

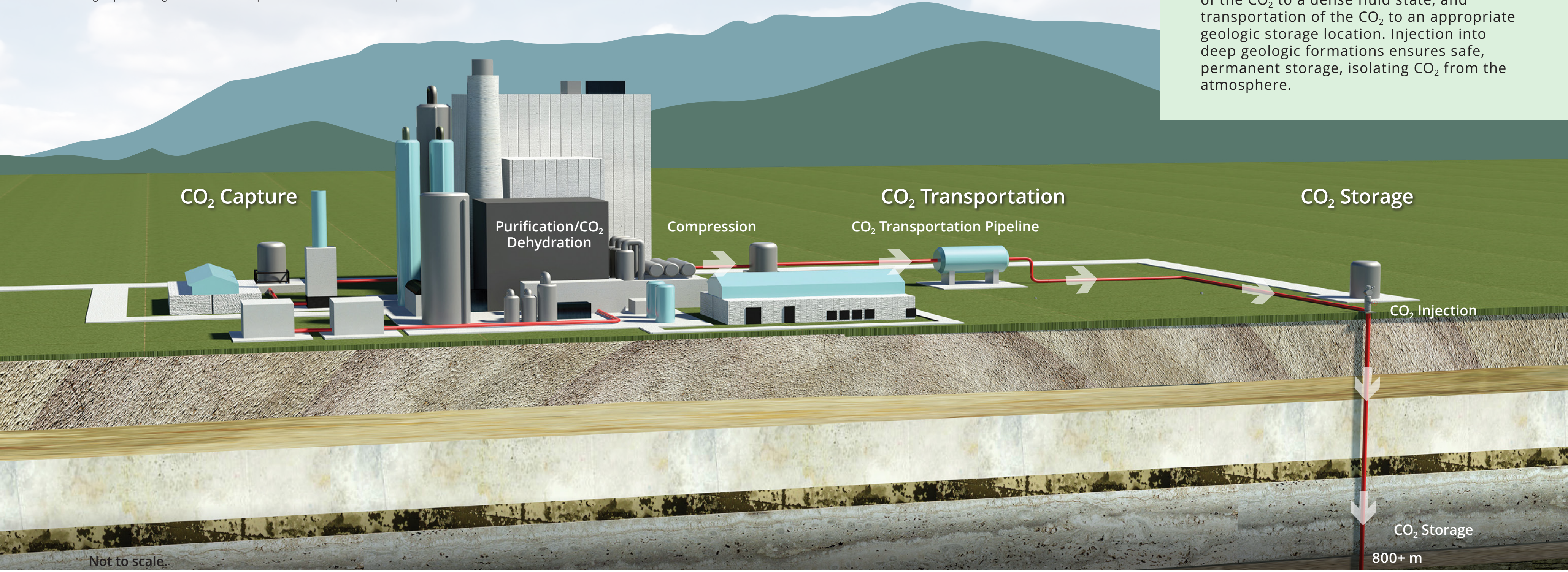
CARBON MANAGEMENT

The need to stabilize atmospheric concentrations of CO₂ 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 CO₂ from the exhaust gas at large stationary sources and placing it 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 CO₂ emissions from large stationary sources before the CO₂ 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 CO₂ emissions 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 separation of CO₂ from other emission gases, compression of the CO₂ to a dense fluid state, and transportation of the CO₂ to an appropriate geologic storage location. Injection into deep geologic formations ensures safe, permanent storage, isolating CO₂ from the atmosphere.

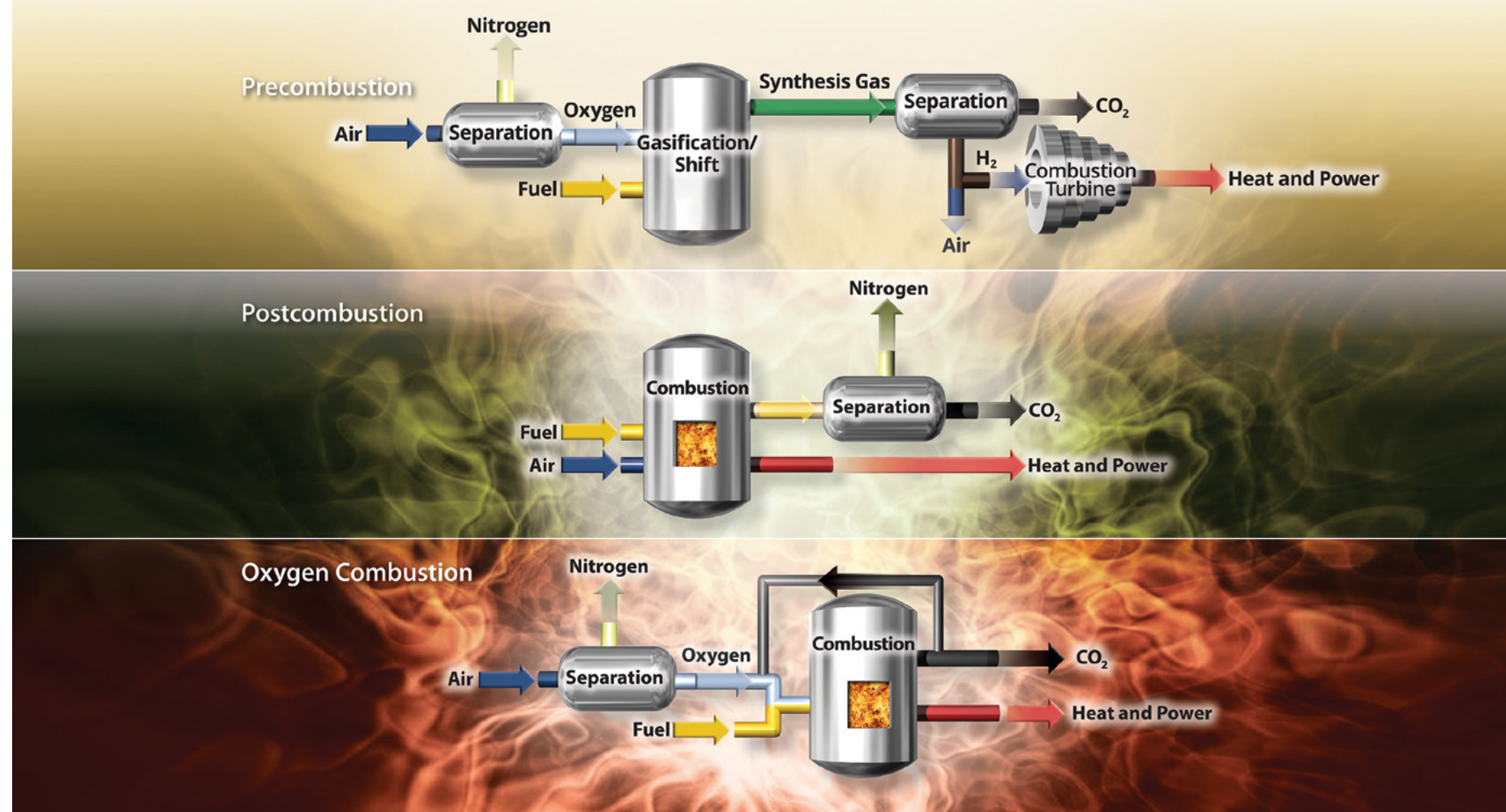


CO₂ CAPTURE FROM INDUSTRIAL PROCESSES

Capture is the separation of CO₂ from a gas stream to prevent atmospheric release. Capture can be performed before, during, or after the combustion process. Precombustion technologies consist of capturing CO₂ 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,²⁰ meaning that the atmosphere in the boiler is not pure oxygen but rather a mixture consisting primarily of oxygen and CO₂. Most capture technologies focus on separating low-concentration CO₂ from the exhaust gas stream after combustion takes place; this is called postcombustion capture. Because the concentration of CO₂ 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),²¹ 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 significant capital investment. The cost of capturing the CO₂ can represent 75% of the total cost of a CCUS operation.²¹ Because capture is the costliest portion of a CCUS project, research is being performed to develop more efficient CO₂ capture processes and improve the economics of existing ones. CO₂ capture has been demonstrated at various scales, from pilot to commercial, in some coal- and gas-fired boilers. Natural gas-processing and fertilizer industries are already capturing CO₂ at commercial scale, and the Great Plains Synfuels Plant in Beulah, North Dakota, uses precombustion techniques to separate CO₂ from its lignite-derived synthetic natural gas.

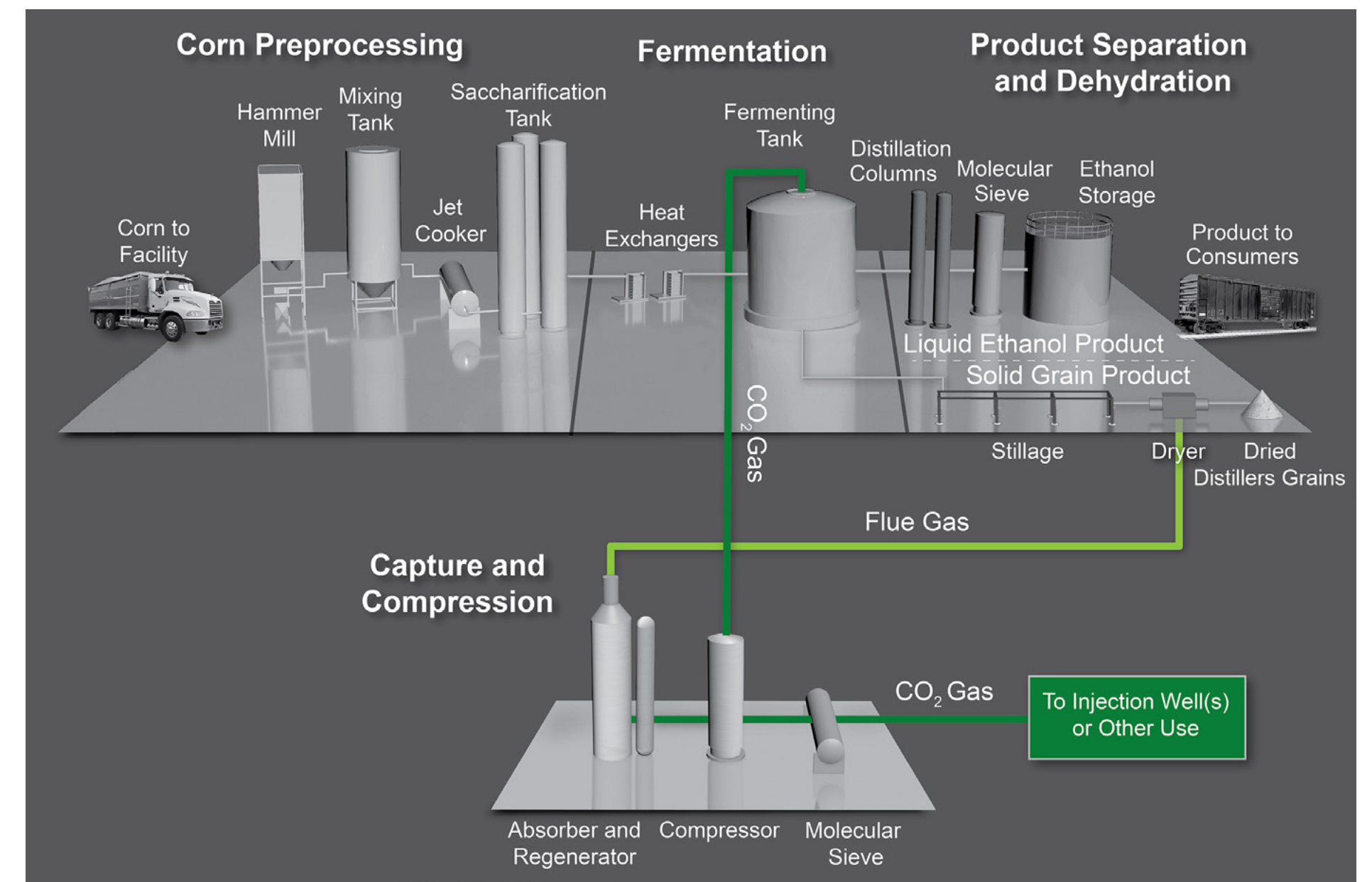


CAPTURE FROM ETHANOL PROCESSES

Ethanol plants typically generate two emission streams containing CO₂. One of these streams comes from the combustion of natural gas or coal used to dry corn ethanol by-products. Capture of CO₂ from this emission stream would require technology like that used to capture CO₂ from power plants.

The second CO₂ emission stream from ethanol plants comes from the fermentation (biogenic) associated with converting corn to fuel. This emission stream contains more than 95% CO₂ 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 CO₂ for use in EOR, the nearly capture-ready nature of biogenic CO₂ makes ethanol plants a prime target for early CCUS projects.

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DIRECT AIR CAPTURE

Another CO₂ capture technology that is gaining interest is direct air capture (DAC). In this case, CO₂ 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 CO₂ sinks such as oil fields for use in EOR or other areas suitable for permanent geologic storage. That proximity eliminates the need to transport the CO₂ over

long distances. Additionally, DAC technologies are typically not subjected to the impurities encountered in point-source capture applications. Challenges include the energy required for the process, which can be more energy-intensive compared to CO₂ removal from concentrated sources. Large volumes of air must be circulated over or through the sorbent material because of the small percentage of CO₂ in the atmosphere.



Banks of fans blow air through a CO₂-capturing solution in this rendering of a DAC plant.

CO₂ AND COMPRESSION

Captured CO₂ must be dehydrated and compressed into a supercritical or liquidlike state before transport to the storage site. CO₂ must be compressed to at least 1200–1700 pounds per square inch (psi) for transport in a pipeline to ensure that CO₂ remains a dense liquid.²² Because compression is energy-intensive, improved compression methods are under development.



CO₂ TRANSPORTATION INFRASTRUCTURE

Following capture and compression, CO₂ is transported to a storage site. Given the quantities of CO₂ 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 8500 km (5300 miles) of CO₂ pipeline is in service in North America, with additional pipeline planned or under construction.²²



CO₂ PIPELINES

Pipelines are a proven technology and have been used to safely transport industrial quantities of CO₂ for over 50 years. CO₂ pipelines are similar in design and operation to natural gas pipelines, although the higher pressures needed for CO₂ transportation require thicker-walled carbon steel pipe.

Building a regional CO₂ pipeline infrastructure for CCUS activities will require thoughtful planning. Pipelines may be built to connect individual CO₂ 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 reduce overall costs, but common carrier issues such as those related to CO₂ stream quality may need to be addressed.

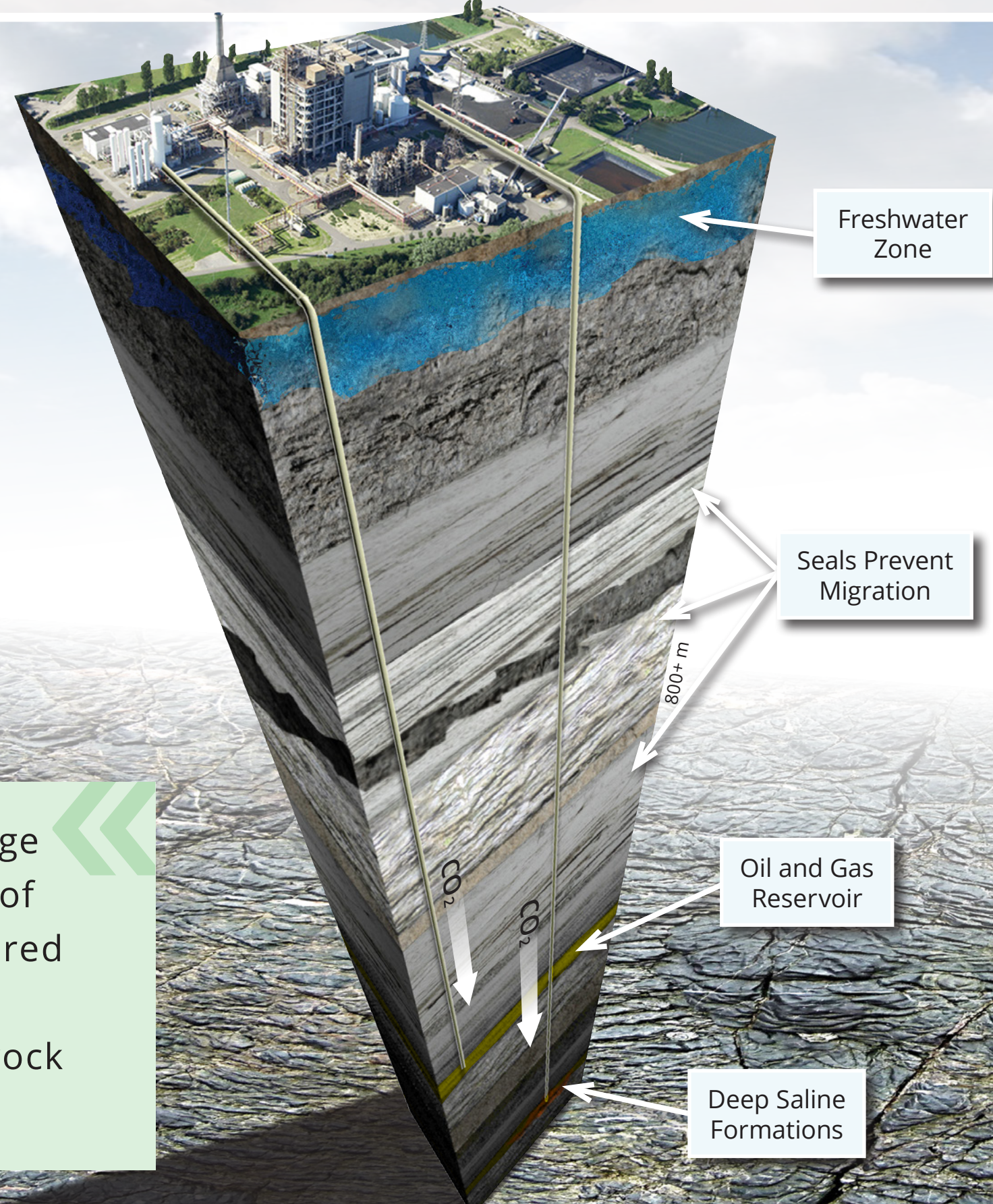
Pipelines carrying CO₂ have an excellent safety record. Strategies undertaken to manage risks include fracture arresters approximately every 300 m, block valves to isolate pipe sections if they leak, the use of advanced seals, and automatic control systems that monitor volumetric flow rates and pressure.

NO fatalities have been reported as a result of CO₂ transport via pipeline.²³



SECURE GEOLOGIC STORAGE

GEOLOGIC STORAGE CRITERIA



Geologic storage involves injecting captured anthropogenic CO₂ 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 CO₂. Scientists have identified many potentially suitable areas across the globe that have the capacity to securely hold hundreds of years of anthropogenic CO₂ emissions deep underground.

Geologic storage is the process of injecting captured CO₂ into deep underground rock formations.

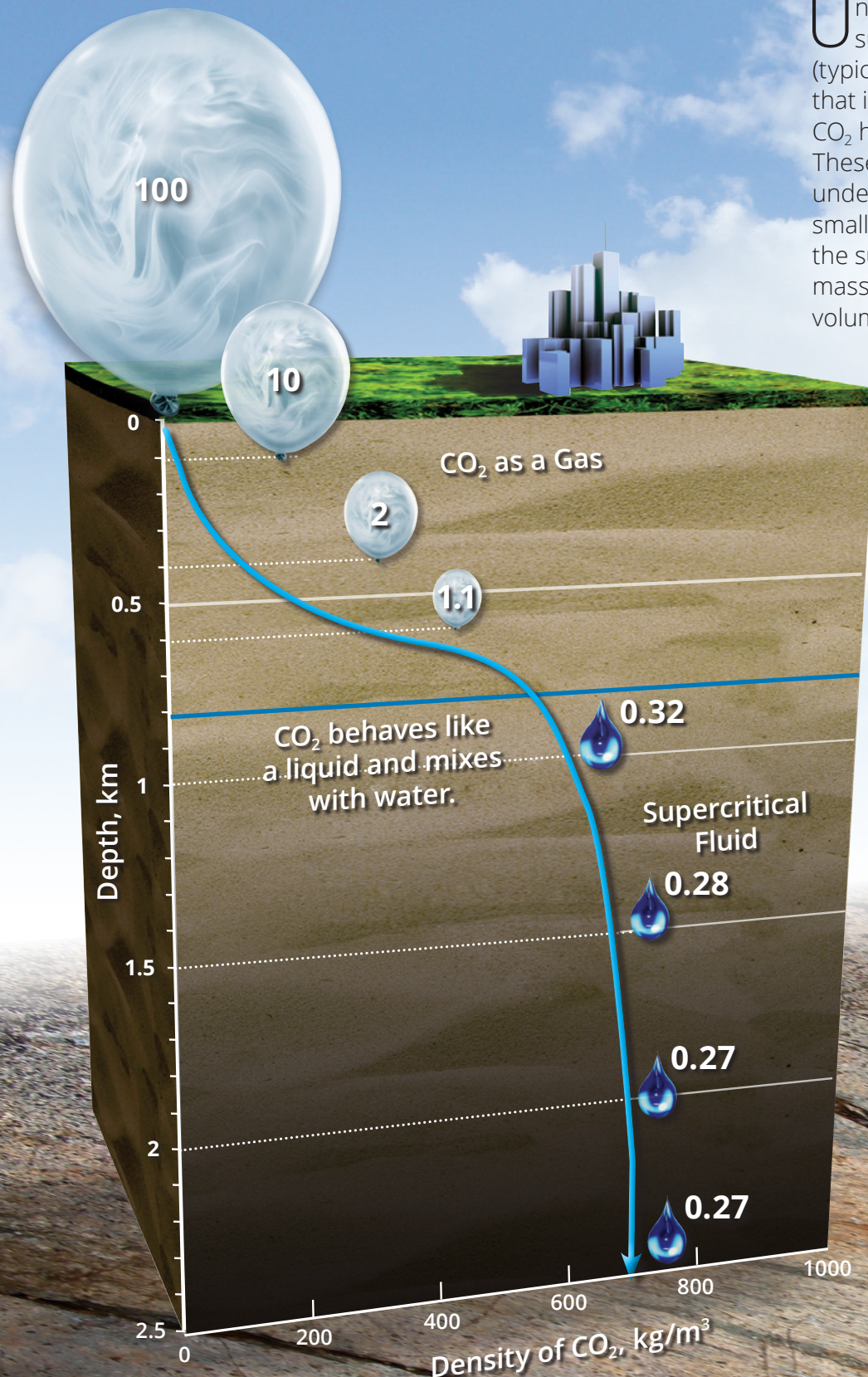
STORAGE RESERVOIR CHARACTERISTICS

Site selection is central to securely storing CO₂ because successful geologic storage requires that CO₂ stay in place and not pose significant risk to human health and the environment. Storage reservoirs should:

- Be capable of storing large quantities of CO₂ permanently.
- Be overlain by thick, laterally continuous seals or cap rocks that prevent upward migration of CO₂.
- Be at depths that take advantage of dense-phase CO₂ (typically >800 m), which allows efficient use of reservoir pore space for storage.
- Not impact underground sources of drinking water (USDWs), defined in the United States as water with salinity values less than 10,000 mg/L.
- Not be located in areas likely to be affected by natural or individual seismic activity.

SUPERCRITICAL CO₂

Under high-temperature and high-pressure conditions, such as those encountered in deep geologic formations (typically greater than 800 m), CO₂ will exist in a dense phase that is referred to as "supercritical." At this supercritical point, CO₂ has a viscosity similar to a gas and the density of a liquid. These properties allow more CO₂ to be efficiently stored deep underground because a given mass of CO₂ 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 CO₂ stored below 800 m occupies around 0.3% of the volume of the same mass at the surface.



The supercritical state of liquidlike CO₂ is not only important for efficient storage in the deep subsurface, but also in a host of other applications, such as decaffeinating coffee. Before the supercritical CO₂ process was used, coffee was decaffeinated with chemical solvents that often left residues, negatively affecting the flavor.

TRAPPING CO₂ IN ROCKS

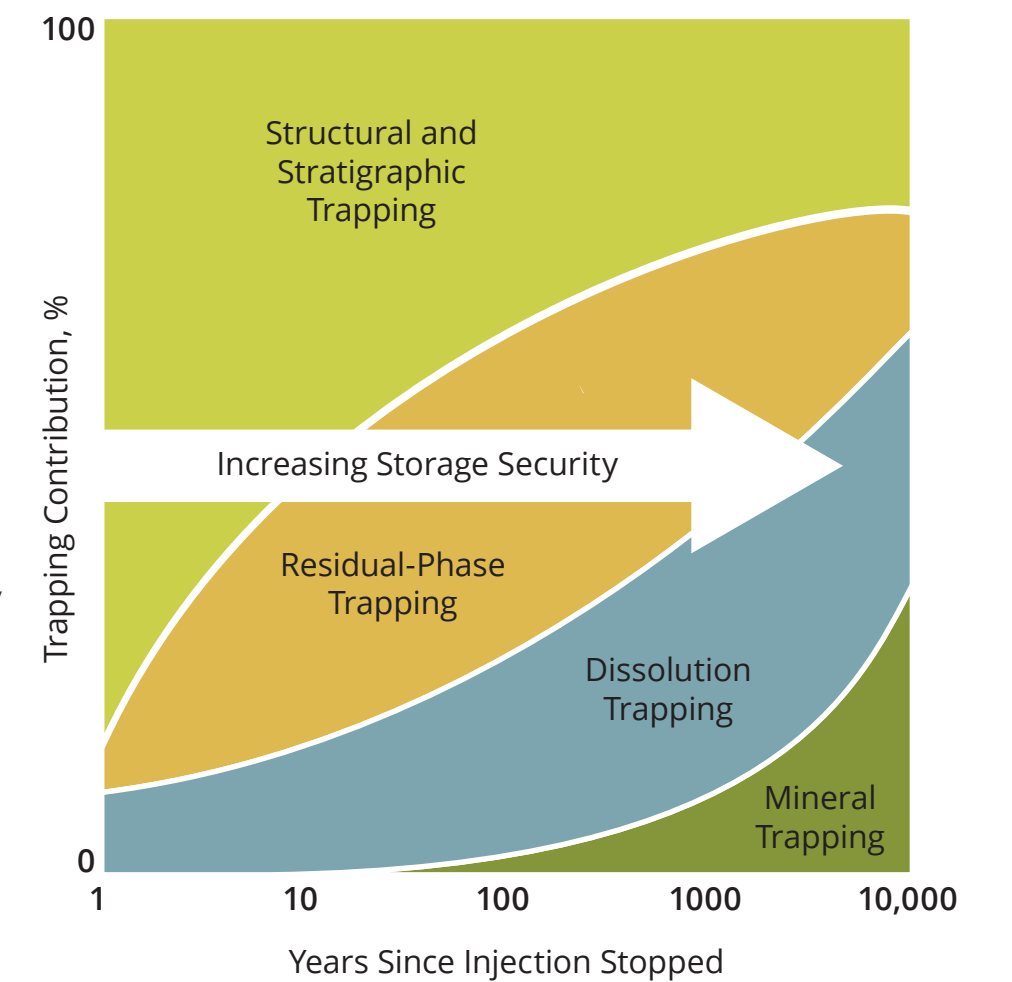
Several mechanisms function to trap and store CO₂ in deep geologic formations.²¹

STRUCTURAL AND STRATIGRAPHIC TRAPPING – Injected CO₂ is typically less dense than native pore fluids, most commonly brine, in deep geologic formations. This lower density causes CO₂ 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 CO₂ for millions of years.

RESIDUAL-PHASE TRAPPING – As injected CO₂ 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.

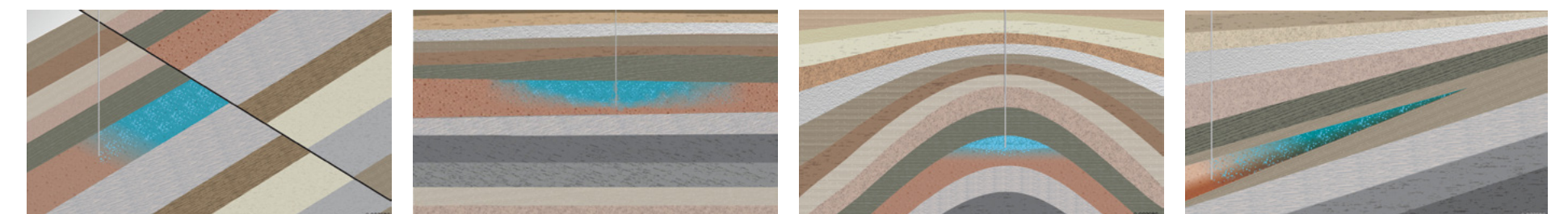
DISSOLUTION TRAPPING – Just as sugar dissolves in water, some of the CO₂ will dissolve into brine in the pore spaces. Brine with dissolved CO₂ becomes denser than the surrounding brine and will sink to the bottom of the reservoir, minimizing the possibility of further migration.

MINERAL TRAPPING – The last stage of CO₂ trapping involves a chemical reaction between the dissolved CO₂ in the formation fluids and the minerals in the target formation and cap rock to form new solid minerals, thus effectively locking the CO₂ in place. Mineral trapping will typically occur over extended timescales and is difficult to predict with accuracy.



As time passes after the injection of CO₂ 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 CO₂ from moving upward out of the formation.

The CO₂ is trapped when there is a sudden change in the rock formations so that the CO₂ cannot move upward.

The buoyant CO₂ will collect under a curved layer of impermeable rock at the highest point, unable to move out of the formation.

CO₂ can become trapped when the rock type in the formation changes from permeable to impermeable.

OIL FIELDS OF THE UNITED STATES AND CANADA

CO₂ IN OIL FIELDS



The geology of CO₂ 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 CO₂. Therefore, the geologic conditions that are conducive to hydrocarbon accumulation (storage) are also the conditions that are conducive to CO₂ 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, CO₂ may be stored in a pool through dissolution into the formation fluids (oil and/or water); as a buoyant supercritical-phase CO₂ 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 CO₂, formation waters, and/or formation rock matrices.

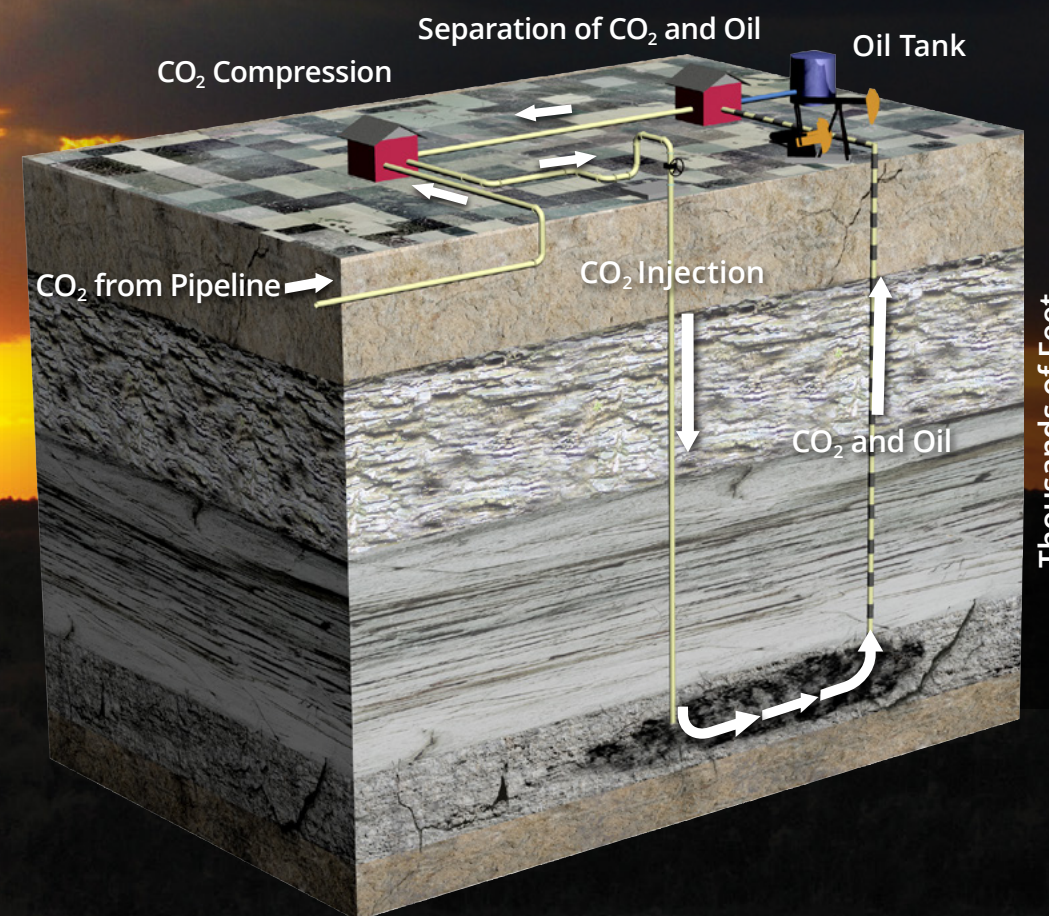


Oil and gas reservoirs have already demonstrated their ability to hold buoyant fluids, including natural CO₂, for millions of years.

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 CO₂ into the reservoirs through the EOR process can recover some of that remaining oil.

HOW EOR WORKS:

When CO₂ comes into contact with oil, a significant portion dissolves into the oil, reducing the oil's viscosity and increasing its mobility. This, combined with the increased pressure from injection, can result in increased oil production rates and extend the lifetime of the oil reservoir. While some CO₂ is produced along with the extra oil, a significant portion of the CO₂ remains in the subsurface. When an oilfield operator is finished with EOR operations, nearly all of the CO₂ remains trapped in the subsurface.



Not all reservoirs are good candidates for CO₂-based EOR. Factors such as geology, depth, and the nature of the oil itself will determine the effectiveness of CO₂ for EOR.

Since the 1970s, operators in West Texas have safely pumped millions of tonnes of CO₂ into oil fields for EOR purposes. As of the end of 2022, there were 139 CO₂ EOR projects underway across 12 states. Although a majority of CO₂ used in this process is sourced from natural underground deposits, the proportion of CO₂ derived from the capture of anthropogenic emissions is increasing. CO₂ 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.

Since 1986, CO₂ EOR projects in the United States have produced about **2.8 billion** barrels of oil.²⁵

CO₂ EOR LIFE CYCLE ANALYSIS

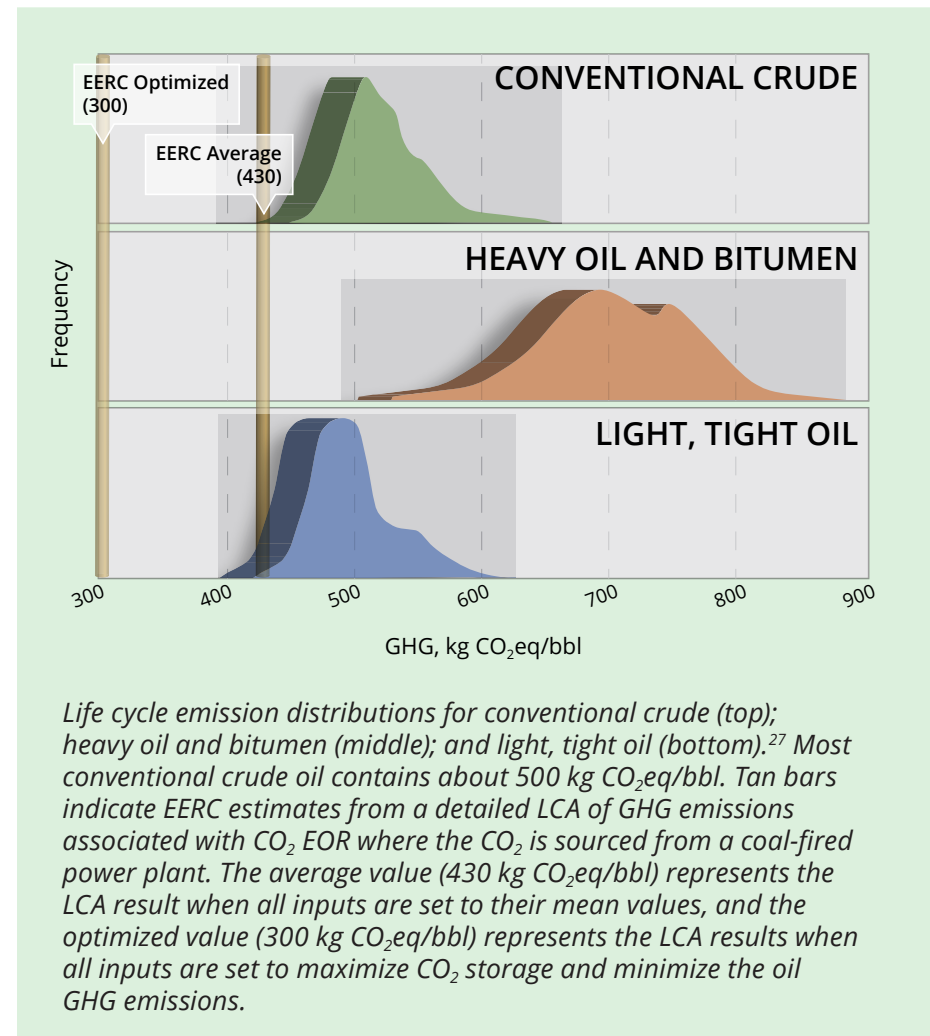
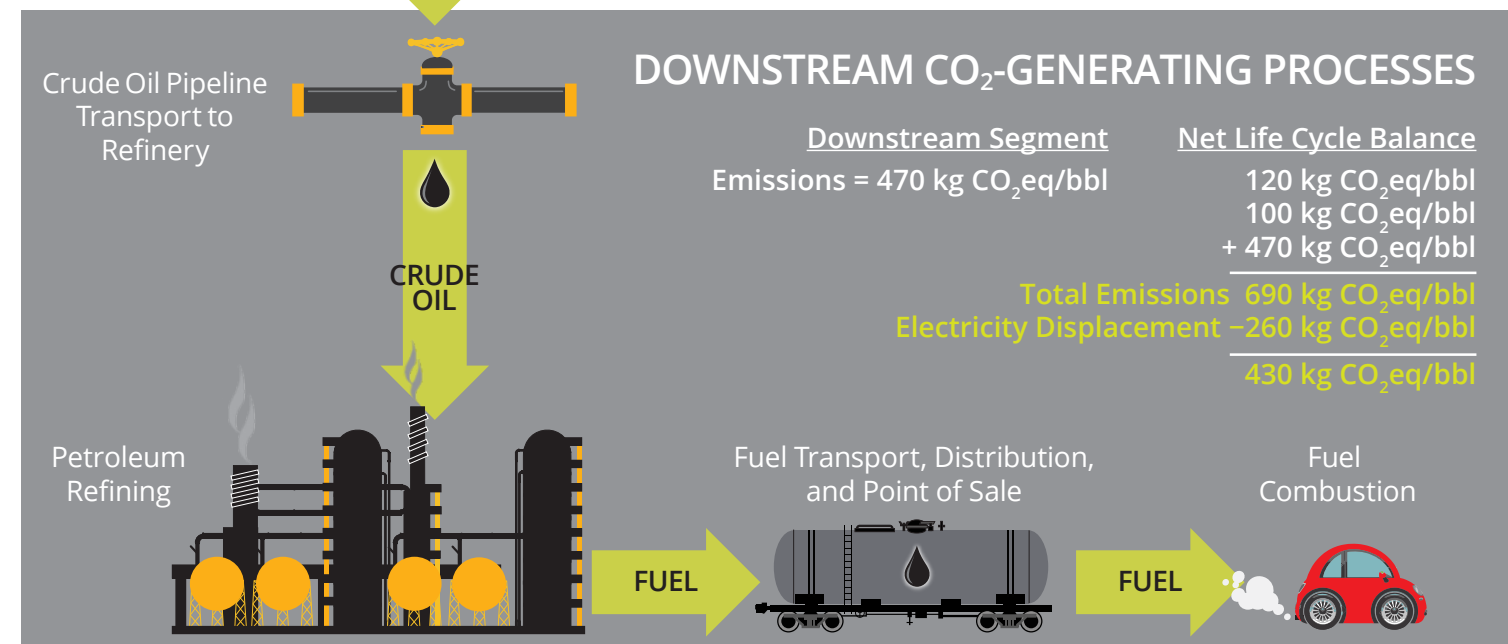
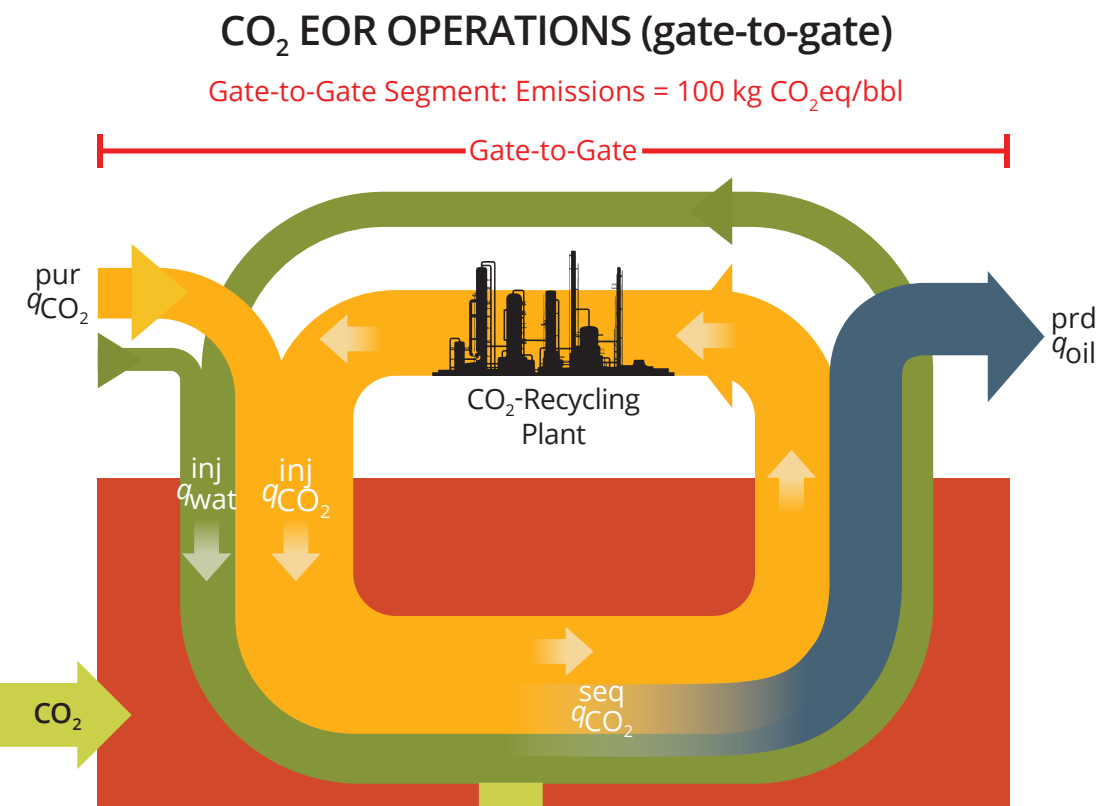
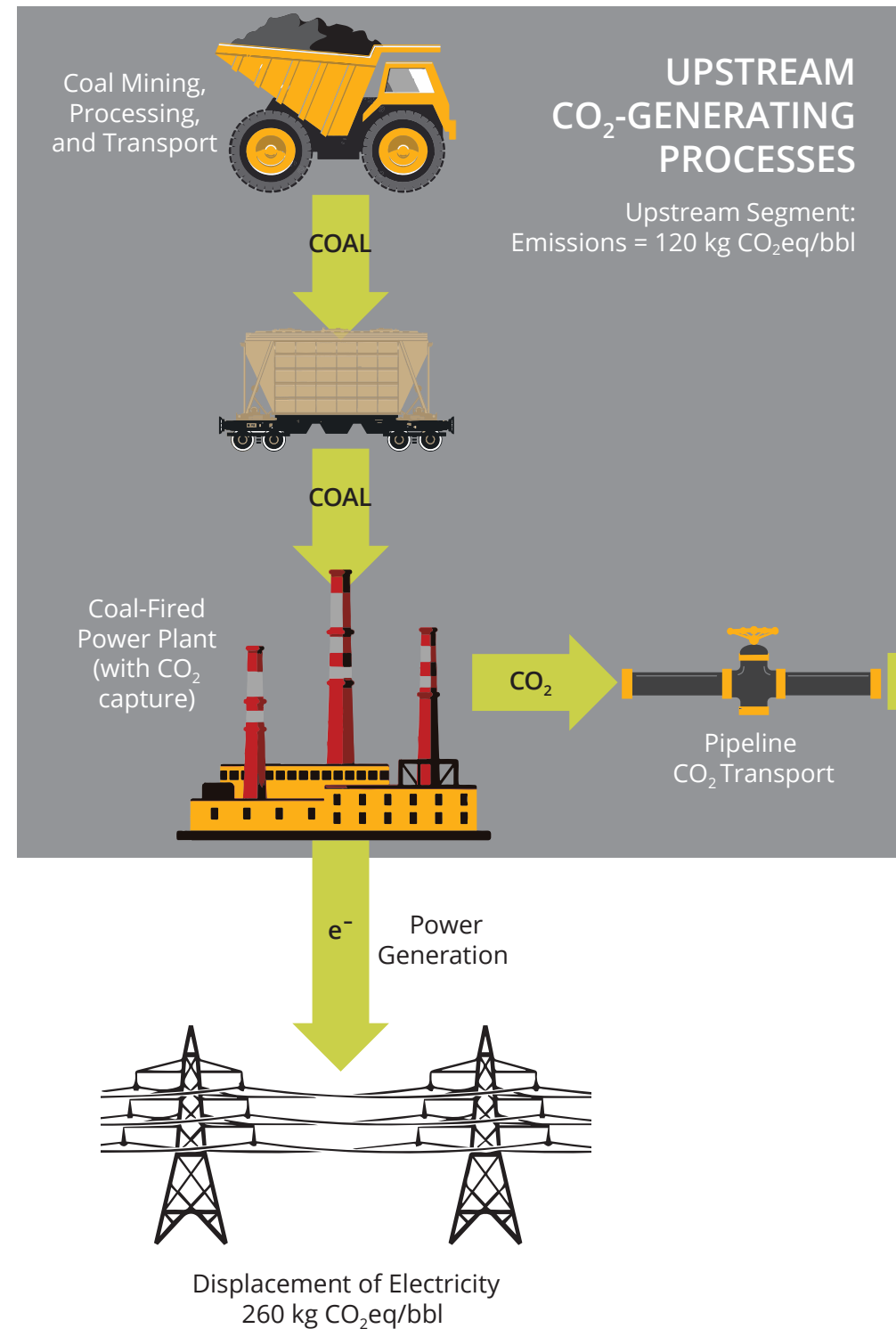
Life cycle analysis (LCA) is an approach to account for CO₂ storage at an EOR site and to track CO₂ emissions at all stages of a CO₂ EOR project. The LCA results may then be used to evaluate the life cycle CO₂ emissions per barrel of oil produced via CO₂ EOR as compared to oil produced by other methods.

The Energy & Environmental Research Center (EERC) conducted a detailed LCA of CO₂ emissions associated with a generic CO₂ EOR project where the CO₂ was sourced from a coal-fired power plant.²⁶ The modeled system included three segments: upstream, gate-to-gate, and downstream CO₂-generating processes. Upstream processes included coal extraction and processing, transport, power generation with CO₂ capture, and CO₂ transport to the CO₂ EOR field. Gate-to-gate processes included CO₂ 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 CO₂ equivalent (CO₂eq) emissions from upstream, gate-to-gate, and downstream segments were 690 kg CO₂eq/bbl.

However, since 85% or more of the required CO₂ 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 CO₂ 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 CO₂ EOR of 430 kg CO₂eq/bbl.

pur = purchased
pro = produced
inj = injected
seq = sequestered

Note: Emissions are expressed as CO₂eq, which includes CO₂, CH₄, and N₂O.



NORTH AMERICAN SEDIMENTARY BASINS



CO₂ 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 CO₂ 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 CO₂ sources. Saline formations suitable for CO₂ 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 CO₂ storage but are also overlain by thick and regionally extensive cap rocks. These cap rocks function as seals to help ensure that the injected CO₂ will remain in place permanently.

Deep saline formations account for most of the world's geologic storage resource and may provide an ideal storage option for facilities not able to take advantage of economical CO₂ EOR opportunities.



PUTTING TDS LEVELS INTO PERSPECTIVE

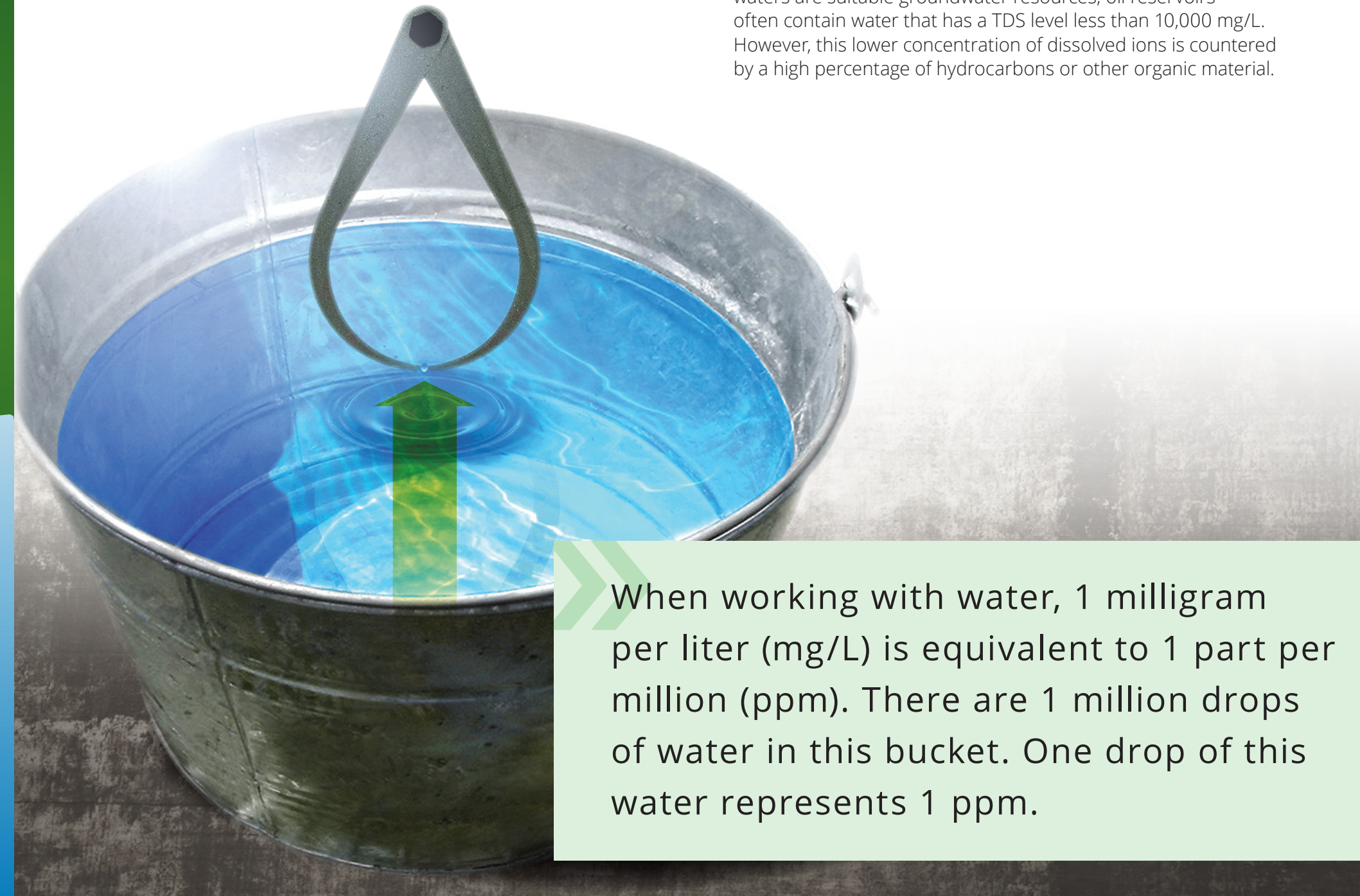
SALINITY



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

In general, EPA has ruled that CO₂ cannot be injected into geologic formations where the TDS level is less than 10,000 mg/L. This stipulation is meant to protect valuable USDWs that may, in the future, be used for drinking water or other municipal water uses. Many of the saline formations targeted for CO₂ 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 (ppm). There are 1 million drops of water in this bucket. One drop of this water represents 1 ppm.