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. Terrestrial storage techniques can be used to better manage the CO₂ naturally stored on Earth’s surface, but one of the most promising approaches involves capturing CO₂ from the exhaust gas at large stationary sources and placing the CO₂ underground into permanent storage. This option is referred to as CCS and is at the forefront for decreasing GHG emissions while retaining our existing energy generation infrastructure. This chapter covers some of the fundamental components of CCS.
Terrestrial storage is a relatively passive mechanism of CO₂ storage that occurs at Earth’s surface through management practices that increase the amount of carbon stored in roots and organic matter in the soil. It can be done by 1) protecting ecosystems that store carbon in order to maintain or increase their carbon stores or 2) managing soils and plants to increase carbon storage beyond the current conditions through natural processes such as photosynthesis.

It is important to remember that terrestrial storage does not store CO₂ as a gas but stores the carbon portion of the CO₂. If the soil is disturbed and the soil carbon comes in contact with oxygen in the air, the exposed soil carbon can combine with O₂ to form CO₂ gas and reenter the atmosphere.

Steady State

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

Benefits

Terrestrial storage is important because it can be implemented immediately and can begin to reduce atmospheric CO₂ levels in several years. Using terrestrial storage now means we can get started on reducing CO₂ levels in the atmosphere while we adopt other carbon control measures. Terrestrial storage also has other benefits to the ecosystem, including biodiversity, water filtration, increased soil health and fertility, and many others.
Benefits of terrestrial storage may include improved soil and water quality, reduced erosion, reduced evaporative water loss, reduced pest problems, and overall ecosystem improvement. Promising land and water management practices that can enhance the terrestrial storage of carbon include the following:

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

Terrestrial carbon storage is a near-term approach to reducing GHGs.
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 geologic storage, is termed CCS and includes a set of technologies that can greatly reduce CO₂ emission from large point sources such as coal- and gas-fired power plants, natural gas-processing facilities, ethanol plants, and other industrial processes.

CCS involves the capture of CO₂ by separation from other gases, compression to a liquid or dense fluid state, and transport to an appropriate location for geologic storage. Injection into deep geologic formations ensures permanent storage, isolating CO₂ from the atmosphere.
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, meaning that the atmosphere in the boiler is not pure oxygen but rather a mixture consisting primarily of oxygen and CO₂. The majority of 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 so low (ranging from 3% by volume for some natural gas-fired plants to about 13% by volume for coal-fired plants), any postcombustion capture process must be sized to handle the entirety of the exhaust gas. The large scale of equipment, quantities of chemicals required, and energy needed to operate the capture system make it relatively expensive. In fact, the cost of capturing the CO₂ can represent three-fourths of the total cost of a CCS operation. Because capture is the most costly portion of a CCS 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 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.
Captured CO₂ must be dehydrated and compressed into a supercritical or liquidlike state for either storage before truck transport or piping to the storage site. CO₂ must be compressed to at least 1200 to 1500 pounds per square inch (psi) for transport in a pipeline to ensure that CO₂ remains in a dense liquid state. Because compression is energy-intensive, improved compression methods are under development.
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 appear to be the most likely mode for transporting the captured gas to geologic storage sites. Currently, more than 6000 km of CO₂ pipeline is in service in North America, with additional pipeline planned or under construction.23
Pipelines are a proven technology and have been used to safely transport industrial quantities of CO₂ for over 30 years. CO₂ pipelines are similar in design and operation to natural gas pipelines, although the higher pressures needed for CO₂ transportation require construction using thicker-walled carbon steel pipe.

Building a regional CO₂ pipeline infrastructure for CCS 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 offer reduced overall costs, but common carrier issues such as those related to CO₂ stream quality may need to be addressed.

Pipelines carrying CO₂ have a superior safety record in comparison to natural gas or hazardous chemical pipelines. Strategies undertaken to manage risks include the inclusion of fracture arresters approximately every 300 m, block valves to isolate pipe sections if they leak, the use of advanced seals, and automatic control systems that monitor volumetric flow rates and pressure.

NO serious human injuries or fatalities have been reported as a result of CO₂ transport via pipeline.
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.

Storage Reservoir Characteristics
Site selection is central to the secure storage of 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 (USDW, defined in the United States as water with salinity values less than 10,000 mg/L).
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 viscosity similar to a gas and the density of a liquid. These properties allow more CO₂ to be more 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. This liquidlike form of carbon dioxide has 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.
Several mechanisms function to trap and store CO₂ in deep geologic formations.25

**Structural and Stratigraphic Trapping** – Injected CO₂ is typically less dense than native pore fluids in deep geologic formations, most commonly brine. 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.

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As time passes after the injection of CO₂ into a deep geologic environment, the effective trapping mechanism shifts. Storage security increases as the trapping mechanism moves from the physical process of structural and stratigraphic trapping toward geochemically based processes.
Distribution of Oil Fields

Note: Mexico has many oil fields; however, they are not pictured because of data limitations.
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 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 a process called EOR can recover some of that remaining oil. It is estimated that U.S. production from EOR could increase to over half a million barrels of oil per day by 2020, thereby reducing the need to import as much oil.

How EOR Works

When CO₂ comes into contact with oil, a significant portion dissolves into the oil, reducing oil viscosity and increasing its mobility. This, combined with the increased pressure, can result in increased oil production rates and an extension of the lifetime of the oil reservoir. However, not all reservoirs are good candidates for CO₂-based EOR. Factors such as geology, depth, and the nature of the oil itself will determine the effectiveness of CO₂ for EOR.

Economics of EOR

EOR is a proven, economically viable technology for CO₂ storage that can provide a bridge to future non-EOR-based geologic storage.

Since the 1970s, operators in West Texas have safely pumped many millions of tons of CO₂ into oil fields for EOR purposes. The success of the technique has seen a steady increase in the number of fields (now over 100) employing CO₂ EOR in West Texas and other 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.
Life cycle analysis (LCA) is a useful way 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 CO2 EOR where the CO2 is sourced from a coal-fired power plant. The modeled system includes three segments: upstream, gate-to-gate, and downstream CO2-generating processes. Upstream processes include coal extraction and processing, transport, power generation with CO2 capture, and CO2 transport to the CO2 EOR field. Gate-to-gate processes include 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 include crude oil transport, refining, fuel transport, and combustion. Total CO2 emissions from upstream, gate-to-gate, and downstream segments are 685 kg CO2eq/bbl.

However, since 85% or more of the required CO2 is captured at the power plant, emissions associated with electricity generation are significantly reduced. This is termed displacement and would reduce the total emissions to 426 kg CO2eq/bbl for typical CO2 EOR operations. Optimization of operations for storage could further reduce LCA emissions to 256 kg CO2eq/bbl. The box graph shows this compares favorably to other sources of oil production.

How Does Oil Produced via CO2 EOR Compare to Oil Produced Using Conventional Methods?

<table>
<thead>
<tr>
<th>Production Course</th>
<th>CO2 EOR (base case)</th>
<th>CO2 EOR (optimized case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. Domestic</td>
<td>117 kg CO2eq/bbl</td>
<td>98 kg CO2eq/bbl</td>
</tr>
<tr>
<td>U.S. Status Quo</td>
<td>96 kg CO2eq/bbl</td>
<td>98 kg CO2eq/bbl</td>
</tr>
<tr>
<td>Imported Crude Oil</td>
<td>470 kg CO2eq/bbl</td>
<td>470 kg CO2eq/bbl</td>
</tr>
<tr>
<td>Saudi Arabia (light)</td>
<td>470 kg CO2eq/bbl</td>
<td>470 kg CO2eq/bbl</td>
</tr>
<tr>
<td>Canada</td>
<td>470 kg CO2eq/bbl</td>
<td>470 kg CO2eq/bbl</td>
</tr>
<tr>
<td>Mexico</td>
<td>470 kg CO2eq/bbl</td>
<td>470 kg CO2eq/bbl</td>
</tr>
<tr>
<td>Venezuela</td>
<td>470 kg CO2eq/bbl</td>
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<tr>
<td>United Kingdom</td>
<td>470 kg CO2eq/bbl</td>
<td>470 kg CO2eq/bbl</td>
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<tr>
<td>Mexico</td>
<td>470 kg CO2eq/bbl</td>
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<tr>
<td>Venezuela</td>
<td>470 kg CO2eq/bbl</td>
<td>470 kg CO2eq/bbl</td>
</tr>
</tbody>
</table>
North American Sedimentary Basins

Distribution of Sedimentary Basins Greater than 800 m Deep

Sedimentary Basins
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 provide an ideal storage option for facilities not able to take advantage of economic CO₂ EOR opportunities.
Putting TDS Levels into Perspective

<table>
<thead>
<tr>
<th>Water Source</th>
<th>TDS, mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>~63</td>
</tr>
<tr>
<td>Missouri River</td>
<td>~250</td>
</tr>
<tr>
<td>Drinking Water</td>
<td>&lt;500*</td>
</tr>
<tr>
<td>Ocean Water</td>
<td>35,000</td>
</tr>
<tr>
<td>Great Salt Lake</td>
<td>50,000 to 270,000</td>
</tr>
<tr>
<td>Dead Sea</td>
<td>350,000</td>
</tr>
</tbody>
</table>

* 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).

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 USDW which 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. There are 1 million drops of water in this bucket. One drop of this water represents 1 part per million.
Coal Regions of the United States and Canada

Note: Mexico has many coalfields; however, not all are pictured because of data limitations.
Because of their fractured nature, coal seams have a relatively large internal surface area, and these surfaces have the capacity to accumulate large amounts of gases. Some gases, such as CO$_2$, have a higher affinity for the coal surfaces than others, such as nitrogen. As a result, coal seams that are too deep (generally >150 m) or too thin to be economically mined may prove to be viable sites for CO$_2$ storage. Carbon storage in unminable coal seams relies on the adsorption of CO$_2$ on the coal and the permeability of the coal bed. The more microstructures there are in the coal, the more surface area it has for CO$_2$ to accumulate onto.

In addition to the potential for CO$_2$ storage, many coal beds contain commercial quantities of adsorbed natural gas (methane). As with oil reservoirs, initial coalbed methane (CBM) recovery methods can leave methane in the coal seam. Additional CBM recovery can be achieved by sweeping the coal bed with CO$_2$, which preferentially adsorbs onto the surface of the coal, displacing the methane. Depending on the coal rank, up to 13 molecules of CO$_2$ can be adsorbed for each molecule of methane that is displaced. This enhanced coalbed methane (ECBM) procedure could create revenue to offset the costs associated with the injection and storage of CO$_2$ in coal beds.

World CO$_2$ storage potential in coal seams is estimated to be 40 billion tonnes.