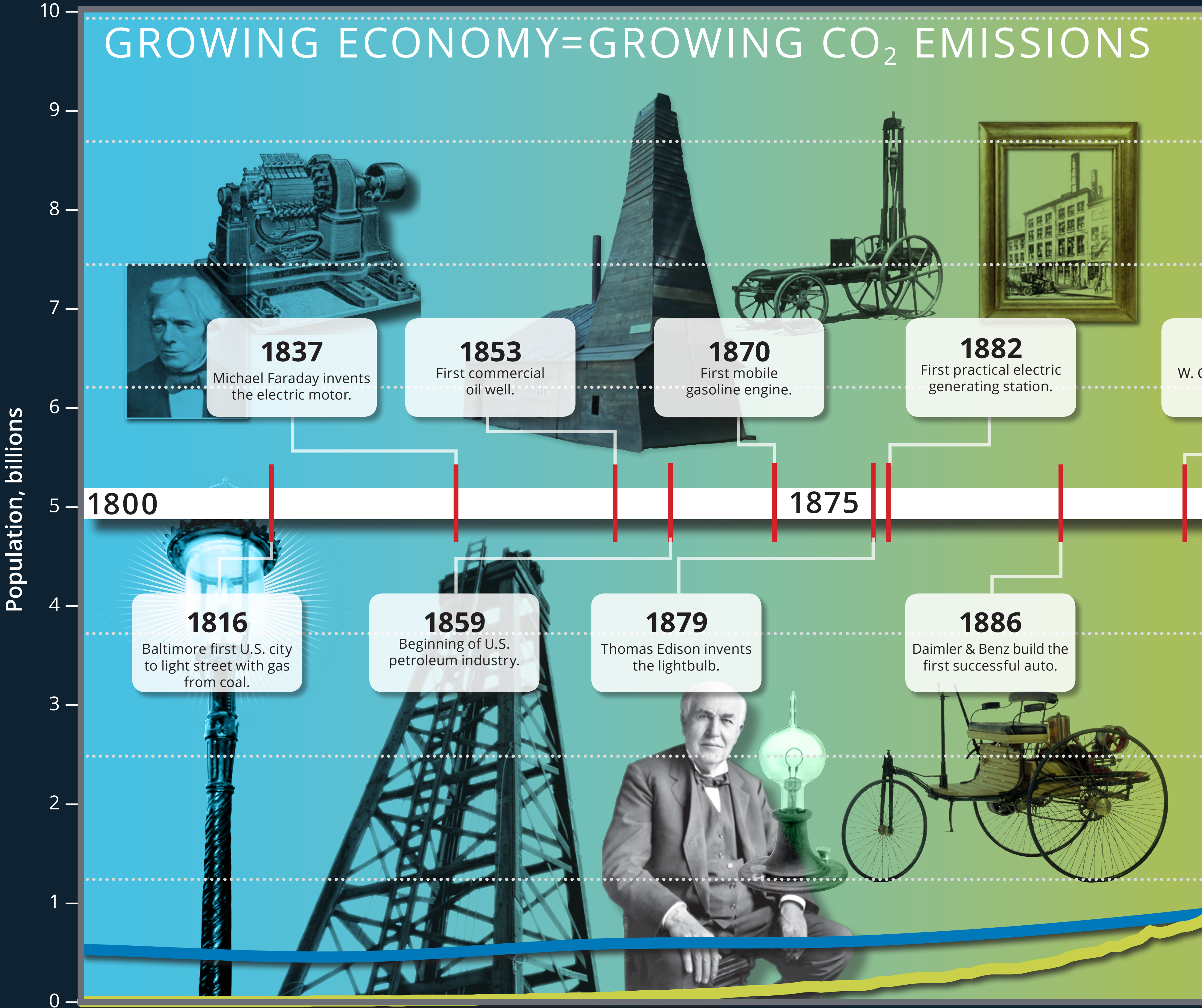
WHAT IS CO_2? Carbon dioxide is a colorless, odorless, naturally occurring gas comprising one atom of carbon and two atoms of oxygen. At temperatures below −76°C, CO_2 condenses into a white solid called dry ice. When warmed, dry ice vaporizes directly from a solid to a CO_2 gas in a process called sublimation.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

2018 GLOBAL GREENHOUSE GAS EMISSIONS[8]

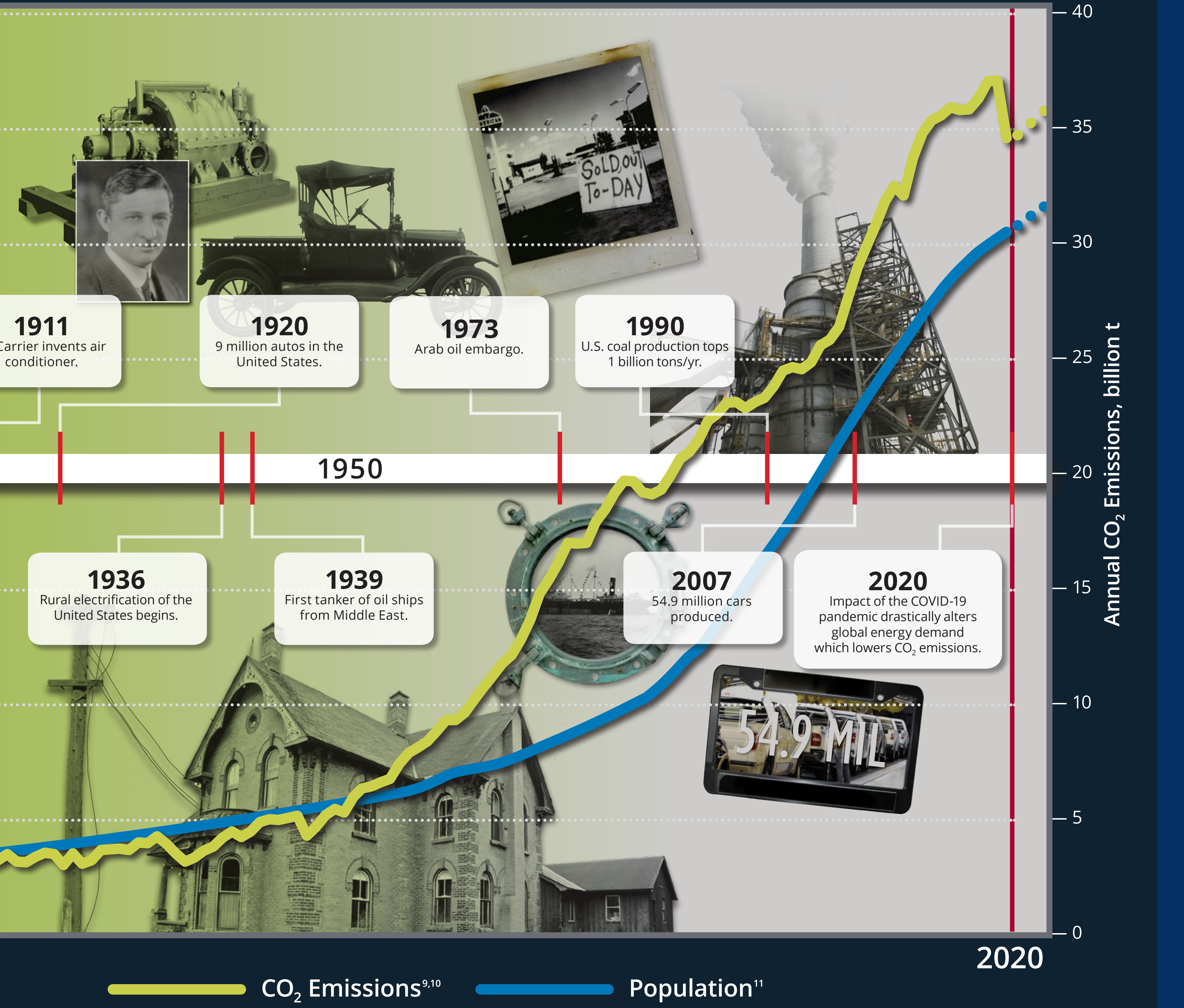


About 2.4% of CO_2 emissions in 2018 results from agricultural, land use, and forestry practices. Other GHG emissions occurred in agriculture, fugitive emissions, manufacturing and construction, waste, industry, other fuel combustion, land use changes, and forestry.

**Percentages exceed 72% because of rounding. The other category includes 3.1% industry, 1.3% other fuel combustion, and 0.5% fugitive emissions.*

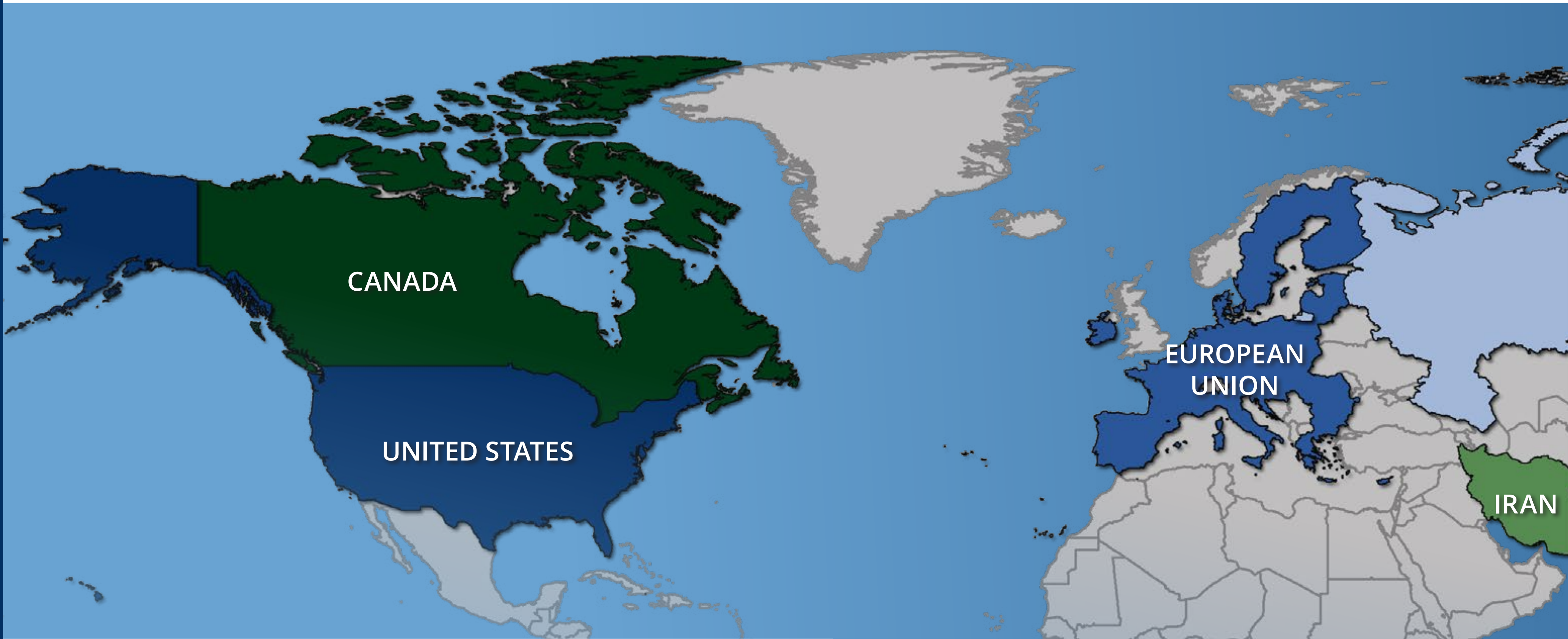


The amount of CO_2 in the atmosphere was relatively constant for 10,000 years until the Industrial Revolution in the 1800s, when the amount of anthropogenic CO_2 increased considerably. Currently, the world's economies annually emit approximately 35 Gt of CO_2 to the atmosphere from the combustion of fossil fuels to produce electricity. Increasing global populations, higher standards of living, and increased demand for energy will likely result in continued increases in global CO_2 emissions.



1911
Carrier invents air conditioner.
1920
9 million autos in the United States.
1973
Arab oil embargo.
1990
U.S. coal production tops 1 billion tons/yr.
1950
1936
Rural electrification of the United States begins.
1939
First tanker of oil ships from Middle East.
2007
54.9 million cars produced.
2020
Impact of the COVID-19 pandemic drastically alters global energy demand which lowers CO_2 emissions.
SOLD OUT TO-DAY
54.9 MIL
40
35
30
25
20
15
10
5
0
Annual CO_2 Emissions, billion t
2020
CO_2 Emissions[9,10]
Population[11]

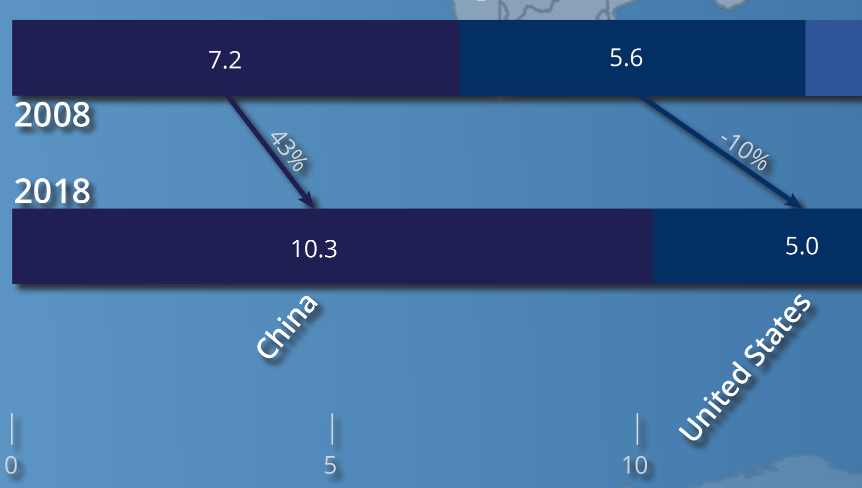
WORLD CO_2 EMISSIONS



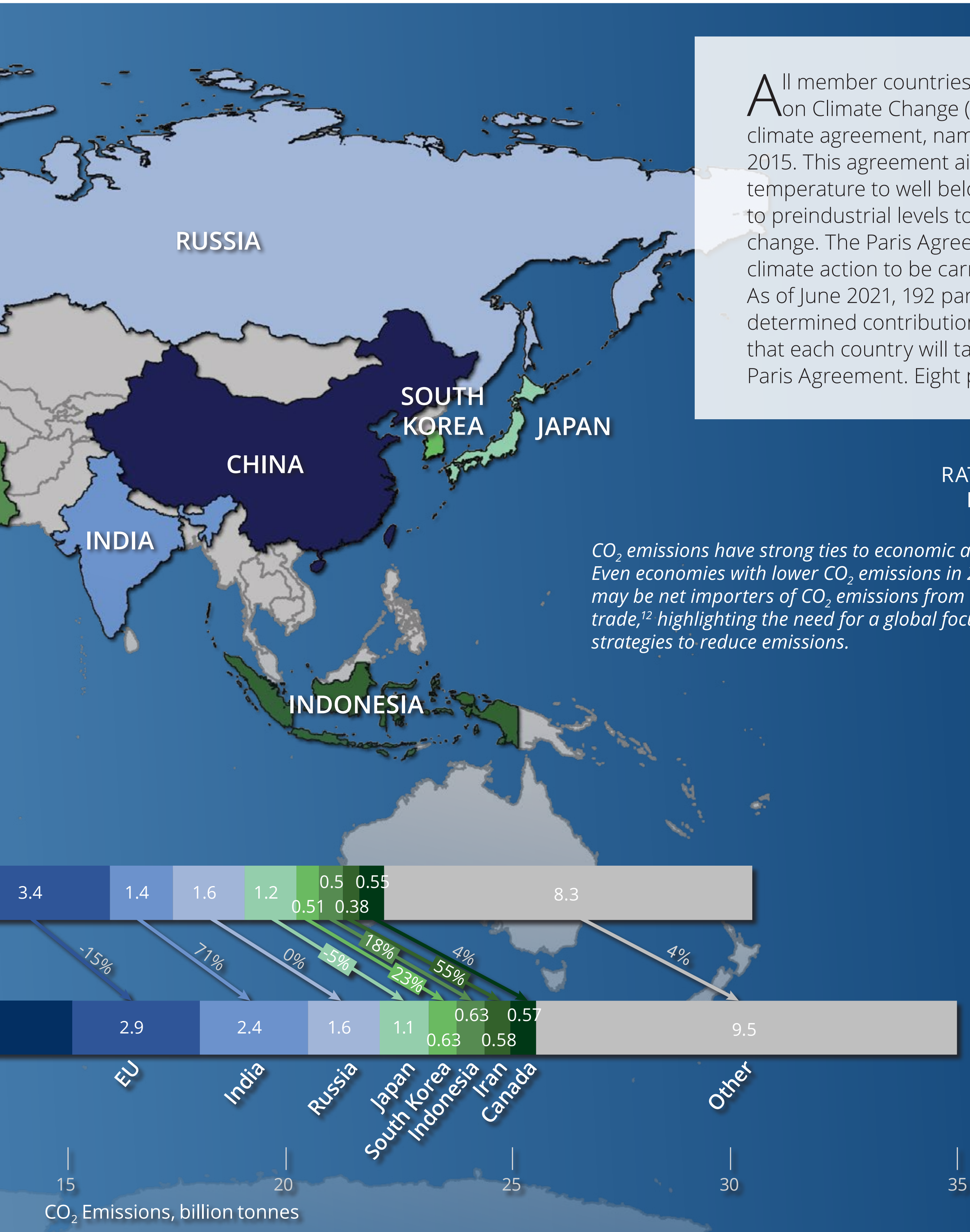
Since 1970, global CO_2 emissions have increased nearly 150%,[12] with emissions from fossil fuel combustion and industrial processes contributing nearly 75% of the total emissions in 2018.[13] To reduce the growing impact of CO_2 emissions on climate change, policies and regulations have been developed on a national and global level.

Ten economies account for about 73% of global CO_2 from energy and industrial processes. Illustrated in the comparison, the 4.6-billion-metric-ton increase in emissions from 2008 to 2018[13] comes mainly from five of these countries, including major increases in emissions in China, India and, to a lesser extent, Indonesia as they work to modernize their economies and provide more economic opportunities for their inhabitants.

Four of the top ten emitting economies had lower CO_2 emissions in 2018 as compared to 2008. The savings from these four economies offset the 14% increase in CO_2 emissions from the rest of the world. The greatest percentages of decrease are 15% and 10% for the European Union (EU, 27 nations) and the United States, respectively.



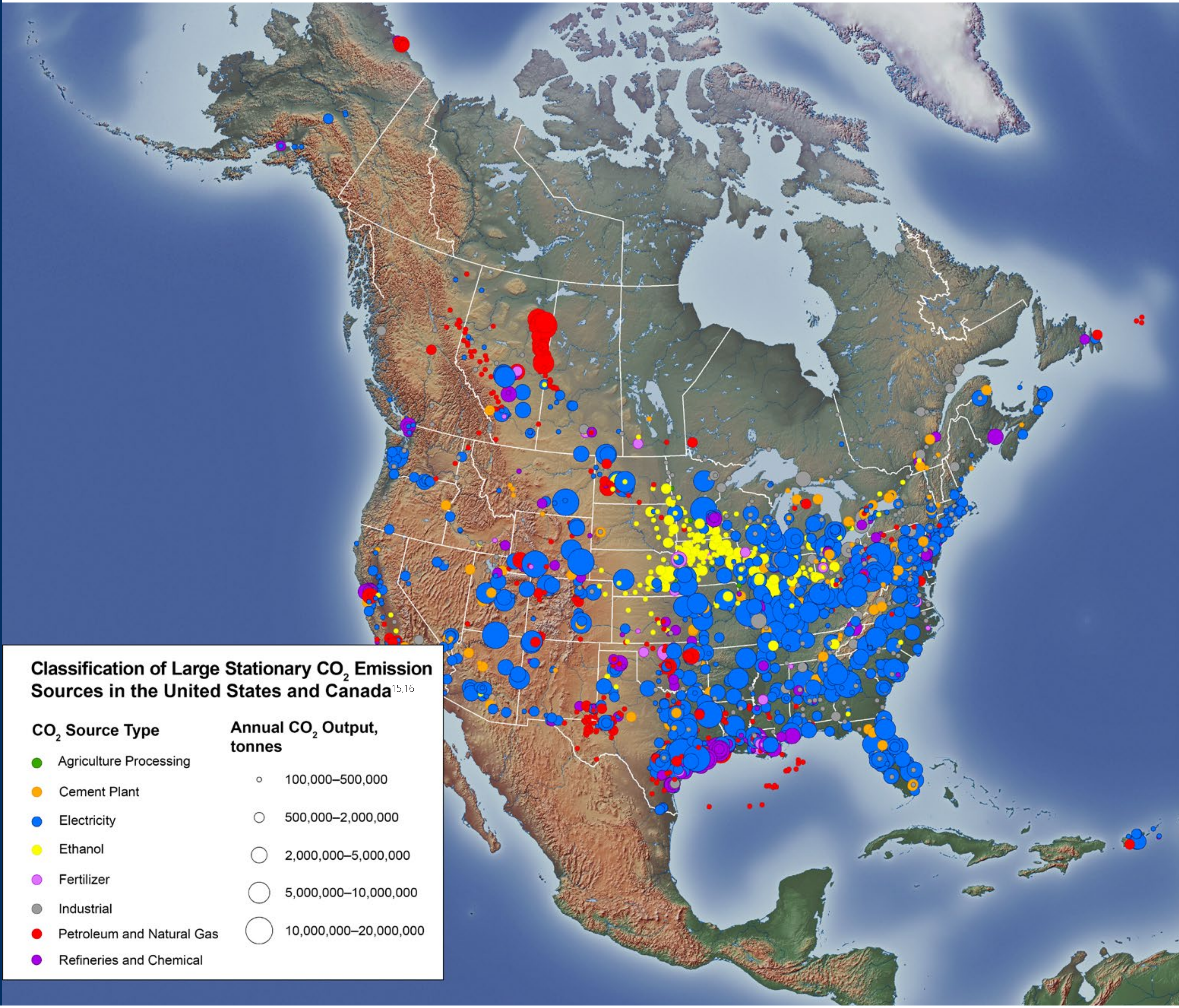
All member countries of the United Nations Framework Convention on Climate Change (UNFCCC) agreed to adopt a new global climate agreement, named the Paris Agreement, in December 2015. This agreement aims to limit the rise in global average surface temperature to well below 2°C, and preferably below 1.5°C, compared to preindustrial levels to avoid the most dangerous impacts of climate change. The Paris Agreement requires 5-year cycles of increasing climate action to be carried out by the participating countries. As of June 2021, 192 parties have submitted their first nationally determined contributions (NDCs). The NDCs are the climate actions that each country will take to contribute to reaching the goals of the Paris Agreement. Eight parties have submitted their second.[14]



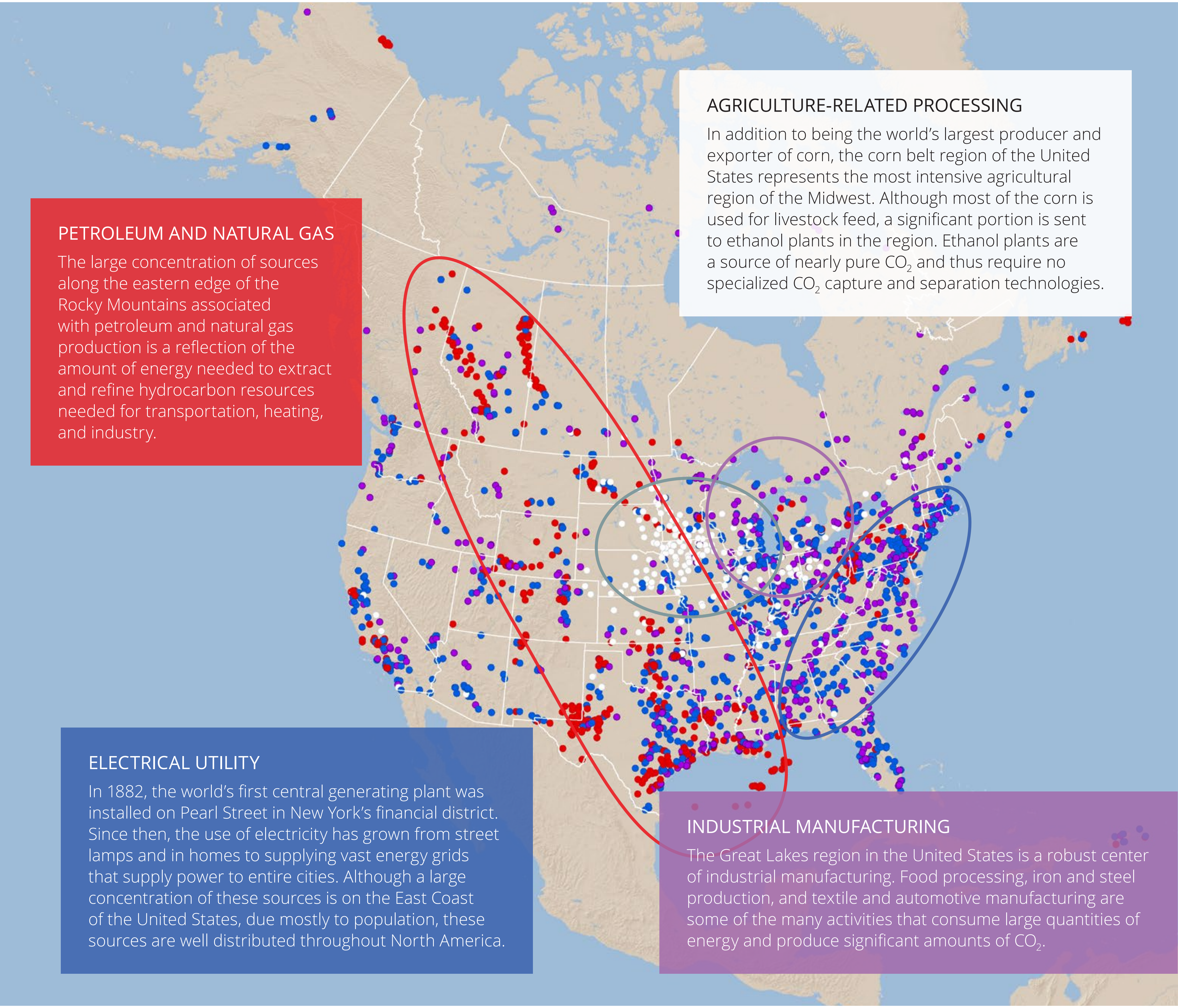
CO_2 emissions have strong ties to economic activity. Even economies with lower CO_2 emissions in 2018 may be net importers of CO_2 emissions from trade,[12] highlighting the need for a global focus on strategies to reduce emissions.

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

U.S. AND CANADIAN CO_2 SOURCES



U.S. AND CANADIAN PROFILE



AGRICULTURE-RELATED PROCESSING

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

PETROLEUM AND NATURAL GAS

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

ELECTRICAL UTILITY

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

INDUSTRIAL MANUFACTURING

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

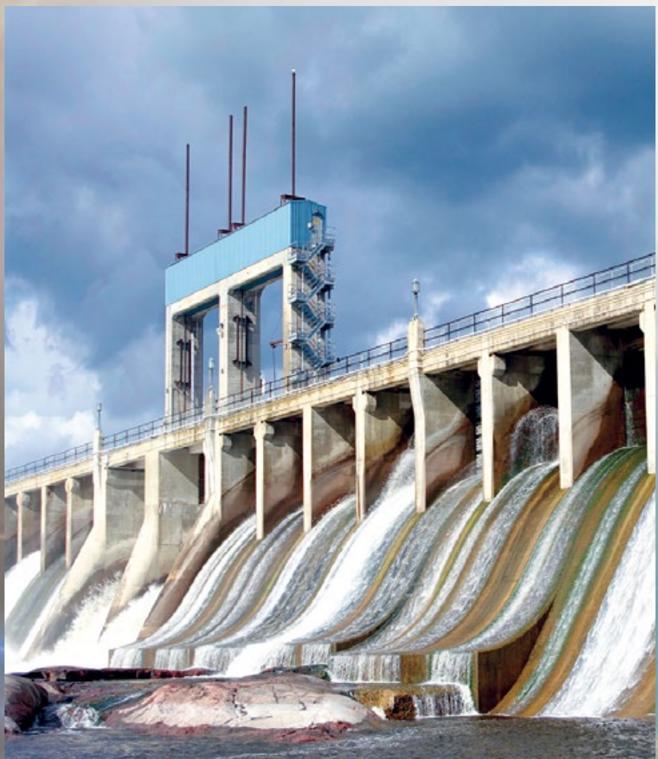
FINDING A CO_2 SOLUTION

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

A number of techniques can be employed to reduce CO_2 emissions, including 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, CCUS provides an opportunity to combine the continued use of fossil fuels with a significant reduction in GHG emissions. CCUS lies at the intersection of energy, the economy, and the environment, which makes it a critical approach to meet our world's clean energy needs. The PCOR Partnership is working to ensure that CCUS is developed and implemented in a practical and environmentally sound manner.

CCUS captures around 40 million metric tons of CO_2 per year worldwide, with 17 new CCUS projects coming online in 2020.[17]

Global Status of CCS Report 2020

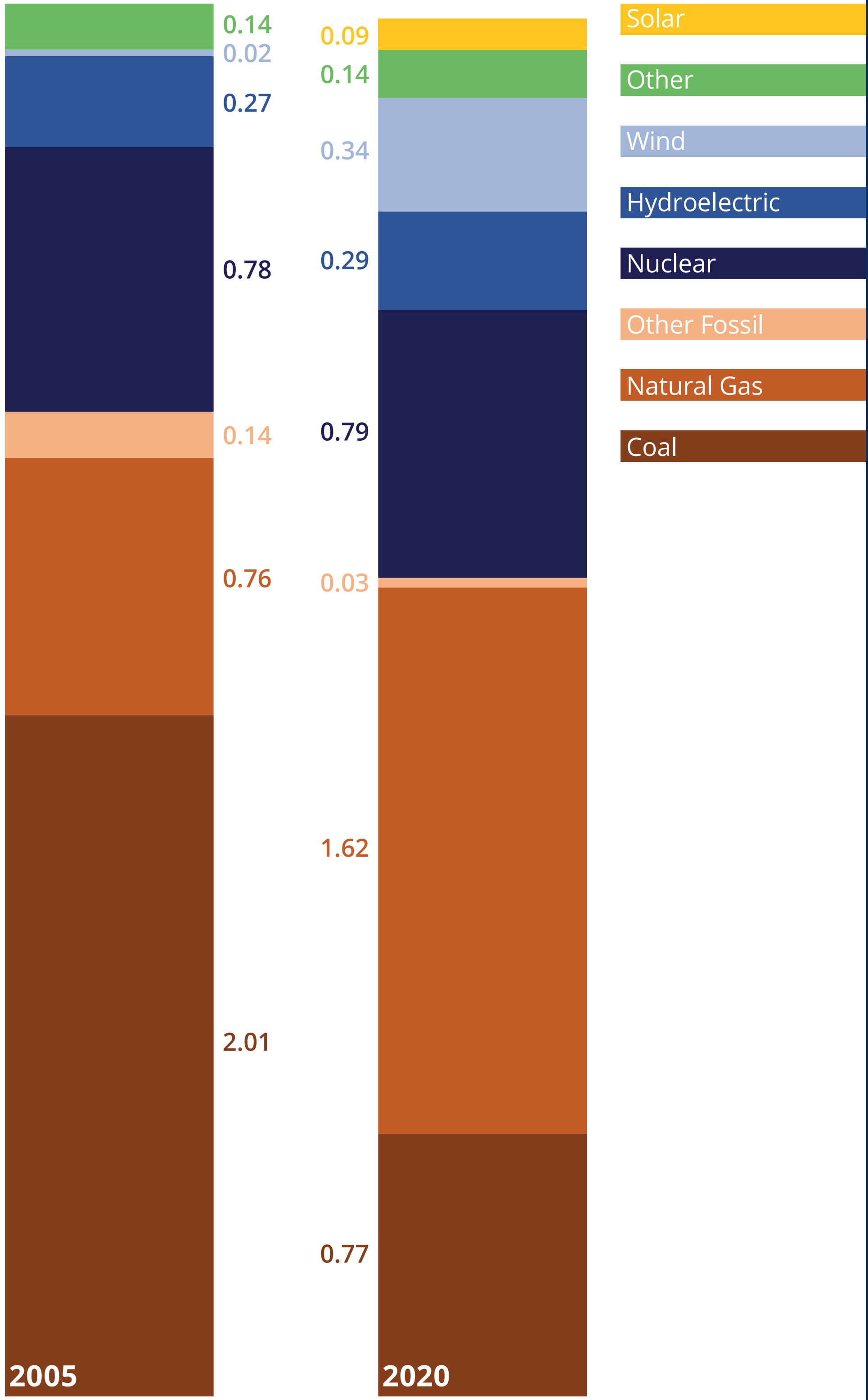


Over the past 15 years, increasing concerns over the potential impacts of climate change and increasing competition from natural gas and renewable energy sources have caused a significant shift in the U.S. energy production profile. Today coal generates about 20% of the U.S. net power generation—down from 50% in 2005. Although much of that decrease has been offset by natural gas power generation, an increasingly larger portion of power generation is coming from low-carbon renewables, such as wind and solar.

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

Traditional power plants equipped with CCUS technology can play an important roll to ensure that low-carbon power generation of the future can evolve without sacrificing resilience and reliability. A recent study by the International Energy Agency (IEA) concludes that when accounting for system reliability and flexibility, the competitiveness of carbon capture in the power system increases relative to other generation sources.[18] Thus CCUS-enabled power production can contribute to energy security while complementing and facilitating the increased deployment of renewables.

U.S. NET ELECTRICITY GENERATION FOR ALL SECTORS[18]
(billion MWh)



Although the total amount of electricity generated for the U.S. grid has remained relatively constant over the last 15 years, the primary energy used to generate electricity has changed dramatically. Factors in the change include the price of natural gas, tax incentives for renewables, and pressure to reduce CO_2 emissions from energy production.


CO2
CO2

CHAPTER 2

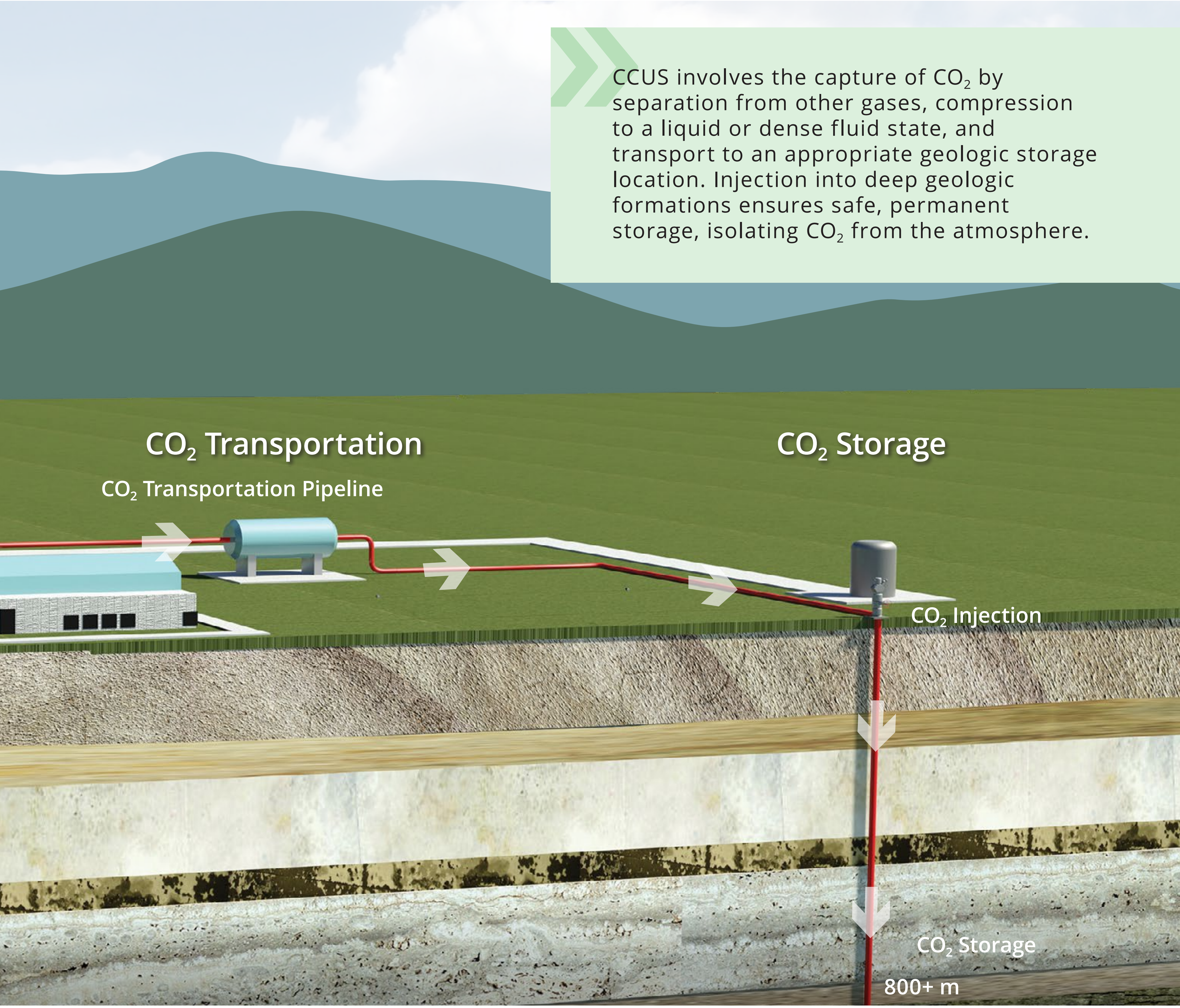
CARBON MANAGEMENT

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

CARBON CAPTURE, UTILIZATION, AND STORAGE

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

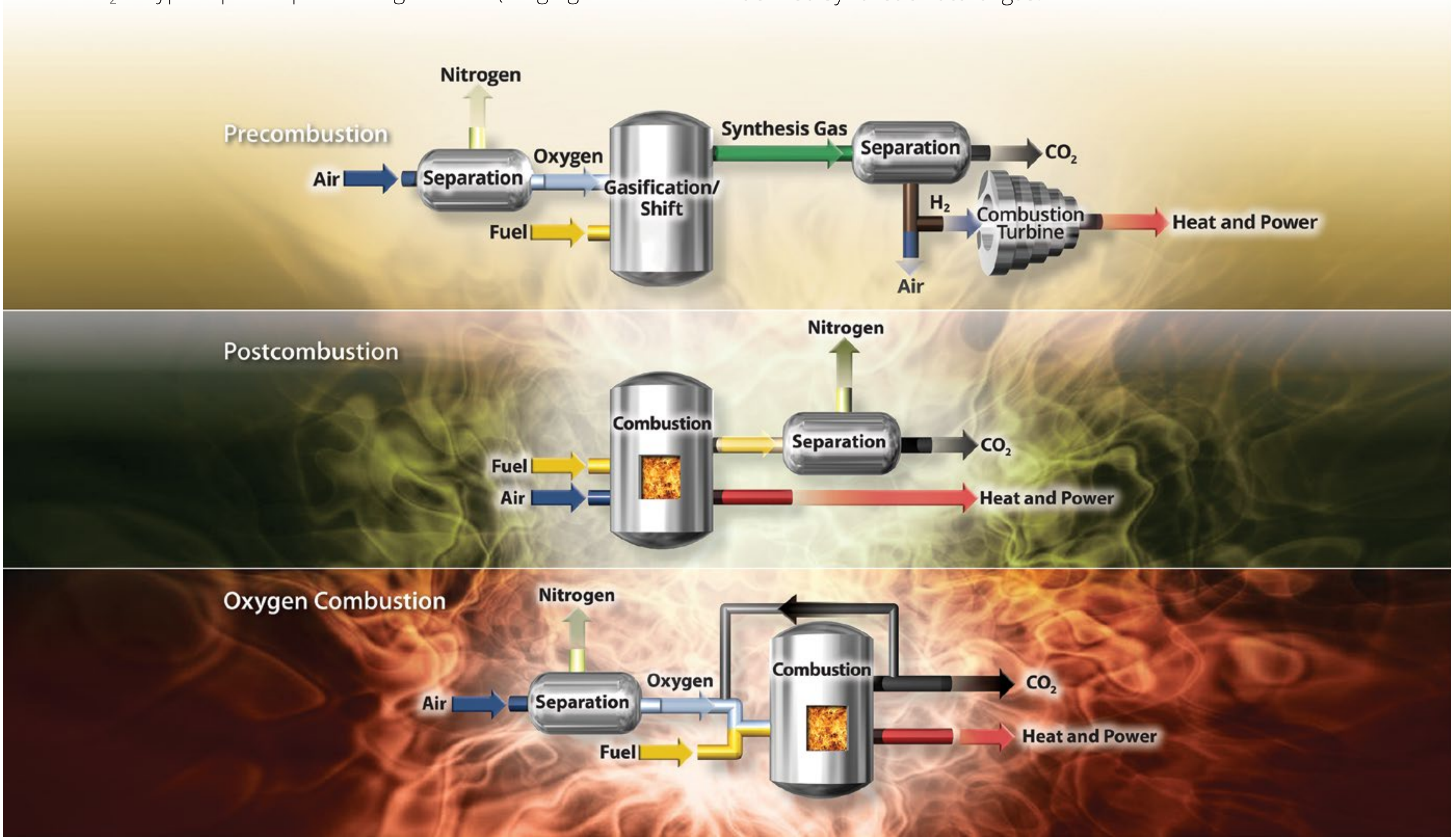
CCUS involves the capture of CO_2 by separation from other gases, compression to a liquid or dense fluid state, and transport to an appropriate geologic storage location. Injection into deep geologic formations ensures safe, permanent storage, isolating CO_2 from the atmosphere.



CO_2 CAPTURE FROM INDUSTRIAL PROCESSES

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

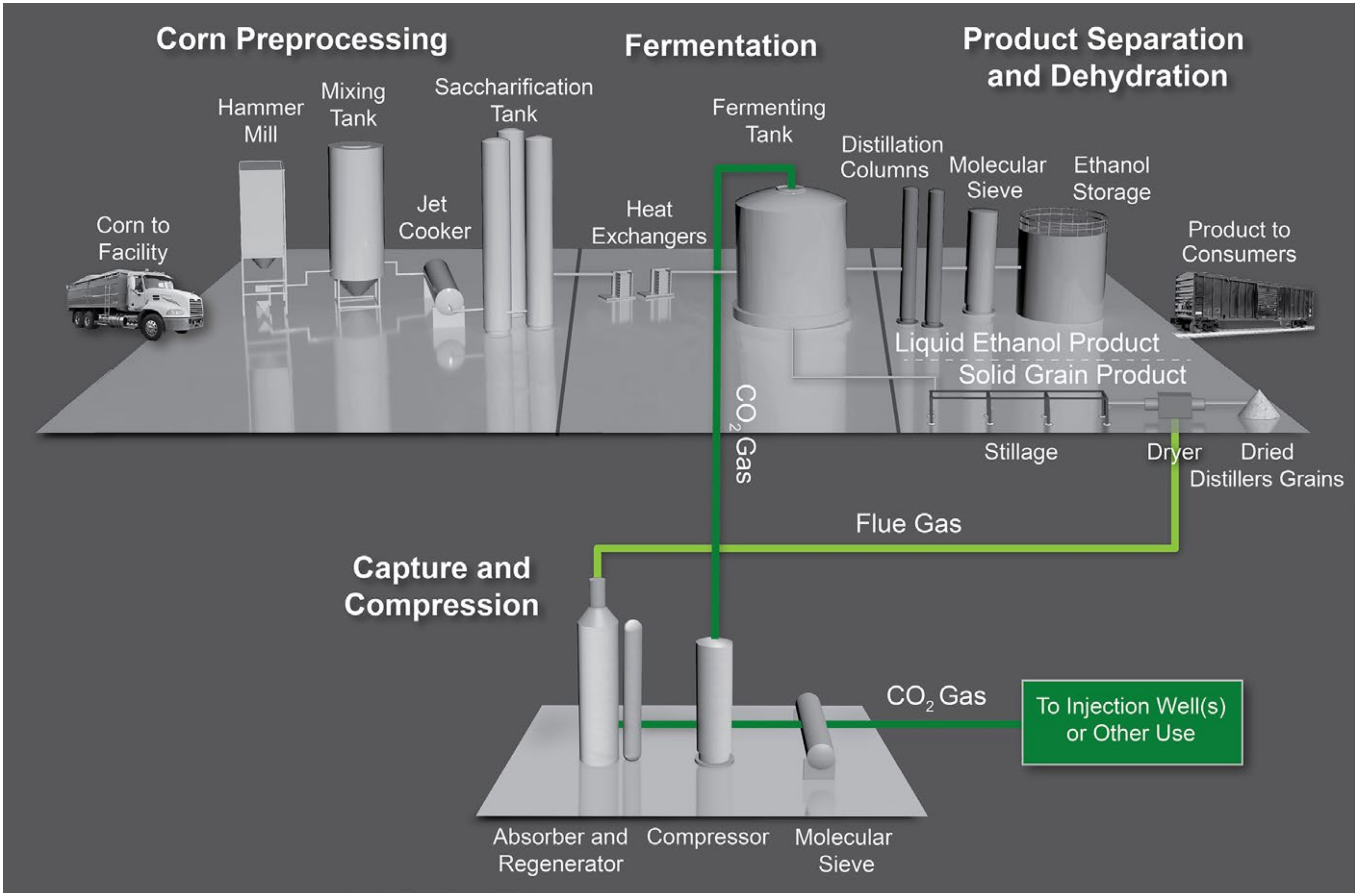
To maintain the correct boiler temperature, some flue gas is recycled to the boiler during oxygen combustion,[19] meaning that the atmosphere in the boiler is not pure oxygen but rather a mixture consisting primarily of oxygen and CO_2. Most capture technologies focus on separating low-concentration CO_2 from the exhaust gas stream after combustion takes place; this is called postcombustion capture. Because the concentration of CO_2 in typical power plant flue gas is low (ranging from 3% by volume for some natural gas-fired plants to about 13% by volume for coal-fired plants),[20] any postcombustion capture process must be sized to handle the entirety of the exhaust gas. The large scale of equipment, quantities of chemicals required, and energy needed to operate the capture system require large capital investment. The cost of capturing the CO_2 can represent 75% of the total cost of a CCUS operation.[20] Because capture is the most costly portion of a CCUS project, research is being performed to develop more efficient CO_2 capture processes and improve the economics of existing ones. CO_2 capture has been demonstrated at various scales, from pilot to commercial, in coal- and gas-fired boilers. Natural gas-processing and fertilizer industries are already capturing CO_2 at commercial scale, and the Great Plains Synfuels Plant in Beulah, North Dakota, uses precombustion techniques to separate CO_2 from its lignite-derived synthetic natural gas.



CAPTURE FROM ETHANOL PROCESSES

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

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



DIRECT AIR CAPTURE

Another CO_2 capture technology that is gaining interest is direct air capture (DAC). In this case, CO_2 is removed directly from the atmosphere by using liquid solvents or by flowing air over or through solid sorbents. An advantage of DAC is that the plant can be located near CO_2 sinks such as oil fields for use in EOR or other areas suitable for permanent geologic storage. The flexibility is that siting eliminates the need to transport the CO_2 over long distances. Disadvantages include the energy required for the process and its relative inefficiency compared to CO_2 removal from concentrated sources. Large amounts of air must be circulated over or through the sorbent material because of the small percentage of CO_2 in the atmosphere. In addition, the energy source for the capture must have a minimal carbon footprint for the whole process to be at least carbon-neutral.

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

CO_2 AND COMPRESSION

Captured CO_2 must be dehydrated and compressed into a supercritical or liquidlike state before transport to the storage site. CO_2 must be compressed to at least 1200 to 1700 pounds per square inch (psi) for transport in a pipeline to ensure that CO_2 remains in a dense liquid state.[21] Because compression is energy-intensive, improved compression methods are under development.

CO_2 TRANSPORTATION INFRASTRUCTURE

Following capture and compression, CO_2 is transported to a storage site. Given the quantities of CO_2 that are likely to be captured from industrial sources, pipelines are the most efficient mode for transporting the captured gas to geologic storage sites. Currently, more than 8000 km (5000 miles) of CO_2 pipeline is in service in North America, with additional pipeline planned or under construction.[21]

Image provided by Denbury Resources Inc.

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

Building a regional CO_2 pipeline infrastructure for CCS activities will require thoughtful planning. Pipelines may be built to connect individual CO_2 sources and storage sites in a "point-to-point" fashion; however, pipelines may also be used to connect multiple sources and storage sites in a network. Network options may offer reduced overall costs, but common carrier issues such as those related to CO_2 stream quality may need to be addressed.

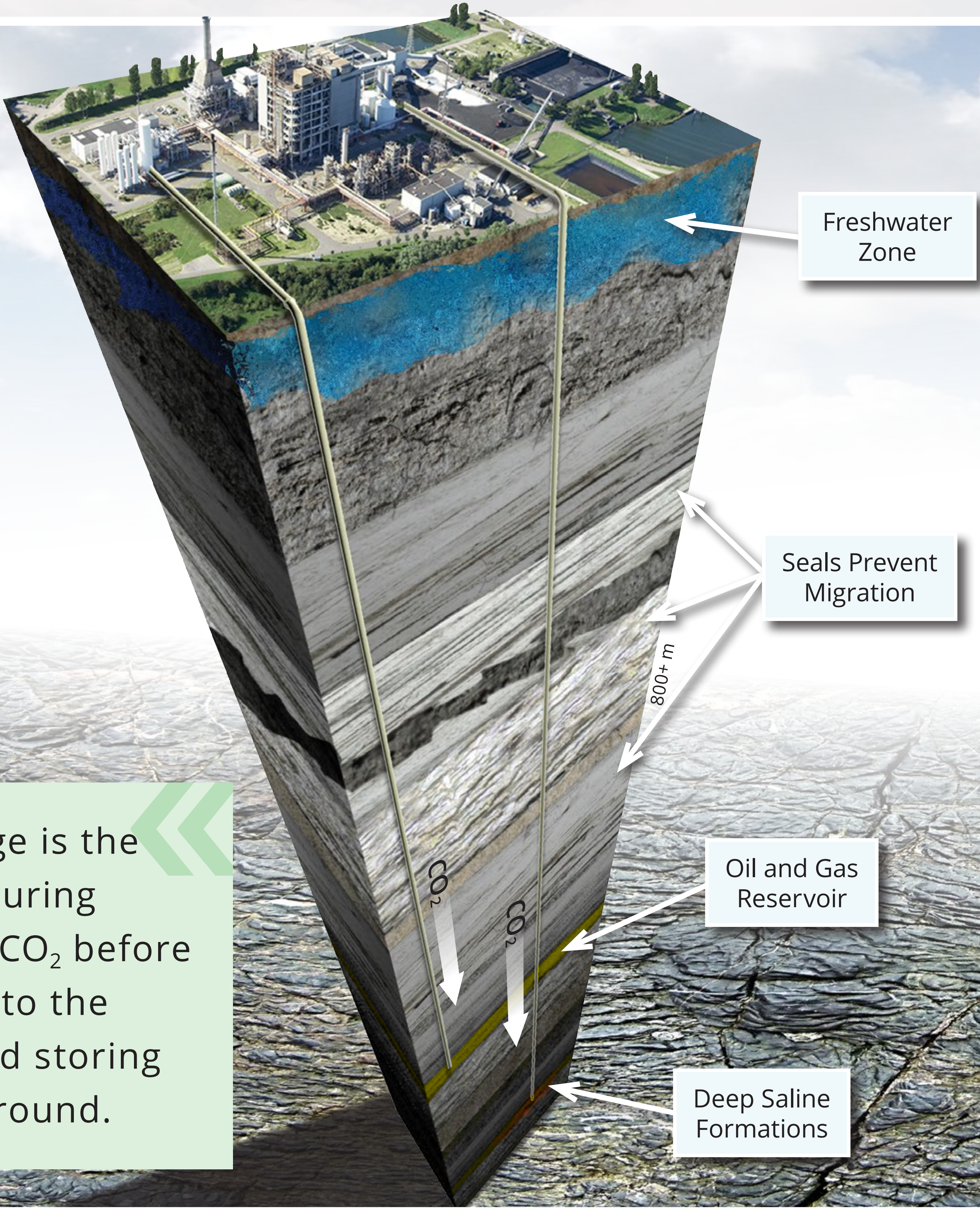
Pipelines carrying CO_2 have an excellent safety record. Strategies undertaken to manage risks include fracture arresters approximately every 300 m, block valves to isolate pipe sections if they leak, the use of advanced seals, and automatic control systems that monitor volumetric flow rates and pressure.

NO serious human injuries or fatalities have been reported as a result of CO_2 transport via pipeline.[22]

Image provided by Denbury Resources Inc.

Image provided by Denbury Resources Inc.

SECURE GEOLOGIC STORAGE



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

GEOLOGIC STORAGE CRITERIA

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

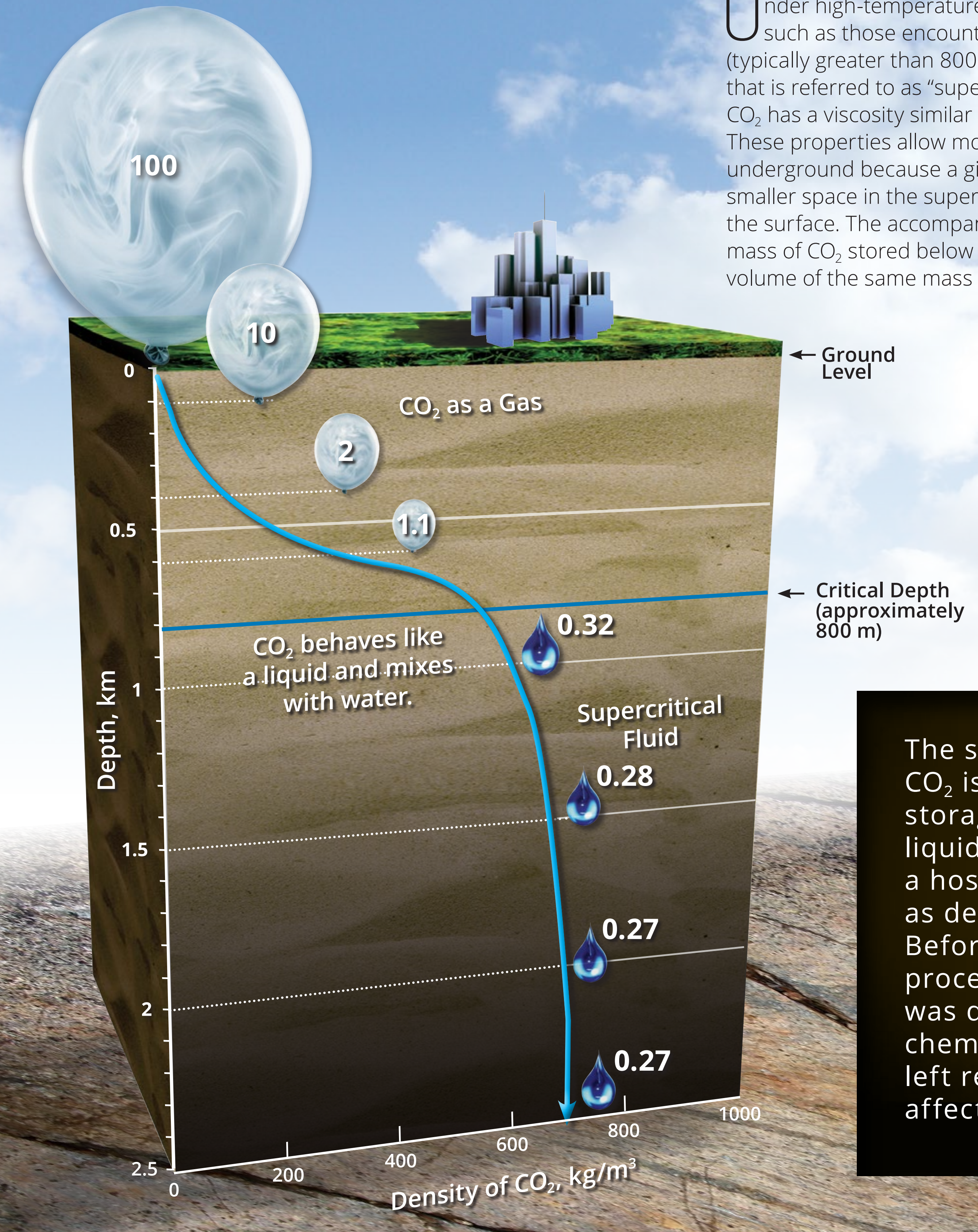
STORAGE RESERVOIR CHARACTERISTICS

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

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

SUPERCRITICAL CO_2

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



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

TRAPPING CO_2 IN ROCKS

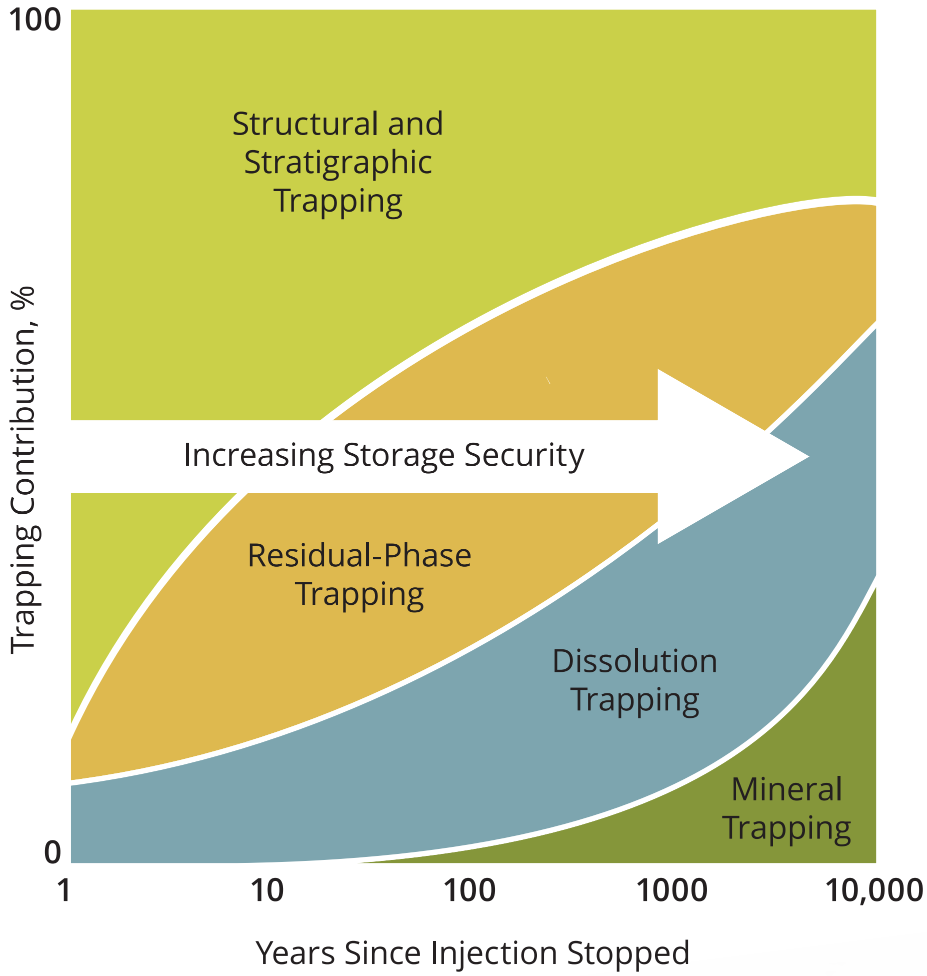
Several mechanisms function to trap and store CO_2 in deep geologic formations.[20]

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

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

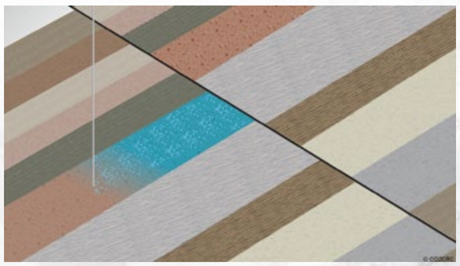
DISSOLUTION TRAPPING – Just as sugar dissolves in water, some of the CO_2 will dissolve into brine in the pore spaces. Brine with dissolved CO_2 becomes denser than the surrounding brine and will sink to the bottom of the reservoir, minimizing the possibility of further migration.

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

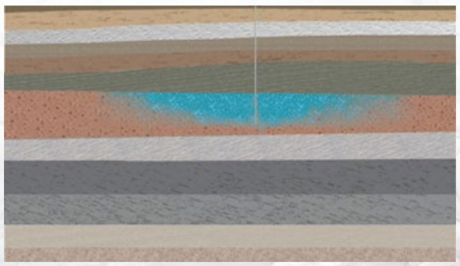


As time passes after the injection of CO_2 into a deep geologic environment, the trapping mechanism becomes more effective. Storage security increases as the trapping mechanism moves from the physical process of structural and stratigraphic trapping toward geochemically based processes.

Structural and Stratigraphic Trapping

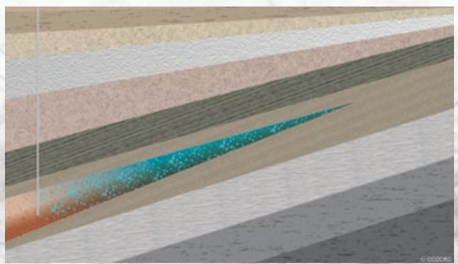


A sealing fault can line up an impervious rock layer with the formation to prevent the CO_2 from moving upward out of the formation.



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

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



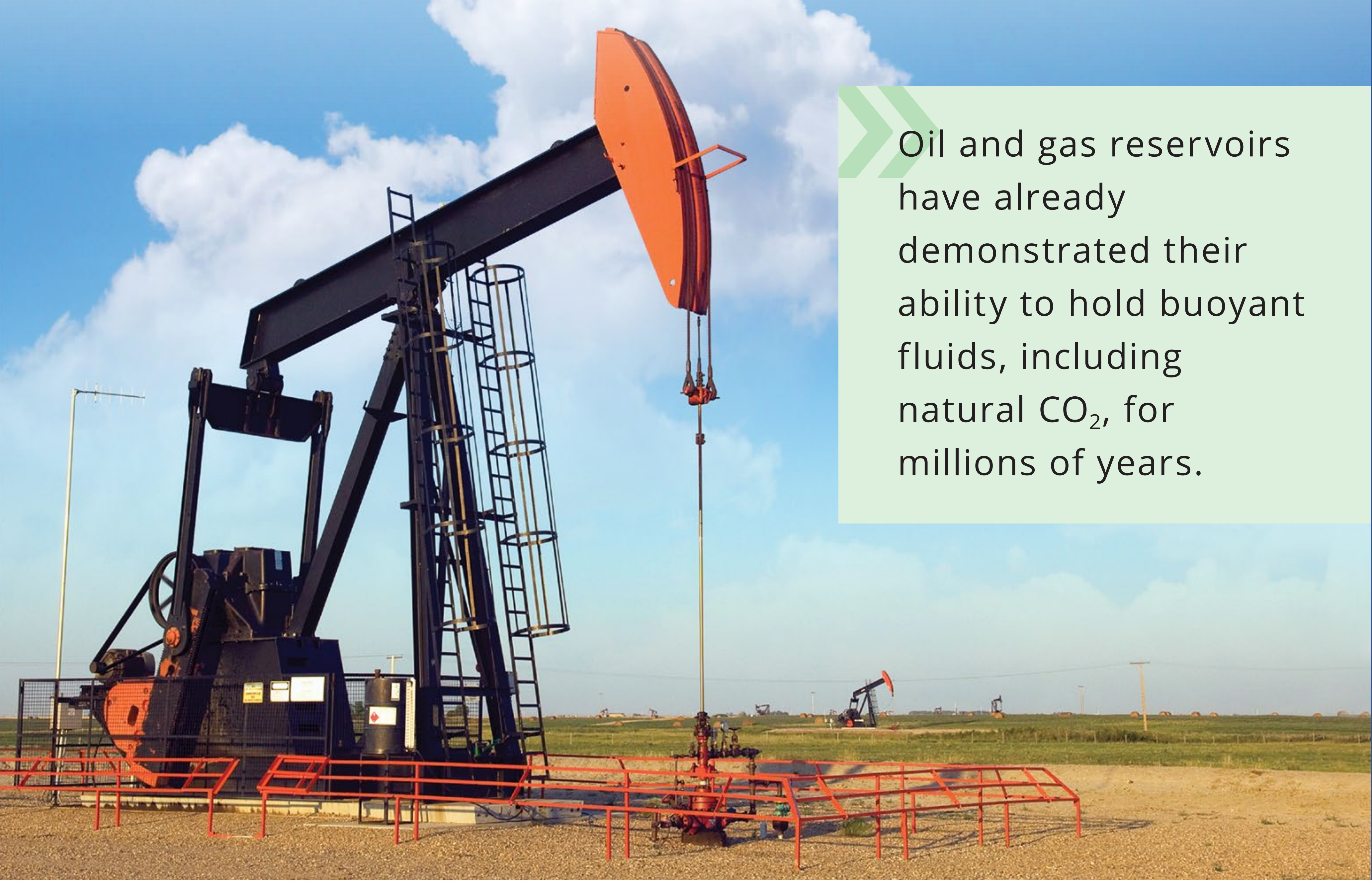
CO_2 can become trapped when there is a change in the type of rock in the formation from a permeable rock to an impermeable rock.

OIL FIELDS OF THE UNITED STATES AND CANADA

CO_2 IN OIL FIELDS

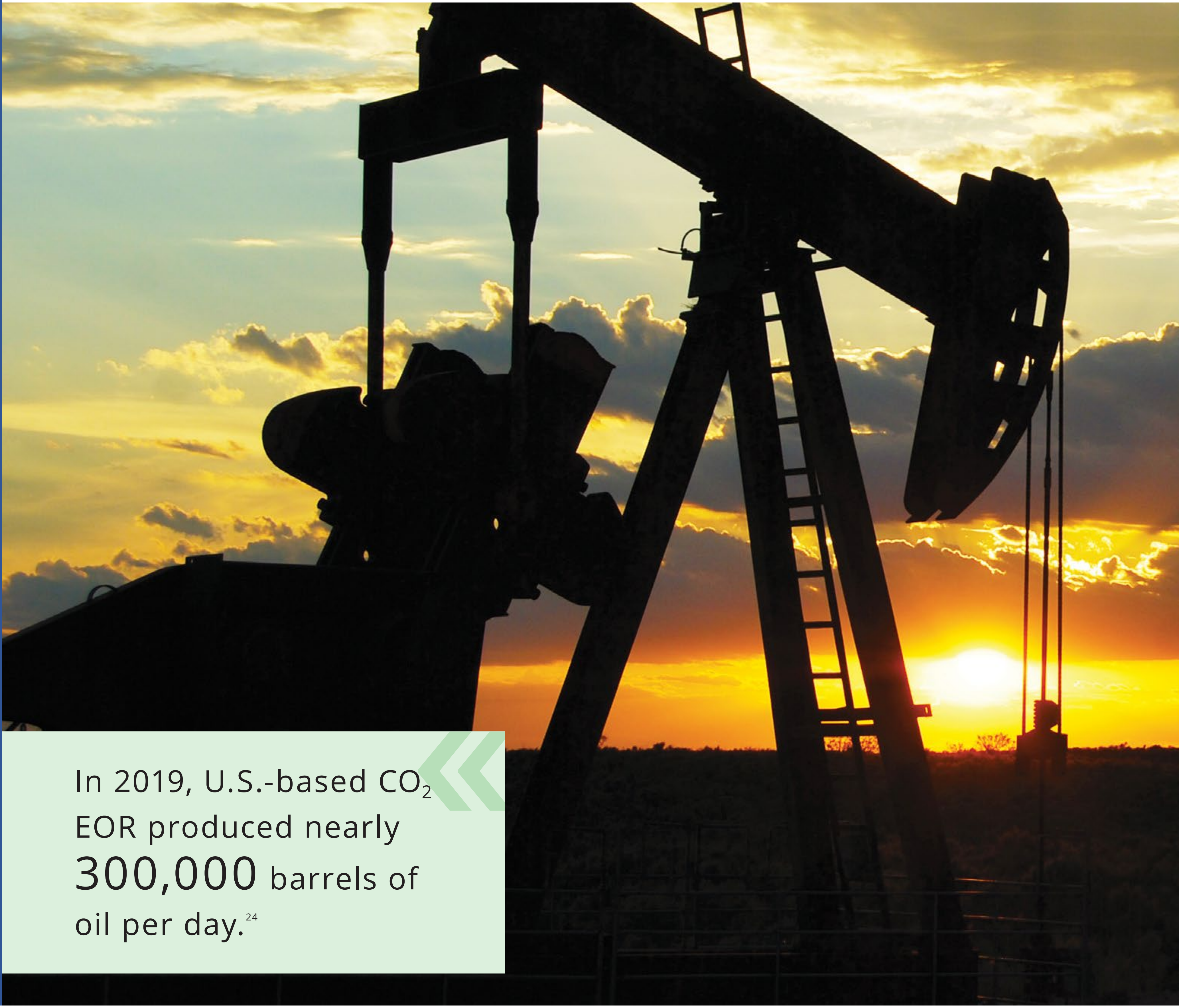
The geology of CO_2 storage is analogous to the geology of petroleum exploration: the search for oil is the search for stored hydrocarbons. Oil fields have many characteristics that make them excellent target locations to store CO_2. Therefore, the geologic conditions that are conducive to hydrocarbon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

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



> Oil and gas reservoirs have already demonstrated their ability to hold buoyant fluids, including natural CO_2, for millions of years.

ENHANCED OIL RECOVERY



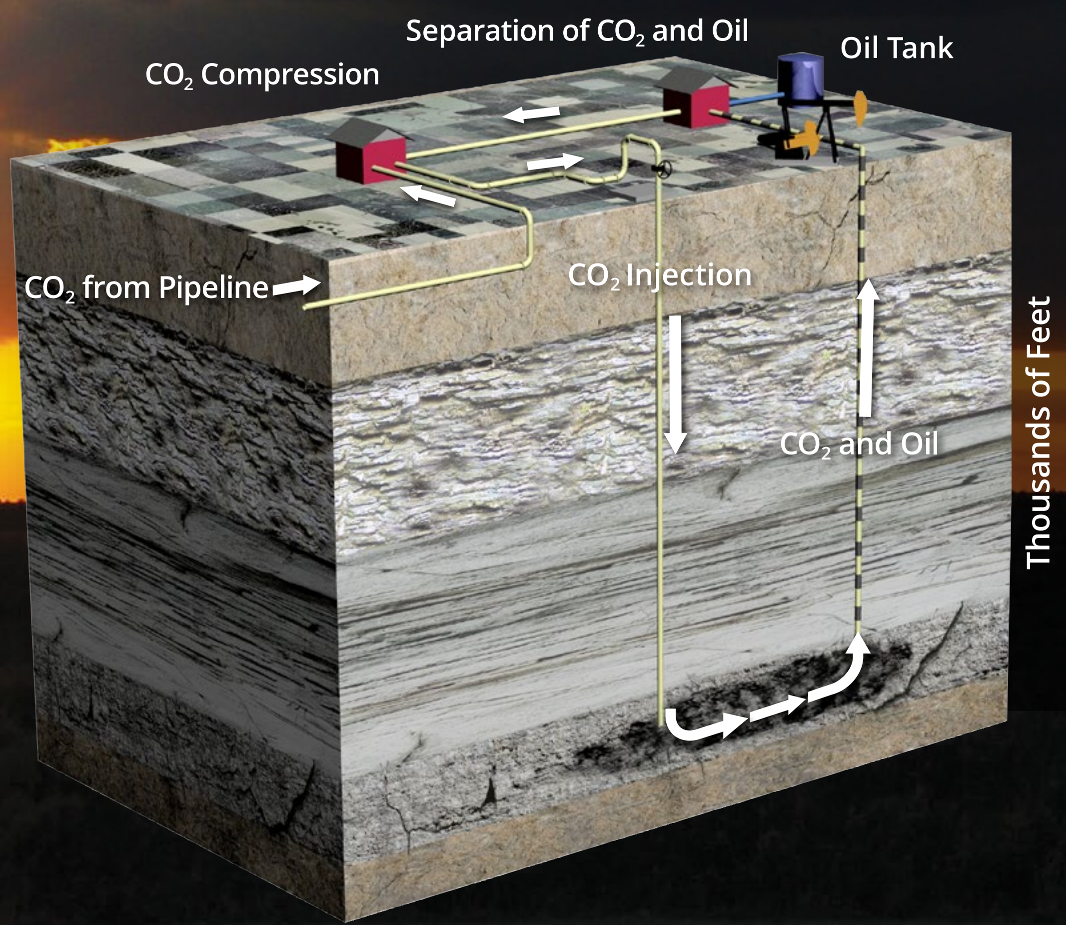
In 2019, U.S.-based CO_2 EOR produced nearly **300,000** barrels of oil per day.[24]

CO_2 GETS THE OIL OUT

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

HOW EOR WORKS:

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



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

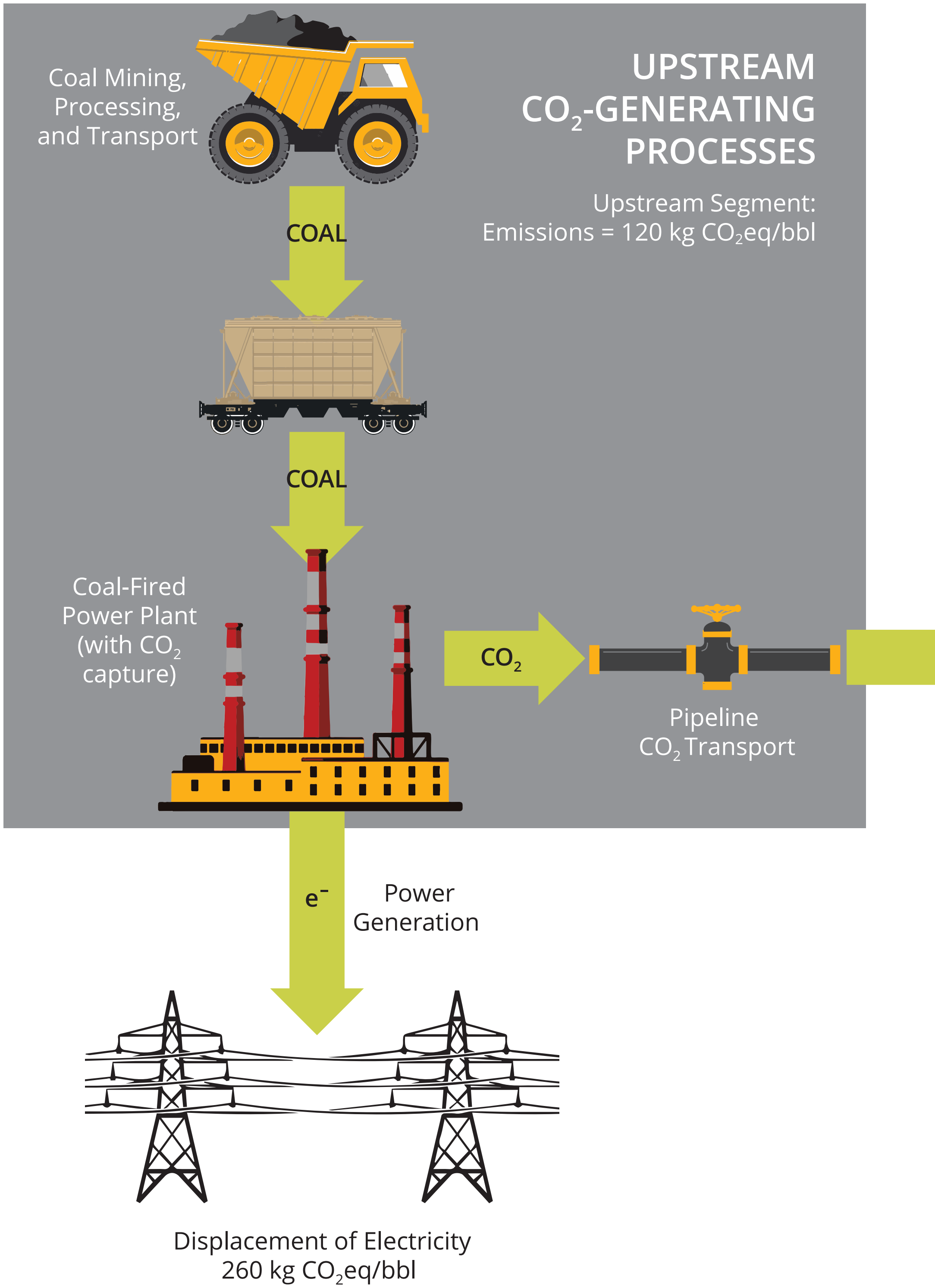
Since the 1970s, operators in West Texas have safely pumped millions of tonnes of CO_2 into oil fields for EOR purposes. The success of the technique has seen a steady increase in the number of fields (now over 130) employing CO_2 EOR in West Texas and other states. Although a majority of CO_2 used in this process is sourced from natural underground deposits, the proportion of CO_2 derived from the capture of anthropogenic emissions is increasing. CO_2 EOR has also been deployed for two decades or more in Canada, and in recent years, China, Saudi Arabia, Brazil, and Mexico have begun pilot- or full-scale projects.

CO_2 EOR LIFE CYCLE ANALYSIS

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

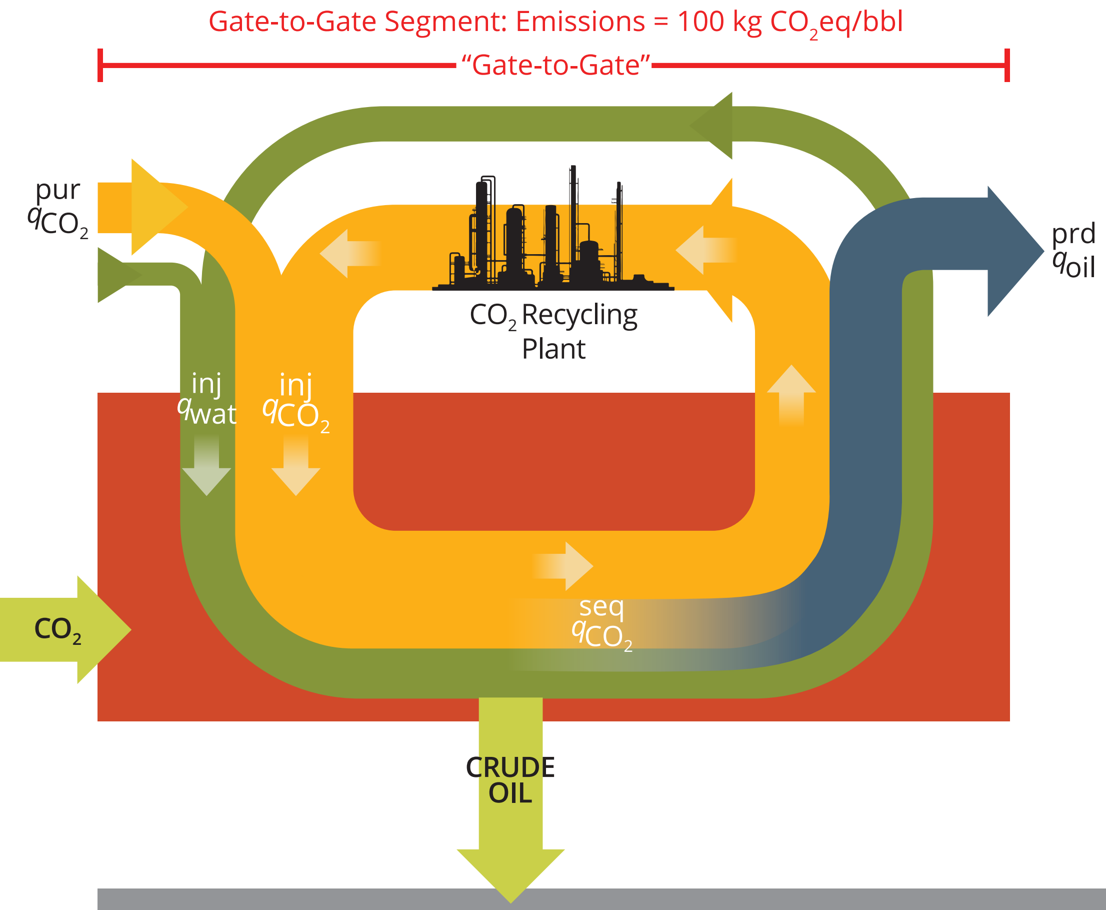
The Energy & Environmental Research Center (EERC) conducted a detailed LCA of CO_2 emissions associated with a generic CO_2 EOR project where the CO_2 was sourced from a coal-fired power plant.[25] The modeled system included three segments: upstream, gate-to-gate, and downstream CO_2-generating processes. Upstream processes included coal extraction and processing, transport, power generation with CO_2 capture, and CO_2 transport to the CO_2 EOR field. Gate-to-gate processes included CO_2 stored at a reservoir, land use, injection and recovery, bulk separation and storage of fluids and gases, and other supporting processes such as venting and flaring gases. Downstream processes included crude oil transport, refining, fuel transport, and combustion. The average total CO_2 equivalent (CO_2eq) emissions from upstream, gate-to-gate, and downstream segments were 690 kg CO_2eq/bbl.

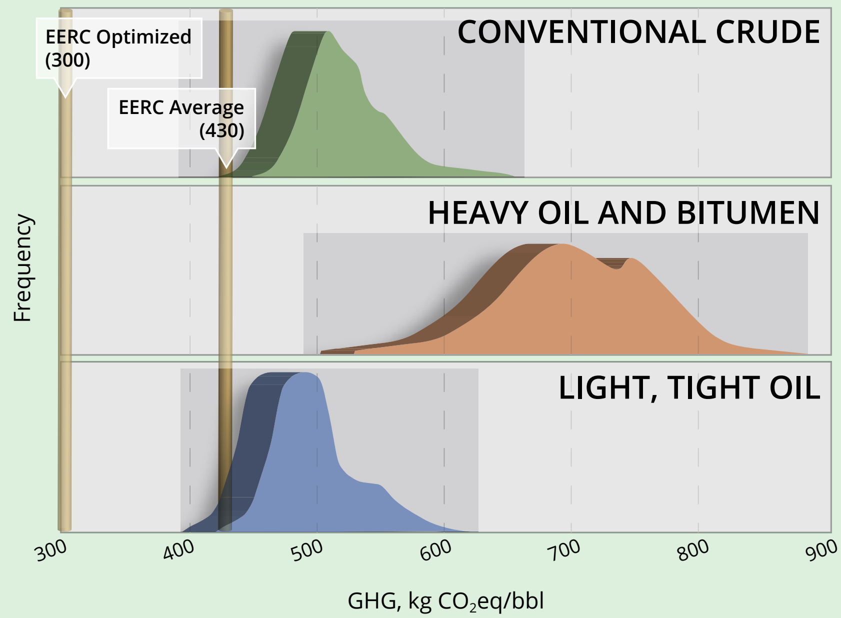
However, since 85% or more of the required CO_2 was captured at the power plant, emissions associated with electricity generation were significantly reduced. This electricity coproduct displaced alternative sources of electricity from the U.S. electricity grid; i.e., each new MWh produced with CO_2 capture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



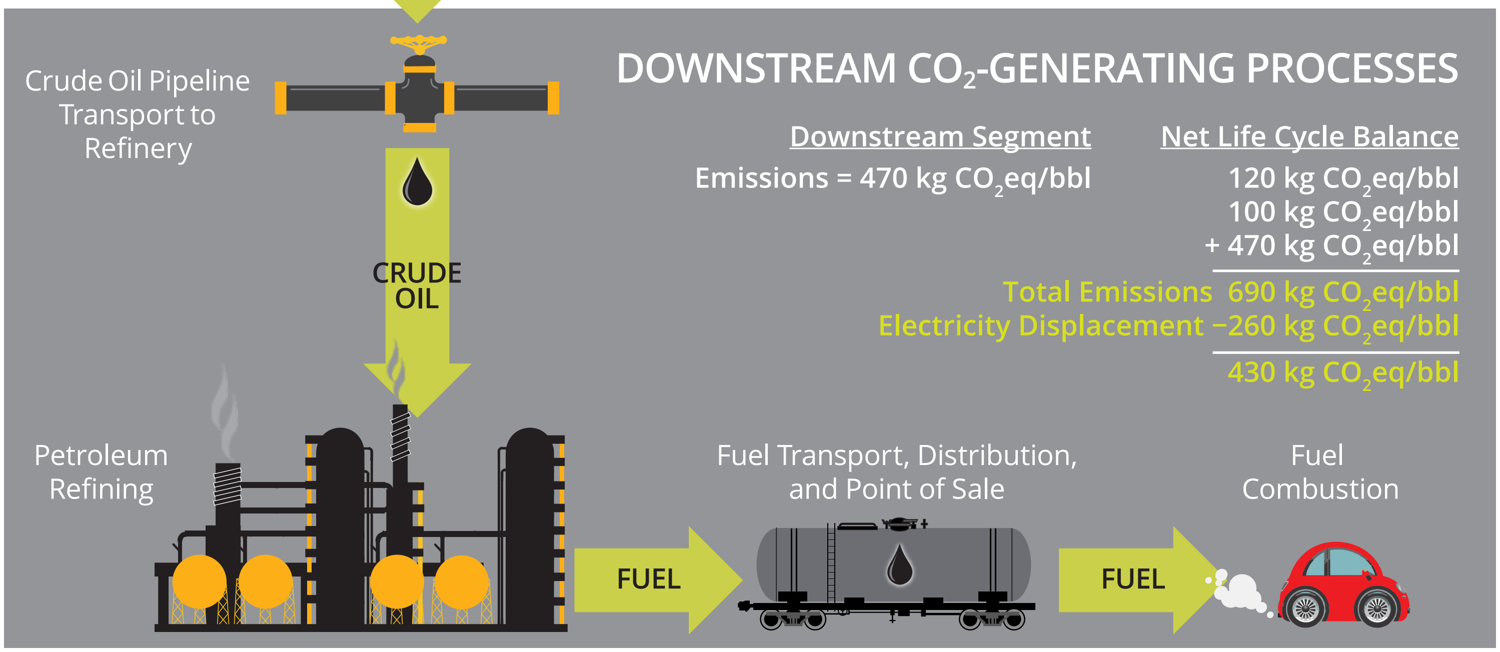
Note: Emissions are expressed as CO_2eq, which include CO_2, CH_4, and N_2O.

CO_2 EOR OPERATIONS (gate-to-gate)





Life cycle emission distributions for conventional crude (top), heavy oil and bitumen (middle), and light, tight oil (bottom).[26] Most conventional crude oil contains about 500 kg CO_2eq/bbl. Yellow bars indicate EERC estimates from a detailed LCA of GHG emissions associated with CO_2 EOR where the CO_2 is sourced from a coal-fired power plant. The average value (430 kg CO_2eq/bbl) represents the LCA result when all inputs are set to their mean values, and the optimized value (300 kg CO_2eq/bbl) represents the LCA results when all inputs are set to maximize CO_2 storage and minimize the oil GHG emissions.



NORTH AMERICAN SEDIMENTARY BASINS

CO_2 IN SALINE FORMATIONS

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

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

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

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

PUTTING TDS LEVELS INTO PERSPECTIVE

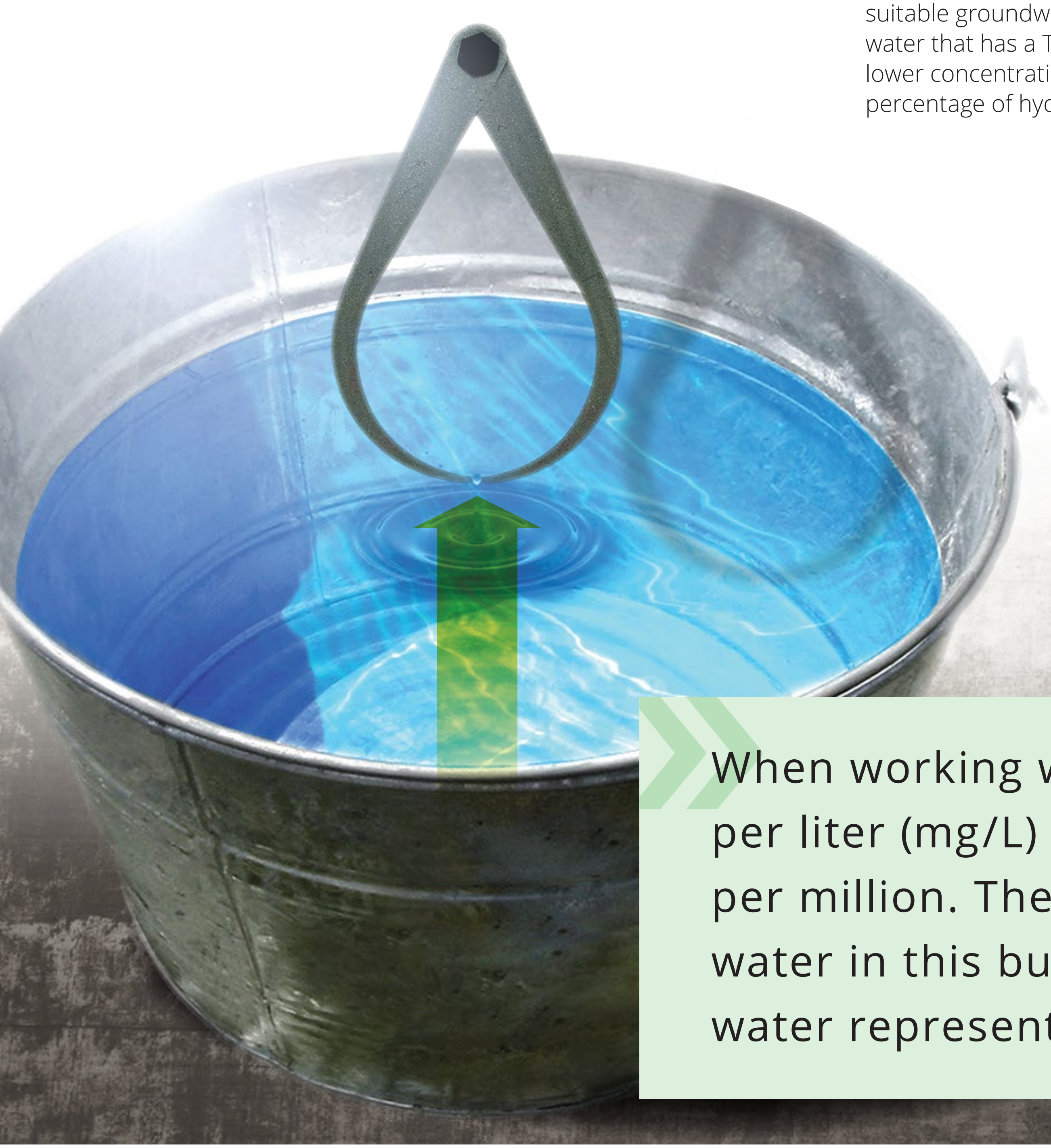
Water Source	TDS, mg/L
Lake Superior[28]	~63
Missouri River[29]	~250
Drinking Water[30]	<500*
Ocean Water[31]	35,000
Great Salt Lake[32]	50,000 to 270,000
Dead Sea[33]	350,000

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

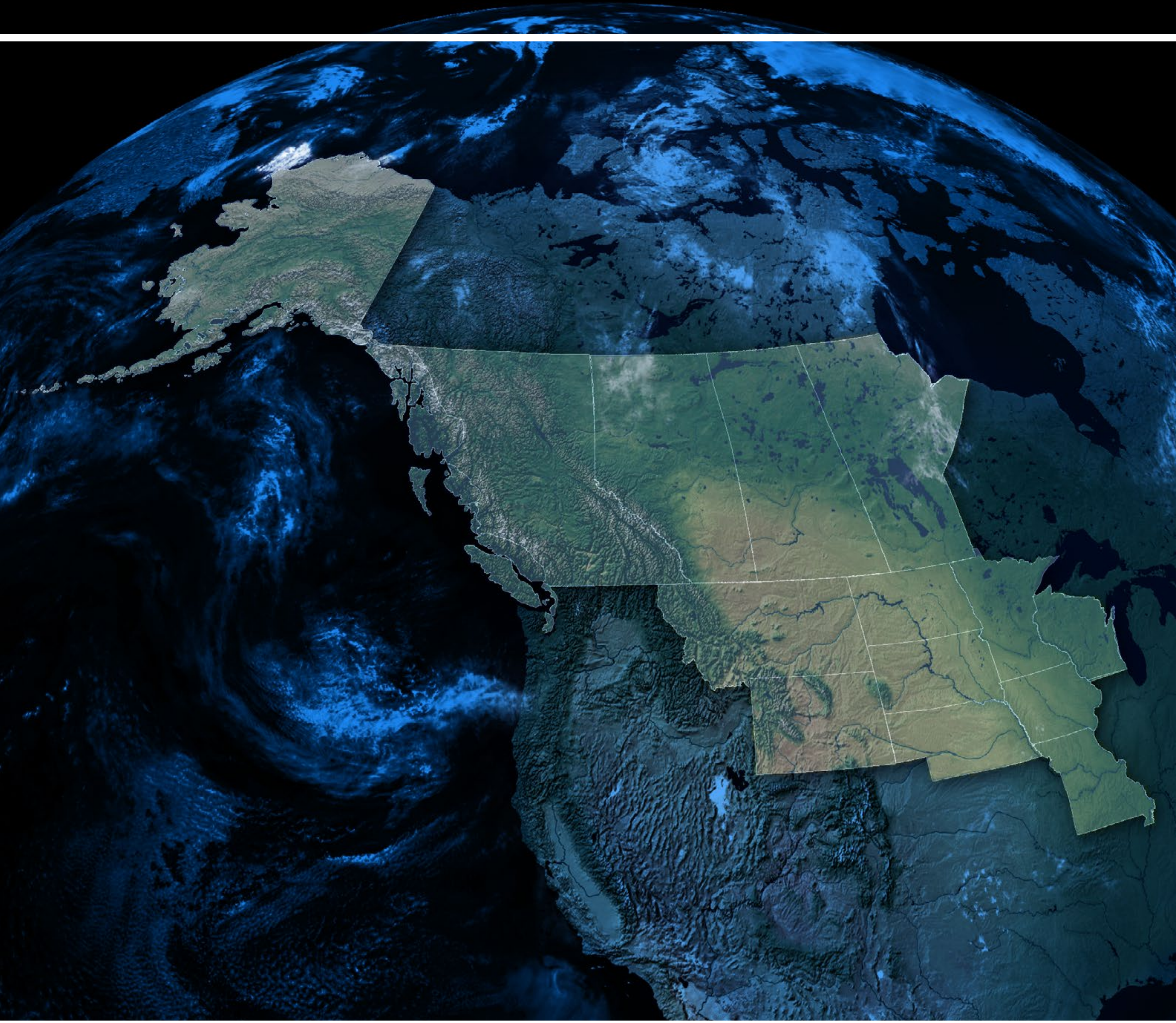
SALINITY

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

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

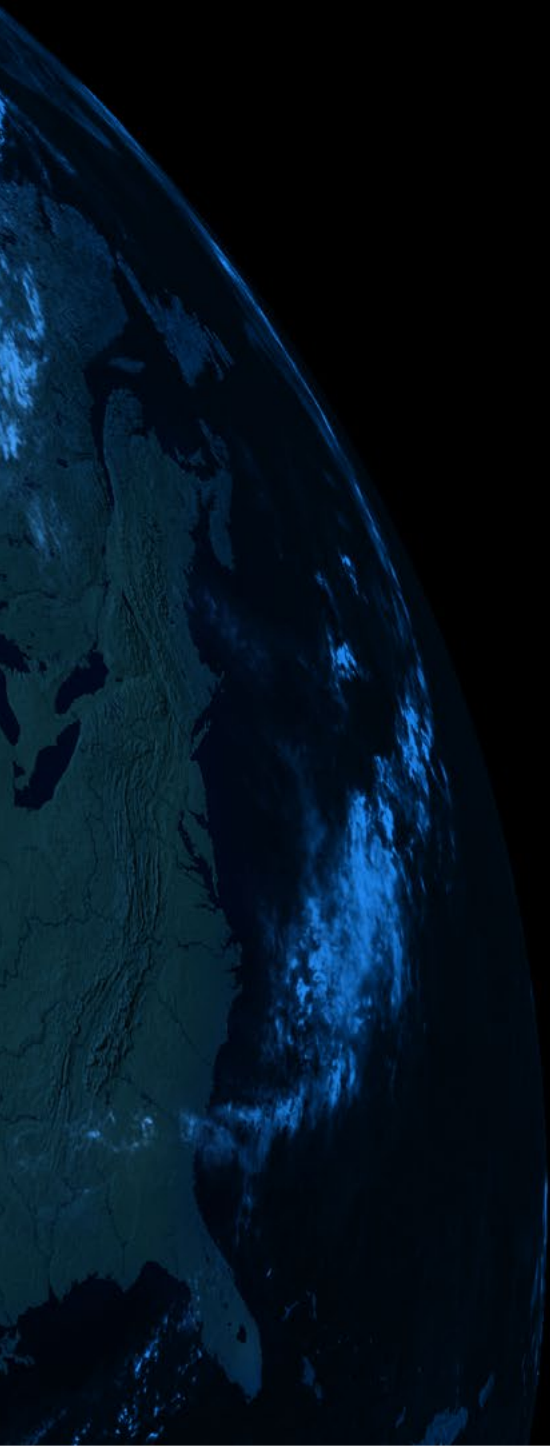


When working with water, 1 milligram per liter (mg/L) is equivalent to 1 part per million. There are 1 million drops of water in this bucket. One drop of this water represents 1 part per million.



CHAPTER 3

THE PCOR PARTNERSHIP

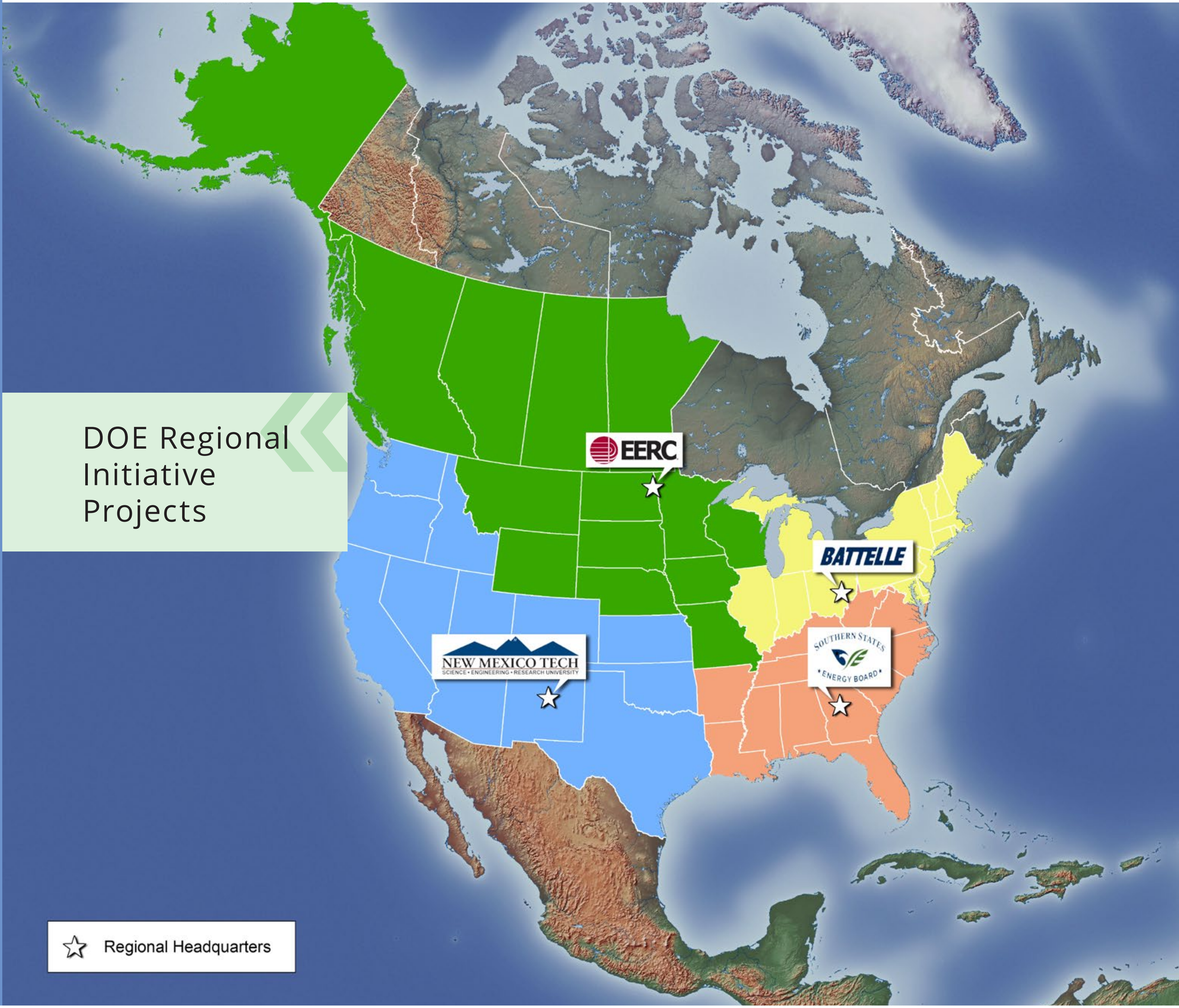


Because CCUS requires a new combination of existing and novel technologies, research and demonstration efforts are needed to advance our knowledge of their potential to better manage CO_2. The PCOR Partnership is assessing and prioritizing the opportunities for CO_2 storage in the region and working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

PCO2R Partnership

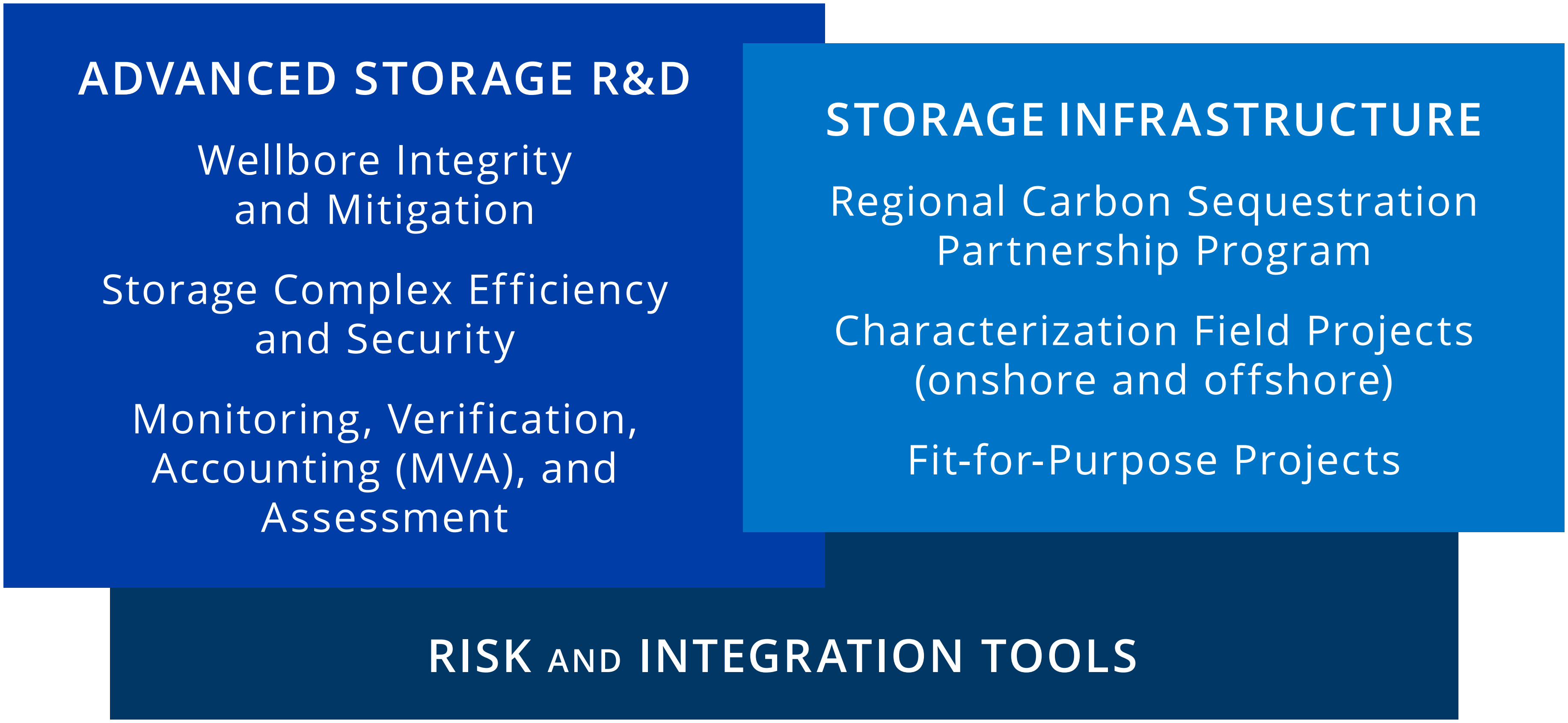
THE RCSP INITIATIVE PROGRAM

DOE Regional Initiative Projects



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

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



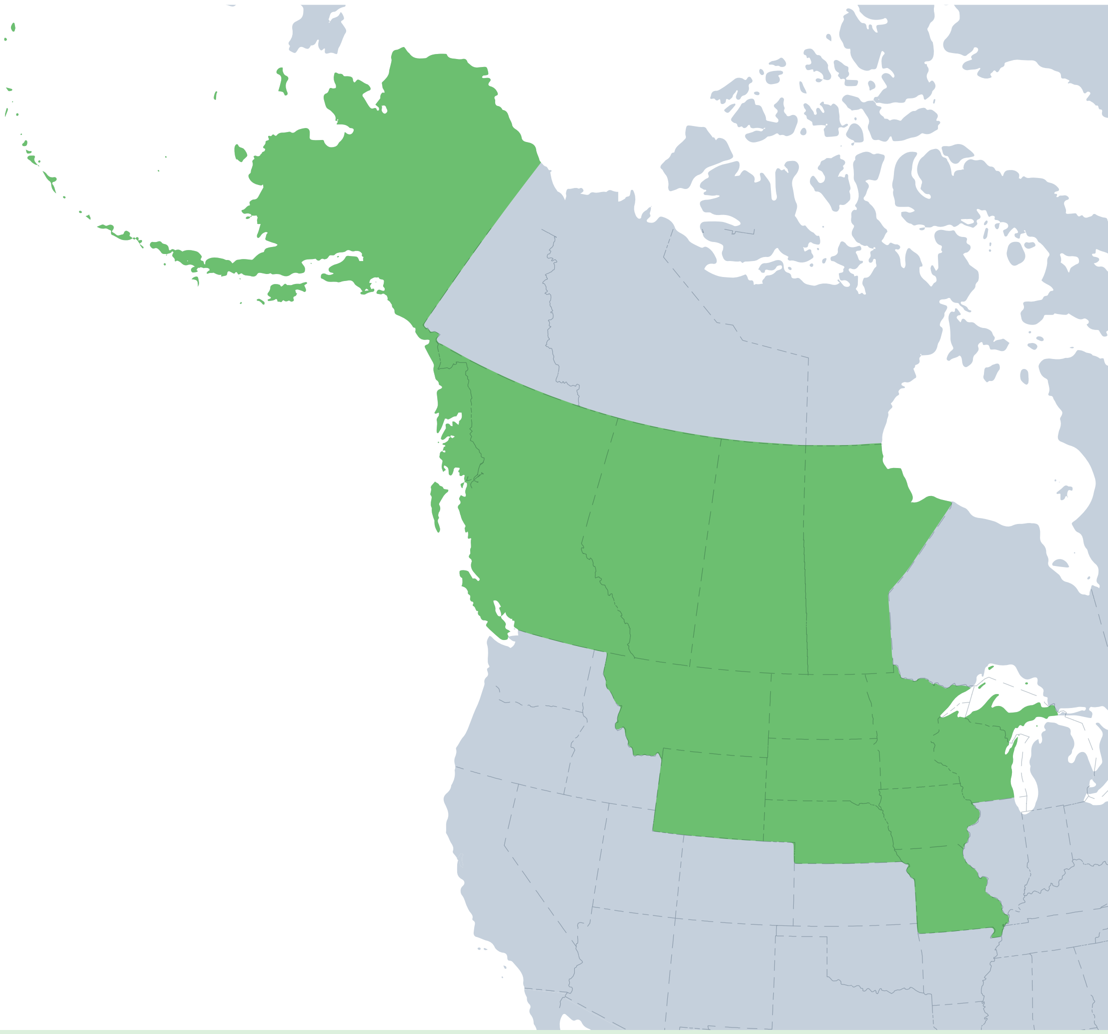
THE DOE CARBON STORAGE PROGRAM[34] comprises three technology areas: Storage Infrastructure, Advanced Storage R&D, and Risk and Integration Tools, which is a crosscutting technology research effort linking Advanced Storage R&D and Storage Infrastructure.

PCOR PARTNERSHIP INITIATIVE REGION

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

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

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



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

NATIONAL ENERGY TECHNOLOGY LABORATORY

EERC UND UNIVERSITY OF NORTH DAKOTA

North Dakota Industrial Commission

UAF Institute of Northern Engineering
University of Alaska Fairbanks

University of Wyoming School of Energy Resources

PHASED APPROACH

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

PHASE I (CHARACTERIZATION PHASE)

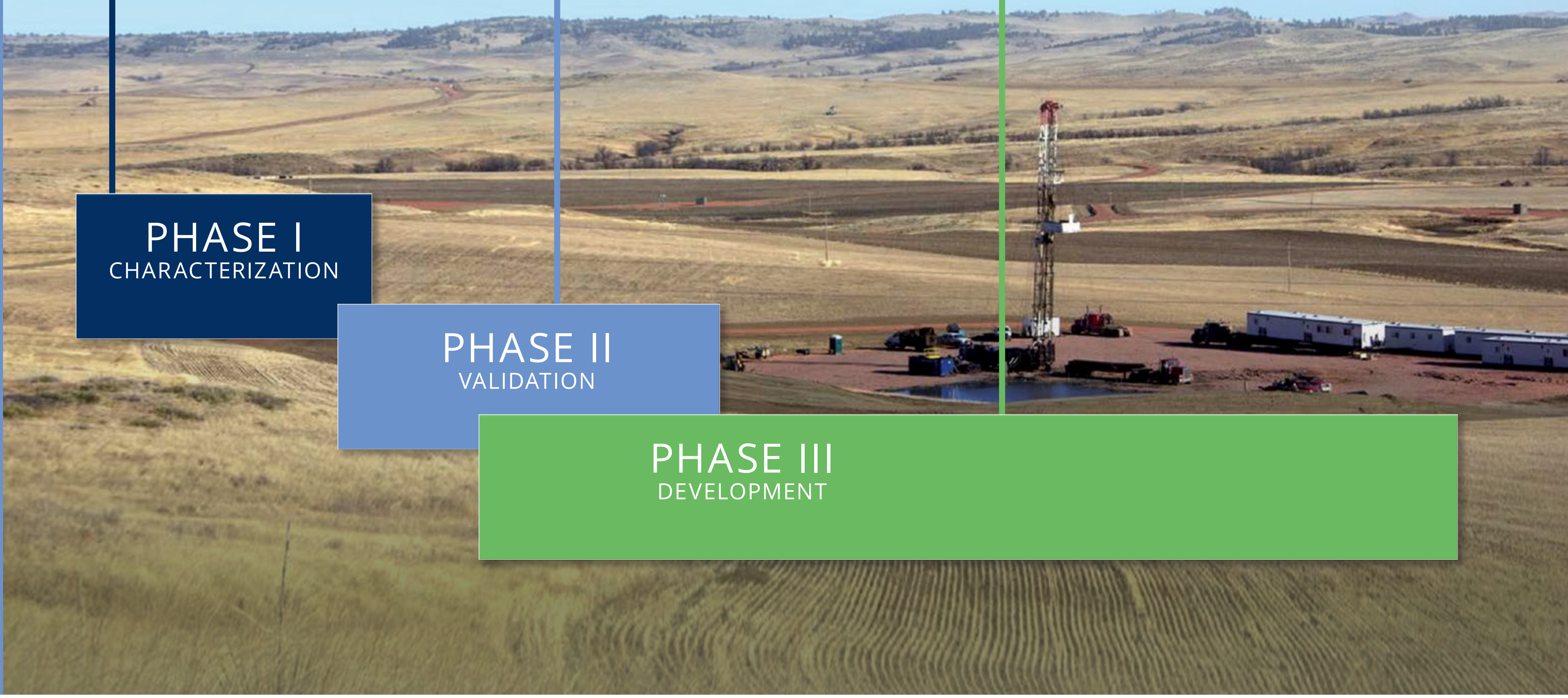
Beginning in 2003, Phase I consisted of characterizing regional CO_2 emission sources and potential geologic storage locations within each RCSP region.

PHASE II (VALIDATION PHASE)

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

PHASE III (DEVELOPMENT PHASE)

In 2008, Phase III focused on large-scale field projects in saline formations and oil and gas fields, with the target goal of injecting at least 1 million metric tons per project. These large-scale demonstration projects advanced CCUS project management knowledge and supported the development of storage-related technologies in characterization, geologic modeling and simulation, risk assessment, mitigation, and monitoring.



CHARACTERIZATION PHASE

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

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

Learnings from Phase I include:

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

VALIDATION PHASE

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

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

Phase II Validation Projects

ZAMA FIELD VALIDATION

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

LIGNITE FIELD VALIDATION

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

NORTHWEST MCGREGOR FIELD VALIDATION

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

TERRESTRIAL FIELD VALIDATION

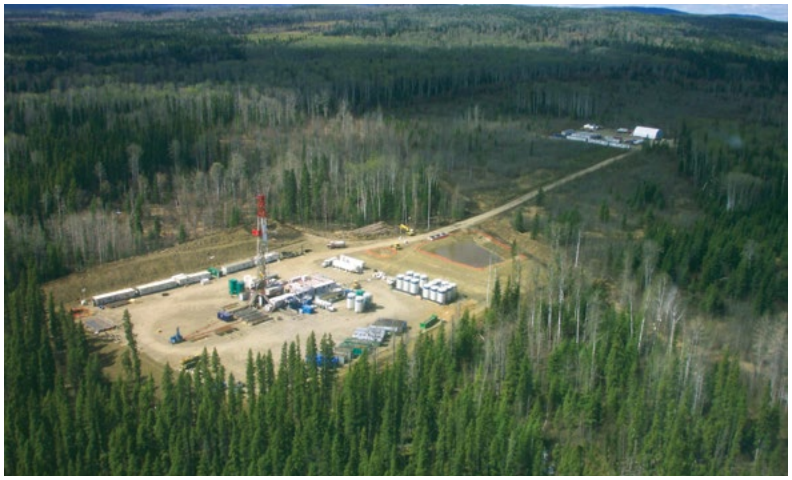
Developed the technical capacity to systematically identify and apply alternative land use management practices to the prairie pothole ecosystem (at both local and regional scales) that result in GHG reductions and potentially salable carbon offsets. The project demonstrated that restoration of previously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

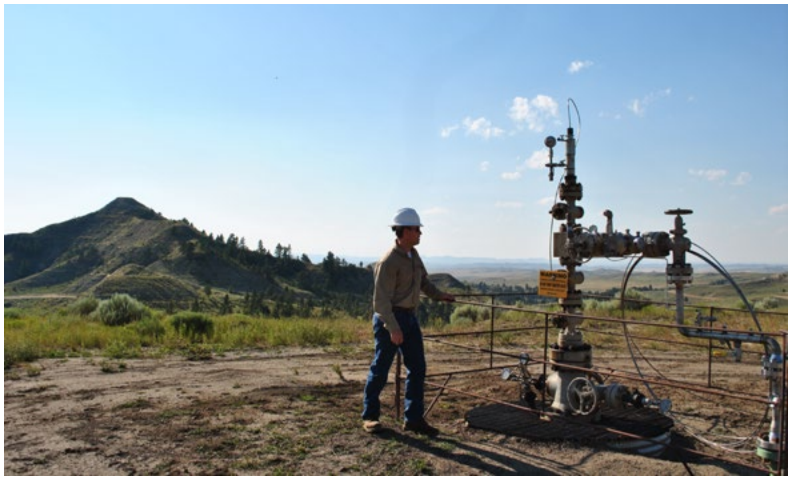
DEVELOPMENT PHASE

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

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

Phase III Commercial Demonstration Projects





FORT NELSON FEASIBILITY PROJECT

Investigated the feasibility that CO_2 from a commercial natural gas-processing facility can be safely and cost-effectively stored in a deep carbonate saline formation. The results of this project suggest that commercial-scale CCS in the area is technically feasible and cost-effective MVA that meets or exceeds the geologic storage standards of the Canadian Standards Association. The project aimed to inject approximately 2.2 million tonnes of CO_2 annually.

BELL CREEK DEMONSTRATION PROJECT

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

AQUISTORE PROJECT

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

PCOR PARTNERSHIP PARTNERS

From 2003 to today, the PCOR Partnership has brought together more than 120 public and private sector stakeholders with expertise in power generation, energy exploration and production, geology, engineering, the environment, agriculture, forestry, and economics. Also during this time, the separate PCO_2C involved more than 40 private industry partners and focused on evaluating and developing cost-effective CO_2 capture solutions for utility application. The combined group of partners shown forms the foundation of the PCOR Partnership and supports its efforts by providing data, guidance, financial resources, and practical experience with CCUS.

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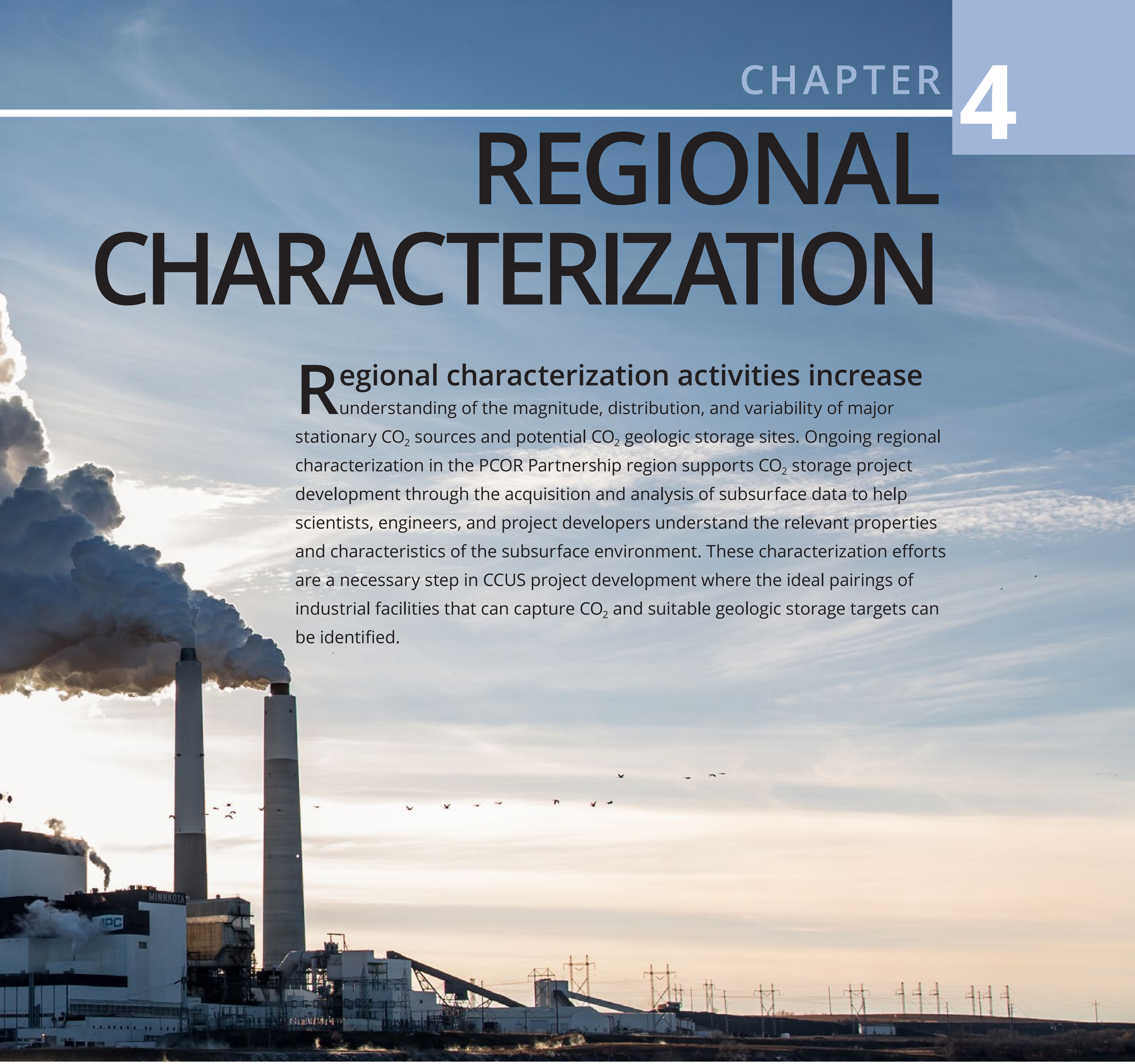
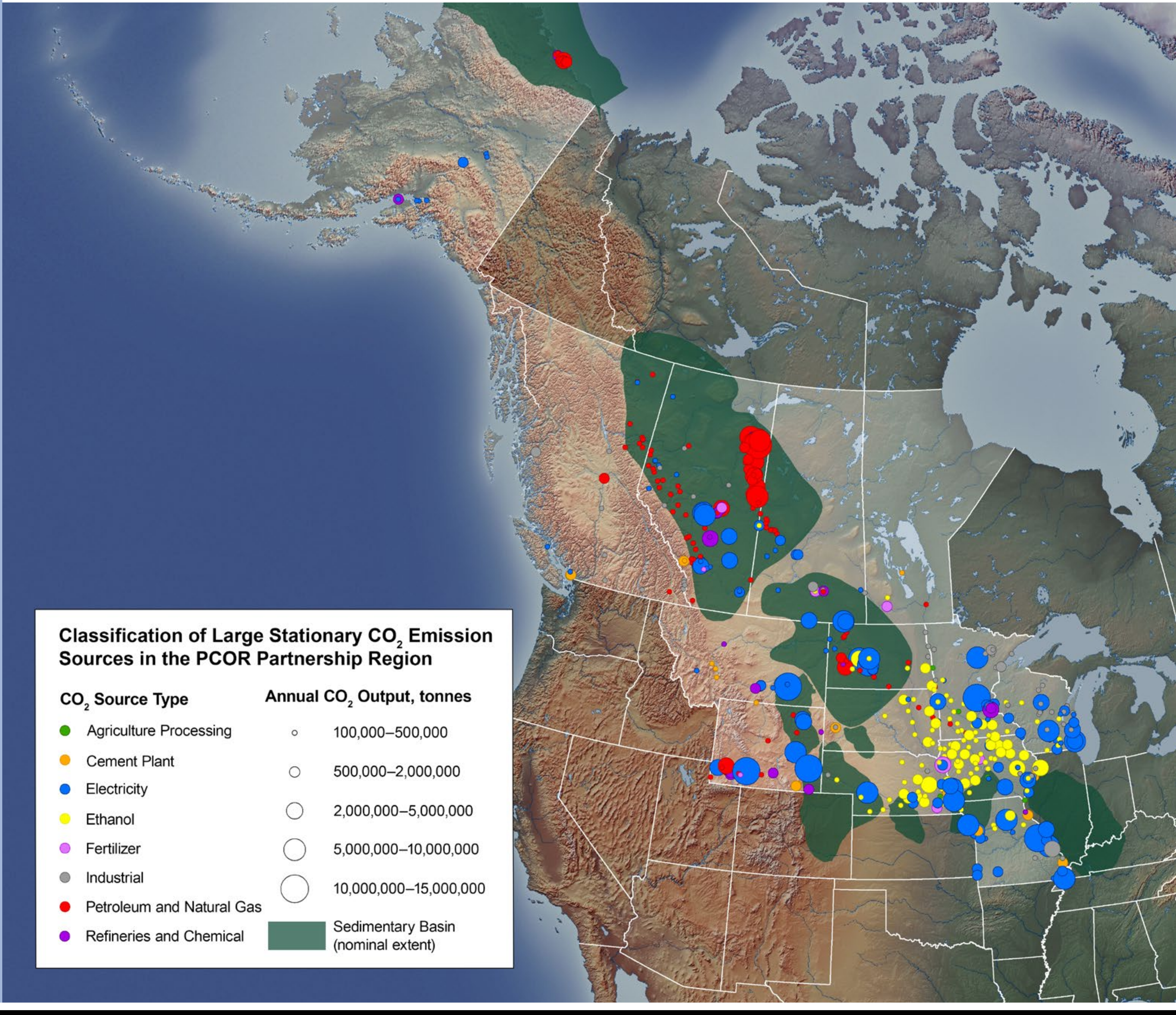


CHAPTER 4

REGIONAL CHARACTERIZATION

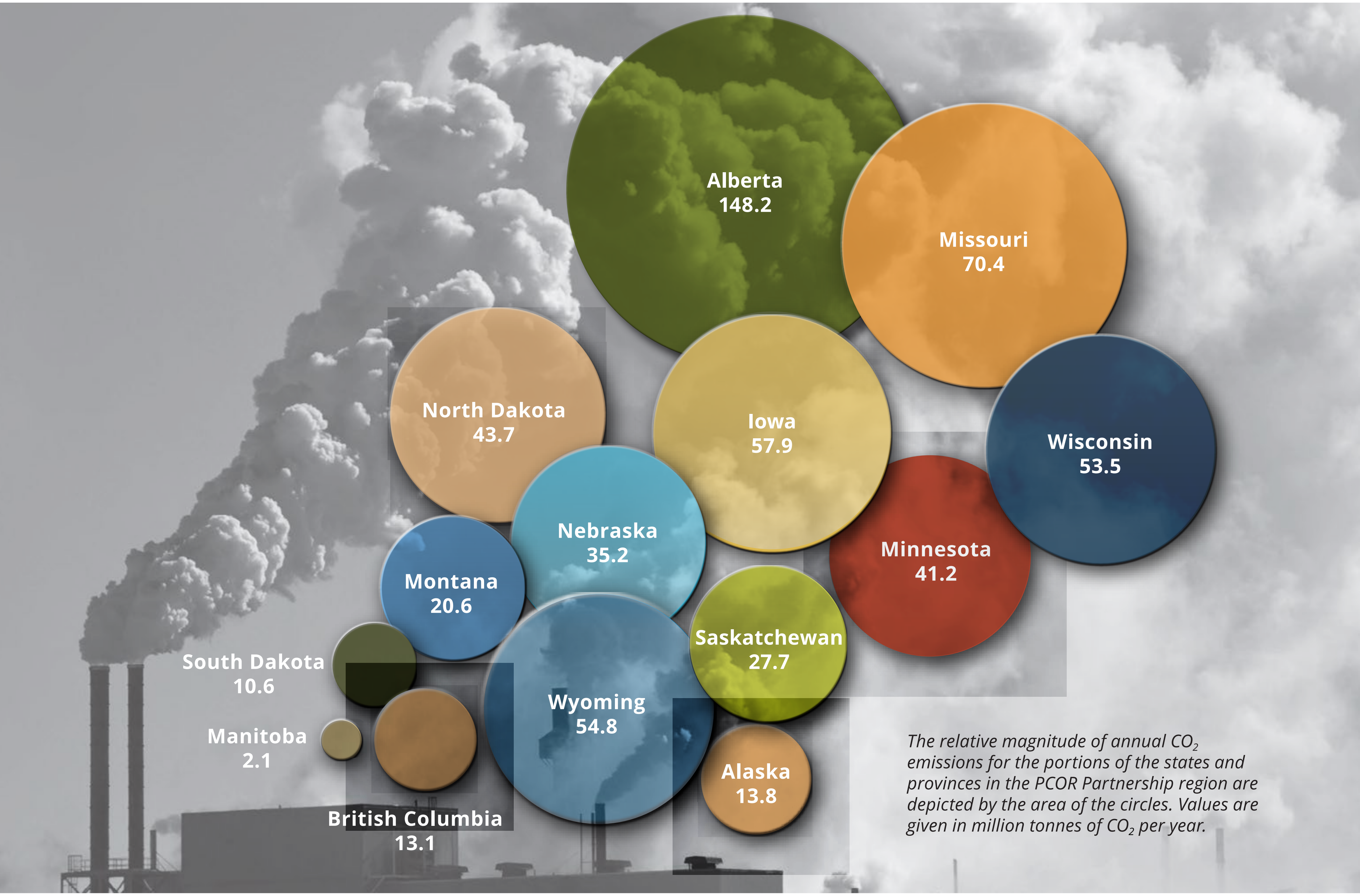
Regional characterization activities increase understanding of the magnitude, distribution, and variability of major stationary CO_2 sources and potential CO_2 geologic storage sites. Ongoing regional characterization in the PCOR Partnership region supports CO_2 storage project development through the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

DISTRIBUTION OF LARGE STATIONARY CO_2 SOURCES



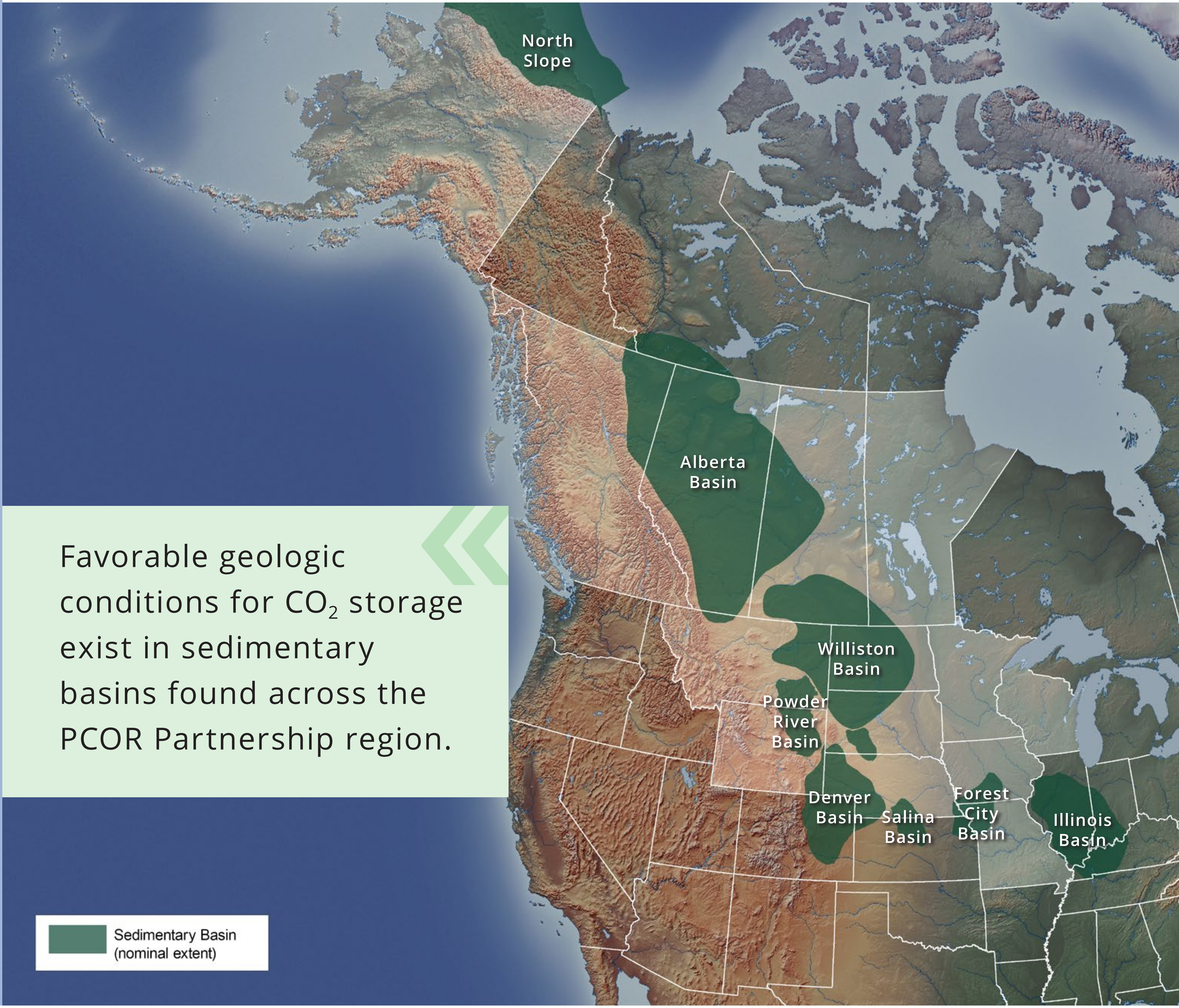
The PCOR Partnership has identified, quantified, and categorized 512 stationary sources in the region that have an annual output of greater than 100,000 tonnes of CO_2. These stationary sources have a combined annual CO_2 output of over 509 Mt. Although not a target source of CO_2 for geologic storage, the transportation sector in the U.S. portion of the PCOR Partnership region contributes nearly 242 million additional tonnes of CO_2 to the atmosphere every year.[15,16,34-38]

The annual output from the various large stationary sources ranges from 100,000 tonnes for industrial and agricultural processing facilities that make up the majority of the sources in the region to over 14 Mt for the largest coal-fired electric generation facility. Fortunately, many of the large point sources are located in areas that are favorable for CO_2 storage because of their concurrence with deep sedimentary basins, such as those areas in Alberta, North Dakota, Montana, and Wyoming.



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

MAJOR REGIONAL SEDIMENTARY BASINS

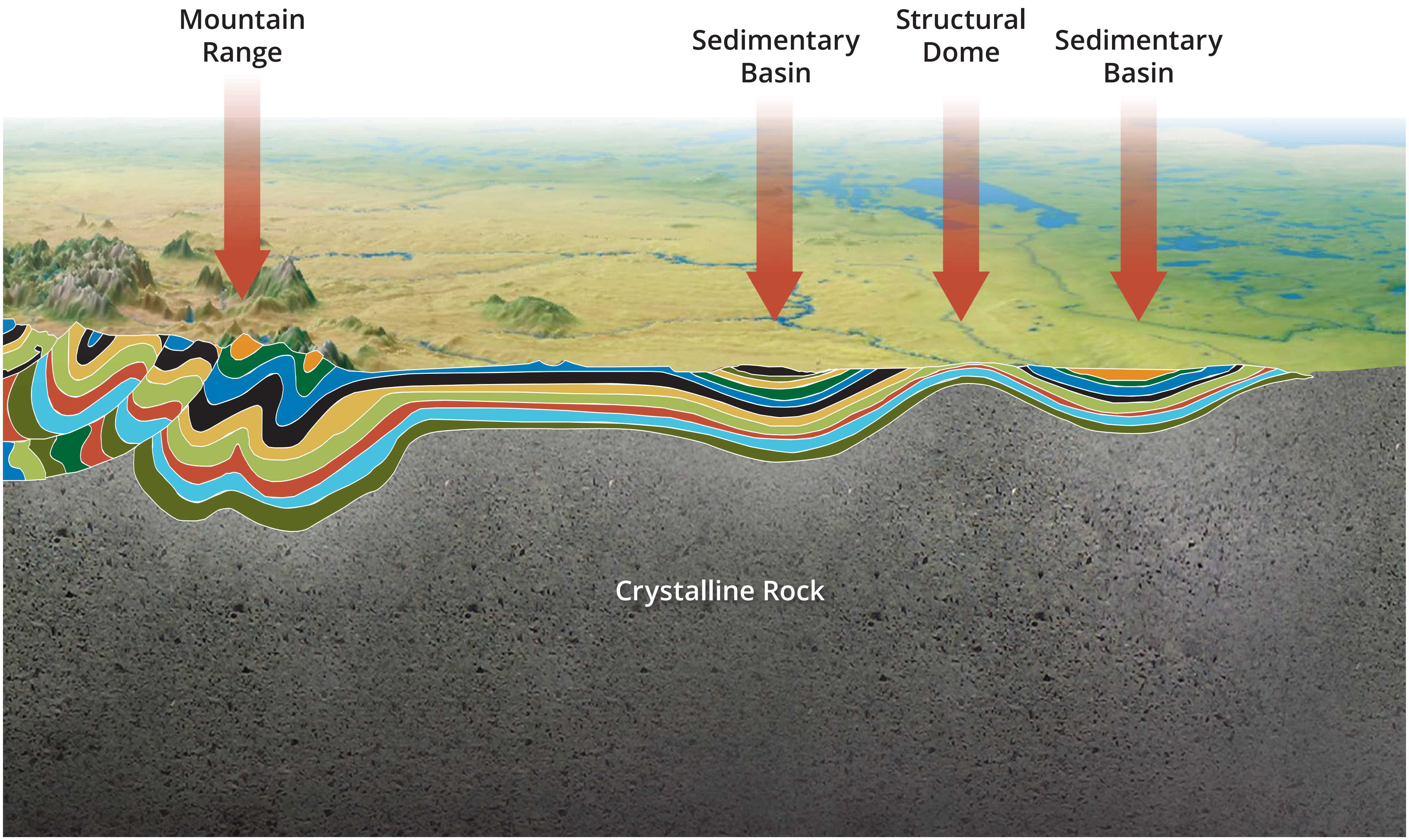


Favorable geologic conditions for CO_2 storage exist in sedimentary basins found across the PCOR Partnership region.

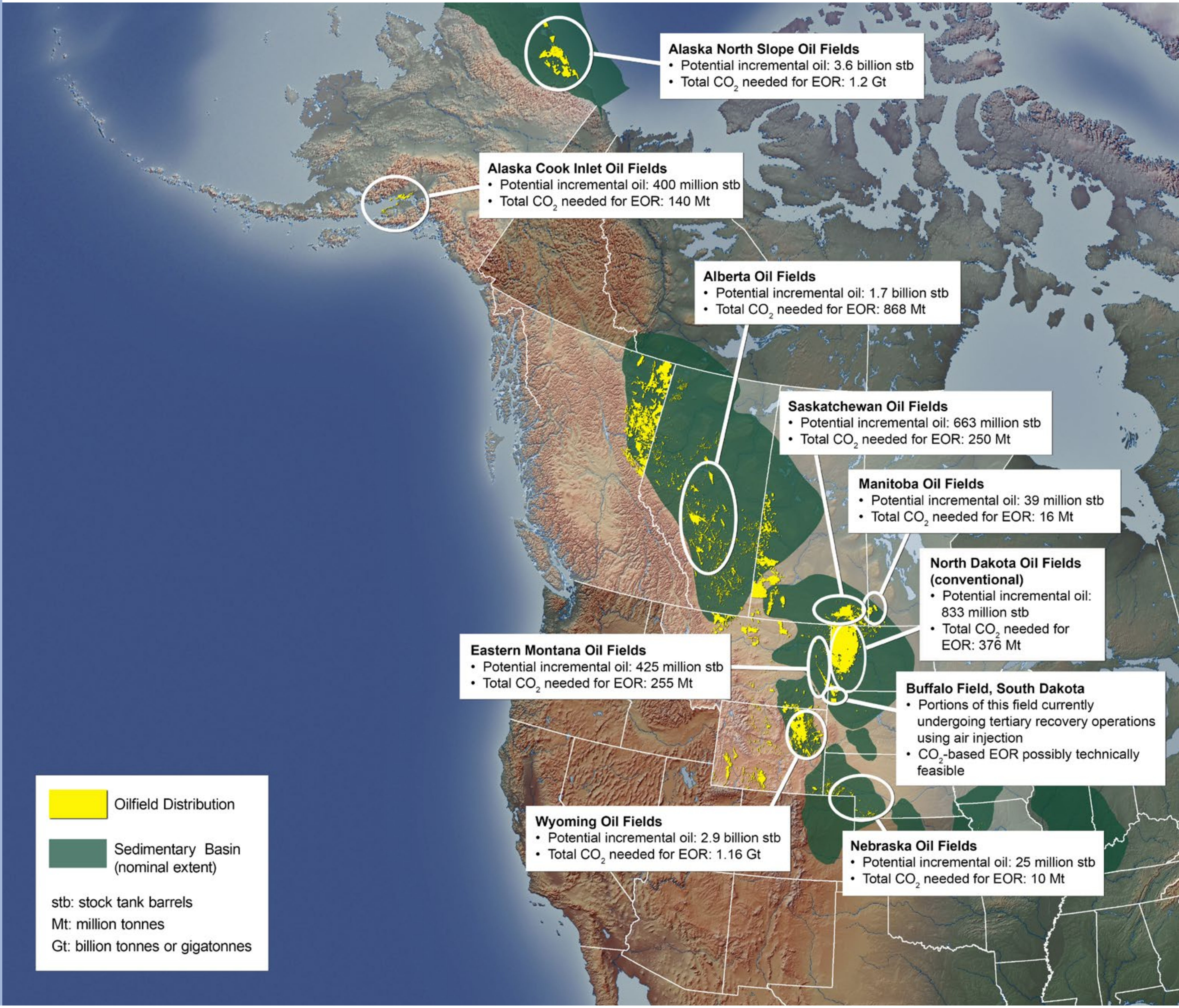
CO_2 STORAGE OPPORTUNITIES

Sedimentary basins are large regional depressions in Earth's crust. These depressions accumulate a considerable thickness of sediment that can cause further subsidence and allow for even more 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.

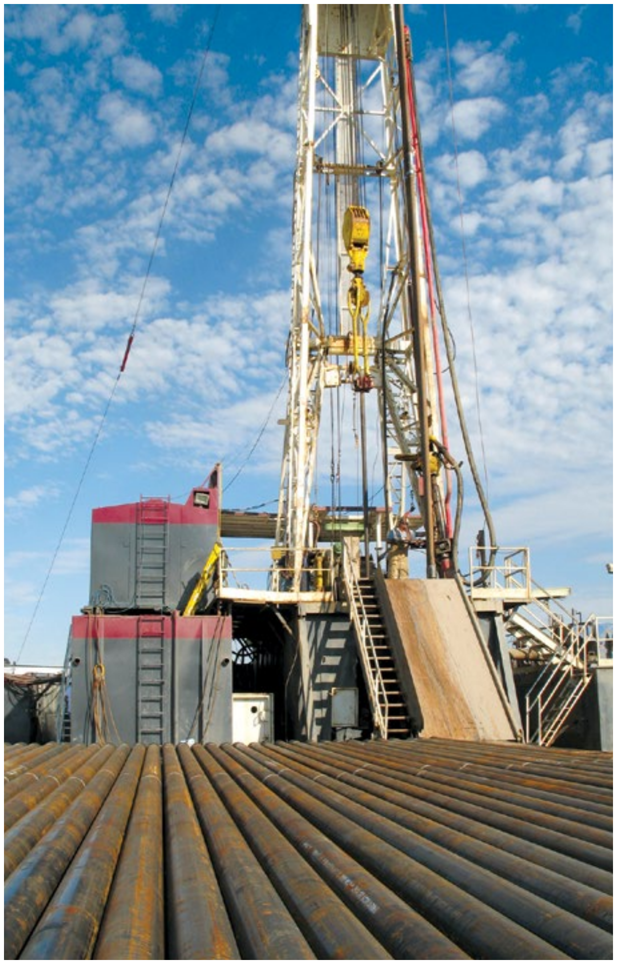
Oil and gas reservoirs and deep saline formations are the two primary CO_2 storage options found within sedimentary basins. These storage formations are commonly situated vertically one above another and separated by sealing formations, an arrangement referred to as stacked storage. Stacked storage offers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



EOR POTENTIAL



CO_2 STORAGE IN OIL FIELDS



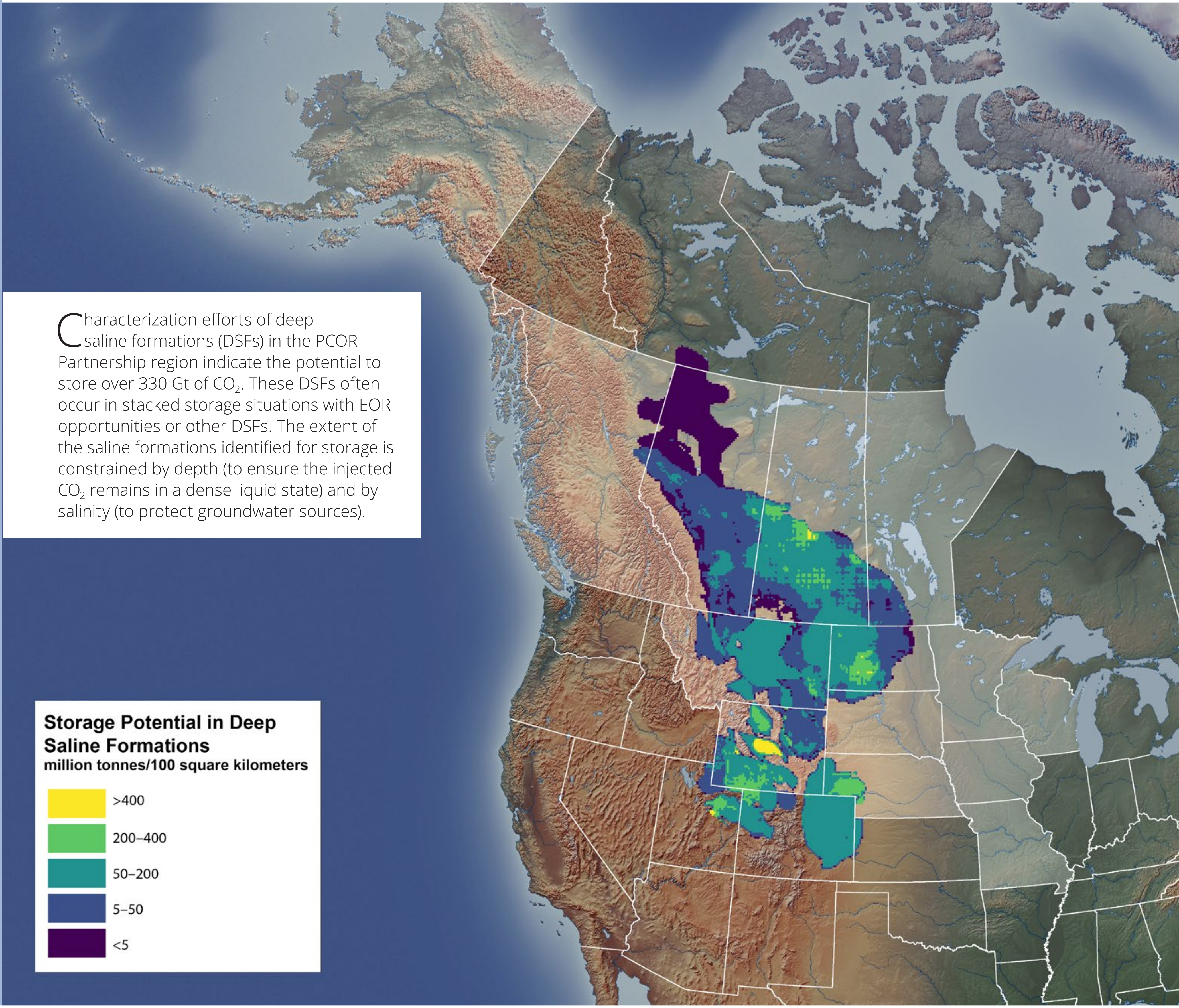
Although oil was discovered in the PCOR Partnership region in the late 1800s, significant development and exploration did not begin until the late 1920s. The body of knowledge gained in the nearly 90 years of exploration and production of hydrocarbons in this region is a significant step toward understanding the mechanisms for secure storage of significant amounts of CO_2. Today, oil is drawn from the many oil fields in the PCOR Partnership region from depths ranging from as little as 60 m to approximately 8000 m below ground level.

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

The region has over 3.7 Gt of CO_2 storage potential in conventional oil fields and 10.2 billion stb of incremental oil potential.

CO_2 STORAGE IN SALINE FORMATIONS

Characterization efforts of deep saline formations (DSFs) in the PCOR Partnership region indicate the potential to store over 330 Gt of CO_2. These DSFs often occur in stacked storage situations with EOR opportunities or other DSFs. The extent of the saline formations identified for storage is constrained by depth (to ensure the injected CO_2 remains in a dense liquid state) and by salinity (to protect groundwater sources).



CO_2 STORAGE IN COAL

The PCOR Partnership region is home to significant coal resources. Much of this vast resource is used to generate electricity at coal-fired power plants in the region and beyond. However, a significant portion of this resource lies at depths that are not economically recoverable.

The evaluation of three major coal horizons in the PCOR Partnership region identified nearly 7.3 Gt of CO_2 storage resource. However, because most of the coal resource in the PCOR Partnership region is positioned in the freshwater horizons of the subsurface, no current activities or potential CCUS projects are looking to use coal as a CO_2 storage target.


CARE, ACT SAFE TO BE SAFE
devon

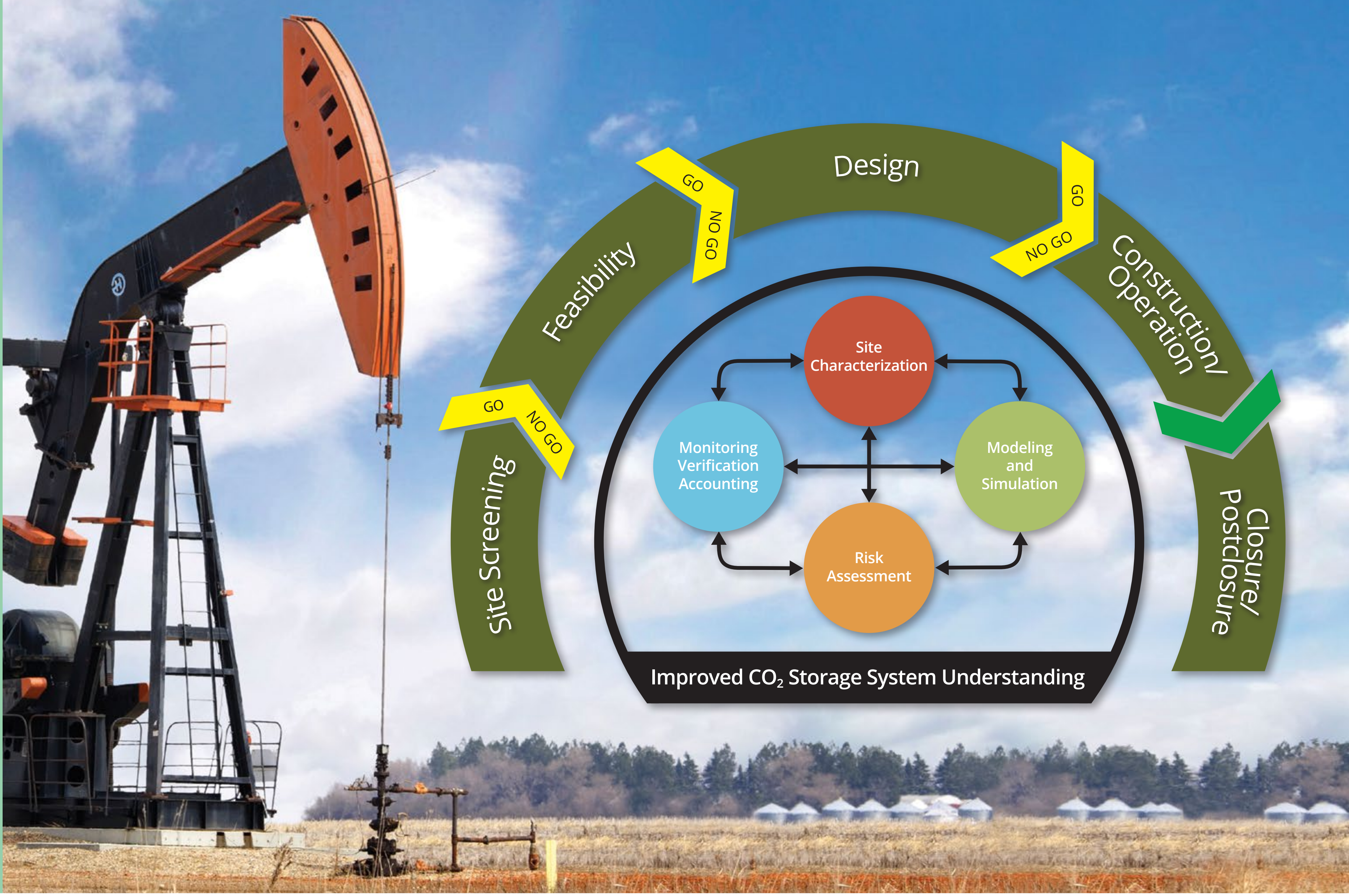
CHAPTER 5

TAKING ACTION

The pathway to developing a commercial CCUS project includes an iterative assessment of a prospective CO_2 storage location and moving efficiently through the permitting process. Several commercial CCUS projects are active in the PCOR Partnership region, with these projects containing combinations of CO_2 capture, transportation, dedicated and associated storage, EOR, and production of low-carbon fuels. The lessons learned from these projects at all stages of development are a catalyst to support future commercial CCUS development in the region.

PHILOSOPHY OF APPROACH

The PCOR Partnership employs a philosophy that integrates site characterization, modeling and simulation, risk assessment, and MVA strategies into an iterative process to produce meaningful results for large-scale CO_2 storage projects. Elements of any of these activities are crucial for understanding or developing the other activities. For example, new knowledge gained from site characterization reduces uncertainty in geologic reservoir properties. This reduced uncertainty can then propagate through modeling, risk assessment, and MVA efforts. Because of this process, the PCOR Partnership Program is in a strong position to refine characterization, modeling, risk assessment, or MVA efforts based on the results of any of these activities and has produced a best practices manual for this adaptive management approach.



SITE CHARACTERIZATION

Site characterization comprises collection, analysis, interpretation, and application of data to understand CO_2 storage potential and assessment of factors that could impact CO_2 storage project performance. Data collection methods range from accessing existing reports and documentation available from public and private sources to using a wide array of field technologies for determining or measuring various geologic/physical/chemical properties of subsurface and surface environments.

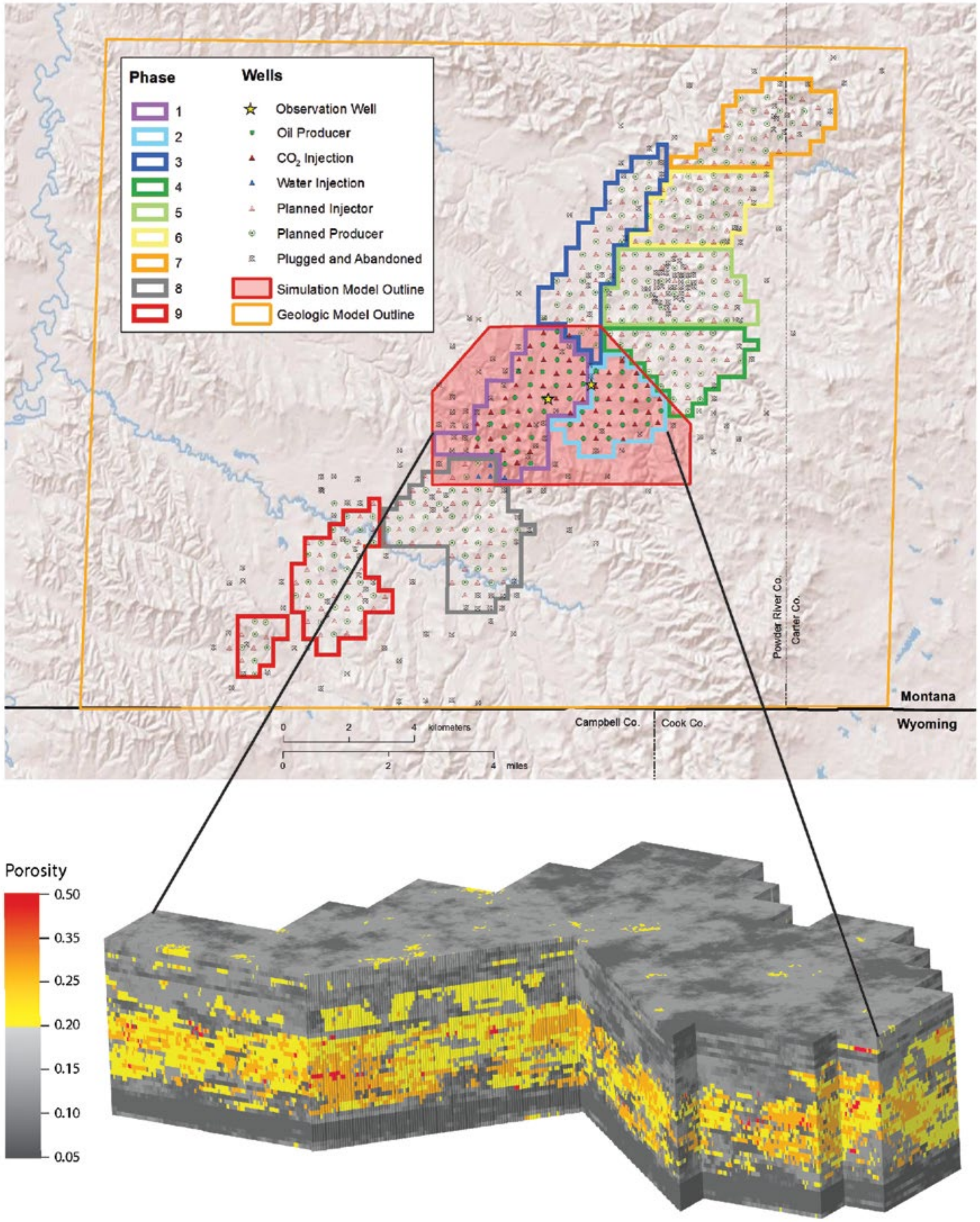
Site characterization activities serve as direct inputs into the various modeling and simulation activities to better predict CO_2 migration pathways, assess technical subsurface risks, and aid in the monitoring of CO_2 migration in the subsurface. These elements of the project help evaluate expected and actual performance during commercial-scale CO_2 injection, storage, and EOR.

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

A geologic model is a computerized 3D rendering of the subsurface that provides a digital framework of CO_2 reservoir complexities, critical to understanding CO_2 storage. The model provides a 3D understanding of the storage horizon and associated cap rock to allow design and implementation of a CO_2 injection project. Common components of geologic models include information generated from site characterization activities, with estimates of rock properties (e.g., rock type, porosity, permeability) and structural framework (i.e., geologic surfaces, geologic layers, faults).

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

Geologic models serve as the basis for the fluid flow simulations to predict the subsurface extent of the injected CO_2 and the potential pressure effects associated with storing CO_2. These predictions are important for the design of a CO_2 storage system, assessment of project risks, and design and interpretation of the results of a monitoring and accounting program. Geomechanical and geochemical simulations are also conducted to identify potential risks and guide monitoring programs.



Muddy Sandstone (Bell Creek Field reservoir)

RISK ASSESSMENT

Risk assessment is a vital component of the adaptive management approach for CO_2 storage project development.

"Risk" is the severity of consequences (negative impacts) of an event weighed against how likely those consequences are to occur. In the context of a CO_2 storage project, risks can affect operational performance and long-term permanence of CO_2 storage. "Risk assessment" is the iterative process of identifying, analyzing, and evaluating potential project risks.

For over a decade, the PCOR Partnership has conducted risk assessments for CO_2 storage projects consistent with international standard protocols.[39-42] These best practices provide reliable methods for identifying project-related risks, including analyzing probability and potential impacts and evaluating risk treatment and priority.

Identifying and assessing potential risks for a CO_2 storage project start early in the development of a project when the project team identifies and evaluates potential risks grouped into broad categories (e.g., capacity, injectivity, and lateral and vertical migration).[43] These risks are refined over time as more data become available.

Risk assessment outcomes inform CO_2 storage project development through every phase. Additionally, the risk assessment informs the monitoring, reporting, and verification (MRV) plan for a CO_2 storage project, ensuring higher-ranking risks are being monitored by one or more measurements.

ESTABLISH THE CONTEXT

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

RISK IDENTIFICATION

- Use an independent risk management expert to facilitate the process.
- Elicit input from project stakeholders and subject matter experts.
- Generate a functional model of the storage complex.
- Identify potential risks that would negatively impact the storage project.
- Ensure that the following four technical risk categories are considered:
  - Storage capacity
  - Injectivity
  - Lateral and vertical containment of CO_2 and formation fluids
  - Induced seismicity
- Thoroughly document each potential risk, and generate a risk register.

RISK ANALYSIS

- Develop a set of quantifiable physical consequences and a means to link these to project impacts.
- Consult the available site characterization, geologic modeling, and reservoir simulation results.
- Evaluate predictive simulations to forecast storage project performance during CO_2 injection.
- Capture risk probability and impact scores from subject matter experts.
- Quantify uncertainty in the risk scores.

RISK EVALUATION

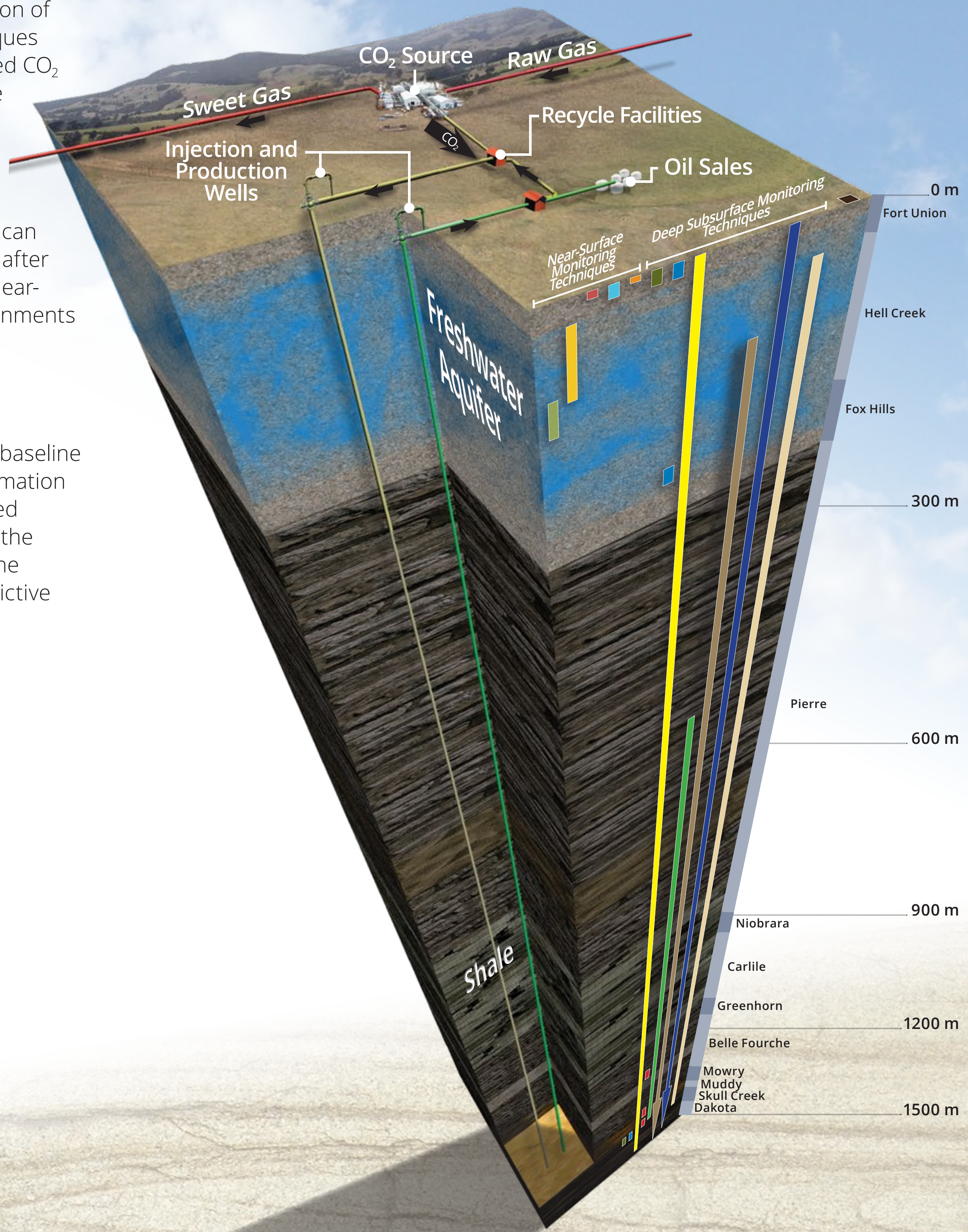
- Plot each individual risk onto a risk map, and evaluate uncertainty in the risk scores.
- Identify moderate and high-ranking risks that plot in the orange and red fields.
- If a more quantitative evaluation is needed, then employ a probabilistic method such as Monte Carlo simulation or Bayesian methods.

MONITORING, VERIFICATION, AND ACCOUNTING

Monitoring, verification, and accounting, known as MVA, is the combination of monitoring technologies and techniques used to track the migration of injected CO_2 as well as to confirm that the surface and subsurface environments are not negatively impacted by injection activities.

A variety of monitoring technologies can be implemented before, during, and after injection operations in the surface, near-surface, and deep subsurface environments at a CO_2 storage site.

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



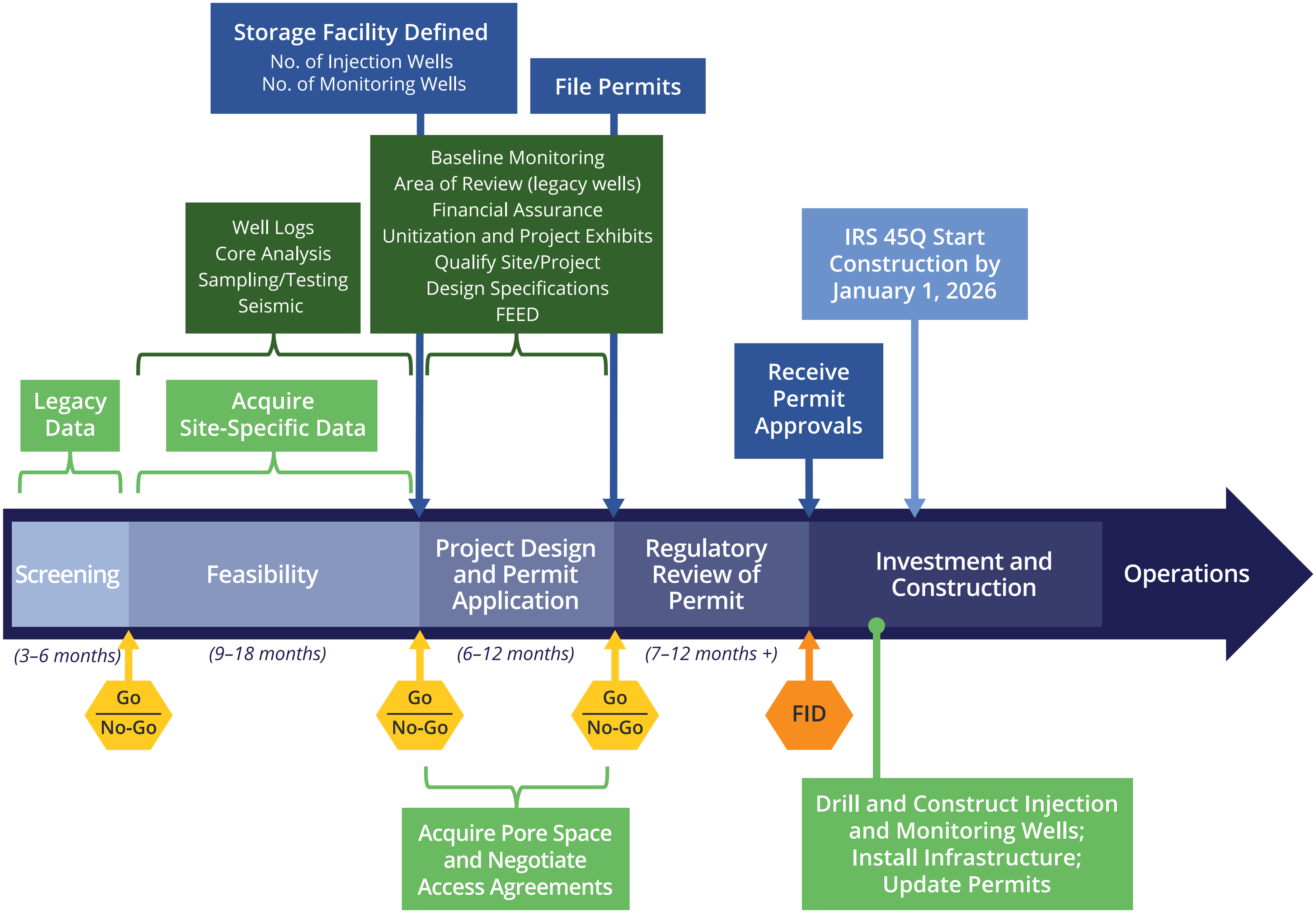
- Fox Hills Groundwater Wells
- Groundwater Wells
- Surface Water
- Soil Gas Profile Stations
- Soil Gas Probes
- Production and Injection Rates
- Wellhead Pressure Monitoring
- Temperature PDM*
- Pressure PDM
- 3D Time-Lapse VSP**
- 3D Time-Lapse Seismic
- Passive Seismic Monitoring
- Neutron Logging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

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

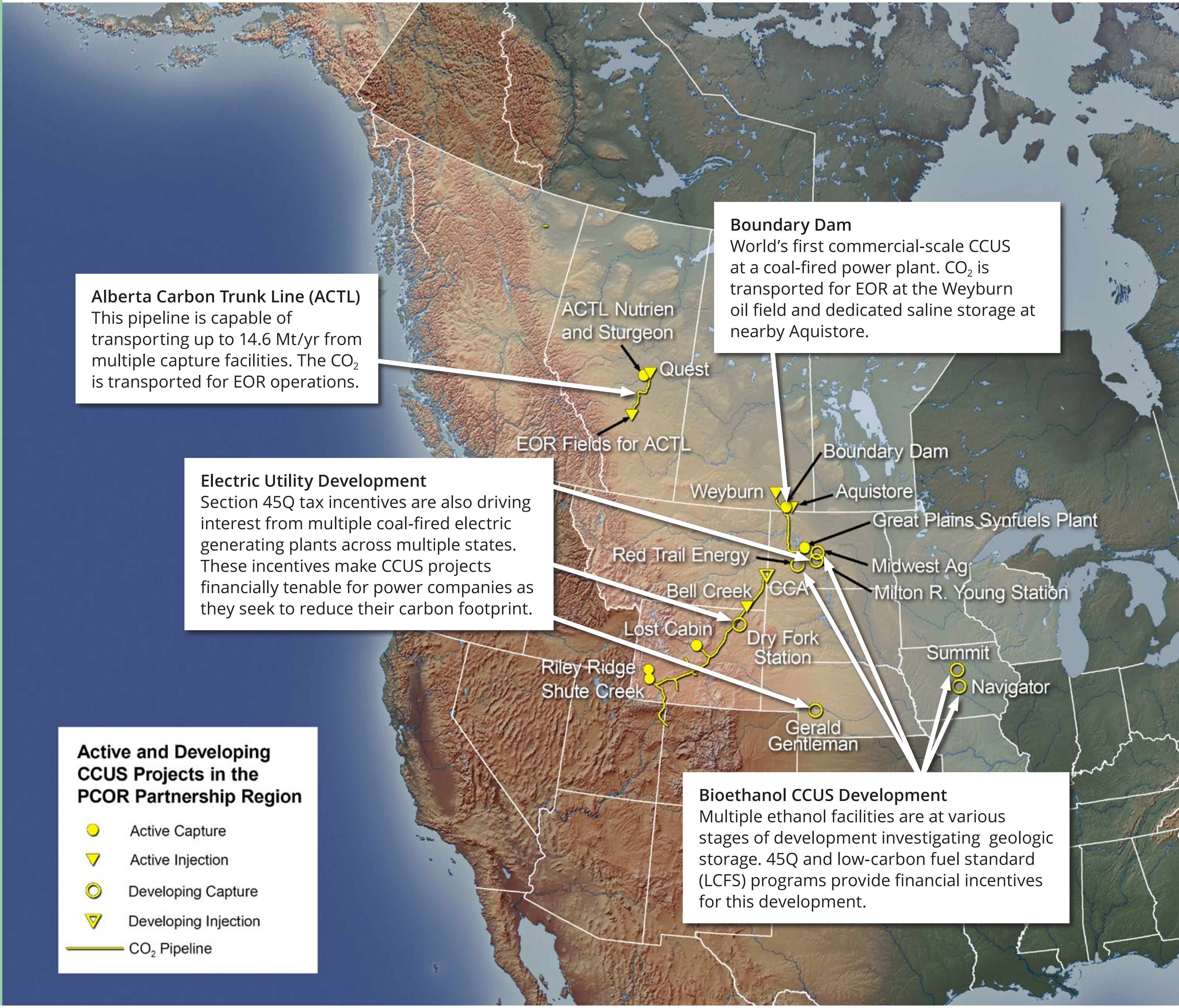
A PERMITTING PROCESS

Permitting considerations for a CO_2 storage project are important even at the earliest stages of project development. Data and information about project feasibility and geologic suitability of the potential storage site(s) will eventually be used to support the permits needed to store CO_2. The figure shows the CCUS project development and permitting process for the state of North Dakota, which begins by the gathering of any existing data in or near the site(s) of interest.

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



ACTIVE AND DEVELOPING CCUS PROJECTS



Alberta Carbon Trunk Line (ACTL)
This pipeline is capable of transporting up to 14.6 Mt/yr from multiple capture facilities. The CO_2 is transported for EOR operations.

Boundary Dam
World's first commercial-scale CCUS at a coal-fired power plant. CO_2 is transported for EOR at the Weyburn oil field and dedicated saline storage at nearby Aquistore.

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

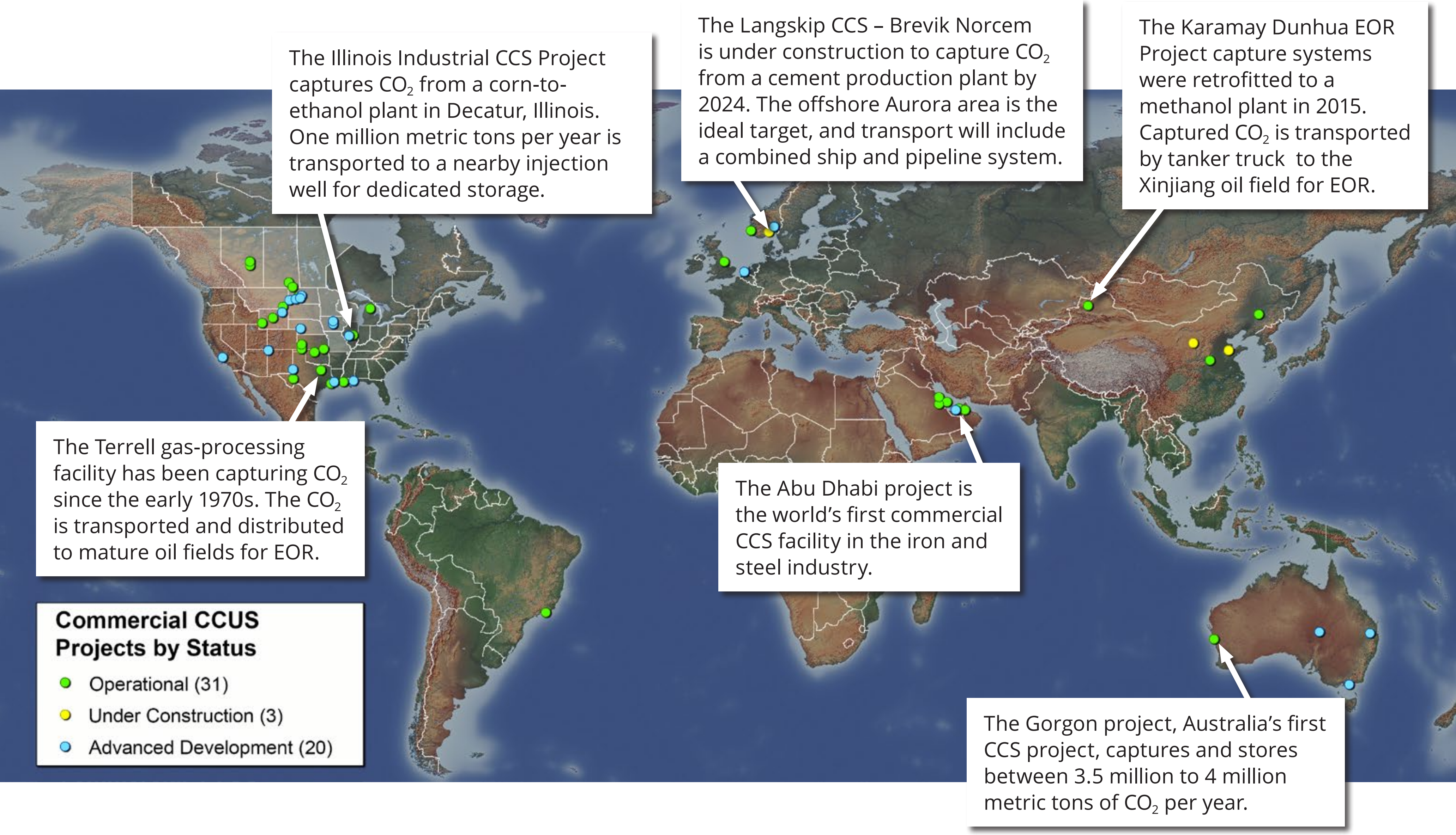
Bioethanol CCUS Development
Multiple ethanol facilities are at various stages of development investigating geologic storage. 45Q and low-carbon fuel standard (LCFS) programs provide financial incentives for this development.

CCUS EFFORTS OUTSIDE OF NORTH AMERICA

Although significant activity is happening across the PCOR Partnership, successful development and operation of full-scale commercial CCUS projects across the world will be required to seriously abate CO_2 emissions from electric generation and industrial sources.

Across North America, numerous CCUS projects are in operation, with the earliest projects dating back to the 1970s and 1980s. While most of those projects have targeted EOR, many of the projects under development are targeting dedicated storage.

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



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

CO_2 CAPTURE AT GREAT PLAINS SYNFUELS PLANT

The majority of the CO_2 used in the Weyburn–Midale EOR project comes from the Dakota Gasification Company's Great Plains Synfuels Plant, the only commercial-scale coal-to-natural gas facility in the United States. In November 2020, the Great Plains Synfuels Plant reached a milestone: capturing 40 million metric tons of CO_2 since 2000. Approximately 2 million metric tons of CO_2 is captured each year, making it one of the largest carbon capture facilities in the world.[44]

Dakota Gas and its Canadian subsidiary, Souris Valley Pipeline Ltd., operate a 205-mile pipeline to transport the CO_2 from the synfuels plant in Beulah, North Dakota, United States, to the Weyburn and Midale oil fields in Saskatchewan, Canada, for EOR. CO_2 EOR at Weyburn has generated 104 million barrels of incremental production to date.[45]

In July 2020, during the COVID-19 pandemic, Dakota Gas had its first shipment of beverage-grade CO_2 captured from the Great Plains Synfuels Plant's ammonia production facility and shipped to be sold in the commercial food and beverage industry. The first load was used to help balance pH levels in the water at water treatment plants in North Dakota. In December 2020, Dakota Gas worked with the North Dakota Department of Health to provide beverage-grade liquefied CO_2 to aid in keeping the COVID-19 vaccine at the recommended storage temperature.[44]


Photo courtesy of Basin Electric Power Cooperative.

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

CO_2 MONITORING AND STORAGE PROJECT

THE WEYBURN AND MIDALE OIL FIELDS AND ASSOCIATED IEAGHG WEYBURN–MIDALE CO_2 MONITORING AND STORAGE PROJECT

Injection of CO_2 for EOR purposes began in the Weyburn oil field in 2000 and at the Midale oil field in 2005. The Weyburn Field was operated by Cenovus Energy until 2017 when it sold its majority stake in the project to Whitecap Resources.[46] In 2020, 2 million tonnes of CO_2 was stored, with more than 34 million tonnes of CO_2 stored since 2000, mainly sourced from the Great Plains Syfuels Plant but with an additional supply of CO_2 from Boundary Dam since 2014.[47]

The Midale Field was operated by Apache Canada until it was sold to Cardinal Energy Ltd. in 2017.[48] In 2020, approximately 188,000 tonnes of CO_2 was injected in the Midale unit. Since 2005, nearly 5 million tonnes of CO_2 has been injected.[49] To date, the sale of CO_2 from the Dakota Gasification Company to Whitecap Resources and Cardinal Energy Ltd. represents the only instances of large quantities of captured CO_2 being traded across an international border.

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

CO_2 CAPTURE AT BOUNDARY DAM

THE BOUNDARY DAM CARBON CAPTURE PROJECT

The Boundary Dam Carbon Capture Project is the world's first commercial-scale, fully integrated CCS project at a coal-fired power station, with postcombustion capture of CO_2 from the rebuilt Unit 3. The capital cost of Can$1.2 billion was supported by funding from the provincial government of Saskatchewan and the federal government of Canada. Operated by the government-owned utility SaskPower, the project is designed to capture up to 1 Mt of CO_2 per year; between the commencement of operations in October 2014 and May 2021, SaskPower reports that 4.14 Mt of CO_2 has been captured.[50]

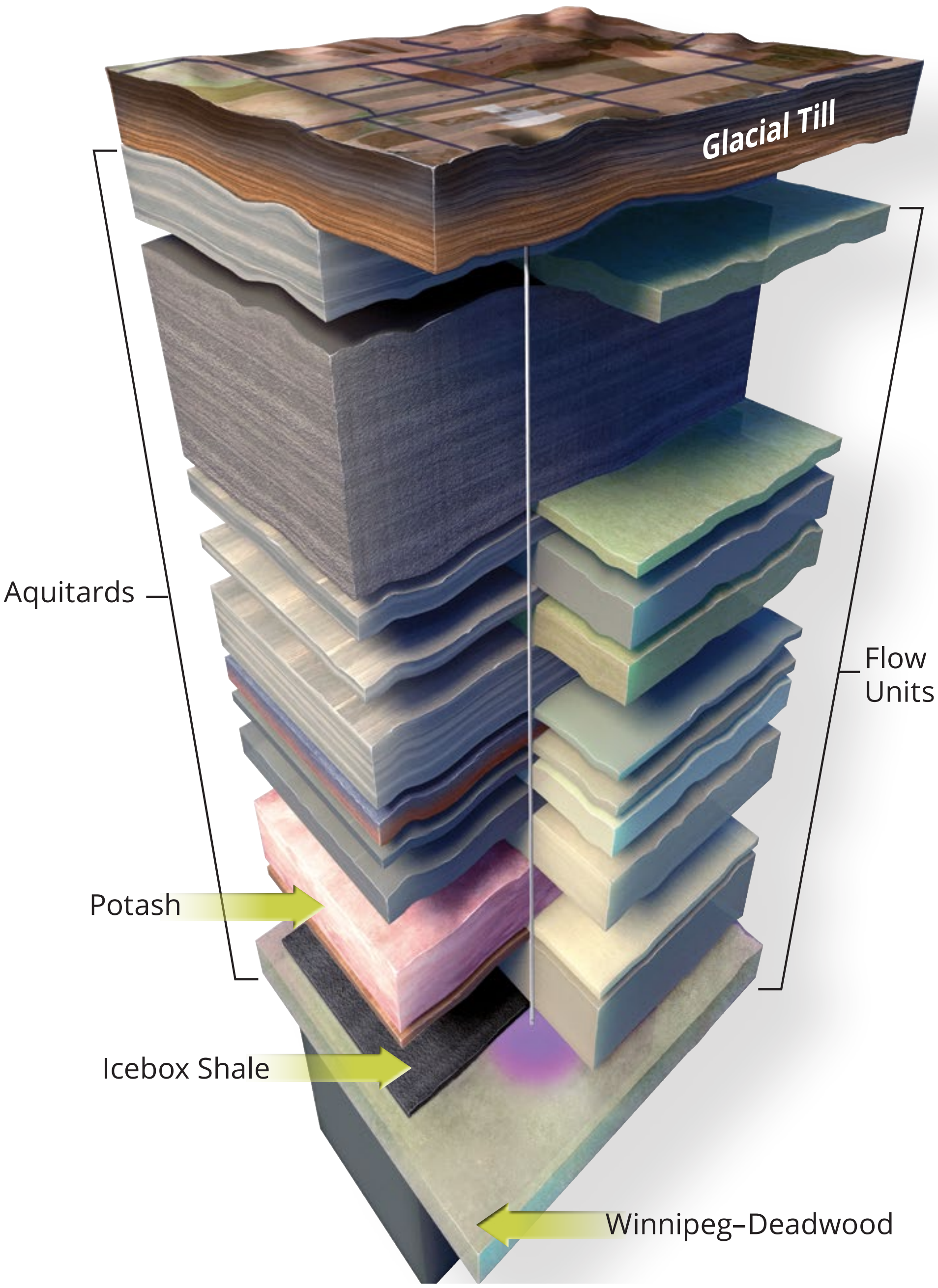
Unit 3 provides 115 MW of power. In addition to reducing CO_2 emissions from Unit 3 by up to 90%, the capture process removes 100% of SO_2 emissions which are converted to sulfuric acid for industrial use.

The main destination for captured CO_2 is the Weyburn oil field, with Whitecap Resources transporting the purchased CO_2 via a 66-km pipeline. A branch of the pipeline in close proximity to the power station feeds the Aquistore Project, which is designed to provide dedicated storage for unsold CO_2.

Photo provided by and is property of SaskPower.

THE AQUISTORE PROJECT

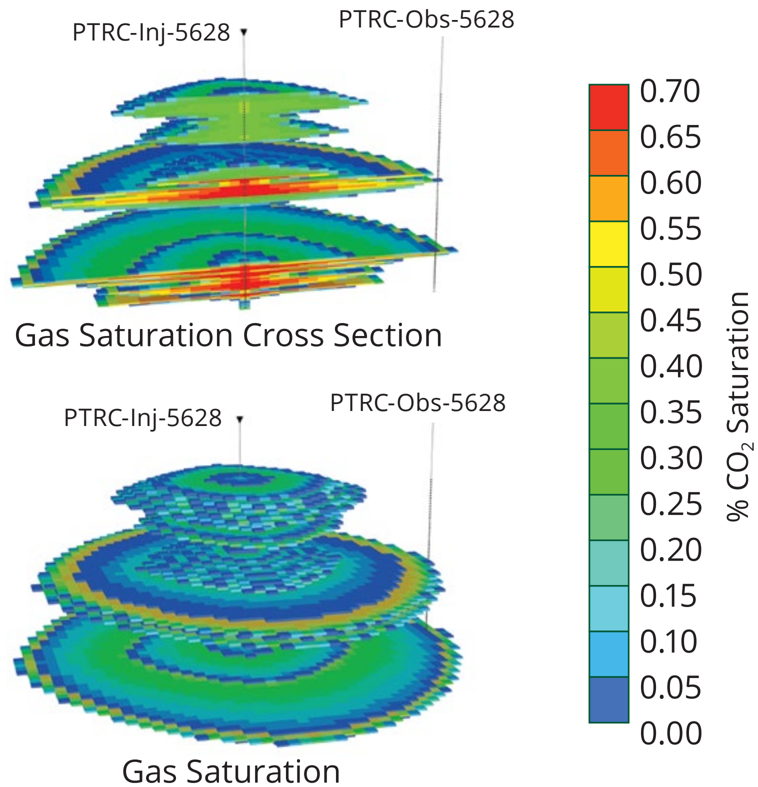
Aquistore is a dual-purpose project.[51] From a commercial perspective, Aquistore provides a dedicated storage option for unsold CO_2 from Boundary Dam—in effect providing buffer storage so as to prevent any need for SaskPower to vent CO_2 from capture operations. Injection operations commenced in April 2015, making Aquistore the first dedicated storage project to be operating in Canada. As of April 2021, over 370,000 tonnes of CO_2 has been injected.[52]



Injection of CO_2 at Aquistore is via a single vertical well into the Winnipeg and Deadwood Formations at a depth of approximately 3.4 km below ground level.[51]

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

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



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

QUEST CCS PROJECT

Shell Canada Energy commenced operations at Quest, a fully integrated CCS project located northeast of Edmonton, in November 2015. As of July 2020, the Quest CCS facility has captured and stored 5 million tonnes of CO_2. The cost to operate Quest is about 35% lower than what was forecast in 2015, and if Quest were to be built today, it would cost about 30% less thanks to capital efficiency improvements.[54]

The capture plant, located at the Scotford Refinery, was built as a modification to an existing steam methane reformer that produces hydrogen for upgrading oil sands bitumen into synthetic crude oil. Licensed Shell amine technology is used in the capture process, which reduces CO_2 emissions from the upgrading operations by approximately one-third.

Captured CO_2 is transported via a 60-km pipeline to a dedicated storage site and injected into the Basal Cambrian sandstone, a DSF, at a depth of around 2 km below the surface. Infrastructure at the site includes three injection wells and a host of monitoring technologies that provide opportunities for international research collaborations. The project is expected to store at least 27 Mt of CO_2 over the anticipated 25-year life of the upgrader, although the storage reservoir has a much greater storage potential.

ALBERTA CARBON TRUNK LINE

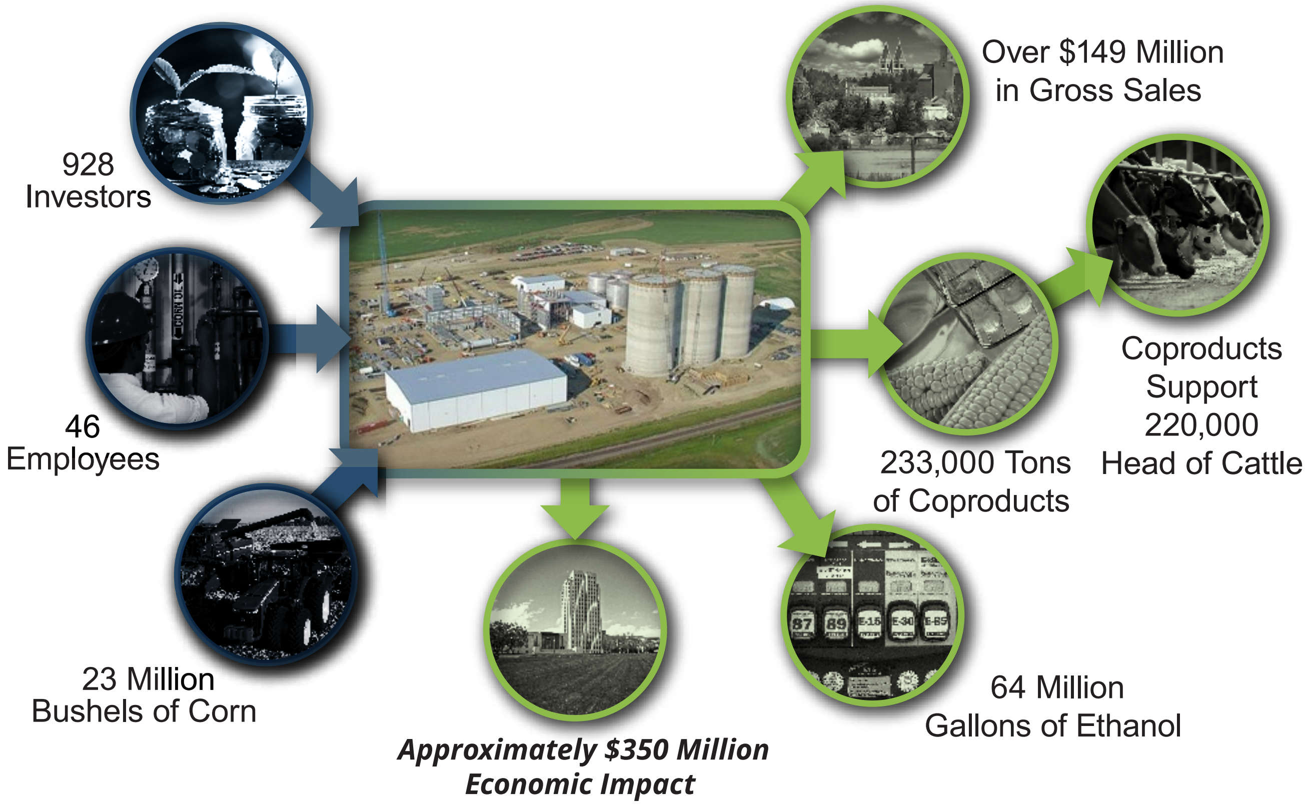
The ACTL system is the world's newest integrated, large-scale CCUS system.[55] Located in central Alberta, CO_2 captured from the NWR (North West Redwater Partnership) Sturgeon Refinery and the Nutrien Fertilizer facility is transported down a 40-cm-diameter, 240-km-long pipeline to mature oil fields near Clive, Alberta. Designed as the backbone infrastructure needed to support a lower carbon economy in Alberta, the ACTL system captures industrial emissions and delivers the CO_2 to mature oil and gas reservoirs for use in EOR and permanent storage. The ACTL can transport up to 14.6 Mt of CO_2 per year, and as of March 2021, 1 Mt of CO_2 has been injected and stored in the Clive oil field.

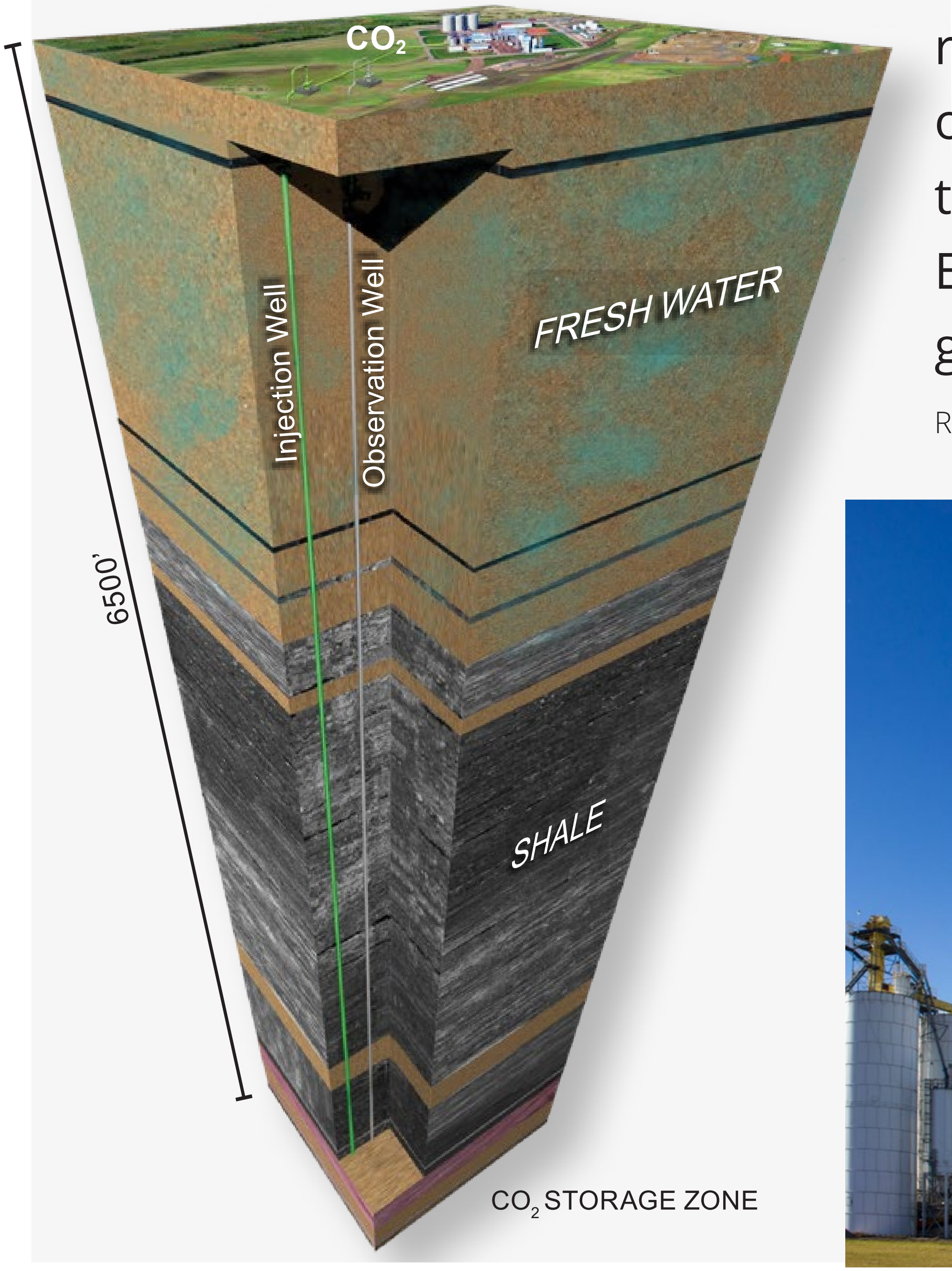
RED TRAIL ENERGY

Red Trail Energy, LLC (RTE) is pursuing a commercial-scale CCUS project at its ethanol manufacturing facility near Richardton, North Dakota. The goal of this effort is to make a CCUS fuel that qualifies for low-carbon fuel programs and capitalize on the Section 45Q tax credit program. Through this project, an average of 180,000 metric tons of CO_2 will be captured annually from RTE's 64-million-gallon dry mill ethanol facility.

RTE partnered with the EERC, NDIC, and DOE to conduct a feasibility and implementation study for the CCUS project. Fieldwork that included drilling two wells and collecting 3D seismic data confirmed that the Broom Creek Formation at a depth of approximately 6400 feet is a safe and viable storage horizon for the captured CO_2.

A North Dakota carbon storage permit application was developed and formally submitted in February 2021. The Department of Mineral Resources (DMR), in consultation with the North Dakota Department of Environmental Quality, evaluated the permit application to determine whether approval should be granted. This first-time regulatory process has taken about 8 months, including a public comment period and hearing. Approval was granted in October 2021 and brings RTE one step closer to becoming the first facility in North Dakota to commercially capture and permanently store CO_2 in the deep subsurface.





"We're excited to submit the first application in the state for safe, permanent geologic storage of CO_2. Using CCS to reduce the CO_2 emissions of our ethanol ensures the long-term viability of Red Trail Energy in a highly competitive global market."

Red Trail Energy CEO Gerald Bachmeier

PROJECT TUNDRA (CARBONSAFE NORTH DAKOTA)

Project Tundra is a bold initiative to build the world's largest carbon capture facility in North Dakota. Innovative technologies are being designed to capture 90% of the CO_2 produced at the Milton R. Young Station (about 4 million metric tons per year). This capture rate is the equivalent to taking 800,000 gasoline-fueled vehicles off the road. North Dakota-based Minnkota Power Cooperative is leading the project, along with research support from the EERC through DOE's CarbonSAFE initiative.

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

The field activities gathered various geologic data on three potential injection targets about 1 to 2 miles below the surface to demonstrate their suitability to permanently store CO_2. These data were used to prepare two North Dakota CO_2 storage facility permit applications that were submitted in May of 2021. Those storage permit applications represent the second and third CO_2 storage facility applications submitted in North Dakota.

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

May 2021	Storage Facility Permit Applications Submitted
Summer 2021	Front-End Engineering and Design (FEED) Study Complete
2022	Construction Started
2025	First CO_2 Captured

DRY FORK STATION (CARBONSAFE WYOMING)

The University of Wyoming School of Energy Resources (UWY SER) leads the Wyoming CarbonSAFE project at Dry Fork Station in the Powder River Basin. Funded by DOE, Wyoming CarbonSAFE investigates the practical, secure, and permanent geologic storage of CO_2 emissions from coal-based electricity generation facilities near Gillette, Wyoming. The Wyoming CarbonSAFE team is characterizing the subsurface geology for suitability of CO_2 storage, preparing permitting documents, working to integrate CO_2 capture technologies, assessing regulatory and business issues, and helping to advance the project toward commercialization. Along with many committed industry, academic, and government partners, UWY SER has drilled a stratigraphic test well, conducted downhole petrophysical tests, analyzed core, collected and analyzed seismic data, and been committed to developing robust monitoring plans and communicating project details to the public.

THE INTEGRATED TEST CENTER

Located outside of Gillette, Wyoming, and opened in May of 2018, the Integrated Test Center (ITC) is a facility designed for applied testing of CCUS technologies using the coal-based flue gas from Dry Fork Station. Only the second such facility in the country, the ITC is a public–private partnership that provides an opportunity for research and development of CO_2 capture technologies as well as technologies to turn flue gas into marketable commodities.

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

CHAPTER 6

ACCELERATING CCUS

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

CHALLENGES TO CCUS DEPLOYMENT

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

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

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

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

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

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

RAMPING UP CCUS DEPLOYMENT

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

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

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

REGULATION

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

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

Because of the evolving nature of regulatory frameworks at various levels of government, this atlas provides general overviews of select rules and policies currently under debate; this atlas can be considered up to date as of June 2021, unless otherwise noted.

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

PRIMACY

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

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

UNDERGROUND INJECTION CONTROL PROGRAM

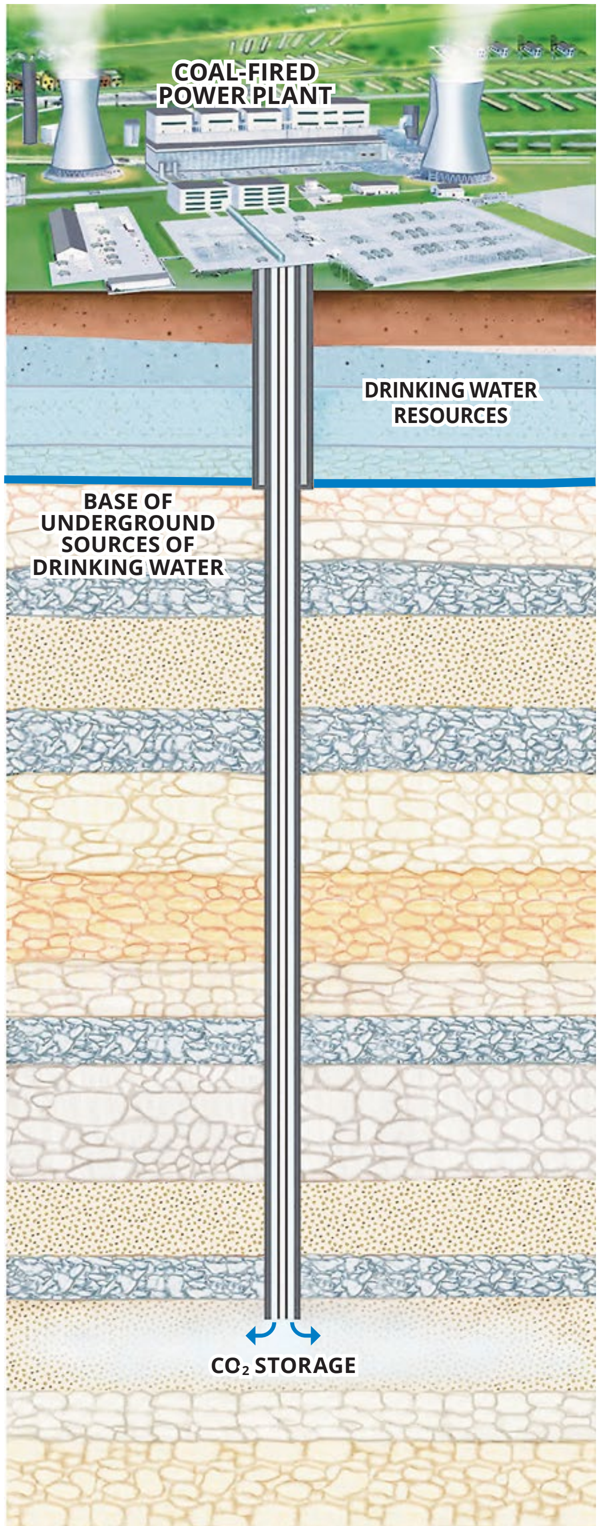
Regulations for CO_2 injection are established under the SDWA UIC Program. The UIC Program is a U.S. federal regulatory program administered by EPA and designed to protect USDWs.

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

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

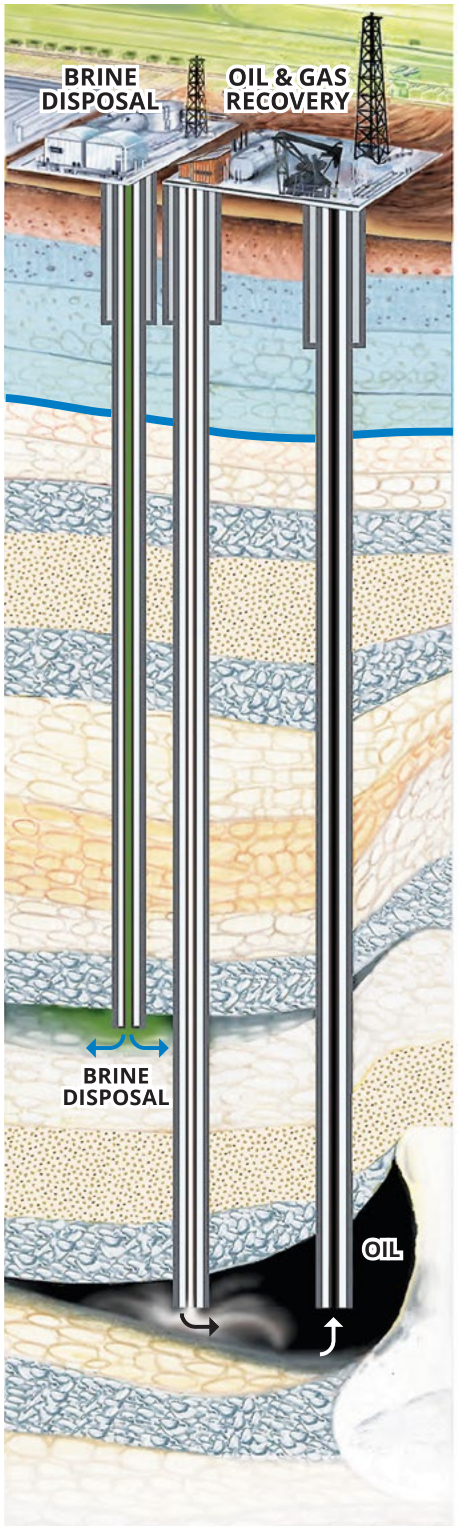
CLASS VI WELLS

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

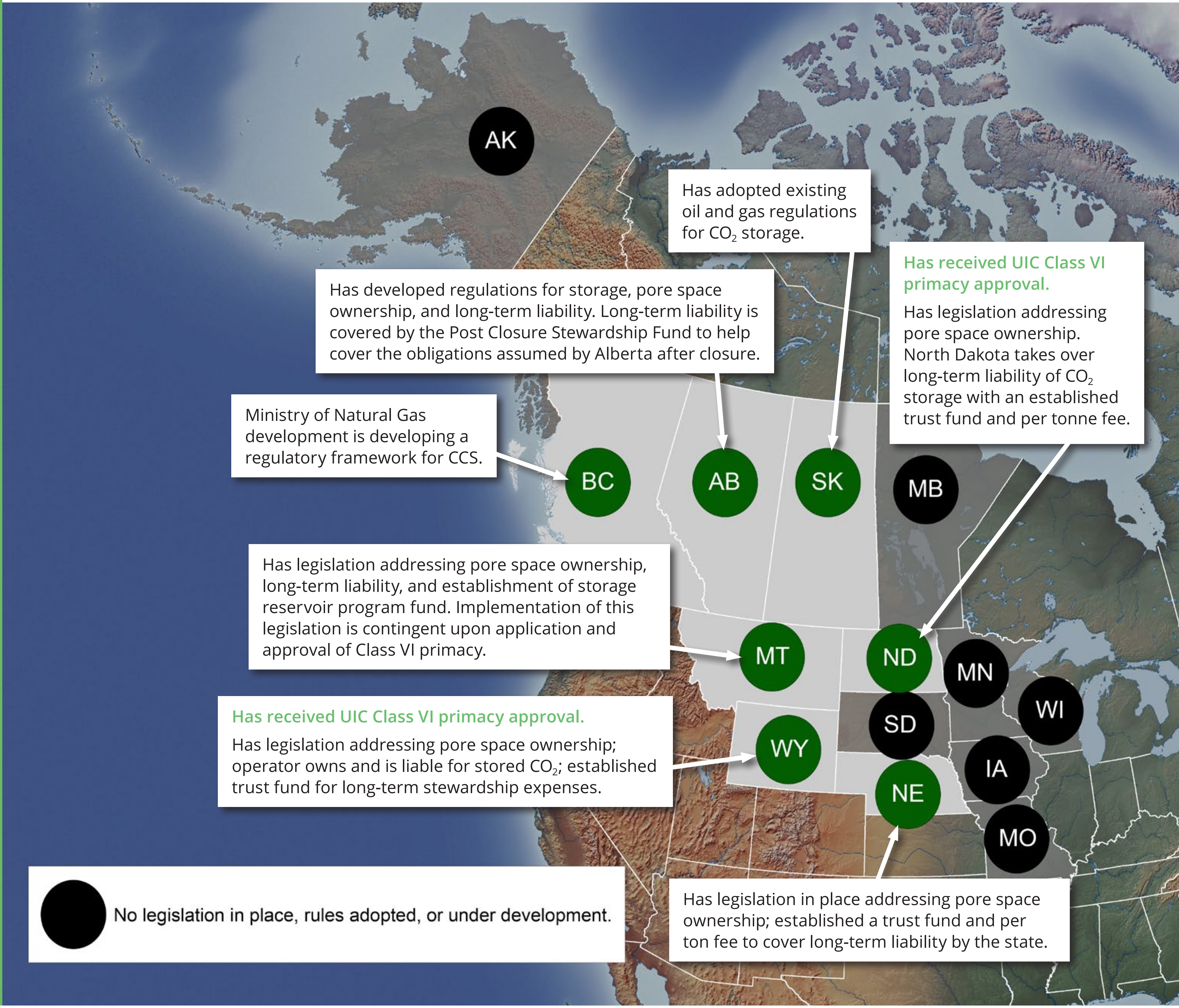


CLASS II WELLS

Inject Oil and Gas Production Fluids



REGULATORY STATUS



PORE SPACE

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

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

LONG-TERM LIABILITY

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

45Q TAX CREDIT

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

Tax credit can be claimed when an eligible project has:

- Securely stored the captured CO_2 in geologic formations, such as oil fields and saline formations.
- Beneficially used captured CO_2 or its precursor carbon monoxide (CO) as a feedstock to produce fuels, chemicals, and products such as concrete in a way that results in emission reductions as defined by federal requirements.

Generally, the 45Q tax credit is claimed by the taxpayer that:

- Owns the carbon capture equipment.
- Physically or contractually ensures the capture and disposal, injection, or utilization of the carbon dioxide.

The owner of the carbon capture equipment does not need to own the industrial facility where the equipment is located to qualify for 45Q tax credits. The tax credits may also be transferred from the owner of the carbon capture equipment to another party that disposes of, injects, or uses the carbon dioxide.

	2008–2018	2018–Today
Constraint	Ends after collective 75 million tonnes claimed	Commence construction by January 1, 2026
Duration to Claim Credit	No limit	12 years
Minimum Capture Target (tonnes)	500,000	Power: 500,000 Industrial: 100,000 Direct air capture: 100,000 Small power/industrial: 25,000
Credit Value ($/tonne)	Saline storage: $20 Via EOR: $10	Saline storage: up to $50 Via EOR and other utilization: up to $35
Eligibility	Power, industrial	Power, industrial, direct air capture

STATE TAX CREDIT

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

State	2008–2018
North Dakota	Sales and use tax exemption Property tax exemption Gross receipts tax reduction
Wyoming	Sales tax exemption Severance tax credit
Montana	Reduced property tax

North Dakota, Wyoming, and Montana offer a variety of tax incentives for projects involving CCUS.[56]

45Q Globally, the most progressive CCUS-specific incentive.[57]

Recent Actions

February 2020 Treasury Department provides clarification on "beginning of construction" and revenue procedure.

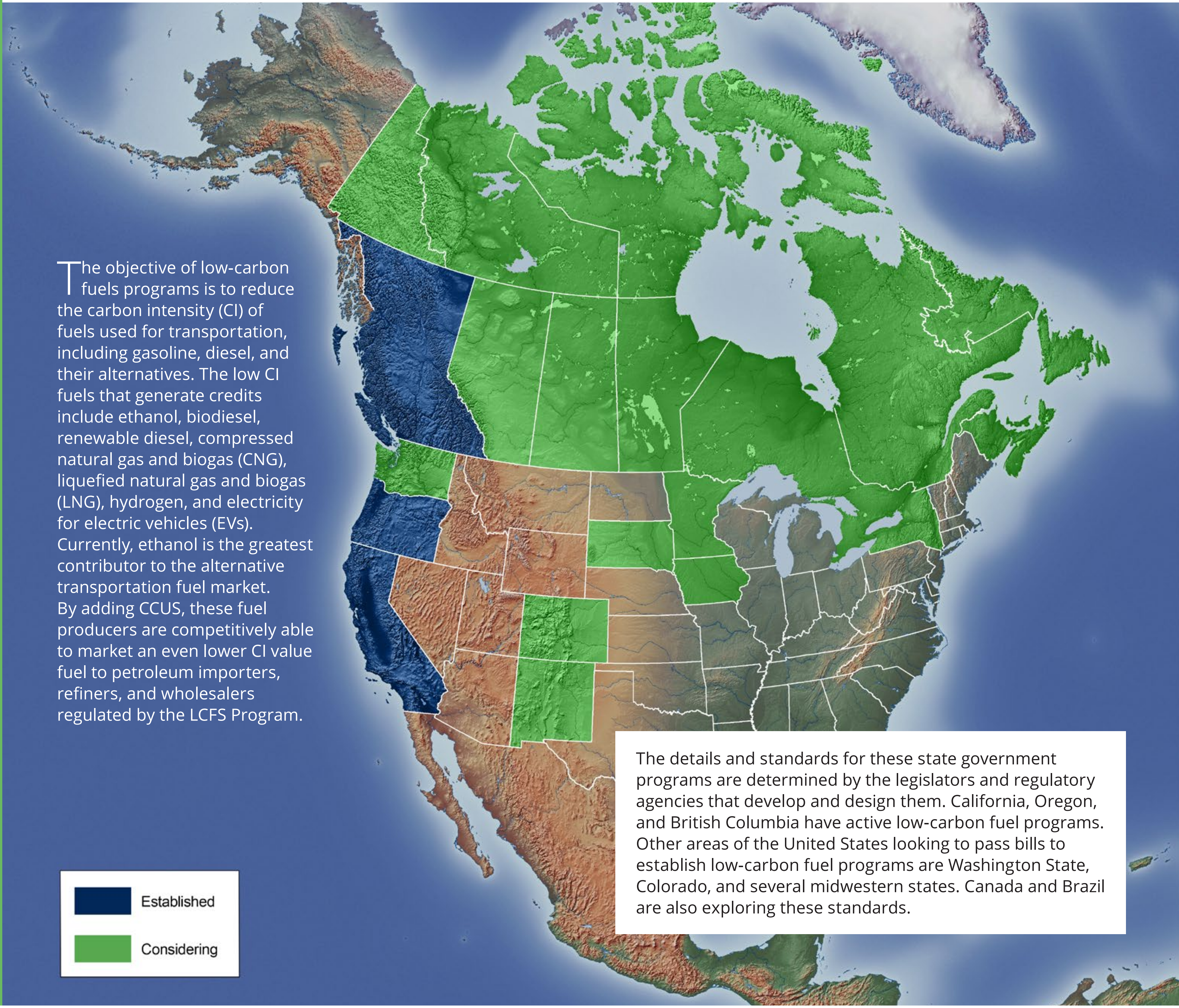
May 2020 Internal Revenue Service proposes regulation for 45Q. Also provides clarification on "secure geologic storage," transfer of credit, recapture of credit, and LCA.

December 2020 Congress approves 2-year extension of 45Q tax credit. Construction must start by January 1, 2026.

January 2021 Treasury Department releases final 45Q tax credit regulation.

LOW-CARBON FUEL MARKETS

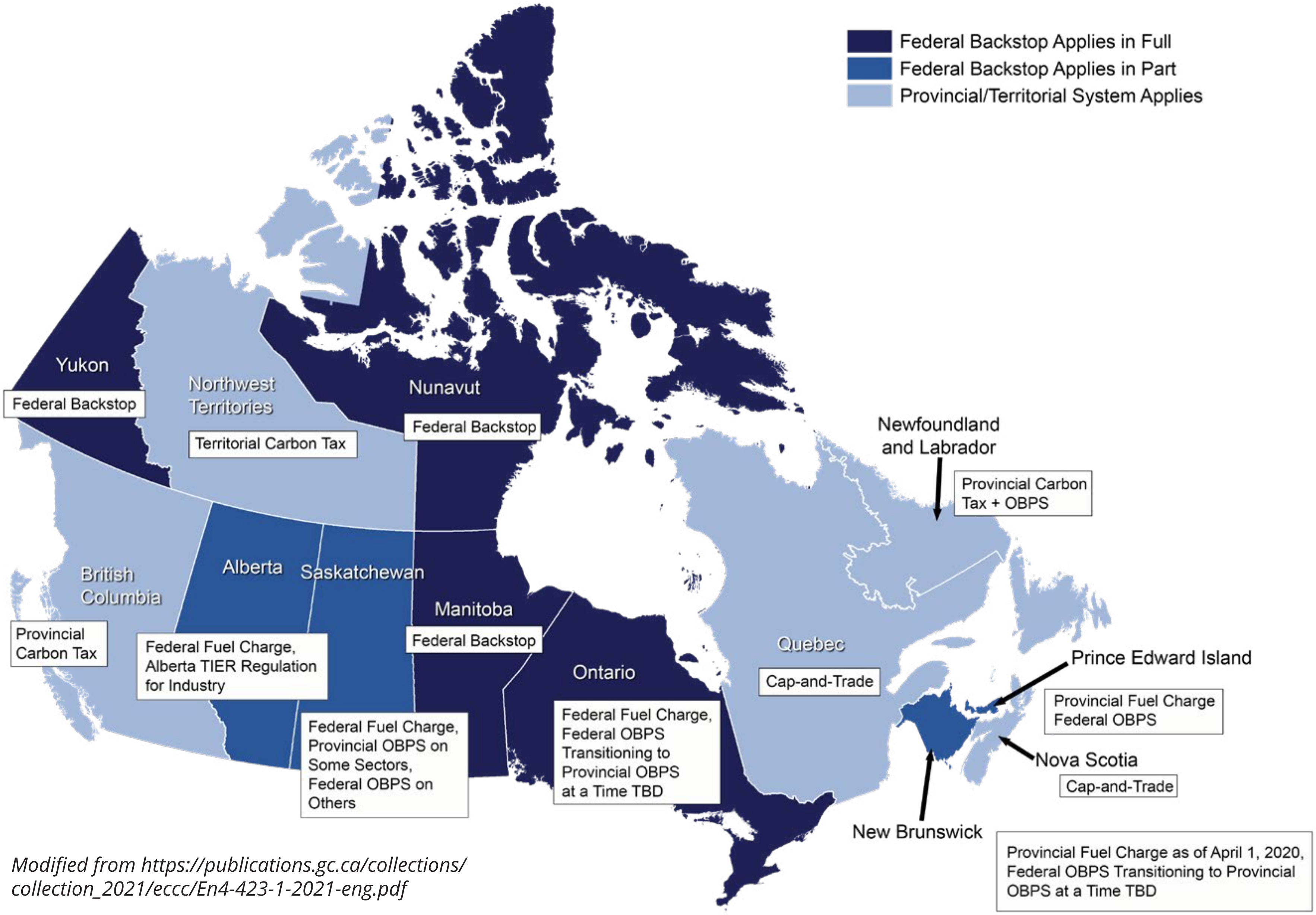
The objective of low-carbon fuels programs is to reduce the carbon intensity (CI) of fuels used for transportation, including gasoline, diesel, and their alternatives. The low CI fuels that generate credits include ethanol, biodiesel, renewable diesel, compressed natural gas and biogas (CNG), liquefied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



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

In its 2021 budget, the Canadian federal government proposed to introduce an investment tax credit for capital invested in CCUS projects, with the goal of reducing CO_2 emissions by at least 15 Mt annually. The investment tax credit, the Output-Based Pricing System (OBPS), will be available to multiple industrial sectors, including cement, refining, power generation, hydrogen generation, and direct air capture. The tax credit is not intended for CO_2 EOR projects. The proposed legislation would come into effect in 2022.[58,59]

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



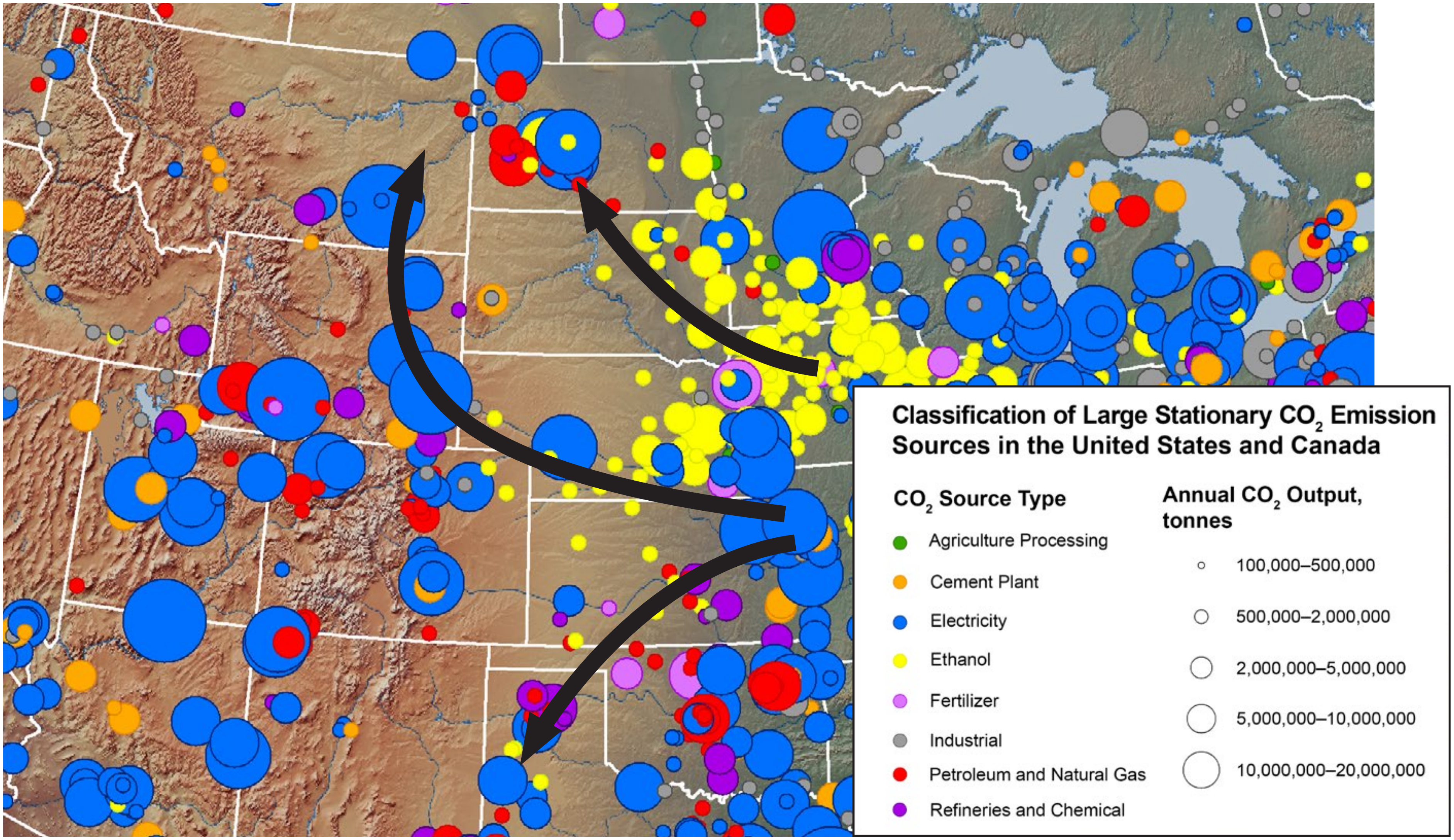
Modified from https://publications.gc.ca/collections/collection_2021/eccc/En4-423-1-2021-eng.pdf

INFRASTRUCTURE

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

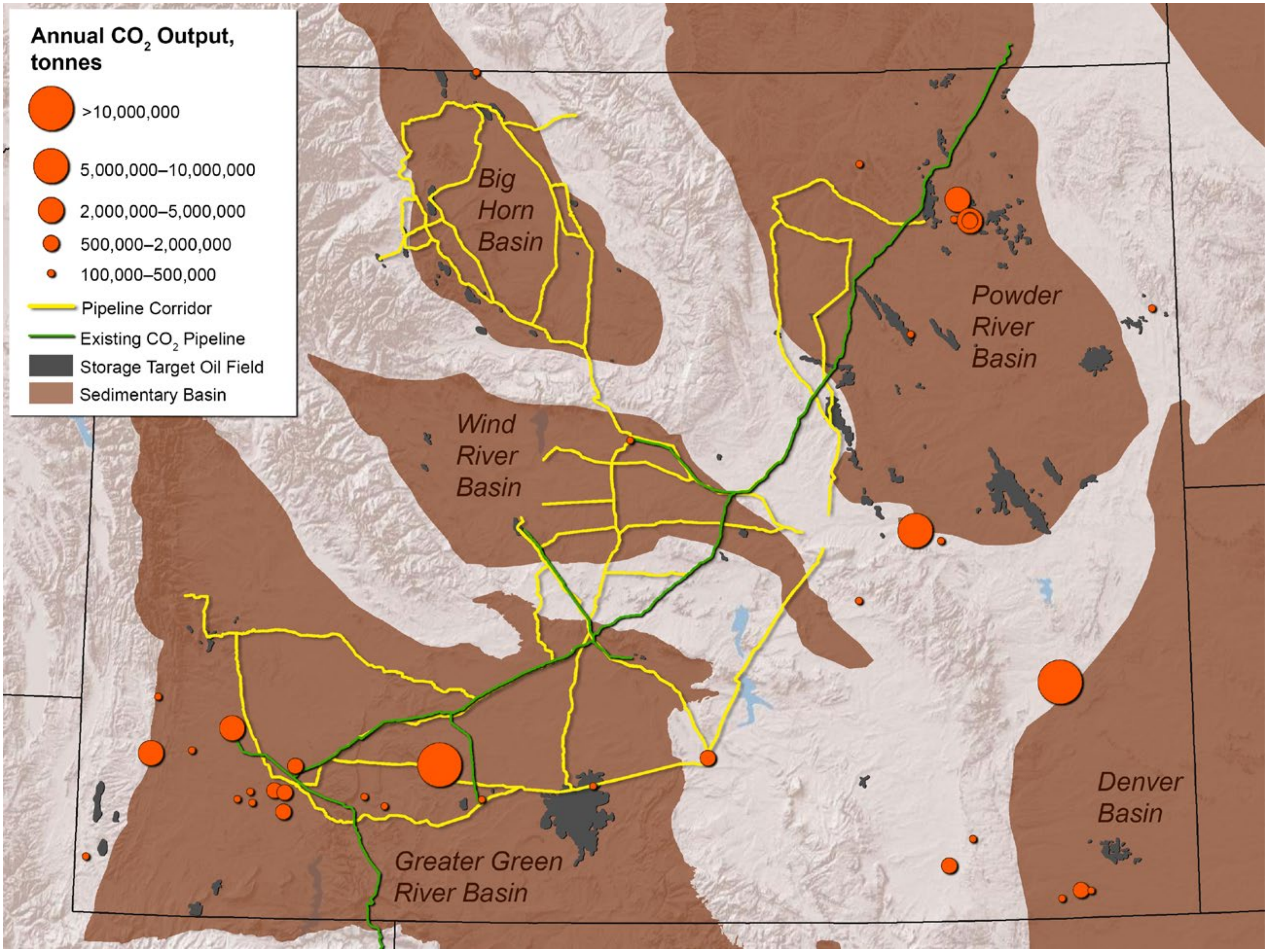
Instead of constructing many new point-to-point pipelines, a more strategic approach using prescribed trunk lines and connector pipelines would be economically advantageous for efficiently enabling widespread commercial CCUS deployment. For example, the ACTL, which had strong Canadian government infrastructure support, was designed for future expansion of CCUS. The 240-km pipeline has nearly 90% of its capacity available to accommodate future CO_2 sources. Two newly planned projects in the PCOR Partnership region involve the development of industrial CCUS hubs with shared CO_2 transport and storage infrastructure.[60,61] The development of additional shared infrastructure such as pipelines can be a strong incentive to trigger new investments.

Hypothetical CO_2 Truck Line Routes



WYOMING PIPELINE CORRIDOR INITIATIVE

A notable example of facilitating infrastructure development in the PCOR Partnership region is the Wyoming Pipeline Corridor Initiative (WPCI). WPCI was formed to promote the development of a network of CO_2 pipelines throughout Wyoming for transportation of CO_2 from emission sources (such as power plants) to suitable storage locations or for other uses (such as EOR). Under the leadership of Wyoming's Governor's Office and in collaboration with researchers, industries, and other state agencies, WPCI proposes pipeline routes that would cover almost 2000 miles and cross federal, state, and private lands in central and eastern Wyoming. More than half of the proposed corridors are through Bureau of Land Management (BLM) land, and in January 2021, BLM approved the WPCI proposal to designate over 1000 miles to the pipeline network. This approval is expected to accelerate the development of pipeline projects by reducing the time and cost of permitting.



THE BUSINESS CASE FOR CCUS

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

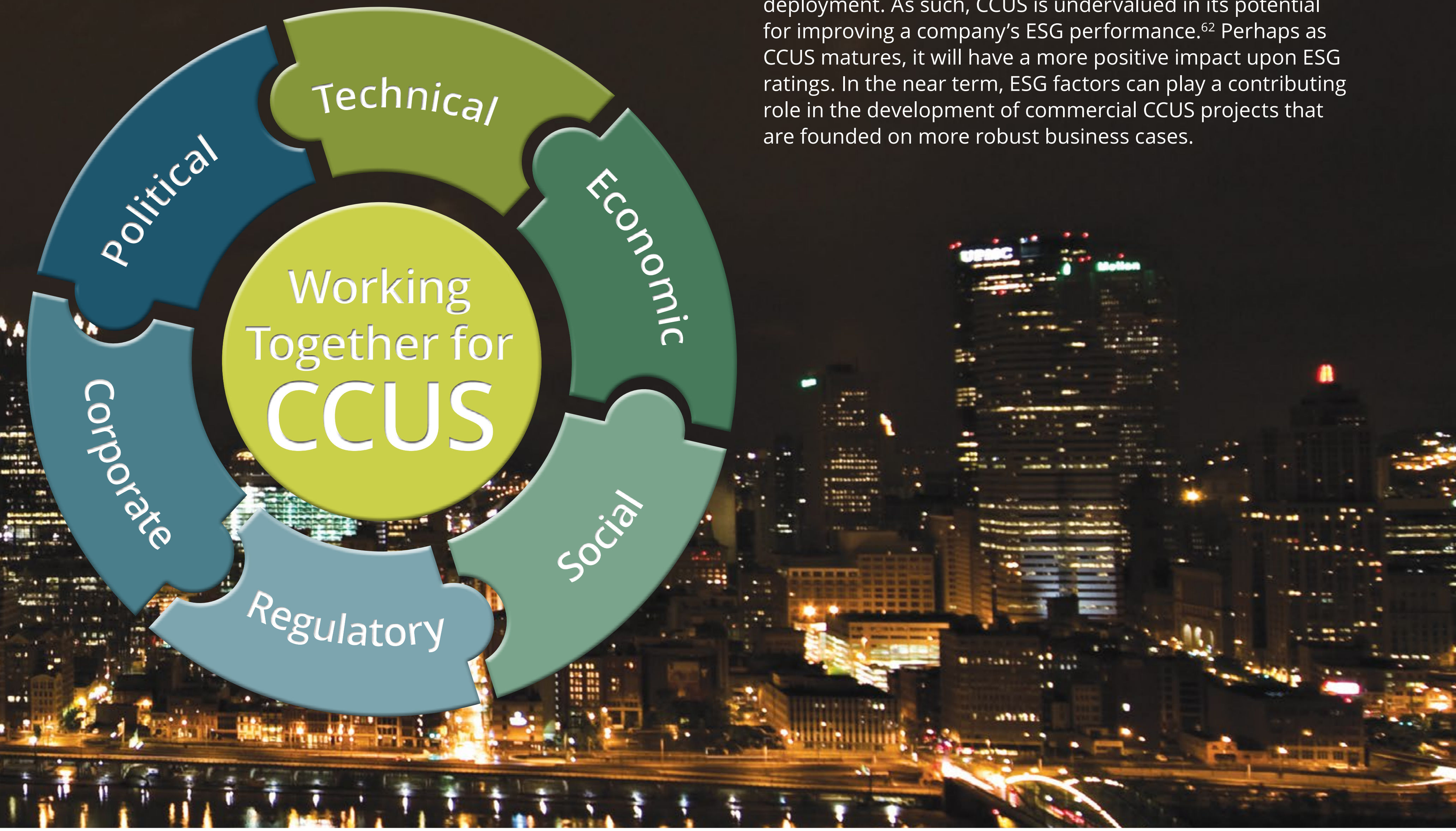
Selling captured CO_2 as a commodity is the easiest business model if the buyer and seller can reach an agreement on the CO_2 sale price and a long-term contract. This type of arrangement defines a traditional CO_2 EOR situation.

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

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

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

CCUS can play a vital role in reducing atmospheric CO_2 levels while simultaneously preserving the option of using abundant and low-cost domestic fossil energy resources. However, the scale of CCUS deployment needed to result in significant reductions will require thousands of CCUS deployments around the world over the next 3–4 decades. The expansion of a new technology at that rate is challenging but achievable, particularly when the technology becomes routine and impediments are mitigated. Research, development, and demonstration (RD&D) programs such as those currently conducted by DOE's RCSP Program are critical for demonstrating CO_2 storage in diverse geologic settings and will establish the basis for CCUS's widespread global deployment.



ENVIRONMENTAL, SOCIAL, AND CORPORATE GOVERNANCE AND CCUS

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

Despite broad awareness of the potential for CCUS within the investment and rating communities, substantial uncertainty remains regarding its more widespread deployment. As such, CCUS is undervalued in its potential for improving a company's ESG performance.[62] Perhaps as CCUS matures, it will have a more positive impact upon ESG ratings. In the near term, ESG factors can play a contributing role in the development of commercial CCUS projects that are founded on more robust business cases.

ENGAGING THE PUBLIC

Public awareness and support are critical to the development of new energy technologies and are widely viewed as vital for CCUS projects. CCUS remains an unfamiliar technology to many members of the public, and local opposition to specific project proposals can be significant in some cases. However, enhanced and coordinated public outreach is improving awareness of the role of CCUS as one option to reduce GHG emissions.

Developing public support for CCUS is an essential component of any potential CCUS project. To that end, the PCOR Partnership is working to increase CCUS knowledge among the general public, regulatory agencies, policy makers, and industry.

Educational Workshops

Media Relations

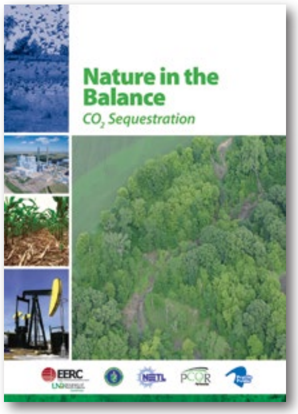
Landowner/ Stakeholder Relations

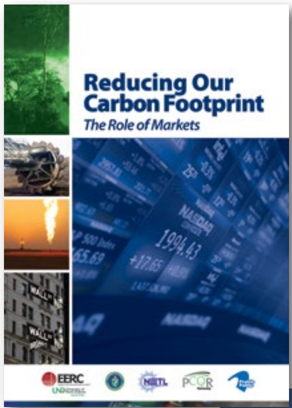
TAKE IT ON THE ROAD

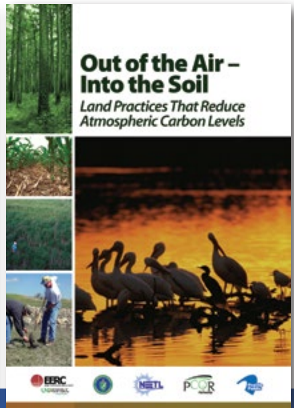
Engaging the public, policy makers, and industry on CCUS remains an essential component of PCOR Partnership activities. This is done through presentations and participation at meetings and public and industry events throughout the region.

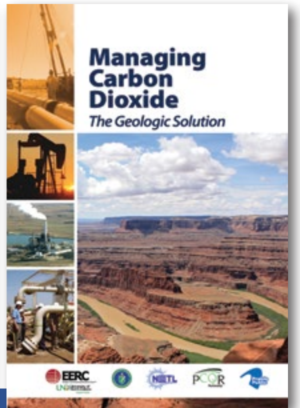
TAKE IT TO PRIME TIME

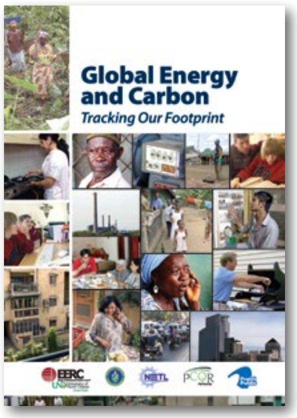
The PCOR Partnership continues its long-standing collaboration with Prairie Public Broadcasting to provide educational activities and documentary productions.



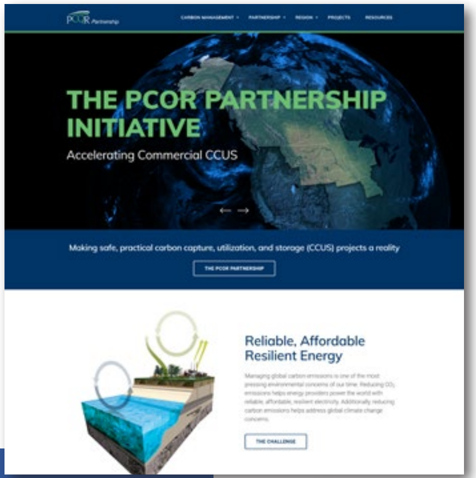




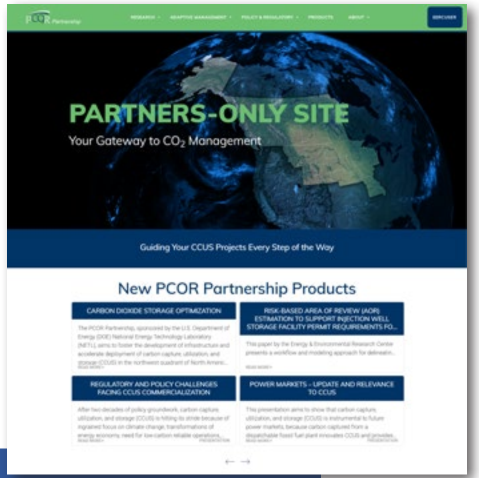




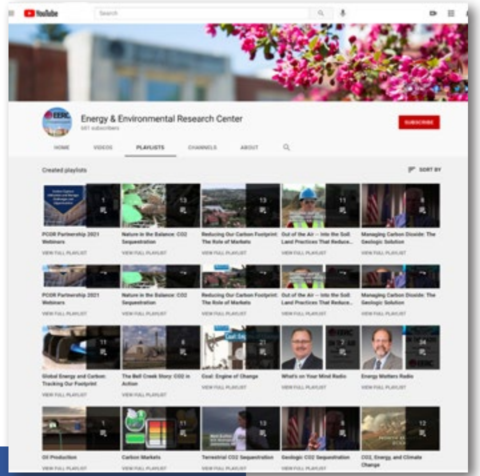
Award-Winning Documentaries



Public Web Site



Partners-Only Web Site



Video Clip Library

TAKE IT ONLINE

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

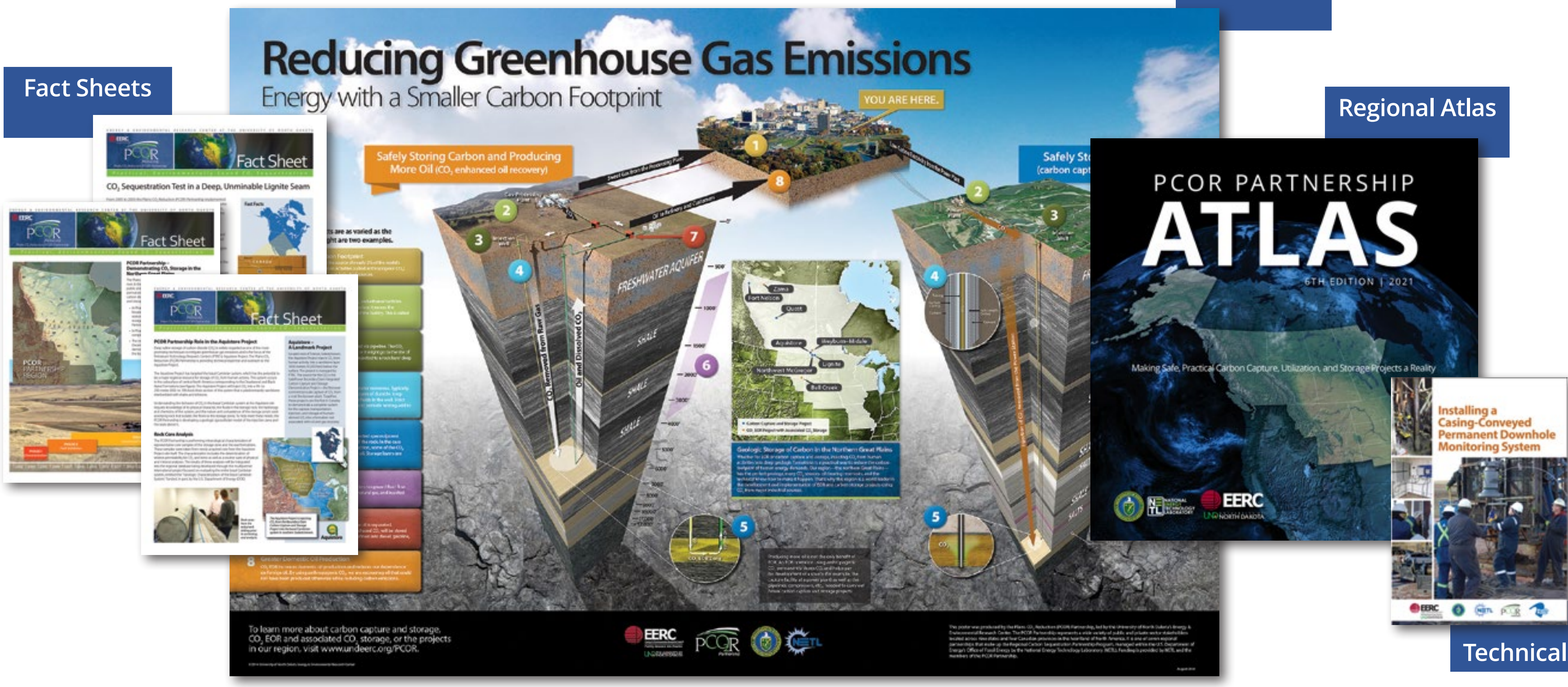
TAKE IT WITH YOU

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

Posters

Fact Sheets

Regional Atlas



Technical Videos

NOMENCLATURE

ACTL	Alberta Carbon Trunk Line
bbl	barrel
BLM	Bureau of Land Management
CCUS	carbon capture, utilization, and storage
CH_4	methane
CI	carbon intensity
CO	carbon monoxide
CO_2	carbon dioxide
CNG	compressed natural gas
CO_2eq	CO_2 equivalent
DAC	direct air capture
DMR	Department of Mineral Resources
Denbury	Denbury Resources Inc.
DOE	U.S. Department of Energy
DSF	deep saline formation
ECBM	enhanced coalbed methane
EERC	Energy & Environmental Research Center
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ESG	environmental, social, and corporate governance
EU	European Union
EV	electric vehicle
FEED	front-end engineering and design
GHG	greenhouse gas
Gt	gigatonnes or billion tonnes
H_2O	water
IEA	International Energy Agency
InSAR	interferometric synthetic aperture radar
ITC	Integrated Test Center
LCA	life cycle analysis
LCFS	low-carbon fuel standard
LNG	liquefied natural gas
mg/L	milligram per liter
MRV	monitoring, reporting, and verification
Mt	million tonne
MVA	monitoring, verification, and accounting
MWh	megawatt · hour
NDC	nationally determined contribution
NDIC	North Dakota Industrial Commission
NWR	North West Redwater Partnership
NETL	National Energy Technology Laboratory
N_2O	nitrous oxide
O_3	ozone
OBPS	output-based pricing system
PCOR	Plains CO_2 Reduction (Partnership)
PCO_2C	Partnership for CO_2 Capture
PDM	permanent downhole monitoring
psi	pound per square inch
PTRC	Petroleum Technology Research Centre
RCSP	Regional Carbon Sequestration Partnership
R&D	research and development
RD&D	research, development, and demonstration
RTE	Red Trail Energy, LLC
SDWA	Safe Drinking Water Act
SER	School of Energy Resources
stb	stock tank barrel
TDS	total dissolved solids
UIC	underground injection control
UNFCCC	United Nations Framework Convention on Climate Change
USDW	underground sources of drinking water
UWY	University of Wyoming
VSP	vertical seismic profile
WPCI	Wyoming Pipeline Corridor Initiative

CCUS UNITS AND CONVERSION FACTORS

Prefixes

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

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

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

Mcf = 1000 ft^3

Volume

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

Weight

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

Length/Area

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

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

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