Chapter 2
Simultaneous CO_2-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 CO_2 storage technology via simultaneous CO_2-EOR and storage strategy. These LSIPs mainly utilize anthropogenic CO_2 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 CO_2-EOR and storage strategy based LSIPs and large-scale geologic CO_2 storage projects.

2.1 Introduction

For more than four decades, the petroleum industry in the USA has been using the anthropogenic CO_2 for EOR purposes. In CO_2-EOR operations, a significant portion of injected CO_2 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 CO_2-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 CO_2 for EOR, has helped the world to embrace the geologic CO_2 storage as first-order technology for abating the anthropogenic GHG emissions. It is

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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,

CO_2 injection in the historic West Hastings oil field began in 2010 and a research MVA program to study the movement and sequestration of CO_2 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 CO_2 for the Denbury Resources-operated Bell Creek oil field in Montana (NETL 2015c). More than 230 miles long Greencore pipeline supplies the CO_2 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 CO_2-EOR Project and Shut Creek Gas Processing Facility are operational for more than three decades and supply anthropogenic CO_2 to several depleted oil fields in Oklahoma and Wyoming, respectively. As mentioned above, the Shut Creek LSIP also supplies CO_2 to the Bell Creek site. Similarly, captured CO_2 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 CO_2 for the North Burbank Unit (NBU) which is the one of the largest oil fields in Oklahoma and was originally discovered in 1920. CO_2 injection into NBU for simultaneous EOR and storage purposes started in June 2013. However, for various reasons including injection and storage of supplied CO_2 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 CO_2-EOR and storage strategy as a commercially viable option for geologic CO_2 storage.

Apart from the operational LSIPs, there are two notable simultaneous CO_2-EOR and storage projects in North America, namely, Michigan Basin Project, Michigan, and Farnsworth Unit Project, Texas. In Michigan Basin Project, CO_2 injection into an oil field located within Michigan's Northern Reef Trend started in April 2013 and the monitoring and tracking of the injected CO_2 was started in July 2013 (MIT CC&ST Program 2016). The Chaparral Energy began CO_2 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 CO_2-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 CO_2 captured by natural gas processing or industrial separation units (Table 1.1). The natural gas

Table 2.1 Key geologic characteristics and reservoir parameters of the storage sites of some of the currently operational North American LSIPs and other large-scale simultaneous CO_2-EOR and storage projects

Geologic characteristic/reservoir parameter[a]	Unit	Weyburn oil unit	Bell Creek	SACROC unit	West hastings	North Burbank oil unit	Pinnacle Reefs (Michigan's Northern Reef Trend)	Farnsworth unit
Formation		Charles formation [Marly (upper dolostone unit) + Vuggy (lower limestone unit)]	Muddy (Newcastle)	Canyon Reef (limestone)	Frio sandstone	Burbank Sandstone	Guelph formation (brown Niagaran)	Upper morrow
Geological age		Mississippian	Cretaceous	Pennsylvanian	Oligocene	Pennsylvanian	Silurian	Pennsylvanian
Hydrocarbon trap type		Truncated stratigraphic	Stratigraphic	Reef	Structural	Stratigraphic	Reef	Stratigraphic
Overlying caprock(s)		Midale evaporite with Watrous aquitard as regional seal	Mowry shale	Wolfcamp shale	Anahuac shale	Cherokee shale	A-2 evaporite (top) A-1 evaporite (flank)	Thirteen Finger limestone
Caprock(s) average thickness	ft.	6.5–36 (Midale evaporite)	>3000	600–1100	600	45–70	>290	118
Formation depth	ft.	4900	4500	6200–7000	5500	3000	5400–5700	7545–7950
Avg. reservoir thickness	ft.	19.5 (Marly) 49 (Vuggy)	30–45	229	>700	50	278 (maximum)	54
Formation pressure at discovery	psi	2300	1180	3122–3300	2740	1350–1600	2400	2200
Formation temperature	°F	138	110	130	160	122	108	167
Cumulative oil production to date	Million barrels	366	133	1400	582		0.47 (Dover 33)	19
Oil gravity	°API	25–34	32–41	42	31	39–41	47.9	38
Formation water salinity	ppm	20,000–310,000	5000	159,000	>100,000	85,000	Very high	3600

(continued)

Table 2.1 (continued)

Geologic characteristic/reservoir parameter[a]	Unit	Weyburn oil unit	Bell Creek	SACROC unit	West hastings	North Burbank oil unit	Pinnacle Reefs (Michigan's Northern Reef Trend)	Farnsworth unit
Avg. porosity	%	26 (Marly) 11 (Vuggy)	25–35	9	29	20	4	3–21
Avg. permeability	mD	10 (Marly) 15 (Vuggy)	150–1175	30	500–1000	50–80	12	0.1–700
EOR type		Combined miscible simultaneous but separate CO_2 only, water only, and water alternating gas injection strategy using a combination of horizontal CO_2 injectors and horizontal producers and vertical water injectors and vertical producers	Continuous miscible CO_2 injection (5-spot pattern)	Miscible Water Alternating Gas (WAG) (5-spot well pattern)	Continuous miscible CO_2 injection, water only, and water alternating gas (5-spot pattern)	Miscible Water Alternating Gas (WAG) (staggered line drive well pattern)	Top down CO_2 injection (vertical injector + horizontal producer)	Hybrid water alternating with CO_2 gas injection (WAG) (5-spot well pattern)
Reported reservoir pressure prior to CO_2 injection	psi	2150–2250	1572	2400	1800	900	790	4700

[a]Data sources include Ahmmed (2015), Ampomah et al. (2016), (Balch and McPherson 2016), Davis et al. (2011), Ganesh et al. (2014), Global CCS Institute (2016d), Gorecki et al. (2014), Grigg et al. (2012), Han (2010), Meng (2015), Li and Schechter (2014), Miller et al. (2014), MIT CC&ST Program (2016), NETL (2015c), Pan et al. (2016), Riding and Rochelle (2005), White et al. (2014), Whittaker (2005), Whittaker et al. (2011), Wood et al. (2006)

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 CO_2-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 CO_2 at its natural gas processing facilities. However, there appears to be a major push by China to capture CO_2 at its coal-fired power plants and use it for simultaneous CO_2-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 CO_2 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 CO_2) into porous media. Also, the industry relies on a mix of traditional water alternating gas (WAG) and a top down continuous CO_2 injection in near miscible/miscible mode strategy for recovering additional oil and storing large quantities of CO_2 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, CO_2 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 CO_2 (55 million tonnes) among all operational large-scale North American simultaneous CO_2-EOR and storage project. The Weybun-Midale LSIP is operational since 2000 and have stored almost 22 million tonnes of CO_2 so far. In both the West Hastings (site for Air Products LSIP) and the Bell Creek (Lost Cabin LSIP) oil fields, CO_2 injection was started in 2013 and, by May 2016, both have stored 3 million tonnes and 2.75 million tonnes of captured CO_2, 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 CO_2) 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 CO_2. 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 CO_2-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 CO_2-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. CO_2 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 CO_2 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 CO_2 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 CO_2 per day into the ADNOC Al Rumaitha oilfield via a CO_2 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 CO_2 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 CO_2-EOR and storage project is an offshore (Santos Basin) project in which pre-combustion capturing (natural gas processing) of CO_2 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.

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