2012-2015 Triennium Work Reports

Overview of Carbon Capture and Storage (CCS) Development towards a Sustainable Gas Industry

International Gas Union
Programme Committee A (Sustainability)
Study Group 1 (CCS study group)

June 2015

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Executive Summary:

The world requires secure, reliable, and affordable energy supplies to sustain economic growth. The fossil fuels are expected to continue to play a significant role in supplying the needs of future global energy. In the meantime, carbon dioxide emissions associated with fossil fuels are thought to be the main cause of global warming. There is an increasingly urgent need to mitigate greenhouse gas emissions, including those related to energy production and consumption.

Carbon Capture and Storage (CCS) is one of the most viable technologies currently available to mitigate GHG emissions from large-scale fossil fuel usage. CCS involves the capture, transport, and injection of CO_2 into suitable geological formations. The injected CO_2 is monitored to verify its storage.

Although CCS from coal has generally received most attention, the use of CCS with gas can enhance natural gas' advantage of the low carbon emissions. This report studies the various merits and synergies of CCS on gas and examines how CCS can be applicable and advantageous to gas industries.

Produced by:
International Gas Union

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Table of Contents

Acknowledgement

This report was prepared by Study Group 1 (Carbon Capture and Storage) in International Gas Union's (IGU) Programme Committee A (Sustainability). IGU's first CCS report "The role of Carbon Capture and Storage (CCS) in a Sustainable Gas Industry" was published in World Gas Conference 2012 at Kuala Lumpur in June 2012. This report is the second CCS report by IGU and is the culmination of intensive discussion among the following Study Group 1 members during 2012 and 2015.

The following IGU members authored this report:

Ichiro Fukuda (Tokyo Gas, Japan)
Gro Jofrid Trovåg Amundsen (Statoil, Norway)
Dominique Copin (TOTAL, France)
Nor Hazleen Madros (Petronas, Malaysia)
Thirupathi Rao AL Narayanamoorthy (Petronas, Malaysia)
Mohamed Djeouna (Sonatrach, Algeria)
Nonglak Pinitniyom (PTT, Thailand)
Gharaghooshi Ahmad Zamani (NIGC, Iran)

1. Introduction

The world requires secure, reliable, and affordable energy supplies to sustain economic growth. Fossil fuels are expected to continue to play a significant role in meeting future global energy needs. In the meantime, the emission of carbon dioxide (CO_2) associated with fossil fuels is thought to be the main cause of global warming. There is an increasingly urgent need to mitigate greenhouse gas (GHG) emissions, including those related to energy production and consumption. According to the International Energy Agency's (IEA) World Energy Outlook 2014, coal was the largest source of CO_2 emissions (13.9 billion metric tons) in 2012, followed by oil (11.2 billion metric tons) and natural gas (6.5 billion metric tons). It is expected that global CO_2 emissions from the combustion of natural gas will increase by 55.2% from 2012 to 2040, while those from coal and oil will increase by 11.5% and 11.2% respectively during the same period.

Carbon (or CO_2) capture and storage (CCS) is one of the most viable technologies currently available to mitigate GHG emissions from large-scale fossil fuel usage. CCS involves the capture, transport, and injection of CO_2 into suitable geological formations. The injected CO_2 is monitored to verify long-term containment.

The world needs to target close-to-zero CO_2 emission rates within this century. To achieve that target, CCS will play a significant role in mitigating global warming while sustaining global economic growth. The IEA's Energy Technology Perspective 2014 indicates that CCS will account for 14% of the reduction in emissions that is necessary to limit predicted temperature increase to less than 2 degrees Celsius by 2050. The successful deployment of CCS will allow countries to continue using fossil fuels and its associated massive infrastructure while simultaneously achieving major GHG emissions reductions.

However, the development of CCS has been slower than anticipated in IGU's previous CCS report published in June 2012. The main challenges for the expansion of CCS are classified as:

- lack of commercial incentives
- the high cost of implementing CCS
- difficulty of public acceptance of CCS
- underdeveloped legal and regulatory framework

Although CCS from gas-fired power generation has generally received less attention than its use with coal-fired power generation, the application of CCS to natural gas can enhance natural gas' advantage of low-carbon emissions. This report studies the various merits and synergies of CCS from gas and examines how CCS can be applicable and advantageous to the gas sector by highlighting the lessons learnt and recommendations from other literature reviews, in particular those on legal and social acceptance issues. The report starts with an executive summary and introduction. Chapter 2 discusses why CCS is important for a sustainable gas industry by summarizing IGU's previous CCS report. Chapter 3 presents CCS projects currently planned, under construction, and in operation, and analyzes the trend of current and future CCS projects. Chapter 4 provides an overview of the CCS legal and regulatory framework worldwide and presents a case study of Malaysia. Chapter 5 examines four case studies that provide lessons in success or failure in securing public acceptance. Chapter 6 discusses perspectives on CO_2 utilization. Chapter 7 concludes this report by summarizing the challenges and requirements of CCS for sustainable development of the gas industry.

2. Why is CCS important for a sustainable gas industry?

Natural gas is a clean and abundant energy source, and its CO_2 emission during combustion is the lowest of all the fossil fuels. However, natural gas systems still discharge CO_2 and are potentially required to further reduce such emissions as part of the possible low-carbon society of the future.

According to scenario analyses presented in Energy Technology Perspective 2014 by IEA, CCS is expected to play a major role in various measures against global warming, accounting for 14% CO_2 reduction in 2050 to limit the expected temperature increase to less than 2 degrees Celsius (see Figure 2.1).

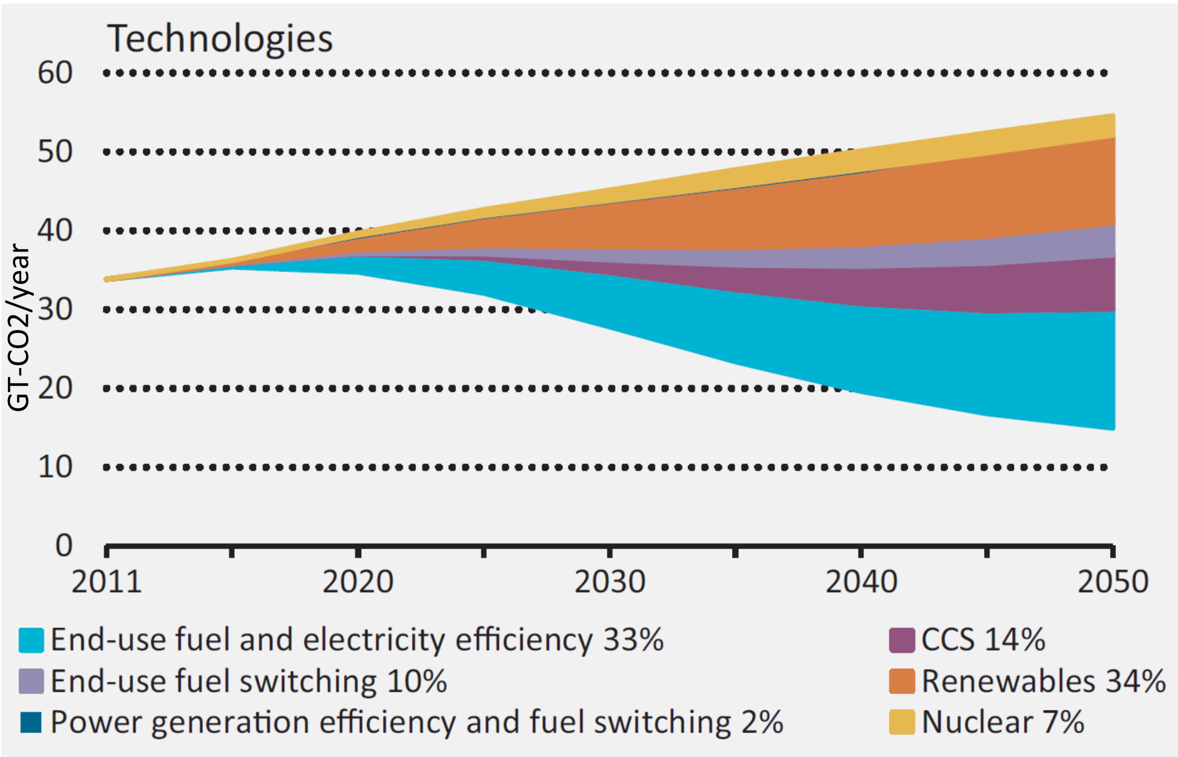


Figure 2.1 Contribution of various measures to annual emission reduction
(Source: IEA, Energy Technology Perspective 2014)

CCS is a technology that enables the capture of CO_2 emitted during the extraction of natural gas from reservoirs, industrial processes, or by combustion. Although most attention has been given to the use of CCS with coal-fired generation, the application of CCS to gas-fired power generation can enhance natural gas' advantage of having the lowest carbon emissions of all the fossil fuels. As coal-fired generation is more CO_2-intensive per MWh than gas, the emissions avoided are larger for the application of CCS to coal-fired generation. It costs less to capture and store a ton of CO_2 from coal-fired generation than from gas-fired generation, as CO_2 concentrations are four to five times higher in the flue gas from a coal-fired plant than from a combined cycle gas turbine (CCGT), which means that the capture system for a CCGT needs to process more flue gas to capture each ton of CO_2. Thus, the cost of avoiding the emission of each ton of CO_2 is lower for a coal-fired plant. However, the primary determinant of investment decisions in electricity generation capacity is the cost of electricity, not the cost of CO_2 avoided. This depends not only on how much it costs to capture and store each ton of CO_2, but also how many tons need to be captured per MWh. From this viewpoint, gas-fired generation with CCS can be more competitive than the coal-fired equivalent if certain conditions of fuel and CO_2 prices are met (see Figure 2.2) (IEA, Energy Technology Perspective 2014).

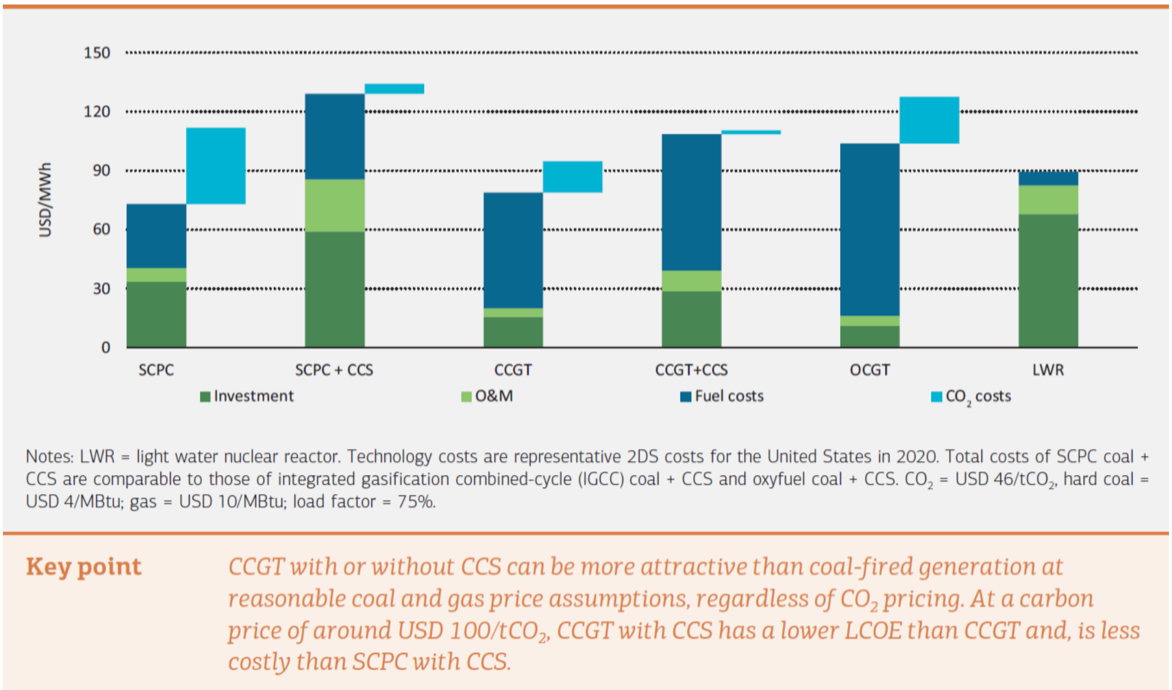


Figure 2.2 Levelized cost of electricity of dispatched power generation technologies in the IEA's 2DS scenario in 2020 (Source: IEA, 2014)

Furthermore, CCS can expand business opportunities within the gas industry by creating new value. Natural gas can help the formation of a low-carbon energy portfolio by working with other energy sources. Figure 2.3 below illustrates the three roles and interactions of CCS for a natural gas supply system (IGU, 2012).

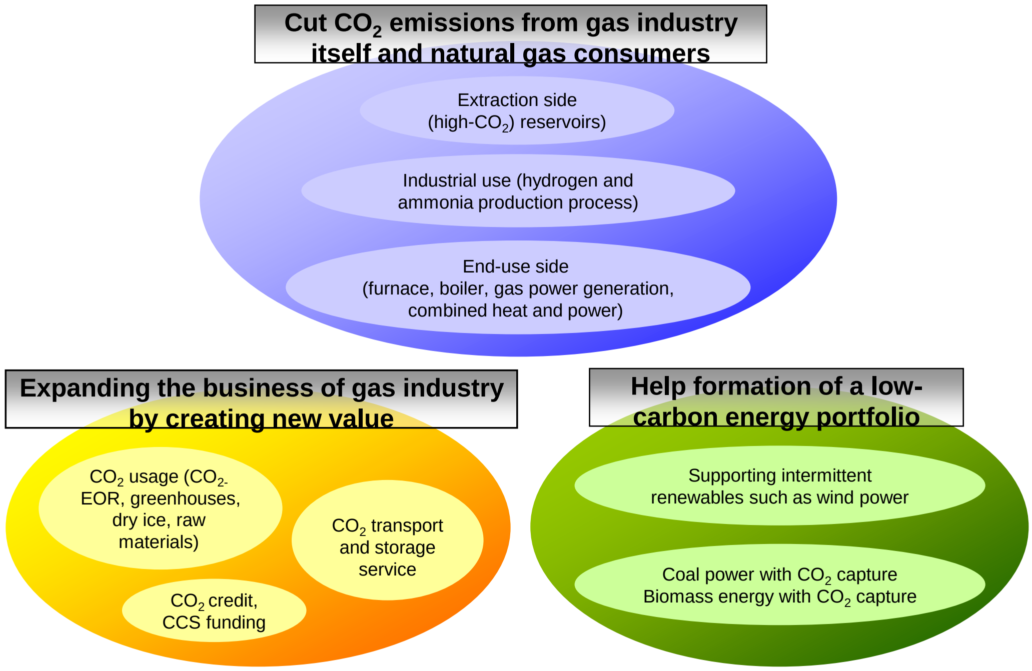


Figure 2.3 Three roles of CCS system for a natural gas supply system

2.1 Cut CO_2 emissions from the gas industry itself and natural gas consumers

Natural gas is extracted from natural gas reservoirs, transported by pipeline or in the form of liquefied natural gas (LNG), and finally consumed by end-users. The extraction of natural gas is accompanied by the emission of CO_2 gas. The recent rise in global energy demand has increased the importance of developing gas fields with higher CO_2 content.

Meanwhile, CO_2 is emitted at the end-user site when natural gas reacts with oxygen, which typically occurs as a form of air combustion. CO_2 is also released in the course of transportation or liquefaction; the pipeline transportation requires energy for compression and liquefaction of natural gas, and LNG transportation also requires energy. However, the amount of CO_2 emitted from transportation is considerably less than that generated by natural gas extraction and combustion. Figure 2.4 shows a schematic of the CCS system for a natural gas system.

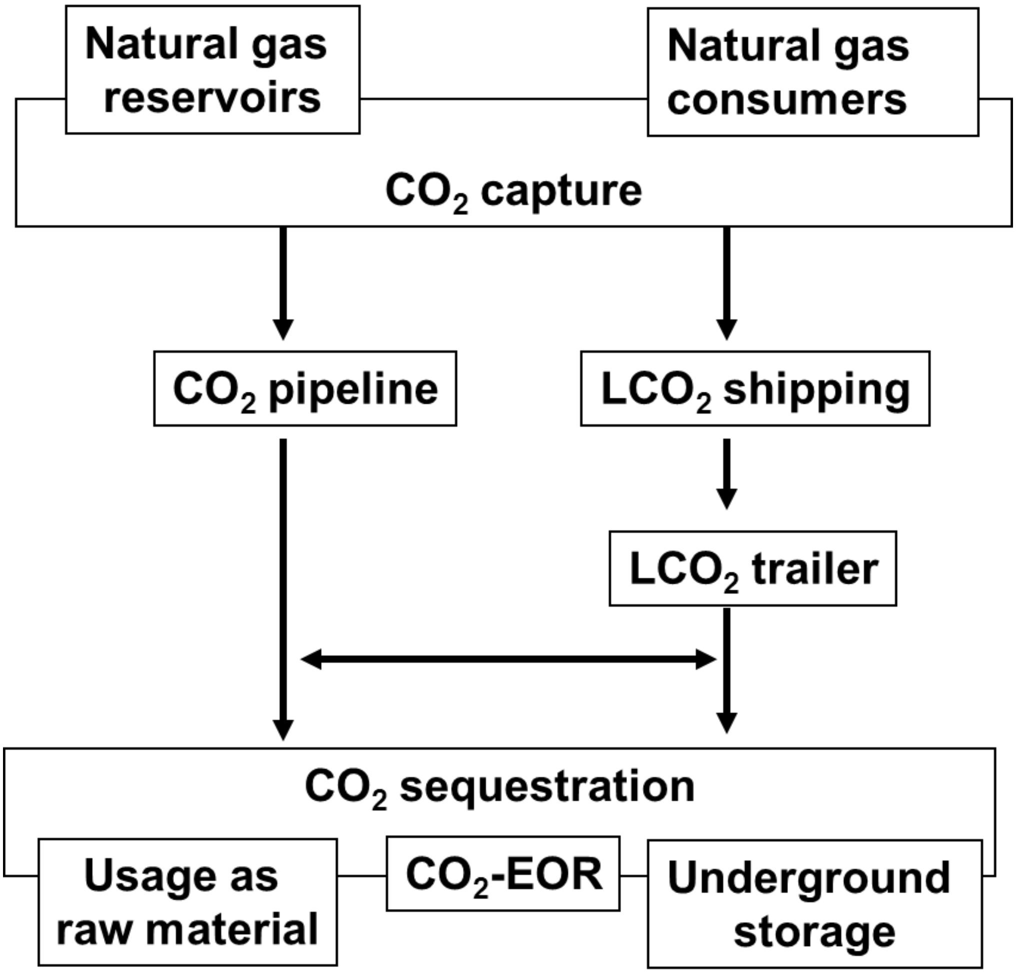


Figure 2.4 CCS system for natural gas supply system (IGU, 2012)

In the CCS system, generated CO_2 is captured at the extraction site and at the natural gas end-use side, is transported through pipelines or as liquid CO_2 (LCO_2), and sequestrated in geological formations. From an economic perspective, in the absence of a carbon price in society, CCS is feasible only if CO_2 sequestration technologies can generate revenue. CO_2-enhanced oil recovery (CO_2-EOR) and the use of CO_2 as a raw material are considered good examples of such technologies. If the carbon price in society is sufficiently high, commercial CCS using CO_2 underground storage could become prevalent.

The Intergovernmental Panel on Climate Change (IPCC) categorizes some CO_2 capture and transportation options as “mature market” technologies, and storage as an “economically feasible” technology. In the use of natural gas as a power source, CCS of flue gas from generation systems is a realistic technology and will be one of several measures to drastically reduce CO_2 emissions. Considering current international arguments, the gas industry is implicitly/explicitly expected to reduce CO_2 emissions from future natural gas systems around 2030 or later. There are three areas in which the gas industry can work to reduce CO_2 emissions by using CCS technologies.

1) Cut CO_2 emissions from natural gas extraction site (High-CO_2 reservoirs)

Natural gas extracted from reservoirs usually contains CO_2. Therefore, the CO_2 separation process is essential for natural gas purification at extraction sites, and this indicates that natural gas wells at high-CO_2 reservoirs are sources of large CO_2 emissions. At such sites, a large amount of condensed CO_2 is continuously available, implying a major opportunity to apply CCS at natural gas extraction sites. The well-known Sleipner case (IPCC, 2005) is a typical example of CCS applied to natural gas extraction sites. Currently, a great proportion of the large-scale, operative CCS projects (injecting more than one million tons CO_2 per year) use associate gas in natural gas extraction. The gas industry has developed technologies over many years, which separate CO_2 from natural gas in order to guarantee the specifications of gas supplied to customers.

2) Cut CO_2 emissions from natural gas industrial use (hydrogen and ammonia production process)

Hydrogen and ammonia plants using natural gas as a raw material are relatively large sources of condensed CO_2. Currently, global hydrogen production is 48% from natural gas, 30% from oil, 18% from coal, and only 4% is from water electrolysis (Guerrero-Lemus & Martínez-Durant, 2010). Although hydrogen is mainly used as an intermediate product in industrial processes such as ammonia production, hydrogen has the potential to become a key energy carrier for the gas and automobile industries. Natural gas reforming with CCS can produce almost CO_2-free hydrogen that would contribute to creating a low-carbon society as well as providing low-carbon electricity. Electricity and hydrogen are major energy carriers that do not contain carbon at the point of end-use. A few currently operating CCS projects are based on these processes.

3) Cut CO_2 emissions from natural gas end-use side (furnace, boiler, gas power generation, and combined heat and power)

The amount of energy required to capture CO_2 from combustion exhaust gas is much larger compared to that of associated CO_2 in natural gas extraction or condensed CO_2 in hydrogen and ammonia plants, because CO_2 concentration in exhaust gas is leaner. That would result in higher energy and equipment costs for CCS on the end-use side. However, the potential for CO_2 reduction at the end use, especially in electricity generation, is much larger than that in upstream gas production or in industrial processes. Therefore, CCS for natural gas-fired power plants (NGCC: Natural Gas Combined Cycle) is considered to be a major target of CCS (IPCC, 2014). Furthermore, applications of CCS to smaller point sources such as furnaces, boilers, and CHP are explored at the R&D stage and are considered feasible if some conditions are met (IEA-GHG, 2007).

2.2 Support other energy systems and expand the gas industry via CCS

1) Supporting intermittent renewables such as wind power and photovoltaics (PV) by NGCC with CCS

The enhanced deployment of renewables is regarded as important for realizing a low-carbon society. Among renewables, PV and wind power are expected to play significant roles in future electricity supply. However, outputs from PV and solar fluctuate and can be intermittent. Therefore, reliable and responsive power sources are required to make up a stable power portfolio including renewable energy. To support renewables, the use of NGCC has an advantage over the use of coal-fired generation pulverized coal-fired boiler (PC) or integrated coal gasification combined cycle (IGCC)) in load-following capability. Even though the CO_2 emission factor of NGCC is about half that of PC and IGCC, NGCC with CCS has the potential to contribute to a future low-carbon society if it is combined with renewables.

2) CO_2 utilization (CO_2-EOR, greenhouses, dry ice, raw materials)

The gas industry has additional potential to expand its business, by utilizing CO_2 to create new value. CO_2 is a valuable product in some industries, but is generally utilized in limited quantities compared with globally emitted CO_2-tonnage. For example, CO_2 can be used for EOR in some oil fields. Other well-known examples include the use of CO_2 for welding. CO_2 is also used as a “growth prompter” of crops by commercial greenhouses in the Netherlands and elsewhere. If the gas industry could supply CO_2 at an appropriate price, it would contribute to establishing a CO_2 value chain.

3) Expanding the business of the gas industry by creating new value using CCS technology

The potential large-scale deployment of CCS in natural gas, coal, and other industries with large CO_2 emissions raises the question: “who will take care of CO_2 transportation?” The gas industry obviously has great technical potential to provide CO_2 transportation services, because of its experience in engineering and operating natural gas transportation. Furthermore, considering that the gas industry has experience of geological activity in gas production, it can be expected that the industry would provide CO_2 transport and storage services, thereby significantly expanding the business domain of the industry.

As previously described, CO_2 is extracted as an associated gas on the extraction side, and is emitted on the end-user side when natural gas is combusted. However, natural gas can contribute to the realization of a low-carbon society if natural gas systems are combined with CCS. Furthermore, natural gas systems have many strengths; for example, flexible operation of NGCC has a high affinity with fluctuating renewables. CO_2 from gas systems can be utilized for EOR, raw materials, and in commercial greenhouses to increase business value. Natural gas has an essential role in achieving a low-carbon society through combination with CCS technology.

References

Energy Technology Perspective 2014 (IEA, 2014)
World Energy Outlook 2014 (IEA, 2014)
The role of Carbon Capture and Storage (CCS) in a sustainable Gas Industry (IGU, 2012)
The Global Status of CCS: 2014 (Global CCS Institute, 2014)

3. Status of CCS around the world

3.1 Overview of CCS around the world

Fossil fuels such as natural gas are considered to retain an important role in the future energy mix. However, the CO_2 emitted during combustion of fossil fuels is thought to be one of the potential causes of global warming. While various technologies are already in practical use or under development, CCS is one of the most viable technologies currently available to mitigate greenhouse gas emissions from large-scale fossil fuel usage.

Although the development of CCS has been slower than anticipated in IGU's previous CCS report published in 2012, the year 2014 might signal the beginning of a historic period for the spread of CCS. In October 2014, the world's first large-scale CCS project in the power sector commenced operation at the Boundary Dam power station in Saskatchewan, Canada. Two additional large-scale CCS projects in the power sector—at the Kemper Country Energy Facility in Mississippi and the Petra Nova Carbon Capture project in Texas—are under construction and planned to come into operation in 2015 and 2016, respectively. Although coal is the CO_2 source of those three projects, two CCS projects with gas-fired power stations—Sargas Texas Point Comfort Project in the USA and Peterhead CCS project in the UK—are already in the final stage of planning.

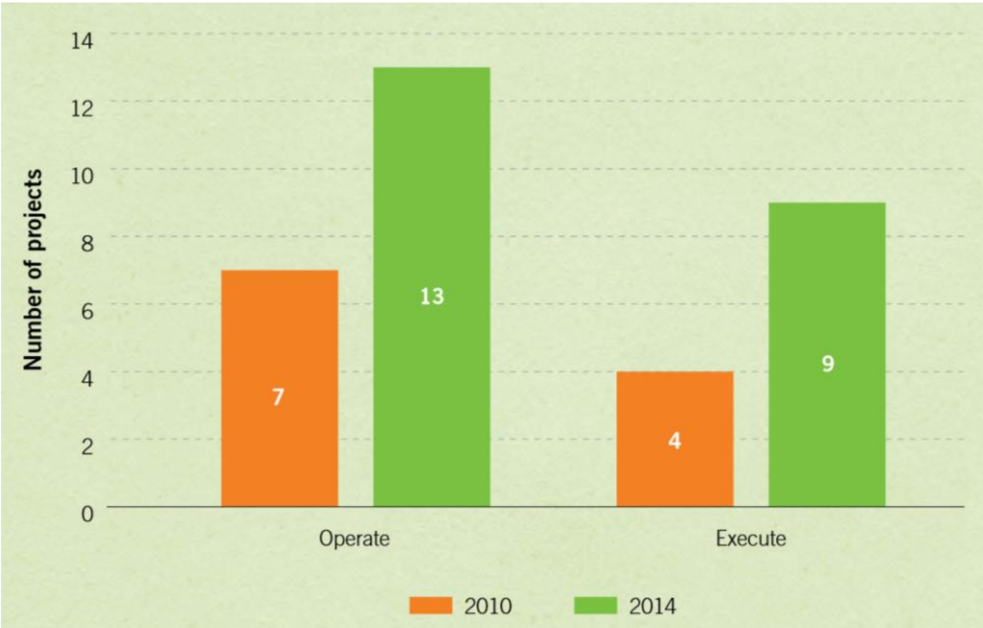


Figure 3.1 Number of large-scale CCS projects in the operational and execute stages (Source: Global CCS Institute, 2014)

This chapter discusses large-scale CCS projects that are in operation, under construction, and planned. Subsequently, 13 CCS projects related to gas industries are investigated.

3.2 List of worldwide CCS projects

Tables 3.1 to 3.3 show worldwide CCS projects in operation, under construction, and planned. The Global CCS Institute "Status of CCS Project Database" was used as a reference.

Table 3.1 CCS projects in operation (source: Global CCS Institute, 2014)

No.	Country	Project Name	Year of Operation	Primary Industry	Capture Type	Capture Capacity (MTPA)	Transport Type	Storage Type
1	Algeria	In Salah CO_2 Storage	2004	Natural gas processing	Pre-combustion capture (natural gas processing)	0 (Injection suspended)	Pipeline (Onshore)	Onshore deep saline formations
2	USA	Val Verde Natural Gas Plants	1972	Natural gas processing	Pre-combustion capture (natural gas processing)	1.3	Pipeline (Onshore)	EOR
3	USA	Enid Fertilizer CO_2-EOR Project	1982	Fertilizer production	Industrial separation	0.7	Pipeline (Onshore)	EOR
4	USA	Shute Creek Gas Processing Facility	1986	Natural gas processing	Pre-combustion capture (natural gas processing)	7	Pipeline (Onshore)	EOR
5	Norway	Sleipner CO_2 Storage Project	1996	Natural gas processing	Pre-combustion capture (natural gas processing)	0.9	Direct injection	Offshore deep saline formations
6	Canada	Great Plains Synfuel Plant and Weyburn-Midale Project	2000	Synthetic natural gas	Pre-combustion capture (gasification)	3	Pipeline (Onshore)	EOR
7	Norway	Snøhvit CO_2 Storage Project	2008	Natural gas processing	Pre-combustion capture (natural gas processing)	0.7	Pipeline (Offshore)	Offshore deep saline formations
8	USA	Century Plant	2010	Natural gas processing	Pre-combustion capture (natural gas processing)	8.4	Pipeline (Onshore)	EOR
9	USA	Air Products Steam Methane Reformer EOR Project	2013	Hydrogen production	Industrial separation	1	Pipeline (Onshore)	EOR
10	USA	Coffeyville Gasification Plant	2013	Fertilizer production	Industrial separation	1	Pipeline (Onshore)	EOR
11	USA	Lost Cabin Gas Plant	2013	Natural gas processing	Pre-combustion capture (natural gas processing)	0.9	Pipeline (Onshore)	EOR
12	Brazil	Petrobras Lula Oil Field CCS Project	2013	Natural gas processing	Pre-combustion capture (natural gas processing)	0.7	Direct injection	EOR
13	Canada	Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project	2014	Power generation	Post-combustion capture	1	Pipeline (Onshore)	EOR

Ten of the thirteen projects in Table 3.1 are related to natural gas (either natural gas processing, fertilizer production from natural gas, or hydrogen production from natural gas). Three exceptions are the Great Plains Synfuel Plant and Weyburn-Midale Project (synthesis of natural gas from lignite and brown coal), Coffeyville Gasification Plant (fertilizer production from petcoke), and Boundary Dam (power generation from lignite and brown coal). CO_2 is utilized for EOR in ten projects and is dedicated to geological storage in three projects. Boundary Dam, in Canada, is the only project in operation that utilizes post-combustion CO_2 capture.

Table 3.2 CCS projects under construction (Source: Global CCS Institute, 2014)

No.	Country	Project Name	Year of Operation	Primary Industry	Capture Type	Capture Capacity (MTPA)	Transport Type	Storage Type
1	USA	Kemper County Energy Facility (formerly Kemper County IGCC Project)	2015	Power generation	Pre-combustion capture (gasification)	3	Pipeline (Onshore)	EOR
2	Canada	Quest	2015	Hydrogen production	Industrial separation	1.08	Pipeline (Onshore)	Onshore deep saline formations
3	USA	Illinois Industrial CCS Project	2015	Chemical production	Industrial separation	1	Pipeline (Onshore)	Onshore deep saline formations
4	Saudi Arabia	Uthmaniyah CO_2–EOR Demonstration Project	2015	Natural gas processing	Pre-combustion capture (natural gas processing)	0.8	Pipeline (Onshore)	EOR
5	Canada	ACTL with Agrium CO_2 Stream	2015	Fertilizer production	Industrial separation	0.3–0.6	Pipeline (Onshore)	EOR
6	Australia	Gorgon Carbon Dioxide Injection Project	2016	Natural gas processing	Pre-combustion capture (natural gas processing)	3.4–4.0	Pipeline (Onshore)	Onshore deep saline formations
7	USA	Petra Nova Carbon Capture Project (formerly NRG Energy Parish CCS Project)	2016	Power generation	Post-combustion capture	1.4	Pipeline (Onshore)	EOR
8	UAE	Abu Dhabi CCS Project (formerly ESI CCS Project)	2016	Iron and steel production	Industrial separation	0.8	Pipeline (Onshore)	EOR
9	Canada	ACTL with North West Sturgeon Refinery CO_2 Stream	2017	Oil refining	Pre-combustion capture (gasification)	1.2–1.4	Pipeline (Onshore)	EOR

As seen from Table 3.2, the CCS projects under construction are more diverse than those already in operation. The sources of CO_2 include power generation from coal, hydrogen production from methane, ethanol production plant, fertilizer production from natural gas, and iron and steel production as well as natural gas processing. It is noteworthy that two new post-combustion CCS projects on coal-fired power plants, Kemper County and Petra Nova, will join the operating Boundary Dam Project.

Table 3.3 Planned CCS projects (source: Global CCS Institute, 2014)

No.	Country	Project Name	Year of Operation	Primary Industry	Capture Type	Capture Capacity (MTPA)	Transport Type	Storage Type
1	China	Sinopec Qilu Petrochemical CCS Project (formerly Sinopec Shengli Dongying CCS Project)	2016	Chemical production	Pre-combustion capture (gasification)	0.5	Pipeline	EOR
2	China	Yanchang Integrated CCS Demonstration Project	2016	Chemical production	Pre-combustion capture (gasification)	0.46	Pipeline	EOR
3	China	PetroChina Jilin Oil Field EOR Project (Phase 2)	2016–2017	Natural gas processing	Pre-combustion capture (natural gas processing)	0.8	Pipeline	EOR
4	USA	FutureGen 2.0 Project	2017	Power generation	Oxyfuel combustion capture	1.1	Pipeline	Onshore deep saline formations
5	Netherlands	Rotterdam Opslag en Afvang Demonstratieproject (ROAD)	2017	Power generation	Post-combustion capture	1.1	Pipeline	Offshore depleted oil and/or gas reservoir
6	China	Sinopec Shengli Power Plant CCS Project	2017	Power generation	Post-combustion capture	1	Pipeline	EOR
7	USA	Sargas Texas Point Comfort Project	2017	Power generation	Post-combustion capture	0.8	Pipeline	EOR
8	USA	Medicine Bow Coal-to-Liquids Facility	2018	Coal-to-liquids (CTL)	Pre-combustion capture (gasification)	2.5	Pipeline	EOR
9	Canada	Spectra Energy's Fort Nelson CCS Project	2018	Natural gas processing	Pre-combustion capture (natural gas processing)	2.2	Pipeline	Onshore deep saline formations
10	UK	White Rose CCS Project	2019–2020	Power generation	Oxy-fuel combustion capture	2	Pipeline	Offshore deep saline formations
11	UK	Don Valley Power Project	2019	Power generation	Pre-combustion capture (gasification)	5	Pipeline	Dedicated geological storage, with potential for enhanced oil recovery, offshore deep saline formations
12	USA	Hydrogen Energy California Project (HECA)	2019	Power generation	Pre-combustion capture (gasification)	2.7	Pipeline	EOR
13	USA	Texas Clean Energy Project	2019	Power generation	Pre-combustion capture (gasification)	2.7	Pipeline	EOR
14	UK	Peterhead CCS Project	2019	Power generation	Post-combustion capture	1	Pipeline	Offshore depleted oil and/or gas reservoir

Nine power generation projects with CCS are planned worldwide, of which two projects—Sargas Texas Point Comfort Project and Peterhead CCS Project—adopt post-combustion CO_2 capture from natural gas power generation. This represents very important progress for the gas industry.

As described, the number of CCS projects will increase significantly throughout the world toward 2020. Meanwhile, CCS with power generation will move into the mainstream of the project types from natural gas processing, as shown in Figure 3.3 below.

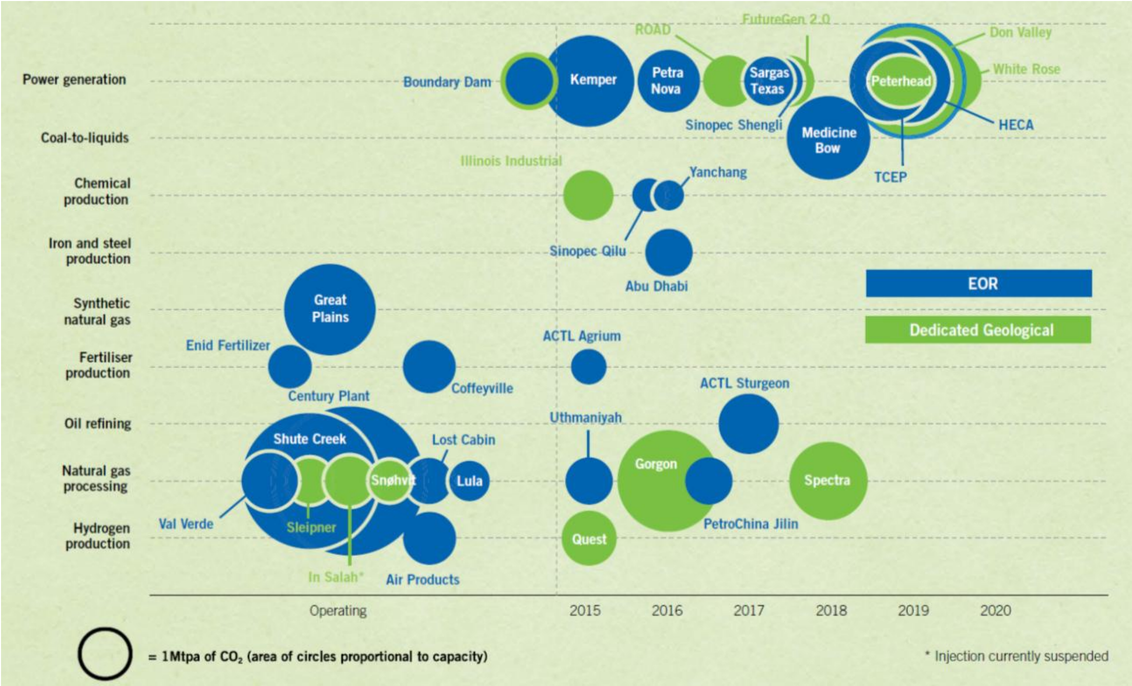


Figure 3.3 Actual and expected operational dates for large-scale CCS projects by industry and storage type (Source: Global CCS Institute, 2014)

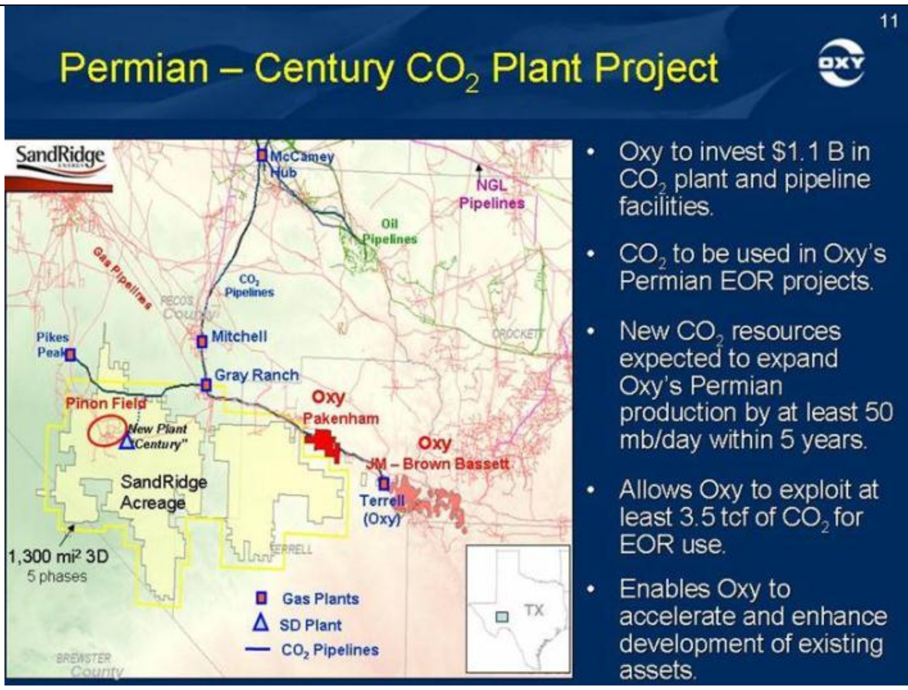
3.3 Survey of 13 specific CCS projects worldwide related to gas industry

In this section, eleven projects from Tables 3.1 to 3.3 and two small-scale characteristic projects (Tomakomai and Lacq) are selected for investigation by taking geographical balance into account.

Table 3.4 Selected worldwide CCS projects

Region	No.	Country	Project Name	Primary Industry	Status	Selection criteria
North America	1	USA	Century Plant	Natural gas processing	Operational	The largest project in USA
	2	Canada	Great Plains Synfuel Plant and Weyburn-Midale	Synthetic natural gas	Operational	The only project operated in Canada
	3	USA	Sargas Texas Point Comfort Project	Natural gas-fired power generation	Planned	Only a few planned projects with natural gas post-combustion capture
South America	4	Brazil	Petrobras Lula Oil Field	Natural gas processing	Operational	The only project in South America
Asia	5	Japan	Tomakomai Demonstration Project	Oil refining (Hydrogen production)	Execute	The only demonstration project in Japan
	6	China	PetroChina Jilin Oil Field EOR (Phase 2)	Natural gas processing	Planned	Most advanced CCS project with natural gas processing in Asia
Oceania	7	Australia	Gorgon	Natural gas processing	Execute	The only project in Australia
Middle East	8	Saudi Arabia	Uthmaniyah	Natural gas processing	Execute	Most advanced project in Middle East
Europe	9	France	Lacq Pilot	Oxy-combustion gas boiler	Concluded	The first pilot project in EU
	10	Norway	Sleipner	Natural gas processing	Operational	Operated in Europe
	11	Norway	Snøhvit	Natural gas processing	Operational	Operated in Europe
	12	UK	Peterhead	Natural gas-fired power generation	Planned	Only a few planned projects with natural gas post-combustion capture
Africa	13	Algeria	In Salah	Natural gas processing	Operational	The only project in Africa

1) Century Plant (USA)

Status	Started operation in 2010
Company	Occidental Petroleum (“Oxy,” owner), Sandrine Energy (constructor)
Source of CO_2	Natural gas field (Bravo Dome, Permian basin)
Method of CO_2 Capture	Selexol technology (Honeywell UOP)
Method of CO_2 transportation	260-km newly constructed pipeline to McCamey Hub
Storage	EOR in Permian basin (60% of the oil in the basin is produced by EOR)
Capacity	8.4 Mt/y (1st train: 5 My/y from 2010; 2nd train: 3.4 Mt/y from 2012)
Budget	USD 1.1 billion for construction
Schematic, etc.	 Layout of the project

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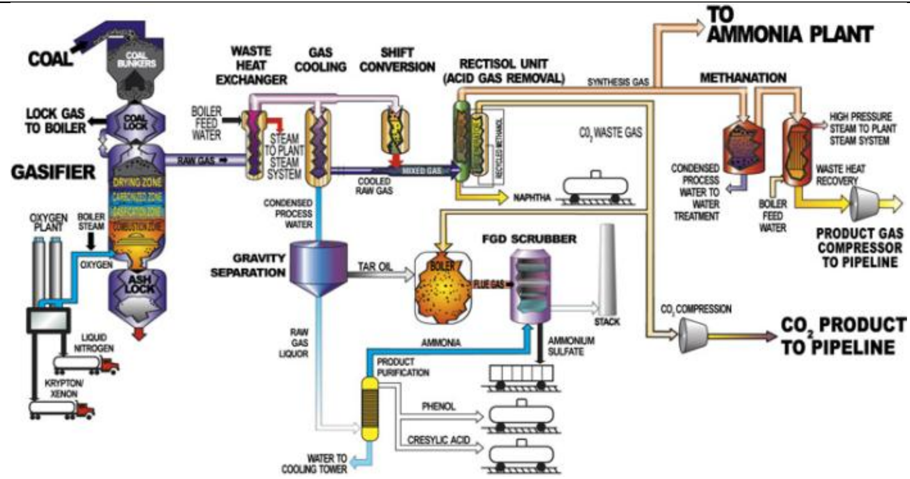
- Stephen I. Chazen (2008), “Oxy,” Lehman Brothers 2008 CEO Energy/Power Conference, Sep. 3, 2008.

2) Great Plains Synfuel Plant and Weyburn-Midale Project (Canada)

<table>
<tr><td>Status</td><td>Started operation in 2000</td></tr>
<tr><td>Company</td><td>Cenouvus Energy (Encana's special subsidiary for EOR, operator of Weyburn field), Apache Canada (operator of Midale field)
Supported by BP, Nexen, SaskPower, Chevron Texaco, TOTAL, Dakota Gasification, TransAlta, and RITE</td></tr>
<tr><td>Source of CO_2</td><td>SNG plant owned by Dakota Gasification</td></tr>
<tr><td>Method of CO_2 Capture</td><td>Pre-combustion in brown coal gasification furnace (Lurgi)</td></tr>
<tr><td>Method of CO_2 transportation</td><td>Pipeline (diameter: 12 and 14 inches, Length: 320 km, Pressure: 2,200 psi (15.4 MPa)</td></tr>
<tr><td>Storage</td><td>EOR in bedded salt (20,000 bbl/d is enhanced production, of 30,000 bbl/d in total)</td></tr>
<tr><td>Capacity</td><td>7,700 t/d in total (Weyburn: 6,500 t/d; Midale: 1,200 t/d)
The accumulated amount since 2000 is 20 Mt.</td></tr>
<tr><td>Budget</td><td>N.A.</td></tr>
<tr><td>Schematic, etc.</td><td>

Process of CO_2 capture in Weyburn-Midale Project</td></tr>
</table>

- GCCSI (2013), http://www.globalccsinstitute.com/project/great-plains-synfuel-plant-and-weyburn-midale-project
- Petroleum Technology Research Centre, "Weyburn-Midale," http://ptrc.ca/projects/weyburn-midale
- Japan Gas Association (Japanese only) http://www.meti.go.jp/meti_lib/report/2010fy01/E000829.pdf
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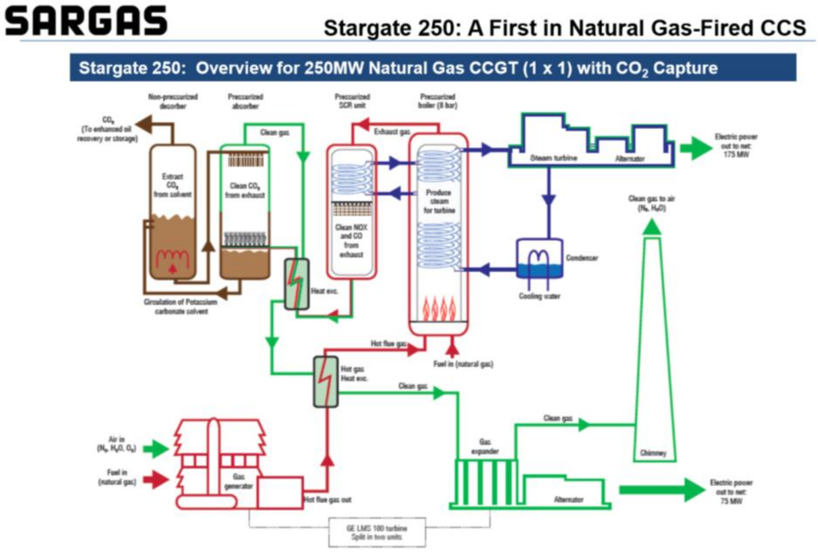
- Cenovus Energy, "Weyburn Facility Profile," http://www.cenovus.com/operations/docs/Weyburn-Facility-Profile.pdf
- The Canadian Press, "CO_2 Leaks Worry Sask. Farmers," Jan 11, 2011. http://www.cbc.ca/news/canada/saskatchewan/co2-leaks-worry-sask-farmers-1.977078
- IPAC-CO_2 (2011), "The Kerr Investigation: Technical Briefing," http://64.190.51.133/documents/KerrReportTechnicalWebinar-GWS-CW-V5.pdf

3) Sargas Texas Point Comfort Project (USA)

<table>
<tr><td>Status</td><td>Planned to start operation in 2017</td></tr>
<tr><td>Company</td><td>Sargas Texas LLC (a subsidiary of Sargas AS, Norway)</td></tr>
<tr><td>Source of CO_2</td><td>500 MW natural gas combined cycle power plant</td></tr>
<tr><td>Method of CO_2 Capture</td><td>Post-combustion, absorption chemical solvent</td></tr>
<tr><td>Method of CO_2 transportation</td><td>Pipeline</td></tr>
<tr><td>Storage</td><td>Not specified</td></tr>
<tr><td>Capacity</td><td>0.8 Mt/y</td></tr>
<tr><td>Budget</td><td>N.A.</td></tr>
<tr><td>Schematic, etc.</td><td>


Overview for 250MW Natural Gas CCGT with CO_2 Capture
</td></tr>
</table>

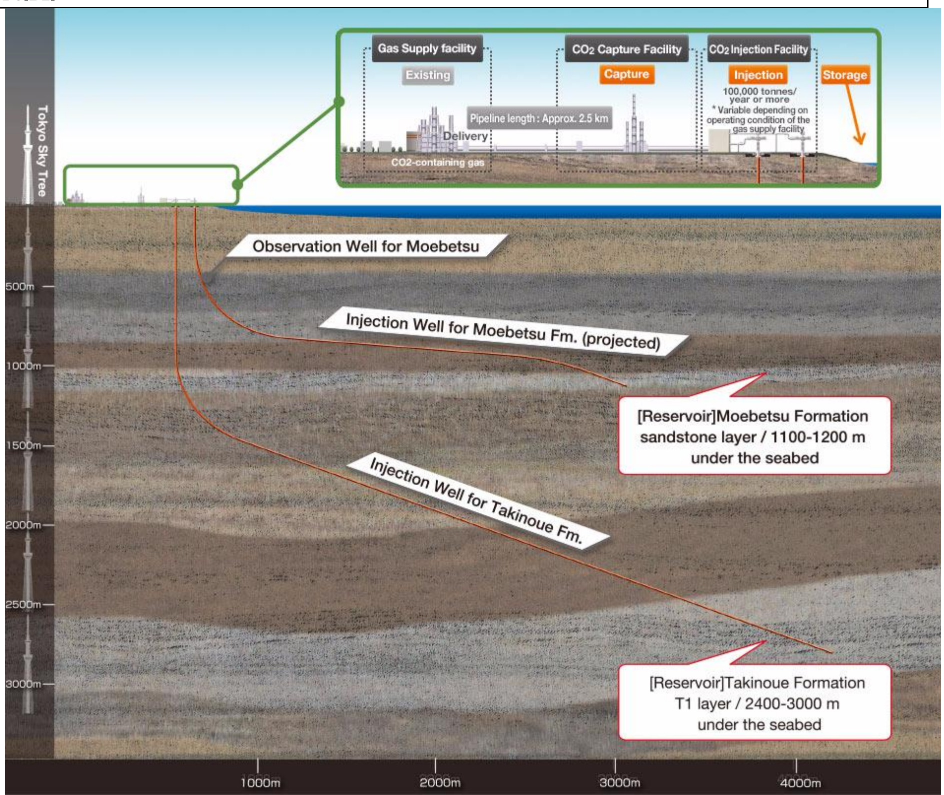
- GCCSI (2014), http://www.globalccsinstitute.com/projects/sargas-texas-point-comfort-project
- Wyoming Infrastructure Project, http://wyia.org/wp-content/uploads/2014/05/Chris-elrod.pdf

4) Petrobras Lula Oil Field CCS Project (Brazil)

Status	Started CO_2 injection on a pilot scale in 2011 and started commercial-scale project in 2013
Company	Petrobras (65%), BG EIIBrazi (25%), Petrogal Brazil S.A. (10%)
Source of CO_2	Offshore Petrobras Lula oilfield
Method of CO_2 Capture	Separation of associated natural gas on FPSO
Method of CO_2 transportation	Direct injection (no transportation needed)
Storage	Direct CO_2 injection via 2000-m length injection riser
Capacity	0.7 Mt/y
Budget	N.A.
Schematic, etc.	 Lula oil field (Zero Emission Resource Organisation)

- GCCSI (2013), http://www.globalccsinstitute.com/project/petrobras-lula-oil-field-ccs-project
- Petrobras, http://www.petrobras.com.br/downloads/energy-and-technology/petrobras-technology-2012.pdf
- Reuters, "Petrobras to Begin Offshore CO_2 Sequestration," Feb. 3, 2011
- Zero Emission Resource Organisation, http://www.zeroco2.no/projects/lula-co2-reinjection

5) Tomakomai Demonstration (Japan)

Status	Demonstration project started in 2012; Injection well is planned to be drilled in 2014
Company	Japan CCS Co. (contribution of 35 domestic companies and sponsored by METI)
Source of CO_2	Hydrogen manufacturing unit in oil refinery operated by Idemitsu Kosan Co.
Method of CO_2 Capture	Chemical absorption at post-PSA
Method of CO_2 transportation	Pipeline (60-cm diameter, 2.5-km length)
Storage	Offshore saline aquifers (1,000 m and 3,000 m depth)
Capacity	0.1 Mt/y
Budget	N.A.
Schematic, etc.	 Schematic of Tomakomai Demonstration site

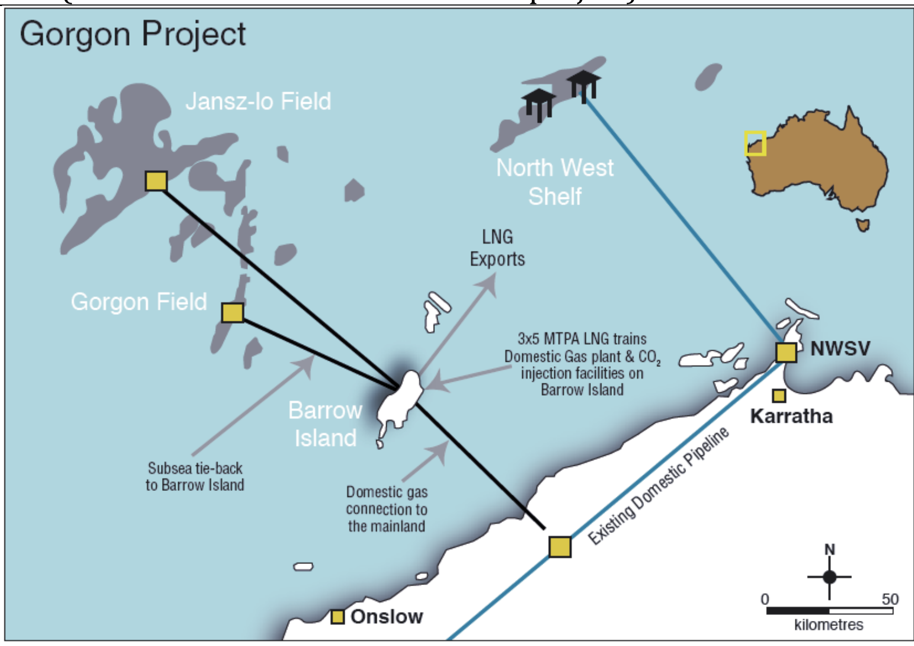
- Japan CCS Co., Ltd., http://www.japanccs.com/ (Japanese only)

6) PetroChina Jilin Oil Field EOR (China)

Status	Pilot-scale project (phase 1) started in 2009; Phase 2 is at the planning stage and is expected to start operation in 2016–2017
Company	CNPC (China National Petroleum Co., PetroChina's leading subsidiary)
Source of CO_2	Natural gas processing
Method of CO_2 Capture	Chemical absorption by monoethanol amine (MEA)
Method of CO_2 transportation	Onshore pipeline (35-km length)
Storage	EOR in Jilin oil field (11.9 Mt total enhanced oil production in phase 1)
Capacity	0.2 Mt-CO_2/y (phase 1); 0.8–1.0 Mt-CO_2/y (phase 2)
Budget	USD 11.0 million for phase 1; N.A. for phase 2.
Schematic, etc.	 Experimental site of CCS-EOR at Jilin Oil Field

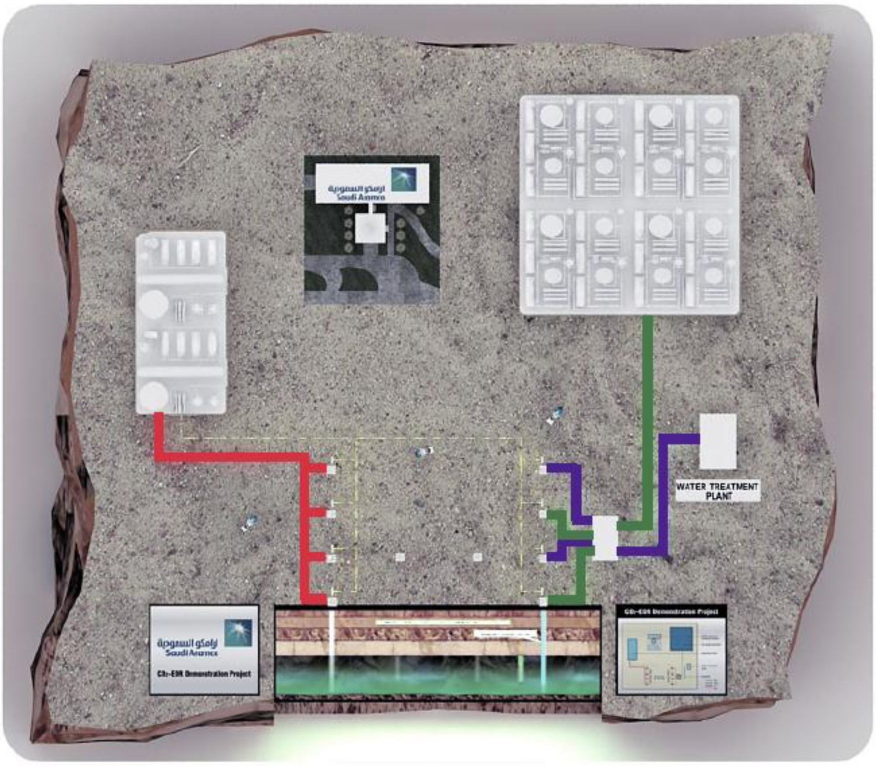
- GCCSI (2013), http://www.globalccsinstitute.com/project/petrochina-jilin-oil-field-eor-project-phase-2
- Zero Emission Resource Organisation, http://www.zeroco2.no/projects/jilin-oilfield-eor
- China National Petroleum Corporation (2012), Corporate Social Responsibility Report.
- Ministry of Science and Technology, PetroChina's CO_2-EOR Research and Demonstration Project in the Jilin Oil Field, http://www.ccuschina.org.cn/English/News.aspx?NewsId=736, 26 Oct. 2012.
- NEDO, http://www.nedo.go.jp/events/report/ZZEV_100006.html

7) Gorgon Carbon Dioxide Injection Project (Australia)

Status	Under construction; expected to start in 2016
Company	Gorgon Joint Venture (Chevron Australia (operator) 47.333%, Shell 25%, ExxonMobil 25%, Osaka Gas 1.25%, Tokyo Gas 1%, Chubu Electric 0.417%)
Source of CO_2	Natural gas field (CO_2 concentration: 14 mole% in Gorgon field and 0.9 mole% in Jansz-lo field)
Method of CO_2 Capture	Three units located on Barrow Island, for chemical absorption by mono-ethanol amine (MEA).
Method of CO_2 transportation	65-km and 130-km pipelines from gas field to Barrow Island
Storage	Saline aquifer (Dupuy layer) 2,300 m below Barrow Island
Capacity	3.4–4.1 Mt/y
Budget	N.A. (USD 54 billion for the whole LNG project)
Schematic, etc.	 Overhead view of Gorgon Project

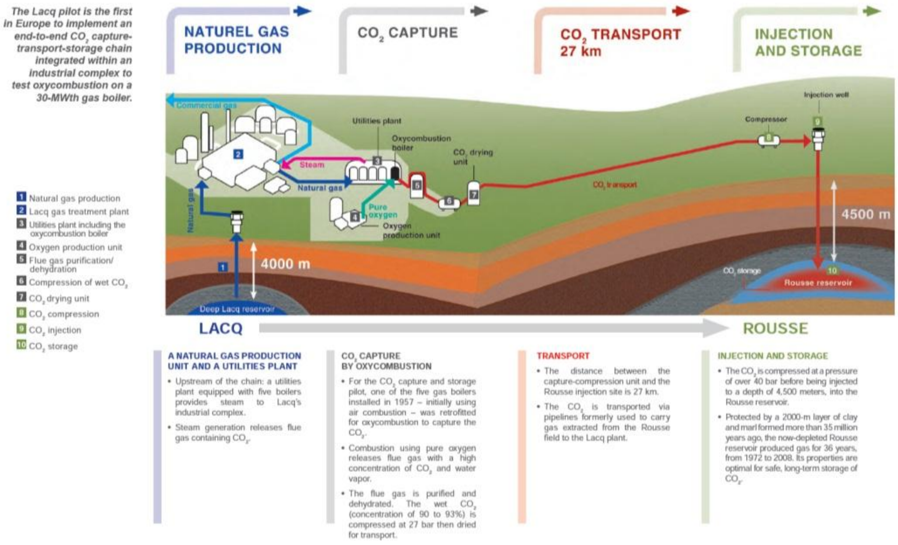
- GCCSI (2013), http://www.globalccsinstitute.com/project/gorgon-carbon-dioxide-injection-project
- Department of State Development, Government of Western Australia, “Gorgon Project Factsheet,” Aug. 2010.
- Chevron, “Gorgon Project Fact Sheet,” Jan. 2014.
- Chevron, “Gorgon Project Update,” Nov. 2013.

8) Uthmaniyah CO_2 EOR Demonstration Project (Saudi Arabia)

Status	Expected to start CO_2 injection in 2015
Company	Saudi Aramco
Source of CO_2	Processing plant for non-associated natural gas in Hawiyah
Method of CO_2 Capture	Pre-combustion
Method of CO_2 transportation	70-km onshore pipeline
Storage	EOR in Ghawar oilfield (4 injection wells, 2 monitoring wells, and 4 oil production wells)
Capacity	0.8 Mt for 3 years
Budget	N.A.
Schematic, etc.	 Layout planning of the project

- GCCSI (2013), http://www.globalccsinstitute.com/project/uthmaniyah-co2-eor-demonstration-project-0
- Zero Emission Resource Organisation, http://www.zeroco2.no/projects/uthmaniyah-co2-eor-demonstration-project
- Carbon Capture Journal, “CSLF Endorses Five New Projects,” (Nov. 10 2013) http://www.carboncapturejournal.com/news/cslf-endorses-five-new-projects/3389.aspx
- Ali Almeshari (2013), “UTMN CO_2-EOR Demonstration Project,” http://www.cslforum.org/publications/documents/rome2013/Meshari-UthmaniyahProject-PIRT-Rome0413.pdf
- Saudi Arabian Oil Co., “Hawiyah Gas Plant,” http://www.saudiaramco.com/en/home/our-operations/gas/major-gas-processing-plants/hawiyah-gas-plant.html

9) Lacq Pilot Project (France)

<table>
<tr><td>Status</td><td>Started operation in February 2007, ended January 2010</td></tr>
<tr><td>Company</td><td>TOTAL S.A.</td></tr>
<tr><td>Source of CO_2</td><td>30 MW oxycombustion gas boiler</td></tr>
<tr><td>Method of CO_2 Capture</td><td>NA (dehydrated)</td></tr>
<tr><td>Method of CO_2 transportation</td><td>27-km onshore pipeline</td></tr>
<tr><td>Storage</td><td>Depleted Rousse reservoir (2,000 meter-thick clay and marl layer, 4,500 m below ground)</td></tr>
<tr><td>Capacity</td><td>More than 51,000 metric tons of CO_2 were injected in total</td></tr>
<tr><td>Budget</td><td>N.A.</td></tr>
<tr><td>Schematic, etc.</td><td>


CO_2 capture, transport, and storage chain in Lacq pilot project</td></tr>
</table>

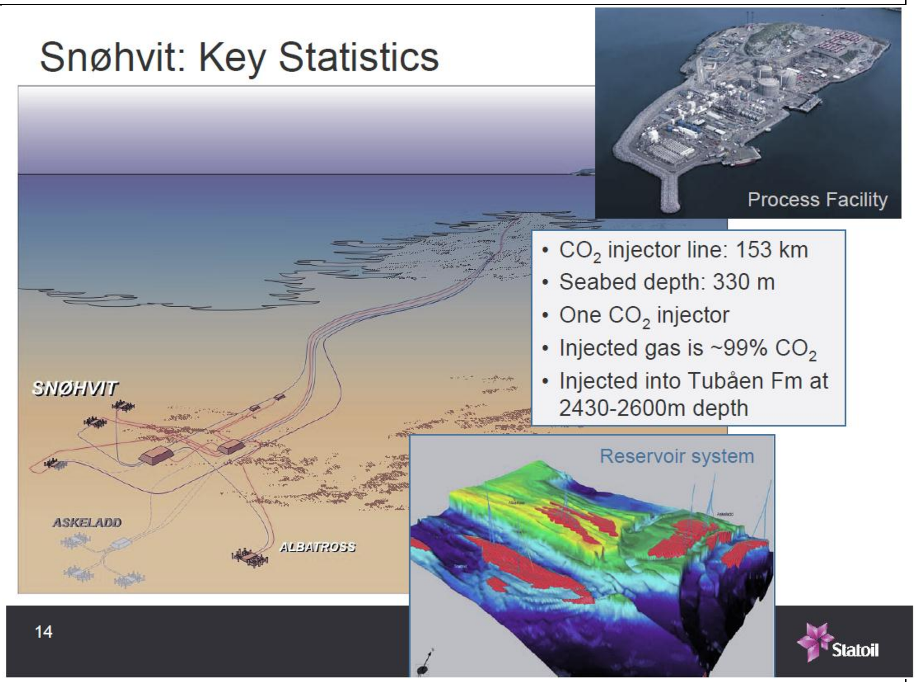
- GCCSI (2013), http://www.globalccsinstitute.com/files/project/descriptions/FranceLacqCCSPilot.pdf
- TOTAL, http://www.total.com/en/society-environment/environment/climate-and-carbon/carbon-capture-and-storage/lacq-pilot-project/how http://www.total.com/sites/default/files/atoms/file/co2-lacq-total-project-information-dossier
- TOTAL, http://www.total.com/sites/default/files/atoms/file/Captage-Carbon-capture-and-storage-the-Lacq-pilot

10) Sleipner CO_2 Injection (Norway)

Status	Started operation in 1996
Company	Statoil ASA
Source of CO_2	Natural gas field (9% CO_2 concentration)
Method of CO_2 Capture	Chemical absorption on offshore platform (45wt% MDEA, 100 atm, 60–80°C)
Method of CO_2 transportation	No transportation, as there is direct CO_2 injection
Storage	Utsira Formation (200 meter-thick saline aquifer, 800 m below seabed)
Capacity	Maximum 17 Mt in total (14 Mt was already injected)
Budget	N.A.
Schematic, etc.	 Sleipner gas field

- GCCSI (2013), http://www.globalccsinstitute.com/project/sleipner%C2%A0co2-injection
- MIT, "Sleipner Fact Sheet," http://sequestration.mit.edu/tools/projects/sleipner.html
- Statoil, "The Sleipner area," http://www.statoil.com/en/OurOperations/ExplorationProd/ncs/sleipner/Pages/default.aspx
- Statoil, "Gas Machine Sleipner Turns 20," http://www.statoil.com/en/OurOperations/ExplorationProd/ncs/sleipner/Pages/Sleipner20years.aspx
- British Geological Survey, "CO_2 Storage—Sleipner Field Beneath the North Sea," http://www.bgs.ac.uk/science/CO2/home.html
- Sveinung Hagen et al. (2012), "Sleipner Knowledge Sharing in CCS Projects—Workshop: Mobile, Alabama," http://www.secarbon.org/wp-content/uploads/2011/05/Hagen.pdf
- Greenpeace (2009), "Reality Check on Carbon Storage—Recent Developments in the Sleipner Project and Utsira Formation," http://www.greenpeace.org/international/Global/international/planet-2/report/2009/5/reality-check-on-carbon-storage.pdf

11) Snøhvit CO_2 Injection (Norway)

Status	Started CO_2 injection in 2008
Company	Statoil ASA, Petro AS (Norwegian state direct interest), TOTAL E&P Norge AS, GDF Suez E&P Norge AS, Norsk Hydro, Hess Norge
Source of CO_2	Pre-combustion (natural gas processing)
Method of CO_2 Capture	Chemical absorption (amine absorbent)
Method of CO_2 transportation	153-km offshore pipeline
Storage	Tubåen formation (45–75 meter-thick saline aquifer 2,600 m below seabed)
Capacity	0.7 Mt-CO_2/y (maximum 40 Mt-CO_2;19 Mt-CO_2 injected so far)
Budget	N.A.
Schematic, etc.	

Overview of Snøhvit CO_2 Injection Project

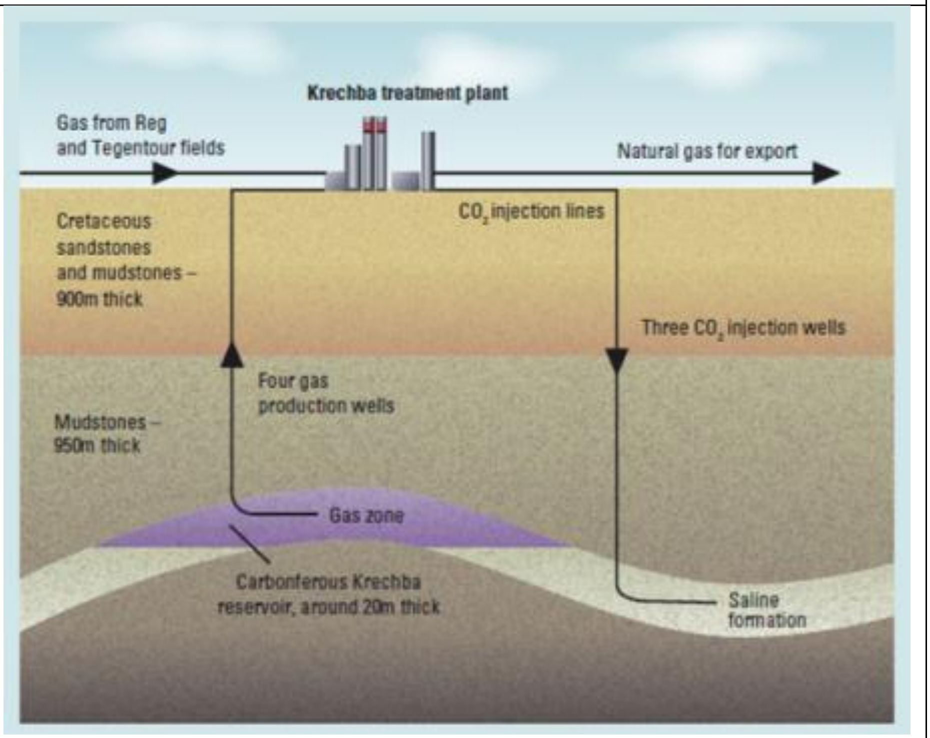
- GCCSI (2013), http://www.globalccsinstitute.com/project/sn%C3%B8hvit-co2-injection
- MIT, “Snøhvit Fact Sheet,” http://sequestration.mit.edu/tools/projects/snohvit.html, Jan. 2014.
- Statoil (2013), “Snøhvit,” http://www.statoil.com/en/ouroperations/explorationprod/ncs/snoehvit/pages/default.aspx
- Statoil (2013), “Snøhvit—Unlocking Resources in the Frozen North,” http://www.statoil.com/en/OurOperations/ExplorationProd/ncs/Pages/SnohvitNewEnergyHistoryInTheNorth.aspx
- Phil Ringrose et al. (2011), “Sleipner and Snøhvit Projects,” CSLF Interactive Workshop: Saudi Arabia, 01–02 Mar., 2011.

12) Peterhead CCS project (UK)

Status	Planned to started operation in 2019.
Company	Shell UK Ltd., with strategic support from SSE Ltd. (formerly Scottish and Southern Energy)
Source of CO_2	Flue gas from natural gas power generation
Method of CO_2 Capture	Post-combustion capture by absorption chemical solvent-based process (Amine)
Method of CO_2 transportation	120-km pipeline (20 km onshore; 100 km offshore)
Storage	Offshore depleted gas reservoir, more than 2 km beneath the floor of the North Sea
Capacity	1 Mt-CO_2/y
Budget	N.A.
Schematic, etc.	 Peterhead power station

- GCCSI (2014), http://www.globalccsinstitute.com/project/peterhead-ccs-project
- Shell (2014), http://www.shell.co.uk/gbr/environment-society/environment-tpkg/peterhead-ccs-project.html#textwithimage

13) In Salah CO_2 Storage (Algeria)

Status	Started operation in 2004; In June 2011, BP suspended CO_2 injection
Company	BP (operator), Statoil Hydro, Sonatrach
Source of CO_2	Natural gas processing
Method of CO_2 Capture	Chemical absorption (aMDEA, BASF)
Method of CO_2 transportation	14-km onshore pipeline
Storage	Saline aquifer (2,000 m depth)
Capacity	1 Mt-CO_2/y
Budget	N.A.
Schematic, etc.	 Overview of In Sarah CO_2 storage project

- GCCSI (2013), http://www.globalccsinstitute.com/project/salah-co2-storage
- BP, "In Salah CO_2 Project," http://www.insalahco2.com/
- Frontiers, "Sealed Under the Sahara," Dec. 2008, http://science.uwaterloo.ca/~mauriced/earth691-duss/CO2_General%20CO2%20Sequestration%20materilas/CO2_bp%20f23_18-25_insalah.pdf
- Carbon Sequestration Leadership Forum (2011), "World-Class Carbon Capture and Storage Projects Honored by International Body," http://www.cslforum.org/pressroom/publications/beijing_cslf_awards.pdf

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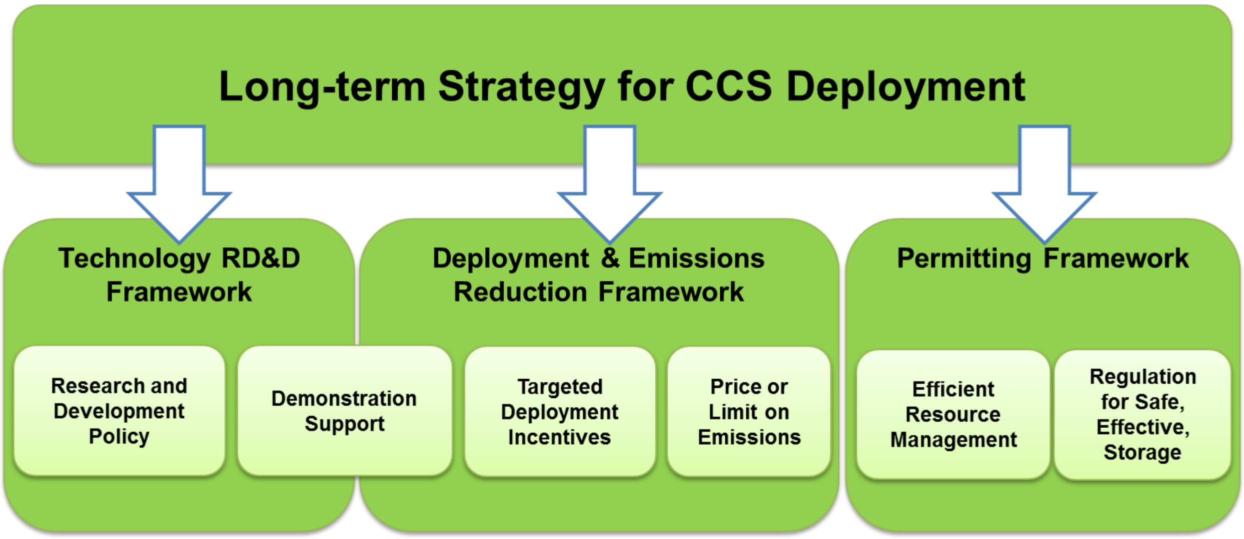
- Global CCS Institute, "The Global Status of CCS: 2014," http://www.globalccsinstitute.com/in-focus/global-status-ccs-2014
- Global CCS Institute, "Status of CCS Project Database," http://www.globalccsinstitute.com/projects/status-ccs-project-database
- International Energy Agency, "Energy Technology Perspective 2014," http://www.iea.org/etp/etp2014/

4. Overview of the legal and regulatory framework for CCS

CCS is one proposed method to reduce GHG emissions while continuing to use fossil fuels to meet the world's growing energy demand. CCS technologies are able to capture CO_2 emissions from gas processing plants, high-CO_2 fields, coal- or gas power plants, or even other industrial facilities, and store the CO_2 in underground geological formations.

A robust legal and regulatory framework is necessary, as the deployment of CCS technology is likely to involve many parties in the process of capture, transport, and storage. To further complicate matters, assurances on the containment of CO_2 and potential financial liability and environmental or social issues related to leakage of CO_2 will need to be clearly defined, even after the operational period is ended.

The CCS legal and regulatory framework should cover the long-term strategy for CCS deployment, starting from R&D, deployment, and emission reduction as well as the permitting framework. Global climate change negotiations at the United Nations Framework Convention on Climate Change (UNFCCC), enabling regional or national policies on climate change, carbon trading or tax by countries, internal carbon pricing initiatives by corporations, and incentives for R&D, are also seen as components for enhancing the CCS legal and regulatory framework.



Source: Carbon Capture and Storage: Legal and Regulatory Review, Edition 4, OECD/IEA, 2014

Figure 4.1 Key elements of a comprehensive CCS policy framework

A number of countries have established legal and regulatory frameworks to facilitate CCS EOR or demonstration projects. The demonstration projects related to the 'permanent storage' operations (i.e., those not involving enhanced recovery operations) have been the primary focus of legislation. In many instances, EOR operations can already be conducted under existing legal and regulatory pathways. The following diagram illustrates the countries that already have—and are in the process of developing—specific legal and regulatory frameworks for CCS.

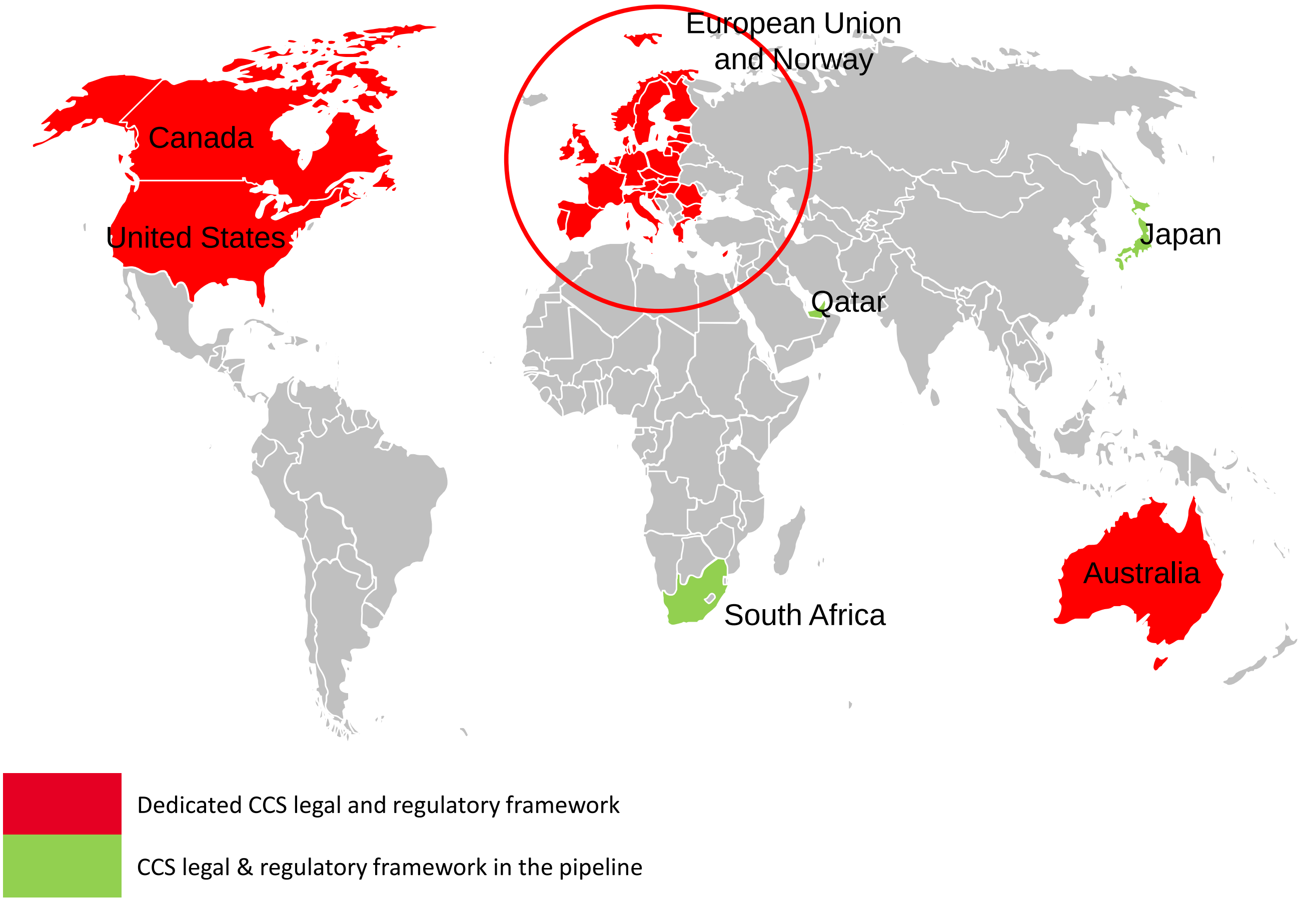


Figure 4.2 Status of the development of CCS legal and regulatory framework by country

The development of CCS regulatory frameworks will encourage responsible operations and investment. It is pertinent that the CCS policies should consider the whole chain of CCS, i.e. capture, transport, and injection/storage. A comprehensive CCS policy should consider the availability of geological data and public acceptance; injection site characterization and certification; site operation and closure; monitoring and verification requirements; long-term liability; ownership; and safety and environmental risks.

Additionally, CCS policies should also consider the concept of capture readiness; incentivization; intellectual property rights; technology transfer in addition to environmental impacts and safety issues related to the operation of the capture plant; CO_2 transport regulation, and considerations for routing of the CO_2 pipeline; ownership and liabilities.

The Global CCS Institute has recommended that a regulatory system for CO_2 storage should address the following areas:

- Manage risks and liabilities.
- Balance the competing needs of all players in a CCS project.
- Consider financial issues related to financial security or regulatory interactions with carbon trading schemes.
- Consider issues of climate change commitments.
- Consider ownership, access, and property rights.
- Obey the requirements of international treaties.

4.1 Review of existing CCS regulatory frameworks

Table 4.1 summarizes the aspects covered by existing CCS legal frameworks around the world.

Table 4.1 Summary of aspects covered by existing CCS legal frameworks (NZEC WP5-5.1 International Regulations)

Policy Aspects	EU	UK	USA	Australia
CO_2 capture	√	√	√	X
CO_2 transport	√	√	√	X
Details on exploration permits	√	√	√	√
Details on site characterization	√	√	√	√
Site certification and storage permits	√	√	√	√
Risk assessment	√	√	√	√
Classification of CO_2	√	√	√	√
Details of CO_2 composition	√	√	X	X
Access, property rights, and ownership	√	√	√	√
Site operation and closure	√	√	√	√
Limits on injection pressure	X	X	√	X
Details of parameters to be monitored post-closure	X	X	X	X
Post-closure, transfer of responsibility and liability issues	√	√	√	√
Recommended period for transfer of responsibility	√	X	√	√
Measurement, monitoring, and verification (MMV) requirements	√	√	√	√
MMV specifications (accuracy of instruments and acceptable parameter ranges)	X	X	X	X
Intellectual property right (IPR) issues	X	X	X	X
Financial issues	√	√	√	√

None of the existing CCS regulations in the European Union (EU), United Kingdom (UK), United States (USA), and Australia cover the details of: parameters that need to be monitored following post-closure; specifications on measurement, monitoring, and verification (MMV) in relation to the accuracy of instruments and acceptable parameter ranges; or intellectual property right (IPR) issues.

Recent developments in the MMV technologies will help close the regulatory gaps; the details are given in Annex A.

4.2 Emerging regulatory framework on CCS—A Malaysian Case Study

Malaysia has increased the number of coal-fired power plants in the last 10 years. CCS is considered a potential technology to meet the country's voluntary 40% GHG emission intensity by the year 2020 (ton of CO_2e per GDP, base year of 2005) as announced at the 2009 UNFCCC Copenhagen Conference by the Malaysian Prime Minister. Malaysia has potential to develop high-CO_2 fields with minimal resulting climate change impact through the use of CCS technology. Thus, reviewing the need for a CCS regulatory framework integrating the power and oil and gas sector is important. The government and private sector are working together to review and develop CCS legal requirements in Malaysia. There are two options: either developing new, standalone acts and regulations; or embedding the identified requirements within the existing legal and regulatory framework.

A mapping exercise was conducted using a conceptual project case of capturing CO_2 from a coal-fired power plant and transporting the gas via onshore and offshore pipeline to a depleted oil and gas field offshore of Malaysia. This exercise revealed a number of permits and requirement under the existing legal and regulatory framework, which can be applied to CCS. However, some issues need to be addressed in developing CCS legislation in Malaysia. Participants at a stakeholder workshop, held in Malaysia in March 2013, identified the following issues:

- CO_2 is not defined as a pollutant within Malaysia's regulatory framework.
- It is not clear which Malaysian agency would regulate the capture, transport, or storage components of the process.
- Requirement for dedicated legislation specifically for the whole CCS chain and its application to all relevant CCS sectors.
- Need to develop/adopt standards for CO_2 capture; CO_2 pipeline specifications; site characterization and selection; monitoring, measurement, and verification.
- Need to manage occupational health and safety issues across the whole CCS chain.
- Need to develop a liability regime to delineate ownership and liability for all components of the CCS chain.
- Public engagement and raising awareness of the technology would be crucial; both the land acquisition requirements and environment impact assessment process could be important mechanisms to realize this objective.
- Coordinating regulation and management across state and international boundaries will be challenging and important.

(Source: Global CCS Institute, 2013).
http://cdn.globalccsinstitute.com/sites/default/files/publications/109316/malaysian-ccs-legal-and-regulatory-workshop-report.pdf

Table 4.2 summarizes the components of CCS and the elements of existing regulations that might be used to embed CCS legal requirements.

Table 4.2 Existing regulations possibly applicable to CCS

CCS Components	Existing Regulations
CO_2 Capture	Air Pollution Control Environmental Impact Assessment
CO_2 Transport	Transport pipeline
CO_2 Storage	Non-CCS regulations cover permitting, construction, operations, and abandonment of sites
CO_2 Storage Sites	EOR Regulations (exploration permits)

The above framework is not specific to the Malaysian case study, but is also applicable to other countries that are trying to develop CCS legal and regulatory frameworks. Further work is being done in investigating the legal and regulatory framework in Malaysia.

4.3 Conclusions

Geographically, the necessary CCS legal and regulatory framework is mostly established in developed nations. These countries could be large emitters of CO_2, have large coal reserves, are committed to strong climate change policies, or may pioneer CCS R&D and technologies. Nevertheless, some of the issues are not explicitly covered in the existing legal and regulatory model.

- Post-closure, e.g. long-term liabilities and financial responsibility.
- Monitoring and verification.
- Ownership and property rights.
- Emerging health and safety issues arising from CO_2 storage.
- Stakeholder management.

It should also be noted that many of the CCS-specific legal and regulatory frameworks also 'delegate' the regulation of these issues to other pre-existing legal frameworks. Future legislation should explicitly cover the above aspects in order to minimize such liabilities and provide clarity. As more CCS projects are developed and operated for longer periods of time, stakeholder management and post-closure issues should be resolved. A robust legal and regulatory framework is vital for making CCS a preferred technology as part of climate change mitigation strategies.

References

IEA, 2012, Carbon Capture and Storage: Legal and Regulatory Review, Edition 3
OECD/IEA, 2014, Carbon Capture and Storage: Legal and Regulatory Review, Edition 4
Odeh, N. and Haydock, H., International CCS Policies and Regulations, WP5.1a/WP5.4 Report
Global CCS Institute Website
CO2CRC Website

Appendix A: Australia

A) Federal legislation:
http://www.industry.gov.au/resource/LowEmissionsFossilFuelTech/Pages/Carbon-Capture-Storage-Legislation.aspx
B) Victoria state legislation:
http://www.energyandresources.vic.gov.au/energy/about/legislation-and-regulation/ccs-regulations
C) Queensland state links:
http://mines.industry.qld.gov.au/mining/carbon-capture-storage.htm
D) Links to the Barrow Island Act and further detail on the Gorgon CO_2 Injection Project:
http://www.dsd.wa.gov.au/7599.aspx

Federal/State	Legislation/Regulation	Brief Description	Date of Enforcement
Federal	Offshore Petroleum and Greenhouse Gas Storage Act 2006 (OPGGS Act)	This Act amends the Offshore Petroleum Act 2006 to establish a system of offshore titles for carbon dioxide storage in Commonwealth offshore waters, including a framework for the transfer of long-term liability to the Government at the end of a ‘closure assurance period’ (a minimum of 15 years).	22 Nov 2008
Federal	Offshore Petroleum and Greenhouse Gas Storage (Environment) Regulations 2009	To ensure that any offshore petroleum or GHG activities are carried out in a manner consistent with the principles of ecologically sustainable development and in accordance with an environmental plan.	17 Dec 2009
Federal	Offshore Petroleum and Greenhouse Gas Storage (Safety) Regulations 2009	Include offshore GHG activities in the safety provisions for offshore petroleum activities.	8 Jun 2010
Federal	Offshore Petroleum and Greenhouse Gas Storage (Resource Management and Administration) Regulations 2011	These regulations consolidate and repeal a number of existing regulations, including the Offshore Petroleum and Greenhouse Gas Storage (Management of Greenhouse Gas Well Operations) Regulations 2010.	29 Apr 2011
Queensland	Greenhouse Gas Storage Act 2009	This Act facilitates GHG storage by: • providing for the granting of authorities: GHG authorities to explore for or use underground geological formations or structures to store CO_2 or carry out related activities • creating a regulatory system for conducting activities	18 Dec 2009

Federal/State	Legislation/Regulation	Brief Description	Date of Enforcement
		relating to GHG authorities.	
Queensland	Greenhouse Gas Storage Regulation 2010	This regulation provides requirement for: • work programs and development plans • test plans • notices: intention to drill; completion, alteration/abandonment of GHG well; intention to carry out seismic survey; and completion of seismic survey • reports: well (daily drilling, well completion & well abandonment); survey; and GHG (injection testing, storage capacity, and storage injection)	9 Apr 2010
Victoria	Offshore Petroleum and Greenhouse Gas Storage Act 2010	Key difference OPGGS vs. Victoria Act: • Separate additional state consents and the application of the Victorian criminal legislation • Relation to long-term liability for GHG activities	23 Mar 2010
Victoria	Greenhouse Gas Geological Sequestration Act 2008	To facilitate and regulate the injection of greenhouse gas substances into underground geological formations for the purpose of permanent storage of those gases, including facilitating and regulating the exploration for suitable underground geological storage formations, as part of Victoria's commitment to the reduction of atmospheric greenhouse gas emissions.	5 Nov 2008
Victoria	Greenhouse Gas Geological Sequestration Regulations 2009	Prescribe the content of the various plans required to support CCS, the collection and retention of samples and data, reporting requirements, probity matters for public servants, monitoring the expected behavior of stored greenhouse gas substances and the level of fees payable.	1 Dec 2009
Western Australia	Barrow Island Act 2003	• Intended to ratify and authorize the implementation of an agreement between the State and the Gorgon joint venture • The Act states the Petroleum Pipelines Act 1969 applies to pipelines on Barrow Island. The definition of 'pipeline' was modified to include a 'pipeline for the conveyance	20 Nov 2003

Federal/State	Legislation/Regulation	Brief Description	Date of Enforcement
		of carbon dioxide to a place on Barrow Island for the purpose of disposing of the CO_2 in underground reservoir or other subsurface formation'	

Relevant Guidelines

Australian Guiding Principles for Carbon Dioxide Capture and Geological Storage (Guiding Principles)	Environmental Guidelines for Carbon Dioxide Capture and Geological Storage

• Endorsed by the Ministerial Council on Mineral and Petroleum Resources (MCMPR)
• Relevant reference, non-legally binding.
• Purpose: to promote consistency in the development of a CCS regulatory framework across the Australian states and territories.
• Address the following issues:
  • assessment and approval processes
  • access and property rights
  • transportation issues
  • monitoring and verification
  • liability and post-closure responsibilities
  • financial issues
	• Endorsed by Australian Environment Protection and Heritage Council (EPHC)
	• Non-legally binding
	• Provide relevant supplementary information on:
	  • environmental assessment of CCS activities
	  • monitoring of injected GHG substances
	  • site closure
	  • the need for co-ordination across jurisdictions.

Appendix B: Canada

http://www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/00_08036_01

Federal/State	Legislation/Regulation	Brief Description	Date of Enforcement

Alberta	Carbon Capture and Storage Statutes Amendments Act 2010	• This Act amends the following regulations to clarify the regulatory structure for CCS in Alberta:
		  • the Energy Resources Conservation Act
		  • the Mines and Minerals Act
		  • the Oil and Gas Conservation Act
		  • the Surface Rights Act
		• Alberta Government has the ownership of pore space and is authorized to grant licenses and leases for the injection of CO_2.
		• Requirements for Site Closure Certificate:
		  • Licensee to make payments into a post-closure stewardship fund that will contribute to covering the province's assumed liability, the costs of monitoring the site, and the management costs of CCS facilities.
			2 Dec 2010

Alberta	Carbon Sequestration Tenure Regulation (AR 68/2011)	• Defines pore space • Establishes the term for permits and leases • Limits the size of land for permits and leases and sets the annual rental fee • Establishes a minimum depth for the injection of CO_2 • Creates the requirement for monitoring, measurement, and verification plans, and closure plans, which must be approved by the Minister and updated every three years.	28 Apr 2011
Alberta	Carbon Capture and Storage Funding Act 2009	Allocates $2 billion of funding for CCS demonstration projects	4 Jun 2009
British Columbia	Petroleum and Natural Gas Act [RSBC 1996]	• CO_2 storage rights	
British Columbia	Oil and Gas Activities Act [SBC 2008]	• To regulate oil and gas activities: • provides for sound development of the oil and gas sector by fostering a healthy environment, a sound economy, and social	

Federal/State	Legislation/Regulation	Brief Description	Date of Enforcement
		well-being • conserves petroleum and natural gas resources • ensures safe and efficient practices • assists owners of petroleum and natural gas resources to participate equitably in the production of shared pools of petroleum and natural gas; • To provide for effective and efficient processes for the review of applications for permits and to ensure that applications that are approved are in the public interest having regard to environmental, economic, and social effects; • To encourage the participation of First Nations and aboriginal peoples in processes affecting them; • To participate in planning processes; • To undertake programs of education and communication in order to advance safe and efficient practices and the other purposes of the commission.	
Saskatchewan	The Pipelines Act 1998	• Covers pipelines transporting CO_2. It regulates the licensing, by the Ministry of Energy and Resources, of the construction and operation of CO_2 pipelines in Saskatchewan. • Amended in 2009 to cover CO_2 pipelines for non-oil and gas purposes.	
Saskatchewan	Pipelines Regulation 2000	The Regulations implement the Pipeline Act.	
Saskatchewan	Crown Minerals Act	Authorizes agreements for the lease of spaces and Crown ownership of minerals on Crown lands	
Saskatchewan	Oil and Gas Conservation Act	• Amendments in 2011 to expand powers and oversight for the storage of CO_2 and other greenhouse gases. • Term ‘non-oil-and-gas waste’ replaced with ‘non-oil-and-gas substance’ to clarify scope to substances from ‘prescribed industry’. • The long-term liability for storing CO_2 is borne by well license holders. • This Act covers the construction, operation, and decommissioning of flowlines, pipelines that connect a wellhead to another facility, such as a gas compression unit	

Federal/State	Legislation/Regulation	Brief Description	Date of Enforcement

Saskatchewan	Oil and Gas Conservation Regulations, 2012	• Part VIII – Production Operations:
		  • Minister may approve or refuse CO_2 disposal plan subject to terms and conditions and be provided with any information required
		• Examples of other applicable parts to CO_2 disposal:
		  • Well testing and measurement and data requirements
		  • Records and reporting	

Regulatory Update

Released Natural Gas Strategy in February 2012.

- One of six action items within 'Natural Gas Is a Climate Solution' is to promote CCS:
  - Completing development of a regulatory framework
  - Amending legislation, if required
  - Working with the BC Oil and Gas Commission to develop regulations
- BC oil and gas legal and regulatory framework update to identify gaps and changes to facilitate CCS projects. Some gaps identified to date include:
  - site selection
  - monitoring, reporting, and verification
  - long-term liability
  - Nova Scotia (NS) introduced the Environmental Goal and Sustainable Prosperity Act
  - Emission reduction target of 10% relative to 1990, by 2020.
  - Energy efficiency and renewables are the focus.
  - Emissions from the power sector will be reduced by 46% by imposing increasingly stringent caps on power plants in NS, and CCS is briefly mentioned as an option for reductions.

Appendix C: European Union

Legislation/Regulation	Brief Description	Date of Enforcement

Directive 2009/31/EC on the Geological Storage of Carbon Dioxide	Applicability: Within the territory of the Member States, their exclusive economic zones, and on their continental shelves, thus envisaging storage both onshore and offshore.
	
	Capture Requirements:
	• Incorporation within the EU's Integrated Pollution Prevention and Control (IPPC) Directive (Art. 37)
	• All operators of capture installations:
	    • to obtain an IPPC permit
	    • to carry out an assessment of the likely significant effects on the environment of any capture facilities in accordance with the provisions of the Environmental Impact Assessment (EIA) Directive (Art. 31)
	• Public consultation must be conducted and taken into account for permitting the facility under IPPC.
	
	Transport Requirements:
	• Environmental Impact Assessment
	
	Storage Requirements: Site selection and exploration:
	• Conduct site characterization to ensure storage site poses no risk of leakage/damage to the environment and human health.
	• Apply for exploration permit if drilling is required.
	• Storage permits.
	• Permit is granted to suitable sites only.
	• Permit is required to operate the site.
	• Operator to demonstrate they are technically competent and reliable to operate the site.
	• Operator to demonstrate they are financially sound and able to provide financial security to cover costs relating to the operation and post-closure periods of the storage site until responsibility is transferred.
		25 Jun 2009

Legislation/Regulation	Brief Description	Date of Enforcement
Council Directive 85/337/EEC	• Applies to the capture and transport of CO_2 streams • Assessment of the effects of certain public and private projects on the environment	27 Jun 1985
2009/31/EC Directive	• Selection of storage sites, exploration permits; • Storage permits (application procedure, conditions, content, and the requirement for the EC to review permits, and changes and withdrawal of permits). • Operation, closure, and post-closure obligations including CO_2 stream acceptance criteria, monitoring, reporting by operator, inspections by authority, measures in case of leakage, transfer of responsibility, financial security, and financial mechanisms	
EU Directive (Directive 2009/31/EC)	• Applies to projects with intended storage of >100 kt CO_2. • Permitting of exploration and storage.	25 Jun 2009
Directive 2008/1/EC	• Applies to capture of CO_2 streams. • Regulating risks of CO_2 capture to the environment and human health.	

Regulatory Update

- European Commission to carry out assessment on carbon capture readiness requirement. Review will consider:
    - The need for, and practicability of, imposing CO_2 emission performance standards (EPSs), which would place a quantitative limit on the amount of CO_2 that can be emitted from the regulated combustion plants.

Appendix D: Germany

http://www.iea.org/publications/insights/insightpublications/CCSReview_4thEd_FINAL.pdf

Legislation/Regulation	Brief Description	Date of Enforcement

• CO_2 Storage Act
• CCS Act
• Environmental Damage Act
• Act on Administrative Procedure
• Mountain Act
• Regulation on Large Combustion Plants and Gas Turbines
	• Limitations to CO_2 storage
	  ◦ Only research, pilot, and demonstration projects permitted
	  ◦ Storage of CO_2 restricted to certain parts of Germany
	• CO_2 storage and exploration permits
	• Liability
	  ◦ Closure of the storage site and permit withdrawal
	  ◦ Liability of the operator
	  ◦ Transfer of liability from the operator to competent authority.
	• Capture and transport
	  ◦ Carbon capture readiness requirement for large combustion plants and gas turbines.
	  ◦ Construction, operation, and substantial change of pipelines for the transportation of CO_2 require a permit.
	• Public participation
	  ◦ Public has the right to obtain technical information on the proposed and future pipeline.
	  ◦ Publicly available register contains information on:
	    ▪ All CO_2 transport lines that were applied for or permitted
	    ▪ All CO_2 storage permits that were applied for or granted
	    ▪ Storage sites that were closed or responsibility that was transferred to a public authority.
	  ◦ Applications are made available to the public for review.
		24 Aug 2012

Appendix E: Norway

Legislation/Regulation	Brief Description	Date of Enforcement
Pollution and Waste Act (Act No. 6)	• Protection Against Pollution and Concerning Waste. • Covering application and withdrawal of permits, the authority's responsibilities, inspection, provision of information, closure, and liability of CO_2 storage.	13 Mar 1981
Petroleum Act (Act No. 72)	• Provides the main regulatory framework for the storage of CO_2 from petroleum activities • Oil deposits in Norwegian territorial seas are owned by the Norwegian State. • All petroleum activities, e.g., EOR or permanent storage under the continental shelf. • Permit for storage.	29 Nov 1996
CO_2 Tax Act (Act No. 72)	Tax on discharge of CO_2 in the petroleum activities on the continental shelf.	21 Dec 1990
The Continental Shelf Act (Act No. 12)	• Scientific research and exploration for, and exploitation of, subsea natural resources other than petroleum resources. • Covers the building and operation of pipelines, exploration of offshore reservoirs for permanent storage, need for an EIA, monitoring, or third party access to pipelines or storage.	12 Jun 1963
Royal Decree of 2009	Delegation of Authority in CCS matters under the Act of 21 June 1963 No. 12, relating to Scientific Research and Exploration for and Exploitation of Subsea Natural Resources Other than Petroleum Resources. • The Norwegian Government has delegated regulatory authority to the Ministry of Petroleum and Energy, and to the Ministry of Labour and Social Affairs in respect of the exploration for and transport and offshore storage of CO_2.	13 Mar 2009
Petroleum Regulations	Regulations to the Petroleum Act, laid down by Royal Decree on 27 June 1997, last amended by Royal Decree No. 729.	2 Jul 2012
Pollution Control Act	Applicability: • Emission permit is required prior to emitting large amounts of CO_2. • CO_2 emissions from industrial plants are considered to be pollution. Areas covered: • Permit application	

Legislation/Regulation	Brief Description	Date of Enforcement
	• Permit withdrawal • Responsibility of authority • Duty to provide information • Right of inspection • Closure and stoppage of operations and liability.	
Norwegian Greenhouse Gas Emission Trading Act	• Power plants that install CCS • Submit quotas equivalent to their remaining emission. • Stored CO_2 will be considered as non-emitted but leakage may occur from capture, transport, and storage, and so there will be a need to clarify the responsibility for leakage in Norwegian law (which is currently not regulated)	

Regulatory Update

- A party to the Agreement on the European Economic Area. Considering transposing the EU CCS Directive into Norwegian legislation and regulation.
- Draft CCS-specific regulations relating to transport and storage of CO_2 in offshore reservoirs were intended to be published for public consultation in 2012, but had not occurred as of March 2013 (Bellona, see website)
    - The draft will be based on the provisions of the EU CCS Directive as well as existing national petroleum legislation.
    - The Norwegian Greenhouse Gas Emission Trading Act covers the capture, transportation, and storage of CO_2 at power plants.

Appendix F: The Netherlands

Regulatory update

- Amending the Dutch Mining Act of 2003 to withdraw production licenses where there are no more activities.
- Gas companies would like to inject CO_2 into their existing gas fields.
- Difficulty in transferring licenses in cases where the storage licenses are given to different operators while the production licenses are still valid.

Appendix G: United Kingdom

Legal and Policy Framework to Support CCS	In the Pipeline
• Launched Climate Change Program in Nov 2010 • Climate Change Act Nov 2008 • Energy Act 2010—focus on CCS, and established explicit levy on electricity suppliers to provide financial assistance. • Office of Carbon Capture and Storage Oct 2010—a CCS roadmap combining renewable energy, CCS, nuclear, and other low-emission sources. • Transposed a Directive from the European Parliament on safe geological storage of CO_2. • Petroleum, Energy Act and Crown Estate license requirement for any drilling or injection (1 Oct 2010) • Emissions Performance Standard—set a legal limit on the emission from power generation. Energy Act 2013 with Contract for Difference (CfD) mechanism to provide a stable revenue stream for developers of eligible low-carbon electricity generation, i.e., with CCS.	• Develop common principles for managing and regulating the transport, injection, and permanent storage of CO_2 in the North Sea sub-seabed (UK Government and North Sea Basin Task Force). • Capture plant and pipelines will be regulated under the Health and Safety at Work etc. Act 1974.

Items	Energy Act 2008	Energy Act 2010
Applicability	• Territorial sea adjacent to Scotland (0 to 12 nautical miles). • Any controlled space or the transformation of a controlled space for the purpose of CO_2 storage including EOR.	
Areas Covered	• Gas importation and storage • Importation and storage of combustible gas • CCS • Electricity from renewable sources • Decommissioning of energy installations	• Matters relating to the demonstration, assessment, and use of carbon capture and storage. • Reporting on the decarbonization of electricity generation and development and use of CCS technology in the UK. • Gives the UK Government powers to provide financial assistance to projects in Great Britain that

	• Offshore renewables installations • Oil and gas installations, feed-in tariffs, and other general areas	demonstrate and assess CCS technology through its use in commercial electricity generation.
Relevant Chapters	Part 1, Chapter 3 • Exploration permits • Site certification and storage permits • Licensing of CO_2 storage for the purpose of its permanent disposal • Enforcement of the license	Part 1: CCS technology and decarbonization with respect to its financing.

Regulations that accompany the Energy Acts' provisions:

a) The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010:

http://www.legislation.gov.uk/uksi/2010/2221/contents/made

b) The Storage of Carbon Dioxide (Termination of License) Regulations 2011
http://www.legislation.gov.uk/uksi/2011/1483/crossheading/termination-where-a-storage-site-has-been-closed-in-accordance-with-the-terms-of-a-licence/made

c) Storage of Carbon Dioxide (Access to Infrastructure) Regulations 2011

Appendix H: USA

Legislation/Regulation	Brief Description
American Clean Energy and Security Act	• Passed by House of Representatives on 26 June 2009. • Companion Bills currently at various stages in the Senate. • Overall Act will not be implemented until it approved by the US Senate.
Carbon Capture and Storage Early Deployment Act (Boucher Bill)	• Introduced 24 March 2009; currently in committee. • Provides for a referendum of relevant industries to incorporate a CCS Research Body to raise and distribute funds to CCS programs.
Carbon Capture and Sequestration Program Amendments Act	• Introduced 7 May 2009. • Would establish a demonstration program for CCS. • Has been partly incorporated within the American Clean Energy Leadership Act, so may not proceed.
American Clean Energy Leadership Act	• Introduced 16 July 2009; awaiting consideration by Senate. • Provides a regulatory framework for CCS as well as financial assistance for demonstration programs. • Include process to obtain certification; requirements for monitoring, record keeping, and reporting; public participation in the certification process; and sharing of data between states, Indian tribes, and the EPA. • Requirements to maintain evidence of "financial responsibility for remedial and emergency responses, well plugging, site closure, and post-injection site care"
Carbon Storage Stewardship Trust Fund	• Introduced July 22, 2009. • Provides for long-term Federal stewardship of storage sites, accompanied by a trust fund to meet costs and liabilities.
Underground Injection Control (UIC) Program for CO_2 Geological Storage	• To create a new category of well (Class VI) under its existing UIC
Interstate Oil and Gas Compact Commission (IOGCC) Guidelines	• Published September 2007. • Detailed rules based on EOR, acid gas injection, and natural gas storage regulation. • Includes ownership, permitting, verification, monitoring, and liability. • Legal and Regulatory Guide for States. States will choose whether or not to adopt IOGCC models, modify them, or just ignore them. • H_2S, NO_X, and SO_2 impurities remain covered by existing regulations. • The regulator is the "State" regulatory agency not the "Federal" EPA.

Appendix I: Current Regulatory and Legislation Framework Updates on CCS

Country	Legal and Policy Framework to Support CCS	In the Pipeline
Japan	• The Marine Pollution Prevention Law was revised in Sep 2007 to allow CO_2 storage in the sub-seabed. • Environmental and safety guidelines "for safe operation of a CCS demonstration project" were formulated in 2008.	• N/A
Qatar	• Law No. 30 of 2002—requirement for the reduction of GHG emissions, i.e. offset the effects of pollution and to prevent environmental damage in general.	• Submitted a proposal to the UN in 2012 for greater emphasis on CCS in the Clean Development Mechanism (CDM) of the Kyoto Protocol. • Qatar University's Gas Processing Centre released the Carbon Capture and Management Road Map in Oct. 2012.
Poland	• Polish Energy Policy until 2030—requires renewable energy sources to satisfy 15% of the country's energy consumption by 2030. • Swedish–Polish Sustainable Energy Platform—exploring the implementation of CCS technology.	• Amendment of Environmental Impact Assessment Act and the Energy Law to include CCS related activity.
Scotland	• Climate Change Act 2009—set a target of producing 80% of Scotland's energy from renewable sources by 2050 (excluding nuclear).	• Amendment to Schedule 1 of PPC (Scotland) Regulations 2000 to include license for storage 12–200 nautical miles from the coast.
South Africa	• National Climate Change Response Policy (endorsed by Cabinet on 12 Oct 2012), identifies CCS as one of eight Near-term Priority Flagship Programs. • CCS Roadmap was endorsed by the Cabinet on May 2012.	• Currently exploring how a test injection project can be accommodated within the existing regulatory regime, including undertaking further basin-scale storage studies.

Appendix J: Malaysia

http://cdn.globalccsinstitute.com/sites/default/files/publications/109316/malaysian-ccs-legal-and-regulatory-workshop-report.pdf

Potential Permitting Matrix for CCS Projects in Malaysia

CCS Aspects	Design and Construction	Operations	Decommissioning
Capture	• New power plant—development approval process • New industrial facility—development approval process • Land development approval • Threatened species impact approval • Water management plan approval • Environmental licenses • Existing power plant—retrofitting approval • Pollution licenses • Occupational Health and Safety—obligations	• Classification of CO_2—licensing requirements • Liability—failure to capture • Management approvals/qualifications • Taxation of CO_2 • Noise approval	• Decommissioning requirement • Contaminated Land
Transport	• Transport license • Pipelines license • Pipelines—operating existing infrastructure • Pipelines—new pipeline approval • Pipelines—third-party access and existing use rights	• Operation license • Liability for fugitive emissions • Monitoring obligations • Maintenance requirements	• Decommissioning obligation • Contaminated lands • Insolvency event

Storage	• Surface and sub-surface rights—who owns CO_2?
	• Surface and sub-surface rights:
	    • Who owns pore space?
	    • Access to surface infrastructure?
	• Exploration permit
	• Test injection permit
	• Planning approval requirements
		• Classification of CO_2—licensing requirements
		• Storage license
		• Duration of license
		• Monitoring and verification
		• Fugitive emissions
		• Emergency Incidents
		• Occupational Health & Safety
			• Closure certificate
			• Liability for stored CO_2
			• Financial provisions
			• Obligations in the event of insolvency
			• On-going monitoring obligations

5. Public perception on CCS

5.1 Introduction

The experience of CCS demonstration projects worldwide shows that public communication, engagement, and acceptance are central to project success, and to the subsequent development and deployment of CCS at a commercial scale. Building and reinforcing trust between developers and other key stakeholders through various kinds of communication and engagement activities is vital. There is a strong need to increase understanding of CCS technology and its wider low-emission energy context. The pertinent elements of public engagement include the following:

- Shared vision
- Considerations of social context
- Flexible project implementation strategy
- Early engagement with stakeholders
- Constant communication between project proponent and stakeholders
- Targeted framing and messaging

Although the above elements do not guarantee full support from all stakeholders, they provide the project proponent strong fundamentals in addressing stakeholders' concerns.
This report examines four case studies, which were selected based on their success or failure in securing public acceptance. The factors that contributed to each project's success or failure are highlighted, and pertinent lessons are discussed.

5.2 Case Study 1: The Carson Project, California

The Carson Project, located in California, was a joint-venture project and one of the first proposed CCS project in the world. The 500 MW commercial hydrogen power plant project was announced in February 2006 and was designed to generate base-load power from CO_2-rich petcoke and to capture and store 90% of its CO_2 emission. It was the first of its kind to produce low-carbon electricity to power 325,000 homes in California (Global CCS Institute, n.d.). The project location has high potential for CO_2-EOR, but with dense population (see Figure 5.1). The project cost was estimated at USD 2 billion. However, the US Department of Environment and Internal Revenue Service awarded the project USD 90 million in tax credits under the EPA Act of 2005.

Figure 5.1 Site location for the Carson Project, California (Source: CSIRO, 2010)

Capture	• ~90% of CO_2.
Transport	• Option 1: 16 km pipeline, south to Long Beach • Option 2: 160 km pipeline, through Beverly Hills to north of Los Angeles.
Storage	• Depleted oil/gas field or saline aquifer • Potential enhanced oil recovery

The Government of California has not established a clear legal or regulatory framework for CO_2 storage and long-term viability. The Carson community expressed concerns against CCS, including:

- CCS will further dependence on fossil fuels and hinder development of sustainable/renewable energy.
- Potential leakage through old/'orphaned' oil wells (issues of well integrity).
- Burning of petcoke releases 'vast' amounts of pollutants into the air.
- Creation of hydrogen poses a 'huge' fire hazard.
- Exposure to high concentration of CO_2 is fatal.
- The stored CO_2 will be in a liquid form, called carbonic acid. It will eat through the limestone that encases the proposed oilfield and/or the cement that plugs nearby plugged wells, allowing it to escape.
- If large quantities of CO_2 were to leak, it would remain concentrated in the already polluted Los Angeles Valley and constitute a public health disaster.

The proposed location is in a densely populated area with urban and industrial settings. Major sources of employment include nearby petroleum refining, aerospace, and automobile industries, and the Port of Los Angeles. Petcoke with CCS was perceived as a sub-optimal means by which to manage CO_2 emissions. At that time, a natural gas combined cycle gas turbine (CCGT) represented the best available control technology (BACT) for use in the LA basin area. As petcoke is a CO_2-rich source, it was acknowledged that natural gas is a better and cleaner fuel.

In mid-2008, the trade press reported that a new partnership had filed an application for a "Hydrogen Power Plant in the Kern County Area, Comprising CCS related to EOR." In May 2009, the local media reported that the Carson project had been "quietly abandoned."

Lessons learned

- Public outreach could have been integrated into initial project planning and management.
- The proposed power plant had severe pre-existing air quality problems. The earliest media coverage focused on air pollutants from the proposed capture plant, not on the integrity of the storage facility, etc.
- Be prompt and avoid delay in contacting stakeholders for potential support from vocal environmental justice representatives.
- Address all concerns and questions raised by the public: The project proponent failed to address questions about the site of the plant and the storage.
- Wrongly focused public information: The project proponent focused on the power plant and carbon capture instead of the storage site.
- Misalignment between different levels of government can prove exceptionally difficult for projects.
- Visible conflict at these levels erodes public confidence and provides a gap to be filled by groups with inaccurate but well-articulated and damaging views on CCS.
- The Carson project represents a significant attempt to move into uncharted commercial territory at a pivotal time in the development of CCS; the lessons may benefit future projects.

5.3 Case Study 2: Barendrecht CO_2 Storage Project

The Barendrecht CO_2 Storage Project was a small demonstration project located in the North Sea from 2007 to 2010. The project was intended to demonstrate the technical and economic feasibility of a large-scale, integrated CCS-chain. It remains one of the largest CCS demonstration projects in the world.

Figure 5.2 Location of the planned CO_2 pipeline and gasfield in Barendrecht (Source: Shell CO_2 Storage, 2008)

Capture	• Capture and compress CO_2 from hydrogen production plant, which is part of a large oil refinery.
Transport	• 16.5 km steel pipeline along Rotterdam between Pernis and Barendrecht.
Storage	• Expended gas fields 2–3 km beneath Barendrecht, and partly under the neighboring town of Albranswaard. • Smaller field: ~1,700 m depth (Barendrecht–Ziedewii) with capacity: 0.8 million ton. • Larger field: ~2,700 m with capacity of 9.5 million ton.

Barendrecht was identified as suitable for CO_2 storage because it is very close to Pernis, where the CO_2 stream from the hydrogen plant is very pure and requires no additional treatment; it can therefore be collected more cost-effectively, using an existing installation. The first gas field is relatively small. However, the gas fields will be fully depleted in 2010 and 2013, and thus utilizable for CO_2 storage. There are additional other factors supporting Barendrecht as the selected demonstration site, including:

- The Chair of the Rotterdam Climate Initiative (RCI) was formerly the Dutch Prime Minister and also a member of the Dutch CCS Taskforce.
- CCS was acknowledged as a CO_2 abatement option in Dutch Climate and Energy Policies in 2007.
- Establishment of a public–private partnership.
- The Dutch Government released €60 million for two CO_2 storage demonstration projects in November 2008.
- Rotterdam aims to be "the world capital of CO_2-free energy."
- Plans to develop the Rotterdam Port area ('Rijnmond') into a major hub for CCS.
- High concentration of CO_2 point sources in close proximity to onshore and offshore storage sites, and existing CO_2 infrastructure for easy connection.

Despite the positive and supporting factors listed above, the project faced significant difficulties. The local community raised concerns over the CCS project. A generic Environmental Impact Study on CO_2 Storage Study concluded that policy is necessary to prohibit the storage of CO_2 in densely populated areas, due to its potential environmental impacts. Barendrecht is a suburb of Rotterdam in the province of South Holland, which in 2013 had a population of approximately 47,000. The local community raised concerns about the technical details and safety of the project. Debates over these issues took place mostly via press releases and the media, with almost no direct communication between the local government and the project developers. The national government had limited visibility at the public meetings; there was a short presentation by the ministry's representative, and only limited attention was given to the standpoint of the national government, the role of this project in a national context, and to related national policy. This created the feeling that the project was Shell's and was intended to serve the company's private and personal interests. At the same time, a project in Geleen received a grant from the same tender, meaning that the internal debate and normal dualism between the local council and executive board was put aside. The Barendrecht community responded by:

- Growing participation during public meetings:
  - 60 people attended the first public meeting
  - 180 people attended the second public meeting
  - 1,000–1,100 visitors attended the public information meeting

- One of the local party leaders scrutinized Shell's EIA procedure on the CCS study.
- Local political debate successfully raised a motion in Jun 2008: more research was needed before the project could be accepted or rejected.
- A consultation group was established, with most local party leaders as members.
- GroenLinks (the local Green Party) initiated a petition (900 signatures) and a protest walk against CCS (300–400 people participated).
- Consultation group, the Council and Alderman set up a checklist (finalized in Dec. 2008) consisting of 100 questions covering general issues, safety, risk analysis, geological research, effects on property values, legal issues, and monitoring.

Lessons learned

- Early start of communication activities.
- Timely, sufficient, and transparent information.
- Involvement of relevant stakeholders.
- Two-way communication (e.g. active listening, responsiveness).
- Involvement of stakeholder interests in decision-making process.
- Clarity on objectives and expectations.
- Good and open relations with local governments (e.g. Aldermen) are a valuable asset for CCS projects.
- Local government representatives can act as bridgehead between local communities and a CCS project.

5.4 Case Study 3: Jänschwalde CCS Demonstration Project, Germany

The Jänschwalde CCS demonstration project was proposed by a Swedish state-owned energy company in 2008. The 300-MW plant was to be located at Jänschwalde, Brandenburg, Germany, and would have obtained CO_2 from lignite coal from nearby opencast mines. Figure 5.3 gives an overview of the project.

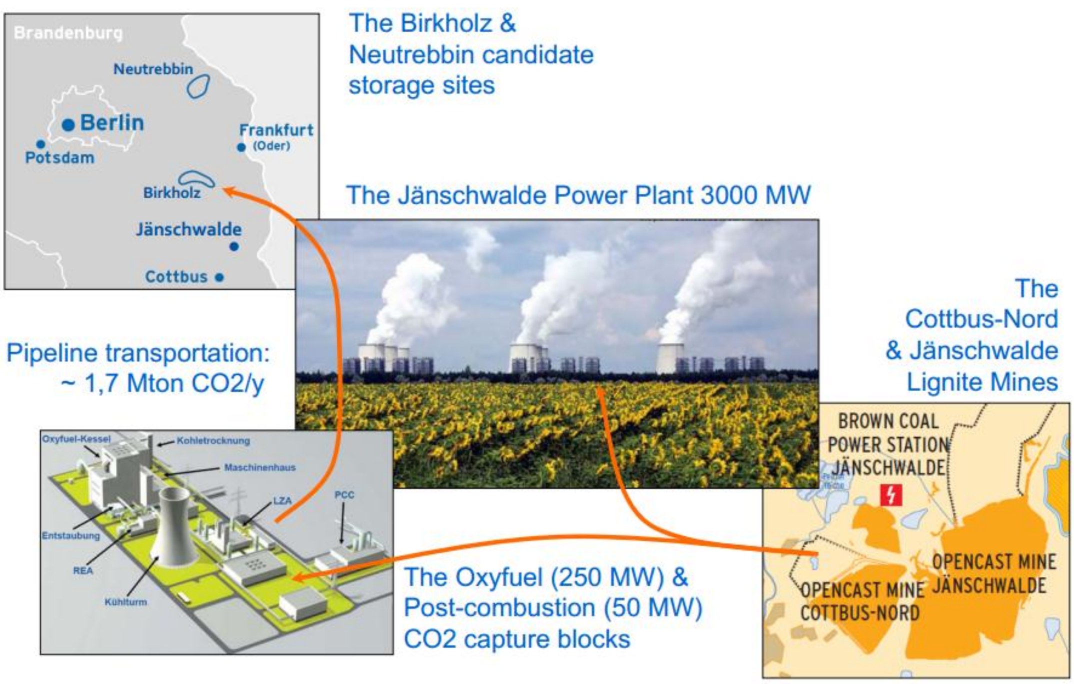


Figure 5.3 An overview of the demonstration project in Jänschwalde

Capture	• Oxy fuel combustion and post-combustion
Transport	• Road

Storage	• Mesozoic and Cenozoic sandstones in the eastern part of the North-German Basin.
	• Open and closed structures at a depth of 900 to 4000 meters.
	• Two structure formations:
	    • the Birkholz structure (50 km from the project)
	    • the Neutrebbin structure (140 km from Jänschwalde power plant)

The project proponent has a structured plan for its stakeholder engagement and management.

- Invested in public outreach activities, such as brochures, public meetings, exhibitions, information center, expert presentations, school visits, pilot plant tours, documentary film, direct mail shot, and a website (www.vattenfall.de/ccs).
- Integrated public outreach in its project management. This was apparent when the planned public activities were suspended, based on suggestions from communications experts, due to a public initiative against new opencast mines in Brandenburg.
- Established a strong outreach team that included setting up a local information center where residents, tourists, and employees can obtain information, hold discussions, and learn about the project. This center is operated by a colleague living in the city, enabling the company to make use of various personal contacts.
- Identification of key stakeholders, resulting in close working relationship with the Ministry for Economy in the Federal State of Brandenburg, who has been involved in the planning of the whole process and has played an active role from the start. The project proponent has also set up a local advisory council that complements the permitting process, and acts as a hub between the project proponent and the authorities on the one side and the local community on the other.
- Conducted and applied social characterization. The project proponent conducted surveys and interviews with the local community to identify issues faced by the community. They made efforts to address these issues through small engagements with the local communities, such as helping school classes to realize their projects, etc.
- Developed an outreach strategy and communication plan. The project proponent has reiterated the following messages in their public outreach:
    - Global climate protection is only possible with CCS
    - The project proponent holds a leading position in the development of this technology
    - High-tech: made in Germany
    - Safety is the top priority when it comes to storing CO_2
    - Security of supply is only possible with CCS
    - CCS needs support(ers)

However, regardless the project proponent's continuous efforts to structure stakeholder engagement and management, there was still opposition to the project among the local community.

Figure 5.4 Opposition campaigns against Jänschwalde CCS Demo Project

Additionally, the project proponent also experienced external pressure from other aspects, such as a legal requirement on CCS where the German Bundesrat (Federal Council) rejected the CCS bill on 23 September 2011 because CCS is not perceived to be a green technology in Germany; lack of funding (total investment: €1.5 billion: €1.2 billion for capture and €0.3 billion for transport and storage); inappropriate communication tool (initially, the project proponent had been working with the "standard" material that the company used for all purposes, and had produced a brochure matching that style. Later, it became clear that glossy brochures were not the right communication tool to encourage local people to trust the company); the local community seemed to trust academic experts rather than the project proponent's employees, who are experts in their respective fields; and public perception: Any large-scale project will experience difficulty securing public approval in Germany.

Lessons learned

- Massive need to increase the general awareness of CCS.
- CCS should be an integral part of national energy plans.
- Building trust in local areas.
- Develop models for co-ownership.
- Early emphasis on understanding who defines the acceptance criteria for exploration and site selection, and then deciding what the acceptance criteria are.

After much consideration, the project proponent cancelled the proposal in December 2011. The project was in the final engineering phase when it was called off. This provides clear evidence that there is a great need for CCS legislation in Germany to support CCS projects and give assurances to local communities on the health, safety, and environment issues.

5.5 Case Study 4: The ROAD Project, North Sea

The Rotterdam Opslag and Afvang Demonstratieproject (Rotterdam Capture and Storage Demonstration Project; better known as ROAD) was a project located in the North Sea. The project was announced in April 2008 to demonstrate the technical and economic feasibility of a large-scale integrated CCS chain. It remains one of the largest CCS demonstration projects in the world.

Figure 5.5 Location of ROAD CCS chain: Rotterdam port and industrial area and North Sea

Capture	• Applies post-combustion technology to capture CO_2 from flue gases of a new 1,100 MWe coal-fired power plant (Maasvlakte Power Plant 3) in the port and industrial area of Rotterdam. • Capacity of capture unit: 250 MWe equivalent. • Aim: 1.1 million ton of CO_2 per year. • Operation target: 2015.
Transport	• Pipelines 5 km over land and 20 km across the seabed to the P18-A platform in the North Sea.
Storage	• Depleted gas reservoirs under the North Sea. • Location: Block P18 of the Dutch continental shelf, ~ 20 km offshore; depth: ~ 3,500 m below the seabed of the North Sea; estimated storage capacity: ~ 35 million ton.

Understanding that the ROAD project represented one of the largest CCS projects in the world, the project proponent assigned a dedicated team to stakeholder management, consisting of the following specialists:

Specialist	Roles and Responsibilities
Communication and public engagement	• Communicating objectives, strategy, key messages, activities, and materials. • External communication activities and materials with (possible) high exposure for stakeholders are reviewed by technical specialists for accuracy of facts and figures. • Technical specialists have received presentation training for public events. • Periodic meeting of the communication task force, providing a platform to regularly exchange views on communication objectives, strategy, key messages, on-going activities, and materials of the project. In addition, regularly updated insights from stakeholder contacts are taken into account, to enhance an outside-in perspective and create positions that are mutually beneficial.
Regulatory affairs	• Identifying and managing all relevant legislative dossiers. • Supporting all relevant stakeholders to develop an effective legislative and regulatory framework for deploying large-scale CCS projects in the Netherlands.
Permitting	• Managing EIA procedure and permitting application. • Coordinating relations with all relevant authorities.
Funding agreement management	• Managing funding agencies and related matters.
Knowledge dissemination	• Managing circulation of information on the project.

The project proponent made substantial investment in their public outreach plan, which included individual presentations to key stakeholders; a project brochure and project website; frequently asked questions; town hall meetings; working visits; press releases, media briefings, op-ed articles, and advertorials; stakeholder roundtables; and a regional advisory committee on CCS.

Figure 5.6 Town hall meetings and E.ON visitor center

The proponent has mapped the social–political context and issues in order to further understand their stakeholders.

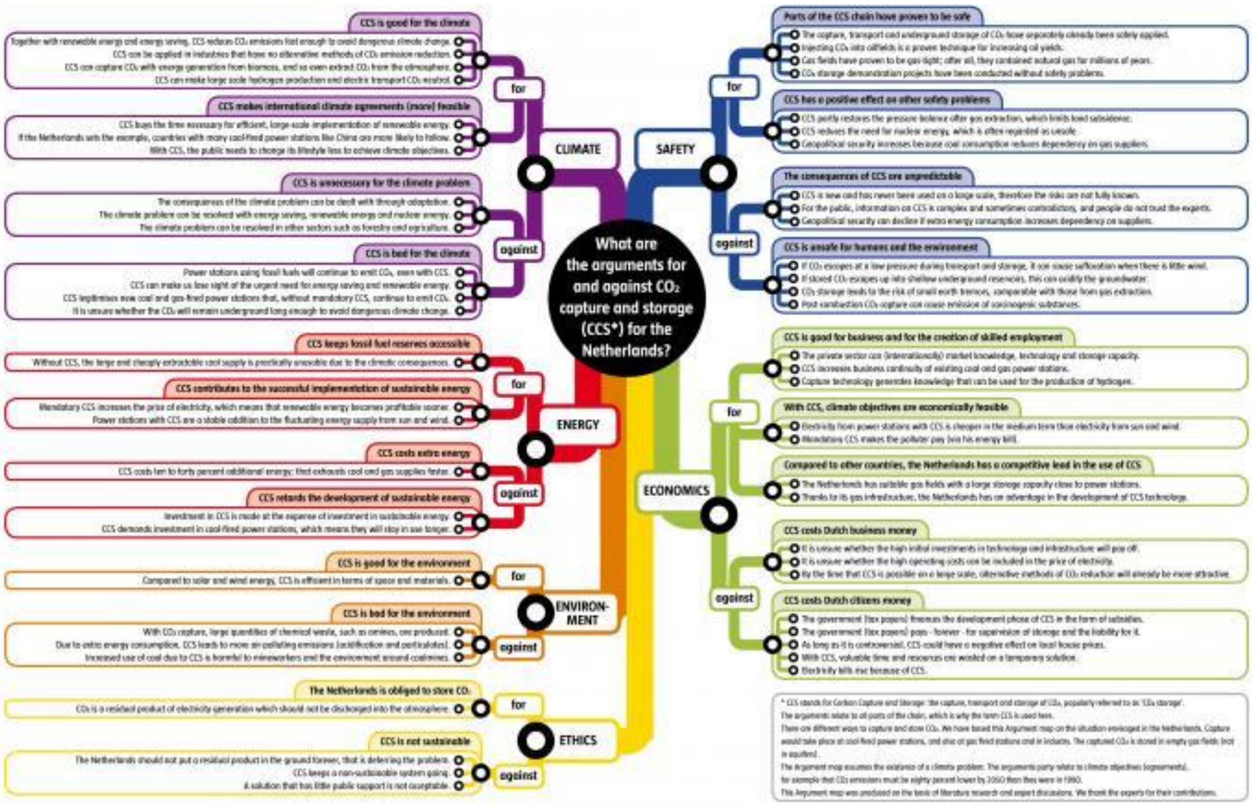


Figure 5.7 Mapping of the social-political context and issues (http://www.co2-cato.org)

They also have mapped their stakeholders, to determine in which quadrant of the stakeholder map they are located (see Figure 5.8).

- Local communities and civic groups
- Regional NGOs
- Local and regional governments and authorities
- Regional business platforms (e.g. ports and industrial areas)
- National government and parliament
- Local and national media
- National NGOs
- Knowledge institutes

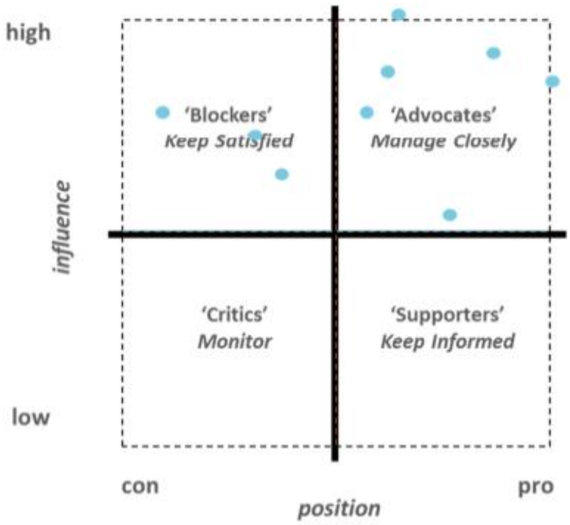


Figure 5.8 Stakeholder map

The project proponent has utilized different methods to understand the stakeholders' perceptions, including:

- Opinion surveys and focus groups
- Consultation of regional stakeholders
- NEARCO2 research project (e.g. Energy Centre of the Netherlands) on public perceptions of CCS; and
- Consultation of the Global CCS Institute on public engagement.

Lessons learned
• Integrate stakeholder management and communication functions within the project management. • Technical experts should receive training in presentation, conversation, and how to adequately cope with emotional situations. • The stakeholders' positions in and perceptions of the project are largely determined by how the project affects the daily life of local communities. • Include structural mechanisms to inform key stakeholders who can act as ambassadors and advocate for the project. • With a two-way communication strategy and insights into the expectations and mutual interests of stakeholders, the project will be better able to secure public acceptance in the long term. • Focus not only on climate change, but also on the economic benefits and local value propositions that CCS can offer to local communities. • CCS is technical and complex; for local communities, it is easier to understand and experience images and tangibles than words and numbers.

5.6 Public Perception Study by GCCSI

The Global CCS Institute conducted a study on social acceptance of CCS projects. Their report, "Synthesis of CCS Social Research: Reflections and Current State of Play in 2013," examined more than 25 social research reports prepared by established organizations, including CSIRO. Analysis of the social reports identified seven key themes:

- Framing CCS
- Local context
- Trust
- Communication and engagement processes
- Information
- Risk perception
- Governance

The report also recommended ways in which those developing or funding CCS demonstration projects might generate stakeholder support, as summarized in Figure 5.9.

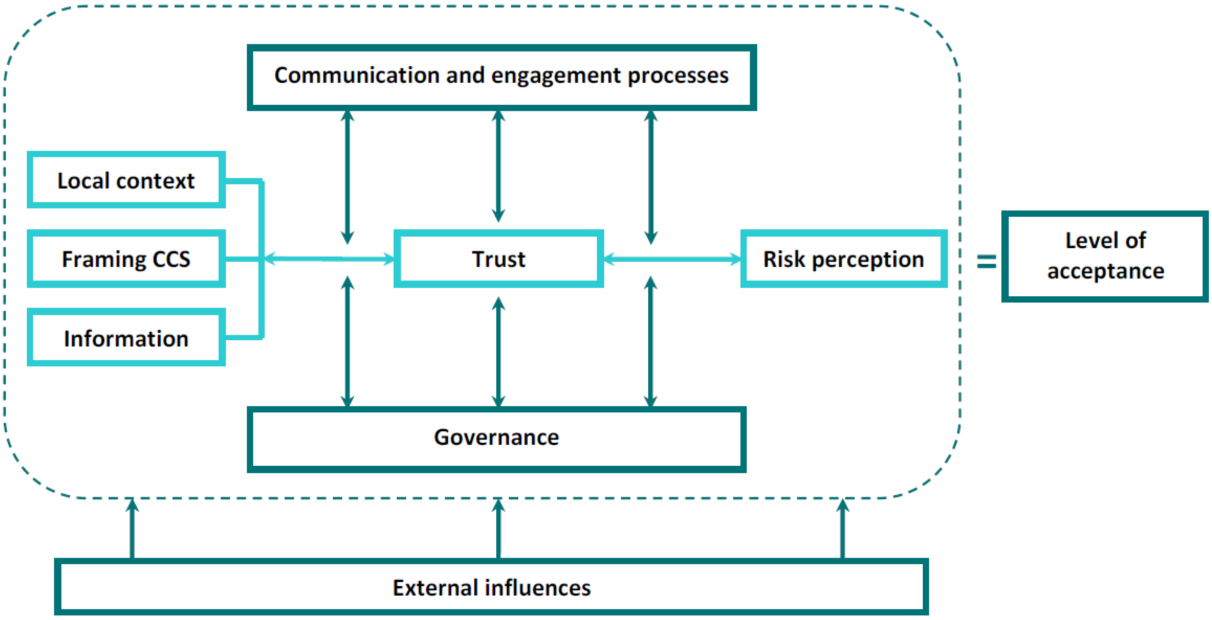


Figure 5.9 A framework of interactions for CCS projects
(Source: Global CCS Institute, 2013)

Based on the framework, it is pertinent to **frame CCS** appropriately in order to accommodate various stakeholder groups, as there is commonly resistance to proposals for CCS as a standalone project. The project proponent needs to take careful account of the **local context** of potentially impacted communities in terms of social, cultural, economic, and political characteristics. In engaging with stakeholders, it is imperative for the project proponent to improve the access to quality, relevant, and factual **information** about CCS and its wider energy and climate change context. The project proponent is encouraged to use a wide variety of engagement processes and tools that promote transparent dialogue and help establish stakeholder relationships. They also need to engage and communicate the project plans well in advance, to avoid any surprise elements. The **communication and engagement processes** should focus on the gaps in local knowledge around CCS that have been identified through the baseline understanding of the local communities. The project proponent needs to ensure that advice and information disseminated to the stakeholders is seen to be trusted, reliable, and informative. These will eventually help to develop **trust** between the project proponent and stakeholders. Government and relevant authorities should play their role in **governing** the proposed project. This should ensure that the project complies with legal requirements and takes stakeholder concerns seriously. Detailed explanations of the key elements and some recommendations for projects proponents are appended to this report. The combinations of these key elements will influence **perceptions of the risks** that the proposed project might impose on stakeholders, which eventually will determine the **level of acceptance** of the project in the short and long term.

5.7 Conclusion

Public acceptance of CCS projects has been identified as a factor in successful development and deployment at a commercial scale. Based on the four case studies, it is apparent that public perception plays a major role in determining the outcome of CCS projects. Some of the key lessons learned from these case studies are:

- Integration of stakeholder engagement and communication functions within project management.
- Develop a good rapport with all stakeholders to gain trust and support for the project.
- Practice a two-way communication strategy to gain insights into the expectations and mutual interests of stakeholders in order to secure public acceptance of the project in the long term.
- Communicate accurate information in a timely manner and be transparent in all communication activities so that the information shared is considered trustworthy.
- Communication and engagement with stakeholders needs to take place prior to the official announcement of the project, in order to minimize any potential element of surprise and to continuously create awareness of the needs of the project throughout each stage, including post-completion of the project.
- Understand local context and develop communication and engagement strategies to suit the stakeholders.
- Technical experts should be trained to communicate project information in a manner that can be easily understood by various stakeholders.

Notably, all the projects currently operational or under construction managed to get accepted by the public. The Lacq Pilot Project in France shows that the local communities will accept a project if they are told about the advantages of the project in a way that can be easily understood by them (see Annex B). In conclusion, it is important to note that there is no single strategy to ensure successful public acceptance of a CCS project. The formula for public acceptance is unique to each project location and dependent on political, social, and cultural diversity.

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6. Perspective on CO_2 utilization

CO_2 is a very stable compound that is usually considered as chemically inert. Unfortunately, many industries associated with the petroleum and petrochemical sectors also produce CO_2 during their activities and their processes, such as fermentation, production of cement, fertilizer, natural gas separation, and power plants. CO_2 has many impacts on the planet, including its role as a GHG.

Increasing population and per capita resource consumption present great challenges to achieving the necessary reductions in global CO_2 emissions. However, carbon capture, utilization, and storage (CCUS) technology is considered promising for CO_2 reduction, and the technologies are developing rapidly. Figure 6.1 provides an overview of CCUS that shows general topics necessary for implementing the technology path.

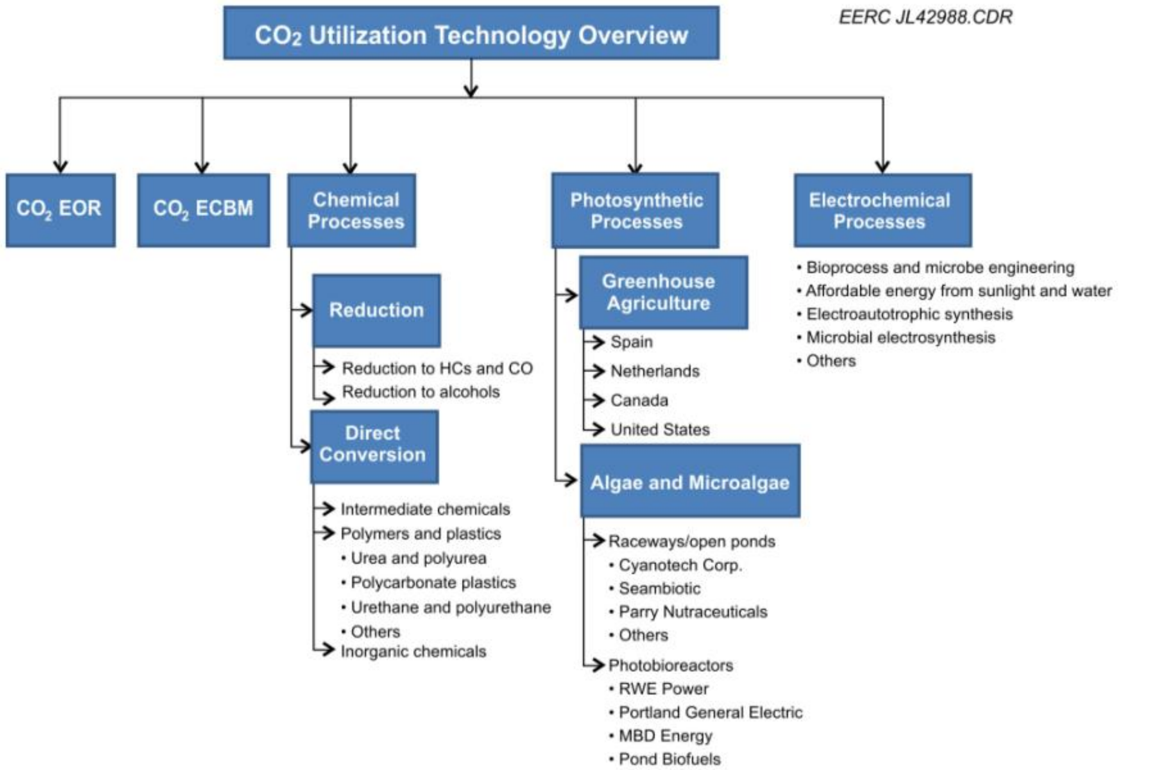


Figure 6.1 A general overview of CO_2 utilization technology
(J.D. Laumb et al. (2013) Energy Procedia 37, 6987–6998)

CO_2 utilization technologies were divided into the following six categories:

- The direct use of CO_2, such as in carbonated beverages, as a dry cleaning solvent, or for energy recovery processes such as EOR or enhanced coal bed methane recovery (ECBM).
- The mineralization of CO_2 by reaction with metal oxides or metal hydroxides to form metal carbonates or metal bicarbonates that may be used in construction materials.

- Use as a feedstock in the manufacture of chemicals, including chemical products or precursor chemicals that require chemical reduction of the carbon to a less oxidized form.
- Use as a feedstock in the manufacture of chemicals including chemical products or precursor chemicals such as urea or bicarbonate that do not require chemical reduction of the carbon.
- Photosynthesis-based technologies that reduce the carbon in CO_2 to organic carbon for use as food, fuel, or a chemical feedstock.
- Novel technologies based on the direct use of engineered microorganisms, electricity, and/or the direct use of sunlight for the production of fuels and/or chemical precursors.

The various technologies are summarized in Table 6.1 below, in terms of the amount of CO_2 utilized:

Table 6.1 Summary of CO_2 utilization technology and CO_2 usage

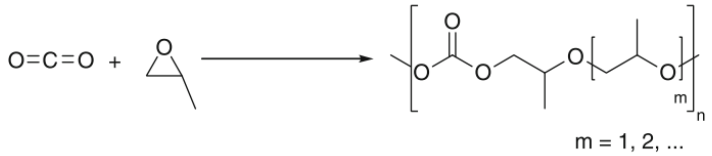
Form of utilization	Usage (tons/year)
Urea production	78,500,000
Cyclic carbonate production	40,000
Salicylic acid production	45,000
Acetylsalicylic acid production	8,000
Methanol production	2,000
Polycarbonate	302,500
Polypropylene carbonate	38,000

Currently, the major technological pathways for CO_2 utilization comprise mineralization, and biological (photosynthetic), electrochemical, and chemical conversion processes. However, at present, few of these technologies are commercially viable. One technology that shows potential for commercial application is the synthesis of cyclic carbonate from CO_2 and epoxide.

6.1 Synthesis of cyclic carbonate from CO_2 and epoxide technology

The technology uses CO_2 and epoxide as raw materials to produce biodegradable plastic. Presently, only polyethylene carbonate (PEC) and polypropylene carbonate (PPC) have been launched to market. However, this technology can also produce plastics from a wide range of epoxides; for example: polybutylene carbonate from butylene oxide and polycyclohexene carbonate from cyclohexene oxide. The products are still undergoing pre-market evaluation because the use of raw materials containing multicarbon compounds will have effects on processing methods and the properties of the resulting plastic, such as degradability.

PEC and PPC can be used to produce foams and elastomers (polyurethane foam), coatings, adhesives, and composite resins for use in the graphic arts. Howsoever, PPC has more advantageous physical properties than PEC, because of its higher glass transition temperature ($T_{g,PPC} \approx 40°C$, $T_{g,PEC} \approx 10–28°C$) and greater stability in different applications. Therefore, the polypropylene carbonate is the product leader for synthesis of cyclic carbonate from carbon dioxide and epoxide. The reaction equation (1) shows the reformation of PPC from CO_2 and propylene oxide.



(1)

The technology necessary for practical production of PPC on a commercial scale has been developed over recent decades. The most important consideration for this technology is the catalyst. Many generations of catalyst have been developed, and have been improved from the first generation of heterogeneous catalyst to the current generation of homogeneous catalysts that are available in ionic liquid form.

Nowadays, propylene carbonate (PC) and PPC catalyst technology is developing rapidly. Earlier technologies used a heterogeneous catalyst as a fixed-base reactor, although it was also suitable for batch and continuous reactor processes. Some problems were encountered with low conversion and impurity of the product, resulting from the catalyst's low stability and narrow active zone. The new generation of PC and PPC catalysts is used in homogeneous form, and many studies have examined the use of ionic liquid catalysts. Normally, this type of catalyst is suitable for use in batch and continuous reactor processes. However, catalyst impurities led to problems of poor degradability of the PPC product performance, such as when excessive concentrations of a homogeneous catalyst (for example, a zinc metal catalyst) remained within the PPC product. Such problems can be overcome with a high-performance reaction and high-stability catalyst, which can achieve high productivity while utilizing a small quantity of catalyst.

Although it is possible to produce environmentally friendly materials from carbon dioxide and propylene oxide, the properties of the resulting plastic remain a concern for many developers. These products offer many advantages for a range of future applications. However, successful commercialization will further investment and development to overcome the remaining technical challenges.

The merits of PPC, when used and/or adapted to an application, include: transparency, toughness, UV-stability, biodegradable/compostable, low smoke density, good gas barrier (H_2O, CO_2, O_2), excellent printability, strong adhesion to glass, and suitability for a range of processes. Furthermore, it is also approved by the US Food and Drug Administration (FDA) and the European Union (EU) for food contact and human health applications. Nevertheless, a remaining weakness is the glass transition temperature. This disadvantage has proven problematic for PPC application, because when pure PPC is processed it is fragile at temperatures in excess of the glass transition temperature (approximately 40°C), resulting in softening and melting. Pure PPC is therefore unstable at high-temperature conditions.

The CO_2 reduction concept would use PPC technology to capture CO_2 in the form of bio degradable plastic. Biodegradable plastic offers potential for direct utilization of CO_2, as the resulting PPC plastic can be degraded by *Rhizopus arrhizus* and *Rhizopus delemar* under suitable conditions of soil pH 5.6–7.2 at 37°C. Although at present, the physical properties of PPC are not appropriate for normal conditions of use, the blending of materials can enhance the performance of PPC and result in a new form of engineering plastic. Many studies have blended PPC with bio-plastics such as polybutylene succinate (PBS), polylactic acid (PLA), and thermoplastic starch (TPS). This resulted in a new material with "win–win" properties: effective gas barrier and stable application. The price of PBS plastic is about 5,000 USD/ton, whereas that of PPC is far lower; PPC could therefore offer a cost-effective blended plastic while retaining some functions of PPC and improving upon the performance of PBS.

On the other hand, when we focus on CO_2 capture, PPC can be utilized by blending with conventional plastics such as polyethylene (PE) and polypropylene (PP) and so on. Furthermore, many licensors such as Bayer have expressed interest in using PPC as a raw material for polyurethane (PU) foam. Although the blending of PPC and conventional plastics results in a non-bio degradable plastic, it would represent a good choice for capturing CO_2 in many viable applications for the reduction of GHG.

Although PPC technology has been available for a long time, there are only a few commercial production lines around the world which are approaching commercialization, such as Nanyang Zhongju Tianguan Low-carbon Technology, Inner Mongolia Mengxi High-Tech Group, and Sumitomo Chemical Co. However, many companies and licensors intend to launch PPC products onto the world market, such as SK Chemicals, Novomer Inc., Bayer, Siemens, and BASF. For example, the PPC market in China is growing, and prices are very competitive at around 3,000 to 5,000 USD/ton depending on PPC grade which is mainly determined by molecular weight, when propylene oxide (PO) and CO_2 prices are around 2,000 USD/ton and 35 USD/ton respectively. Obviously, China is the largest global market for PPC production. One reason is that the Chinese Government has emphasized the carbon credit mechanism, thereby facilitating the establishment and expansion of a commercially viable PPC market. However, this technology has the potential to be commercially successful anywhere in the world, if the producers of engineering plastics develop appropriate PPC applications. It is possible that PPC prices might decline slightly in the near future, because of technological competitiveness, PPC market development, carbon credit options, propylene oxide price, CO_2 price, and demand for PPC consumption.

PPC technology is still developing toward commercial-scale production. Some parts of the world (China) can expand their production to more than 50,000 tons/year (total capacity) at prices between 3,000 and 5,000 USD/ton, but the catalyst technology must be continuously developed. The established leader in PPC catalyst technology is considered SK Chemical in Korea, which is a developer of the catalyst and process technology, although their commercial plant has not been launched yet. Over and above the catalyst performance, the degradability properties of the plastic must be retained, because many catalysts are able to achieve high productivity but contain impurities that inhibit the production of biodegradable plastic for PPC technology. Alongside PPC application, it is necessary to find other possible applications. At the moment, a blending plastic would be more suitable than pure PPC for practical applications. Blended PBS and PPC plastic appears promising for certain applications or end-products and would remain biodegradable.

6.2 PPC Applications

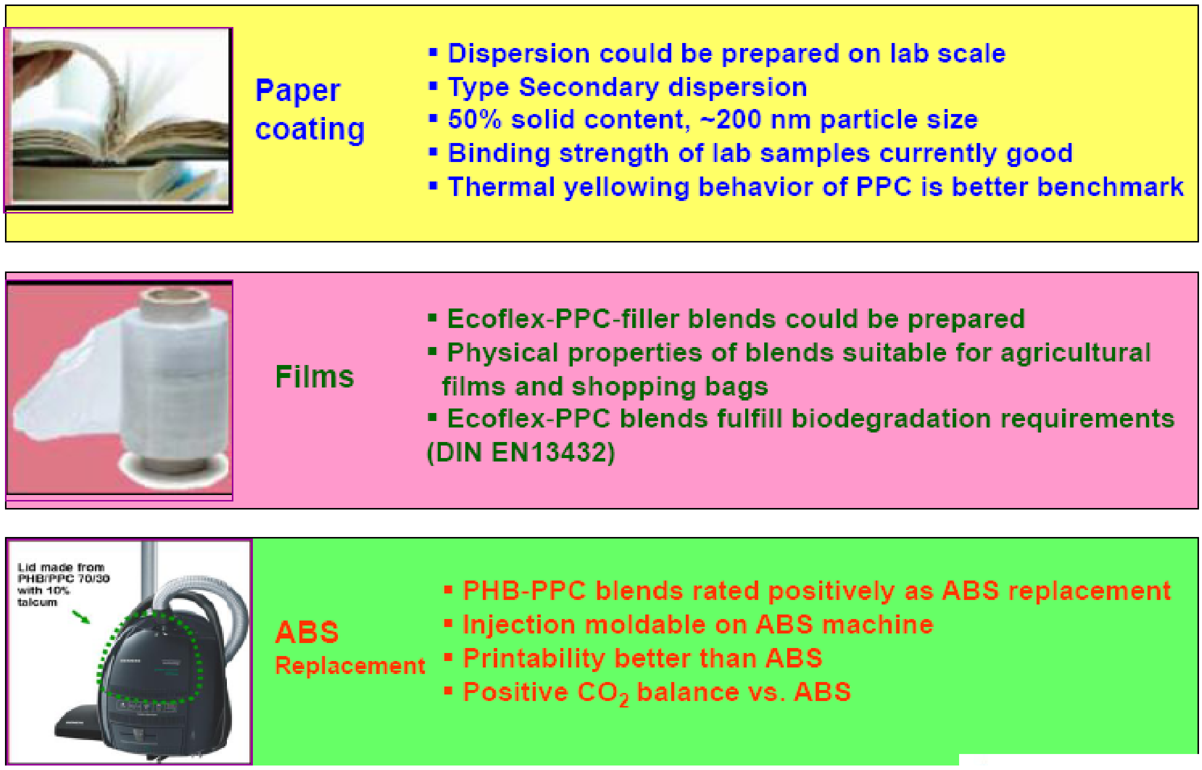


Figure 6.2 PPC applications

Finally, PPC technology is nearing market deployment and will probably be the best alternative technology for CO_2 capture and utilization. The price is highly competitive but suitable applications need to be identified.

6.3 Approach to emerging CO_2 utilization technologies

Besides CO_2 and epoxide technology, photosynthesis or bio-reactor technology is also nearing commercial viability as a means of CO_2 utilization. For many years, researchers and developers have investigated the use of microalgae and bacteria to convert CO_2 into chemicals and fuel. The process employs photosynthesis, by which plants convert CO_2, nutrient, and light into chemicals and oxygen.

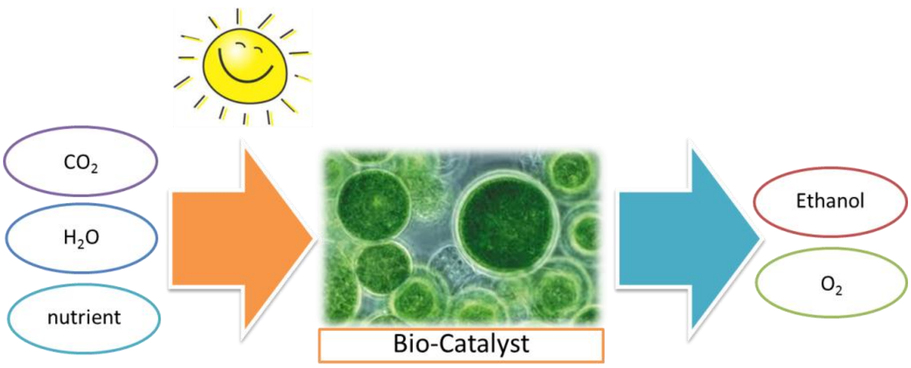


Figure 6.3 Overview of bio-catalyst process converts raw materials to products

Cyanobacteria are one of many algae species that show high possibility of approaching commercial scale, and many studies have achieved ethanol productivity of more than 20,000 Liters/(hectare. year) in suitable locations that have high and long light intensity, surficial CO_2 and water supply, and appropriate temperature of around30–45°C. Many companies in the USA have already reported successful pilot and demonstration plants since 2009, and are making efforts to improve the technology toward commercial viability. However, some barriers to commercial-scale deployment include: ethanol price, productivity, investment cost, finding appropriate locations, the discovery of shale gas, and so on.

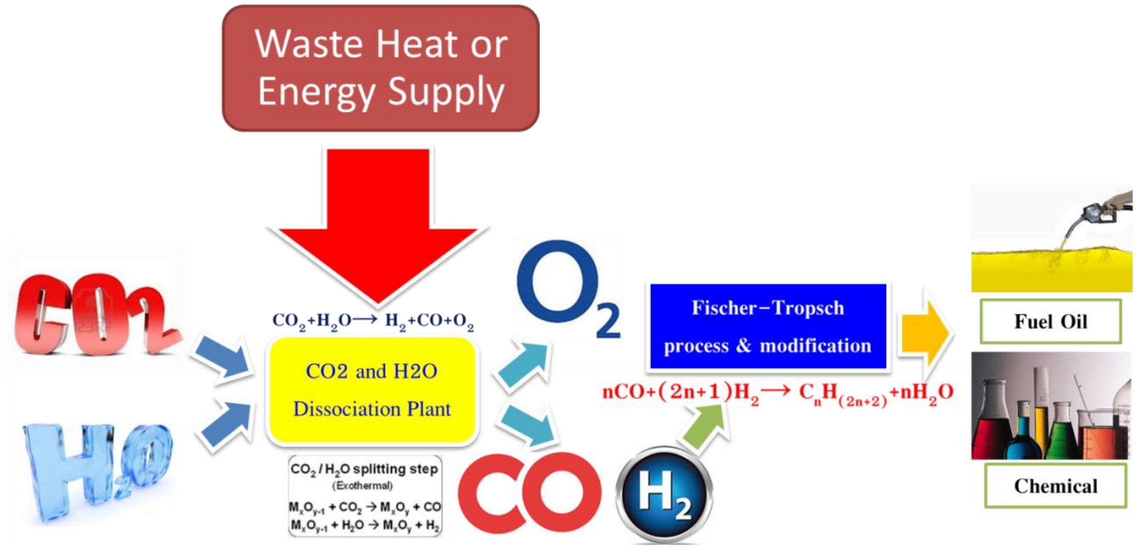


Figure 6.4 Overview of dissociation reaction to convert CO_2 and water to syngas and Fischer–Tropsch technology

Another emerging technology that also shows promise as an integrated waste heat and CO_2-recovery technology is a dissociation technology that can convert CO_2 and H_2O to syngas (CO and H_2). After obtaining syngas from the reaction, it can be used to produce chemicals and fuel by many technologies, such as the Fischer–Tropsch process. However the reaction is problematic because it consumes an amount of heat or energy to convert CO_2 and water to syngas. The developers therefore focus on the integration of waste heat and the reaction.

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7. Conclusions

CCS is expected to be a major contributor to climate change mitigation. The world needs to target a close-to-zero emission rate within this century. If fossil energy continues to be a significant part of the energy mix, this can only be achieved with the development of CCS (IPCC, 2014).

CCS from natural gas will account for a significant part of the global CCS industry, as it will deal with the CO_2 emissions associated with power generation, with production of CO_2 contained in natural gas reservoirs, with natural gas liquefaction, and with industrial applications. One can anticipate that the need for CCS from gas will increase due to the competitive advantages of gas versus other types of energies, at least two of which are connected to climate change issues: firstly, gas emits less CO_2 than coal for a given amount of generated power; secondly, power generation from gas is more flexible than from renewables and will be a candidate to provide back-up capacity to renewable power production.

For many years, the gas industry has developed knowledge, operational skills, and infrastructures that will make it a significant contributor to the development of CCS. On the capture side, it has studied and operated operations by which native CO_2 is separated from natural gas: these technologies can be adapted for combustion processes. It has put in place important transport infrastructures for natural gas, whether liquefied or not: some of these infrastructures can be used when the CCS industry takes off. Finally, the knowledge of geosciences and the experience of operations for gas production will be highly relevant to the storage side: methodologies for estimating CO_2 storage capacity, and methods of operation, including monitoring are—and will be—in many cases derived from those developed by the gas industry.

The CO_2 emissions associated with production from natural gas reservoirs represent an opportunity for the gas industry, because CO_2 is already separated from the marketed natural gas in order to fulfill the market specifications. Thus, the incremental capture costs are much lower than for gas combustion processes. This gives the gas industry a lead to conduct CCS projects and gain additional experience of transport and storage, thereby benefiting CCS from gas and, more generally, CCS from other fossil energies.

Significant investments in research and development, and pilot and demonstration projects are still needed to reduce costs and risks across the whole CCS chain. Due to its development potential, it is essential that a significant share of these investments deals with gas CCS, particularly on the capture side of the chain.

In addition to science, technology, and infrastructures, at least three important factors must be considered for the development of CCS: economics, the legal framework, and public support.

In the early years, public involvement will be necessary to ensure that the industry is economical. This can be achieved via incentives or taxes on CO_2, by cap-and-trade schemes, or mandated requirements. It is important that CCS from gas is considered on an even playing field as CCS from coal, and more specifically, when considering the application to power generation, to consider an economic criterion based on cost of CCS per kWh rather than per ton of CO2. The fact that CCS from gas power generation will require less CO_2 transportation infrastructure and CO_2 storage capacity must also be considered.

An established legal framework is a prerequisite for the development of CO_2 storage. The need to store CO_2 almost permanently is an important issue that requires appropriate consideration everywhere on the globe, particularly in areas with high CO_2 emissions, and where storage capacities are likely to be identified and used for the purpose of CO_2 storage.

The support of the public is an absolute necessity, and will involve many stakeholders. The development of robust and economical monitoring, measurement and verification processes is an absolute necessity to achieve public support.

The gas industry is well placed to provide opportunities for the early developments of CCS projects, and to take a significant share of overall CCS activities.

Annex A

Monitoring, Measurement, and Verification (MMV) in a CCS Project

Monitoring, measurement, and verification (MMV) is the process by which an operator of a CO_2 storage site measures the amount of CO_2 sequestered, monitors the site to ensure storage integrity, and verifies that the stored CO_2 is acting as predicted and without adverse effects on the surrounding ecosystem.

The MMV plan is achieved by different monitoring techniques, such as measuring the pressure of the storage site, seismic sensors, and sensors to detect changes in CO_2 levels at the surface, in order to confidently predict and demonstrate that CO_2 will remain permanently sequestered beyond the lifespan of the CCS project.

The risks associated with storage of CO_2 in geological reservoirs mainly involve the release of CO_2 to the atmosphere, which might contribute significantly to climate change and hazards for humans, ecosystems, and groundwater. However, a reliable MMV plan is required to:

- Verify storage performance conformity, which implies normal operating conditions and assumes that containment can be managed using well-established industry practices for well and reservoir management.
- Verify containment, well integrity, and the absence of any environmental effects outside the storage reservoir.
- Deliver significant additional risk reductions to ensure safeguards that prevent any threats to containment from escape of CO_2.
- Give early warning of potential loss of containment.
- Meet the regulatory requirements defined by legislation and public acceptance.
- Collect sufficient data to enable transfer of long-term liability to the regulatory government authority.

The importance of MMV implementation in a CCS project is clearly defined in the EU Directive on the geological storage of carbon dioxide, which states that:

- Monitoring is essential to assess whether injected CO_2 is behaving as expected, whether any migration or leakage occurs, and whether any identified leakage is damaging the environment or human health.
- The responsibility for the storage site, including specific legal obligations, should be transferred to the competent authority, if and when all available evidence indicates that the stored CO_2 will be completely and permanently contained.

<u>1. MMV Concept and Design</u>

Under normal operating conditions, MMV collects the necessary evidence to verify that the actual storage performance is consistent with expectations. For that, sufficient information gained through monitoring the storage reservoir must demonstrate that:

- All the injected fluids enter the intended disposal formation.
- No fluids migrate out of the storage reservoir.

- The development through time of CO_2 plumes and fluid pressures inside the storage reservoir is consistent with model-based predictions.

Although unlikely, there is the possibility of CO_2 migrating out of the storage reservoir. In order to protect against this possibility, MMV must also provide:

- Multiple independent monitoring systems with the sensitivity, speed, and scale to ensure reliable early warning of any potential loss of containment.
- Intervention options to prevent and attenuate any potential consequences due to the potential loss of containment.

In order to assess the main risk in CO_2 geological storage, one needs a full understanding of the processes and pathways for release of CO_2, which exists as a separate phase (supercritical, liquid, or gas) and may escape from formations used for geological storage through the following pathways regardless of the storage type:

- Through the pore system in low-permeability cap rocks such as shales, if the capillary entry pressure at which CO_2 may enter the cap rock is exceeded;
- Laterally, along unconformities or along porous rocks that end at the sea bottom or land surface;
- Through openings in the cap rock or fractures and faults;
- Through man-made pathways, such as poorly completed and/or abandoned pre-existing wells.

2.1 MMV Approach

An MMV plan should be designed according to the risk associated with the geologic characteristics of the storage reservoir. MMV activities will mainly focus on detecting unlikely events that may occur during the life of the carbon storage and sequestration facility. Tailoring MMV activities to the particular qualities of the individual storage site will maximize the additional protection of the storage reservoir against leakage.

The MMV planning strategy requires a systematic approach to risk assessment, as the range and balance of the MMV activities are designed for the site-specific qualities of the storage reservoir. The initial available appraisal and site characteristics form the foundation of the initial conceptual MMV design. As more information becomes available during further appraisal and early operations, the MMV plan will need to adapt to accommodate the ever-increasing understanding of the storage area.

Figure A.1 below illustrates the steps involved in developing a reliable monitoring and measurement plan.

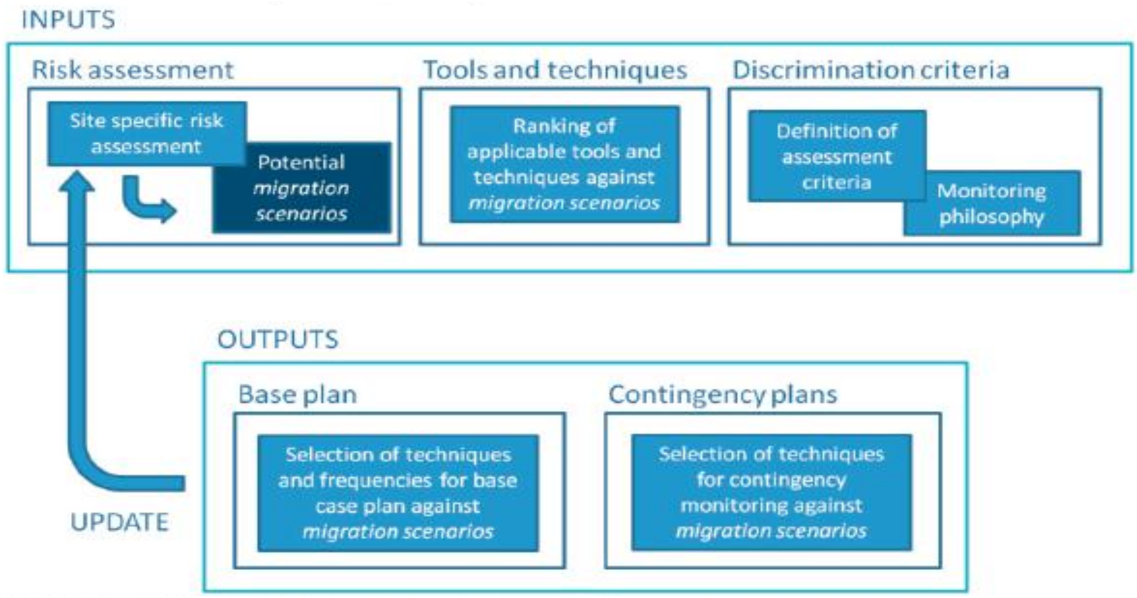

Figure A.1 Steps in the development of the monitoring plan

Various approaches to MMV planning specify that the site characteristics of the storage area represent the first step in developing a monitor program. Most elements of site characterization are considered to be normal practice, based on existing regulations for subsurface oil and gas activities.

Following site characterization, the second step involves developing a working hypothesis as a risk assessment perspective on important mechanisms that control the behavior of injected CO_2. This is based on a fundamental understanding of the processes active in the ground at the pore level, and is guided by available injection and monitoring data. Simulations are used to predict temporal and spatial migration of the injected gas plume, the effect of geochemical reactions on trapping of CO_2 and long-term porosity and permeability, in addition to caprock and wellbore integrity.

Hypothetical simulation is considered the most critical step in the systematic development of a monitoring program for a particular geological storage site because selection of an appropriate measurement method is based on whether it can provide the data necessary to answer a particular technical issue.

There are three levels of monitoring applicable to commercial or non-commercial fields (operational monitoring, verification monitoring, and environmental monitoring), as shown in the figure below, depending on targeted geological levels.

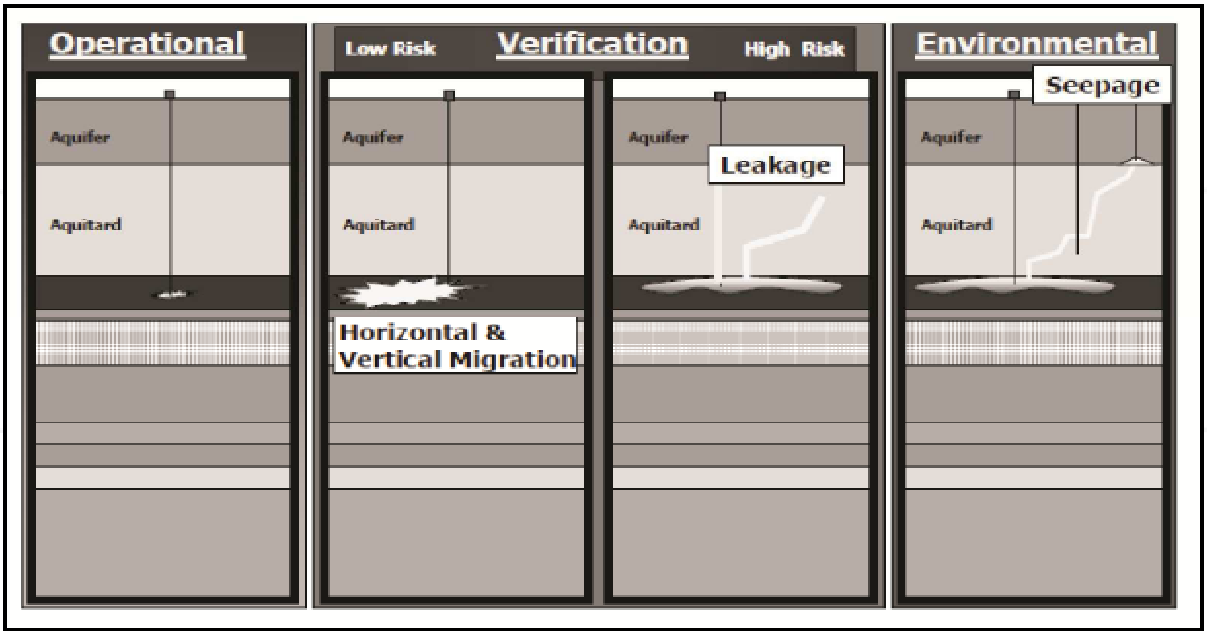

Figure A.2 Monitoring objectives, as a function of the monitored geosphere targets

These levels represent an increasing progression of monitoring intensity, duration, and technology deployment, as described below:

- Operational Monitoring: refers to the monitoring and control of in situ processes by changes in injection strategy, based on measured variables such as down-hole pressure and fluid composition. Before injection, it is important to establish a baseline to help identify any changes resulting from injection. Minimal requirements are specified by regulations, and additional operation monitoring is guided by the ongoing complexities of injection and production.
- Verification Monitoring: refers to additional measurements that improve the understanding of complex processes occurring in situ. This level of monitoring is linked to predictive modeling. Models are refined based on the history of the measured variables, important mechanisms are hypothesized, and future behavior is predicted.
- Environmental Monitoring: refers to monitoring aimed at safeguarding against risks to health, safety, and the environment. Depending on the risk level of the project, aspects of environmental monitoring may be part of operational monitoring.

2.2 MMV Design Principles

The need for monitoring of a CO_2 storage site is essentially to monitor the performance of the storage site and to detect early warning signs of leakage to demonstrate that a CO_2 plume is evolving towards permanent stability, as required by appropriate regulations or directives, for example the EU CCS Directive.

In general, the MMV plan is designed on the following principles:

- Regulatory Compliance: The MMV plan shall comply with specific regulatory requirements from national and international organizations involved in the CCS projects.
- Site Characterization: This is the initial risk assessment and implementation of initial safeguards through site selection, site appraisal, and selection of site-appropriate engineering concepts.
- Risk-based: Monitoring tasks are identified through a systematic risk evaluation. The scope and frequency of monitoring tasks depend on the findings of this risk assessment. Project safeguards are implemented to minimize storage risks as far as reasonably practicable.
- Site-specific: Monitoring technologies are selected for each monitoring task based on the site-specific assessments, to ensure optimal monitoring performance under local conditions particular to the storage site.
- Adaptive Evaluation: The performance of the storage site and the monitoring systems are continuously evaluated. Control measures should be implemented to ensure effective responses to any unexpected events.

The extent of an MMV plan is determined by the life cycle of a CCS project and the implementation phases of the monitoring activities. The MMV baseline is identified in the project planning stage and is implemented prior to the injection operation, as indicated in Figure A.3 below, which shows the life cycle of a CCS project.

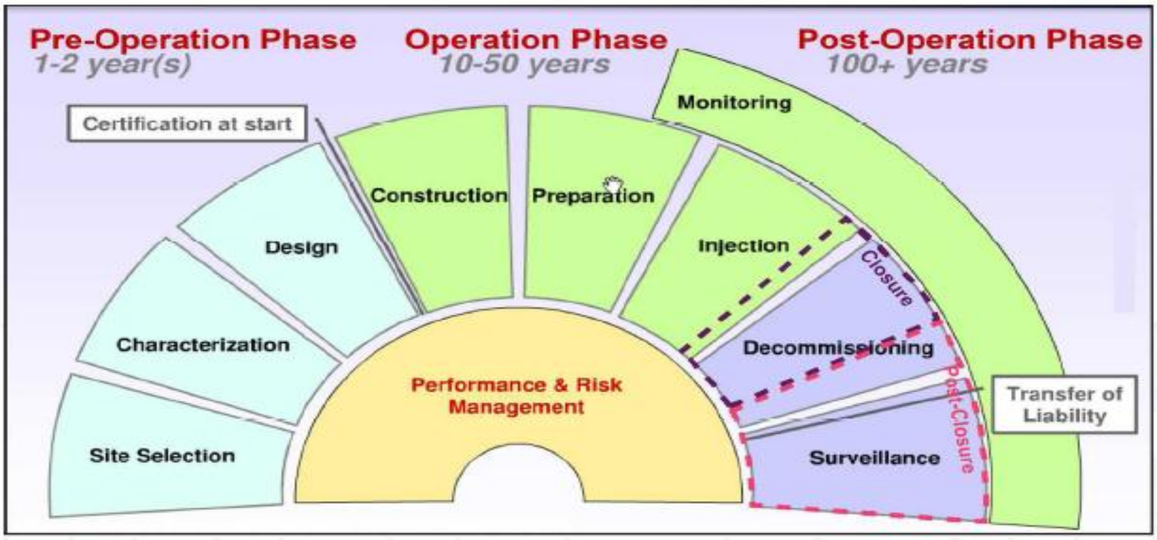

Figure A.3 Life cycle of a CCS project (Modified, after Marquette, 2010)

The operation phase deals with verification of the injection rate, tacking the plume location, and detection and prevention of any environmental impact. The post-operation phase can be divided into two periods: site closure and post-closure. The closure phase implies the end of CO_2 injection, the decommissioning of the injection wells and surface facilities, and confirmation of long-term storage security. The post-closure phase aims to decommission the monitoring wells and complete the records that will be provided to the regulatory authorities. Long-term monitoring may only be needed if long-term storage security is not established.

For the security of the CCS project, the MMV plan should satisfy appropriate minimum standards for design requirements and characteristics. The international Energy Agency (IEA)

Model Regulatory Framework suggests the following guidelines and criteria for the MMV program and throughout the life cycle of the CCS Project:

- Providing baseline data on CO_2 and assessing the integrity of a storage formation;
- monitoring injection facilities, a storage site (including the CO_2 plume), and the surrounding environment;
- comparing ongoing monitoring data with baseline data;
- assessing actual behavior of the plume and anticipated future behavior of the plume through modeling;
- detecting and assessing significant leakage of CO_2, unintended migration of CO_2, or other irregularities;
- quantifying the volumes of CO_2 associated with leakage or unintended migration;
- assessing the effectiveness of any corrective actions taken;
- including post-closure monitoring.

2.3 Updating MMV Plans

In general, the monitoring plan will be reviewed by the regulator on a five-year interval. Updates will be based on revised static and dynamic models that incorporate the results from monitoring and verification surveys.

Updated strategies should specify any shortcomings in history matching and could include options for new/updated technologies or technological improvements. History matching is the comparison of observed behavior of the injected CO_2 in the storage site with the behavior predicted by the dynamic modeling.

Three circumstances would initiate a revision to the original monitoring plan:

- Unexpected plume migration behavior during injection operation.
- Migration of CO_2 out of the primary containment formation but within the storage reservoir.
- Changes in the cost and detection limits of monitoring technologies. This can be expected to occur as monitoring technologies for CCS are in their infancy, especially in the offshore environment.

3. MMV Technologies

An integrated MMV program must include technologies to track CO_2 through the entire CO_2 storage area. The figure below describes the different monitoring targets of the bio- and geo-sphere for both onshore and offshore CO_2 storage sites:

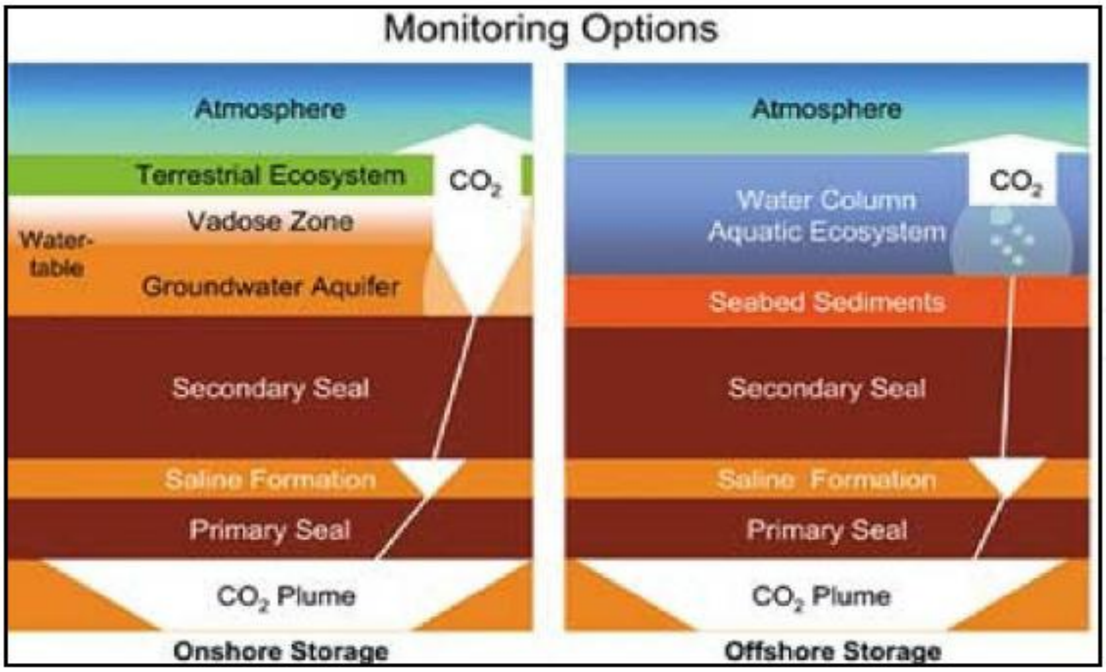

Figure A.4 Monitoring targets for onshore and offshore CO_2 storage sites

MMV technologies range from seismic survey to monitoring of soil gas, pressure, and well fluids. A complete MMV program includes many technologies and is specific to the needs to the project. Various MMV technologies will be utilized at different stages of the project (pre-injection, injection, closure, post-closure) and to demonstrate various parameters to the public and regulators.

3.1 MMV Technology Classification

The MMV technologies covering either the environmental or the operational monitoring criteria can be classified into five categories:

- In-well monitoring.
- Geochemical monitoring.
- Geophysical monitoring.
- Near-surface monitoring.
- Surface deformation monitoring (SDM).

Many available technologies have independent capabilities for measuring different physical, chemical, or biological changes, whereas other technologies provide similar or overlapping capabilities. The frequency of monitoring and the region of coverage are both critical factors affecting the value that each technology offers for MMV.

Surface deformation monitoring (SDM) has recently become available to improve the seismic-based imaging methods used for many years.

In-well Monitoring:
In-well monitoring provides direct measurements of down-hole changes, made either by permanent sensors incorporated into the well design or by occasional petro-

physical logging or well integrity testing that require well intervention.
The obtained data primarily measure the well logs and wellhead pressure.
This category provides detailed information about changes within the well and the near-well environment (approximately 5 m), but provides no information about changes further afield.

Geochemical Monitoring:
In addition to control of the CO_2 injection rate and pressure, chemical changes throughout the subsurface are monitored using geochemical measurements within observation wells. These measurements are made either by permanent sensors incorporated into the well design or by occasional collection of fluid samples from the well for laboratory analysis.
Fluid samples from observation wells are generally used to monitor changes in brine composition or the presence of tracers.
The most rapid and inexpensive on-site measurement parameters for geochemical monitoring are PH, alkalinity, and gas composition.
This category of MMV technology may provide detailed information about the transport and reaction of chemical species above the storage reservoir, indicating any loss of containment and its potential impacts.

Geophysical Monitoring:
These are methods of monitoring physical changes throughout the subsurface using remote sensing techniques. This category of MMV technology may provide detailed images of the spatial distribution of CO_2 and increased pore fluid pressure within or above the selected storage reservoir.
Several methods are used to observe the migration of the CO_2 plume. Seismic imaging can detect changes in wave velocity and attenuation caused by the presence of CO_2. Electromagnetic imaging can detect decreases in electrical conductivity when CO_2 is present in rock pores as a separate phase. Gravity measurements are sensitive to the decrease in bulk rock density when CO_2 is present. To date, seismic imaging has been used most extensively and with great success.

Near-surface Monitoring:
These are methods of monitoring near-surface changes within the biosphere or atmosphere. This form of monitoring is mainly achieved by periodic control of atmospheric CO_2 concentrations, and by measuring emissions from the capture system and surface facility to ensure worker and public safety. In case of an offshore CCS project, seawater gas CO_2 monitoring is conducted to protect the marine ecosystem, including different organisms and corals.

Surface Deformation Monitoring:
SDM measures ground surface movements of CO_2 using tilt-meters, or may be determined from satellite or radar images such as InSAR (Interferometric Synthetic Aperture Radar), as shown in the figure below.
This category of monitoring has the potential to provide near-real-time notification of subsurface CO_2 leakage deep in the Earth.
Surface deformation monitoring is generally used in combination with coupled geochemical and geophysical monitoring to provide a reliable MMV program.

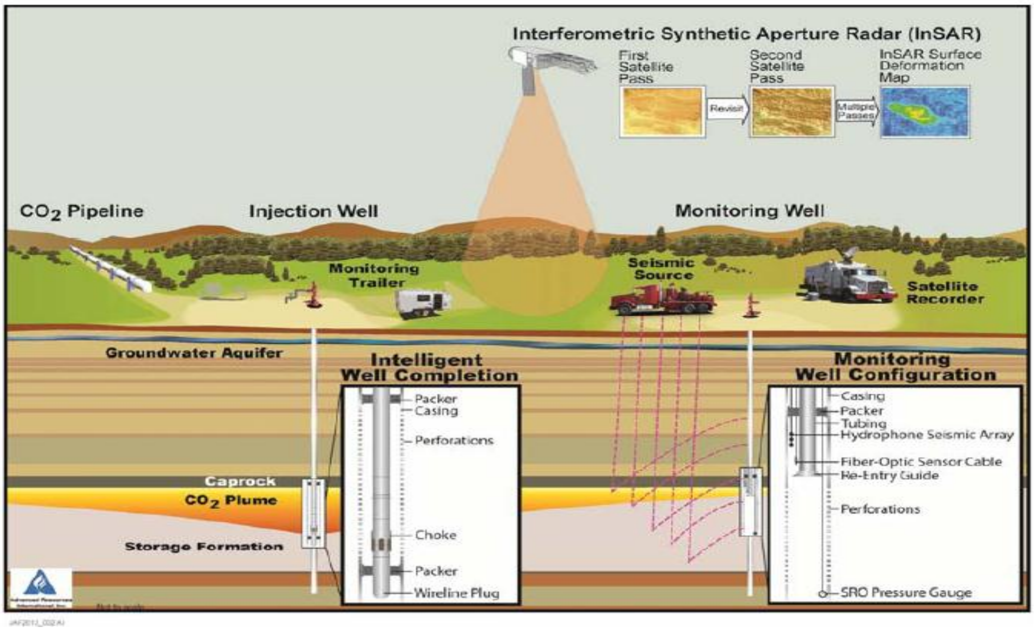

Figure A.5 Methods of measuring ground surface movements of CO_2

The classical monitoring programs that are used over the lifetime of a sequestration project are presented in the table below (Source: Benson et al.).

Table A.1 Classical monitoring programs used over lifetime of sequestration project

Basic monitoring program	**Enhanced monitoring program**
Pre-operational monitoring	*Pre-operational monitoring*
Well logs Wellhead pressure Formation pressure Injection- and production-rate testing Seismic survey Atmospheric-CO_2 monitoring	Well logs Wellhead pressure Formation pressure Injection- and production-rate testing Seismic survey Gravity survey Electromagnetic survey Atmospheric-CO_2 monitoring CO_2-flux monitoring Pressure and water quality above the storage formation
Operational monitoring	*Operational monitoring*
Wellhead pressure Injection and production rates Wellhead atmospheric-CO_2 monitoring Microseismicity Seismic surveys	Well logs Wellhead pressure Injection and production rates Wellhead atmospheric-CO_2 monitoring Microseismicity Seismic survey Gravity survey Electromagnetic survey Continuous CO_2-flux monitoring Pressure and water quality above the storage formation
Closure monitoring	*Closure monitoring*
Seismic survey	Seismic survey Gravity survey Electromagnetic survey CO_2-flux monitoring Pressure and water quality above the storage formation Wellhead pressure monitoring

3.2 Monitoring Tools

A wide range of monitoring tools has been used in different CCS project, whereas others are currently being evaluated by other projects or are at the research and development stages. In order to understand some of the most important tools used in MMV, a summary is presented in Table A.2 below, emphasizing the lessons learned from implementation of these technologies and their principal capabilities.

Table A.2 Tools used in MMV technology

MMV Technology	Advantages
3D seismic baseline survey	Improved quality 3D seismic baseline survey with imaging of overburden
4D seismic monitoring	Significant benefits for overburden imaging and time-lapse responses with improved acquisition plan, but is costly.
Micro-seismic monitoring	Micro-seismic data are very useful for monitoring geochemical response to injection. Consider deploying a full array with relatively cheap, shallow wells.
Satellite InSAR monitoring	Extremely valuable and cost-effective for monitoring onshore CO_2 injection sites. Requires calibration (e.g. Digital GPS) and careful processing of atmospheric and surface artifacts.
Tracers in CO_2 injection wells	Valuable and cost-effective method for checking the origin of O_2 observations at wells and in the storage area.
Core analysis (storage unit)	Good geophysical data are essential. Rock mechanical properties are especially critical.
Core analysis (cap-rock unit)	Core sampling throughout most of the cap-rock interval is desirable for assessing long-term storage integrity.
Well log data	An advanced array of well logging tools is extremely valuable; resistivity image logs and sonic array are especially useful for storage integrity issues.
Soil and surface gas sampling	Need for more reference data on natural C variations in different environments and associated seasonal fluctuations.
Groundwater monitoring wells	Establishing local and regional hydraulic gradients and natural variations in water chemistry is essential for establishing a useful baseline for groundwater hydrology.
Seawater Gas Monitoring	The effects of CO_2 on the marine ecosystem are monitored via oceanographic measurements and continuous physical-chemical monitoring.

4. MMV Experiences

To understand the different techniques used in an MMV program, cases studies of six MMV plans throughout the world (four commercial projects and two research projects) are presented, with lessons learned from their implementation and utilization.

4.1 Sleipner West Field Project, Norway

The Sleipner project off the Norwegian coast, which started CO_2 injection in 1996, is considered the world's first commercial CCS facility. It utilized an MMV program based on time-lapse seismic surveys, drawing on core analysis, wireline logging, geochemical monitoring, pressure/temperature, and injection rate monitoring, as well as micro-seismic and gravitational techniques.

> *The migration of the CO_2 is readily monitored using 4D time-lapse seismic surveys. The results have shown that the injected CO_2 has migrated neither towards the Sleipner installations, nor upwards into the cap rock shales.*
> *High quality monitoring data also lowers the detection threshold for any potential leakage, which increases the confidence in the storage projects. At Sleipner, 4D seismic monitoring is of sufficient quality to confirm that there are no signs of leakage into the overburden.*

4.2 Weyburn Project, USA/Canada

The Weyburn project started in 2000, to recover CO_2 from the Dakota Synfuels plant in the Unites States and inject it into the Weyburn EOR field in Canada. It has used a broad range of MMV technologies including time-lapse seismic surveys, core analysis, wireline logging, geochemical sampling and analysis, cross-well seismic monitoring, and sampling of the soil and atmosphere to ensure retention of the injected CO_2.

> *The research project program (phases I and II) on monitoring techniques used has been successful, with tremendous learning and extensive data collected.*
> *CCS is gaining important attention, and so the Weyburn CO_2 monitoring and storage project, along with the Government of Canada, have come together to create a website to support the sharing of experience between the Weyburn community, project operators, and researchers.*

4.3 In Salah Gas Project, Algeria

The In Salah gas project in the southern Sahara of Algeria started CO_2 injection in 2004. It uses an MMV program based on seismic core, wireline logging, geochemical sampling and analysis, monitoring of pressure/temperature/injection rate, micro-seismic monitoring, gravitational surveys, differential InSAR, soil/shallow surface and atmospheric monitoring techniques, as well as tracer-based monitoring.

> *The InSAR data have proven highly valuable in monitoring millimeter-scale surface deformation related to subsurface pressure changes caused by injection and production.*
> *CO_2 plume development is highly heterogeneous and requires high-resolution reservoir characterization and specific modeling.*
> *Rock mechanical data, fractured rock characterization, and geochemical modeling were more important than initially anticipated.*

4.4 Snøhvit Project, Norway

The Snøhvit project off the Norwegian coast, operated by Statoil, started CO_2 injection in 2008. It has mainly used an MMV program based on time-lapse seismic surveys, pressure monitoring, along with time-lapse gravimetric surveys.

> *Statoil experienced a gradual rise in reservoir pressure as CO_2 injection progressed, more rapidly than predicted by reservoir modeling. The limited injection rate and capacity was a cause for concern and was investigated by use of a repeat seismic survey and 4D processing in 2009.*
> *The results of this analysis indicated that the reservoir permeability was lower than expected. A well intervention operation was successfully completed in May 2011 and the injection continues successfully.*
> *Lessons learned should include the need for extensive characterization of reservoir bulk permeability, particularly far-field effects with respect to initial well testing.*

4.5 Nagaoka Project, Japan

The "Research and Development of Underground Storage for CO_2" project is located at Nagaoka, Japan and is managed by the Research Institute of Innovative Technology for the Earth. Injection started in July 2003 and ended in January 2005.

> *This CCS project has mainly used core analysis, wireline logging, geochemical sampling and analysis, injection operation monitoring, and cross-well seismic and micro-seismic detection to monitor CO_2 injection during the operation phase.*

4.6 CO_2 Sink Project, Germany

The CO_2 Sink injection project at Ketzin, Germany started injection in April 2004 and is considered the first demonstration and research project of onshore CO_2 storage in Europe. It was designed to use surface seismic, core analysis, wireline logging, and geochemical monitoring of formation fluids in and above the storage area; injection rate/in situ pressure and temperature monitoring, cross-well seismic, and surface/shallow subsurface monitoring techniques.

> *An array of geochemical investigations were also being used to monitor variations in fluid composition pre- and post-injection. Microbial analysis, such as FISH (Fluorescent In Situ Hybridization) was used to study processes linking the injected CO_2, the rock substrate, the formation fluid, and micro-organisms.*

5 Costs Associated with MMV

The MMV costs for a CCS project are mainly associated with drilling observation wells, monitoring operation activities, and a final seismic survey. These costs can be impacted by poorly engineered data and poorly integrated sensor systems.

In accordance with the EU CCS Directive, MMV costs during injection operations and for 20 years prior to complete abandonment can contribute between 4% and 13% of total costs to the emitters, depending on the project timeframe. Extending the MMV period from the end of the injection operations to complete abandonment, would effectively delay abandonment (which can account for up to 50% of total capital costs). The further into the future the end of injections operations, the lower the impact of MMV on total costs on a net present value basis.

There are only a limited number of studies and reports focusing specifically on the cost of CO_2 storage in a CCS facility. However, we present in this report the costs associated with MMV plans from European and Canadian studies.

According to a recent study on the costs of CO_2 projects in the EU, published in 2010 by the European Technology Platform for Zero Emission Fossil Fuel Power plants (ZEP), six cases are highlighted (see Figure A.6, below) for onshore and offshore projects, where MMV costs can vary from 0.6 to 1.8 euros per stored ton of CO_2.

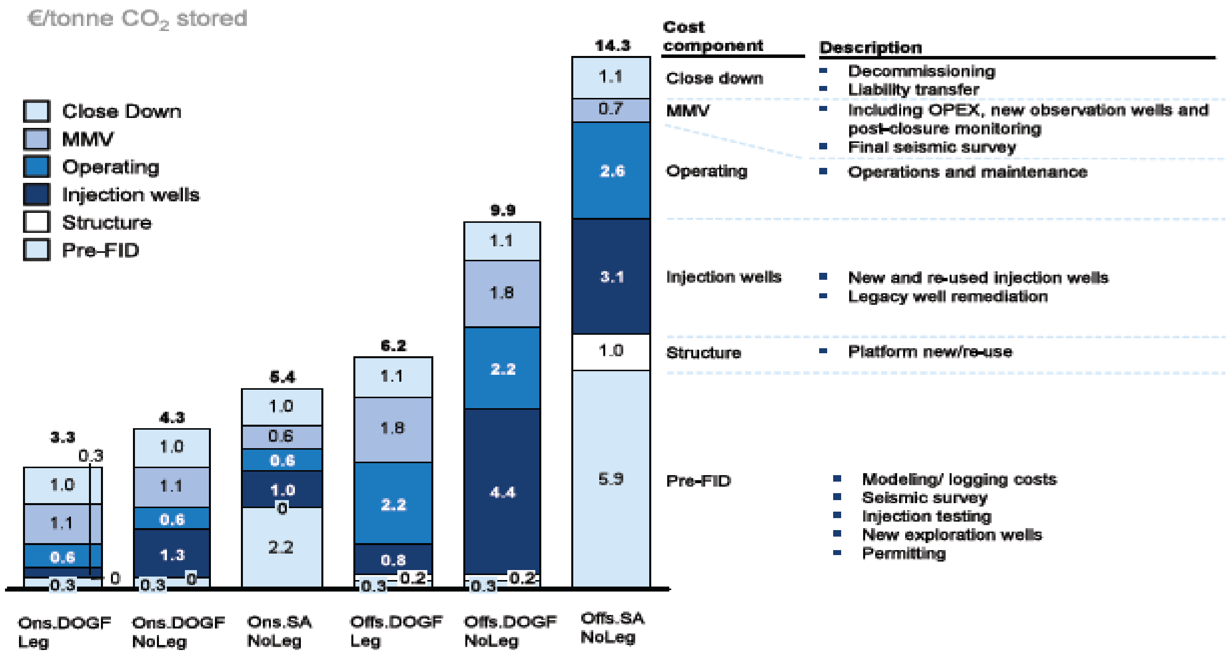

Figure A.6 Breakdown of costs for onshore and offshore CCS projects

In some cases, MMV costs could be reduced if exploration wells could be reused as injector wells or observation wells. Similarly, the pre-FID (Final Investment Decision) seismic survey may lead to cost savings for MMV, in the event that no new baseline survey would be required.

If we take as a reference a CCS project consisting of an onshore deep saline aquifer, from the last figure we have for Ons.SA the MMV cost is 0.6 euros, which is about \$0.8 per ton of stored CO_2.

On the other hand, and based on a recent report published by Trans Alta corporation in 2013 regarding the Pioneer CCS Project, the sequestration capital costs estimation covering the MMV activities are presented in Table A.3 below:

Table A.3 Sequestration capital costs estimation by Trans Alta Corporation

	1 Million Tonne Case	3 Million Tonnes Case
Wells	$7.9 million	$16.2 million
Seismic	$4.6 million	$10.3 million
MMV	$0.7 million	$1.2 million
Staff	$6.1 million	$7.2 million
Lease and Regulatory Fees	$0.4 million	$0.6 million
Contingency	$2.5 million	Not defined
Total	$22.2 million	$35.5 million

For the Pioneer Project, the MMV associated cost was $0.7 per ton of stored CO_2.

In general, and according to different CCS projects around the world, the costs associated with MMV are within the range of $0.5 to $1 per ton of stored CO_2.

5.1 MMV Technology Cost

Based on actual costs from 2007/2008 CCS projects and estimates from various vendors, a report was published in 2009 on MMV costs associated with various techniques, as presented in Figure A.7 below.

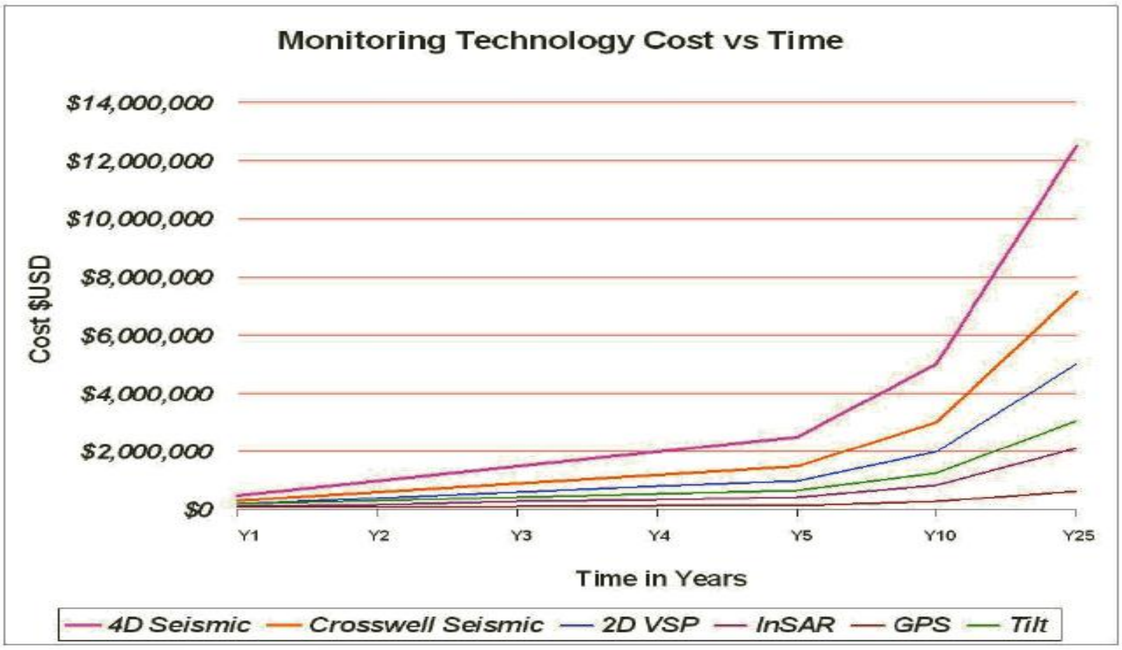

Figure A.7 MMV monitoring costs

It can be seen that, for a limited storage site, SDM technologies are individually less expensive than seismic-based technologies and may offer a 2- to 6-fold cost advantage over a monitoring period of ten years. If we expand the area to be imaged, new monitoring wells will have to be drilled from cross-well and VSP surveys, and costs for large seismic shoots will escalate to millions of dollars. On the other hand, InSAR costs will, for the most part, remain the same. It is primarily in larger, full-scale injections that the tremendous cost benefit of SDM technologies becomes apparent.

6. Challenges for MMV Development

The development of an effective monitoring program will ultimately depend on the nature of the storage location. Once characterization process has been undertaken and any risks of leakage and/or environment impacts evaluated, a monitoring program can be established that will take into account the possible risks and migration pathways for CO_2.

MMV will remain an area of development with a need for better tools to predict the capacity of reservoirs and the lateral and vertical movement of injected CO_2 over time. This is especially the case, since most of the technical or public concerns expressed are linked to the long-term effects on storage areas and the possibility of either gradual or slow leakage.

Despite the variety of MMV technologies, some techniques are becoming standard, particularly down-hole pressure and temperature sensors; others, such as 3D seismic, are proving themselves to be powerful tools if they can be utilized appropriately. Characterization of the local rock/fluid/stress system is very important and appropriate baseline measurements are critical.

6.1 MMV Implementation Concerns

Concerns have been expressed about the technical integrity of carbon storage at potential sites, and the associated environmental and health risks. Projects such as Weyburn, In Salah, and Sleipner have demonstrated that commercial quantities of CO_2 can be injected into the subsurface, and that the gas will not return to the surface. However, more work still needs to be done and the major barriers to the deployment of CO_2 injection in saline formation addressed in order to gain public and regulator acceptance for bulk CO_2 storage. Some of these barriers are listed below:

- Differences in geological formations cause the containment at some sites to be more certain than others; thus, as demonstrated in some CCS projects around the world, detailed knowledge of the regional geology is very important.
- In an MMV plan, comprehensive understanding of the geological factors affecting the CO_2 plume distribution is important, since the geologic and flow characteristics such as permeability and porosity, capillary pressure, lateral and vertical permeability, anisotropy, geologic structure, and thickness all influence the plume distribution to varying degrees. Depending on the variations in these parameters, one may dominate the shape and size of the plume.
- Seismic monitoring is not necessarily applicable to all geologic storage projects, especially where the storage target is located below a tick salt/evaporate section, as may be the situation for some deep saline aquifers. Further research is required to

confirm whether the observed seismic response to CO_2 injection is due to pressure or saturation changes, and to identify the general application limitations of seismic monitoring.

- MMV techniques need to be better developed, and research should be focused more on CO_2 properties, geophysical data of reservoirs, measurement of rock properties, and on modeling tools.
- Clear regulatory and legal protocols for injection of CO_2 into saline aquifers or elsewhere have to be developed.

6.2 Research and Development in MMV

The major concern in a CCS monitoring program is to avoid any leakage from the reservoir, by tracking the injected CO_2 throughout the life time of the project. To ensure this objective, protocols and technologies are developed for tracking the behavior of the injected CO_2 in the reservoir and to understand what is happening in the cap rock. Not all potential reservoir rock beds are the same, and researchers are developing techniques and technologies that will provide better monitoring in difficult situations. At the Sleipner project, for instance, better results are obtained using only seismic imaging to monitor CO_2.

However, for the different geology of Alberta, seismic monitoring alone is not sufficiently sensitive to detect small changes. Refining seismic monitoring and developing other complementary monitoring methods is therefore critical to the advancement of CCS projects in Canada and for confidence in CCS around the world. Various studies have been undertaken by Carbon Management Canada (CMC), mainly examining the effects of in situ CO_2 phase changes (gas, liquid and super-critical) on the seismic properties of the rock.

Future geochemical research into CO_2 storage monitoring will be carried out to identify fluid resources and explain the physicochemical processes occurring during the injection operation. Assessing the relationships between chemical changes of the rock and fluid composition, and the evolution of porosity and permeability induced by mass transfers during percolation is necessary. Recently, isotopic monitoring has also been performed during flow-through experiments, consolidating the interpretation of cation concentration evolution, and allowing quantification of trapping. Emissions quantification technologies that measure dissolved CO_2 in the water column and free CO_2 at the surface are in development, along with specific down-hole and seabed fluid sampling systems. These technologies will require further testing, especially in the marine environment, in which there is a gap in quantification and detection of CO_2.

The Aquistore CCS project in Canada is one of the best examples of a research project where an innovative MMV program will test and develop effective methods of monitoring CO_2 storage sites and ensure conformance of the storage process through continuous monitoring.

One unique element of the Aquistore MMV program is the project's permanent seismic array, as shown in the next figure. Traditionally, 3D seismic is the primary technology for CO_2 monitoring. Though effective, 3D seismic can be relatively costly. In March 2012, the project installed a permanent seismic array consisting of many geophones, used in comparison with a traditional 3D seismic survey. Aquistore's permanent array aims to demonstrate a significantly more cost-effective seismic acquisition method.

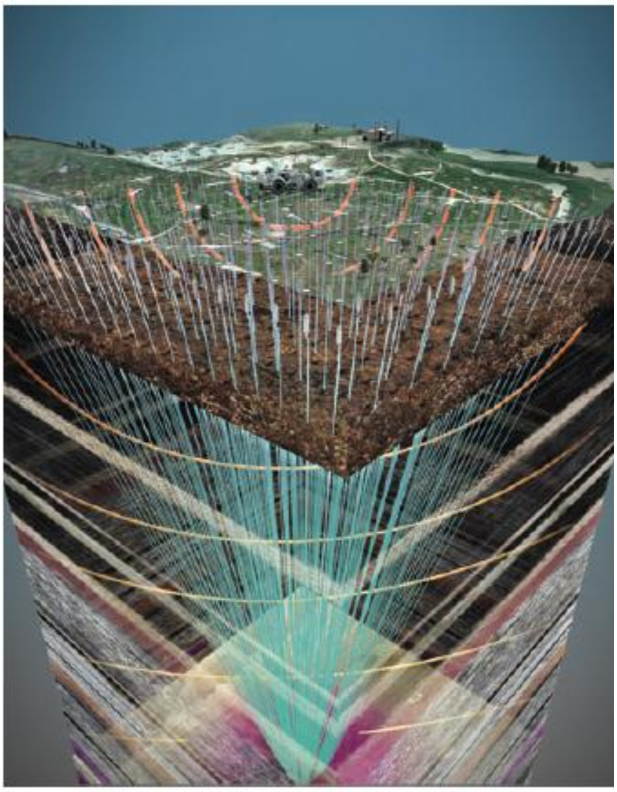

Figure A.8 An illustration of Aquistore's permanent seismic array

7 Conclusion

The principal technology used for remotely monitoring CO_2 storage in a CCS project is seismic imaging, but necessary supporting technologies include well logging, gravity surveys, and tilt-meters, and interferometric synthetic aperture radar (InSAR) for surface deformation measurements. Integration of geophysical, geochemical, and geomechanical datasets will also need to be undertaken. Seismic imaging fulfills a principal role in monitoring because no other method can match its volumetric coverage and resolution; however, major issues relate to poorly constrained and highly non-linear seismic response gas saturation relationships, and the poor repeatability of seismic surveys. For CCS in general, potential challenges exist for CO_2 capacity, injectivity, pressure management, and resource interface.

Going forward, more work is required on monitoring technologies and techniques. In particular, further work is required on costs, needs, data interpretation, on triggers for communication with regulators, and especially the need for public engagement.

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Annex B

CCS integrated Lacq project and public perception

This project has the following four characteristics:

- It is an integrated project that involves all operations from capture (combustion) to storage.
- It is based on gas-fired combustion.
- It uses oxycombustion technology.
- In this project, CO_2 is stored in a depleted natural gas reservoir.

The industrial chain became operations from January 8, 2010. Over the next three years, more than 51,000 metric ton of CO_2 was successfully injected in the Rousse reservoir.

Explaining the project to stakeholders

TOTAL developed and implemented a method to foster clear understanding of the stakes of the CO_2 pilot among local residents, elected representatives, citizens' groups, government officials and local economic actors. The method consists of the following methods:

Launching a stakeholder consultation: In 2007, well before the administrative authorization and public inquiry procedures, TOTAL held meetings with the local population to provide them information and answer their questions on the future CO_2 capture-transport-storage pilot. At the same time, an exhibition, a website, and an opinion register for comments were made available to the general public.

Creation of a local information and monitoring commission (CLIS) to keep associations, elected representatives, government officials, and neighboring populations informed of the project's progress. Since 2007, the minutes of meetings have been published on the website of the regional planning authority (DREAL).

Forming a scientific committee: Its members (French Ministry for Ecology, Sustainable Development and Energy, Institute of Earth Physics Paris (IPGP), French Geological Survey (BRGM), French Environment and Energy Management Agency (ADEME), French Academy of Sciences, French National Center for Scientific Research (CNRS), French Institute of petroleum and New Energies (IFPEN), and French National Research Agency (ANR)) do not belong to the company, and hence, they have an independent expert view. The scientific committee has met seven times since the project became operative in January 2010.

Informing local inhabitants: A newsletter entitled "CO_2 capture and geological storage in the Lacq basin" is being published quarterly by TOTAL E&P France since the start of injection and is sent by name to the people living close to the installations.

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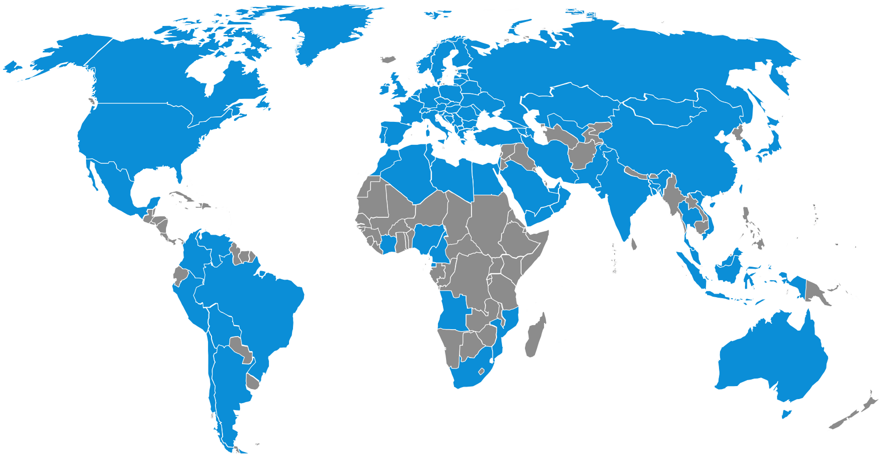

The International Gas Union (IGU) was founded in 1931 and is a worldwide non-profit organisation promoting the political, technical and economic progress of the gas industry with the mission to advocate for gas as an integral part of a sustainable global energy system. The IGU has more than 142 members worldwide and represents more than 97% of the world's gas market. The members are national associations and corporations of the gas industry. The working organisation of IGU covers the complete value chain of the gas industry from upstream to downstream. For more information please visit **www.igu.org**

Address: Office of the Secretary General
c/o Statoil ASA, P.O. Box 1330, Fornebu, Norway

Telephone: +47 51 99 00 00
Email: secrigu@statoil.com
Website: www.igu.org

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