An Overview of Power Plant CCS and CO_2-EOR Projects

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Abstract

CO_2 has been used for many decades in the industrial processes and food manufacturing, including soft drinks. Likewise, it is an essential component of other everyday items such as fire extinguishers. In very high concentrations, CO_2 like any dense gas, can act as an asphyxiate material, which can be dangerous to humans with its adverse impact on respiration. Thus, CO_2 is captured to minimize risks to humans' health and the environment. A general overview of the current carbon capture and storage (CCS) and CO_2 based enhanced oil recovery (CO_2-EOR) projects is presented in this paper. This work provides a summary of the current worldwide CCS and CO_2-EOR projects along with their potential benefits. CCS is a process used to capture CO_2 that is produced by industrial facilities. The CCS technology involves CO_2 capture, transport and storage. On the other hand, EOR is a generic term for various techniques to increase recovery from oil fields. The injection of CO_2 into underground rock formation of oil reservoirs in order to improve their recovery is called CO_2-EOR.

Keywords

CO_2 Capture and Storage, CO_2-EOR, ECBM, EGS, Post-combustion, Pre-combustion, and Oxy combustion

1. Introduction

Since the industrial revolution, the fossil fuel (coal, oil and natural gas) has become key energy source which generates significant amount of CO_2 emissions in the atmosphere. This is believed to be the main cause of climate change and a concern due to the CO_2 emissions adverse effect on the environment. According to Global Carbon Emissions (2017), CO_2 emissions totaled between 35 and 40 billion tons in 2015. Moreover, fossil fuel emissions were 0.6% above emissions in 2013 and 60% above emissions in 1990. Fig. 1 presents the monthly average atmospheric ppm CO_2 concentration during November 1959 and November 2016. The figure shows the global CO_2 concentration in November 2016 passed 403 ppm. On the other hand, according to an intergovernmental panel on climate change report (IPCC, 2000), without climate change mitigation policies it is estimated that global greenhouse gas (GHG) emission in 2030 increases by 25-90% over the year 2000 level, with CO_2-equivalent concentrations in the atmosphere growing to as much as 600–1550 ppm. Likewise, Boden et al. (2015) reported that in 2011 the top CO_2 emitters were 28% from China, 16% from the United States, 10% from the European Union, 6% from India, 6% from the Russian Federation, 4% from Japan, and 30% from other countries. Fig. 2 demonstrates the countries' share of GHG emissions. These data include CO_2 emissions from fossil fuel combustion, as well as cement manufacturing and gas flaring.

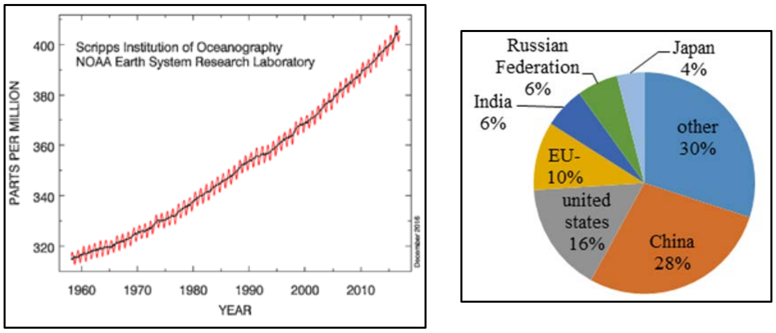


Fig. 1- Monthly average atmospheric CO_2 concentration Nov. 1959 – Nov. 2016 (left) and Global CO_2 emission during 2011(right)

It is worth mentioning that, according to IEA (2010), more than 12 billion tons per year of CO_2 emissions are released into the atmosphere from the fuel combustion of power plants. The electricity production from fossil fuels is predicted to increase by about 30% by 2035. Therefore, there must be genuine measures undertaken to minimize the CO_2 emissions in order to reduce climate change. Similarly, CO_2 emissions should be captured and further utilized or alternatively safely disposed. This study covers the overview of large-scale CCS projects, and then focuses on projects that use CO_2 emitted from power plants in EOR projects. This is due to the fact that CO_2 emissions from power plants are the highest compared to other sources. Raw data was taken from Global CCS Institute website (KAPSARC Data Portal — Large Scale Carbon Capture Projects Database).

Commonly, the amount of CO_2 produced when fuel are burned is function of carbon content of the fuel. Amount of energy produced, when fuel are burned, is mainly determined by carbon and hydrogen content of the fuel. Natural gas has higher energy content relative to other fuels and produces relatively less CO_2. According to a special report on CCS by IPCC (2005), a critical GHG mitigation technology can contribute up to 55% of the cumulative global mitigation effort. In 2013, IEA Global CCS roadmap predicts that CCS contributions to both coal and natural gas must amount to 14% of cumulative CO_2 emissions reductions required through 2050 in order to adequately stabilize atmospheric levels of CO_2. It has been identified that 44 large scale integrated CCS projects are currently presented around the world. Global CCS Institute defined large-scale integrated CCS projects as projects involving capture, transport and storage of CO_2 at a scale of at least 800,000 tons of CO_2 annually for a coal–based power plant, or at least 400,000 tons of CO_2 annually for other emissions–intensive industrial facilities including natural gas–based power generation. Table 1 shows the life cycle stage of those projects along with emission sources and capture capacity. The table illuminates that there are 15 large-scale CCS projects in operation stage, 7 in execute stage, 10 under define, 9 under evaluation, and 3 CCS under identify stage. Combined CO_2 capture capacity of all these 44 projects is around 49.4 million tons per year.

2. Carbon capture and storage (CCS)

CCS involves a portfolio of technologies as described in Fig. 2. The figure shows that there are three stages to CCS; capture, transport, and utilization/safe storage. In capture stage, CO_2 is removed or separated from power plants or from the manufacturers such as steel and cement. In storage stage, CO_2 is compressed and transported to safe and suitable storage sites.

2.1 Emission sources

Anthropogenic CO_2 sources are part of our everyday activities and include those from power plants, public transportation, industrial sources, chemical productions, petroleum productions, and agricultural practices. Many of these source types burn fossil fuels including coal, oil, and natural gas, which are, as mentioned above, the leading cause of CO_2 emissions. A breakdown of the major stationary source emissions, shown in Fig. 3, provides a visual representation of CO_2 emission contributions of the power plants along with other industrial activities have on anthropogenic CO_2 emissions. The largest contributor to these emissions is from electricity (73 %). In fact, electricity generation using carbon base fuels is responsible for a large fraction of CO_2 emission worldwide. Of the fossil fuels, coal is more carbon intensive than oil or natural gas, resulting in general volumes of CO_2 emission per unit of electricity generated. In fact, for every ton of coal burned, approximately 2.5 tons of CO_2 are produced (Derfa, 2014).

Table 1- Large-scale CCS projects

Project location	CCS Projects	Life Cycle stage					Source		Capture Capacity 106t/yr
		Operate	Execute	Define	Evaluate	Identify	Non Power Plant	Power Plant	
Algeria	1	1	-	-	-	-	1	-	1.2*
Australia	3	-	1	-	2	-	3	-	11.5
Brazil	1	1	-	-	-	-	1	-	0.7
Canada	6	3	2	1			5	1	9.2
China	9	-	-	4	2	3	5	4	10.4
Netherlands	1	-	-	1	-	-	-	1	1.1
Norway	2	2	-	-	-	-	2	-	1.6
Saudi Arabia	1	1	-	-		-	1	-	0.8
South Korea	2		-		2		-	2	2
United Arab Emirates	1	-	1	-	-	-	1	-	0.8
United Kingdom	4	-	-	2	2	-	1	3	10.1
United States	13	7	3	2	1	-	9	4	33.3
Total	44	15	7	10	9	3	29	15	49.4

* Carbon Capture and Sequestration Technology (http://sequestration.mit.edu)

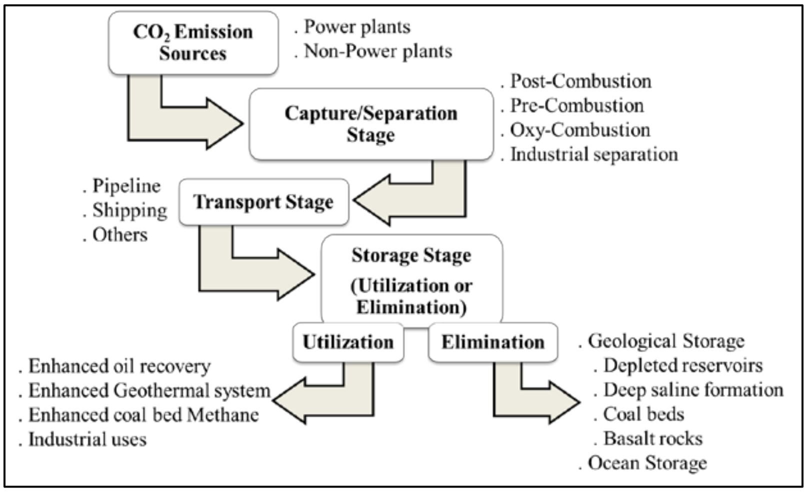


Fig. 2 - CCS technology stages

As a result, in 2011, fossil fuel released 33.2 billion tons of CO_2 emissions worldwide. According to IEA (2012), coal is responsible for 43% of CO_2 emissions; whereas, 36% is produced by oil and 20% from natural gas as explained in Fig. 3. However, Table 1 shows that 15 large-scale CCS projects (34%) out of the total 44 projects have CO_2 sources from power plants; whereas the remaining 29 projects (66%) are from different CO_2 sources. Moreover, 23 out of the 44 projects are CO_2-EOR and only 6 of which are from power plants' CO_2 capture as illustrated in Table 2.

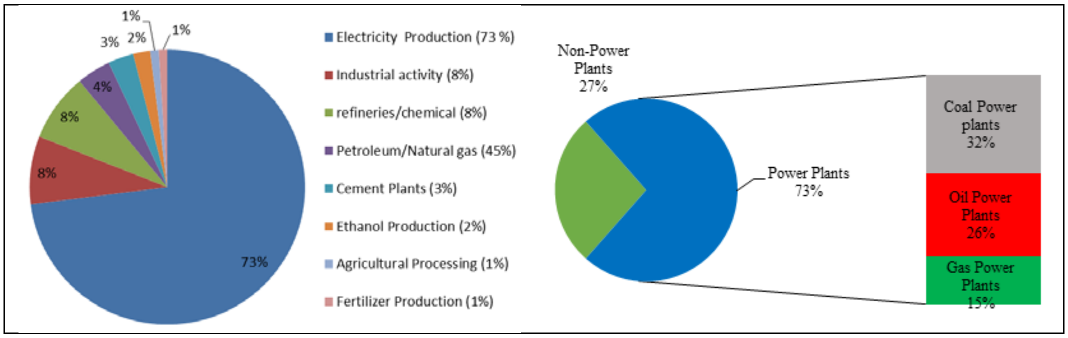


Fig. 3- Stationary anthropogenic CO_2 emissions by major industry

Table 2- Large-scale CO_2-EOR projects

Project Location	CO_2-EOR	Life Cycle stage					CO_2-EOR Projects		
		Operate	Execute	Define	Evaluate	Identify	Non-Power Plant	Power Plant	Capture Capacity 10^6t/yr
Brazil	1	1	-	-	-	-	1	-	0.7
Canada	4	2	2	-	-	-	3	1	6
China	5	-	-	4	1	-	3	2	6
Saudi Arabia	1	1	-	-	-	-	1	-	0.8
United Arab Emirates	1		1	-	-	-	1	-	0.8
United States	11	7	2	1	1	-	8	3	0.29
Total	23	11	5	5	2	-	17	6	14.59

2.2 Capture and separation stage

Several studies addressed CO_2 capture and separation technologies. Among them; Yx et al. (2012); Yang et al. (2008); Blomen et al. (2009); Olajire (2010); Elwell and Grant (2006); and Buhre el al. (2005). It can be implemented to isolate CO_2 for power plants and non-power plants, such as absorption, adsorption, chemical looping combustion, membrane separation, hydrate-based separation and cryogenics desalination. However, in power plants there are three main technology options to capture CO_2 namely; post-combustion, pre-combustion, and oxy combustion as explained in Fig. 4. However, according to the large-scale CCS database, pre-combustion technology is the most mature process for CO_2 capture. It has been identified that 23 (52%) pre-combustion large scale CCS projects are currently presented in different life cycles. The second place occupied by industrial separation technology with 11 projects (25%) as illustrated in Fig. 5.

2.3 Transport and storage (utilization or elimination) stage

Once CO_2 is captured, it needs to be transported to the facilities for its utilization (industrial or CO_2-EOR projects) or disposed in a suitable storage site. Whatever option is chosen, transport system should be safe and economically feasible. Pipelines, trains, ships and trucks are used to deliver CO_2 for pilots and smaller-scale operations. Leung et al. (2014) pointed out that best option for CO_2 transportation depends on variety of parameters including; (1) CO_2 volumes to be transported; (2) planned life time of CO_2 source (power plants or non-power plants); (3) distance between CO_2 source and storage area; (4) onshore vs. offshore; and (5) typology of transporting infrastructure available. Fig. 6 shows the transporting system of most of large-scale CCS projects; 91% is pipelining. Only two projects (Sleipner CO_2 Storage Project in Norway and Petrobras Lula Oil Field CCS Project in Brazil) do not require transporting captured CO_2 since it is injected underground in place. Storage stage procedure is described in Fig. 7.

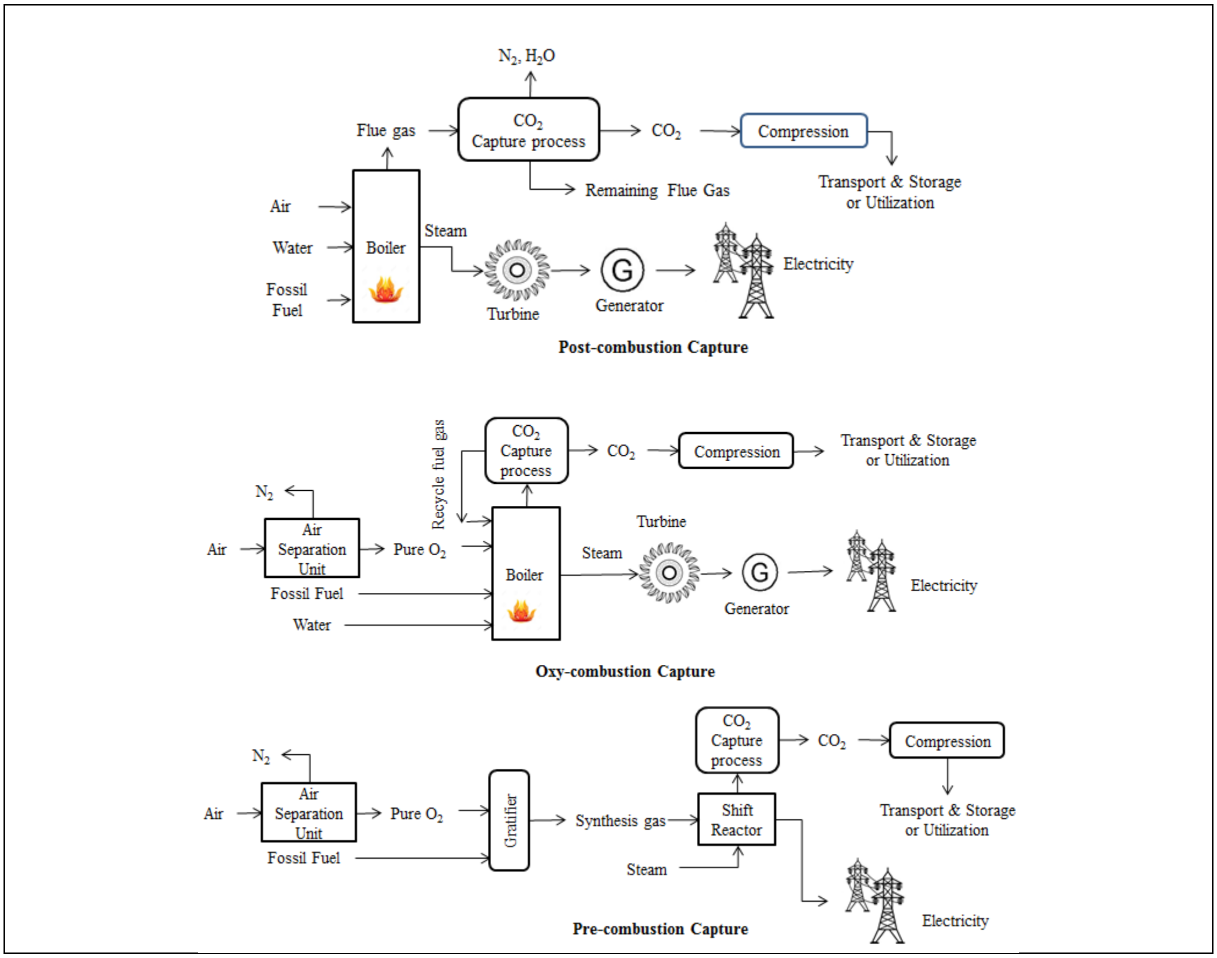


Fig. 4- Power plants CO_2 capture technologies

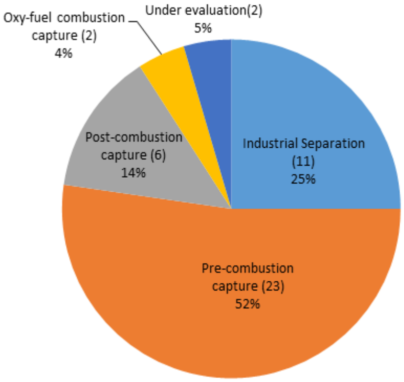


Fig. 5- Capture technology of large-scale CO_2

2.3.1 CO_2 utilization

Researchers are considering a range of options for captured CO_2 utilization in oil and gas industry or as a raw material in different industrial processes. However, industrial uses of CO_2 include chemical and biological processes where CO_2 is a reactant, such as in urea and methanol production, as well as in various technological applications e.g. in horticulture industry, food packaging, welding, beverages and fire extinguishers. Typical lifetime of CO_2 storage by industrial processes is only few days to months and do not contribute meaningfully to climate change mitigation. Furthermore, total industrial use of CO_2 is trivial compared to anthropogenic CO_2 emissions.

Table 4- CO_2 capture technology for large scale ccs projects

Project Location	CCS Projects	Power Plants Capture –Technology				Non-Power Plants Capture –Technology				
		Post-Combustion	Pre-combustion	Oxy-Combustion	Under Evaluation	Post-Combustion	Pre-combustion	Oxy-Combustion	Industrial separation	Under Evaluation
Algeria	1	1								
Australia	3						1		1	1
Brazil	1						1			
Canada	6	1					2		3	
China	9	2	1	1			4		1	
Netherlands	1	1								
Norway	2						2			
Saudi Arabia	1						1			
South Korea	2	1			1					
United Arab Emirates	1								1	
United Kingdom	4		2	1						
United States	13	1	3				5		4	
Total	44	7	6	2			16		10	1

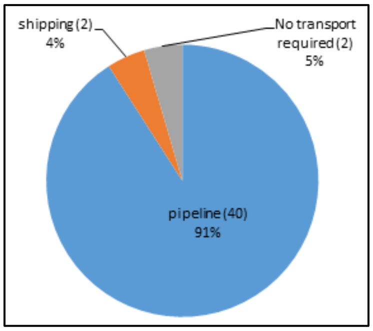


Fig 6 - Transportation system in large-scale CO_2 projects

CO_2-EOR has emerged as a major option for productively utilizing CO_2 emissions captured from electric power and other industrial plants. Typically, only about one-third of original oil in place is recovered from a conventional oil field with traditional primary and secondary methods. In most cases, CO_2 is compressed and pumped to oil reservoirs to recover a significant portion of this “left behind” oil in a process known as enhanced oil recovery (EOR) as described in Fig. 8a.

Likewise, coal beds that are too deep or too thin to be economically mined for coal represent potential CO_2 storage sites. Since these formations typically contain a certain amount of methane (CH_4), CO_2 can be used for the recovery of CH_4 gas, known as enhanced coal bed methane (ECBM) recovery. It is a method of producing additional coal bed CH_4 from a source rock, which is similar to CO_2-EOR applied to oil fields. CO_2 is injected into a coal bed that would occupy porous space and would also adsorb in coal at almost twice the rate of CH_4, allowing potential for enhanced gas recovery. This process is further clarified in Fig. 8b. Due to higher absorptivity of CO_2 with respect to CH_4, CO_2 stays in the coal beds and displaces the adsorbed methane. Ultimately, most of CH_4 is recovered and the coal bed contains mainly CO_2 which remains there permanently separated from the atmosphere.

Geothermal energy offers clean, consistent and reliable power without the need for grid-scale energy storage, unlike most renewable energy alternatives (Randolph and Saar, 2011). A geothermal heat pump can extract enough heat from shallow rocks anywhere in the world to provide heat, but industrial applications need higher temperatures of deep resources (Lund, 2007). The techniques have some shortcomings such as low heat extraction, precipitation and dissolution of rock minerals, large power requirements for water circulation, and water scarcity in some regions (Pruess, 2010). Brown (2000) proposed to operate EGS with CO_2 instead of water as heat transmission fluid. He pointed out that CO_2 has attractive properties as an operating fluid for EGS. This process is further illuminated in Fig. 8c.

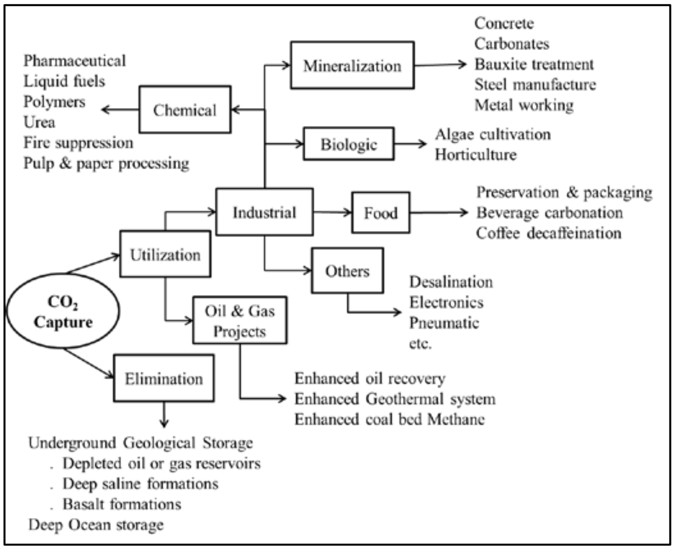


Fig. 7 – CO_2 storage (utilization or elimination stage) stage

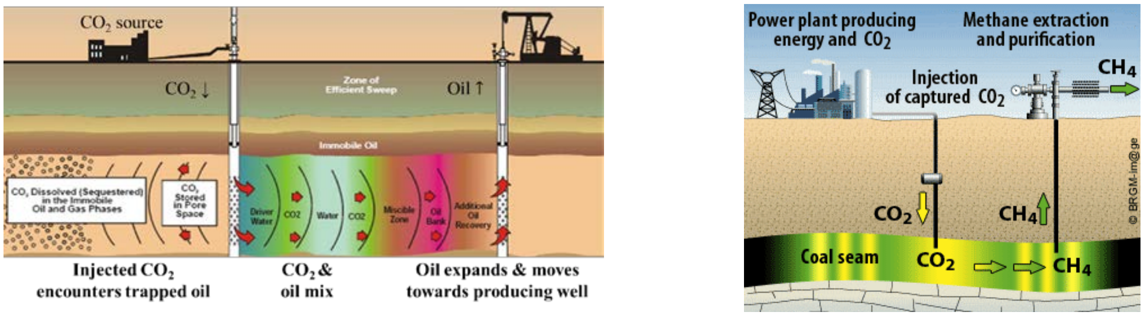
2.3.2 CO_2 elimination

Researchers are considering a range of options for CO_2 exclusion, but mainly focus on underground geological storage (Gunter et al., 2004; Hepple and Benson, 2005; Benson and Surles, 2006; Marini, 2007). Depleted oil or gas reservoirs, deep saline formations, and unmineable coal seams are relatively well-known geological formations that can provide safe storage of CO_2. In any of the above sequestration scenarios, CO_2 is trapped by impermeable rocks known as cap rock. Moreover, in order to start a CCS project, one of the main priorities is to define and estimate the site's CO_2 storage capacity. Methods of estimating CO_2 storage capacity have been extensively studied and discussed (DOE, 2007; CSLF, 2008; Burruss et al., 2009; Brennan et al., 2010; Jin et al., 2012; IEA, 2013; Blondes et al., 2013).

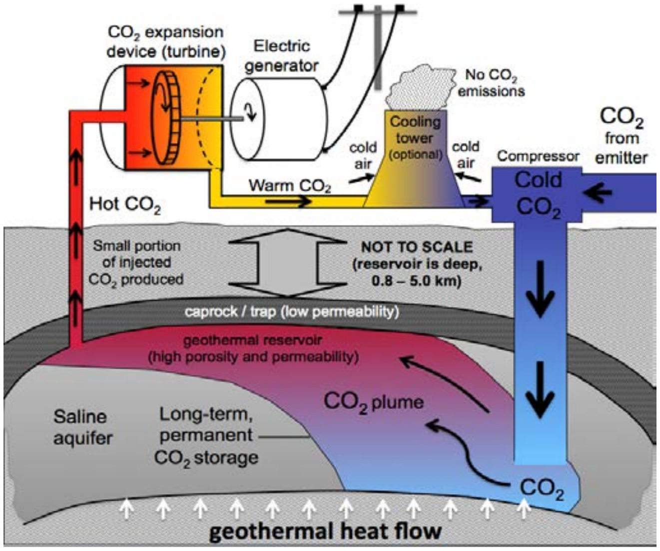
Other options of CO_2 disposal include deep underground salt water formations as they are brine-saturated layers of porous rock. Similarly, basaltic rocks have the potential to store large volumes of CO_2 (Goldberg et al., 2008; Kelemen and Matter; 2008; and Andreani et al., 2009). Basaltic rocks are composed of up to 25% calcium, magnesium and iron and are also common, covering up to 10% of the Earth’s surface as well as significant areas of the ocean floor. This technology is currently under investigation.

Ocean storage is likewise considered as an option for CO_2 disposal. It could be done by injecting CO_2 into the water column, where CO_2 is denser than water which delays its dissolution into the surrounding environment. However, ocean storage and its ecological impacts are still under investigation.

According to the database of large-scale CCS projects 52% (23 project) captured CO_2 is stored into geological strata while 41% (18 project) captured CO_2 is utilized in EOR as shown in Fig. 9.



(a) CO$_2$-EOR project (b) ECBM project



(c)

Fig. 8 – CO$_2$ utilization in oil and gas projects

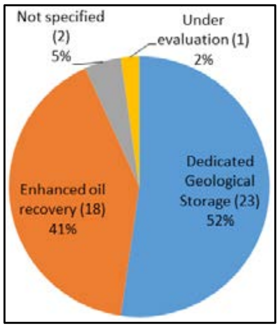


Fig. 9 - Large-scale CO$_2$ storage technology

3. Current CO$_2$-EOR large-scale projects

The database of the large-scale CCS projects shows that there are only 6 CO$_2$-EOR large-scale projects that obtain their CO$_2$ from power plants. The projects are briefly described below.

3.1 Boundary Dam carbon capture and storage project

Boundary Dam Power Station is the largest coal fired station owned by SaskPower, located near Estevan, Saskatchewan, Canada. SaskPower operates eighteen electricity generating facilities that include three coal-fired base load facilities, 6 natural gas-fired facilities, seven hydroelectric facilities and two wind power facilities. Despite that, SaskPower suffered some start-up problems, the CO_2 capture facility currently delivers CO_2 through Cenovus Energy via a separate pipeline of 66 km to Weyburn oil field for EOR purposes (Brown, et al., 2016). Boundary Dam power station entered into operation in October 2014; it captures CO_2 from a retrofitted coal-fired power station. It was announced to capture one million tons of CO_2 per year, but in its first year of operation the CO_2 captured was around 400,000 tons, falling short of the announced design capacity of one million tons per year. The project currently captures 2200 to 3000 tons per day (Brown, et al., 2016, D'Aprile, 2016). SaskPower keeps exact figures private to the paid sponsors of the Weyburn-Midale Project (SaskPower, 2017).

Initial CO_2 injection rates in the Weyburn field amounted to approximately 5,000 tons/day or 95 million scf/day (2.7 million m3/d); this would otherwise have been vented to the atmosphere from the Dakota Gasification facility. Current CO_2 injection by Cenovus at Weyburn is up to 6500 tons per day. Apache Canada is injecting approximately 1500 tons per day into the Midale field.

The impact of injecting CO_2, as an EOR method, into Weyburn oil field is significant in terms of increased oil production. CO_2 injection currently accounts for 5,000 oil barrels of the 20,000 barrels per day total production at Weyburn oil filed. Moreover, it is estimated that CO_2 will directly lead to an increase in the recovery factor by 10% (an additional 130 million oil barrels) of stock tank original oil in place and prolong the life of the field by 25 years (Verdon, 2012).

3.2 Huaneng GreenGen IGCC project (Phase 3)

The third phase of the program involves construction and operation of a 400 MW IGCC power plant with associated carbon capture facilities capable of capturing up to two million tons of CO_2 per year. It is anticipated that carbon capture at the 400 MW power plants may begin around the 2020 timeframe. Storage locations are presently under evaluation and include EOR opportunities and geologic storage options.

3.3 Sinopec Shengli power plant CCS project

The Shengli oil field is the second largest oil field in China producing around 200 million barrels of annually. The capture facility of its Power Plant CCS project is designed to use an amine-based absorption technology to capture up to 80% or more of CO_2 from a 200 MW flue gas slipstream of the 600 MW coal-fired generating unit. The CO_2 capture facilities are expected to begin operation after 2020. A typical post-combustion CO_2 capture process is implemented for the project including flue gas desulfurization (FGD) and De-NOx units. After FGD and De-NOx, CO_2 is captured by an MEA-based chemical absorption process and high purity CO_2 is produced. The produced CO_2 is then compressed and delivered by pipelines to the Shengli oil field for EOR purposes.

3.4 Petra Nova carbon capture project

Petra Nova is the world's largest post-combustion CO_2 capture system facility in operation which uses an advanced amine-based absorption technology to capture at least 90% or 1.4 Million tons per year of CO_2 from a 240 MW flue gas slipstream of the 610 MW pulverized coal-fired generating unit. The captured CO_2, pure up to 99% or more, is transported by 82-mile long, 12-inch diameter underground pipeline to the West Ranch oil field and injected through nine injection wells for EOR purposes.

3.5 Kemper County energy facility

This Integrated Gasification Combined Cycle (IGCC) plant is supplied by lignite coal and consists of two major systems: lignite gasification including CO_2 capture and combined-cycle power generation. The gasification systems consist primarily of lignite handling, gasification and synthesis gas (syngas) processing and clean-up. A key element of the gasification system is two commercial-scale gasifiers that are able to convert up to 4.5 million tons per year of lignite to produce syngas. The facility also includes a carbon capture system using a physical solvent-process sufficient to reduce CO_2 emissions up to 65% by removing carbon from the syngas during the gasification process. This is equivalent to the capture of around 3 million tons per year of CO_2. It is then pumped from the plant through 61-mile pipeline to be injected in the Jackson Dome for EOR purposes. The facility is expected to be full operational in mid-March 2017 (Mississippi Power, 2017).

3.6 Texas clean energy project (TCEP)

The TCEP is a poly-generation facility incorporating electricity generation, fertilizer manufacture and CO_2 capture of approximately 3.1 million tons per year. Feedstock for the plant is sub-bituminous coal and at full capacity, the plant is expected to use approximately 1 million tons of coal per year. TCEP's integrated gasification combined cycle (IGCC) generating plant with carbon capture technology and its integrated fertilizer manufacturing plant are able to convert the coal feedstock into a hydrogen-rich synthesis gas (syngas). The syngas is further processed and 'cleaned' by an acid gas removal (AGR) system that separates CO_2 from the entire syngas stream. The AGR system also captures sulphur-containing gases for conversion to a sulphuric acid product. Furthermore, after the separation of CO_2, the clean hydrogen-rich syngas is used to generate electricity from the gas combustion and steam turbines and as a feedstock in fertilizer manufacture. Around one-half of this clean hydrogen-rich syngas is used to fuel the combustion turbines, the other half would be used in the ammonia/urea complex. The separated or captured CO_2 stream is partly used in ammonia/urea production with the majority going to EOR operations.

4. Summary

The global CO_2 concentration in the atmosphere in November 2016 passed 403 ppm. In 2011, the top CO_2 emissions from fossil fuel combustion, cement manufacturing and gas flaring were 28% from China, 16% from the United States, 10% from the European Union, 6% from India, 6% from the Russian Federation, 4% from Japan and 30% from other countries. Additionally, more than 12 billion tons per year of CO_2 emissions are released into the atmosphere from fuel combustion of power plants. The electricity production from fossil fuels is predicted to increase by about 30% by 2035. Nonetheless, according to IEA, coal is responsible for 44% of CO_2 emissions; whereas 36% is produced by oil and 20% from natural gas. Consequently, there must be genuine measures undertaken to minimize CO_2 emissions in order to reduce climate change. CO_2 capture is one key to reducing risks of climate change. At the same time, CO_2 emissions should be captured and further utilized or alternatively safely disposed. It has been identified that 44 large-scale integrated CCS projects are currently operational/developed around the world at different life cycles. Out of the 44 projects, 15 large-scale integrated CCS projects have CO_2 sources from power plants; whereas the remaining 29 projects are from different CO_2 sources. Moreover, 23 out of the 44 projects are CO_2-EOR and only 6 of which are from power plants' CO_2 capture.

CCS technologies involve three stages: (1) *Capture stage*: the CO_2 is removed or separated from power plants, or from manufacturers such as steel and cement. However, three are there main technology options to capture CO_2 in power plants namely; post-combustion, pre-combustion, and oxy combustion. According to the large-scale CCS database, the pre-combustion technology is the most mature process for CO_2 capture. It has been identified that 23 pre-combustion large scale integrated CCS projects are currently presented in different life cycles. The second place occupied by industrial separation technology with 11 projects. (2) *Transport stage*: Once CO_2 is captured, it needs to be transported to the facilities for its utilization (industrial or CO_2-EOR projects) or disposed in a suitable storage site. The transporting system of most of the large-scale integrated CCS projects is pipelining. Only two projects do not require transporting captured CO_2 since it is injected underground in place. (3) *Utilization or safe storage stage*: several options are considered for CO_2 utilization in oil and gas industry or as raw material in different industrial processes. However, significant research and industrial experience in recent decades provide great confidence that underground storage of CO_2 is feasible and safe especially with EOR. CO_2 is compressed and pumped to oil reservoirs to recover a significant portion of oil that is left behind after exhaustion of primary and secondary oil production systems. Furthermore, researchers are considering a range of options for CO_2 exclusion. Depleted oil or gas reservoirs, deep saline formations, and unmineable coal beds are relatively well-known geological formations that can provide safe storage of CO_2. Moreover, selling CO_2 for EOR provides revenue to help offset costs of CO_2 capture. The cost gap could be covered through power price premiums and such.

According to the database of the large-scale CCS projects, there are 23 projects that store captured CO_2 into geological strata. Other 18 projects utilize captured CO_2 in EOR. Furthermore, the database shows that there are only 6 CO_2-EOR large-scale integrated projects that obtain their CO_2 from power plants (Boundary Dam carbon capture and storage project, Huaneng GreenGen IGCC project, Sinopec Shengli power plant CCS project, Petra Nova carbon capture project, Kemper County energy facility and Texas clean energy project).

5. References

Andreani, M., Luquot, L., Gouze, P., Godard, M., Hoise, E. & Gibert, B. (2009). Experimental study of carbon sequestration reactions controlled by the percolation of CO_2-rich brine through peridotites. Environ. Sci. Technol. 43(4), 1226-1231

Benson, S. M. & Surles, T. (2006). Carbon dioxide capture and storage: An overview with emphasis on capture and storage in deep geological formations. *Proc. IEEE* 94(10), 1795-1805

Blomen E, Hendrils C, Neele F. (2009) Capture technologies: Improvements and promising developments. Energy procedia; 1: 1550-12

Blondes, M.S., Brennan, S.T., Merrill, M.D., Buursink, M.L., Warwick, P.D., Cahan,S.M., Cook, T.A., Corum, M.D., Craddock, W.H., DeVera, C.A., Drake, R.M., DrewII., L.J, Freeman, P.A., Lohr, C.D., Olea, R.A., Roberts-Ashby, T.L., Slucher, E.R.,Varela, B.A., (2013). U.S. Geological Survey Open-File Report 2013-1055 2013. National assessment of geologic carbon dioxide storage resources – methodology implementation

Boden, T.A., Marland, G., and Andres, R.J. (2015). National CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2011,

Brennan, S.T., Burruss, R.C., Merrill, M.D., Freeman, P.A., Ruppert, L.F., (2010). U.S. Geological Survey Report Series, Report 2010-1127 2010. A probabilistic assessment methodology for the evaluation of geologic carbon dioxide storage

Brown, D.W. (2000). A Hot Dry Rock Geothermal Energy Concept Utilizing Supercritical CO_2 Instead of Water, Proceedings, Twenty-Fifth Workshop on Geothermal Reservoir Engineering, pp. 233–238, Stanford University Gunter, W. D., Bachu, S. & Benson, S. M. (2004). The role of hydrogeological and geochemical trapping in sedimentary basins for secure geological storage for carbon dioxide. In: *Geological Storage of Carbon Dioxide: Technology*, S. Baines and R. H. Worden, eds., London, U.K. Geological Society, Special Pub. 233

Brown, K. et al., (2016) The history and development of the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project in Saskatchewan, Canada (the world largest CO_2 for EOR and CCS program), Petroleum, http://dx.doi.org/ 10.1016/j.petlm.2016.12.002

Buhre BJP, Elliott LK, Sheng CD, Gupta RP, Wall TF. (2005). Oxy-fuel combustion technology for coal-fired power generation. Prog Energy Combust Sci; 31: 283–307.

Burruss, R.C., Brennan, S.T., Freeman, P.A., Merrill, M.D., Ruppert, L.F., Becker, M.F.,Herkelrath, W.N., Kharaka, Y.K., Neuzil, C.E., Swanson, S.M., Cook, T.A., Klett,T.R., Nelson, P.H., Schenk, C.J., (2009) U.S. Geological Survey Open-File Report 2009-1035 2009. Development of a probabilistic assessment methodology for evaluation of carbon dioxide storage.

Carbon Capture & Sequestration Technologies http://sequestration.mit.edu

Carbon Sequestration Leadership Forum (CSLF), (2008) Phase III Report. Comparison between methodologies recommended for estimation of CO_2 storage capacity in geological media.

D'Aprile, Aurora, (2016). Advances and Slowdowns in Carbon Capture and Storage Technology Development (April 27, 2016). FEEM Working Paper No. 33.2016. Available at SSRN: https://ssrn.com/abstract=2771044

Defra,U.K.(2014) The 2014 Government Greenhouse Gas Conversion Factors for Company Reporting. London: U.K. Department for Environment, Food & Rural Affairs

Department of Energy (DOE), 2007. Carbon Sequestration Technology Road map and Program Plan. National Energy Technology Laboratory Office of Fossil Energy.

Elwell L C, Grant W S. (2006) Technology options for capturing CO_2 – special reports. Power; 150: 60–5

Global Carbon Emissions, (2017) www.co2.earth/global-co2 -emissions

Goldberg DS, Takahashi T, Slagle AL. (2008). Carbon dioxide sequestration in deep-sea basalt. Proc. Nat. Acad. Sci. 105(29); 9920-9925

Hepple, R. P. & Benson, S. M. (2005). Geologic storage of carbon dioxide as a climate change mitigation strategy: performance requirements and the implications of surface seepage. *Environ. Geol.* 47, 576-585

IEA (International Energy Agency), (2013). Methods to Assess Geologic CO_2 Storage Capacity: Status and Best Practice. International Energy Agency Workshop Report

IEA, (2013). Technology Roadmap, Carbon capture and storage. 2013 edition

International Energy Agency, IEA (2012) CO_2 Emissions from Fuel Combustion. Paris: Organization for Economic Co-operation and Development, 2012.

International Energy Agency, IEA, (2010) World energy outlook. OECD/IEA

IPCC (2000). Special report on emissions scenarios: a special report of working group III of the Intergovernmental Panel on Climate Change, , 92-9169-1135Cambridge University Press, New York

IPCC (2005). Special Report on Carbon Capture and Storage. Available from Cambridge University Press, The Edinburgh Building Shaftesbury Road, Cambridge CB2 2RU ENGLAND

Jin, M., Pickup, G., Mackay, E., Todd, A., Sohrabi, M., Monaghan, A., Naylor, M., (2012). Static and dynamic estimates of CO_2 storage capacity in two saline formations in the UK. SPE J. 17, 1108–1118.

Kelemen PB, Matter JM. (2008). In situ carbonation of peridotite for CO_2 storage. PNAS; 105(45): 1795-17300. http://www.pnas.org/content/105/45/17295.full.pdf

Leung, Dennis Y.C., Caramanna, G. and Maroto-Valer, MM. (2014) An overview of current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews 39 426-443]

Lund, John W. (2007), Characteristics, Development and utilization of geothermal resources, Geo-Heat Centre Quarterly Bulletin, Klamath Falls, Oregon: Oregon Institute of Technology, 28 (2), pp. 1–9

Lv YX, Xu CQ, Yan GH, Guo DY, Xiao Q. (2012) A review on CO_2 capture using membrane gas absorption technology. Adv Mater Res: 616–618:1541–5.

Marini, L. (2007). Geological Sequestration of Carbon Dioxide: Thermodynamics, Kinetics, and Reaction Path Modeling. Vol. 11, Developments in Geochemistry. Elsevier, Amsterdam, 453 p.

Mississippi Power, (2017) http://mississippipowernews.com/2017/02/22/mississippi-power-issues-statement-regarding-kemper-county-energy-facility-progress-and-schedule-2/

Monthly average atmospheric CO_2 concentration) (www.co2.earth)

National Energy Technology Laboratory (NETL), www.netl.doe.gov

Olajire Abass (2010). CO_2 capture and separation technologies for end-of-pipe application – a review. Energy; 35: 2610 – 28.

Parsons, W. (2009) Strategic Analysis of the Global Status of Carbon Capture and Storage. Global CCS Institute

Pruess, K. (2010). Enhanced geothermal systems (EGS) with CO_2 as heat transmission fluid--A scheme for combining recovery of renewable energy with geologic storage of CO_2

Quéré, C Le et al, (2012). The global carbon budget 1959–2011. Earth System Science Data Discussions 5, no. 2, 1107-1157

Randolph, J., and Saar, M. (2011). Coupling carbon dioxide sequestration with geothermal energy capture in naturally permeable, porous geologic formations: Implications for CO_2 sequestration. Energy Procedia, 4, 2206-2213

SaskPower, (2017) http://www.saskpower.com/our-power-future/carbon-capture-and-storage/carbon-storage-research-centre

Verdon, J. P., (2012) Microseismic Monitoring and Geomechanical Modelling of CO_2 Storage in Subsurface Reservoirs, Springer Theses, Chapter 2 The Weyburn Project CO_2 Injection, DOI: 10.1007/978-3-642-25388-1_2, Springer-Verlag Berlin Heidelberg

Yang H.Q., Xu Z, Gupta R, Slimane RB, Bland AE, Wright I. (2008) Progress in carbon dioxide separation and capture: a review. J Environ Sci; 20: 14–27

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