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.
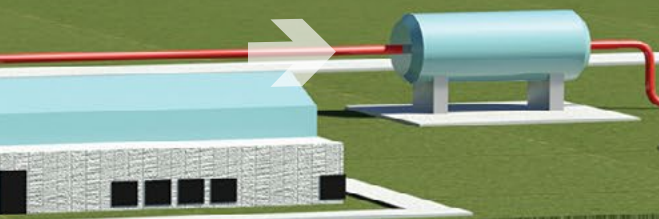
CO$_2$ Capture

Purification/CO$_2$ Dehydration

Compression

Not to scale.

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.

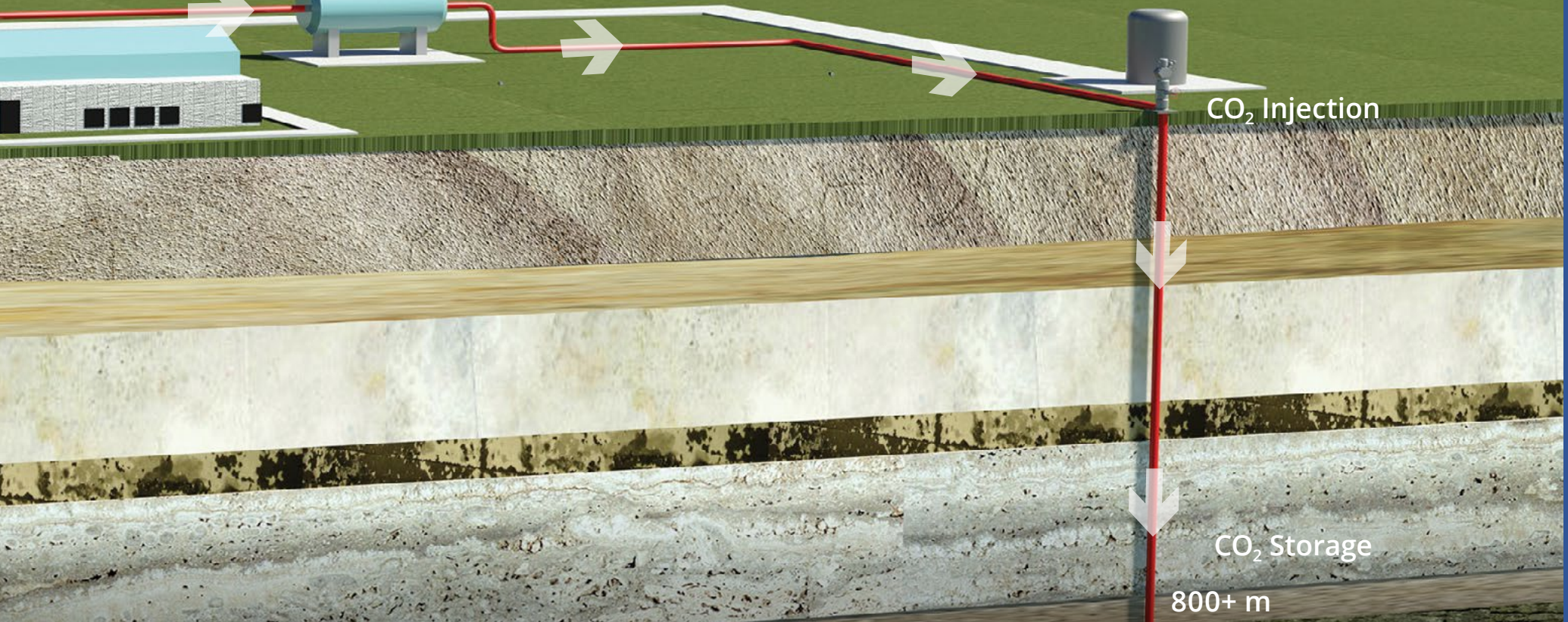## CO_2 Transportation

CO_2 Transportation Pipeline

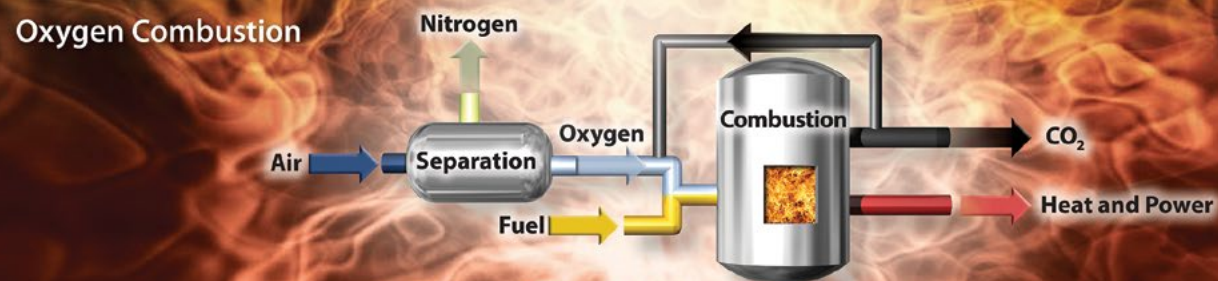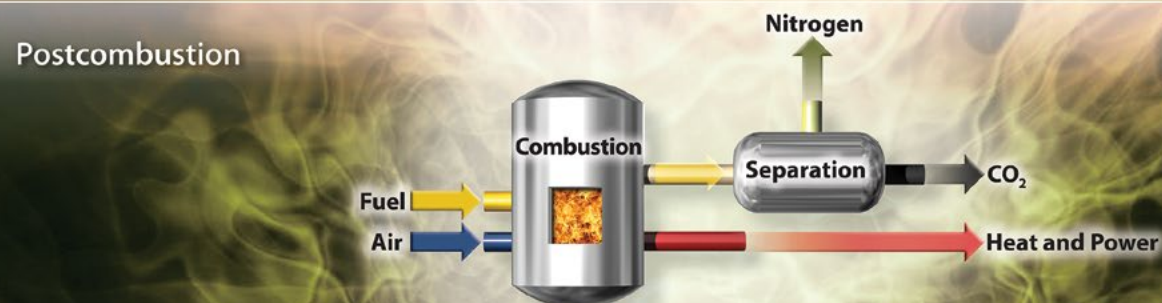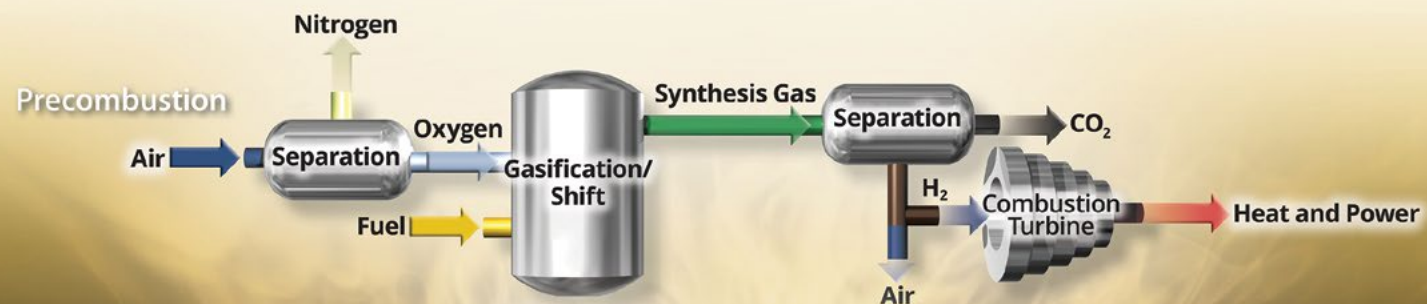## CO_2 Storage

CO_2 Injection

CO_2 Storage

800+ m

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.

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.
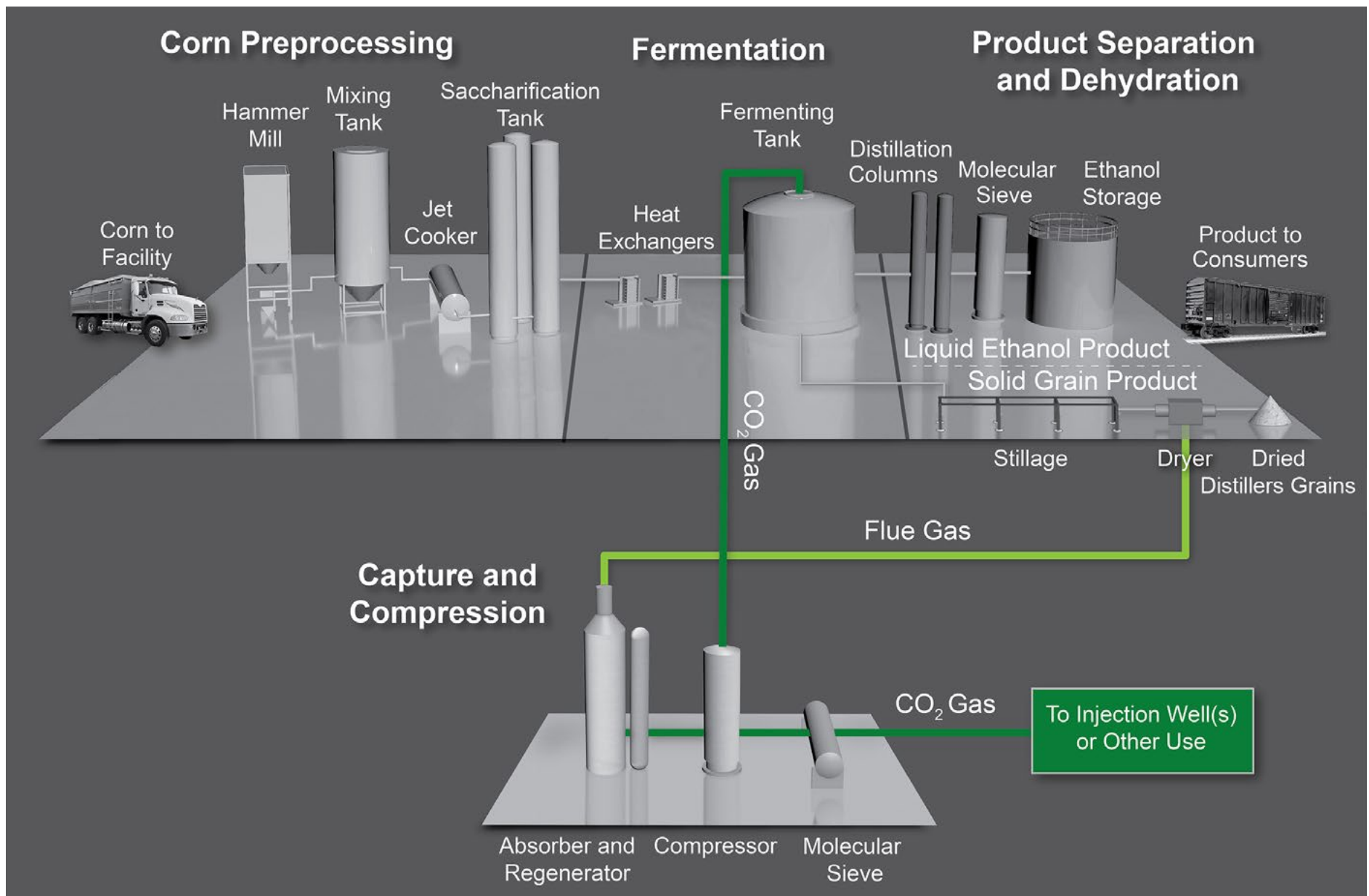
DIRECT AIR CAPTURE

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.

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.

CO$_2$ PIPELINES

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.

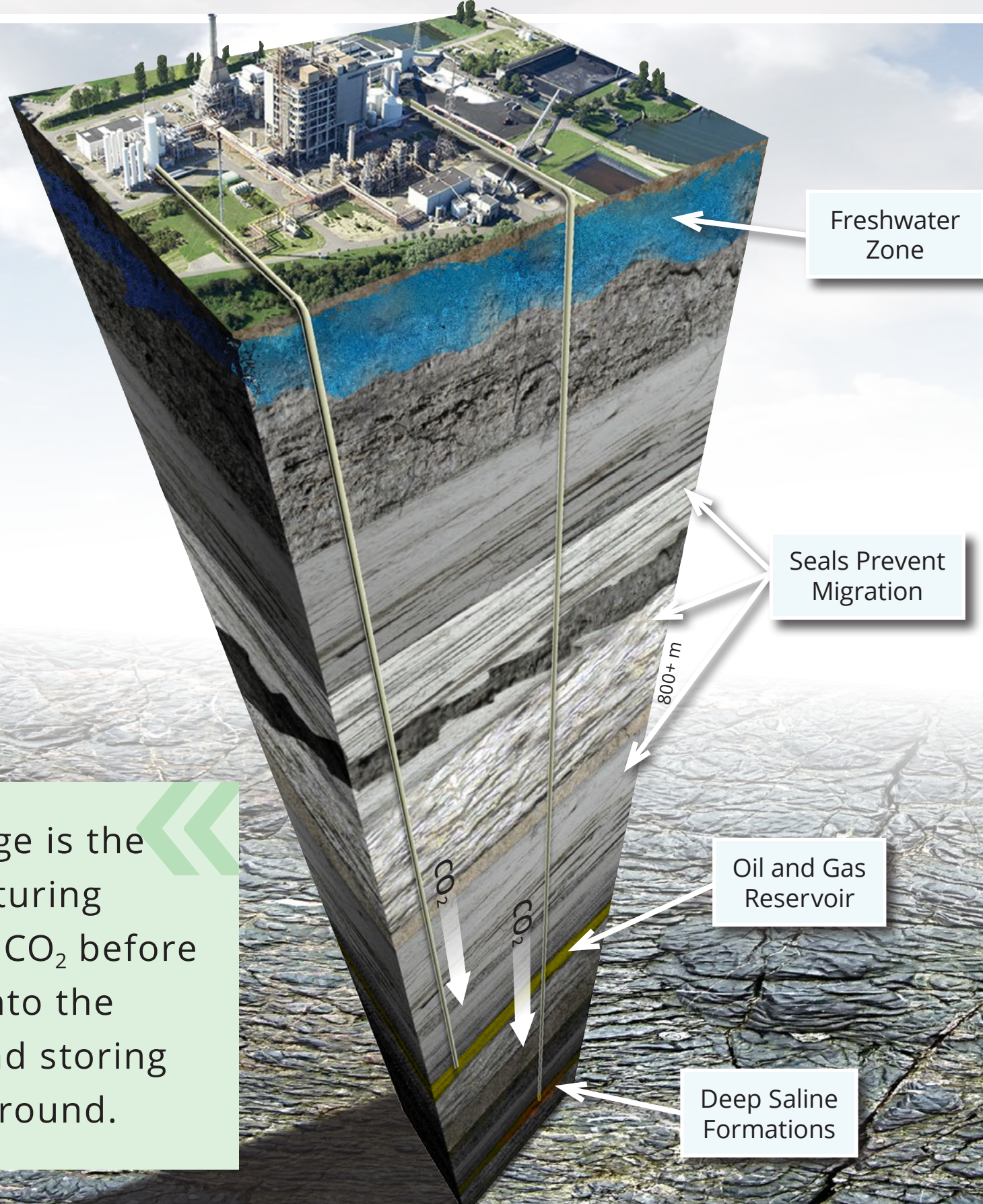NO serious human injuries or fatalities have been reported as a result of CO$_2$ transport via pipeline.[22]

Image provided by Denbury Resources Inc.

Image provided by Denbury Resources Inc.

SECURE GEOLOGIC STORAGE

Freshwater Zone

Seals Prevent Migration

800+ m

CO_2

CO_2

Oil and Gas Reservoir

Deep Saline Formations

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

PCOR Partnership

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.
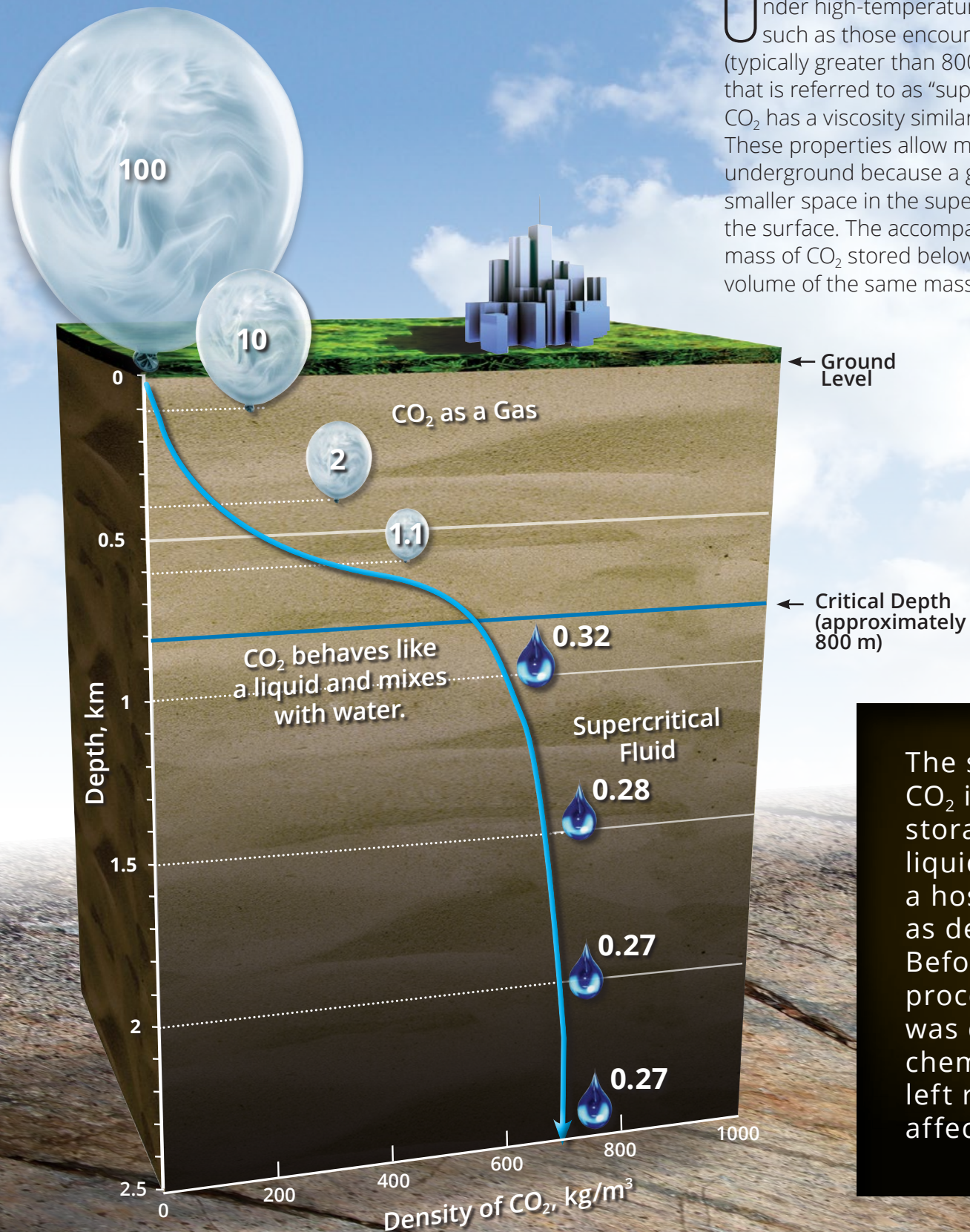
STORAGE RESERVOIR CHARACTERISTICS

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$_2$

U nder 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.

100

10

← **Ground Level**

CO$_2$ **as a Gas**

2

1.1

← **Critical Depth (approximately 800 m)**

0.32

CO$_2$ **behaves like a liquid and mixes with water.**

Supercritical Fluid

0.28

0.27

0.27

Depth, km

0

0.5

1

1.5

2

2.5

Density of CO$_2$, kg/m^3

0   200   400   600   800   1000

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.

PCOR Partnership

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.
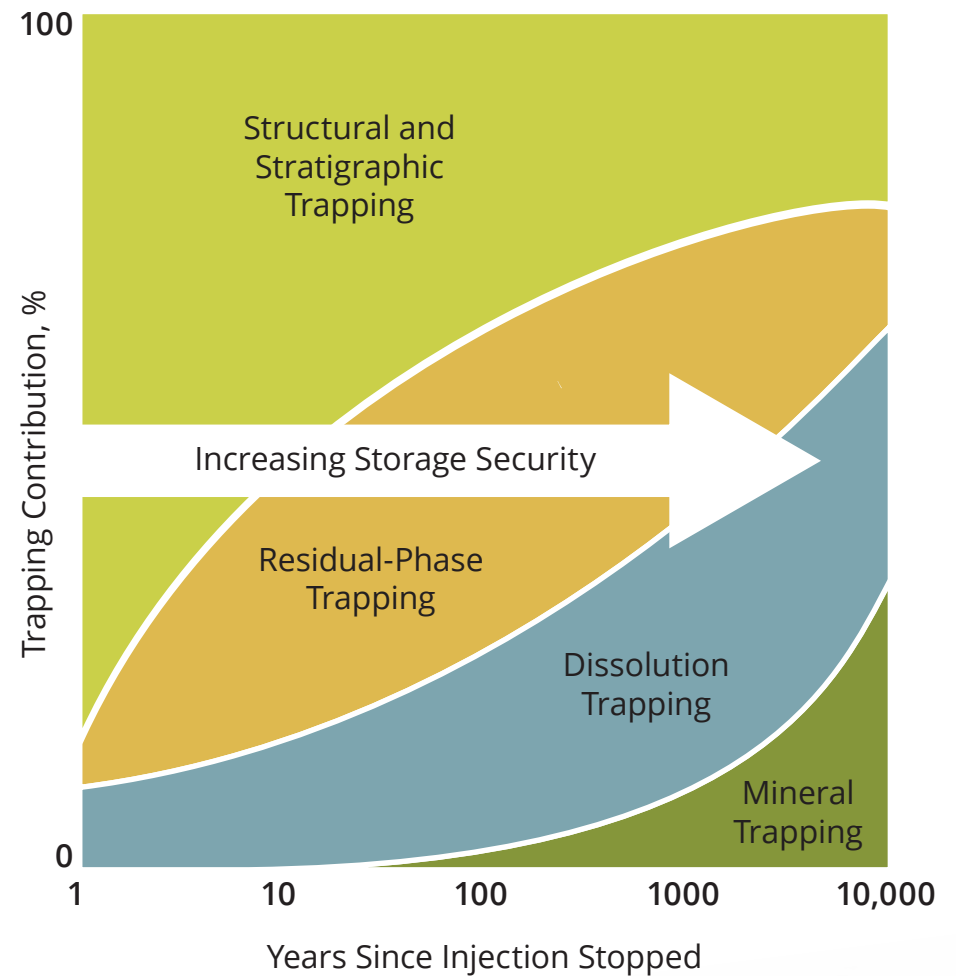

As time passes after the injection of CO$_2$ into a deep geologic environment, the trapping mechanism becomes more effective. Storage security increases as the trapping mechanism moves from the physical process of structural and stratigraphic trapping toward geochemically based processes.
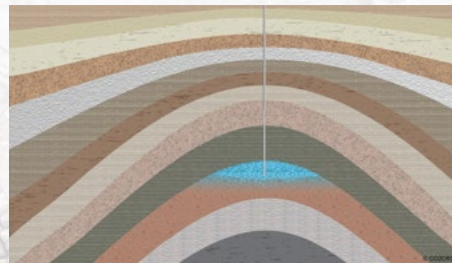
Structural and Stratigraphic Trapping
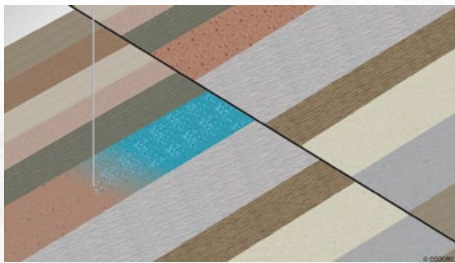
A sealing fault can line up an impervious rock layer with the formation to prevent the CO$_2$ from moving upward out of the formation.
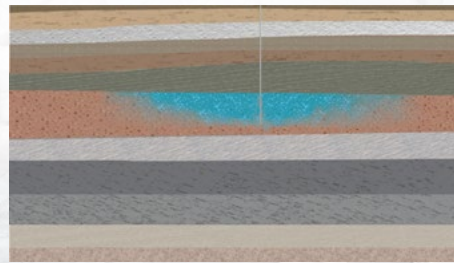
The CO$_2$ is trapped when there is a sudden change in the rock formations, so that the CO$_2$ cannot move upward.

The buoyant CO$_2$ will collect under a curved layer of impermeable rock at the highest point, unable to move out of the formation.
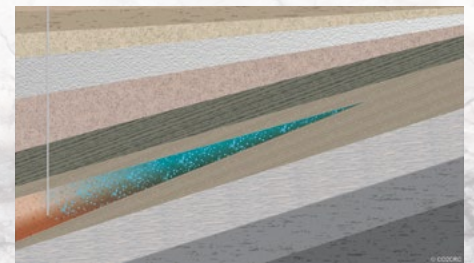
CO$_2$ can become trapped when there is a change in the type of rock in the formation from a permeable rock to an impermeable rock.

CANADA

UNITED STATES

MEXICO

Oil and Gas Field Distribution[23]

Note: Mexico oil fields are not pictured because of data limitations.

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.

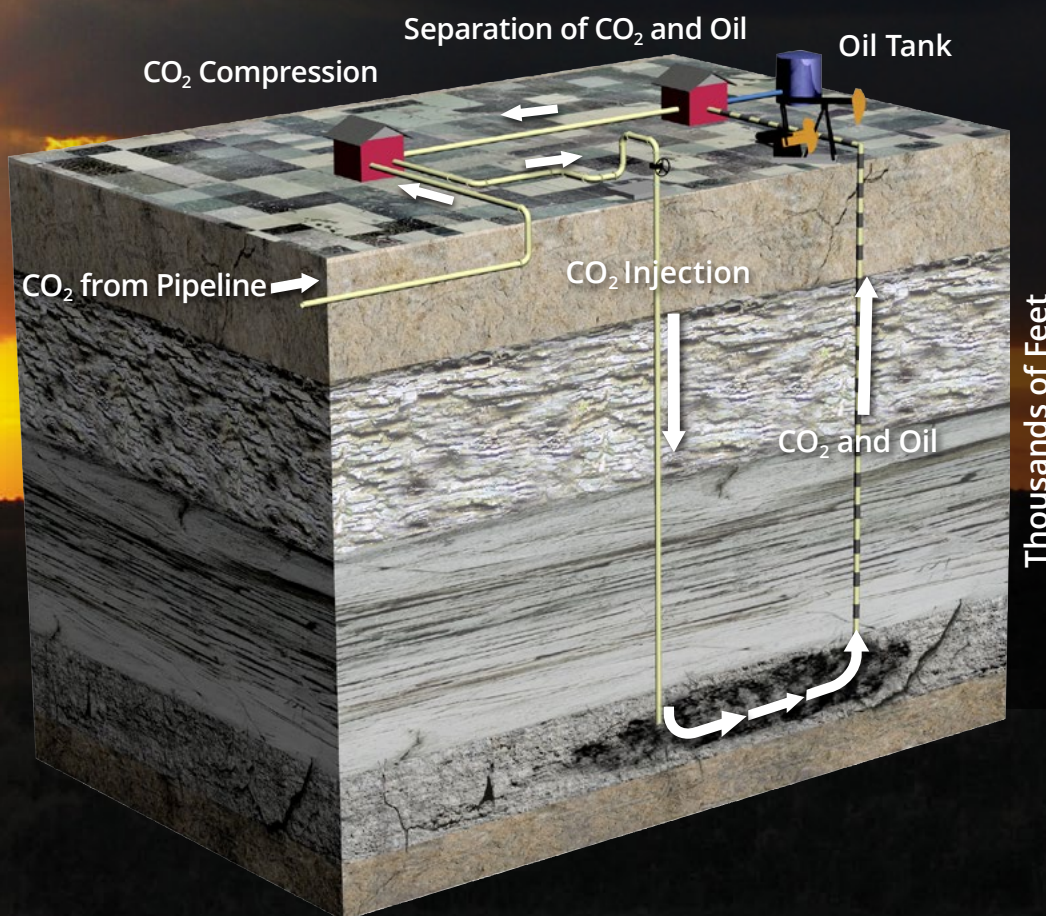Oil and gas reservoirs have already demonstrated their ability to hold buoyant fluids, including natural CO$_2$, for millions of years.
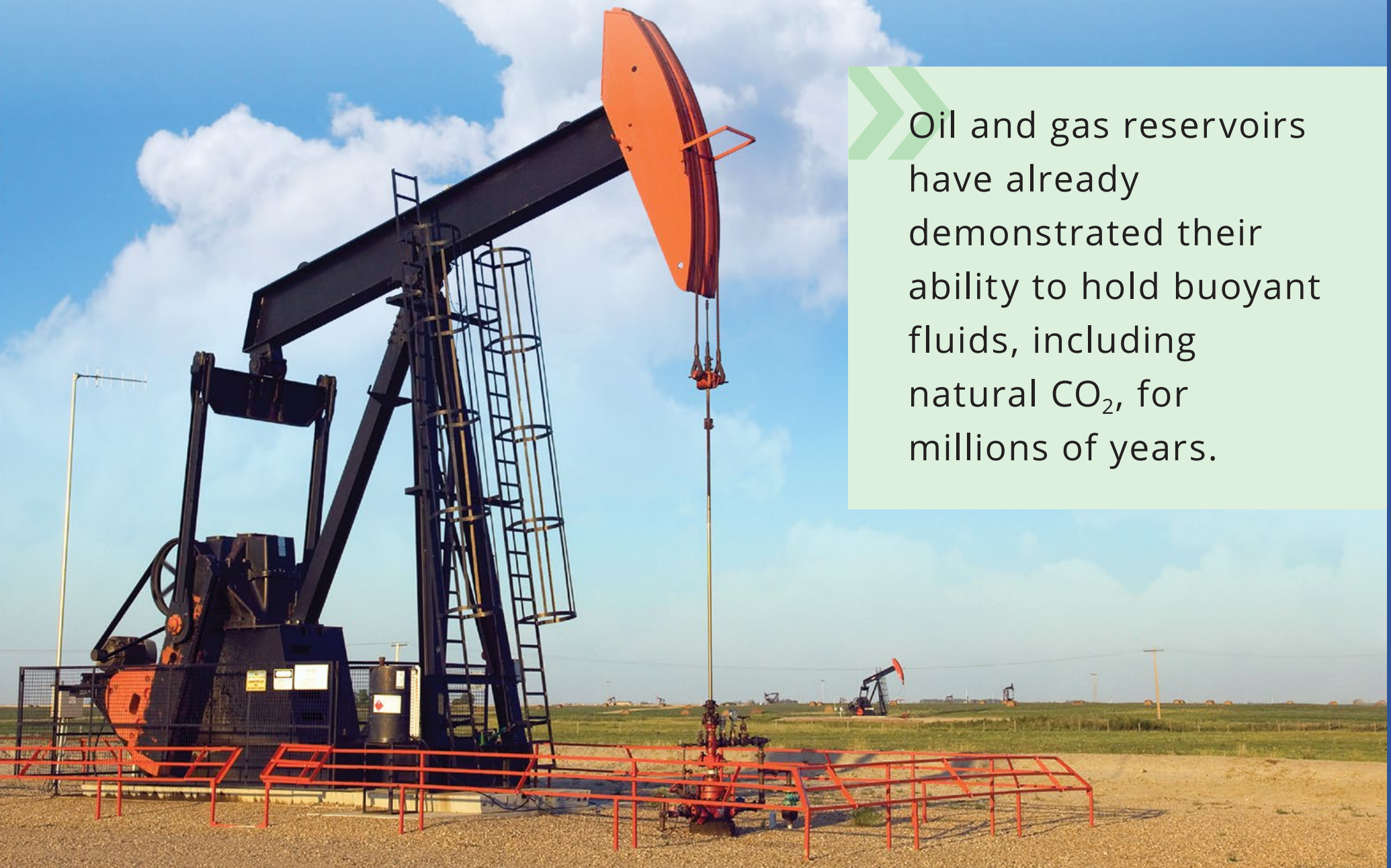
In 2019, U.S.-based CO_2 EOR produced nearly **300,000** barrels of oil per day.[24]

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.

Separation of CO_2 and Oil

CO_2 Compression

Oil Tank

CO_2 from Pipeline

CO_2 Injection

CO_2 and Oil

Thousands of Feet

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.
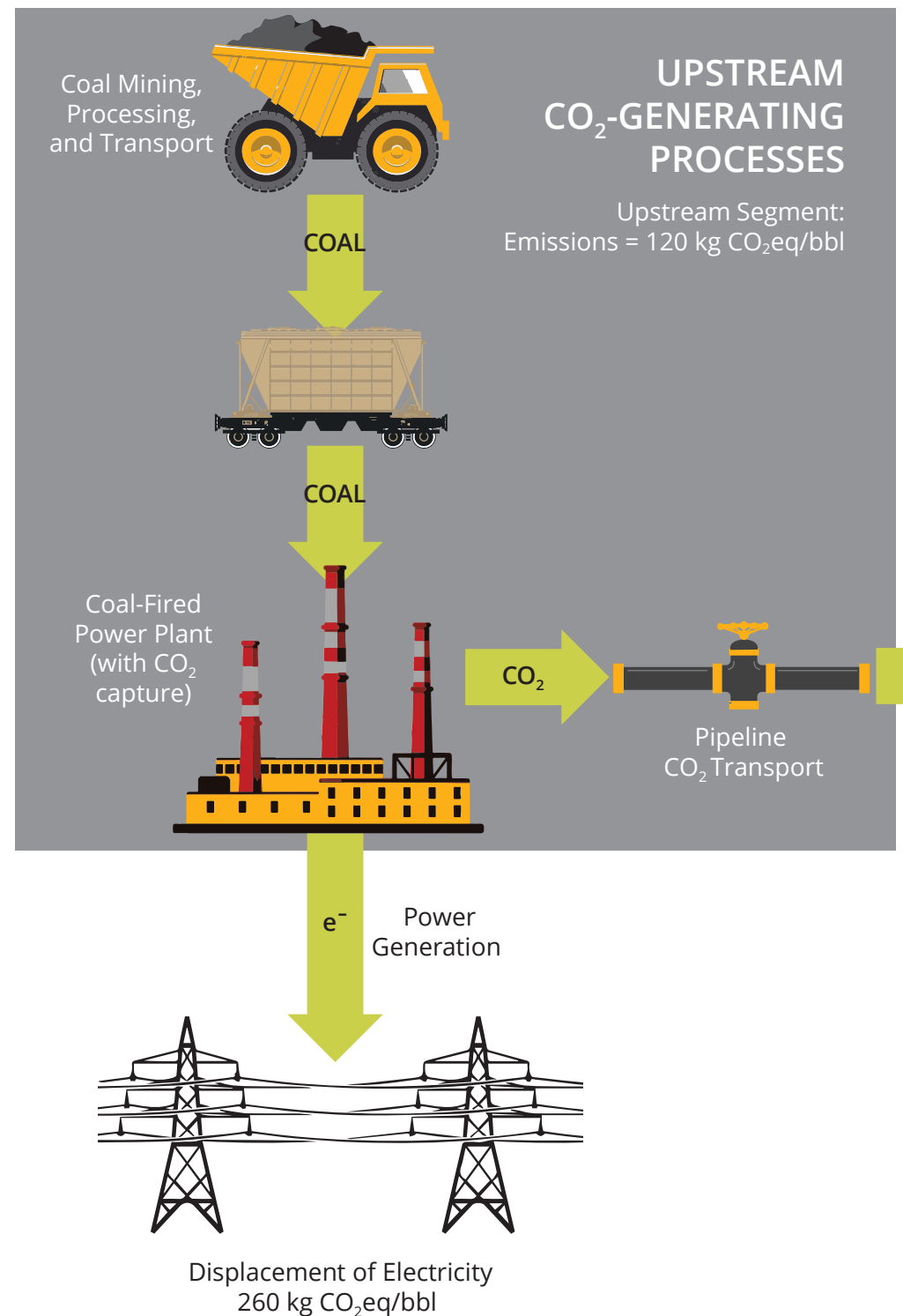
Since the 1970s, operators in West Texas have safely pumped millions of tonnes of CO_2 into oil fields for EOR purposes. The success of the technique has seen a steady increase in the number of fields (now over 130) employing CO_2 EOR in West Texas and other states. Although a majority of CO_2 used in 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$_2$eq) emissions from upstream, gate-to-gate, and downstream segments were 690 kg CO$_2$eq/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$_2$eq/bbl.

Coal Mining, Processing, and Transport

UPSTREAM CO$_2$-GENERATING PROCESSES

Upstream Segment: Emissions = 120 kg CO$_2$eq/bbl

COAL

COAL

Coal-Fired Power Plant (with CO$_2$ capture)

CO$_2$

Pipeline CO$_2$ Transport

e$^-$ Power Generation

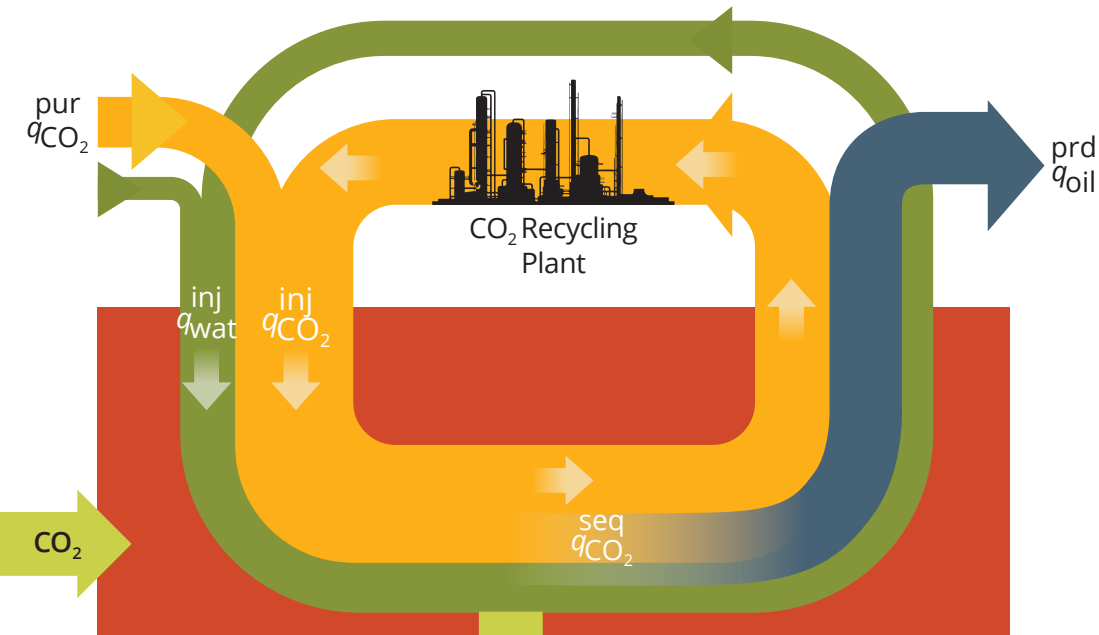Displacement of Electricity
260 kg CO$_2$eq/bbl

Note: Emissions are expressed as CO$_2$eq, which include CO$_2$, CH$_4$, and N$_2$O.

CO$_2$ EOR OPERATIONS (gate-to-gate)

Gate-to-Gate Segment: Emissions = 100 kg CO$_2$eq/bbl

"Gate-to-Gate"

pur
q_{CO_2}

prd
q_{oil}

CO$_2$ Recycling Plant

inj
q_{wat}

inj
q_{CO_2}

CO$_2$

seq
q_{CO_2}

CRUDE OIL

CONVENTIONAL CRUDE

EERC Optimized (300)

EERC Average (430)

HEAVY OIL AND BITUMEN

LIGHT, TIGHT OIL

Frequency

300 400 500 600 700 800 900
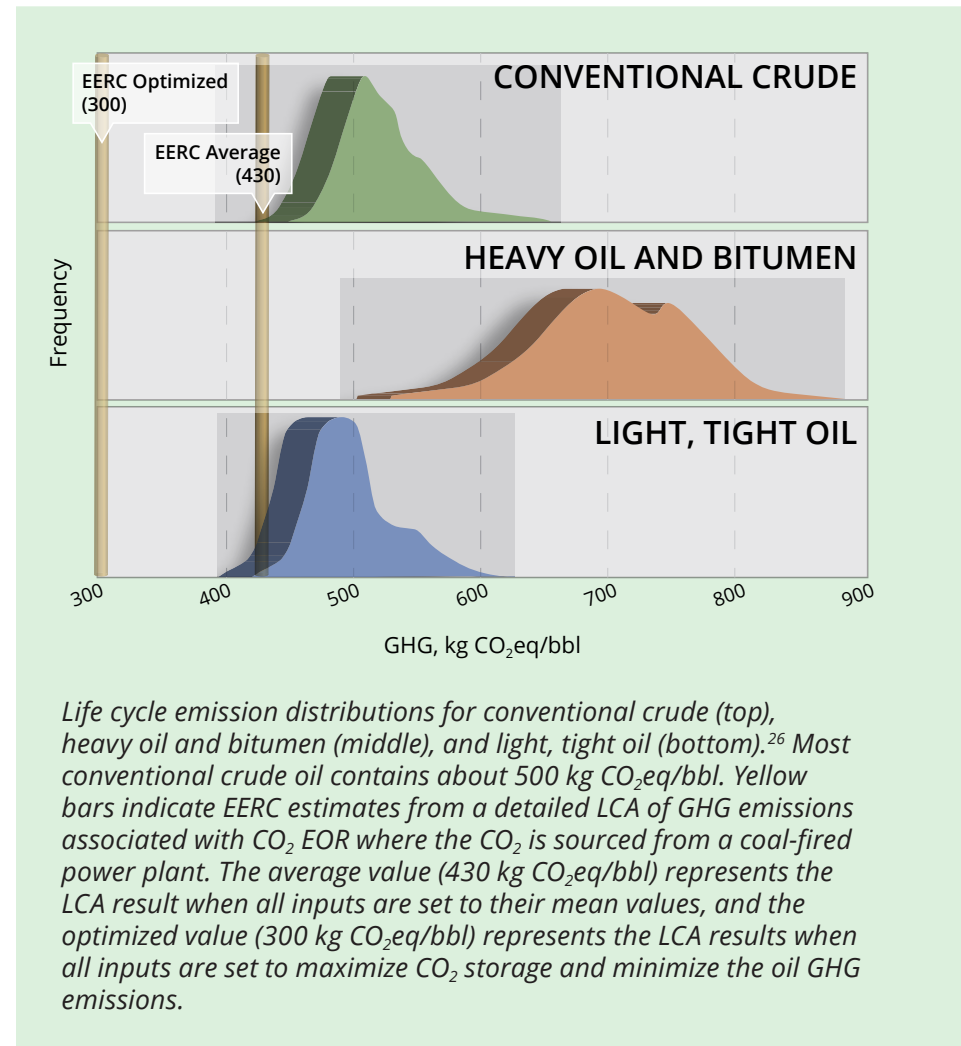
GHG, kg CO$_2$eq/bbl

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$_2$eq/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$_2$eq/bbl) represents the LCA result when all inputs are set to their mean values, and the optimized value (300 kg CO$_2$eq/bbl) represents the LCA results when all inputs are set to maximize CO$_2$ storage and minimize the oil GHG emissions.

DOWNSTREAM CO$_2$-GENERATING PROCESSES

Crude Oil Pipeline Transport to Refinery

CRUDE OIL

Downstream Segment	Net Life Cycle Balance
Emissions = 470 kg CO$_2$eq/bbl	120 kg CO$_2$eq/bbl
	100 kg CO$_2$eq/bbl
	+ 470 kg CO$_2$eq/bbl
Total Emissions	690 kg CO$_2$eq/bbl
Electricity Displacement	−260 kg CO$_2$eq/bbl
	430 kg CO$_2$eq/bbl

Petroleum Refining

Fuel Transport, Distribution, and Point of Sale

Fuel Combustion

FUEL

FUEL

Sedimentary Basin [27]

Greater than 800 m in depth

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

Missouri River

Lake Superior

Great Salt Lake

Ocean Water

Dead Sea

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.

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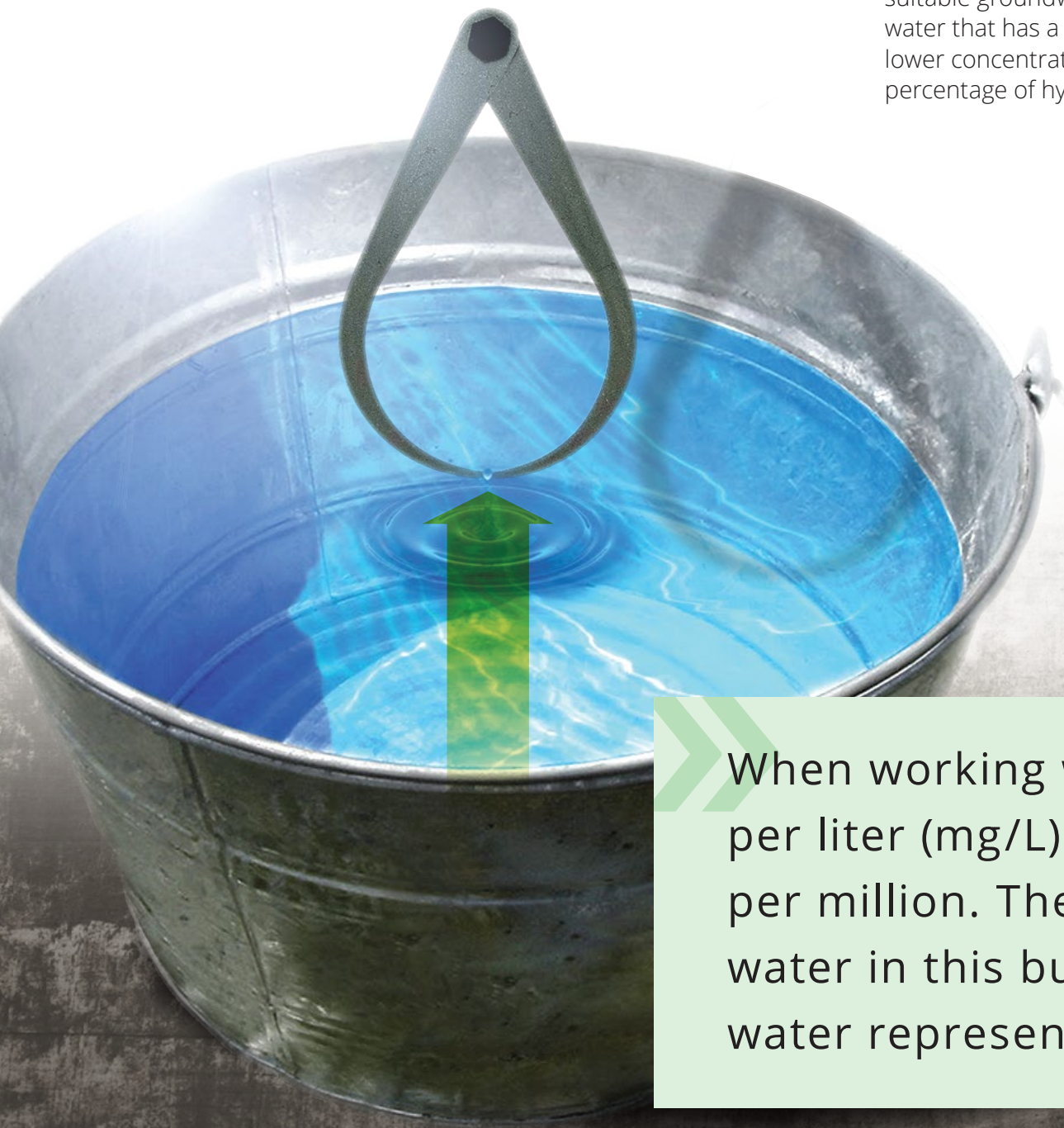
When working with water, 1 milligram per liter (mg/L) is equivalent to 1 part per million. There are 1 million drops of water in this bucket. One drop of this water represents 1 part per million.