Chapter 2
Simultaneous CO₂-EOR and Storage Projects

Abstract  Majority of currently operational large-scale integrated carbon capture and storage projects (LSIPs) are in the USA and Canada. This demonstrates the leadership of the North American petroleum industry in successful implementation of geologic CO₂ storage technology via simultaneous CO₂-EOR and storage strategy. These LSIPs mainly utilize anthropogenic CO₂ captured at the natural gas processing plant used by the petroleum industry for processing the natural gas resulting from its routine oil and gas extraction operations. Other oil producing countries such Saudi Arabia, United Arab Emirates (UAE), and Brazil are also following suite by launching simultaneous CO₂-EOR and storage strategy based LSIPs and large-scale geologic CO₂ storage projects.

2.1 Introduction

For more than four decades, the petroleum industry in the USA has been using the anthropogenic CO₂ for EOR purposes. In CO₂-EOR operations, a significant portion of injected CO₂ is lost in the reservoir in anyway leading to its partial (incidental) storage even though they are not designed with long-term storage purposes. With an inclusion of additional storage-focused activities (i.e. a dedicated MVA/MMA program) a EOR project can become a storage project (i.e. simultaneous CO₂-EOR and storage project). A MVA/MMA program essentially includes a minimum of following four activities (IEA 2015b):

1. additional site characterization and risk assessment to evaluate the storage capability of a site;
2. additional monitoring of vented and fugitive emissions;
3. additional subsurface monitoring, and
4. change to field abandonment practices.

The petroleum industry’s long and successful record of secure underground injection of CO₂ for EOR, has helped the world to embrace the geologic CO₂ storage as first-order technology for abating the anthropogenic GHG emissions. It is
substantiated from the fact that in 12 out of 15 currently operational LSIPs, primary storage type is EOR. The Global CCS Institute (2016a) defines the LSIPs as projects involving the capture, transport, and storage of CO$_2$ at a scale of:

1. at least 800,000 metric tons (tonnes) of CO$_2$ annually for a coal–based power plant, or
2. at least 400,000 metric tons (tonnes) of CO$_2$ annually for other emissions–intensive industrial facilities (including natural gas–based power generation).

Projects categorized by the Global CCS Institute as LSIPs must inject anthropogenic CO$_2$ into either dedicated geological storage sites and/or enhanced oil recovery (CO$_2$-EOR) operations. Obviously, majority (9) of LSIPs are in North America [the USA (7) and Canada (2)] where the petroleum industry has already mastered the commercial CO$_2$-EOR technology. Brazil, Saudi Arabia, and the United Arab Emirates, each, have one simultaneous EOR and storage LSIP.

Apart from LSIPs, numerous pilot and demonstration projects and commercial CO$_2$-EOR projects which use either natural or anthropogenic CO$_2$, have also helped in gaining necessary information on technical feasibility of various capture, injection, storage, and monitoring technologies and in gaining operational experience within the scope of policy, regulatory, and project economics framework.

### 2.2 North-American Projects

If we look at the project histories of the current large-scale North American simultaneous EOR and storage projects (Table 1.1), The Great Plains Synfuel Plant LSIP in southwestern North Dakota is the only commercial-scale coal gasification plant in the US and has been capturing and transporting CO$_2$ to oil fields in Canada since October 2000 (Global CCS Institute 2016d). The captured CO$_2$ is transported via (the Souris Valley) pipeline to the Weyburn and Midale Oil Units in Saskatchewan, Canada. The International Energy Agency (IEA) as a part of its Greenhouse Gas R&D Programme (IEAGHG), performed the most comprehensive MVA/MMA program alongside CO$_2$-EOR operations between 2000 and 2011. The IEAGHG Weyburn-Midale CO$_2$ Monitoring and Storage Project, as it is called, is the largest full-scale CCS field study ever conducted that included the study of mile-deep seals that contain the CO$_2$ reservoir, CO$_2$ plume movement, and the monitoring of permanent storage (Global CCS Institute 2016d). In October 2014, the Weyburn Oil Unit also started to receive the CO$_2$ captured at the Boundary Dam Carbon Capture and Storage Project LSIP (Global CCS Institute 2016e).

CO$_2$ injection in the Vale Verde Natural Gas Plants LSIP in Texas has ongoing since 1972. However, at the SACROC Unit of the Kelly Snyder oil field which is the largest storage site among many nearby sites, new injection coupled with dedicated MVA/MMV commenced in 2008 (Grigg et al. 2012). In case of another LSIP in Texas, namely, the Air Products Steam Methane Reformer EOR Project,
CO₂ injection in the historic West Hastings oil field began in 2010 and a research MVA program to study the movement and sequestration of CO₂ through existing EOR operations was implemented and is continuing. Both the Lost Cabin Gas Plant and the Shut Creek Gas Processing Facility in Wyoming, provide the CO₂ for the Denbury Resources-operated Bell Creek oil field in Montana (NETL 2015c). More than 230 miles long Greencore pipeline supplies the CO₂ for the Bell Creek site from these LSIPs. The Bell Creek Project had collected a relevant baseline MVA data before injection began in May 2013 and a continued robust MVA program is in place as project is moving forward with its injection, production, and storage operations.

Two other LSIPs, namely, Enid Fertilizer CO₂-EOR Project and Shut Creek Gas Processing Facility are operational for more than three decades and supply anthropogenic CO₂ to several depleted oil fields in Oklahoma and Wyoming, respectively. As mentioned above, the Shut Creek LSIP also supplies CO₂ to the Bell Creek site. Similarly, captured CO₂ at Century Plant in Texas is distributed to many oil fields in the Permian basin. The Coffeyville Gasification Plant LSIP in Kansas is the source of CO₂ for the North Burbank Unit (NBU) which is the one of the largest oil fields in Oklahoma and was originally discovered in 1920. CO₂ injection into NBU for simultaneous EOR and storage purposes started in June 2013. However, for various reasons including injection and storage of supplied CO₂ into multiple sites, there is little information on the MVA/MMV programs for these three LSIPs is available in public domain. Nevertheless, these LSIPs are playing a key role in establishing simultaneous CO₂-EOR and storage strategy as a commercially viable option for geologic CO₂ storage.

Apart from the operational LSIPs, there are two notable simultaneous CO₂-EOR and storage projects in North America, namely, Michigan Basin Project, Michigan, and Farnsworth Unit Project, Texas. In Michigan Basin Project, CO₂ injection into an oil field located within Michigan’s Northern Reef Trend started in April 2013 and the monitoring and tracking of the injected CO₂ was started in July 2013 (MIT CC&ST Program 2016). The Chaparral Energy began CO₂ injection in December 2010 into the Morrow Sandstone Formation within the Farnsworth Unit (FWU) for EOR and the MVA program was launched in October 2013.

2.2.1 Key Features

Table 2.1 along with Table 1.1 provide a summary of key geologic characteristics, reservoir parameters, and other operational characteristics and statistics of the main storage sites of simultaneous CO₂-EOR and storage strategy based LSIPs and other large-scale projects that are currently operational in the North America. It is remarkable that majority of these projects (9 out of 11) rely on the CO₂ captured by natural gas processing or industrial separation units (Table 1.1). The natural gas
<table>
<thead>
<tr>
<th>Geologic characteristic/reservoir parameter</th>
<th>West Hastings unit</th>
<th>North Burbank oil unit</th>
<th>SACROC unit</th>
<th>Weyburn oil unit</th>
<th>Bell Creek unit</th>
<th>Peach oil unit</th>
<th>Cretaceous (Marl) 49 ( (Vuggy) )</th>
<th>Oil gravity °API</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geologic age</td>
<td>Cretaceous</td>
<td>Pennsylvanian</td>
<td>Mississippian</td>
<td>Jurassic</td>
<td>Pennsylvanian</td>
<td>Devonian</td>
<td>Permian</td>
<td>Jurassic</td>
</tr>
<tr>
<td>Hydrocarbon trap type</td>
<td>Stratigraphic</td>
<td>Stratigraphic</td>
<td>Stratigraphic</td>
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<td>Stratigraphic</td>
<td>Stratigraphic</td>
<td>Stratigraphic</td>
<td>Stratigraphic</td>
</tr>
<tr>
<td>Overlying caprock(s)</td>
<td>Wolfcamp shale</td>
<td>Wolfcamp shale</td>
<td>Mowry reef</td>
<td>McFaddin reef</td>
<td>Wolfcamp shale</td>
<td>Wolfcamp shale</td>
<td>Wolfcamp shale</td>
<td>Wolfcamp shale</td>
</tr>
<tr>
<td>Overlying caprock(s) average thickness</td>
<td>&gt;3000 ft.</td>
<td>&gt;3000 ft.</td>
<td>&gt;3000 ft.</td>
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<td>&gt;3000 ft.</td>
<td>&gt;3000 ft.</td>
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<td>&gt;3000 ft.</td>
</tr>
<tr>
<td>Formations depth</td>
<td>6200–7000 ft.</td>
<td>5500 ft.</td>
<td>5500 ft.</td>
<td>4900 ft.</td>
<td>5500 ft.</td>
<td>5500 ft.</td>
<td>5500 ft.</td>
<td>5500 ft.</td>
</tr>
<tr>
<td>Avg. reservoir thickness</td>
<td>45–70 ft.</td>
<td>600 ft.</td>
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<td>600 ft.</td>
<td>600 ft.</td>
<td>600 ft.</td>
<td>600 ft.</td>
<td>600 ft.</td>
</tr>
<tr>
<td>Formation pressure at discovery</td>
<td>2400 psi</td>
<td>2740 psi</td>
<td>2740 psi</td>
<td>2900 psi</td>
<td>2740 psi</td>
<td>2740 psi</td>
<td>2740 psi</td>
<td>2740 psi</td>
</tr>
<tr>
<td>Formation temperature</td>
<td>167 °F</td>
<td>122 °F</td>
<td>122 °F</td>
<td>108 °F</td>
<td>108 °F</td>
<td>108 °F</td>
<td>108 °F</td>
<td>108 °F</td>
</tr>
<tr>
<td>Cumulative oil production to date</td>
<td>0.47 (Dover 33)</td>
<td>1.08 (Dover 33)</td>
<td>1.08 (Dover 33)</td>
<td>108 (Dover 33)</td>
<td>108 (Dover 33)</td>
<td>108 (Dover 33)</td>
<td>108 (Dover 33)</td>
<td>108 (Dover 33)</td>
</tr>
<tr>
<td>Oil gravity °API</td>
<td>38 ppm</td>
<td>47.9 ppm</td>
<td>47.9 ppm</td>
<td>47.9 ppm</td>
<td>47.9 ppm</td>
<td>47.9 ppm</td>
<td>47.9 ppm</td>
<td>47.9 ppm</td>
</tr>
<tr>
<td>Formations water salinity</td>
<td>&gt;100,000 ppm</td>
<td>&gt;100,000 ppm</td>
<td>&gt;100,000 ppm</td>
<td>&gt;100,000 ppm</td>
<td>&gt;100,000 ppm</td>
<td>&gt;100,000 ppm</td>
<td>&gt;100,000 ppm</td>
<td>&gt;100,000 ppm</td>
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</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>Geologic characteristic/reservoir parameter</th>
<th>Unit</th>
<th>West hostages</th>
<th>North Burbank oil unit</th>
<th>Pinnacle Reefs (Michigan’s Northern Reef Trend)</th>
<th>Farsworth oil unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. porosity %</td>
<td>26 (Marly)</td>
<td>9</td>
<td>20</td>
<td>4</td>
<td>3-21</td>
</tr>
<tr>
<td>Avg. permeability (mD)</td>
<td>10 (Marly)</td>
<td>15</td>
<td>50-1175</td>
<td>500-1000</td>
<td>12</td>
</tr>
<tr>
<td>EOR type</td>
<td>Combined miscible CO₂ injection, water only, and water alternating gas</td>
<td>Miscible Water Alternating Gas (WAG) (5-spot pattern)</td>
<td>Top-down CO₂ injection (vertical injector + horizontal producer)</td>
<td>Hybrid water alternating with CO₂, gas (WAG) (5-spot well pattern)</td>
<td>Continuous miscible CO₂ injection (5-spot pattern)</td>
</tr>
<tr>
<td>Reported reservoir pressure prior to CO₂ injection (psi)</td>
<td>2150-2250</td>
<td>1572</td>
<td>1800</td>
<td>900</td>
<td>4700</td>
</tr>
</tbody>
</table>

processing facilities are the one of the essential elements of the petroleum industry’s core business i.e. oil and gas production operations. Only the Boundary Dam and the Great Plains Synfuel are the two coal-based (power generation or synthetic natural gas production) facilities that supply the Weyburn-Midale CO2-EOR and storage project in Canada.

Most of the future LSIPs around the world (Global CCS Institute 2016d) will also rely on petroleum industry’s ability of capturing CO2 at its natural gas processing facilities. However, there appears to be a major push by China to capture CO2 at its coal-fired power plants and use it for simultaneous CO2-EOR and storage projects. If successful, it is going to open the door for the future carbon storage industry that is mostly absent in countries like China and India, where coal-fired plants will still be the main source of electricity generation for several decades to come (EIA 2016).

It is worth to mention here that all the storage sites (Table 2.1) had significant history of waterflooding and/or CO2 injection prior to launch of MVA/MMV programs there. It implies that petroleum industry already had the infrastructure and technical knowhow needed for injecting large quantities of fluids (water or CO2) into porous media. Also, the industry relies on a mix of traditional water alternating gas (WAG) and a top down continuous CO2 injection in near miscible/miscible mode strategy for recovering additional oil and storing large quantities of CO2 in these storage sites (depleted oil fields). Vertical wells are being used for injection and production is all but two operational projects. The Michigan Basin and the Weyburn-Midale Projects, horizontal wells have also been used for production and both injection and production, respectively.

Because, CO2 injection is going on in SACROC Oil Unit (storage site for Val Verde LSIP) since 1972, it is obvious that it has stored the maximum CO2 (55 million tonnes) among all operational large-scale North American simultaneous CO2-EOR and storage project. The Weybun-Midale LSIP is operational since 2000 and have stored almost 22 million tonnes of CO2 so far. In both the West Hastings (site for Air Products LSIP) and the Bell Creek (Lost Cabin LSIP) oil fields, CO2 injection was started in 2013 and, by May 2016, both have stored 3 million tonnes and 2.75 million tonnes of captured CO2, respectively.

Interestingly, majority of the storage sites are either stratigraphic traps or closed pinnacle reef structures encased in thick impermeable formations that have served as effective seals for the hydrocarbon accumulations at first place. Obviously, significant production (cumulative oil production) and injection (water and/or CO2) histories of these depleted oil fields indicate that these sites can store large amounts of injected fluids. It has given additional confidence to the operators to select these sites as prime locations for storing anthropogenic CO2. The access to wealth of geologic and reservoir characterization data resulting from the industry’s efforts to recover stranded oil from these depleted oil fields appear to be another great reason to select them as first-order storage sites.
2.3  Current Projects (Rest of the World)

2.3.1  Uthmaniyah CO₂-EOR Demonstration Project

Even though the Kingdom of Saudi Arabia has abundant conventional hydrocarbon reserves and EOR is not likely to be required at production scale for decades to come, Uthmaniyah CO₂-EOR Demonstration Project is meant to demonstrate the proactive approach of Saudi Aramco, and industry leader and operator of the project, for addressing global environmental challenges. CO₂ at the injection site (a small flooded area in the Uthmaniyah production unit) comes from the Hawiyah Natural Gas Liquids (NGL) Recovery Plant via an 85 km (52 miles) long pipeline and is injected into Jurassic organic-rich mudstones at a depth of between 1800 and 2100 m (6000 – 7000 ft.) at a rate around 0.8 million tonnes per year (Global CCS Institute 2016f). The injection site includes four injection wells, four producers, and two observation wells. Injection strategy is conventional WAG. The project design is based on reservoir simulation studies and has a comprehensive monitoring and surveillance plan, including routine and advanced logging and use of new technologies for plume tracking and for CO₂ saturation modeling (seismic, chemical tracers, and electromagnetic surveys and borehole gravimetry) (Global CCS Institute 2016f).

2.3.2  Abu Dhabi CCS Project (Phase 1: ESI CCS Project)

In November, 2016, world’s first commercial carbon capture facility at Emirates Steel Industries (ESI) steel production plant in Abu Dhabi, United Arab Emirates (UAE), started to capture around 0.8 million tonnes CO₂ per year to supply it via a 43 km (27 miles) pipeline for EOR injection into NEB (Al Rumaitha) and Bab onshore oil fields of the Abu Dhabi National Oil Company (ADNOC) (Global CCS Institute 2016g). Prior to launching the project, operators undertook a pilot project that involved injection of approximately 60 tonnes of CO₂ per day into the ADNOC Al Rumaitha oilfield via a CO₂ injection well (Global CCS Institute 2016g). The pilot project also included an observation well and an oil producing well. The pilot provided information on the amounts of CO₂ required for field-scale injection and the potential volume of oil recoverable from the Al Rumaitha and Bab oil fields.

2.3.3  Petrobras Santos Basin Pre-salt Oil Field CCS Project

This Brazilian simultaneous CO₂-EOR and storage project is an offshore (Santos Basin) project in which pre-combustion capturing (natural gas processing) of CO₂ is done at floating production, storage, and offloading (FPSO) vessels anchored in
the Santos Basin. The captured CO$_2$ is injected at a rate of approximately 1 million tonnes per year into the pre-salt carbonate reservoir of the Lula and Sapinhoá oil fields at a depth of between 5000 and 7000 m (16,400–23,000 ft.) below sea level (Global CCS Institute 2016h).

Because both Uthmaniyah and Abu Dhabi projects have become operational recently, lesson learned in these projects will take time to become available in public domain. Being an offshore project, the Petrobras CCS Project, is a unique project and lesson learned there will provide valuable insights for the future geologic CO$_2$ storage projects in offshore environment.

References


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