Carbon Dioxide—Challenges and Opportunities

In the early days of the oil and gas industry, companies noted that carbon dioxide had corrosive effects on well internals; operators later found opportunities to use the compound to their advantage. Projects now underway in the oil field reflect several priorities—managing carbon dioxide’s corrosive effects, using it to recover more oil after waterflood and storing it in underground formations. Because of its role in climate change, carbon dioxide has emerged as a topic of significant public interest and scientific investigation as well as the focus of hydrocarbon producers.

Carbon dioxide is in the news. Whether because of the link to climate change and its consequences or for the concept of long-term storage, carbon dioxide has captured the interest of the public and the global scientific community.

Carbon dioxide phases. Phase boundary lines (blue) define the areas in which each CO₂ phase exists. At the triple point, all three phases—solid, liquid and gaseous CO₂—coexist in thermodynamic equilibrium. Along the solid-gas line below the triple point, CO₂ sublimes—converts directly—from a solid to a gas without going through a liquid phase. The marked sublimation point corresponds to 0.101 MPa [14.7 psi] of CO₂ vapor. Along the solid-liquid line above the triple point, solid CO₂ melts to a liquid. Along the liquid-gas line above the triple point, liquid CO₂ evaporates to a gas. At the critical point, the liquid and gaseous states of CO₂ are indistinguishable, and phase boundaries no longer exist. These attributes at the critical point and at higher temperature and pressure characterize the area in which CO₂ is a supercritical fluid (green). (Adapted with permission from Bassam Z. Shakhashiri, University of Wisconsin—Madison, USA.)
Carbon, one of the two constituents of carbon dioxide \([\text{CO}_2]\), is an essential element on Earth. The mass of carbon on Earth is \(5.37 \times 10^{16} \text{ kg} \) \([11.83 \times 10^{16} \text{ lbm}]\), which is distributed among several reservoirs: the Earth’s atmosphere; plants; animals; soil; minerals; the shallow and deep ocean; and coal, oil and gas. The movement of carbon between these reservoirs—the carbon cycle—maintains a balance between carbon in the atmosphere and in the ocean and rocks. This cycle has two components: a slow cycle that takes 100 to 200 million years to move carbon between the oceans, soil, rock and the atmosphere and a fast cycle that takes 50 to 100 years to move carbon through the biosphere.

Historically, the carbon cycles have resulted in a nearly constant level of carbon in the atmosphere, but that is changing. Current data point to deforestation and combustion of fossil fuels as prime causes for changes in the fast carbon cycle. Plants, trees and microscopic marine plants are important components of the fast carbon cycle. During decay, burning and consumption of these life forms, carbon, present as \(\text{CO}_2\), is released and accrues in the atmosphere. Similarly, much of the \(\text{CO}_2\) from anthropogenic activities also accumulates in the atmosphere. Plants and the oceans absorb about 55% of this anthropogenic \(\text{CO}_2\), but the rest stays airborne. Scientists attribute persistent changes in the composition of the atmosphere, such as the increasing \(\text{CO}_2\) content, to be an important driver of climate change.

The role of \(\text{CO}_2\) in climate change is significant, but the compound has a different function in the oil and gas industry. Carbon dioxide can be captured and stored in depleted reservoirs, which helps arrest atmospheric accumulation. For EOR, \(\text{CO}_2\) enables increased yield from oil fields after primary recovery and waterflood. This article discusses and illustrates these aspects of \(\text{CO}_2\), its effect on climate change and its role in the oil and gas industry. Examples from oil and gas fields in Canada, Algeria and Turkey demonstrate the use and storage of carbon dioxide.

**Carbon Dioxide Characteristics**

Carbon dioxide, a molecule that consists of two oxygen atoms covalently bonded to a single carbon atom, has a molecular weight of about 44 g/mol. Depending on temperature and pressure, \(\text{CO}_2\) can exist as a solid, liquid or gas (Figure 1). At temperatures and pressures at or above the critical point, \(\text{CO}_2\) is a supercritical fluid, which has some properties of a gas and some of a liquid. As a supercritical fluid, \(\text{CO}_2\) develops miscibility—the ability...
to mix homogeneously—with crude oil and improves oil recovery.

Carbon dioxide is stable in the atmosphere. Its concentration in the atmosphere depends on competing processes within the carbon cycles that consume or release CO₂. Photosynthesis is one chemical reaction that involves CO₂. During photosynthesis, plants, algae, ocean plankton and certain types of bacteria use light energy to convert CO₂ and water to oxygen, carbohydrates and water. Each year, more than 10% of the atmospheric CO₂ is reduced to carbohydrates by photosynthesis. Plants, algae and plankton use carbohydrates for growth whereas animals, including humans, use it as an energy source.

Carbon dioxide may be produced in several ways. Natural sources of CO₂ production include plant and animal respiration and decay, fires and volcanic release. Anthropogenic sources include fossil fuel combustion and certain manufacturing activities, including cement and ammonia production, natural gas processing and petrochemical manufacturing. Humans release CO₂ indirectly through deforestation.

Carbon dioxide may undergo several reactions of interest in the oil field. For example, dissolved in water, CO₂ forms carbonic acid [H₂CO₃] and other H₂CO₃ analogs. The CO₂ may also react with the minerals of the reservoir; in carbonate reservoirs, the reaction can be relatively rapid while in silicate reservoirs, the reactions are generally much slower. These reactions may result in some of the CO₂ being mineralized and permanently trapped.

Another important set of reactions involving CO₂ is associated with corrosion. Carbon dioxide may be corrosive or noncorrosive depending on the materials employed, temperature at the contact surface, water vapor concentration and CO₂ partial pressure. The most likely metal to corrode is carbon steel in storage environments and casing and tubular steel in wells. At a moderate pressure of 1.0 MPa [145 psi], the corrosion rate of X65 pipeline steel is independent of temperature from 50°C to 130°C [120°F to 270°F]. Increasing water concentration, on the other hand, causes a significant increase in corrosion for steel. For example, at a pressure of 8 MPa [1,160 psi] and a temperature of 40°C [104°F], increasing the water concentration in supercritical CO₂ from 1,000 to 10,000 parts per million (ppm) causes the corrosion rate of steel to increase by 87%. Similarly, for carbon steel in aqueous CO₂ solutions at 25°C [77°F], increasing the CO₂ partial pressure from 0.1 MPa [14.5 psi] to 1 MPa produces a corrosion rate increase of about 450%.

Another potential area of concern for oilfield operators is the effect of CO₂ on cement in wells. Carbon dioxide saturated with water deteriorates the cement used in wells. This deterioration can occur in cement that is adjacent to the well casing either in the annulus between the casing and rock or at the interface between the casing and a cement well plug (Figure 2). Therefore, the cement used in CO₂ injection wells must be able to resist the damaging effects of CO₂ because operational periods can last from 25 to 100 years and mandated safety periods that last much longer. For wells to reach these time objectives intact, using additives that make the cement more resistant to harm from CO₂ may be advantageous. Reaction of CO₂ with wellbore cement is slow in a well in which good construction practices and appropriate materials were used; in these cases, CO₂ should not pose a problem. Many old, abandoned wells—completed and shut in using practices and cement acceptable at the time—are not suitable to use in long-term CO₂ storage systems. Leakage from abandoned wells has been identified as a significant risk in geologic storage of CO₂.

**Greenhouse Gas Effect and Climate Change**

The greenhouse gas (GHG) effect is the process by which atmospheric insulation, imparted by certain gases, keeps the Earth warmer than it
would be without them (Figure 3). Although the concept of climate change associated with greenhouse gases may seem recent, the idea of the GHG effect dates back to the 19th century. Scientists then were intrigued by the possibility that lower levels of CO₂ might explain the ice ages. In 1896, Swedish scientist Svante Arrhenius calculated that industrial emissions from coal combustion might someday cause an increase in the Earth’s surface temperature. More recently, in the 1960s and 1970s, Russia considered ways to warm its large areas of icy tundra and convert them to fertile farmland through human-engineered climate change. These and subsequent attempts to alter the climate are encapsulated by the term climate engineering, also known as geoengineering. Geoengineering is the intentional manipulation of planetary-scale processes to affect Earth’s climate system—for example, to cool down the Earth’s atmosphere or remove CO₂ from the Earth’s atmosphere.

The GHG effect comprises a natural and an enhanced component. Warming of the Earth’s surface associated with indigenous gases is the natural GHG effect. The main GHGs are, in order of abundance, water vapor [H₂O], CO₂, methane [CH₄], nitrous oxide [N₂O], ozone [O₃] and other minor components. These gases in the atmosphere heat the Earth’s surface by absorbing and reradiating some of the infrared radiation coming from the surface. In addition to the natural GHG effect, an enhanced effect occurs when human activities increase the level of greenhouse gases—primarily CO₂ but also CH₄, N₂O, sulfur hexafluoride [SF₆] and other fluorinated hydrocarbons. Increased concentrations of these gases add to the atmosphere’s insulating qualities, thereby increasing Earth’s surface temperatures.

In 2012, CO₂ accounted for 82% of all GHG emissions in the US. Electrical power generation was responsible for 32% of the CO₂ emitted, and transportation contributed 28%. Industry accounted for 20% and the remaining 20% was attributable to emissions from residences, commercial buildings and agricultural activity. The end result of the enhanced GHG effect and increased concentrations of CO₂ is that the Earth’s surface is getting warmer.

8. When CO₂ dissolves in water, it forms H₂CO₃ and H₂CO₃. The former is the concentration of H₂CO₃ present and is typically about 0.3% of the CO₂. The latter is another state entirely and could be called liquid CO₂. For more on H₂CO₃ states: Langmuir D: Aquous Environmental Geochemistry. Upper Saddle River, New Jersey, USA: Prentice Hall, 1997.
Global surface temperatures measured since 1900 have risen 0.79°C [1.4°F]. During the same period, the CO₂ level in the atmosphere rose from 296 ppm in 1900 to 392 ppm in 2010. The CO₂ level in 1900 was typical of levels for the 400,000 years before 1950, in which the CO₂ level was never above 300 ppm (Figure 4). The effect of rising CO₂ on the Earth’s surface temperatures is well documented. Less well documented is the effect of increased atmospheric CO₂ on global oceans.

Researchers believe that the effects of increased CO₂ can be observed in global oceans. Oceans absorb about one-third of the CO₂ added to the atmosphere. Ocean absorption of CO₂ is not benign—CO₂ has caused a significant increase in ocean acidification. The weather station at Mauna Loa, Hawaii, USA, measured atmospheric CO₂ and ocean pH from 1990 to 2010. During that 20-year period, atmospheric CO₂ rose from 352 ppm in 1990 to 387 ppm in 2010. Concomitant with this rise in CO₂, the ocean pH decreased from 8.12 to 8.08, indicating an increase in ocean acidification.

Acidification of oceans and the warming effects from climate change are leading to the extinction of some types of ocean animal life. Coral reefs are sensitive to both acidification and warming. The net effect of acidification is an increase in the hydronium [H₃O⁺] ion concentration and a corresponding decrease in the carbonate ion [CO₃²⁻], which results in less coral being formed than in healthy ocean waters. Coral reefs are also sensitive to increases in temperature as small as 1°C to 2°C [1.8°F to 3.6°F] over times that are too short for the corals to adapt. These changes in temperature affect many of the microscopic and higher marine life forms that live in a symbiotic relationship with coral.

Figure 4. Increase in CO₂ in the atmosphere. The levels of atmospheric CO₂ can be measured from the distant past by analyzing ancient air bubbles trapped in polar ice. Data from 400,000 years before 1950 and to the present show a cyclic pattern dipping lower than 200 ppm during cold cycles and rising to nearly 300 ppm during warmer periods. Starting in the mid-1950s (inset), atmospheric CO₂ level rose above 300 ppm and continues to rise to the current level—slightly more than 400 ppm. (Adapted from “Global Temperature” and “Trends in Atmospheric Carbon Dioxide: Recent Monthly Average Mauna Loa CO₂,” reference 23.)
Carbon Dioxide Flooding

The oil and gas industry injects CO₂ into oil and gas fields for two primary purposes—rejuvenating producing fields and storing in depleted or unused reservoirs; these processes contribute to the global effort to minimize climate change. Carbon dioxide can be used in EOR to recover additional oil following primary production and waterflood.\textsuperscript{[23]} In addition, CO₂ can be captured from a variety of sources and stored underground.

The amount of technically recoverable oil worldwide has been estimated at 450 billion bbl [72 billion m\(^3\)].\textsuperscript{[24]} Oil that could theoretically be recovered using CO₂ is concentrated in ten large basins worldwide—in the Middle East, Russia, South America, Mexico, the US and Europe.\textsuperscript{[25]} Oil recovery on this scale using CO₂ EOR would require large sources of CO₂ close to the reservoir; proximity to a CO₂ source is a challenge for most basins. Because the volume of potential recoverable oil worldwide is large, operators have been able to use a variety of EOR techniques to recover additional oil from reservoirs for decades, despite the difficulty of matching CO₂ sources with sinks.

In the 1950s, researchers looking at CO₂ flooding found that the compound was miscible in oil at pressures above 700 psi [5 MPa].\textsuperscript{[26]} Building on this and subsequent findings about CO₂ behavior in oil, operators conducted the early successful field test of miscible CO₂ flooding at the Mead-Strawn field near Abilene, Texas, USA, in 1964.\textsuperscript{[27]} Test results showed a 35% increase in incremental oil recovery using CO₂ over the results of conventional waterflood. Since that field test, many successful operations using miscible CO₂ flooding have been conducted.

Carbon dioxide flooding for EOR can be grouped into two broad categories—miscible and immiscible. The process that is ultimately employed by the oilfield operator will depend on reservoir conditions and characteristics of the oil. Miscible CO₂ flooding is the most common application although immiscible flooding may be applied in some situations because of oil density or reservoir pressure.\textsuperscript{[28]}

Several factors make miscible CO₂ flooding an effective method for additional oil recovery. Carbon dioxide is soluble in crude oils, swells net oil volume and reduces oil viscosity even before it achieves miscibility. As the point of complete miscibility is approached, the CO₂ phase and the oil phase start to flow together homogeneously as a result of reduced interfacial tension and the increase in volume of the combined oil-solvent phase relative to the water phase.

At constant temperature, the lowest pressure at which liquids achieve miscibility is defined as the minimum miscibility pressure (MMP). Miscible CO₂ flooding is applicable in many reservoirs and is most effective when the reservoir has a pressure greater than the MMP. Typically this occurs at a depth greater than 760 m [2,500 ft].\textsuperscript{[29]} Additionally, the oil should have greater than 22 degree API gravity [less than 0.92 specific gravity] and less than 10 cP [10 mPa.s] viscosity. For best results, the reservoir needs to have oil saturation greater than 20% of the pore volume.

Ideally, a typical miscible flood injects CO₂ at one end of the desired zone and recovers oil driven to producer wells (Figure 5).\textsuperscript{[30]} Although miscible floods account for the majority of CO₂ EOR projects, some systems may benefit from immiscible flooding. Immiscible CO₂ EOR projects depend on a reduction in oil viscosity accompanied by oil swelling to achieve additional oil recovery. Projects that would benefit from immiscible CO₂ EOR have low-gravity crude oil and reservoir pressures less than the MMP.

A dependable source for CO₂ is a prerequisite for both miscible and immiscible CO₂ flooding. Natural and industrial sources of CO₂ are available.\textsuperscript{[31]} In 2008, the US produced about 3 billion ft\(^3\)/d [80 million m\(^3\)/d] of CO₂, primarily from natural sources in New Mexico, Colorado and Mississippi. Approximately 75% of the naturally produced CO₂ in the US is sent by pipeline to the Permian Basin, Texas, from the McElmo Dome, which is located near the border between Utah and Colorado and has one of the world’s largest accumulations of naturally occurring CO₂.

Industrial sources of CO₂ within the US include natural gas processing plants in Texas, Oklahoma, Wyoming and Michigan, an ammonia plant in Oklahoma, a coal gasification plant in North Dakota and power plants that have carbon capture capability. In Europe, significant industrial CO₂ sources are located in the UK, the Netherlands, Belgium, France and Germany. However, none of these sources have yet been used for CO₂ EOR operations.

Carbon Dioxide Storage

More than 80% of the world’s energy comes from the combustion of fossil fuels, and a rapid transition to low-carbon energy sources will likely be difficult and expensive.\textsuperscript{[32]} One method of mitigating the effects of CO₂ on climate change is carbon capture and storage (CCS). Because about 7,400 industrial sources worldwide have CO₂ emissions greater than 100 thousand metric tons/yr [110 thousand tonUS/yr], CCS and other strategies will be necessary over a 50-year period just to arrest the increase of CO₂ in the atmosphere. To actually reduce CO₂ will require an even greater effort (See “Taming Carbon Dioxide Emissions,” page 42).

(continued on page 44)
Data about the state of the Earth suggest that CO₂ must be brought under control to arrest the deleterious effects of climate change. Although not the only culprit, of all potential factors, CO₂ carries the most weight in influencing undesired changes in the atmosphere, surface temperatures and oceans. A variety of proposals have been suggested to bring CO₂ under control. Two such proposals illustrate the magnitude of the CO₂ emissions challenge and show workable paths for halting emissions growth and reducing the absolute level of those emissions over the next 15 to 35 years. Climate change caused by CO₂ and other factors can be arrested and reduced, but concrete action must be taken now to accomplish the task.

**Stabilization Wedges**
The stabilization wedge concept, introduced in 2004 and refined in 2007, shows how CO₂ emissions could be brought under control. An illustration of the stabilization triangle and wedges is shown in Figure S1. The area of the stabilization triangle represents 200 billion metric tons (220 billion tonUS) of carbon that will not be released to the atmosphere over the 50-year span. Once emissions have stabilized, industry and the public must begin to employ technologies that reduce emissions (right, blue line). (Adapted with permission from the Carbon Mitigation Initiative, Princeton University, New Jersey.)
eventually reduce global carbon emissions by 1 billion metric tons/yr [1.1 billion tonUS/yr] by 2057.

Figure S3. Bridge scenario. Two bounding curves define the emissions reduction envelope of the bridge scenario. The upper curve (black) is the trend line for the carbon emission rate if the global community honors its INDC pledges. The bottom curve (red) represents the emission rate reduction possible under the bridge scenario. The largest contributor to reduced carbon emissions in 2030 is energy efficiency (light orange), which contributes a 49% reduction. Increased investments in renewable energy sources (green) provide a 17% reduction. Upstream methane reduction (light blue), fossil fuel subsidy reform (purple) and reducing inefficient coal use (brown) make up the remaining 34% reduction. (Adapted from the IEA, reference 2.)

Bridge Scenario
A major climate meeting, the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change, will take place in Paris in December 2015. In advance of the COP21 conference, countries have pledged to make intended nationally determined contributions (INDCs) for reducing energy-related greenhouse gas (GHG) emissions toward the objective of slowing the pace of climate change. Under this INDC scenario, if countries adhere to their pledges, the growth of the carbon emission rate is projected to slow down but not stop (Figure S3).

An alternative path to taming and eventually reducing CO₂ emissions has been developed by the International Energy Agency (IEA). This concept, called the bridge scenario, seeks a more aggressive approach to battling carbon emissions than does the INDC scenario. Implicit in the bridge scenario is the recognition that global economic output and energy-related GHG emissions are independent phenomena. The bridge scenario calls for implementing five policy measures:

- Increase energy efficiency.
- Reduce the use of inefficient coal-fired power plants.
- Increase investment in renewable energy.
- Phase out subsidies for fossil-fuel consumption.
- Reduce upstream methane emissions.

Adoption of these measures is a start toward achieving a maximum surface temperature rise of 2°C [3.6°F] from current levels. However, other measures will be required to achieve the goal.

If these five strategies are fully employed immediately worldwide, under the bridge scenario, the carbon emission rate will peak in 2018 followed by a steady reduction. When compared with the INDC scenario, the bridge scenario promotes a reduction of 1.3 billion metric tons/yr [1.4 billion tonUS] from the calculated 2030 carbon emission rate to the 2010 emission rate of 8.9 billion metric tons/yr [9.8 billion tonUS/yr].

3. IEA, reference 2.
4. Energy efficiency is using less energy to provide the same service.
5. Renewable energy sources include solar, wind, hydropower and biomass.
Depleted oil and gas reservoirs and deep saline formations either onshore or offshore are options for geologic storage of CO₂. To store CO₂, the gas is injected into reservoirs that are at depths of 1 km [0.6 mi] or greater to ensure the CO₂ remains in a dense liquid or supercritical fluid state. Several mechanisms trap and keep CO₂ immobile.\(^{41}\) The primary trapping mechanism is usually a seal of low-permeability rock above the storage area, similar to that for natural oil and gas accumulations. Secondary mechanisms include solubility trapping, a mechanism by which a portion of the CO₂ dissolves in water, and residual gas trapping, a mechanism by which the CO₂ is trapped by capillarity.\(^{42}\) In some formations, CO₂ can be eventually trapped by its reaction with the rock and conversion to solid minerals. These secondary trapping mechanisms tend to become more effective over time, yielding, in most cases, a more secure storage site.

An ideal storage site is close to stationary sources of CO₂, has the capacity to contain the projected volume of material over a long period of time, is able to sustain a high injection rate and has a low-permeability barrier to act as a caprock or seal. In addition, the storage site must be at an appropriate depth for CO₂ to be liquid and have good mechanical strength to withstand injection pressures.

The injection of high volumes of fluid under high pressure into fault zones near a CCS site may create problems; doing so may cause faults to slip and generate microseismic activity.\(^{43}\) Passive seis-
mic methods may be used to monitor and record any injection-induced seismicity. Increased formation pressure may cause some degree of uplift, which can be monitored using interferometric synthetic aperture radar (InSAR) satellite imagery or tiltmeters (Figure 6).44  

The practice of carbon capture and storage continues to expand worldwide. Eight operating industrial-scale projects have come on stream in the past 40 years. These projects represent storage of about 14 million metric tons [15 million tonUS] of CO2 annually.45 Eight additional projects are under construction, representing 13 million metric tons [14 million tonUS] of CO2 annual storage capacity.

At the Sleipner project in the North Sea, CO2 is produced with natural gas, separated offshore and then injected into a disposal interval. About 1 million metric tons [1.1 million tonUS] of the produced CO2 has been injected annually into the Utsira formation over a 15-year period.46 The Boundary Dam Power Plant CCS project is located at Estevan, Saskatchewan, Canada. SaskPower, the owner and operator of the project, invested more than US$ 1 billion to equip one of its generators for carbon capture. SaskPower sells the captured CO2 to Cenovus Energy Inc. who uses it for EOR to boost output from maturing wells nearby.47 SaskPower also operates its own injection well at the power plant site.

Although CCS is a major initiative in several oil fields, CO2 is also being used for EOR in many production environments. A project in Canada is a good example of combined EOR and CCS.

Miscible CO2 Flooding and Storage  
Cenovus Energy Inc. has embraced a long-term commitment to use CO2 for miscible flooding and to store excess amounts underground at the Weyburn-Midale field in Canada. This project is at the forefront of combined CO2-EOR and geologic CO2 storage.48

The Weyburn-Midale field, discovered in 1954, is located in southeast Saskatchewan (Figure 7).49 The operation covers 180 km² [70 mi²] and is one of the largest medium-sour oil reservoirs in Canada. Original oil in place (OOIP) was estimated at 1.4 billion bbl [220 million m³]. Following initial production over a 9- to 10-year period, the operator started waterflooding in 1964 followed by horizontal drilling in the 1990s. Although these measures helped production, the operator opted to use CO2 EOR to reverse the long-term production decline and to demonstrate large-scale geologic storage of CO2.50

The Dakota Gasification Company operates a synfuel plant in Beulah, North Dakota, that generates natural gas from coal.51 The byproduct CO2 produced at the Beulah plant is compressed to 2,200 psi [15 MPa] and transported 210 mi [340 km] via pipeline to the Weyburn-Midale field. Deliveries of CO2 from the Beulah plant vary, ranging from 6,000 to 8,500 metric tons/d [6,600 to 9,400 tonUS/d]. The nearby Boundary Dam CCS project supplies an additional 2,300 metric tons/d [2,500 tonUS/d] to the Weyburn-Midale field.52 Storage of CO2 was initiated in September 2000 in a limited area of the field. This early phase of the operation had 16 vertical and 13 horizontal injection wells. A study of this injection area is ongoing and will address all of the technical aspects of long-term geologic storage (Figure 8).
Miscible CO₂ EOR and geologic storage have been successful at the Weyburn-Midale field, giving the field new life and potentially extending its operational period by more than 25 years. Currently, the field produces about 26,000 bbl/d [4,100 m³/d] of light crude oil (Figure 9). Carbon dioxide injection has tripled oil production from the estimated lowest production rate for the field, about 8,000 bbl/d [1,200 m³/d] in 1988.

To date, about 24 million metric tons [26 million tonUS] of CO₂ have been stored, and about 55 million metric tons [61 million tonUS] will be stored underground over the life of the project.

Carbon Dioxide Storage at In Salah

The In Salah Gas (ISG) project, a joint venture between Sonatrach, BP and Statoil, is currently executing a phased development of eight gas fields in the Ahnet-Timimoun basin in the Algerian central Sahara desert (Figure 10). These fields comprise an area of 25,000 km² [9,600 mi²] and have estimated recoverable gas reserves of 0.23 trillion m³ [8.1 trillion ft³]. The gas from these fields contains 1% to 10% CO₂, which is removed at the Krechba central processing facility (CPF). Carbon dioxide and any residual hydrogen sulfide [H₂S] in the produced gas are removed by monoethanol amine (MEA) absorption. The cleaned up gas from the Krechba CPF contains 0.3% or less CO₂ and is transported by pipeline to export terminals. The ISG project started production in 2004 and is currently producing 9 billion m³/yr [320 billion ft³/yr] of gas for export.

Carbon dioxide recovered from the produced gas was injected about 1,900 m [6,200 ft] into the water-filled downdip flank of the Krechba gas field. The three CO₂ injection wells have horizontal sections measuring up to 1.8 km [1.1 mi] in length (Figure 11). The joint venture conducted extensive monitoring of CO₂ storage using a variety of techniques such as surface and soil gas monitoring, downhole gas measurements and tracer chemical tagging. Geophysical and InSAR satellite monitoring were also conducted to check for ground deformation and microseismicity (Figure 12).

Figure 11. Carbon dioxide injection at Krechba. At the In Salah project, the Krechba central processing facility (CPF, inset) consists of several sections—power generation (right), CO2 removal and dehydration (center) and CO2 injection. Recovery and injection of the CO2 removed from the natural gas are straightforward. The producing gas reservoir is about 20 m [66 ft] thick and lies about 1,900 m [6,200 ft] deep below a 950 m [3,100 ft] thick caprock formation of Carboniferous mudstones. A 900 m [3,000 ft] thick layer of Cretaceous sandstone and mudstone lies above the mudstone section. Produced gas from the reservoir is treated at the CPF to remove CO2, H2S and other impurities. The treated CO2 is then reinjected into water-saturated rock of the same reservoir from which the gas is produced.

Figure 12. Monitoring ground deformation. Ground deformation is monitored at the In Salah project using interferometric synthetic aperture radar (InSAR). This technique uses a dedicated satellite (left) to collect infrared radar images of the ground elevation using side-beam radar. Measurement of the vertical and horizontal displacements requires two passes of the satellite. Displacements are determined by comparing the wave phase changes of the radar signal between the two passes. The deformation and CO2 plume spreads at each well (marked by a cross) were estimated from the InSAR data for 2005, 2007 and 2009 (right). The color intensity indicates the degree of vertical deformation (scale, far right) while the size of the colored area around each well infers the horizontal spread of the CO2 plume.
Figure 13. Bati Raman project. The Bati Raman field and associated CO₂ EOR project in Turkey are located about 720 km [450 mi] southeast of Ankara. The Bati Raman project has two CO₂ injection stations—AP2 (inset) and 3TP2 (not shown). (Photograph used with permission from the Turkish Petroleum Corporation.)

Since 2004, approximately 3.5 million metric tons [3.9 million tonUS] of CO₂ have been separated from the produced gas and reinjected into the Krechba reservoir.

Important lessons were learned about CO₂ storage during the design, startup and operation of the ISG project, including the need for detailed geologic and geomechanical characterization of the reservoir and the overburden. These data helped the operator develop the injection strategy and ensured the long-term integrity of the storage facility. The operator also realized the importance of flexibility in the design and control of the capture, compression and injection well systems.

Immiscible CO₂ Flooding

The Bati Raman field, in southeast Turkey, is one of the largest oil fields in that country (Figure 13). Owned and operated by the Turkish Petroleum Company (TP), the field was discovered in 1961 and produces from a Garzan limestone—a heterogeneous carbonate from the Cretaceous period. The heavy crude produced at the Bati Raman field has 11 degree API gravity [0.99 specific gravity], high viscosity and low solution–gas content. The OOIP was estimated to be 1.85 billion bbl [300 million m³]. From 1965 to 1970, the number of producing wells increased from almost 20 to more than 130.

During the primary production period from 1961 to 1986, reservoir pressure decreased from about 1,800 psi [12 MPa] to as low as 400 psi [2.8 MPa] in some parts of the field. Similarly, crude production declined from a peak rate of 9,000 bbl/d [1,400 m³/d] in 1969 to 1,600 bbl/d [250 m³/d] in 1986. During the primary production period, recovery was estimated to be less than 2% of OOIP.

Following the primary recovery period, the operator studied several processes for EOR and chose immiscible CO₂ flooding primarily because of the proximity of the Dodan gas field. The Dodan field is 55 mi [89 km] from the Bati Raman field and produces gas that is mostly CO₂ and has 3,000 to 4,000 ppm H₂S. The wellhead pressure at the Dodan field is about 1,050 psi [7.2 MPa]. After it is cleaned up, the CO₂ from the Dodan field is sent to the Bati Raman field via pipeline (Figure 14).

Before implementing full-scale CO₂ flooding at the Bati Raman field, TP performed a pilot test using 17 CO₂ injection wells in the western part of the field. The original plan was cyclic injection of CO₂ followed by water. After studying the pilot test results, TP engineers converted the initial

injection plan to CO₂ flooding. The operator made several observations based on the pilot test: CO₂ injection helped produce a considerable amount of oil, and diffusion of CO₂ into the oil was effective for displacing oil in the fractured carbonate reservoir. After evaluating the results from the pilot test, TP engineers gradually extended the CO₂ flooding to the rest of the field. Currently, 95% of the production wells in the Bati Raman field are influenced by CO₂ flooding.

In 2012, the CO₂ injection project was 25 years old, far beyond what was envisioned during the initial field design. More than 6% of the OOIP has now been recovered, a significant increase over the less than 2% recovered during primary field production. Primary recovery was 32 million bbl [51 million m³] while total field production, including that from primary, secondary and EOR recovery, was 114 million bbl [18 million m³] as of the end of 2014 (Figure 15).

Figure 14. Dodan and Bati Raman process flow. At the Dodan gas plant (left), produced gas is stripped of H₂S and water, compressed and sent by pipeline to the Bati Raman process facility, where it is injected (right). At the Bati Raman facility, oil and CO₂ in the produced stream are separated—the oil goes to refining and the gas to cleanup. The cleaned up CO₂ is compressed and sent to the injection wells. (Adapted with permission from the Turkish Petroleum Corporation.)

Figure 15. Bati Raman production history. The Bati Raman field started producing in 1961, and as additional wells were brought on stream, production ramped up and peaked in 1970 at almost 10,000 bbl/d [1,600 m³/d]. Following this peak, production declined because of decreasing reservoir pressure. Water flooding started in 1975 and slowed the rate of production decline but did not reverse it. In 1986, primary production reached a low of about 2,000 bbl/d [300 m³/d], and CO₂ injection for EOR was initiated. After CO₂ EOR was introduced, production peaked around 1992 at about 15,000 bbl/d [2,400 m³/d]. Production decreased until 2004 when the practice of integrated reservoir management was implemented and arrested the decline. Production has held steady at about 7,500 bbl/d [1,200 m³/d] since that time. (Adapted with permission from the Turkish Petroleum Corporation.)
Carbon Dioxide and the Future

Scientists have had an interest in CO₂ for more than a century. The business sector, government regulators and the public have joined scientists in the quest to slow the atmospheric accumulation of CO₂. The oil industry is tackling this challenge in part by injecting CO₂ underground, both for EOR and for long-term storage purposes.

In addition to EOR and storage, the industry can also take advantage of new, less-expensive sorbents for CO₂ capture, which will also help reduce CO₂ emissions into the atmosphere. Current technology depends on absorbents, including aqueous MEA, to remove CO₂ from streams such as power plant flue gas. The MEA solution is corrosive, degrades into toxic byproducts and requires a large amount of energy to clean it up for reuse.

The unfavorable characteristics of current sorbents such as MEA have led researchers to develop new ones—both solid and liquid. One of these new sorbents is solid, microporous carbon that is synthesized from asphalt (Figure 16). This sorbent is inexpensive, has high surface area CO₂ uptake and excellent properties for reversibly capturing CO₂. Another new sorbent is a liquid carbonate enclosed within polymer microcapsules with shells of highly permeable silicone. These microcapsules are reported to have rapid CO₂ uptake and release.

Although new sorbent technology can help, it is only part of the solution for emissions. The reduction and mitigation of GHG emissions will require simultaneous implementation of several technologies and significant governmental action on a worldwide basis. These technologies range from efficiency improvements to alternate energy sources to conservation tillage. Likewise, governments can help, for example, by reducing subsidies for inefficient hydrocarbon use and intelligent mandates on fuel efficiency.

One area in which the oil and gas industry can play an important role is geologic storage in CCS. A technical challenge related to geologic storage is risk associated with faulty CO₂ confinement. The oil and gas industry has the technical tools to assess the potential and risk for CO₂ migration away from storage sites. Although extra costs associated with large-scale geologic storage of CO₂ will be incurred, these costs are fundamentally no different than additional costs already borne by the public for cleaner water and air.

The consequences of climate change are potentially enormous. In the last decade, as evidence for the effects of climate change mounts, moving beyond maintaining the status quo and doing business as usual has become important. Although it can help to reduce the problem, the oil and gas industry can offer only some solutions. Worldwide, industries, governments and the public must be educated and ready to support a vigorous effort to arrest climate change.

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